STABLE ISOTOPE STUDIES OF SALTS AND WATER FROM DRY VALLEYS, ANTARCTICA
I. ORIGIN OF SALTS AND WATER, AND THE GEOLOGIC HISTORY OF LAKE VANDA

Nobuyuki NAKAI*, Yasuhiro KIYOSU*, Hideki WADA* and Mikio TAKIMOTO*

Abstract : Possible origins of lake water and salts which are dissolved in water of saline lake, Lake Vanda, and contained in cored sediments of the lake were investigated on the basis of the stable sulfur, carbon and oxygen isotopic compositions. The present-day lake water is concluded to be neither marine nor volcanic in origin in spite of the high salt concentration, H_2S concentration and water temperature, but it is fresh surface water, and dissolved salts are of marine origin.

The genesis and historical events of the saline lake also were examined. Sea water was present in the lake basin as a fjord and isolated from the ocean by glaciation after the Tertiary period. After the isolation of the lake from ocean, evaporation of lake water in cold climate and supply of glacial melt water in warm climate have alternately taken place several times.

1. Introduction

Lake Vanda is situated in the western part of the Wright Valley about 50 km west of the east coast of Victoria Land, Antarctica (77°32'S, 161°30'E), and occupies the lowest part of the valley, at the height of 95 m above sea level (Fig. 1). It is
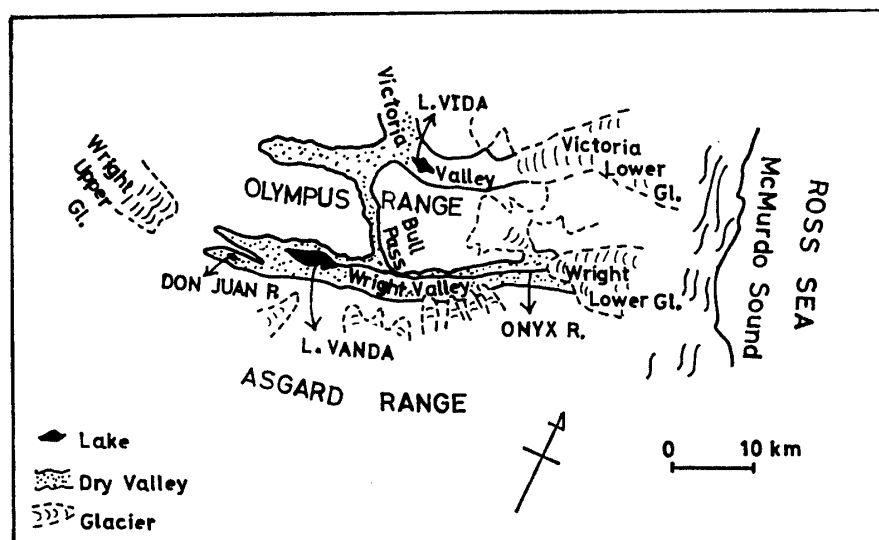

Fig. 1. Map of Dry Valleys, Victoria Land, Antarctica.

* Department of Earth Sciences, Nagoya University, Furo-cho, Chikusa-ku, Nagoya.

approximately 5.6 km long, 1.4 km wide, and 68 m deep. The lake is permanently covered with 4 m thick ice. It is supplied with melt water of glaciers from the east via the Onyx River in summer, has no outflow and water is lost only by evaporation. This valley is blocked by the Wright Lower Glacier 26 km east and by the Wright Upper Glacier 17 km west of the lake.

Lake Vanda is distinguished by three specific features of its bottom water layers: relatively high water temperature, high salinity and high concentration of hydrogen sulfide. The temperature increases towards the lake bottom reaching the highest value of 24.5 to 25.7°C at the bottom water layer (WILSON et al., 1962; RAGOTZKIE et al., 1964; HOARE, 1966; TORII et al., 1967; YOSHIDA et al., 1971). The lake water is permanently density-stratified by salinity. The lowest salinity of $n \times 10$ mg Cl^-/l was found just under the surface ice sheet and the highest chloride content up to 75.88 g/l at the bottom layer (YAMAGATA et al., 1967). According to YOSHIDA et al. (1971), the maximum H_2S content of lake water was found to be 32.6 mg/l at the bottom layer.

Many workers had attempted to elucidate the above characteristic features. However, on the basis of significant information obtained so far, even the origin of salts in the lake cannot be definitely disclosed yet. A new source of information, therefore, is required. The origin of salts in the lake may be disclosed by studies of bottom sediments which keep the record of the past geologic events.

The Dry Valley Drilling Project (DVDP) was initiated in 1971 to start airborne and surface geological and geophysical studies. The first drilling was started in early 1973 on Ross Island. During 1973–1974 field survey season, DVDP #4 hole was drilled near the center of Lake Vanda and sediments were collected with a core sampler. In this study, the origin of salts dissolved in water and contained in sediments of the lake is investigated on the basis of the stable isotopic compositions. The origin of water itself also is examined, and the genesis and historical events of saline lake are discussed in the following sections.

2. Description of Samples

2.1. Cored unconsolidated sediments from DVDP #4

The drilling site was set on the surface of ice near the center and over the deepest part of the lake, which is approximately 68.3 m below the ice surface. Cored sediments were sampled about 11.2 m long to reach basement granite at the depth of 80.7 m below the ice surface. The sediments are unconsolidated, black to brown in color, sandy to silty in grain size, and contain generally less than 5 percent of pebbles and granules of gray gneiss, granitic rocks, diabase and quartz arenite.

A few unconsolidated gravel layers were found in the sediments. The first of two main gravel layers in glacial sediments is approximately 50 cm in thickness and lies at the depth of about 72 m below the ice surface. The second gravel layer is 30 cm in thickness at the depth of 75 m below the ice surface.

Several bands of salts which consist of gypsum and calcite were found in the upper few meters of sediments above the first glacial gravel layer.

2.2. Lake water and ground water samples

Water samples of Lake Vanda were collected vertically at the site near the center of the lake where DVDP #4 drilling was performed. Ground water samples were collected from two gravel layers through the casing during drilling.

2.3. Ice samples in cored rocks from DVDP #3 and #6

DVDP #3 and #6 were drilled at McMurdo Station on Ross Island and at the shore of Lake Vida, Victoria Valley, respectively. The former was drilled to a depth of 381 m and the cored samples consist of basaltic and pyroclastic rocks. The latter reached a depth of 330 m, consisting mostly of granite gneiss. In both #3 and #6 core samples, ice occurred in cavities and fractures.

3. Analytical Procedures

Temperature and pH of lake water and ground water were determined *in situ*. H_2S dissolved in water was fixed as CdS immediately after collecting water samples to prevent oxidation. $SO_4^=$ and H_2S contents were determined by ordinary gravimetric methods.

Isotopic compositions, $^{18}O/^{16}O$, $^{13}C/^{12}C$ and $^{34}S/^{32}S$, were determined with a Varian Mat CH-7 mass spectrometer. These ratios are expressed by permil deviations from standards as follows,

$$\delta^{18}O, \ \delta^{13}C \ \text{or} \ \delta^{34}S = \frac{R_x - R_{std.}}{R_{std.}} \times 1,000 \ (\text{\textperthousand}),$$

where R_x and $R_{std.}$ denote $^{18}O/^{16}O$, $^{13}C/^{12}C$ or $^{34}S/^{32}S$ for samples and standards, respectively. SMOW (standard mean ocean water), PDB (*Belemnitella americana* from the Cretaceous PeeDee formation, South Carolina), and troilite sulfur in Canyon Diablo meteorite were used as standards for oxygen, carbon and sulfur, respectively.

4. Results and Discussions

4.1. Source of the lake water

The analytical results for lake and ground waters are listed in Table 1. $\delta^{18}O$ values of the lake are small, ranging from -30.3 to -31.9‰. The very small values found in the lake suggest that the lake water is not marine in origin, because $\delta^{18}O$ of ocean water is almost constantly 0‰. Since evaporation of water from the lake could only have increased these values, such small $\delta^{18}O$ values of lake water cannot be explained by evaporation of ocean water. Therefore, even if the salts dissolved in lake water have been derived from ocean water, present water in the lake must have been supplied from other sources.

The low ^{18}O concentration of lake water suggests that its source is to be surface fresh water. The evidence for surface fresh water may be given by $\delta^{18}O$ measurements of permafrost in DVDP #3 and #6. Figure 2 is a plot of $\delta^{18}O$ agaist the depth. As shown in this figure, the value gradually increases with increasing depth, varying from -34.2 to -0.1‰ at depths of 11.39 to 330.10 m and from -34.4 to -32.0‰ at the depths of 10.83 to 121.5 m, in DVDP #3 and

Table 1. Analytical results for lake and ground water samples from Lake Vanda.

Depth (m)*	Temp. (°C)	pH	$\delta^{18}O$ of H_2O (‰)	SO₄⁼ (mg/l)	SO₄⁼ $\delta^{18}O$(‰)**	SO₄⁼ $\delta^{34}S$(‰)	H_2S (mg/l)	H_2S $\delta^{34}S$(‰)
Water column								
4	3.0	7.80	−30.7	8.7	—	+15.0	0.0	—
8	5.0	7.98	−31.0	12.6	—	+15.9	0.0	—
12	6.0	8.02	−30.9	12.4	—	+15.5	0.0	—
16	7.5	7.78	−31.4	18.9	—	+15.8	0.0	—
20	7.5	7.75	−31.4	20.2	—	+16.0	0.0	—
40	8.2	7.60	−31.7	23.5	—	+16.6	0.0	—
45	10.2	7.55	−31.8	27.2	—	+17.5	0.0	—
50	15.0	6 82	−31.9	55.3	—	+18.7	0.0	—
55	20.9	5.98	−31.6	235	−10.0	+22.0	0.0	—
60	24.7	5.95	−31.1	237	− 9.9	+22.5	0.0	—
65	24.8	5.65	−30.4	606	+ 6.0	+42.1	53.4	+ 7.7
68	—	5.60	−30.3	611	+ 6.2	+46.0	78.6	+10.5
Ground water in sediments								
72	8.0	6.30	−28.5	573	—	+48.8	0.5	—
75	12.2	6.30	−27.7	345	—	+39.1	0.5	—

* Below the lake surface.
** Analyzed by Y. MIZUTANI.
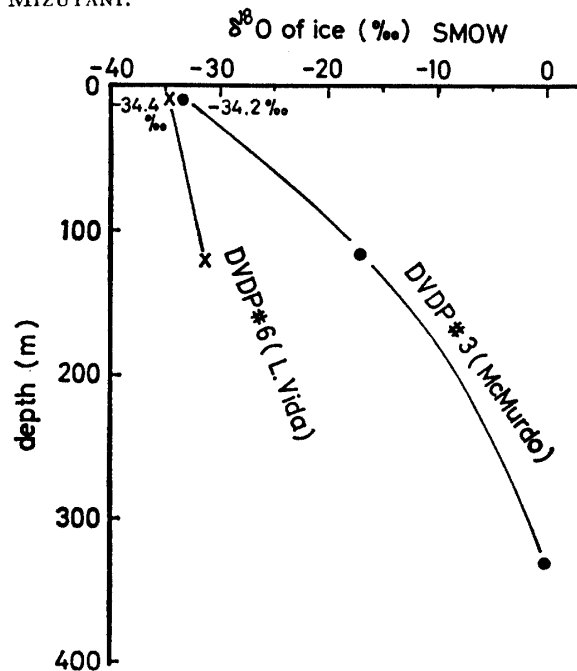
Fig. 2. Vertical distribution of $\delta^{18}O$ for ice from DVDP #3 (McMurdo) and #6 (Vida) drillings.

#6, respectively. The $\delta^{18}O$ values of water near the ground surface apparently converge to −34 to −34.5‰ for both cores. LYON (1974) reported that the $\delta^{18}O$ values of ice from DVDP #2 and #3 are about −33‰ near the ground surface. Furthermore, the value of snow accumulating on the ice shelf in the McMurdo Sound ranges from −32 to −34‰ (JOHNSEN et al., 1972). In general, concentrations of heavy isotopes in fresh water decrease with increasing latitude and altitude (DANSGAARD, 1954), and these values are considered to be typical as those of fresh water in this area (DANSGAARD, 1964). If thermal or magmatic waters could have contributed as supposed from relatively high temperature of bottom lake water, $\delta^{18}O$ should be much higher (WHITE, 1973).

The $\delta^{18}O$ values for all lake water samples are in the $\delta^{18}O$ value ranges of ice occurring near the top of drilling cores (DVDP #2, #3 and #6), of present-day precipitation in this area, and of water flowing into the lake (−29.5‰). The present-day water of the lake in arid ' Dry Valley ' is concluded to have originated mainly from melt water of glaciers.

The vertical distribution of $\delta^{18}O$ is shown in Fig. 3. The minimum value, −31. 9‰, was observed at the depth of 50 m. The ^{18}O concentration sharply increases with depth below 50 m, and the highest $\delta^{18}O$ value, −27.7‰, was observed for ground water in the second gravel layer at the depth of 75 m below the lake surface. Consequently, water enriched with ^{18}O is supposed to have been included in sediments of the deep lake basin. The isotope data suggest that the lake water in deep layers is a remnant resulted from evaporation of fresh water or may be a trace of sea water.

On the other hand, surface lake water shows a $\delta^{18}O$ value of −30.7‰ which is similar to or somewhat lower than that of inflowing water. The present surface
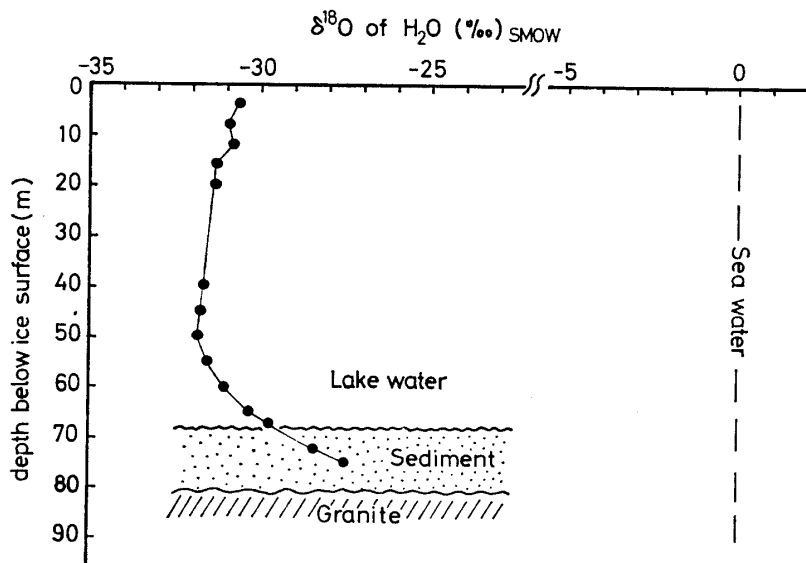

Fig. 3. Vertical distribution of $\delta^{18}O$ for water in Lake Vanda.

water of the lake, therefore, is assumed to have resulted from mixing of inflowing water from the Wright Lower Glacier via the Onyx River and lake water with low $\delta^{18}O$ value in middle layers.

With regard to the minimum $\delta^{18}O$ value in the middle layers of lake water, the isotopic composition cannot be explained by mixing of surface and bottom waters or by the isotopic fractionation through physical process such as evaporation and freezing of lake waters. Other possible sources of water must be considered. The ^{18}O concentrations of precipitations and glaciers tend to be smaller with increasing altitude and distance from the coast, as expected from the results obtained by DANSGAARD (1954, 1964), FRIEDMAN et al. (1964) and others. As mentioned above, this Wright Valley is blocked by glaciers at both ends, and the water of the present lake is supplied only by the Onyx River coming from the Wright Lower Glacier. Between the lake and the Wright Upper Glacier, however, an old stream bed can be recognized, suggesting that glacial melt water once flowed into the lake from the direction of the Wright Upper Glacier. The melt water would have been more depleted in ^{18}O than that of the Wright Lower Glacier, because the Wright Upper Glacier is situated at a higher altitude, above 2,000 m, and in an area distant from coast. It is, therefore, probable that the water of low ^{18}O in middle layers was once supplied from the Upper Glacier. Numerous ancient shorelines are visible around the lake, the highest resting approximately 50 m above the present lake surface. They suggest that the level of the lake surface has fluctuated largely, extending probably to some depths, and melt water of the Upper Glacier possibly flowed into the level of the present middle layers of the lake.

4.2. Origin of salts in the lake and historical events

4.2.1. Salts dissolved in lake waters

As shown in Table 1, high concentrations of salts and exceptionally high temperatures were observed in bottom layers of the lake water. High concentration of H_2S up to 78.6 mg/l could be found. The salts dissolved in lake waters have been studied by many workers and the suggested origins include thermal springs (ARMITAGE et al., 1962; ANGINO et al., 1962, 1965), a marine invasion of the valley (ANGINO et al., 1963; CRAIG, 1966; NICHOLS, 1963), leaching of evaporite beds by glacial melt water, marine aerosols (NICHOLS, 1963; ANGINO et al., 1965) and rock weathering (JONES et al., 1967). Most workers suggested multiple sources to account for all the salts, and the origin of salts in lake waters is thus still controversial.

In the present study, isotopic compositions and concentrations of sulfur compounds were analyzed for lake and ground water samples. The data are listed in Table 1 and are shown graphically in Fig. 4. The concentration of $SO_4^=$ varies with depth, ranging from 8.7 mg/l just under the surface ice to 611 mg/l for bottom water at the depth of 68 m below the ice surface. Discontinuities in the concentration profile occur at approximately 15 and 55 m below the surface. In the ground water, the concentration decreases with depth. H_2S appears only
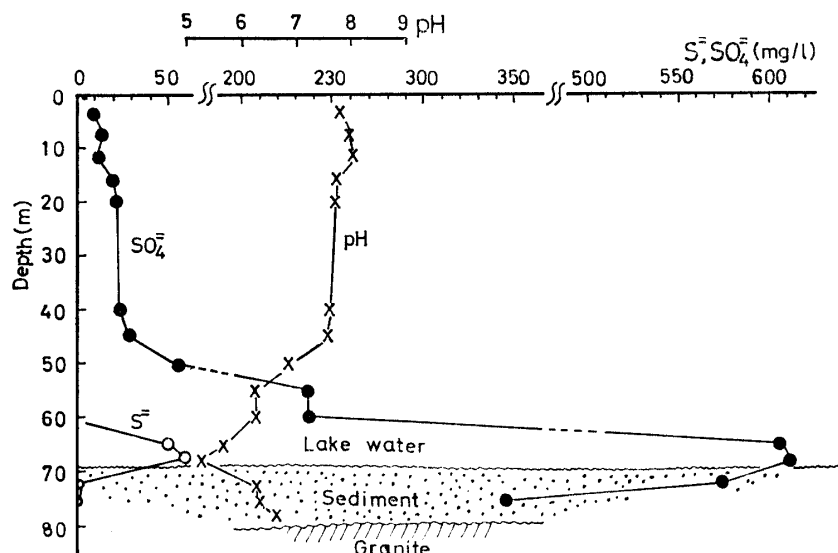
Fig. 4.   Vertical variations of $SO_4^=$ and $S^=$ contents and pH of water
in Lake Vanda.

in bottom layers below the discontinuity at the depth of 50 m and almost disappears in ground waters. Vertical distributions of $SO_4^=$ and H_2S indicate clearly that they were not supplied by thermal springs through bed rocks and lake sediments.

The $\delta^{34}S$ values of $SO_4^=$ increase with depth as seen in Table 1, especially sharply below the depth of 60 m, where H_2S appears, and the maximum value reaches +48.8‰. On the other hand, the $\delta^{34}S$ values of H_2S range from +7.7 to +10.5‰. The difference of the $\delta^{34}S$ values between $SO_4^=$ and coexisting H_2S is calculated to be 34.4 to 35.5‰. Such large fractionations cannot be explained by high temperature products of volcanic activities, but by bacterial reduction of $SO_4^=$ to H_2S (Nakai, 1964). The $\delta^{34}S$ values of H_2S from volcanic gases and thermal springs are presented in Table 2, being quite different from those of the lake water.

Sulfate in bottom water layers is highly enriched with ^{34}S. This is due to the isotopic fractionation in the process of bacterial reduction of $SO_4^=$ to H_2S in which the light isotope, ^{32}S, is preferentially reduced to H_2S. In shallower water containing free oxygen, in contrast, $SO_4^=$ are depleted in ^{34}S and the lowest $\delta^{34}S$ value, +15.0‰ is found at the depth of 4 m below the ice surface. The low $\delta^{34}S$ values of $SO_4^=$ in shallower water layers are explained by addition of secondary $SO_4^=$ produced in the bacterial oxidation of H_2S which migrated from depths to shallow water layers, because the isotopic fractionation in the process of bacterial oxidation is so small that the produced $SO_4^=$ are expected to have the isotopic composition similar to that of original H_2S. The $\delta^{34}S$ values of $SO_4^=$ in lake waters are thus variable depending on bacterial activities. Origin of $SO_4^=$, there-

Table 2. $\delta^{34}S$ of H_2S from volcanic activities in Japan.

	Numbers of analyzed samples	$\delta^{34}S$ (‰)
Hot springs		
Tamagawa	3	$-7.1\sim-1.1$
Narugo	4	$-1.8\sim+1.1$
Geothermal gases		
Matsukawa	13	$-6.6\sim+3.3$
Onikobe	7	$-2.3\sim+3.3$
Volcanic gases		
Nasu	13	$-4.4\sim-1.2$
Showashinzan	5	$+1.7\sim+5.1$
Kusatsu	4	$-6.6\sim-3.9$

fore, cannot be definitely identified by the isotopic composition. However, the following supposition is possible. The $\delta^{34}S$ of $SO_4^=$ in lake waters near the boundary between layers with and without H_2S is approximately $+20‰$ and if this sulfate is assumed not to have been subjected to bacterial activities, the origin can be postulated to be marine.

4.2.2. Salts deposited in lake sediments

As mentioned before, gypsum and calcite occur abundantly in the upper few meters of sediments. The sulfate content of sediments decreases rapidly below the first gravel layer as shown in Fig. 5. This shows clearly that salts have been deposited after the formation of the first gravel layer (glacial gravel).

Table 3. $\delta^{34}S$ of gypsum concretion in Lake Vanda sediments.

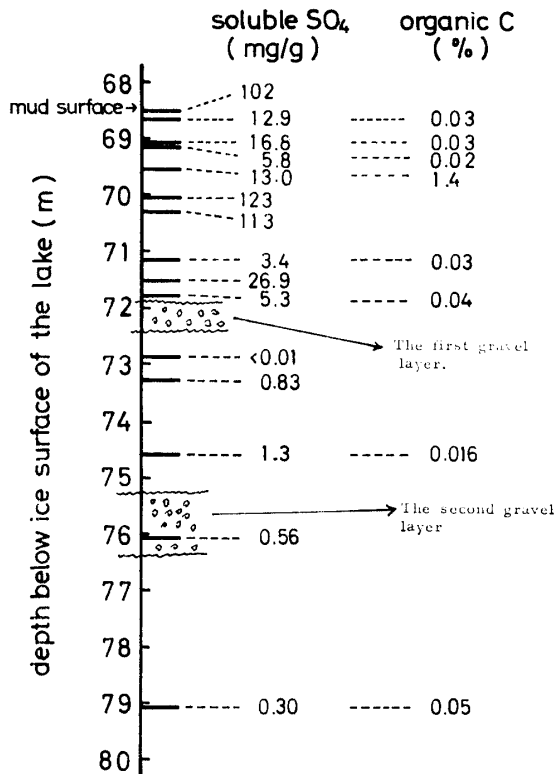| Sample No.	Depth (m)*	$\delta^{34}S$ (‰)
Bottom surface	68.3	$+22.4$
1-4	69.08	$+20.9$
6-a	69.48	$+20.9$
2-c	70.08	$+20.4$
7-5	71.17	$+20.8$

*Below lake surface.

Fig. 5. Vertical distribution of gypsum and organic carbon in sediments of Lake Vanda.
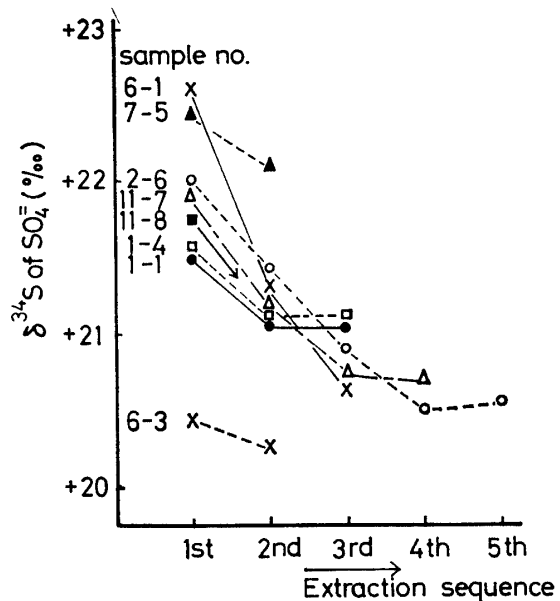
Fig. 6. δ³⁴S of sulfate extracted repeatedly from Lake Vanda sediments with distilled water.

The δ³⁴S values of gypsum in banded salt concretions, which can be found only above the first gravel layer, are listed in Table 3. The values are constant, ranging from +20.4 to +20.9‰, except for a sample from surface sediment. Gypsum having no banded structure was also analyzed for sulfur isotopic composition. Gypsum was extracted repeatedly with 50 ml each of distilled water from sediments until no sulfate is leached in the water extract. The sulfur isotopic values are plotted against extraction sequence in Fig. 6. Sulfate in the first extraction is the richest in ³⁴S in the extraction series. The first or early extract includes SO₄⁼, of course, from interstitial waters, δ³⁴S of which is reasonably considered to have large values such as +46 to 49‰ as expected from those of sulfate in ground and bottom waters of the lake. The progressive extraction results in a gradual decrease in the δ³⁴S values of extracted SO₄⁼. This approaches +20.3 to 21.2‰ after two or three times of extraction for all sediment samples. This means that gypsum in sediments itself has about +20 to 21‰ δ³⁴S.

As expected from the results obtained by HOLSER and KAPLAN (1966), the isotopic composition of oceanic sulfate largely varies with geologic age, and Tertiary and Recent sulfates have the δ³⁴S values of 20±2‰ similar to the range of modern sea water and distinctly differ from that of the Permian

sulfate. The values show a good agreement with those of sulfate minerals analyzed in this work. On the other hand, NAKAI (1967) reported that $\delta^{34}S$ of atmospheric sulfate is always smaller than $+20\%_0$ of sea water, ranging from 0 to $+16\%_0$. Atmospheric aerosols, consequently, cannot be accepted to have significant contribution to salts in the lake. It can be, therefore, concluded that sulfate in Lake Vanda was derived directly from the ocean, and the lake which was previously connected with the ocean became isolated from it since the first gravel layer (glacial gravel) was deposited by glaciation after Tertiary age. After the isolation of the lake from the ocean, evaporation of lake water in cold climate and supply of fresh water in warm climate can be supposed to have alternately taken place several times, resulting in deposition and dissolution of salts, as expected from the occurrence of banded salt concretions in lake sediments.

Table 4. $\delta^{13}C$ and $\delta^{18}O$ of calcite from Lake Vanda sediments.

Sample No.	Depth (m)*	$\delta^{13}C$ $(\%_0)$	$\delta^{18}O$ $(\%_0)$
Bottom surface	68.3	—	—
6-1	68.48	-3.5	$+2.9$
1-a	68.83	$+10.4$	$+1.4$
5-f	68.87	$+10.8$	$+1.7$
6-b	68.98	$+11.4$	$+1.7$
1-4	69.08	$+11.6$	$+1.0$
6-2	69.10	$+10.3$	$+0.8$
6-a	69.48	$+10.3$	$+0.9$
1-5	69.56	$+ 4.4$	$+0.2$
6-3	70.05	$+ 1.9$	-0.5
2-c	70.08	$- 5.3$	-1.3
2-6	70.23	$- 4.2$	-1.5
7-5	71.17	$- 9.3$	$+1.0$
11-7	71.50	$+ 0.3$	$+1.7$
4-e	72.00	$- 7.6$	-2.3
4-9	72.15	$+ 6.4$	-2.1
16-15	74.58	-10.6	$+6.8$

* Below the lake surface.

Evaporation and supply of water having alternately taken place in the past lake can be proved by carbon and oxygen isotopic compositions of calcite in lake sediment samples. The $\delta^{13}C$ and $\delta^{18}O$ values of calcite in cored sediments are summarized in Table 4. The former range from -10.6 to $+11.6\%_0$ and the latter from -2.3 to $+6.8\%_0$. The range of the $\delta^{13}C$ values in cored sediments is exceptionally wide, $20\%_0$, for a limited extent of a field and a cored sample.
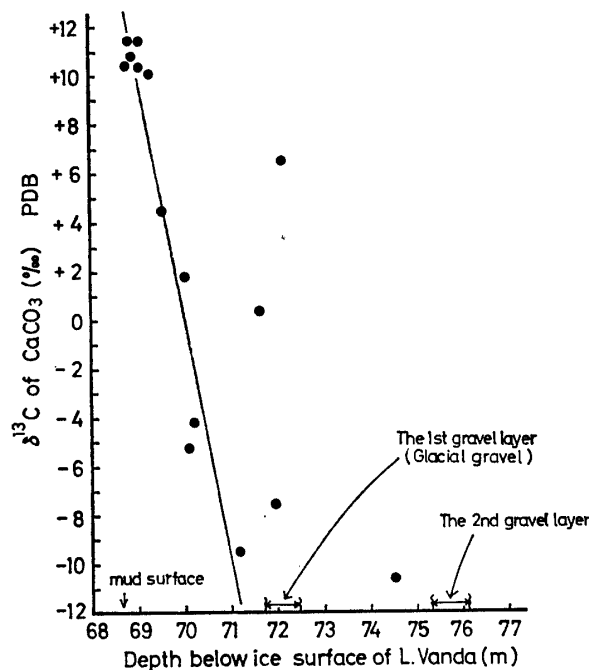
Fig. 7.   Vertical variations of $\delta^{13}C$ for calcite from Lake Vanda sediments.

In the sediment above the first gravel layer, however, the $\delta^{13}C$ values increase linearly with decreasing depth as shown in Fig. 7. This variation of the $\delta^{13}C$ values from the first gravel layer to the surface sediment can be explained only by that deposition and dissolution of $CaCO_3$ were repeated in the sedimentary process on evaporation of lake water and on supply of water and atmospheric carbon dioxide. An example of the explanation is given as follows.

Isotopic fractionation between $CaCO_3$ and CO_2 and between HCO_3^- and CO_2 were calculated for carbon isotopic exchange equilibrium by BOTTINGA (1969) and DEUSER (1967).

Equilibrium temperature	$\delta^{13}C$ $CaCO_3$-CO_2 (‰)	$\delta^{13}C$ HCO_3^--CO_2 (‰)
0°C	13.0	10.2
10°C	11.8	9.6
20°C	10.7	9.0

Calcium carbonate, which was deposited initially by evaporation of lake water after the first gravel layer was formed, is assumed to have a $\delta^{13}C$ value of $-10‰$ judging from the value of calcium carbonates just above the first gravel layer. During the following warm period, inflow of glacial melt water and atmospheric CO_2 resulted in partial dissolution of $CaCO_3$. Assuming $\delta^{13}C$ of atmospheric CO_2 to be constantly $-7.0‰$, we can get the $\delta^{13}C$ value of HCO_3^- dissolved in water to be $-8.5‰$. Furthermore, during the following cold period, lake water was

evaporated again and deposited $CaCO_3$ to form another salt layer at a depth shallower than that of the initially deposited salt layer. In this process, 2 mols of HCO_3^- were converted quantitatively to 1 mol each of $CaCO_3$ and CO_2 which was released to the atmosphere. Assuming an isotopic exchange equilibrium between $CaCO_3$ and CO_2 at 0°C, we can calculate to have $\delta^{13}C$ of $-2.0‰$ for deposited $CaCO_3$, which is much heavier than that just above the first gravel layer. Another set of partial dissolution and deposition of $CaCO_3$ increases the $\delta^{13}C$ value to $+2.0‰$. Thus, after repeated dissolution and deposition $CaCO_3$ is progressively enriched with ^{13}C. We can explain this isotopic distribution in sediments similarly by assuming the isotopic equilibrium between $CaCO_3$ and HCO_3^-, too.
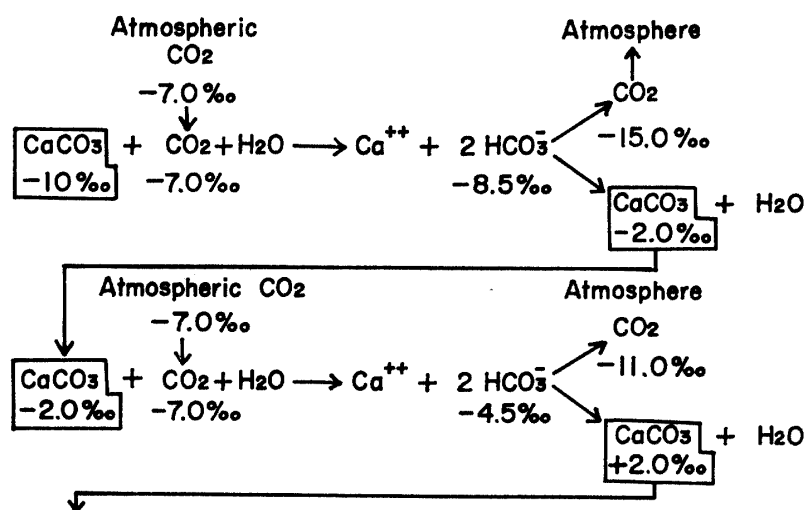
Another possible explanation for the $\delta^{13}C$ variation of $CaCO_3$ with depth is that $CaCO_3$ is dissolved by acid water such as sulfuric acid, as expected from the low pH value, 5.6, of present bottom water in the lake, and alternate deposition and dissolution are repeated in the same way as above. This process also implies that $CaCO_3$ becomes progressively enriched with ^{13}C towards the later stage of deposition.

The vertical distribution of the $\delta^{18}O$ values for $CaCO_3$ in cored sediments is shown in Fig. 8. The $\delta^{18}O$ values increase linearly with decreasing depth of sediment above the first gravel layer in the same manner as that of $\delta^{13}C$. This variation is elucidated by progressive deposition of $CaCO_3$. As is well known, oxygen in $CaCO_3$ is in isotopic equilibrium with water in which the $CaCO_3$ is precipitated. The $\delta^{18}O$ values of $CaCO_3$ are 33.9 and 28.0‰ larger than that of water in the isotopic equilibrium at 0 and 25°C, respectively (BOTTINGA, 1968). If Ca^{++} had been initially trapped in the lake basin by the isolation of the lake from the ocean, the progressive formation of salt bands containing calcium carbonate in sediments decreases the amount of Ca^{++} which can be dissolved in the lake water. In the later formation of salt layers, therefore, further concentration
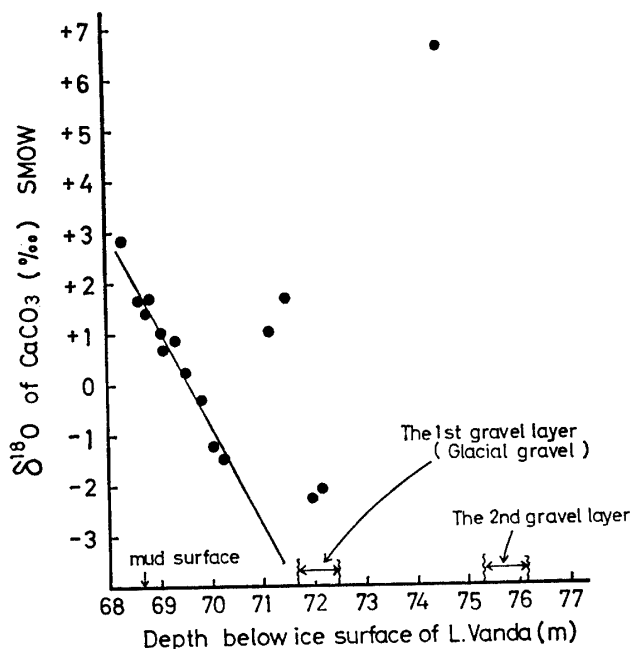
Fig. 8. Vertical variations of $\delta^{18}O$ for calcite from Lake Vanda sediments.

of the lake water is necessary to precipitate calcium carbonate. This means that the $\delta^{18}O$ values of the water from which $CaCO_3$ has been precipitated increase with progress in the formation of salt layers, resulting in a gradual increase in $\delta^{18}O$ of $CaCO_3$ towards shallower salt bands. The $\delta^{18}O$ values of $CaCO_3$ above the first gravel layer range from -1.5 to $+2.9‰$ and suggest that the carbonate was deposited or recrystallized in isotopic equilibrium with fresh water distributed in this Dry Valley area.

Thus on the basis of isotopic data for cored sediments, it is concluded that salts in the lake have been derived directly from the ocean and the lake level has largely fluctuated several times according to climatic changes after the isolation of the lake from the ocean and the following inflow of glacial melt water.

Efflorescences or evaporites composed mainly of sulfate and carbonate minerals occur extensively on the ice-free ground surface around Lake Vanda. They also were collected and the isotopic study is still in progress to recognize the origin and the genetic relation between salts occurring on the ground surface and in Lake Vanda.

5. Summary

Significant conclusions from the foregoing discussion are summarized as follows.

The present-day water of Lake Vanda is clearly neither marine nor volcanic in origin in spite of the high salt concentration, H_2S concentration and water temperature, but is of fresh water origin. Salts contained in the lake, however,

were originated mostly from sea water. They were transported with sea water from the ocean, and were not brought over by wind blowing from the ocean.

Historical events in the past lake were recognized. Before the formation of the first gravel layer (glacial gravel) in lake sediments, sea water was present in the lake basin which was a fjord. When the glacial gravel was deposited in the basin, sea water was isolated from the ocean by glaciation after the Tertiary period. The sea water evaporated to form salt deposits in cold climate and subsequently the basin was flooded by glacial melt water supposedly from the Wright Upper Glacier in warm climate. After repeated evaporation and flooding of water, the Wright Lower Glacier was formed by upheaval in the east of Lake Vanda and the lake have been supplied by the melt water.

Acknowledgments

References

ANGINO, E.E., K.B. ARMITAGE and J.C. TASH (1962): Chemical stratification in Lake Fryxell, Victoria Land, Antarctica. Science, 138, 34–36.

ANGINO, E.E. and K.B. ARMITAGE (1963): A geochemical study of Lakes Bonney and Vanda, Victoria Land, Antarctica. J. Geol., 71, 89–95.

ANGINO, E.E., K.B. ARMITAGE and J.C. TASH (1965): A chemical and limnological study of Lake Vanda, Victoria Land, Antarctica. Kans. Univ. Sci. Bull., 45, 1097–1118.

ARMITAGE, K.B. and H.B. HOUSE (1962): A limnological reconnaissance in the area of Mc-Murdo Sound, Antarctica. Limnol. Oceanogr., 7, 36–41.

BOTTINGA, Y. (1968): Calculation of fractionation factors for carbon and oxygen isotopic exchange in the system calcite- carbon dioxide-water. J. Phys. Chem., 72, 800.

BOTTINGA, Y. (1969): Calculated fractionation factors for carbon and hydrogen isotope exchange in the system calcite-carbon dioxide-graphite-hydrogen-water vapor. Geochim. Cosmochim. Acta, 33, 49–64.

CRAIG, H. (1966): Origin of the saline lakes in Victoria Land, Antarctica. Trans. Am. Geophys. Un., 47, 112–113.

DANSGAARD, W. (1954): The ^{18}O abundance in fresh water. Geochim. Cosmochim. Acta, 6, 241–260.

DANSGAARD, W. (1964): Stable isotopes in precipitation. Tellus, 16, 436–468.

DEUSER, W.G. and E.T. DEGENS (1967): Carbon isotope fractionation in the system CO_2 (gas)-CO_2 (aqueous)-HCO_3^- (aqueous). Nature, 215, 1033–1035.

FRIEDMAN, I., A.C. REDFIELD, B. SCHOEN and J. HARRIS (1964): The variation of the deuterium content of natural waters in the hydrologic cycle. Rev. Geophys., 2, 177–224.

HOARE, R.A. (1966): Problems of heat transfer in Lake Vanda, a density stratified Antarctic lake. Nature, 210, 787–789.

Holser, W.T. and I.R. Kaplan (1966): Isotope geochemistry of sedimentary sulfates. Chem. Geol., 1, 93-135.

Johnsen, S.J., W. Dansgaard, H.B. Clausen and C.C. Langway (1972): Oxygen isotope profiles through the Antarctic and Greenland ice sheets. Nature, 235, 429-434.

Jones, L.M. and G. Faure (1967): Origin of the salts in Lake Vanda, Wright Valley, Southern Victoria Land, Antarctica. Earth Planet. Sci. Letters, 3, 101-106.

Lyon, G.L. (1974): Stable isotope analyses of ice from DVDP 3. DVDP Bull., 3, 160-169.

Morikawa, H. and J. Ossaka (1974): The distribution of secondary minerals at Lake Vanda. DVDP Bull., 4, 18-19.

Nakai, N. and M.L. Jensen (1964): The kinetic isotope effect in the bacterial reduction and oxidation of sulfur. Geochim. Cosmochim. Acta, 28, 1893-1912.

Nakai, N. and M.L. Jensen (1967): Source of atmospheric sulfur compounds. Geochem. J., 1, 199-210.

Nichols, R.L. (1963): Geologic features demonstrating aridity of McMurdo Sound area, Antarctica. Am. J. Sci., 261, 20-31.

Ragotzkie, R.A. and G.E. Likeno (1964): The heat balance of two Antarctic lakes. Limnol. Oceanogr., 9, 412-426.

Ragotzkie, R.A. and I. Friedman (1965): Low deuterium content of Lake Vanda, Antarctica. Science, 148, 1226-1227.

Torii, T., N. Yamagata and T. Cho (1967): Report of the Japanese summer parties in Dry Valleys, Victoria Land, 1963-1965. II. General description and water temperature data for the lakes. Antarct. Rec., 28, 1-14.

Wilson, A.T. and W.H. Wellman (1962): Lake Vanda: an Antarctic lake. Nature, 196, 1171-1173.

Yamagata, N., T. Torii and S. Murata (1967): Report of the Japanese summer parties in Dry Valleys, Victoria Land, 1963-1965. V. Chemical composition of lake waters. Antarct. Rec., 29, 2339-2361.

Yoshida, Y., Y. Yusa, K. Moriwaki and T. Torii (1971): Report of the Japanese summer parties in Dry Valleys, Victoria Land. IX. A preliminary report of the geophysical study of Dry Valleys in 1970-1971. Antarct. Rec., 42, 65-88.

White, D.E., I. Barnes and J.R. O'Neil (1973): Thermal and mineral waters of non-meteoric origin, California Coast Range. Geol. Soc. Am. Bull., 84, 547-560.