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Hydrogen and oxygen isotopic compositions of subsurface water at Bajawa area, central Flores, Indonesia

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Abstract : Samples of spring and stream water, and rainfall were obtained within 50 km of Bajawa City, central part of Flores Island, eastern Indonesia. Hydrogen and oxygen isotopic compositions of the samples were analyzed.

(1) On the relation diagram between hydrogen and oxygen isotopic compositions, water samples were plotted near the meteoric water line. The sample d-values taken in 1998 and 1999 were about 10 and 20, respectively. The change of d-value may reflect the isotopic difference of rainfall in winter and summer.

(2) Altitude (topographical) effects for hydrogen and oxygen isotopic compositions of subsurface water in this area were -0.98 ‰/100 m for hydrogen isotopic composition and -0.13 ‰/100 m for oxygen isotopic composition, which were within the range of those found for other islands.

1. Introduction

Characteristics of hydrogen and oxygen isotopic variations of subsurface water and rainfall due to topographical elevation have been used to infer recharge areas for groundwater or hot spring water, indicate mixing, or delineate different groundwater or hydrothermal system. However, there were no hydrogen and oxygen isotopic data for subsurface water of the eastern part of Indonesia except Bali Island (e.g. Shimada *et al.*, 1992a) and knowledge of subsurface water flow patterns was also so limited.

Precipitation patterns on islands with appreciable topography are very complex, and precipitation isotope data from the International Atomic Energy Agency (IAEA) island stations commonly exhibit patterns different from those found on other continental stations (Yurtsever and Gat, 1981; Dansgaard, 1964). Scholl *et al.* (1996) showed that significant areal differences in precipitation isotopes on the island of Hawaii correlated strongly with general climatological patterns. High rainfall areas have frequent rains owing to the orographic lifting of moist air carried by trade winds or the thermally driven sea breeze cycle. Tang *et al.* (1998) described that on Miyake Island, even at places of the same altitude, the precipitation was different because of the aspect of the landscape and also found that oxygen isotopic compositions for the windward and leeward sides were different from that for precipitation.

The purpose of this study is (1) to show isotopic distributions of subsurface water and rainfall in the

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Keywords: hydrogen isotope, oxygen isotope, subsurface water, meteoric water line, d-value, altitude effect, Bajawa, Flores, Indonesia

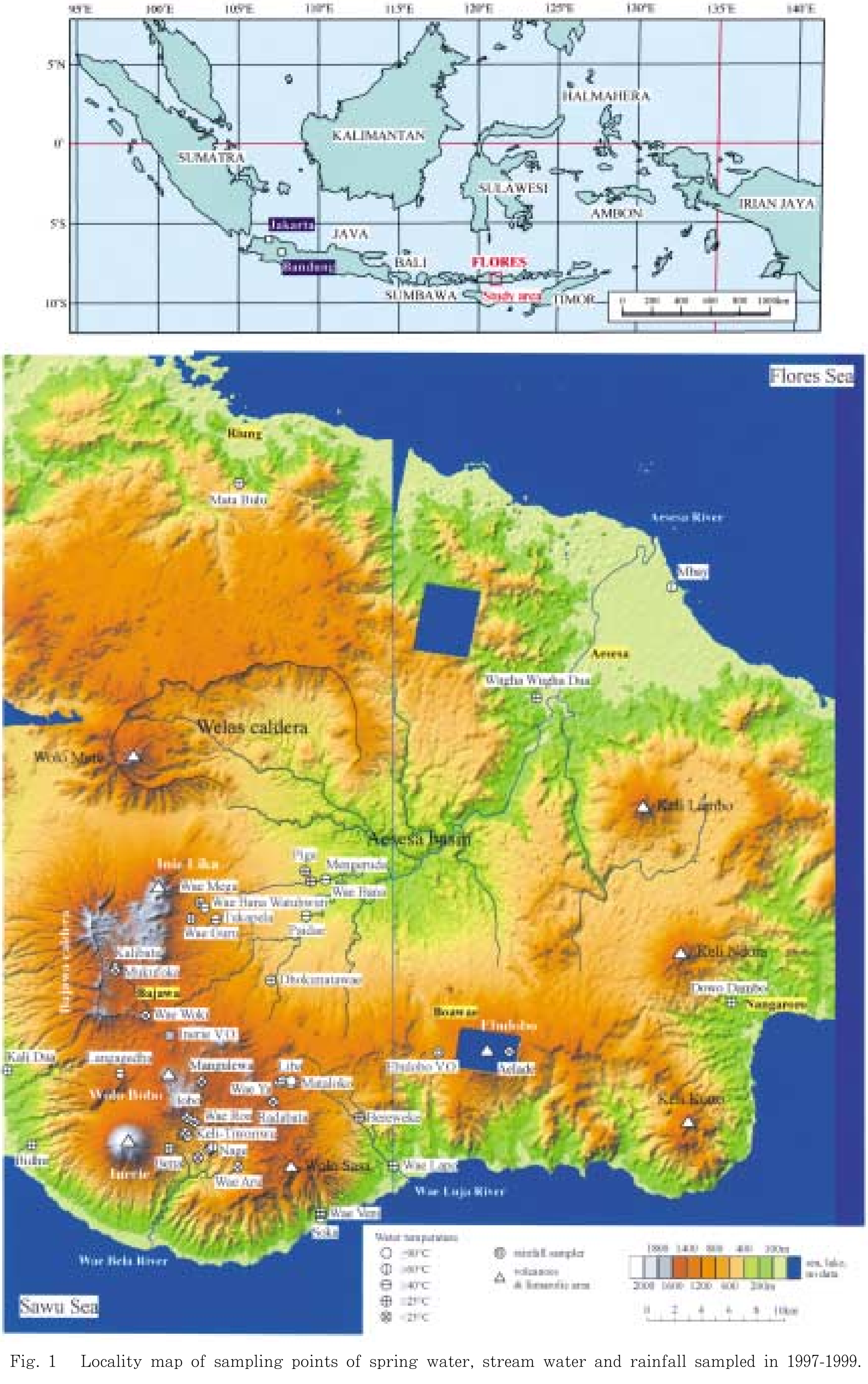

Fig. 1 Locality map of sampling points of spring water, stream water and rainfall sampled in 1997-1999.

Bajawa area, central part of Flores Island, about 500 km east of Bali Island, and (2) describe the topographical (altitude) effects for isotopic compositions of subsurface water.

2. Study area

The islands of Nusa Tenggara span a distance of 1,300 kilometers and lie 8 to 10 degrees south of the equator. They connect the Greater Sunda Islands in the west to the scattered islands of Maluku, Banda Islands and large island of Irian Jaya to the east forming a central link in the 5,600 kilometer Indonesian archipelago. They form two distinct arcs. The long northern arc, Lombok, Sumbawa, Komodo, Flores, Lembata, Alor and other islands is volcanic in origin. The islands of the shorter southern arc, Sumba, Savu, Rote, Timor and other islands are formed of raised coral reef limestone and pelagic sedimentary rocks (e.g. Hamilton, 1979). Most of those volcanic islands have the potential to provide geothermal energy (e.g. PERTAMINA, 1994). Flores Island is in the eastern part of the Nusa Tenggara Islands and a long, narrow island 350 km long (east to west) and 20-70 km wide (north to south). Bajawa City is in the central part of the island and the provincial capital of the Ngada prefecture. In the Bajawa area, there are two volcanic alignments (Fig. 1). The southern-coast-side volcanic alignment is a volcanic front and contains three active volcanoes, Inerie (2160 m), Inie Lika (1800 m) and Ebulobo (2150 m), and more than 30 monogenetic volcanoes. The average height of the southern-coast-side volcanic row (plateau) is 1000-1500 m (see Takahashi *et al.* (2002, Fig. 7)). On the other hand, the northernside volcanic alignment is a back-arc volcanic row and contains the cocoon-shaped Welas caldera 15 km (east to west) by 8 km (north to south) and post-caldera cone called Mt. Wolo Mere (1550m). The average height of the northernside volcanic row (plateau) is 500-1000m (see Takahashi *et al.* (2002, Fig. 7)). This setting is similar to double volcanic belts in the northeast Japan arc (Muraoka *et al.*, 1999). Both volcanic rows rise straight up from the Flores and Sawu Seas. There is an elliptic large basin 20 km (east to west) by 15 km (north to south) sandwiched by two volcanic alignments (Fig. 1). Muraoka *et al.* (1999) named the basin, the Aesesa Basin. The average elevation of the basin is 300 m and becomes lower gradually toward the northeastern coast. There are three large river systems in the Bajawa area (Fig. 1). The Aesesa River, which is the longest river in this area flows to the northeast and discharges into the Flores Sea. The Wae Bela River starts in a small basin near Nage and flows to the southwest. The Wae Luja River starts from the northeastern side of the southernside volcanic row and runs to the southeast. The latter two rivers discharge into the Sawu Sea.

In Indonesia, every volcano observatory (V. O.)

Table 1 Monthly precipitation data (precipitation amount and number of rainy days) and Q-values at the Inerie and Ebulobo volcano observatories from 1996 to 2000.

	Inerie V.O.		R or D	Q value	Ebulobo V.O.		R or D	Q value
	(mm)	(days)			(mm)	(days)		
Jan.96	278.	16.	R		503.	15.	R	
Feb.96	468.	16.	R		299.	13.	R	
Mar.96	134.6	12.	R		37.	3.	D	
Apr.96	78.	3.			53.	2.	D	
May.96	56.	4.	D		191.	6.	R	
Jun.96	0.	0.	D		0.	0.	D	
Jul.96	0.	0.	D	1.00	0.	0.	D	1.20
Aug.96	18.	1.	D		9.	1.	D	
Sep.96	0.	0.	D		0.	0.	D	
Oct.96	63.2	4.			83.	2.		
Nov.96	108.9	11.	R		160.5	6.	R	
Dec.96	554.2	17.	R		366.	4.	R	
Jan.97	504.	18.	R		274.	11.	R	
Feb.97	672.	21.	R		310.	17.	R	
Mar.97	207.	6.	R		71.	3.		
Apr.97	106.8	6.	R		151.	4.	R	
May.97	6.4	1.	D		62.	2.		
Jun.97	33.	5.	D	1.40	97.	5.		1.25
Jul.97	0.	0.	D		0.	0.	D	
Aug.97	0.	0.	D		17.	3.	D	
Sep.97	0.	0.	D		0.	0.	D	
Oct.97	0.	0.	D		0.	0.	D	
Nov.97	33.6	4.	D		30.	3.	D	
Dec.97	358.2	18.	R		245.	11.	R	
Jan.98	156.8	11.	R		381.	14.	R	
Feb.98	324.8	16.	R		423.	14.	R	
Mar.98	357.	14.	R		428.	16.	R	
Apr.98	305.2	14.	R		315.	13.	R	
May.98	89.4	6.			32.	3.	D	
Jun.98	22.	6.	D		8.	1.	D	
Jul.98	87.1	4.		0.50	88.	8.		0.57
Aug.98	0.	0.	D		18.5	2.	D	
Sep.98	37.6	4.	D		40.	4.	D	
Oct.98	83.1	12.			171.	5.	R	
Nov.98	448.	20.	R		233.	13.	R	
Dec.98	440.1	18.	R		391.	14.	R	
Jan.99	415.8	23.	R		476.5	23.	R	
Feb.99	364.6	20.	R		448.5	18.	R	
Mar.99	325.8	18.	R		572.	21.	R	
Apr.99	241.1	14.	R		270.2	15.	R	
May.99	1.2	1.	D		10.	2.	D	
Jun.99	58.6	5.			145.5	7.	R	
Jul.99	0.	0.	D	0.83	7.	3.	D	
Aug.99	0.	0.	D		3.5	1.	D	
Sep.99	0.	0.	D		4.	1.	D	
Oct.99	41.2	5.	D		68.	7.		
Nov.99	330.9	18.	R					
Dec.99	244.2	17.	R					
Jan.00	477.8	23.	R					
Feb.00	268.2	17.	R		482.	21.	R	
Mar.00	541.	21.	R					
Apr.00	402.6	19.	R					
May.00	239.3	16.	R		297.	18.	R	
Jun.00	16.4	2.	D		186.	14.	R	
Jul.00	0.	0.	D	0.57	14.	1.	D	
Aug.00	0.	0.	D		6.	2.	D	
Sep.00	7.9	1.	D		1.5	1.	D	
Oct.00	89.3	4.			105.5	9.	R	
Nov.00	386.5	15.	R		250.	16.	R	
Dec.00	446.3	7.	R		275.5	12.	R	

R or D: Rainy month (≥100mm) or Dry month (<60mm)
Q value: Dry month / Rainy month

monitors the amount of rainfall. Monthly precipitation data at the Inerie and Ebulobo volcano observatories (Fig. 1) are shown in Table 1. In the table, Q-value, which is the ratio between the number of dry months when the monthly precipitation amount is less than 60 mm and number of rainy months when the monthly precipitation amount is more than 100 mm, was also shown (e.g. Center for Southeast Asian Studies, Kyoto University, 1997, p. 468). The Q-values of this area, Sapporo, Tokyo, Osaka and Naha were 0.5-1.4, 0.2, 0.29, 0.29 and 0, respectively, calculated from Table 1 and monthly mean precipitation amounts from 1961 to 1990 shown in the Chronological Scientific Tables 2000. Relatively large Q-values of this area show the existence of the dry season and were concordant with the climatic classification of this area, Tropical Savannah (As). Precipitation amounts were 1200-2500 mm/yr at the Ebulobo V. O. and 1700-2500 mm/yr at the Inerie V. O.

3. Sampling and analytical methods

Location of sampling points is shown in Fig. 1. Water samples were obtained from springs, streams and rainfall within 50 km of the Bajawa City from 1997 to 1999. Rainfall samplers of 9 cmϕ-funnel and 20 l-backet (Kazahaya and Yasuhara, 1994; Scholl *et al.*, 1995) were installed at the Inerie and Ebulobo volcano observatories to collect rainfall from July 1998 to September 1999. Methods for hydrogen and oxygen isotopic analyses were shown in Takahashi *et al.* (2002).

4. Results and discussions

4.1 The d-values of water samples of springs, streams and rainfall

The relation between hydrogen and oxygen isotopic compositions of water samples from springs, streams and rainfall is shown in Fig. 2. Craig (1961) described the interdependence of hydrogen and oxygen isotopic compositions in meteoric water and defined the following relationship:

$\delta D = 8x\delta^{18}O + 10$

The relationship was generally described as the Meteoric Water Line (MWL). Dansgaard (1964) defined the intersect for the Y-axis ($\delta D - 8x\delta^{18}O$) as d-value. As shown in Fig. 2 and Table 2, almost all water samples were plotted near the MWL. The

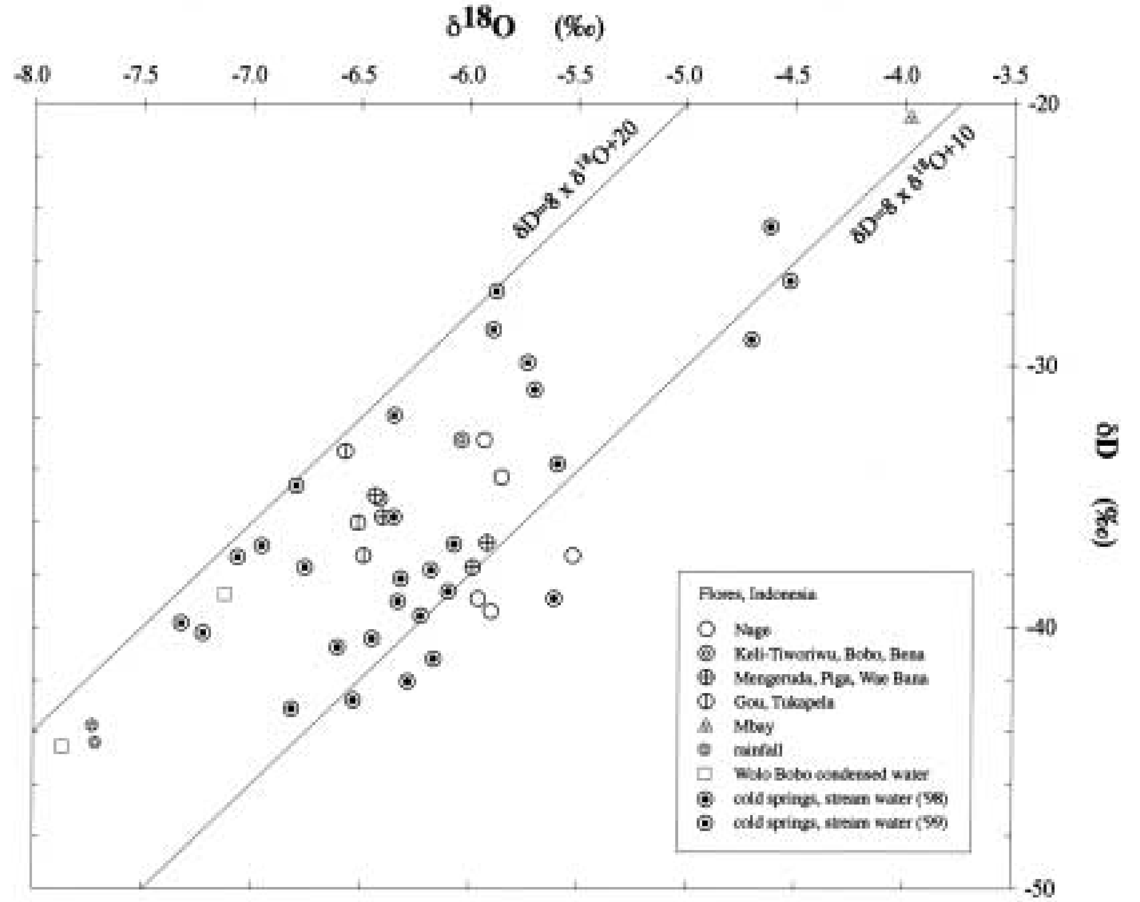

Fig. 2 The relation between hydrogen and oxygen isotopic ratio of spring water, stream water and rainfall on Flores Island, eastern Indonesia.

Table 2 The result of hydrogen and oxygen isotopic analyses of spring water, stream water, condensed water and rainfall sampled in fiscal years 1997, 1998 and 1999. In the table, altitudes of the sampling points are also shown.

sample name	date & sample number	δD (‰)	$\delta^{18}O$ (‰)	d-value	height (m)
Nage-1	98071501	-39.07	-5.974	8.72	537
Nage-2	98071502	-37.44	-5.533	6.82	525
Nage-3	98071503	-39.55	-5.913	7.76	512
Bena(Wae Wowa)	98071504	-39.08	-5.622	5.89	812
Stream of Mataloko	98071602	-42.26	-6.290	8.06	1000
Wae Ya (spring)	98071702	-41.36	-6.177	8.05	1100
Liba	98071703	-42.95	-6.541	9.38	1100
Keli Tiworiwu-1	98071801	-35.25	-6.422	16.13	840
Keli Tiworiwu-2	98071802	-33.00	-6.048	15.39	850
Stream of Keli Tiworiwu	98071803	-36.97	-6.083	11.69	850
Mengeruda	98072001	-37.88	-5.997	10.09	312
Wae Bana	98072002	-36.96	-5.932	10.49	362
Guu (Wae Megu)	98072003	-36.19	-6.523	16.00	800
Guu (Wae Bana Watubwuti)	98072004	-33.43	-6.585	19.25	800
Takapela (Boba-Soa)	98072101	-37.42	-6.498	14.56	775
Paidae (Wae Watu)	98072102	-38.29	-6.328	12.34	350
Soka (Wae Pana)	98072201	-31.08	-5.716	14.65	90
Wae Voni	98072202	-24.87	-4.630	12.17	110
Wae Roa	98072301	-43.30	-6.830	11.34	1025
Bobo (Wae Putih)	98072302	-37.95	-6.191	11.57	1050
Wae Gara	98072401	-39.17	-6.339	11.54	900
Dhokimatawae	98072402	-38.82	-6.110	10.06	550
Malafoka	98072501	-40.93	-6.615	11.98	1275
Wae Woki	98072502	-39.73	-6.236	10.16	1162
Wae Lapo	98072701	-26.96	-4.543	9.38	100
Barewoka	98072702	-33.91	-5.611	10.98	430
Radabata (Wae Ba)	98072801	-35.97	-6.361	14.91	1160
Nage (spring)	98072802	-40.58	-6.457	11.07	462
Wae Ara	98072803	-29.18	-4.722	8.60	610
Langagedha	99083001	-40.01	-7.333	18.66	1030
Kalibatu	99083101	-37.06	-6.968	18.68	1350
Malafoka	99083102	-37.48	-7.075	19.13	1275
Mangalewa (Wae Roa)	99083103	-40.36	-7.233	17.50	1200
Aelada (Boawae)	99090101	-37.87	-6.769	16.28	650
Dowo Dambu (Nangaroro)	99090102	-30.04	-5.744	15.91	75
Mata Bala (Riung)	99090201	-32.05	-6.362	18.85	450
Kali Dua (Aimere)	99090301	-27.33	-5.895	19.83	125
Bidhu (Enam Dusa)	99090302	-34.74	-6.807	19.72	400
Waghu Waghu Dua (Aimere)	99090401	-28.82	-5.905	18.42	50
Mbay	99090402	-20.59	-3.985	11.29	10
Nage-1	99090601	-33.01	-5.947	14.57	537
Nage-2	99090602	-34.41	-5.868	12.53	525
Piga	99090603	-35.94	-6.415	15.38	390
Mengeruda	99090604	-35.16	-6.447	16.42	312
Wolo Bobo-2	99090801	-44.55	-7.723	17.23	1400
Wolo Bobo-1	99090802	-43.89	-7.735	17.99	1400
Inerie VO rainfall	98.7-99.9	-44.68	-7.872	18.29	1200
Ebulobo VO rainfall	98.7-99.9	-38.86	-7.129	18.18	1200

sample d-values taken in 1998 and 1999 were about 10 and 20, respectively. The d-values of rainfall samples taken from July 1998 to September 1999 were 18, which was concordant with d-values of water samples taken in 1999. The IAEA/WMO Global Network for Isotopes in Precipitation (GNIP) showed hydrogen and oxygen isotopic data of monthly rainfall for Jakarta, Jayapura (Irian Jaya) and Darwin (Australia) (IAEA/WMO, 1999). The relation between hydrogen and oxygen isotopic ratio of water samples obtained from springs, streams and rainfall for Flores Island and rainfall for Jakarta, Jayapura and Darwin is shown in Fig. 3. In Fig. 3, the relation between those isotopic compositions of monthly rainfall taken at several points on Bali Island (Shimada *et al.*, 1992a) is also shown. As shown in Fig. 3, small d-values for monthly rainfall were observed for Jayapura, eastern part of the Indonesian archipelago, whereas large d-values for Bali Island, central part of the Indonesian archipelago. The d-values for water samples obtained from Flores Island lie between those at Jayapura

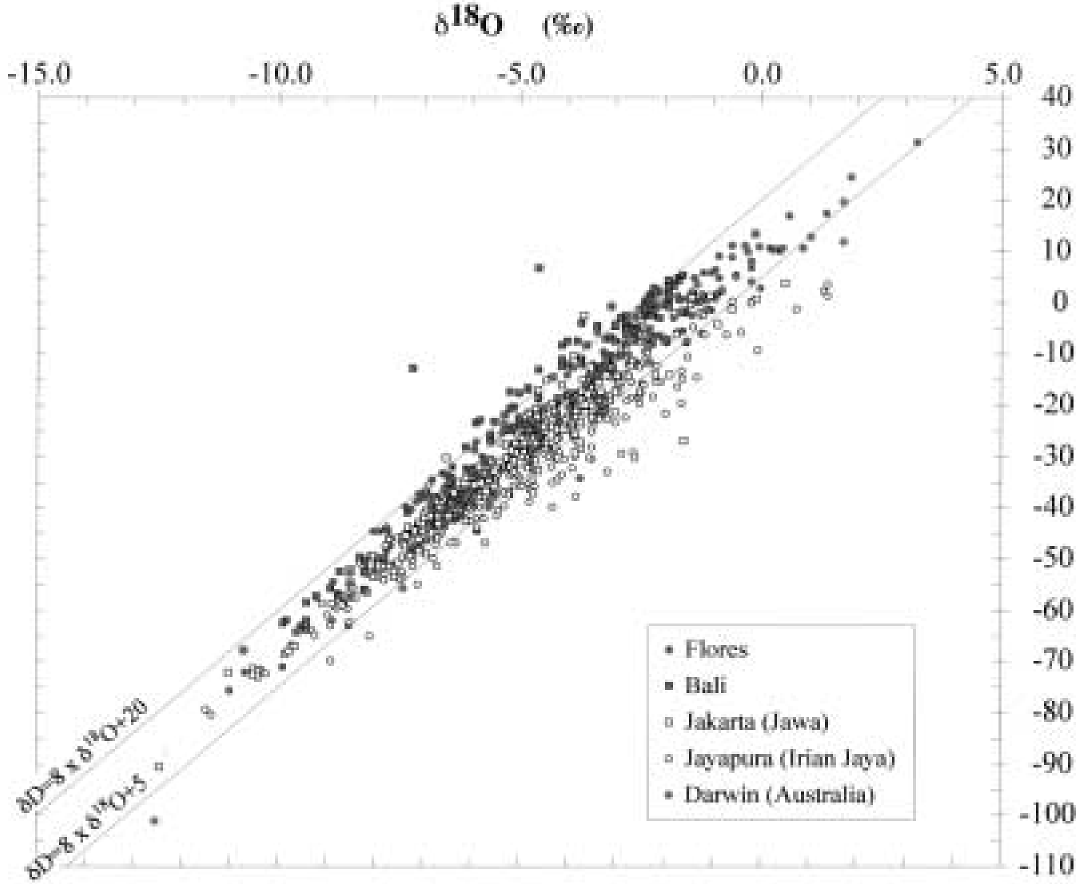

Fig. 3 The relation between hydrogen and oxygen isotopic ratio of rainfall for Flores Island, eastern Indonesia, and rainfall for Bali, Jakarta (Jawa), Jayapura (Irian Jaya) and Darwin (Australia).

and the island of Bali, and were close to those at Jakarta and Darwin.

As shown in Table 1, precipitation amounts at the Inerie V. O. and Ebulobo V. O. in 1998-1999 were both more than in 1997-1998, and the rainy monsoon in 1998-1999 was longer than in 1997-1998. On Flores Island, the wind direction in winter is west, whereas it is southeast in summer (e.g. Center for southeast Asian studies, Kyoto University, 1997, p. 25). Thus, it was suggested that the d-value change of the rainfall is due to the isotopic difference of rainfall in winter and summer. The National Oceanic & Atmospheric Administration (NOAA) showed that the tropical Pacific area was in the El Nino condition from spring 1997 to summer 1998 and in the La Nina condition from autumn 1998 to spring 1999 and summer 1999 to spring 2000 (NOAA, 2002). Generally in the El Nino condition, the precipitation amount in Indonesia is smaller than in the La Nina and normal conditions. As shown in Table 1, precipitation amounts for the Inerie V. O. and Ebulobo V. O. in 1998-1999 were both larger than in 1997-1998, which is concordant with the climatic condition of this period. Thus, it may be also suggested that the change of d-value of rainfall was affected by the climatic condition of this area.

4.2 The gradients of isotopic composition with elevation

The relation between the elevation of sampling points and hydrogen isotopic composition of water samples, and relation between the elevation and oxygen isotopic composition are shown in Figs. 4 and 5, respectively. Regression lines were as follows:

δD (‰) = -(0.0098H±0.0013)-(29.3±1.2), r^2=0.653

$\delta^{18}O$ (‰) = -(0.00128H±0.00023)-(5.35±0.21), r^2=0.499

where H denotes the sampling altitude in meters.

As shown in Table 3, altitude effects of -0.98 ‰/100 m for hydrogen isotopic composition and of -0.13 ‰/100 m for oxygen isotopic composition were within the range of elevation / isotope gradients found for other islands. The high elevation / isotope gradients were observed only in the Martha Brae River basin (Ellins, 1992), Bali Island (Shimada *et al.*, 1992b) and high-elevation area of Hawaii Island (Scholl *et al.*, 1996) areas. Since high-elevation mountains >3000 m were in those areas except Martha Brae River basin area, the large elevation / isotope gradient may be due to the existence of a

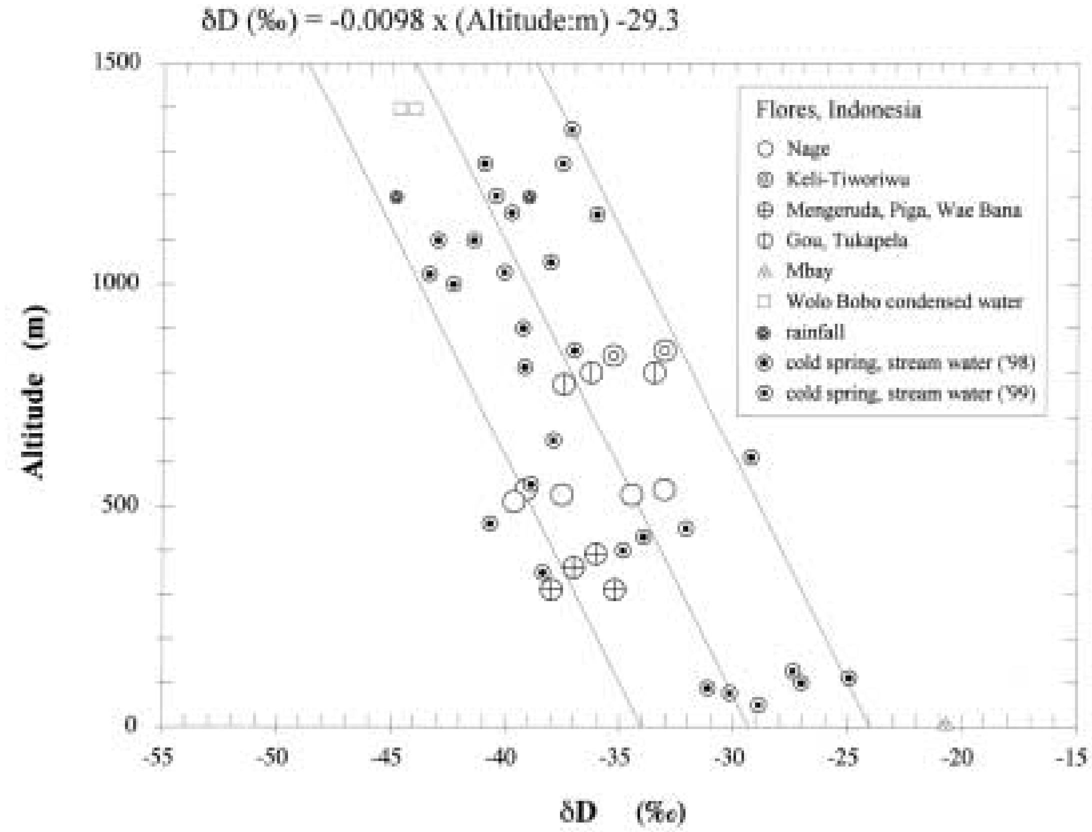

Fig. 4 The relation between sampling altitudes and hydrogen isotopic compositions of water samples.

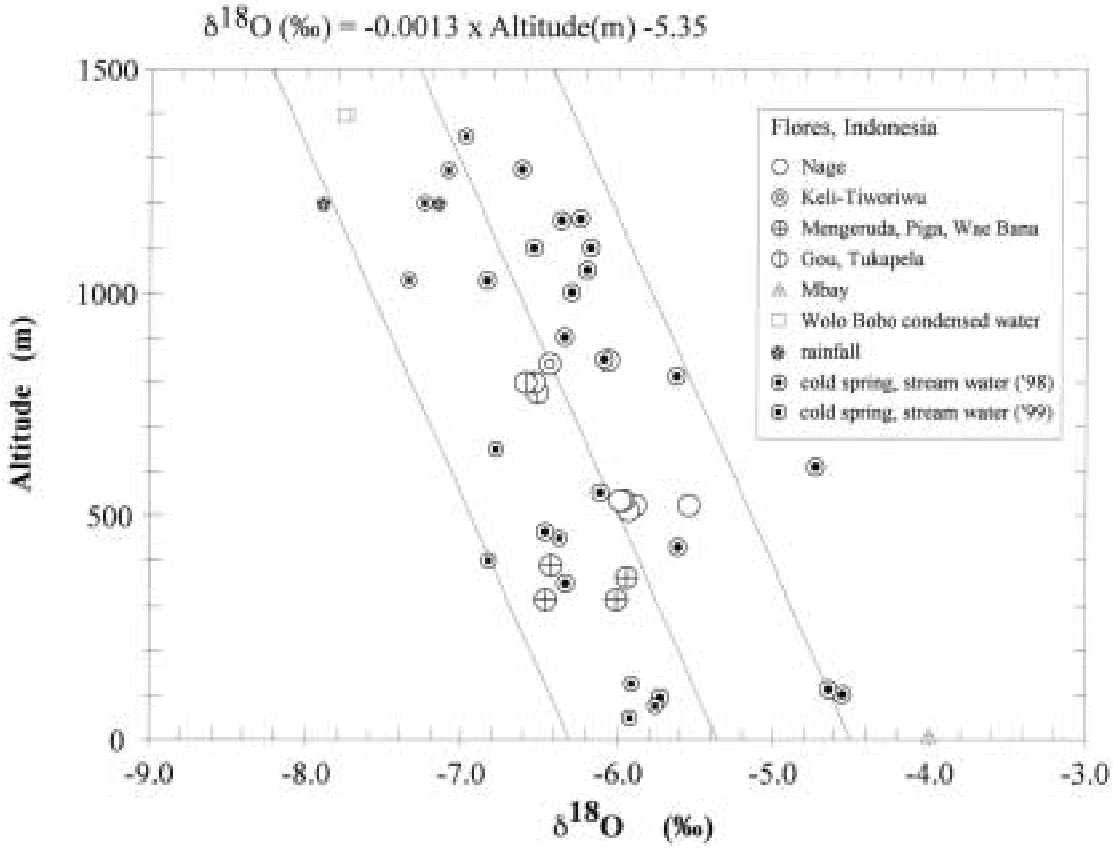

Fig. 5 The relation between sampling altitudes and oxygen isotopic compositions of water samples.

Table 3 Gradients of isotopic composition with elevation from several islands.

Location	Sample type	Isotope/Elevation Gradient, per 100m	Reference
Tatun Shan, Taiwan (Tatun Shan, 1080m)	spring, stream	$\delta^{18}O$ = -0.15‰	Liu, 1984
Cul de Sac Plain, Haiti (La Selle, 2680m)	springs	$\delta^{18}O$ = -0.09‰ δD = -0.59‰	Gonfiantini and Simonot, 1987
Martha Brae River basin, Jamaica (Cockpit, 748m)	precipitation	δD = -0.9 to -2.2‰	Ellins, 1992
Island of Bali, Indonesia (Agung, 3142m)	spring, stream	$\delta^{18}O$ = -0.278 to -0.300‰	Shimada et al., 1992b
Greater Tongonan geothermal field, Philippines (Alto Peak, 920m)	precipitation	$\delta^{18}O$ = -0.07‰ δD = -0.25‰	Avis-Isidro *et al.*, 1993
Negros Island, Philippines (Conlaon, 2464m)	precipitation	$\delta^{18}O$ = -0.19‰ δD = -1.14‰	Gerardo *et al.*, 1993
Island of Hawaii, Kilauea volcano area, USA (Mauna Kea, 4205m; Mauna Loa, 4169m)	precipitation, springs	$\delta^{18}O$ = -0.15 to -0.32‰ δD = -0.98 to -2.6‰	Scholl *et al.*, 1996
Miyake Island, Japan (Oyama, 813m)	precipitation	$\delta^{18}O$ = -0.10 to -0.15‰	Tang *et al.*, 1998
Island of Flores, Indonesia (Inerie, 2160m; Ebulobo, 2150m)	precipitation, springs	$\delta^{18}O$ = -0.128‰ δD = -0.98‰	This study

high-elevation area (Scholl *et al.*, 1996).

5. Conclusion

Water samples were taken from springs, streams and rainfall within 50 km of Bajawa City, Flores, eastern Indonesia. Hydrogen and oxygen isotopic compositions of the samples were analyzed.

(1) On the relation diagram between hydrogen and oxygen isotopic compositions, almost all water samples were plotted near the MWL. The sample d-values taken in 1998 and 1999 were about 10 and 20, respectively. The d-value change may be due to the isotopic difference of rainfall in winter and summer.

(2) Altitude (topographical) effects for hydrogen and oxygen isotopic compositions of subsurface water in this area were shown by following regression lines.

δD (‰) = -0.0098H-29.3

$\delta^{18}O$ (‰) = -0.00128H-5.35

where H denotes the sampling altitude in meters. The elevation / isotope gradients observed in the Bajawa area were within the range of those found for other islands.

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インドネシア，フローレス島中部バジャワ地域の地下水の水素・酸素同位体組成

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要　旨

インドネシア東部，フローレス島中部のバジャワ周辺 50 km 以内にある湧水，河川水及び降水を採取し，その水素・酸素同位体組成を分析した.

（1）水素-酸素同位体組成図上では，水試料は天水線近くにプロットされ，その d 値は 1998 年採取試料は約 10，1999 年採取試料は約 20 であった．d 値の変化は，冬季と夏季の降水の同位体組成の違いを反映している可能性が考えられる.

（2）同位体標高効果は，水素同位体組成で -0.98 ‰ / 100 m，酸素同位体組成で -0.13 ‰ / 100 mであった．これらの値は他の島で観測される値の範囲内である。