

Chemical and isotopic studies of well discharge fluid of the Mataloko geothermal field, Flores, Indonesia

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Abstract: The discharge fluid in a single vapor phase from the exploration well MT-2, drilled to a depth of 162.35 m in the Mataloko geothermal field, Flores Island, Indonesia, is relatively low in non-condensable gas content (0.61 - 0.69 wt%) and its gas component is predominant in CO₂ (91 mole%). The discharge steam is thought to be derived from a liquid water-dominated reservoir existing at a deeper level. Isotopic compositions of hydrogen, oxygen, carbon, sulfur and helium, and chemical composition of minor gases in the discharge fluid from the well MT-2 suggest that its water vapor (H₂O) consists of mainly meteoric water affected by magmatic water or water-rock interaction, while the gaseous components originate mainly from magmatic fluid. Based on several chemical and isotopic geothermometers and measured bore hole temperatures of the well MT-2, the subsurface temperature is estimated to be 192 - 230 °C at the shallow steam-dominated reservoir and 270 - 306 °C at the deep water-dominated reservoir. The discharge steam from the exploration well MT-1 and fumaroles, which are located within 200 m from well MT-2, shows chemical characteristics similar to well MT-2. It suggests that they are derived from a common source, that is a deep water-dominated reservoir possibly having a relatively large extension in the Mataloko field.

1. Introduction

A five-year international cooperation project on geothermal research between Japan and Indonesia, "Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia", was signed in 1998 by three organizations, New Energy and Industrial Technology Development Organization (NEDO; Japan), Geological Survey of Japan (GSJ) and Directorate General Geology and Mineral Resources (DGGMR; Indonesia). One of the main objectives of the project is a geothermal resource assessment of a selected model field, namely the Bajawa geothermal area located in Flores, Nusa Tenggara, Indonesia (Fig. 1). Various geoscientific surveys including geological, geochemical and geophysical surveys have been conducted in and around the Bajawa area since 1998 (Nastion *et al.*, 1999; Matsuda *et al.*, 2000; Muraoka

et al., 2000; Takahashi *et al.*, 2000; Takashima *et al.*, 2000; Yasukawa *et al.*, 2000).

The Mataloko geothermal field, located in southeastern part of the Bajawa area, is one of the most active geothermal fields in the Bajawa area and its activity is manifested by many fumaroles, hot springs and acid altered grounds. Based on the survey results at Mataloko, a site was selected, and three shallow exploration wells were drilled; one well (MTL-1) by VSI (Volcanological Survey of Indonesia); one of the institutes belonging to DGGMR in 1999 and the other two wells (MT-1 and MT-2) by NEDO in 2000 - 2001. The discharge test at the well MT-2 was successfully carried out in NEDO's research program in January 2001. We collected the discharge fluids during the test for chemical and isotopic analyses. This paper describes the geochemical investigation results on the discharge fluids from the well MT-2 and other geothermal fluids occurring in Mataloko, and discusses the geothermal reservoir characteristics of the Mataloko field.

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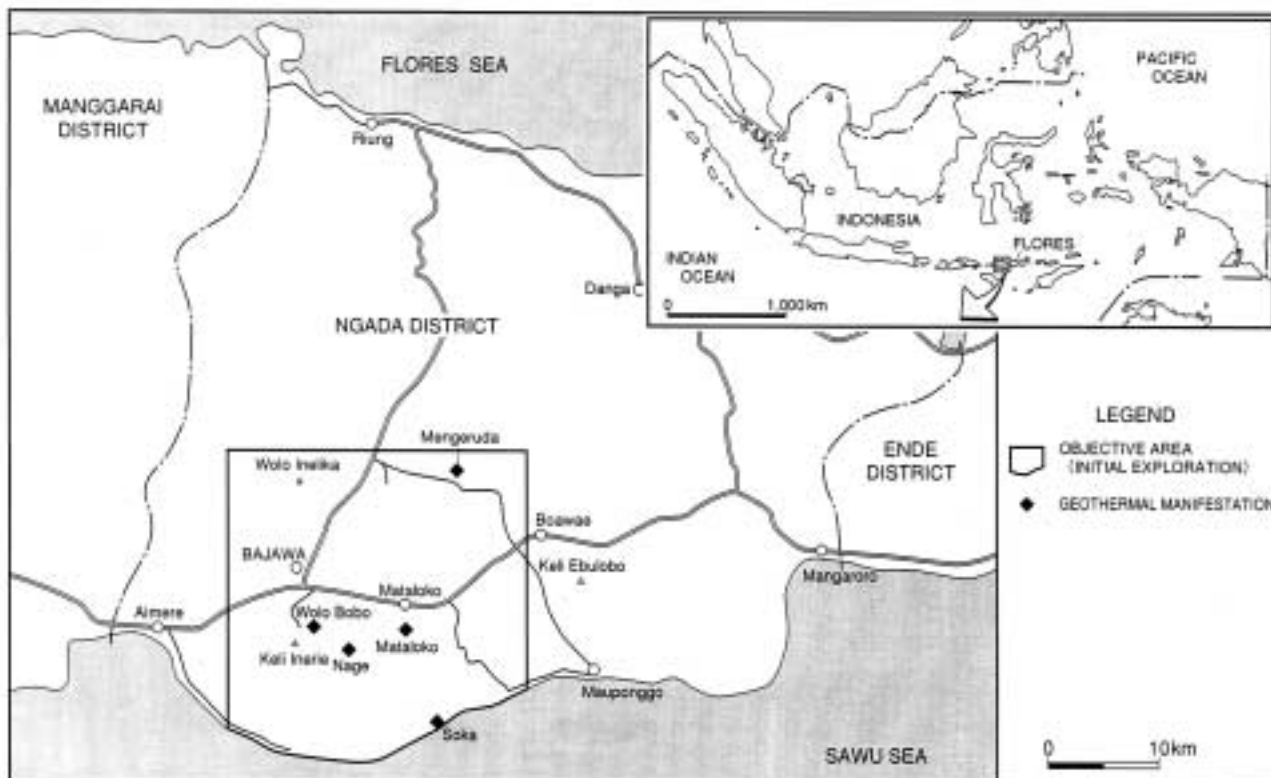


Fig. 1 Location map of Flores Island and Mataloko geothermal field. The target area on the map is for the initial exploration in FY 1999 for "Research Cooperation Project on Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia".

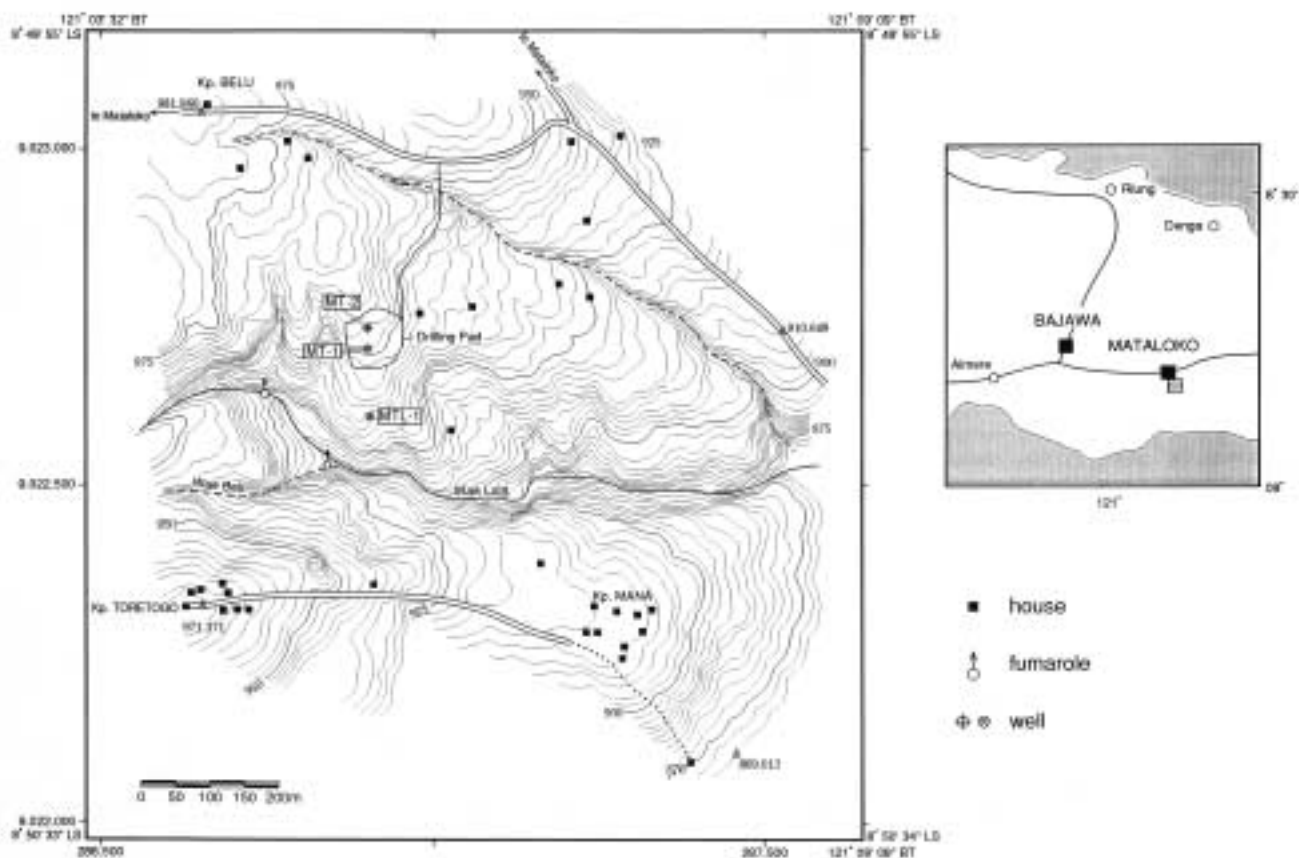


Fig. 2 Location map of exploration wells in the Mataloko geothermal field.

2. Well drilling results

All three exploration wells (MTL-1, MT-1 and MT-2) were drilled on the northern side of the Wae Luja River which flows west to east through the Mataloko surface thermal manifestations (Fig. 2). The intervals between wells MTL-1, MT-1 and MT-2, aligned north-south, are 100 m and 32 m respectively.

Both wells MTL-1 and MT-1 encountered a shallow steam layer during their drilling works at depths of 103.23 m and 207.26 m respectively, and steam was blown out unexpectedly. The discharge steam temperature measured at the well head was 115 °C at well MTL-1 and 150 °C at well MT-1. Further drilling below these depths was impossible so the wells were filled with cement without any well tests, i.e. P-T logging, and injection and discharge tests.

The well MT-2, as well as the other two wells, encountered a steam layer at a depth of 162.35 m, but the steam discharge was controllable. Although complete well tests were not able to be carried out, the bottom-hole temperature at a drilling depth of 104 m was measured. The maximum temperature was 130.4 °C (6.83 hrs after mud circulation stopped) while the temperature was continuously increasing at the end of measurement. The discharge test at the well MT-2 using the Russel-James method (critical lip pressure method; James, 1962) was conducted at the end of January 2001. During the whole discharge period of the test, the discharge fluid was a single vapor phase and no liquid phase discharge was observed. The measured largest steam flow rate was calculated to be 4.57 kg/s (16.5 tons/hr) with the wellhead pressure of 0.37 MPaG, assuming a saturation state (not super-heated) at the end of discharge pipe. After the discharge test, the well was drilled further to the depth of 178.00 m. A borehole logging survey was conducted two months after the drilling in April 2001, and the highest temperature of 192.3 °C was measured near the bottom of the hole (175.0 m).

According to the observation of drill cuttings of the three wells, they consist of altered andesitic lavas and pyroclastic flows which are classified as Bajawa Caldera Volcanics by Takahashi *et al.* (2000) or Mataloko Andesite by Muraoka *et al.* (2000). The wells did not reach older marine sediments (Miocene or Pliocene strata; Muraoka, 2000) which may underlie the young volcanics. Hydrothermal alteration minerals detected by X-ray diffractometer in drill cuttings of wells MT-1 and MT-2 are montmorillonite, kaolinite, heulandite, wairakite, quartz, cristobalite, feldspar, calcite and pyrite with minor chlorite/montmorillonite mixed-layer, sericite/montmorillonite mixed-layer, yugawaralite, epistilbite,

alunite, gypsum, anhydrite, goethite, magnetite and gibbsite. The occurrence of wairakite with minor yugawaralite at depths below 140 m in both wells and logging data collected after additional drilling imply the existence of hydrothermal activity at a temperature around 200 °C in the deeper part of the wells.

3. Sampling and analytical procedures

Three steam samples of the well MT-2 were collected during the discharge test on January 23 - 25, 2001 at different discharge conditions, i.e. wellhead pressures of 0.42, 0.59 and 0.32 MPaG for each sample. Steam from the well was collected using a small separator connected with a horizontal flow pipeline. Steam samples of the well MT-1 were collected in October 2000 for reference at its wellhead with flowing from bleeding line. Sampling of fumaroles and gases from a hot spring was conducted in September 1999 prior to the well drilling. The gas samples were collected at fumaroles at Mataloko (Fig. 2), a fumarole at Wolo Bobo and an acidic hot spring at Nage (Fig. 1).

The steam and gas sampling was carried out following Ozawa (1968) at the well MT-2 and fumaroles, and following Giggenbach (1975) at the well MT-1. The fluid was drawn into a glass syringe or an evacuated bottle containing a 5N NaOH solution. Gas analysis was conducted by a combination of volumetry (H₂O, CO₂ and H₂S), gas chromatography (N₂, H₂, CH₄, O₂, Ar, He and Ne) and mass spectrometry (³He/⁴He, δ¹³C(CO₂), δ¹³C(CH₄), δD(H₂), δD(CH₄) and δ³⁴S(H₂S)). For analysis of δ¹³C(CO₂) and δ³⁴S(H₂S), the gas sample was introduced into solutions of Ba(OH)₂ and Cd(CH₃COO)₂ at the sampling site to fix the CO₂ as BaCO₃ and H₂S as CdS. Steam condensate analysis was conducted by ion chromatography (Cl) and mass spectrometry (δD(H₂O) and δ¹⁸O(H₂O)).

4. Results

Results of the chemical and isotopic analyses are shown in Tables 1 and 2. The MT-2 discharge steam exhibits constant chemical characteristics at wellhead pressures from 0.32 to 0.59 MPaG. They are relatively low in non-condensable gas (NCG) content (0.61 - 0.69 wt%), and their main constituents are C O₂ (90.8 - 91.0 mole%) and H₂S (6.3 - 6.6 mole%). The rest of the NCG component is mostly composed by N₂ and H₂ (ca. 93 mole% in residual gas). The chloride content in steam condensates is low (<0.02 mg/kg), implying the HCl gas does not contribute to the discharge gas. Hydrogen and oxygen isotopic compositions of the steam (-28.5 - -27.7 ‰ and -5.3 - -5.1 ‰, respectively) approximate those of the local

Table 1 Result of chemical analyses of well discharge fluids and fumarolic gases.

Source	Sampling date	Well head pressure MPaG	Discharge temperature °C	Gas content mole%	Gas composition			Residual gas composition							Condensate Cl mg/kg
					CO ₂ mole%	H ₂ S mole%	Residual gas mole%	N ₂ mole%	H ₂ mole%	CH ₄ mole%	O ₂ mole%	Ar mole%	He mole%	Ne mole%	
<i>MT-2 well discharge</i>															
MT-2a	2001/1/23	0.42		0.26	90.8	6.6	2.6	51.2	42.0	6.4	0.06	0.22	0.042	<0.0005	0.02
MT-2b	2001/1/24	0.59		0.29	91.0	6.3	2.7	52.7	40.4	6.6	0.06	0.18	0.066	<0.0005	<0.01
MT-2c	2001/1/25	0.32		0.26	90.8	6.5	2.7	50.4	42.7	5.9	0.76	0.17	0.043	<0.0005	<0.01
<i>MT-1 well discharge (unstable condition)</i>															
MT-1a	2000/10/25			0.22	50.6	3.0	46.4	89.3	0.76	-	9.9	-	-	-	-
MT-1b	2000/10/25			0.11	88.7	5.6	5.8	87.2	11.2	-	1.6	-	-	-	-
MT-1c	2000/10/26			0.32	83.8	6.0	10.2	26.4	73.6	-	n.d.	-	-	-	-
<i>Mataloko fumarole</i>															
G-1	1999/9/27		96.0	1.36	93.5	3.4	3.2	85.8	2.6	11.2	0.05	0.35	0.061	<0.0005	-
G-2	1999/9/28		95.8	0.95	92.0	4.8	3.2	73.9	17.5	8.2	n.d.	0.31	0.049	<0.0005	0.29
<i>Nage hot spring gas</i>															
G-3	1999/9/25		71.9	100	79.1	0.5	20.4	95.5	0.01	n.d.	3.0	1.47	0.008	0.0017	-
<i>Wolo Bobo fumarole</i>															
G-4	1999/9/26		94.7	1.31	91.3	5.6	3.2	84.6	0.22	0.16	14.2	0.84	0.035	<0.0005	0.9
G-4*	1999/9/26		94.7	1.31	93.3	5.7	1.0	98.1	0.68	0.49	0	0.64	0.106	-	-

n.d. : not detected, - : not analyzed

* : Air free corrected

Table 2 Result of isotopic analyses of well discharge fluids and fumarolic gases.

Source	Sampling date	Well head pressure MPaG	Discharge temperature °C	δD	$\delta^{18}O$	$\delta^{13}C$	$\delta^{13}C$	δD	δD	$\delta^{34}S$	$^3He/^4He$
				(H ₂ O)	(H ₂ O)	(CO ₂)	(CH ₄)	(H ₂)	(CH ₄)	(H ₂ S)	$\times 10^6$
				‰SMOW	‰SMOW	‰PDB	‰PDB	‰SMOW	‰SMOW	‰CDT	
<i>MT-2 well discharge</i>											
MT-2a	2001/1/23	0.42		-28.5	-5.2	-4.5	-30.4	-504	-215	-2.8	6.85±0.09
MT-2b	2001/1/24	0.59		-27.7	-5.3	-4.4	-	-	-	-	-
MT-2c	2001/1/25	0.32		-28.3	-5.1	-4.9	-	-	-	-	-
<i>Mataloko fumarole</i>											
G-1	1999/9/27		96.0	-37.0	-5.4	-3.6	-27.7	-582	-189	-2.8	6.80±0.05
G-2	1999/9/28		95.8	-60.0	-10.5	-3.9	-25.0	-583	-162	-2.7	6.62±0.07
<i>Nage hot spring gas</i>											
G-3	1999/9/25		71.9	-	-	-4.5	n.d.	n.d.	n.d.	-10.3	4.95±0.04
<i>Wolo Bobo fumarole</i>											
G-4	1999/9/26		94.7	-47.0	-7.4	-4.8	-18.0	n.d.	n.d.	-4.3	5.53±0.07

n.d. : not determined, - : not analyzed

meteoric water.

The steam chemical composition of the well MT-1 varies due to the unstable discharge and sampling conditions (Table 1). However, the steam composition is roughly comparable to the well MT-2. The samples MT-1b and MT-1c show similar contents of CO₂ (88.7 and 83.8 mole%) and H₂S (5.6 and 6.0 mole%) in NCG as well MT-2, even though their NCG contents do not correspond to each other (0.11 and 0.32 mole% in steam).

Fumarolic gases of Mataloko (samples G-1 and G-2) also exhibit comparable chemical compositions to

the well MT-2, though they are relatively high in NCG, CO₂/H₂S and N₂, and low in H₂ (Table 1). With respect to the isotopic composition, the sulfur and helium isotopic ratios of fumarolic gases are comparable to those in the discharge gas of the well MT-2, and similar in carbon isotope ratio (CO₂ and CH₄) (Table 2).

5. Discussions

5.1 Origin of discharge fluid

The relatively low NCG content, CO₂ dominant

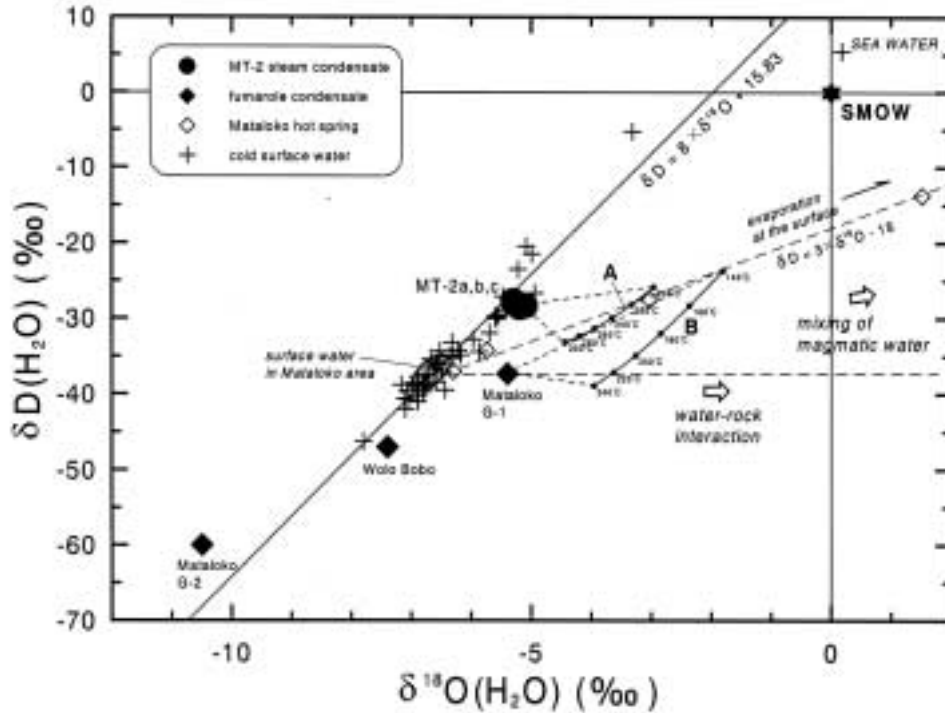


Fig. 3 Hydrogen and oxygen isotopic compositions of thermal fluids and cold surface waters. The data for hot spring waters and cold surface waters are from Matsuda *et al.* (2000). See text for details and discussion.

gas composition and almost no contribution of HCl gas in the well MT-2 discharge steam suggest that the steam is derived from a hot water reservoir possibly existing at a deeper level underlying the well and not derived directly from the magma body. As shown in Fig. 3, hydrogen and oxygen isotopic compositions of the steam are plotted very close to the local meteoric water line that was established based on the isotopic data of cold surface waters in the target area (cf. Fig. 1). It suggests the MT-2 water vapor (H_2O) originates in mainly meteoric water. However, the δD and $\delta^{18}O$ values of the steam are higher than the surface waters in the Mataloko area by 10 ‰ and 1.5 ‰, respectively. Since the discharge steam is possibly separated from the water in the deep reservoir, the influence of the vapor-liquid isotopic fractionation should be taken into account in estimating the isotopic compositions of the deep reservoir fluid. In Fig. 3, the curve A represents the estimated δD and $\delta^{18}O$ values of reservoir water that is assumed to be in an isotopically equilibrium with the well MT-2 steam separated in a single-step boiling at temperatures of 200 - 300 °C. If this assumption on the boiling condition is appropriate, the estimated isotopic ratios show a significant positive shift from the values of surface waters in the Mataloko area, suggesting that the reservoir water is contributed by magmatic water. The isotopic ratios shown as curve B in Fig. 3 are estimated by using the data of Mataloko fumarolic steam (sample G-1) assuming steam separation in a

single-step boiling at temperatures of 140 - 240 °C. These isotope ratios also suggest the contribution of magmatic water; but when the separation temperature is assumed to be about 220 °C, the estimated isotopic composition of the reservoir water exhibiting only $\delta^{18}O$ positive shift could be explained by a water-rock interaction. Consequently, the reservoir water yielding the steam of well MT-2 and fumaroles may originate in meteoric water that isotopically shifted a significant degree, though it is not defined whether the positive shift occurred due to the contribution of magmatic water or water-rock interaction. On the other hand, steam-heated acidic hot spring waters accompanying the fumaroles in Mataloko represent a large isotopic shift as shown in Fig. 3. However, the line with a slope of 3.0 connecting the data points is likely to show a kinetic isotope effect due to surface evaporation at a relatively low temperature (Giggenbach, 1982). The δD and $\delta^{18}O$ values of steam from a Mataloko fumarole (sample G-2) are considerably small, suggesting that the fumarole is affected by secondary steam occurring at a shallow level.

The contribution of magmatic fluid to the steam of well MT-2 (and Mataloko fumaroles) is evidently indicated by the chemical and isotopic data of the gaseous components. The carbon isotope ratios ($\delta^{13}C$) for CO_2 in the steam ranging from -4.9 to -4.4 ‰, as in Table 2, agree well with those of the mantle derived carbon (from -8 to -3 ‰; Hoefs, 1987) and are lower than those of oceanic carbon (about 0

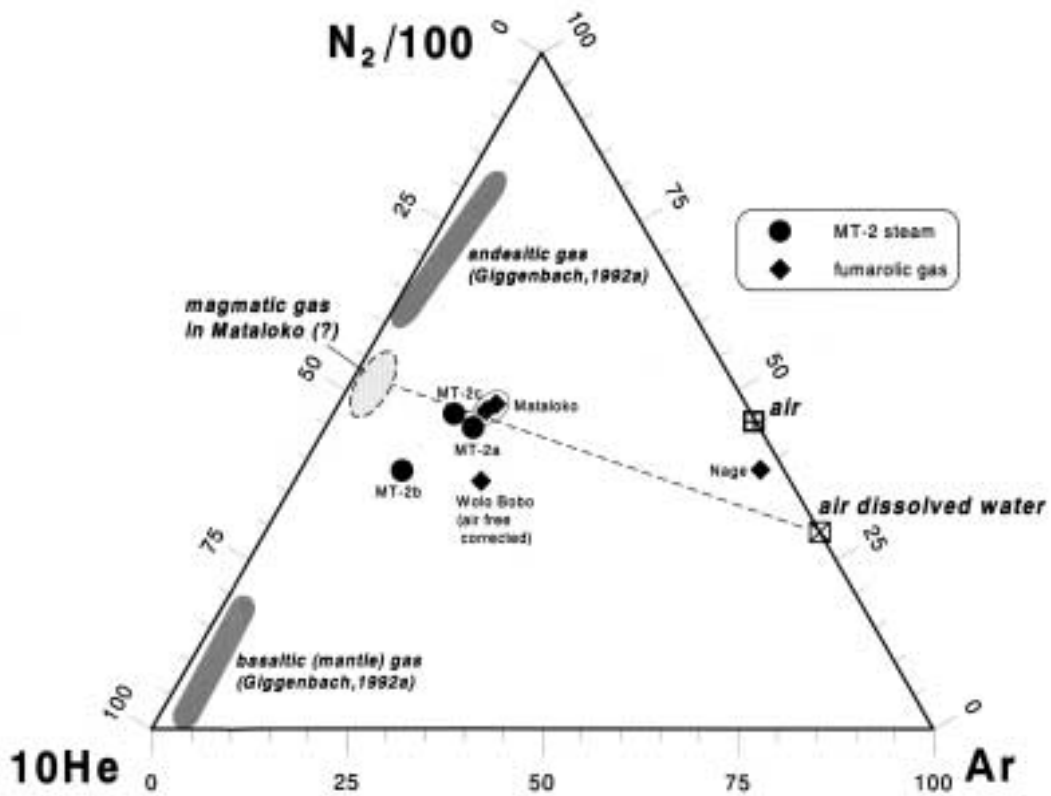


Fig. 4 Triangular diagram of relative abundances of non-reactive gas species, N₂, He and Ar in the steam discharges.

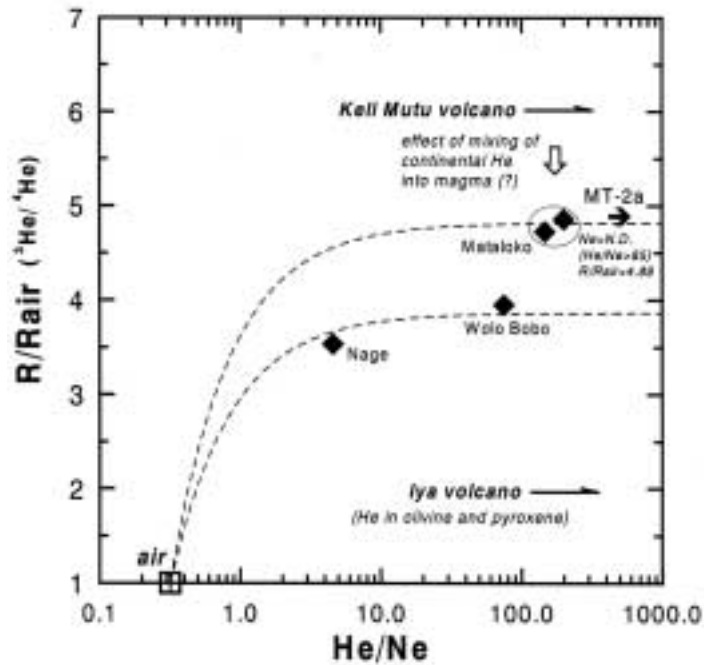


Fig. 5 Plot of R/R_{air} (³He/⁴He) vs. He/Ne. The data for the well MT-2 steam could not be plotted due to its indeterminable He/Ne ratio because of the low Ne concentration that was not detected in the chemical analysis. The data for Keli Mutu and Iya volcanoes on Flores Island are from Hilton *et al.* (1992).

‰; Hoefs, 1987). The sulfur isotope ratio ($\delta^{34}\text{S}$) of -2.8 ‰ for H_2S in the steam lies within the range of mantle rocks (0 ± 3 ‰; Ohmoto and Rye, 1979). The relative abundances of non-reactive gas species, N_2 , He and Ar in the well MT-2 steam indicate a significant contribution of magmatic gas (Giggenbach, 1992a; Fig. 4). The relatively low Ar concentration in the three gases and composition much different from air-saturated water suggest that the non-reactive gases are less contributed by atmospheric gases dissolved in meteoric water. Relatively high helium isotope ratio ($^3\text{He}/^4\text{He}$) of $6.85 \pm 0.09 \times 10^{-6}$ (4.89 R/Rair; normalized by atmospheric $^3\text{He}/^4\text{He}$ ratio) in the steam as well as the geothermal fluid (6.0 R/Rair) in the Keli Mutu volcano located in 80km east of Mataloko in Flores Island (Hilton *et al.*, 1992) show MORB-like value (Fig. 5). However, the helium isotope ratio is lower for the Keli Mutu volcano, suggesting the magmatic fluid contributing to the steam could be influenced by the subducted Australian continental crust, similar to the magmatic fluid in the Iya volcano located 20 km southwest of Keli Mutu (Hilton *et al.*, 1992).

5.2 Reservoir temperature

The calculated geochemical temperatures using analytical data of the gaseous components are presented in Table 3.

The hydrogen isotope temperature of 232 °C for the $\text{H}_2\text{-CH}_4$ pair (D'Amore and Panichi, 1987) is the lowest among the calculated temperatures for the

well MT-2 discharge steam; nevertheless, this temperature is 40 °C higher than the highest measured bottom-hole temperature. However, hydrothermal activity at a temperature around 200 °C or higher is suggested from the existence of wairakite in the drilling cuttings as mentioned above. Thus, this isotope temperature possibly reflects the fluid temperature near the bottom hole or a deeper portion. The estimated temperature of around 230 °C may be appropriate for a relatively shallow reservoir and is essentially consistent with the steam separation temperature assumed to estimate the hydrogen and oxygen composition of the reservoir water as mentioned above. The $T_{\text{H}_2\text{-CH}_4}$ for the fumarolic gases of Mataloko ranging from 122 to 134 °C may reflect the temperature at a relatively shallow level beneath the fumaroles.

The geochemical temperatures of $T_{\text{CO}_2\text{-H}_2\text{S-H}_2\text{-CH}_4}$ (D'Amore and Panichi, 1980), $T_{\text{CO}_2/\text{Ar}}$ (Giggenbach, 1992b), $T_{\text{FT-HSH}}$ (D'Amore *et al.*, 1993) and $T_{\delta^{13}\text{C}}$ ($\text{CO}_2\text{-CH}_4$) (D'Amore and Panichi, 1987) for the well MT-2 steam are roughly coincident with each other in a range from 270 to 306 °C, likely indicating the temperature at a hot water reservoir possibly existing at a deeper part. These geochemical temperatures for the fumarolic gases of Mataloko are similar to the well MT-2 steam in a range from 242 to 366 °C, even though they show a wider range, supporting the higher temperature at a deep reservoir than the measured temperature in the bore hole.

Table 3 Calculated geochemical temperatures for well discharge fluids and fumarolic gases.

Source	Sampling date	Well head pressure MPaG	Discharge temperature °C	$T_{\text{D}\delta^2}$ ¹ °C	$T_{\text{H}_2/\text{Ar}}$ ² °C	$T_{\text{CO}_2/\text{Ar}}$ ³ °C	$T_{\text{FT-HSH}}$ ⁴ °C	$T_{\delta^{13}\text{C}}$ ⁵ °C	T_{D_1} ⁶ °C	T_{D_2} ⁷ °C
<i>MT-2 well discharge</i>										
MT-2a	2001/1/23	0.42		271	335	293	305	275	232	334
MT-2b	2001/1/24	0.59		270	340	296	306	-	-	-
MT-2c	2001/1/25	0.32		273	343	298	304	-	-	-
<i>Mataloko fumarole</i>										
G-1	1999/9/27		96.0	256	236	280	366	300	134	282
G-2	1999/9/28		95.8	242	298	282	331	346	122	297
<i>Nage hot spring gas</i>										
G-3	1999/9/25		71.9	-	10	204	-	-	-	-
<i>Wolo Bobo fumarole</i>										
G-4	1999/9/26		94.7	170	134	261	-	525	-	-
G-4*	1999/9/26		94.7	170	177	291	-	525	-	-

¹ $T_{\text{D}\delta^2}$: $T(\text{CO}_2\text{-H}_2\text{S-H}_2\text{-CH}_4)$ (D'Amore and Panichi, 1980)
² $T_{\text{H}_2/\text{Ar}}$: $T(\text{H}_2/\text{Ar})$ (Giggenbach, 1980)
³ $T_{\text{CO}_2/\text{Ar}}$: $T(\text{CO}_2/\text{Ar})$ (Giggenbach, 1992b)
⁴ $T_{\text{FT-HSH}}$: $T(\text{FT-HSH})$ (D'Amore *et al.*, 1993)
⁵ $T_{\delta^{13}\text{C}}$: $T(\delta^{13}\text{C}(\text{CO}_2\text{-CH}_4))$ (D'Amore and Panichi, 1987)
⁶ T_{D_1} : $T(\delta \text{D}(\text{H}_2\text{-CH}_4))$ (D'Amore and Panichi, 1987)
⁷ T_{D_2} : $T(\delta \text{D}(\text{H}_2\text{-H}_2\text{O}))$ (Lyon and Halston, 1984)

The $T_{H_2/Ar}$ (Giggenbach, 1992b) for the well MT-2 steam ranging from 335 to 343 °C are higher than the other geochemical temperatures. According to the plot of $\log(H_2/Ar)$ and $\log(CO_2/Ar)$ (Giggenbach, 1992b) for the data of this study (Fig. 6), the $T_{H_2/Ar}$ for the well MT-2 steam are 42 - 45 °C higher than the $T_{CO_2/Ar}$, and the plotted data suggest that these gases are in equilibrium within a reservoir containing a vapor phase. The result of FT-HSH analysis according to D'Amore *et al.* (1993) provides a mass steam fraction (y) in the reservoir for well MT-2 samples as 0.015 - 0.017, i.e. 1.5 - 1.7 wt% in the total reservoir fluid, indicating the existence of a vapor phase in the reservoir in a natural state (not in flow condition). Therefore, the calculated $T_{H_2/Ar}$ for the MT-2 steam are probably overestimated due to the loss of Ar caused by vapor loss in the reservoir (Giggenbach, 1992b).

5.3 Geochemical model

Based on the interpretation on the chemical and isotopic compositions of geothermal fluids as mentioned previously, a geochemical model of the Mataloko geothermal field is constructed as shown in Fig. 7.

Taking into account the pure steam discharge from the well MT-2, reservoir fluid is steam-dominated in the vicinity of the bottom of the well.

Nevertheless, the low content of NCG in the steam and its chemical composition suggest an existing water-dominated reservoir at the deeper portion of the hydrothermal system as an origin of the vapor fluid. According to the isotopic compositions of hydrogen and oxygen, the vapor water (H_2O) consists primarily of meteoric water, which is possibly recharged around Mataloko and/or surrounding mountains, i.e. Wolo Nawa and Wolo Riti in the west and Wolo Sasa and Wolo Belu in the north. The meteoric water that penetrated into the depth of the system may be heated by a heat source related to the young volcanic activity in and around Mataloko. The estimated hydrogen and oxygen isotopic composition of the reservoir water could be explained by the contribution of magmatic water (or by water-rock interaction). However, the lack of HCl gas, thought to be derived directly from the magma body, in the discharge steam does not advocate the contribution of magmatic water into the reservoir water. In the case of no or limited contribution of magmatic water, the reservoir water is probably heated by principally conductive heat from the magma body, and strongly acidic gases such as HCl, SO_2 , HF supplied from the magma body are likely trapped into a possible sealing zone near the heat source. Magmatic gases passed through the sealing zone due to their lower solubility, i.e. CO_2 ,

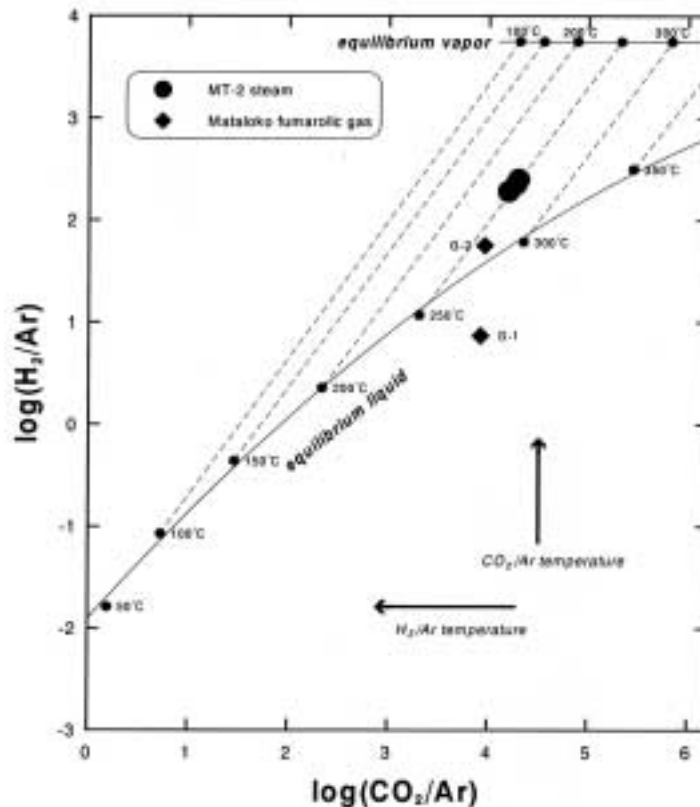


Fig. 6 Plots of $\log(H_2/Ar)$ vs. $\log(CO_2/Ar)$ for the evaluation of $T_{H_2/Ar}$ and $T_{CO_2/Ar}$. The lines for equilibrium liquid and equilibrium vapor are after Giggenbach (1992b).

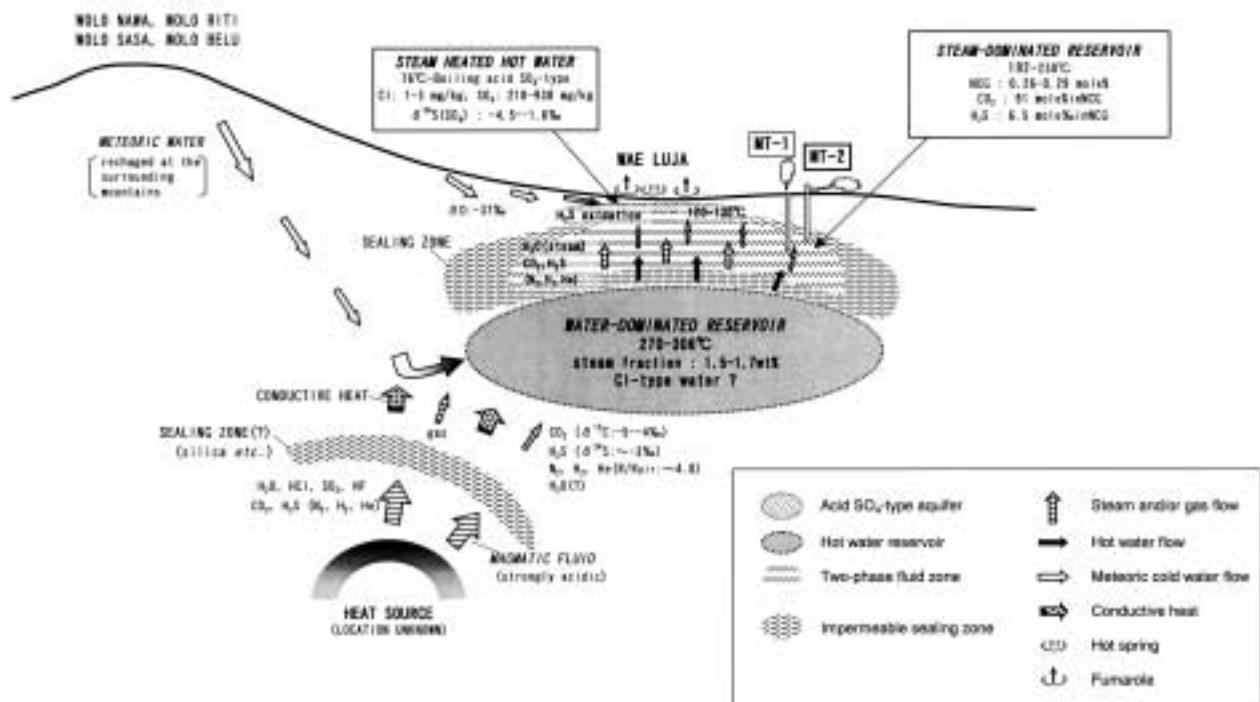


Fig. 7 Geochemical model of the Mataloko geothermal field.

H₂S, N₂, H₂ and He, may contribute the reservoir fluid. The water-dominated reservoir fluid is inferred to a typical Cl-type hot water, and its temperature is estimated to be 270-306 °C based on the geochemical temperatures. The high temperature and low pressure or low permeability of the reservoir possibly yields a vapor phase partially within itself. The steam fraction in the reservoir is estimated at 1.5-1.7 wt% by the FT-HSH analysis using the data set of discharge gas compositions. At a shallow level of the system, pressure decline and the existence of a sealing zone due to deposition of secondary minerals and silica yields further vaporization of the reservoir water and provides a steam-dominated reservoir. Temperature at the maximum depth of the well MT-2 and somewhat deeper level is estimated to be 192-230 °C by the measured bore hole and hydrogen isotope temperatures ($T \delta D(\text{H}_2\text{-CH}_2)$).

The similar discharge gas composition and closeness (32 m) of locality of the two wells strongly suggests that the same reservoir was intersected by wells MT-1 and MT-2. The fumarolic fluid in Mataloko, likewise, is thought to have a common source with the well MT-2 discharge steam, even though there are some discrepancies between their chemistries. As shown in Fig. 8, the higher NCG content in the fumarolic steam is explained by steam condensation due to the ascent of the steam and its cooling, and the higher CO₂/H₂S ratios by the oxidation of H₂S and its dissolution into shallow groundwater. As a result, the discharge steam and

gases from wells and fumaroles in Mataloko have a common source that is likely to be a deep water-dominated reservoir. This suggests that the water-dominated reservoir has a relatively large extension in the Mataloko field.

6. Conclusions

The main conclusions from the results of the chemical and isotopic interpretation in this study are:

- (1) The discharge steam from the well MT-2 is derived from a water-dominated reservoir, providing low NCG content and CO₂-dominant gas composition in the discharge fluid.
- (2) The water vapor (H₂O) in the discharge fluid from the well MT-2 consists of mainly meteoric water, while the gaseous components originate mainly from magmatic fluid. The water vapor shows significant modification of isotopic composition from the local meteoric water, but it is not defined whether the isotopically positive shift occurred due to the contribution of magmatic water or water-rock interaction.
- (3) Temperature at the deep water-dominated reservoir is estimated to be 270-306 °C from several gas geothermometers. The result of FT-HSH analysis based on D'Amore *et al.* (1993) indicates the mass fraction of the vapor phase in the reservoir is 1.5-1.7 wt%.
- (4) A steam-dominated reservoir exists at a shallow

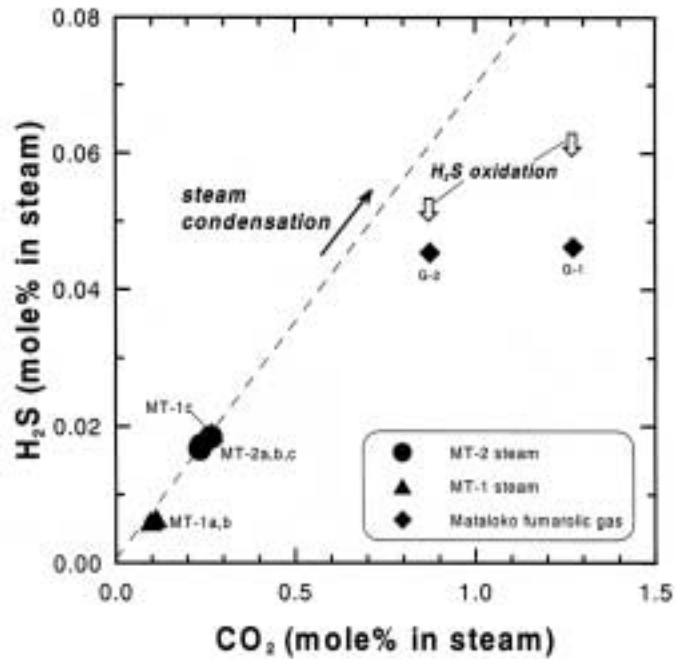


Fig. 8 Correlation of H₂S and CO₂ concentration in the steam discharges.

level of the hydrothermal system of the Mataloko field. Temperature at the reservoir around the well MT-2 is thought to be 192-230 °C from the measured bore hole temperature and hydrogen isotopic geothermometer for the H₂-CH₄ pair.

- (5) Similar chemical and isotopic composition of fluids from wells MT-1 and MT-2 and fumaroles suggests a common original reservoir, i.e. a deep water-dominated reservoir with a relatively large extension in the Mataloko field.

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References

D'Amore, F. and Panichi, C. (1980) Evaluation of deep temperatures of hydrothermal systems by a new gas-geothermometer. *Geochim. Cosmochim. Acta*, **44**, 549-556.
 D'Amore, F. and Panichi, C. (1987) Geochemistry in geothermal exploration. In Economides,

M. and Ungemach, P., eds., *Applied geothermics*, Wiley & Sons, New York, 69-89.
 D'Amore, F., Ramos, M. N., Seastres Jr., J. S., Ruaya, J. R. and Nuti, S. (1993) Applications of gas chemistry in evaluating physical processes in the Southern Negros (Palinpinon) geothermal field, Philippines. *Geothermics*, **22**, 535-553.
 Giggenbach, W. F. (1975) A simple method for the collection and analysis of volcanic gas samples. *Bull. Volcanol.*, **39**, 132-145.
 Giggenbach, W. F. (1980) Geothermal gas equilibria. *Geochim. Cosmochim. Acta*, **44**, 2021-2032.
 Giggenbach, W. F. (1982) Processes controlling the isotopic composition of steam and water discharges from steam vents and steam-heated pools in geothermal areas. *Geothermics*, **11**, 71-80.
 Giggenbach, W. F. (1992a) The composition of gases in geothermal and volcanic systems as a function of tectonic setting. *Proc. Water-Rock Interaction*, **7**, 873-878.
 Giggenbach, W. F. (1992b) Chemical techniques in geothermal exploration. In D'Amore, F., ed., *Applications of geochemistry in geothermal reservoir development. Series of technical guides on the use of geothermal energy*, UNITAR/UNDP Centre on small energy resources, Rome-Italy, 119-144.
 Hilton, D. R., Hoogewerff, J. A., Van Bergen, M. J. and Hammerschmidt, K. (1992) Mapping magma sources in the east Sunda-Banda

- arcs, Indonesia: Constraints from helium isotopes. *Geochim. Cosmochim. Acta*, **56**, 851-859.
- Hoefs, J. (1987) *Stable isotope geochemistry; Third, completely revised and enlarged edition*. Springer-Verlag, 241p.
- James, R. (1962) Steam-water critical flow through pipes. *Proc. Inst. Mech. Engrs.*, **176**, 741-748.
- Lyon, G. L. and Hulston, J. R. (1984) Carbon and hydrogen isotopic compositions of New Zealand geothermal gases. *Geochim. Cosmochim. Acta*, **48**, 1161-1171.
- Matsuda, K., Akasako, H., Koseki, T., Futagoishi, M., Nasution, A. and Kusnadi, D. (2000) Geochemistry of hot spring waters in Bajawa area, Flores, Indonesia. *Jour. Geotherm. Res. Soc. Japan*, **22**, 63. (abstract for the annual meeting of the society; in Japanese)
- Muraoka, H., Nasution, A., Urai, M., Takahashi, M. and Takashima, I. (2000) Regional geothermal geology of the Ngada District, Central Flores, Indonesia. *Proc. World Geothermal Congress 2000*, 1473-1478.
- Nasution, A., Muraoka, H., Takashima, I., Okubo, Y., Takahashi, H., Takahashi, M., Uchida, T., Andan, A., Akasako, H., Matsuda, K., Nanlohi, F., Kusnadi, D., Sulaiman, B. and Zulkarnain, N. (1999) Preliminary survey of Bajawa geothermal area, Ngada District, Flores, East Nusa Tenggara, Indonesia. *Geotherm. Res. Council. Trans.*, **23**, 467-472.
- Ohmoto, H. and Rye, R. O. (1979) Isotopes of sulfur and carbon. In Barnes, H. L., ed., *Geochemistry of hydrothermal ore deposits; second edition*, John Wiley & Sons, 509-567.
- Ozawa, T. (1968) Chemical analysis of volcanic gases. *Geochemistry International*, **5**, 939-947.
- Takahashi, H., Otake, M., Tagomori, K., Sueyoshi, Y., Futagoishi, M. and Nasution, A. (2000) Geothermal geology of the Mataloko area, Central Flores, Nusa Tenggara Timur, Indonesia. *Proc. World Geothermal Congress 2000*, 1803-1806.
- Takashima, I., Nasution, A. and Muraoka, H. (2000) Thermal history of Mataloko area, Flores Island, Indonesia. *Proc. World Geothermal Congress 2000*, 1813-1816.
- Yasukawa, K., Andan, A., Kusuma, D. and Uchida, T. (2000) Self-potential survey in the Mataloko geothermal prospect, Flores, Indonesia. *Proc. World Geothermal Congress 2000*, 1985-1990.

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インドネシア・フローレス島・マタロコ地熱地帯における 調査井噴出流体の化学・同位体的研究

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要 旨

インドネシア・フローレス島のマタロコ地熱地帯において掘削された調査井 MT-2 (深度 162.35 m) から噴出した蒸気一相の地熱流体は、不凝結ガス濃度が比較的低く (0.61~0.69 wt%), そのガス成分は CO₂ を主体 (91 mole%) とするものである。その噴出蒸気は地下深部の熱水卓越層から派生したものと考えられる。水素・酸素・炭素・硫黄・ヘリウムの同位体組成や微量ガス成分の化学組成から、噴出蒸気中の水 (H₂O) は主にマグマ水の混入もしくは岩石との反応の影響を受けている天水を起源とし、一方ガス成分のほとんどはマグマ起源であるとみなされる。各種の化学・同位体温度計及び調査井の坑内実測温度によれば、比較的浅部に発達する蒸気卓越層の温度は 192~230 °C、深部の熱水卓越層の温度は 270~306 °C と推定される。調査井 MT-2 からの距離がほぼ 200 m 以内にある調査井 MT-1 及び噴気帯における噴出蒸気の化学性状は MT-2 の噴出蒸気と類似しており、それらは共に深部の熱水卓越層を起源とし、その熱水卓越層が大きな規模で広がっていることを示唆する。