Deuterium Content of Water Substances in Antarctica Part II. Geochemistry of Deuterium of Lake Waters in Victoria Land

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南極の水物質中の重水素濃度 II. ヴィクトリアランドの湖水の重水素の地球化学

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要旨：1963–1964 および 1964–1965 年の夏期に Victoria Land の Dry Valley にある湖沼を中心に採水された水試料について重水素濃度を測定した.

Wright Valley と Taylor Valley に存在する湖水の重水素濃度は，Ross Island や Ongul 島などの南極の他の地域の水試料に比べて低く，−219～−328 δD_{SMOW}‰ であった.

Vanda 湖および Bonney 湖は化学成分の濃度が高く，特に垂直分布は極めて特徴的であるが，重水素濃度については，Vanda 湖は，底層部において若干増加しているが Bonney 湖は中層部に最低値が見られ，全体的にも濃度が低い．これらの湖の温度分布も含め，湖水の起源について論ずる.

1. Introduction

Two dry valleys of Victoria Land in Antarctica, Wright Valley and Taylor Valley, have several permanently frozen lakes. Some of these lakes have attracted attention of many scientists in the world because of the physical and chemical properties of their waters.

Particularly, Lake Vanda and Lake Bonney are characterized by their high salt contents and their thermal features. The high salt concentration of the lake waters was ascribed to hydrothermal or marine origin (ANGINO *et al.*, 1962 a, b; ANGINO and ARMITAGE, 1963; ANGINO *et al.*, 1964). The increase of the temperature in the middle layer of these two lakes was attributed to the heat from solar radiation through the ice cover (HOARE *et al.*, 1964; RAGOTZKIE and LIKENS, 1964; SHIRTCLIFFE and BENSEMAN, 1964; TORII *et al.*, 1967), and the high temperature in the bottom layer of Lake Vanda was considered to have come from a geothermal source (ANGINO and ARMITAGE, 1963; ANGINO *et al.*, 1964).

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A team of Japanese geochemists headed by Dr. TORII participated in the scientific exploration of the area, in cooperation with the American team. During the Antarctic summer of 1963–1964 a preliminary survey was carried out, to be succeeded by the 1964–1965 and 1965–1966 surveys. Some of the lake water samples collected by the first and second explorations were offered to the author for determination of the deuterium content.

In this paper, the origin of the lake water is discussed on the basis of the deuterium content and the chemical composition of the samples.

2. Topography of the Lakes and the Neighbouring Area

As shown in Fig. 1, Wright Valley has Lake Vanda, Don Juan Pond and Lake South Fork, and Taylor Valley has Lake Bonney and Lake Fryxell. In the north of Wright Valley there lie mountains of 4,000 meters high, and groups of volcanoes between the two valleys. A glacier was observed in the south of Taylor Valley and many marks of glacier retreat were found in the two valleys.

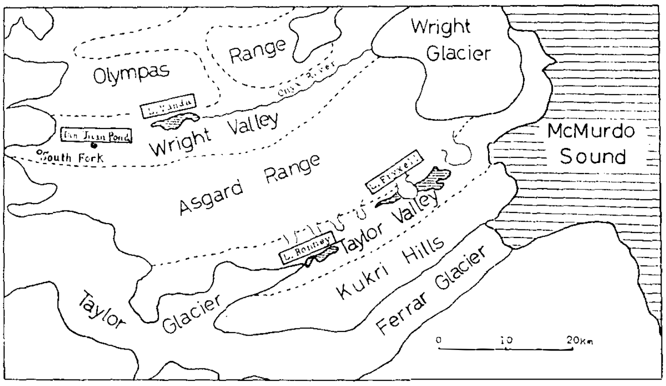

Fig. 1. Map of part of the western coastal area of McMurdo Sound, Victoria Land.

Lake Vanda (77°32′S, 161°30′E) has a length of 7 km and a maximum width of 2 km, and the maximum depth of the lake is 65 m. The surface of the lake was uniformly covered with about 4 m thick ice every summer. The Wright Glacier lies 26 km to the east of this lake, and its melt water flows into the lake by way of the Onyx River from Onyx Pond during the summer.

Lake Bonney (77°43′S, 162°23′E) consists of two basins, the larger eastern one is 4.82 km long and 0.77 km wide, and the smaller western basin is 2.56 km long and 0.84 km wide (RAGOTZKIE and LIKENS, 1964). The maximum depth is measured as 30 m in the eastern basin. The surface of the lake was covered with about 4 m thick ice like Lake Vanda.

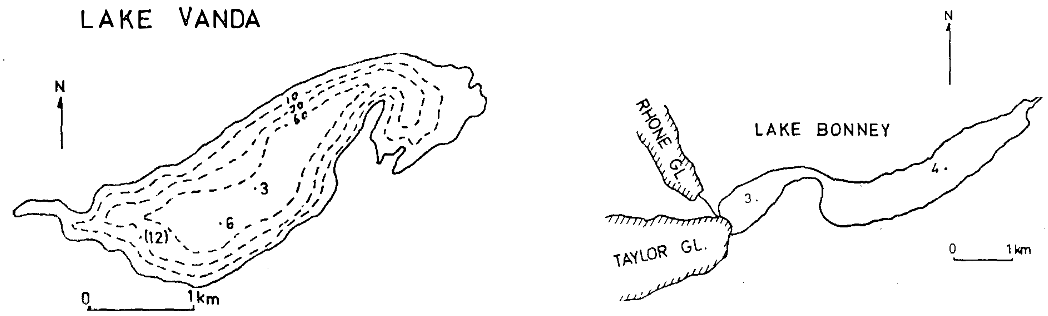

Fig. 2. Location of holes in Lake Vanda and Lake Bonney. Reproduced from TORII et al. (1967) with permission.

3. Sample Collection

The location of coring on the ice cover of Lake Vanda and Lake Bonney for sampling in 1964–1965 is shown in Fig. 2. Holes Nos. C–1 and C–2 in Lake Vanda in 1963–1964 were located near hole No. 12, and No. C–3 was beside V–3. Holes B–1 and B–2 on Lake Bonney were in the east lobe.

The other samples were collected from Cape Royds and Cape Evans of Ross Island, except for the sample from stranded moraine on the continent opposite to McMurdo Station (YAMAGATA, TORII, MURATA and WATANUKI, 1967).

4. Deuterium Content of Lake Waters

The values of the deuterium content of water samples are shown in Tables 1, 2 and 3. The deuterium content was determined by a deuterium mass spectrometer* and represented as deviation (δ) in per mill, from the ratio, HD/H_2, of a Standard Mean Ocean Water (SMOW), as expressed in the following formula (HORIBE and KOBAYAKAWA, 1960):

$$\delta D_{SMOW}(‰) = \left(\frac{(HD/H_2)_X}{(HD/H_2)_{std.}} - 1 \right) \times 1000$$

5. Discussion

The values of δD_{SMOW} (‰) of water samples of Lake Vanda, Lake Bonney, Lake Fryxell and Don Juan Pond ranged from −219 to −328‰ in the preliminary and secondary surveys.

These values were comparable to those of Lake Vanda determined by RAGOTZKIE

* The analysis was performed with the deuterium mass spectrometer of Tokyo Metropolitan University and of Ocean Research Institute, the University of Tokyo.

Table 1. Deuterium content of lake water samples from Victoria Land. (Dec. 1963–Jan. 1964)

Locality	Date of collection	Depth (m)	Temp. (°C)	δD_{SMOW} (‰)
L. Vanda Edge	Dec. 28, 1963	0	2.00	−235
L. Vanda C1	Dec. 29, 1963	5	4.38	−257
C1		10	4.99	−265
C2	Dec. 29, 1963	5	4.49	−255
C2		15	7.42	−263
C3	Jan. 15, 1964	5	4.36	−234
C3		30	6.90	−261
C3		45	8.39	−267
C3		63	23.20	−245
L. Bonney B1	Jan. 1, 1964	5		−276
B1		14		−301
B2	Jan. 1, 1964	5	0.47	−245
B2		14	6.95	−320
B2		30	−1.21	−275
L. Bonney inflow	Jan. 2, 1964	0		−216
L. Fryxell	Jan. 4, 1964	4		−219
		10		−255
		18		−243
South Fork (1)	Dec. 30, 1963	0		−172
(2)		0		−159
Don Juan Pond		0		−223
Cape Royds St. 26	Jan. 14, 1964		4.80	−122
Home Lake			3.40	−124
Blue Lake			0.05	−185
Cape Evans Skua Lake	Jan. 9, 1964		5.80	−186
St. 15			5.40	−205
St. 17			4.50	−174
St. 18			2.20	−190
St. 19			3.65	−190
St. 20			3.30	−151
McMurdo Cinder-cone			1.00	−227
Stranded Moraines	Jan. 10, 1964		0.25	−200
Ice sheet of Lake Vanda C1 5				−237
C1 7				−247
C1 8				−239
C1 9				−254
C1 10				−229
Snow on Shelf Ice	Jan. 17, 1964			−256

Table 2. Deuterium content of waters in and around Lake Vanda. (Dec. 31, 1964)

Sample	Depth (m)	Temp. (°C)	δD_{SMOW} (‰)
Onyx Pond	0	2.7	−216.1
L. Vanda inflow	0	3.5	−217.6
V 3	0	0.5	−229.8
	3.5	0.4	−238.6
	5	4.7	−245.8
	13.5	6.6	−249.6
	15.5	7.7	—
	20	8.0	−249.1
	31.5	8.0	−249.0
	38	8.2	−251.6
	42	9.0	−248.2
	45	10.2	−248.4
	57	22.0	−248.3
	63	24.7	−248.4
V 6	3.6	0.2	−231.0
	5	4.8	−238.0
	15.5	8.0	−243.4
	31.5	8.0	−248.9
	42	8.9	−243.9
	52	17.3	−245.5
	60	24.2	−244.3
	66.8	25.1	−216.7

Table 3. Deuterium content of waters in Lake Bonney. (Jan. 8 and 9, 1965)

Sample	Depth (m)	Temp. (°C)	δD_{SMOW} (‰)
B 3	5	0.1	−304.5
	9.5	1.1	−327.3
	13.5	0.0	−328.5
	18	−2.2	−328.2
	20	−2.8	−325.4
B 4	5	0.0	−298.0
	10.5	5.9	−309.5
	14.5	7.3	−311.7
	19	5.8	−269.0
	22	4.2	−261.4
	25	2.2	—
	28.5	0.2	—
	32	−2.2	−252.2

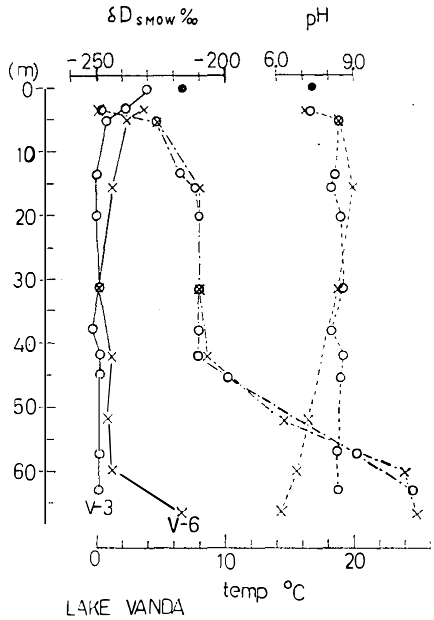

Fig. 3. Vertical distribution of deuterium content, water temperature and pH in Lake Vanda. (Dec. 1964)

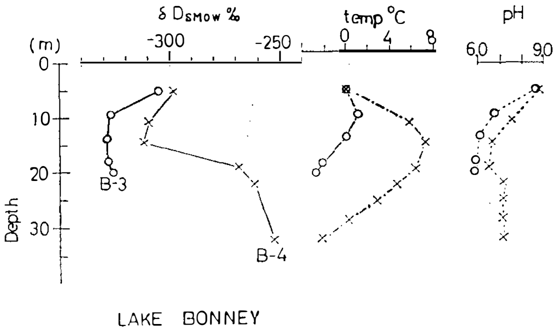

Fig. 4. Vertical distribution of deuterium content, water temperature and pH in Lake Bonney. (Jan. 1965)

(1965) and were lower than that of the samples from South Fork, Cape Royds and Cape Evans (−151 to −205 ‰) as shown in Table 1 and from the other area of Antarctica (AMBE, 1966).

The vertical distribution of the deuterium content was quite different between Lake Vanda and Lake Bonney as shown in Figs. 3 and 4. The deuterium content in Lake Vanda slightly fluctuated ranging from −238. 0 to −251. 6 ‰ at the depths of 5 m to 60 m, but increased to −216. 7 ‰ at 67 m. On the other hand, the minimum value, −311. 7 ‰, was observed at 14. 5 m in hole B-4 of Lake Bonney. The deuterium content in Lake Bonney was lower than that in Lake Vanda in both the first and second explorations (in Tables 1, 2 and 3).

The vertical distribution of the chemical contents of Lake Vanda and Lake Bonney (YAMAGATA, TORII, and MURATA, 1967) is shown in Figs. 5, 6 and 7, and the results of the first survey are shown in Figs. 8 and 9.

A remarkable concentration of salts was observed at the bottom layer of the lakes, but the vertical distribution of the salt content was much different between Lake Vanda and Lake Bonney. In Lake Vanda the salt content of V-6 and C-3 increased sharply below 50 m, but in V-3 it fluctuated slightly throughout the whole layer and the values were nearly the same as that above 50 m in V-6. In Lake Bonney, the content of every component increased with depth, and some of them at 14 m depth amounted to more than 100 times of those at 5 m depth. Below 14 m some components increased and others decreased slightly with depth. Con-

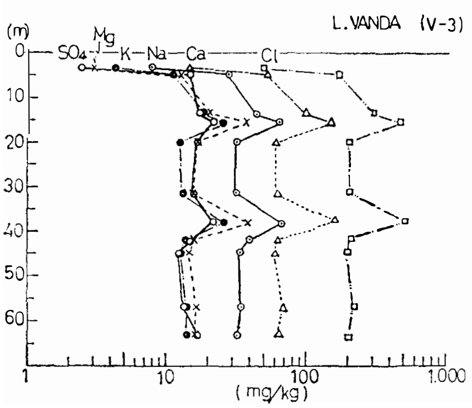

Fig. 5. Vertical distribution of chemical components in V-3 of Lake Vande. (Dec. 1964)

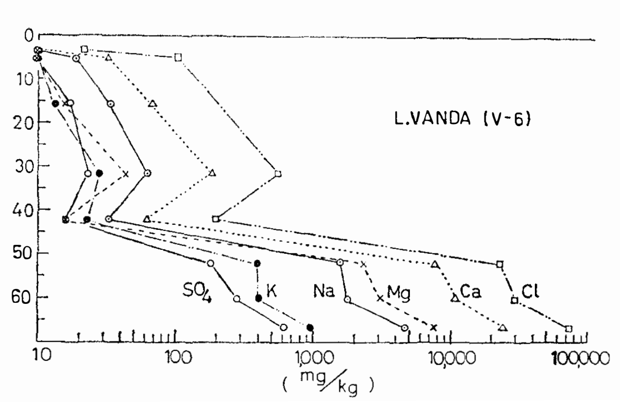

Fig. 6. Vertical distribution of chemical components in V-6 of Lake Vanda. (Dec. 1964)

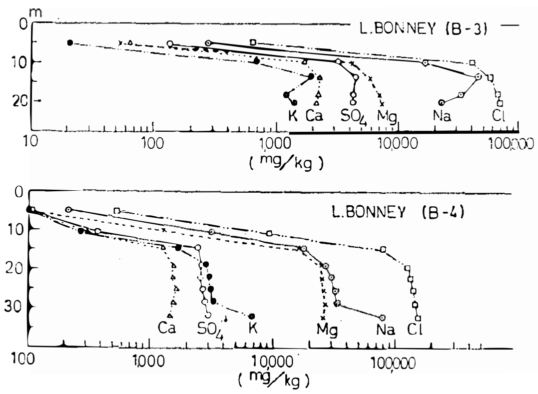

Fig. 7. Vertical distribution of chemical components in B-3 and B-4 of Lake Bonney. (Jan. 1965)

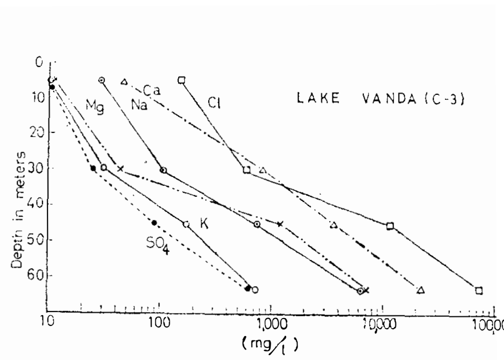

Fig. 8. Vertical distribution of chemical components in C-3 of Lake Vanda. (Jan. 1964)

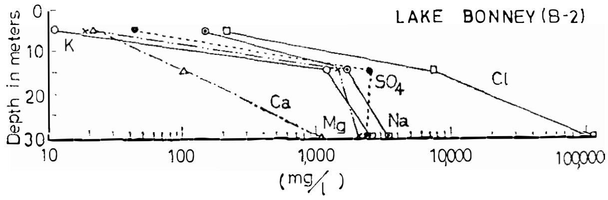

Fig. 9. Vertical distribution of chemical components in B-2 of Lake Bonney. (Jan. 1964)

sequently, the water mass of the Lake Bonney may be distinguished into two parts, above and below the 14 m layer, according to the profile of the salt content.

The thermal profiles of these lakes were unusual. In Lake Bonney, the maximum water temperature 6.95°C was observed at 14 m depth. Below this layer it decreased with depth and finally reached −1.21°C at 30 m. It is noticed that the depth with the maximum value of water temperature corresponded to that with the minimum value of the deuterium content. On the contrary the water temperature of Lake Vanda increased gradually with depth, and reached the highest value 23.2°C at the bottom layer.

Regarding the origin of the salt of the lakes, the scientists' opinions are divided. Some explain that the brine of the lakes resulted from concentration of the water of a once larger lake, with the possible presence of relic sea water (ANGINO *et al.*, 1963), while others favour a geothermal origin (ANGINO *et al*, 1962 a).

The order of the concentration of chemical elements was different between Lake Vanda and Lake Bonney, which means that the origin of the salt in the two lakes was not the same. Even if the salt of lake water is supposed to have originated from sea water, the present lake water should have been derived from other sources, judging from the low deuterium content.

It is, therefore, most probable that the main source of lake water is an inflow of melted ice of glaciers. However the deuterium content of water flowing into Lake Vanda, Lake Bonney and Onyx Pond was recorded as −216 to −217‰, which is higher than that of lake water, ice sheet and snow (Table 1). In physical processes of evaporation, sublimation, freezing and melting, the deuterium content of water is subject to fractionation. The phenomenon that the deuterium content of the water layer just under the ice cover was higher than that of the deeper layer in both lakes might be attributed to the isotopic fractionation of deuterium in the melting process of the covering ice.

In Lake Bonney, however, the deuterium contents of B–3 and 5 to 14 m of B–4 were very low compared with that of inflowing water, and the value of δD in the middle layer of B–4 was lower by 11 to 43‰ than those in the layer above and below it. The density gradient of the water of Lake Bonney showed that the vertical movement of water could not occur (YAMAGATA, TORII and MURATA, 1967). The maximum temperature in the middle layer was explained by solar radiation, but this large difference in the deuterium content and the low value can not be explained simply by the fractionation through physical processes such as freezing of water. The lake water is assumed to have resulted from the inflow of foreign water mass with a low deuterium content.

On the other hand, the vertical distribution of the salt and deuterium contents in Lake Vanda showed a different pattern between V–3 and V–6, though these two points are not far apart and the thermal profiles were fairly similar. Such a large difference of distribution of salt and deuterium between the two points is difficult to elucidate without more observation data. Aside from that, the high temperature in the bottom layer might be ascribed to geothermal heating.

6. Conclusion

The value of δD_{SMOW} of the lake water was so small ranging from -216 to -328 ‰, that it is hardly attributable to the concentration of sea water in the lake basin. So, snow or continental ice is a most likely source.

The high temperature layer in Lake Bonney has the minimum value of δD_{SMOW}, which can not be explained by the physical fractionation, and the inflow of an foreign water mass becomes a necessary supposition. The high temperature layer at the bottom of the Lake Vanda is presumably heated by geothermal water or subterranean heat. The phenomenon is so complex that more detailed analysis based on the life history of the lake is required for the complete explanation.

Acknowledgments

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