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論　文

Origin of Hot Spring Water in the Kotamobagu Geothermal Field, Northern Sulawesi, Indonesia

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Abstract

We conducted a geochemical survey of hot springs and related water in an area 20 km north to south and 30 km east to west at the Kotamobagu geothermal field, northern Sulawesi, Indonesia. Thirty one water samples from hot springs and river water were collected at elevations between 173 m and 1438 m asl and analyzed for their chemical compositions and stable isotopes of water. Rain water was also collected using an open air rainwater collector from five locations with elevations from 556 m to 1500 m between March and June 2010. Most of the hot spring waters of HCO_3 and hybrid type have a neutral pH, and their stable isotope values of water are distributed along the global meteoric water line (GMWL), indicating that they are of meteoric origin. However, the acidic water samples deviated from the GMWL. One sample (MUAH-16) collected near a fumaroles on the summit of Mt. Muayat, indicates of SO_4 type, implying steam-heated water. Thus, the deviation of the acidic water sample from the GMWL is caused by evaporation of meteoric water at shallow depth and/or on the surface. Sample LOBH-10 has a neutral pH and shows a $\delta^{18}O$ shift from the local meteoric water line. This sample is located near the edge of the field and the shift may be caused by reaction with marine origin rocks.

Keywords: Kotamobagu, water origin, stable isotope, geochemistry.

1. Introduction

The Kotamobagu geothermal field is located in North Sulawesi Province, Indonesia, approximately 200 km southwest of Manado City, the capital of the province (Fig.1). The field is a key geothermal prospect in Indonesia (Hochstein and Sudarman, 2008). Reconnaissance and feasibility studies were conducted at the Kotamobagu field by Pertamina Geothermal Energy Co. (PT. PGE) who concluded that the field has a high potential for power generation (Pertamina Geothermal Energy Co., personal communication).

In geothermal areas, the relationships among the stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) of meteoric water, the elevation, and isotope exchange between the water and the rocks at

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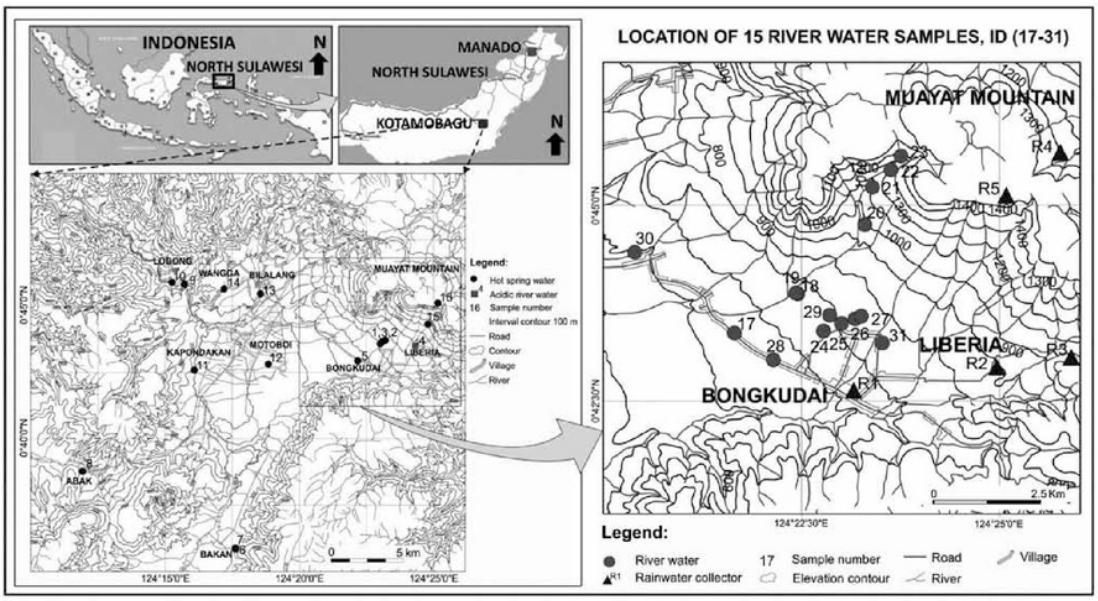

Fig. 1 Location and sampling map of the Kotamobagu geothermal field.

temperature are commonly used to determine the recharge zone. Meteoric water from elevation comes to the surface, infiltrates and percolates into the ground, flowing into a shallow aquifer where it is warmed by an underground heat source and either discharges at lower elevations or continues infiltrating to the depth of the geothermal reservoir before flowing up to the surface. Meteoric waters are continually entering the ground and being heated to a certain degree depending on the depth and the distance to the heat source. The isotope exchange kinetic rate between the water and the rock is very slow at low temperatures. There is no significant change in the δ^2H of the groundwater or aquifer when the water still represents the region of meteoric water recharge. The enrichment of $\delta^{18}O$ in geothermal water occurs due to the interaction of the meteoric water with the rock at high temperatures where the $\delta^{18}O$ composition of the rocks becomes poorer, while that of the water becomes richer (Panichi and Gonfiantini, 1978). Most geothermal waters have an oxygen isotope shift of less than 2 ‰, with oxygen isotopes shifts of 1.8-3.5 ‰ in the Ruidian geothermal field, 1.6-2.0 ‰ in the Hot Sea geothermal field in Tengchong, China (Minzi et al, 1988); and about 1‰ in New Zealand and Columbia (Panichi and Gonfiantini, 1978). In several geothermal fluids where the thermal waters are acidic, the enrichment both of $\delta^{18}O$ and δ^2H occurs by subsurface evaporation and/or evaporation at the surface, at temperatures ranging from 70 to 90 °C (Craig et al., 1963).

The aim of this study is to understand the origin of hot spring water in the Kotamobagu geothermal field, Indonesia using the stable isotopes $\delta^{18}O$ and δ^2H, and geochemical data of waters.

2. Geology

2-(1) Description of geology

A geological map of the Kotamobagu area is shown in Fig. 2 (Pertamina Geothermal Energy Co., personal communication). The area is covered by Paleogene, Neogene and Quaternary rocks. The Paleogene sedimentary rocks consist of shale and sandstone with intercalated limestone and chert, and are overlain by the Neogene and Quaternary volcanic rocks. The Neogene volcanic rocks are the products of the Old volcanoes, and consist of breccia, tuff, andesitic lava, dacite and rhyolite from Mt. Simut and Mt. Lemibut located to the north of Mt. Muayat. The Quaternary volcanic rocks consist of Old and Young Ambang volcanics. Tuff-pumice and andesitic breccia are the products of the Old Ambang Volcano. The Young Ambang volcanic rocks consist of andesitic lava and volcanic breccia, overlain asymmetrically by Mt. Muayat, Mt. Banga, and Mt. Ambang.

2-(2) Geological structure and geothermal manifestations

There are northwest to southeast, northeast to southwest

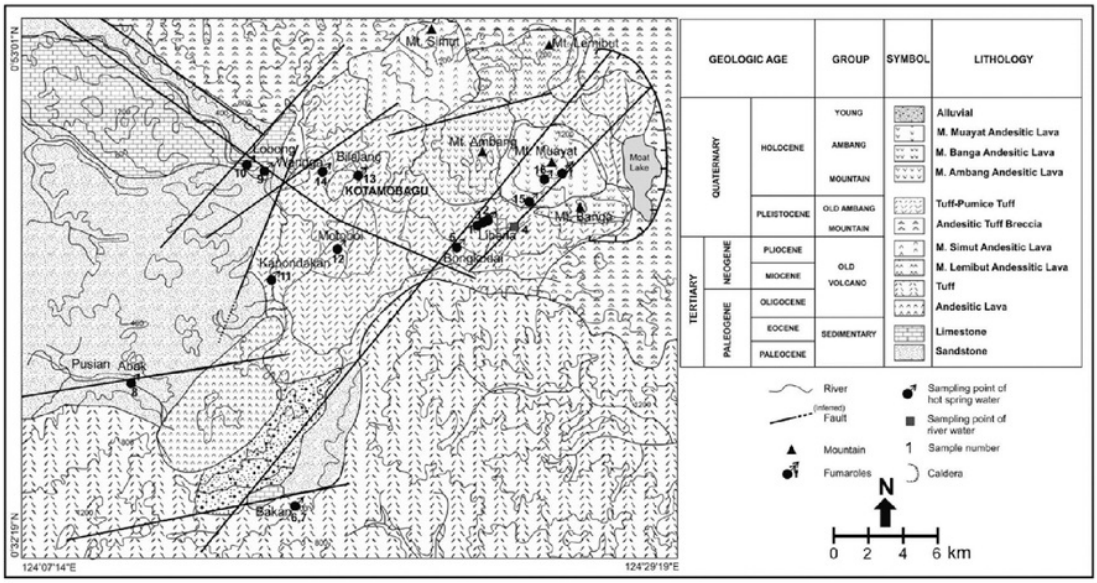

Fig. 2 Geological map of Kotamobagu (modified from Apandi and Bachri, 1997 and Pertamina Geothermal Energy Co., personal communication).

and west to east trending faults in the Kotamobagu field as shown in Fig. 2. Fumaroles at the top of Mt. Muayat (1385 m above sea level (asl)) located in the east of Kotamobagu, have a high temperature of 102.7 °C, and are associated with northeast to southwest trending faults (Pertamina Geothermal Energy Co., personal communication). A west to east fault system which crosses the sedimentary rocks controls the appearance of hot springs at Pusian and Bakan, located to the southwest and south, respectively, of Kotamobagu. A fault system with a northwest to southeast direction controls the presence of hot springs at Lobong in the west of Kotamobagu (Pertamina Geothermal Energy, personal communication). This fault system also controls the appearance of hot springs at Liberia and Bongkudai villages.

3. Sampling locations

Sixteen water samples from hot springs, shallow wells and river were collected. Those are located throughout the area 20 km north to south and 30 km east to west around Kotamobagu (Figs. 1 and 2). The elevations of the sampling sites range from 144 m to 1438 m asl (Table 1). The sample number in Table 1 corresponds to those shown in Fig. 2.

Sample MUAH-16 was collected from a natural discharge at an elevation of 1438 m near fumaroles at the top of Mt. Muayat. A natural discharge on the cliff of Mt. Muayat (MUAH-15) was collected at an elevation 969 m asl. Two warm water samples were collected from shallow wells: LOBH-9 was collected from a well with 20 m depth; and MOTH-12 with a depth of 80 m. Samples were taken from hot springs at Bakan (BAKH-6 and BAKH-7) and Abak (ABAH-8), located at the south western end of Kotamobagu, about 20 km south west of Mt. Muayat. Hot spring samples from Liberia village in eastern Kotamobagu (LIBH-1, LIBH-2, and LIBH-3) were collected in a paddy field. Natural discharge samples were collected from river banks at Kapondakan (KAPH-11), and Lobong (LOBH-10), the river beds at Bongkudai (BONH-6) and Bilalang (BILH-13), and one sample 2 m beside the river at Wangga village (WANH-14). The acidic river water sample (LIBR-4) was collected on the slope of Mt. Muayat.

Rainwater samples were collected at three locations (R1, R2, and R3) to the south and two locations (R4 and R5) to the north of Mt. Muayat (Fig. 1 and Table 2) in the period for March to June 2010 when March belongs to dry season and April to June to rainy season, respectively. The elevations of these locations range from 556 m to 1500 m asl with elevation intervals from 220 m to 300 m.

River water samples were collected in Mt. Muayat from: the Dopo River (17, 18, 19, 20, 21, 22, and 23) at elevations from 463 m up to 1093 m asl; the Kikit River (24, 25, 26 and 27) at elevations from 573 m up to 640 m asl; the Boyobo River (28 and 29) at elevations 483 m and 598 m asl; the

Table 1 Results of chemical and isotopic analyses of hot springs, shallow wells, and river water samples from the Kotamobagu geothermal field.

Sample number	Sample (ID)	Elev. (m)	Temp. (°C)	PH (-)	EC (μS/cm)	Li	Na	K	NH4	Mg	Ca	SO_4	F	Cl	Br	NO_3	HCO_3	PO_4	Fe Total	SiO_2	$\delta^{18}O$	δ^2H
						mg/l													mg/kg		‰	
LIBH-1	1	608	48.0	6.02	516	0.04	36.8	11.4	0.10	13.2	52.4	12.0	ND	9.3	ND	0.13	308	ND	1.70	148	-6.5	-41
LIBH-2	2	645	43.4	5.89	490	0.03	31.0	10.8	1.00	11.7	51.2	6.2	ND	5.8	ND	0.11	290	ND	ND	136	-6.6	-41
LIBH-3	3	629	52.2	6.06	535	0.04	36.5	12.6	0.23	13.8	55.8	10.7	ND	9.0	ND	ND	315	ND	0.22	128	-6.6	-42
LIBR-4	4	752	24.7	2.24	4490	0.10	79.6	10.9	0.48	39.3	224	1940	0.5	285	0.34	ND	ND	0.45	28.9	126	-5.5	-39
BONH-5	5	476	46.4	6.04	698	0.06	44.1	11.6	0.20	21.9	65.1	11.2	ND	8.6	ND	ND	338	ND	0.07	128	-6.5	-40
BAKH-6	6	243	87.0	6.78	1687	1.50	224	22.6	ND	2.44	114	365	1.0	228	0.56	ND	177	ND	0.07	107	-5.8	-36
BAKH-7	7	240	87.0	7.40	1604	1.34	208	20.5	ND	2.77	113	311	0.5	201	0.48	0.09	192	ND	1.84	97	NDA	NDA
ABAH-8	8	185	75.4	7.37	1376	0.16	201	7.56	ND	2.22	97.5	534	0.5	61.6	0.19	ND	97.6	ND	0.22	65	-6.3	-38
LOBH-9	9	172	43.5	6.71	240	0.01	19.3	4.67	ND	5.43	22.1	22.2	ND	12.7	ND	10.3	91.5	0.27	ND	122	-6.1	-40
LOBH-10	10	144	70.0	6.26	3210	2.26	445	75.2	14.3	8.03	179	122	0.6	700	2.38	ND	155	ND	0.22	96	-5.0	-41
KAPH-11	11	185	93.1	7.60	2350	0.33	384	12.2	ND	0.12	107	556	0.5	402	1.15	ND	39.1	ND	0.41	72	-5.6	-35
MOTH-12	12	222	47.7	6.65	2220	0.34	324	53.8	3.33	71.4	109	231	ND	327	0.87	ND	459	0.50	ND	144	-6.7	-46
BILH-13	13	296	48.8	6.34	433	0.01	42.6	7.37	0.12	13.0	39.5	0.8	ND	3.4	ND	ND	269	ND	0.07	112	-6.6	-42
WANH-14	14	344	37.1	6.96	399	0.01	21.8	5.09	ND	14.8	49.9	5.7	ND	1.6	ND	ND	286	ND	ND	94	-6.6	-41
MUAH-15	15	969	49.5	2.72	2860	0.12	88.8	11.8	0.60	40.0	221	1713	0.6	320	0.48	ND	ND	0.72	17.6	152	-6.2	-43
MUAH-16	16	1438	49.1	2.30	5670	0.04	31.6	2.36	0.59	35.4	117	2420	ND	3.6	ND	0.39	ND	ND	10.95	232	-5.7	-47

Note: ND = Not detected, NDA = No Data.

Dakaulu River and the Mati River at elevations 403 m and 642 m asl; with elevation intervals from 7 m to 248 m, as shown in Table 3.

4. Sampling and analysis methods

The thirteen hot spring samples from natural discharges, two wells, and one from acidic river were collected and stored in 250 mL polypropylene bottle after filtering through a 0.45 μm membrane filter. The water temperature, electrical conductivity (EC) and pH were measured on site using portable instruments. The anion (F, Cl, Br, NO_3, PO_4 and SO_4) and cation (Li, Na, NH_4, K, Mg, and Ca) concentrations were determined using an ion chromatography system (Dionex ICS-90). Bicarbonate (HCO_3) was measured by the titration method. The SiO_2 and total Fe concentrations were measured by spectrophotometer (Hitachi U 1800) using the molybdate yellow method and the 1,10-phenanthroline method, respectively.

Twelve rain water samples and fifteen river water samples (Fig. 1) were stored in 50 mL polypropylene bottle after filtering through a 0.45 μm membrane filter. The rainwater collector is of an open type and was mounted on the top of wooden stick and exposed to the open air at 75 cm high from the ground. Rainwater collector used in the study consists of a 2 L high density polyethylene (HDPE) bottle and a plastic funnel. A funnel of 5 cm diameter was fit into the silicon rubber plug that was plugged into the mouth of bottle. Top of funnel was covered with plastic net for avoiding neither insect nor leaf into the stored rainwater. A piece of salan net was squeezed into the neck of funnel to suppress evaporation of the stored water.

The water samples were equilibrated with CO_2 and H_2 for $^{18}O/^{16}O$ and $^2H/H$ analyses, respectively. The isotope ratios were then measured using a DELTA Plus mass-spectrometer at Fukuoka University, Japan. The precision of the measurements is ±0.1 ‰ for the O isotope ratios and ±1 ‰ for the H isotope ratios.

5. Result and Discussion

5-(1) Hydrochemistry of hot springs

The results of the chemical analyses are summarized in Table 1.

The hot spring water of MUAH-15, MUAH-16 and river water LIBR-4 are very acidic with pH values as low as 2, and high conductivities ranging from 2860 to 5670 μS/cm. The other hot spring samples have relatively neutral pH typically 6 to 7. The samples can be divided into two groups with respect to EC; low conductivities of 240–698 μS/cm for LIBH-1, LIBH-2, LIBH-3, BONH-5, BILH-13, WANH-14, and LOBH-9; and high conductivities of 1376-3210 μS/cm for BAKH-6, BAKH-7, ABAH-8, LOBH-10, KAPH-11, and MOTH-12. The temperature of most of the hot spring with high conductivities was relatively high, 70-93 °C, for BAKH-6, BAKH-7, ABAH-8, LOBH-10, and KAPH-11. Hot springs closer to Mt. Muayat, where active fumaroles are present, have relatively low temperatures of 37-52 °C.

A relation of chloride, sulfate and bicarbonate ion is shown in Fig. 3.

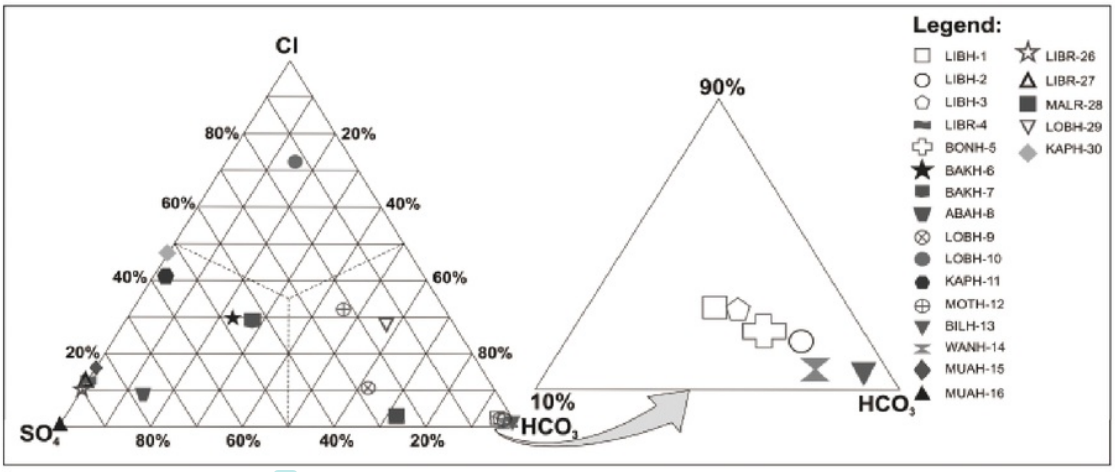

Fig. 3 Ternary plot of hot springs and one river water showing Cl, SO_4 and HCO_3 compositions.

From this figure, four types of water can be identified; SO_4 type of MUAH-16; Cl-SO_4 type of LIBR-4 and MUAH-15; and HCO_3 type of LIBH-1, LIBH-2, LIBH-3, BONH-5, BILH-13, WANH-14, and hybrid type of BAKH-6 and 7, ABAH-8, LOBH-9 and 10, KAPH-11, MOTH-12.

The MUAH-16 sample was plotted in the SO_4 corner of the ternary diagram, indicating steam heated water. This sample was collected near fumaroles at the top of Mt. Muayat, where steam derived from boiling at depth containing H_2S reacts with oxygen rich surface water, and H_2S is oxidized to form SO_4 rich acidic water. At lower elevations on Mt. Muayat, there are natural discharges from the cliff surface where MUAH-15 was collected. This sample is a Cl-SO_4 type water, suggesting volcanic water origin. The high temperature chloride water containing volcanic gases (CO_2 and H_2S) is mixing with cold meteoric water and is flowing up to the surface. Sample LIBR-4 is river water and of acidic. The sample plots between MUAH-16 and MUAH-15 on the SO_4-Cl axis, implying that the acidic river water is a mixture of MUAH-16 and MUAH-15 waters. Samples collected at lower elevations on the southern and southwestern slopes of Mt. Muayat are plotted in the HCO_3 corner and are identified as HCO_3 type waters.

These bicarbonate type waters may occur near the surface in geothermal areas where steam carbon dioxide condenses in an aquifer. Under stagnant conditions, reactions with the rocks leads to a neutral pH, and the water discharges as hot springs such as in Liberia, Bongkudai, Bilalang and Wangga villages (LIBH-1, LIBH-2, LIBH-3, BONH-5, BILH-13 and WANH-14).

The hybrid type of water, may be caused by mixing of different type of water (BAKH-6 and 7, KAPH-11, and 10, MOTH-12) or by interaction with surrounding rocks (ABAH-8 and LOBH-9). For example, the high Cl concentration at Lobong, LOBH-10, may be originated from deep geothermal waters flowing through a fault, leading to interaction with sedimentary rocks prior to discharging as a hot spring.

5-(2) Stable Isotopes of hot springs, river and rainwater

The stable isotope ratios in rainwater and river water are summarized in Tables 2 and 3.

The relationship between the δ^2H and $\delta^{18}O$ isotope values in rainwater, hot springs, shallow wells and river at Kotamobagu are summarized in Fig. 4.

The isotope values in twelve rain water samples collected from March to June 2010 and fifteen river water samples collected in April 2011 were plotted to determine

Table 2 Results of isotope analysis of rainwater from Kotamobagu.

Sample ID	Rainwater collector	Elevation (m)	Sampling date	δ^2H (‰)	$\delta^{18}O$ (‰)
R1/3	R1	556	18/03/2010	-1	-2.2
R2/3	R2	780	23/03/2010	-9	-3.1
R3/3	R3	980	23/03/2010	-9	-3.2
R4/3	R4	1280	19/03/2010	-2	-2.6
R5/3	R5	1500	19/03/2010	-7	-3.1
R4/4	R4	1280	06/04/2010	-35	-6.1
R5/4	R5	1500	06/04/2010	-36	-6.2
R4/5	R4	1280	31/05/2010	-60	-8.9
R5/5	R5	1500	31/05/2010	-60	-9.0
R1/6	R1	556	08/06/2010	-51	-8.1
R2/6	R2	780	08/06/2010	-61	-9.0
R3/6	R3	980	08/06/2010	-59	-8.7

Table 3 Results of isotope analysis of river water from Mt. Muayat, Kotamobagu.

Sample number	Sampling date	Elevation (m)	δ^2H (‰)	$\delta^{18}O$ (‰)
17	22/04/2011	463	-43	-7.2
18	21/04/2011	576	-43	-7.1
19	21/04/2011	585	-43	-7.2
20	22/04/2011	833	-51	-8.2
21	22/04/2011	967	-48	-7.9
22	22/04/2011	1056	-48	-7.9
23	22/04/2011	1093	-47	-7.8
24	22/04/2011	573	-48	-7.3
25	21/04/2011	604	-47	-7.3
26	21/04/2011	634	-49	-7.5
27	21/04/2011	640	-48	-7.4
28	22/04/2011	483	-43	-6.8
29	21/04/2011	598	-47	-6.9
30	22/04/2011	403	-41	-6.5
31	22/04/2011	642	-46	-7.2

the local meteoric water line (LMWL) as shown in Fig. 4 using a linear interpolation with the least squares equation. River water sample (LIBR-4) was not used to determine the LMWL because of the river water being acidic and of the result of mixing between steam heated water (MUAH-16) and volcanic water (MUAH-15). The isotope values in June are plotted close to the global meteoric water line (GMWL) due to altitude. The plot of LMWL ($\delta^2H = 8.2\delta^{18}O + 18.8$) is shifted to left (more negative) compared to the GMWL ($\delta^2H = 8\delta^{18}O + 10$). The most affected mechanism is evaporation speed and kinetics as follows.

Figures 5 and 6 show the relationships between the isotopic values, elevation and season.

The stable isotope values for $\delta^{18}O$ and δ^2H in rainwater range from -6.1 ‰ to -6.2 ‰, and -35 ‰ to -36 ‰, respectively, in April; -8.9 ‰ to -9.0 ‰, and -60 ‰, respectively, in May; and -8.1 ‰ to -9.0 ‰, and -51 ‰ to -61 ‰, respectively, in June. The values are lower than the δ-values of rainwater

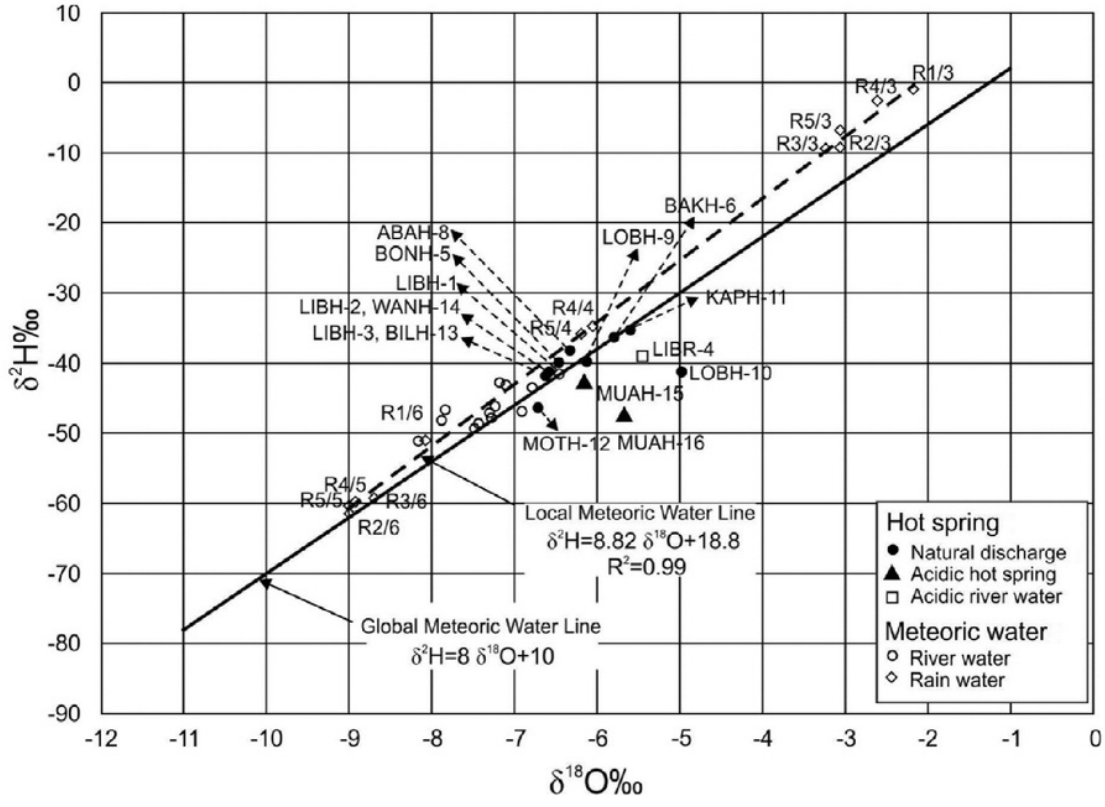

Fig. 4 Relationship between δ^2H and $\delta^{18}O$ for 13 hot spring samples, 2 well (warm water) samples, 1 acidic river (pH=2) sample, 12 rain water samples and 15 river water samples in Kotamobagu. The local meteoric water line was obtained using rain water and river water data.

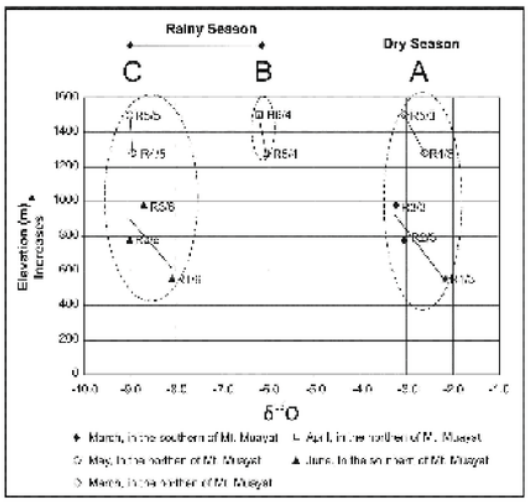

Fig. 5 Sample groupings based on $\delta^{18}O$ values, elevation and season. With increasing elevation, the $\delta^{18}O$-values of precipitation decrease (Dansgaard, 1964)

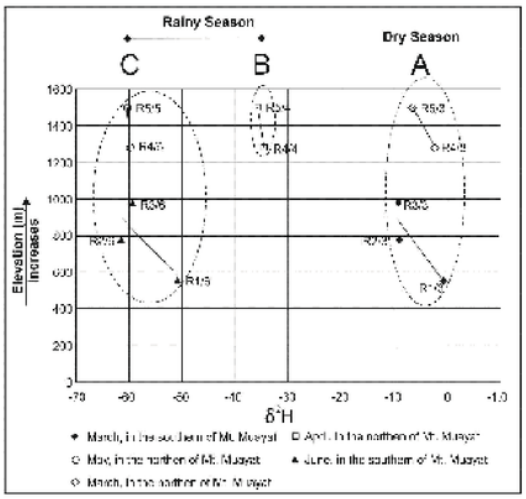

Fig. 6 Sample groupings based on $\delta^{2}H$ values, elevation and season. With increasing elevation, the $\delta^{2}H$-values of precipitation decrease (Dansgaard, 1964).

in March, which range from -2.2 ‰ to -3.2 ‰ for $\delta^{18}O$ and -1 ‰ to -9 ‰ for $\delta^{2}H$. Lower isotope values are often found in rain water at higher elevations. This is called as elevation effect (Dansgaard, 1964, and Panichi and Gonfiantini, 1978). Heavier rainfall, which occurred during the rainy season in April, May and June, was associated with more negative $\delta^{18}O$-values compared to March, which is in the dry season. During the rainy season the $\delta^{18}O$-value becomes more depleted, while the reverse occurs during the dry season (International Atomic Energy Agency, 1981). These are caused by amount of rainfall and are called as amount effect (Dansgaard, 1964).

The stable isotope values for $\delta^{18}O$ and $\delta^{2}H$ in river water that collected in the southern slope of Mt. Muayat range from -6.5 ‰ to -8.2 ‰ , and -41 ‰ to -51 ‰, respectively, in April. These results show a clear trend of elevation effect (Dansgaard, 1964) compared to those of rainwater that collected in the southern and northern slopes of Mt. Muayat.

The δ-values of rain water have different slopes of elevation effect for R1 to R3 and R4 to R5. This may be caused by (i) kinetic effect in fast evaporation (Dansgaard, 1964); (ii) locations of samples R1 to R3 on the southern slope of Mt. Muayat and R4 to R5 in the northern slope of Mt. Muayat.

The data of the hot springs, shallow wells (warm water) and river samples, shown in Table 2, were also plotted in Fig. 4 to identify their origin.

The enrichment of isotope values is positively correlated between $\delta^{2}H$ and $\delta^{18}O$ in acidic hot springs (Panichi and Gonfiantini, 1981). Sample MUAH-16 is enriched in $\delta^{2}H$ and $\delta^{18}O$ probably due to evaporation at shallow depth and/or on the surface (Craig et al., 1963). The isotopic enrichment is represented by a positive shift in the $\delta^{18}O$ from the LMWL, with MUAH-16>1.8 ‰, as shown in Fig. 4. This shift of δ-values may be caused by contribution of steam derived from boiling containing H_2S and/or dissolution of rock forming mineral attacked by the acid water. Sample MUAH-15 is enriched (MUAH-15>0.8 ‰), as a result of mixing of cold meteoric water with a high temperature chloride water which has already experienced oxygen shift at depth. Sample MUAH-16 has more negative (depleted) $\delta^{2}H$ value than samples LIBH-1, LIBH-2, LIBH-3, BONH-5, WANH-14, and BILH-13, because the origin of this sample is recharged at higher elevation. Sample LIBR-4 has more positive $\delta^{2}H$ and $\delta^{18}O$ values than MUAH-15, MUAH-16, LIBH-1, LIBH-2, LIBH-3, BONH-5, WANH-14, and BILH-13. This is caused by: (i) the sample was collected at lower elevation (752 m asl) compared to other two sample, MUAH-15 (969 m asl) and MUAH-16 (1438 m asl); (ii) LIBR-4 is a mixture of surface water and the acidic waters of MUAH-15 and MUAH-16 which have positive shifts for both $\delta^{2}H$ and $\delta^{18}O$. This surface water including rainfall, which has more positive value of $\delta^{2}H$ and $\delta^{18}O$, is affected by elevation effect. Samples LIBH-1, LIBH-2, LIBH-3, BONH-5, WANH-14, and BILH-13 plot close to the LMWL implying no isotope exchange between the water and the rock and only small amounts of evaporation.

Sample MOTH-12 is more depleted for δ^2H than KAPH-11 and BAKH-6 although sampling elevation being same. This may be caused by that MOTH-12 is formed by mixing recharge water from a higher elevation with the local recharge water while KAPH-11 and BAKH-6 are formed only by the local recharge water. Sample ABAH-8 is plotted close to the LMWL and has a relatively low Cl concentration (61.6 mg/L) and high temperature (75.4°C), implying that the hot water is mixing with shallow groundwater. Cold waters can generally be identified by the isotope compositions, which fall on the meteoric water line (i.e., without an oxygen isotope shift) and are usually local to the spring area, although deep recharge travels a long distance. The $\delta^{18}O$ shift of >+1.8 ‰ in LOBH-10 from the LMWL and high concentration of Li, Br and Cl implies that the ^{18}O has exchanged with the sedimentary rocks at depth. This process is accompanied by continuous leaching from the rock at high temperatures. This high Cl concentration may be because of the water flowing through sandstone and limestone formations of marine origin before discharging as hot spring at Lobong village (Apandi and Bachri, 1997).

The fifteen hot spring waters sampled in the Kotamobagu geothermal field have a stable isotope shift of less than 2 ‰ from the LMWL, implying that the origin of the hot spring water in the Kotamobagu geothermal field is mainly meteoric water.

On the basis of the chemistries and stable isotopes results a conceptual model of the Kotamobagu geothermal field was developed, mainly in Mt. Muayat area as shown in Fig.7.

1) The hot spring in the summit of Mt. Muayat is of SO_4 type. The steam derived from boiling at depth containing H_2S reacts with oxygen rich surface water, and H_2S is oxidized to form SO_4 rich acidic water. Enrichment of this water with δ^2H and $\delta^{18}O$ may be caused by mixing of steam and/or dissolution of rock forming mineral attacked by the acidic water.

2) Hot spring discharge in the middle of slope Mt Muayat is of Cl-SO_4 type. The high temperature chloride water containing volcanic gases (CO_2 and H_2S) is mixing with cold meteoric water and discharging to the surface. This water is enriched with respect to water isotopes by mixing cold meteoric water with high temperature water which has already experienced oxygen shift at depth.

3) Hot springs in the lower elevation are of bicarbonate type. The steam containing carbon dioxide condenses in an aquifer, and then stagnant reactions of this water with the rocks leads to a neutral pH before discharging to the surface. This water does not have a significant shift of δ-values (less than 0.3 ‰), because this water is dominated by the meteoric water.

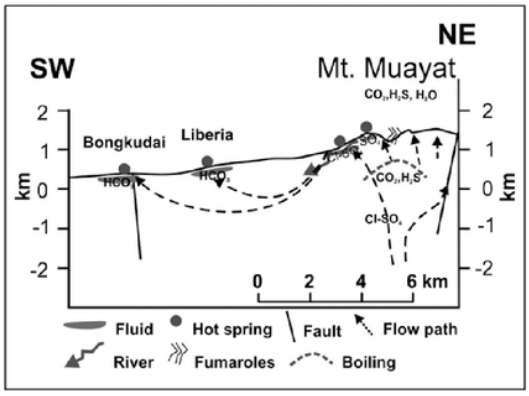

Fig. 7 Conceptual model of the Kotamobagu geothermal field.

6. Conclusions

The chemistries and stable isotopes of 16 hot spring waters, 15 river waters and 5-locations rain falls collected in the Kotamobagu geothermal fields were investigated in order to reveal the origin of the hot spring waters. The results can be concluded as follows:

1. The water samples are characterized into four groups of SO_4, Cl-SO_4, HCO_3 and hybrid type.
2. Hot springs of high elevation of Mt. Muayat are SO_4 (MUAH-16), and Cl-SO_4 (MUAH-15) type waters, indicating that the water at these sites is steam heated and volcanic water, respectively.
3. Hot springs of lower elevation of Mt. Muayat at Liberia, Bongkudai, Bilalang and Wangga villages (LIBH-1, LIBH-2, LIBH-3, BONH-5, BILH-13 and WANH-14) are of HCO_3 type.
4. Samples of the HCO_3 type water plotted close to the local meteoric water line (LMWL), indicating no significant isotope exchange between the water and the rock.
5. A positive shift in $\delta^{18}O$ and δ^2H relative to the LMWL may be due to enrichment by evaporation at shallow depth and/or on the surface.
6. The shift in $\delta^{18}O$ of >+1.8 ‰ in LOBH-10, and the 700 mg/L Cl concentration shows that isotope exchange occurs with the marine sedimentary rocks at depth and high temperature.
7. The fifteen hot spring waters sampled in the Kotamobagu geothermal field have a stable isotope shift of less than 2‰ relative to the LMWL, implying that the origin of the hot spring water is mainly meteoric water.

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論　文

インドネシア国北スラウェジのコタモバグ地熱地域の温泉水の起源

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概　要

コタモバグ地熱地域の東西 30 km，南北 20 km において温泉水および関連した水の地化学調査を実施した。温泉水，河川水からなる 31 試料を標高 173 m から 1438 m の間で採取し，化学成分および水の安定同位体比を測定した。同時に雨水を標高 556 m から 1500 m の間の 5 地点で，2010 年 3 月から 6 月にかけて採取した。ほとんどの温泉水は中性の HCO_3 型および複合型であり，水の安定同位対比のグローバルな天水線上に分布し，天水起源であることを示唆している。しかし，酸性の水はこの天水線からずれている。Muayat 山の山頂付近の噴気地帯近傍で採取された試料（MUAH-16）は SO_4 タイプであり，蒸気加熱型であることを示唆している。酸性水試料が安定同位体の天水線からずれている原因は地表あるいは浅層での天水の蒸発と考えられる。中性でかつ本地域の天水線の $\delta^{18}O$ からずれている試料 LOBH-10 は本地域の周辺部に位置し，このずれは海生起源の岩石との反応が原因と考えられる。

キーワード：コタモバグ，水起源，安定同位体，地化学

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