GEOCHEMICAL ASPECTS OF THE MCMURDO SALINE LAKES WITH SPECIAL EMPHASIS ON THE DISTRIBUTION OF NUTRIENT MATTERS

Tetsuya Torii[1], Noboru Yamagata[2], Shyu Nakaya[3], Sadao Murata[1], Takeo Hashimoto[4], Osamu Matsubaya[5] and Hitoshi Sakai[5]

Abstract: A study of the distribution of nutrient matters in the McMurdo saline lakes is presented, along with the laboratory and field methods used for the analyses of highly saline water. The presence of a large amount of nitrogen compounds in and around the lakes is pointed out and their source is discussed together with the distribution pattern of different nitrogen compounds in the water. Nutrient matters and chemical elements are considered to have been leached from the lake sediments during the formation of the lakes. The ∂D and $\delta^{18}O$ values in the east and west lobes of Lake Bonney are used in an attempt to explain the processes involved in their formation.

1. Introduction

There are more than 20 ice-free areas, so called "oases", throughout Antarctica (Fig. 1; Simonov, 1971). In the Dry Valley regions of South Victoria Land, there are numerous saline lakes as well, such as Lakes Joyce, Bonney, Fryxell in the Taylor Valley and Lake Vanda, Don Juan Pond, Don Quixote Pond in the Wright Valley. The chemical compositions of these lake waters are quite different from sea water, so the geochemical history of the lakes is of particular interest to geochemists. They seem to differ from most of the other saline lakes, especially those located along the coast, such as Lake Dingle, and Lake Stinear on the Vestfold Hills and Lake Nurume and Lake Suribachi in the Syowa Oasis. The latter lakes are considered to be relict lakes which inherited their salts from sea water. Figure 2 shows the chemical compositions of water of typical saline lakes in a triangular diagram. The composition of sea water is also given in the diagram. The saline lakes in the Dry Valleys have the following common features:

(1) They lie in undrainable basins and are perennially covered with ice except for Don Juan Pond and Don Quixote Pond.

(2) Their waters are abnormally high in salinity, conductivity and nutrient matters, and are meromictic.

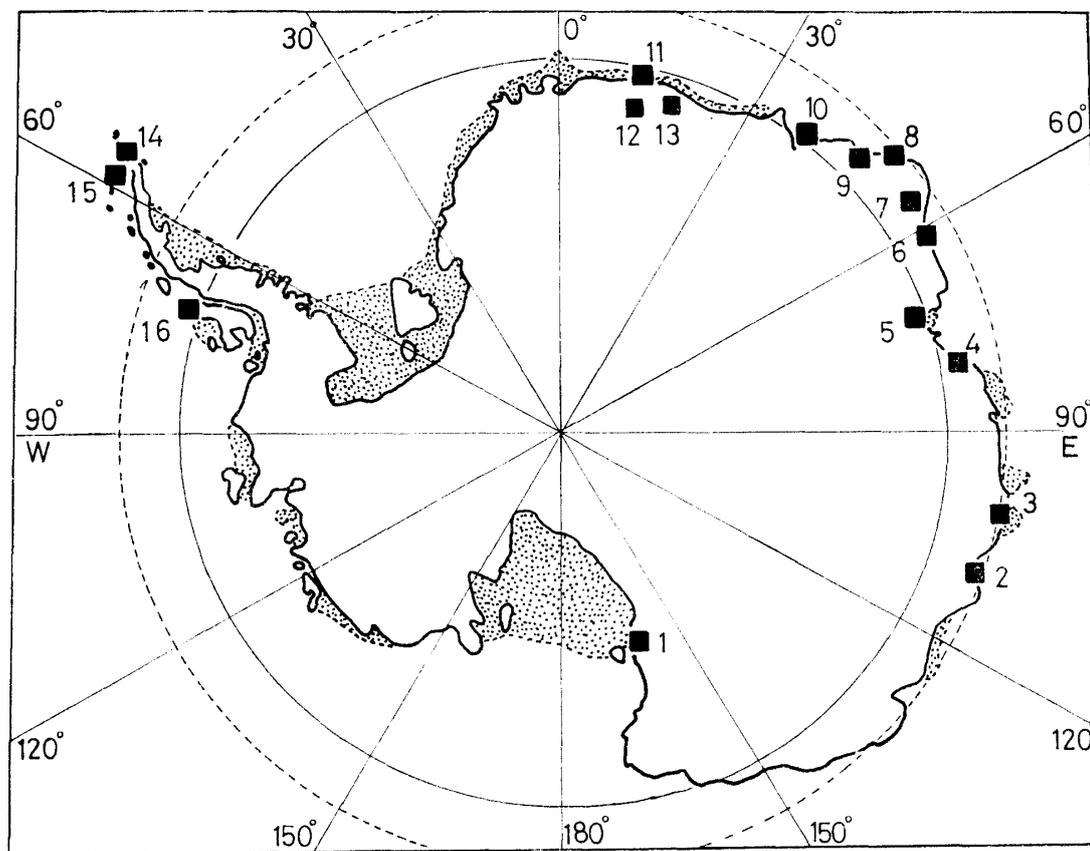(3) The major chemical compositions of their waters differ greatly between

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1.	McMurdo	5.	Amery	9.	Molodezhnaya	13.	Insel
2.	Greason	6.	Stefansson	10.	Syowa	14.	Snow Hill
3.	Bunger	7.	Øygarden	11.	Schirmacher	15.	Bellingshausen
4.	Vestfold	8.	Thule	12.	Zimmermann	16.	Alexander

Fig. 1. Antarctic oases.

the valleys and from lake to lake.

(4) The waters present in these lakes are of fresh water origin according to stable isotope studies such as those by RAGOTZKIE *et al.* (1965), CRAIG (1966), AMBE (1974), NAKAI (1974) and MATSUBAYA *et al.* (1974).

These features indicate that these lakes were formed by complicated processes which would have involved such materials as evaporites, soils, inflow waters, lake bottom sediments and ground waters. Since little inforamtion is available on the nutrient matters in these lakes, efforts have been concentrated on the study of their distribution by the Japanese parties dispatched to this area during three seasons from 1970–1971. Therefore, while this report summarizes the chemical compositions of Lakes Vanda, Fryxell and Bonney, special emphasis will be given to the distribution of nutrient matters.

Although chemical compositions of lake waters have been examined by numerous investigators since 1961, extremely high salinities of the waters often caused
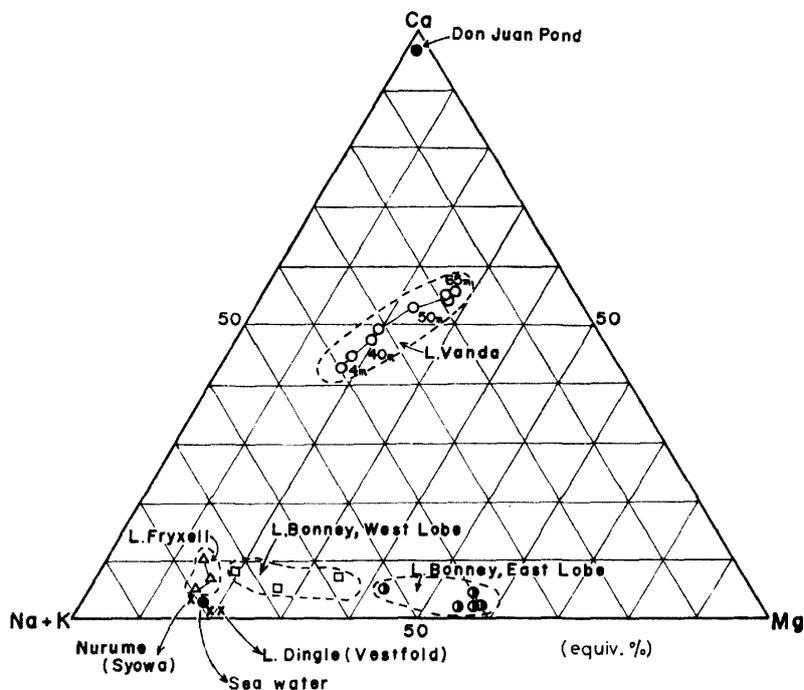
Fig. 2. Relations of Ca, Mg and Na+K in the Antarctic saline lakes.

difficulty in their analyses. For example, the first Japanese party of 1963–1964 found it quite difficult to determine dissolved oxygen and nutrient matters in the bottom waters of Lake Vanda. Since then much improvement in analytical methods has been made in order to overcome these difficulties. The present report will also describe in some detail these analytical techniques that are considered to be the best among those presently available.

2. Experimental, Field and Laboratory

2.1. Field methods

At each observation point, a hole was drilled into lake ice by the use of a SIPRE ice-auger. Then, the water temperature and electric conductivity were measured usually at every 50 cm by a thermister thermometer and an electric conductance meter. After the measurement of the bottom was completed, a specially made $2 l$ water sampler (Kitahara-type of polyacrylate) was introduced. Immediately after sampling, water pH was measured by a Toshiba-Beckman Model N-2 pH meter, dissolved oxygen by the Winkler chemical method*, and when H_2S was smelled, $CdCO_3$ was added into the water in order to fix it as CdS.

Nutrient matters together with alkalinity and sulphide were determined within 5 hours after sampling by the methods which principally are based on the Manual

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* Electric DO-meter usually fails to give good result because of high salinity of lake water.

of Oceanographic Observation (Japan Meteorological Agency, 1970) and STRICKLAND (1968) with some variations as indicated under and with some special devices designed for determination of the presence of H_2S in water. The colorimetric analysis was done in the field camp by using Hirama Laboratories Model 4 C portable photoelectric filter photometer.

SiO_2-Si :   Molybdenum yellow method
PO_4-P :   Molybdenum blue method
NH_4-N :   Modified Richards and Kletsch method (1964)
NO_3-N :   Modified Morris and Riley method (1963)
NO_2-N :   Nishimura's method (NISHIMURA *et al.*, 1969)
Alkalinity :   Titration at pH 4.3 (BCG)

2.2. Laboratory methods

Water samples in polyethylene bottles brought back to Japan were analysed in laboratory by the following methods :

Na :   Low salinity :   Atomic absorption spectrophotometry
      High salinity :   Sodium uranyl zincacetate method (BARKER and KOLTHOFF, 1928)
K :   Atomic absorption spectrophotometry
Ca and Mg :   Atomic absorption spectrophotometry or EDTA titration method
Cl :   Low salinity :   Mercuric thiocyanate colorimetric method (IWASAKI *et al.*, 1956)
     High salinity :   Mercuric nitrate titration method (DOMARK and KOBE, 1952)
SO_4 : Low salinity :   Colorimetric method (IWASAKI *et al.*, 1957)
     High salinity :   Gravimetric method
Br :   Iodometry (KAPLAN *et al.*, 1958)
B :   Titration method using mannitol (GAST and THOMPSON, 1958)

3. Chemical Characteristics of the Waters

The major element compositions and contents of the nutrient components of the waters in and around the lakes are given in the Appendix.

In summary, these data indicate that the predominant major components are Ca and Cl in Lake Vanda, Mg and Cl followed by Na in Lake Bonney, and Na and Cl in Lake Fryxell. The water temperature, chlorinity and dissolved oxygen content of each lake are outlined below.

3.1. Lake Vanda

The mixolimnion of Lake Vanda extends down to about 40 m—showing the temperature from 0.1° to 7.7°C. The monimolimnion under 40 m shows a gradual increase with depth up to 25°C. The increase with depth can be characterized by a step-wise structure.

Water is saturated or super-saturated with dissolved oxygen down to around 55 m, but is depleted quickly with depth until 59 m where an anaerobic state is
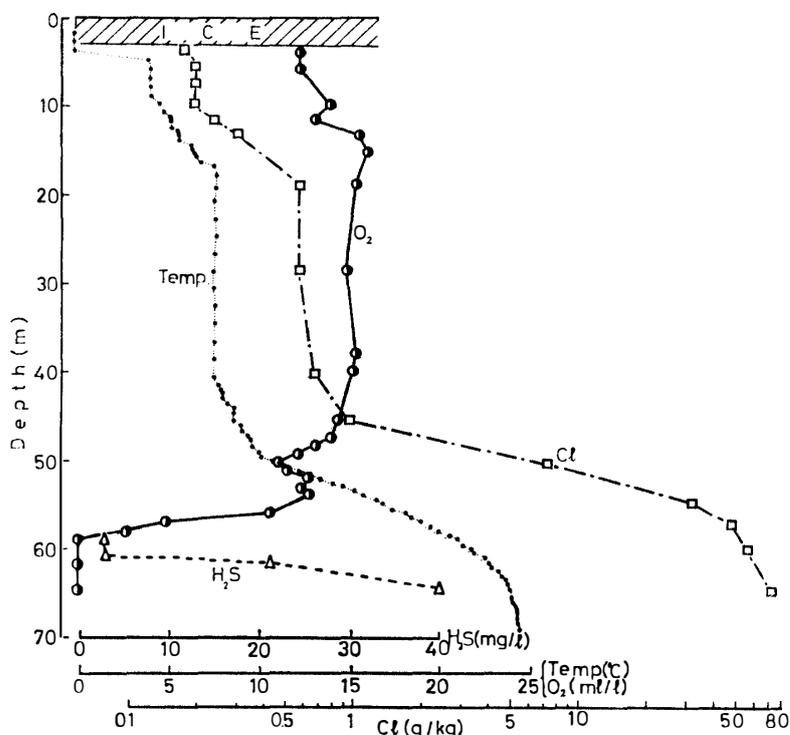
Fig. 3. Vertical distribution of temperature, O_2 and Cl in Lake Vanda.

attained, and hydrogen sulphide begins to appear. The concentration of H_2S reaches 40 mg/l at the bottom of 65 m depth. Such conditions should suggest the presence of sulphate reducing bacteria as indicated by BARGHOORN and NICHOLS (1961).

The chlorinity increases with depth down to the bottom and even further into the ground water, suggesting a supply of salt from the lake sediment (Fig. 3; Table 9).

3.2. Lake Fryxell

Lake Fryxell was first studied limnologically by ANGINO *et al.* (1962). The lake is rather shallow, the maximum depth being 18 m, and the maximum temperature appearing at the 6.5–7 m depth. Down to this layer, water is saturated with dissolved oxygen. It then decreases quickly as an anaerobic condition appears at 10 m depth. Hydrogen sulphide also appears at 8 m depth and increases with depth —showing 22.6 mg/l at the bottom layer. Chlorinity increases with depth, the bottom water having about 1/5 the chlorinity of sea-water (3.7 g/l) (Fig. 4).

In all of the saline lakes in the Dry Valleys chlorinity increases toward the bottom and therefore chloride is thought to come from the sediment layer or the ground water, although the latter case seems less likely.
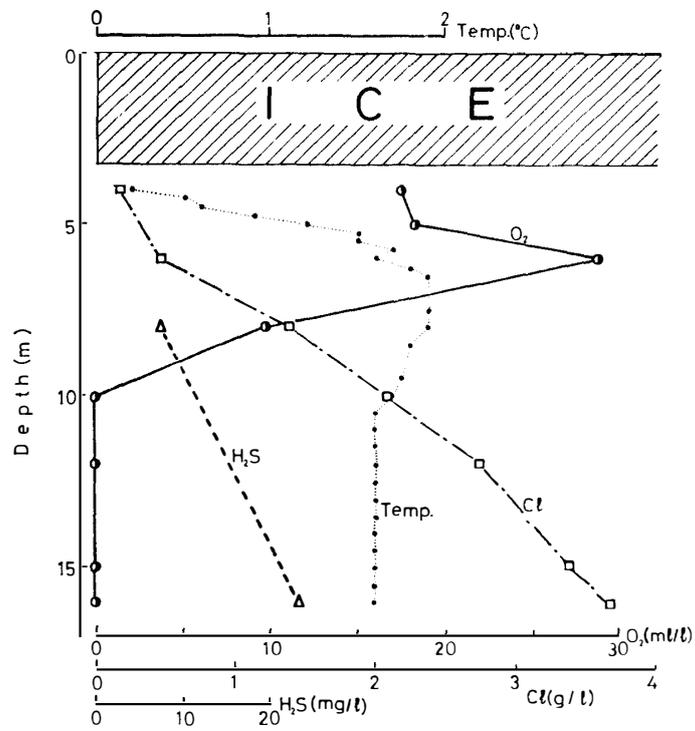
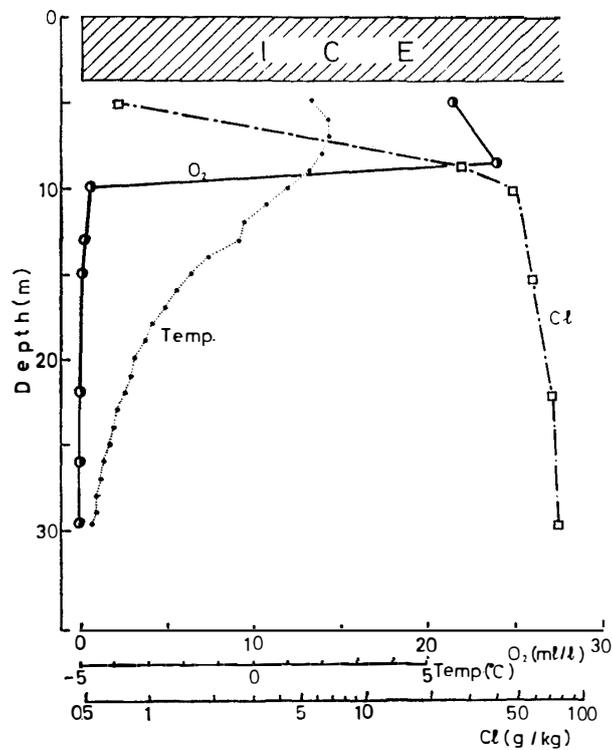Fig. 4.   Vertical distribution of temperature, O_2 and Cl in Lake Fryxell.

Fig. 5.   Vertical distribution of temperature, O_2 and Cl in Lake Bonney, west lobe.

3.3. Lake Bonney

Lake Bonney consists of east and west lobes which chemically are quite different from each other, but are connected by a narrow channel. The mixolimnion in the west lobe extends down to about 12 m with a maximum temperature of 2.2°C at 6-7 m layer. The monimolimnion extends from a temperature of 0°C down to −4.6°C at the bottom of 30 m depth. The lake is saturated with dissolved oxygen down to 8 m, but becomes undersaturated quickly with depth and an anaerobic condition begins to appear at 15 m. But hydrogen sulphide could not be detected. Chlorinity increases with depth below 8.5 m depth (Fig. 5).

The maximum temperature of 6°C occurs in the east lobe at 13-16 m in the presumed mixolimnion and the monimolimnion extends below 0°C down to −2.6°C at the bottom. The east lobe is super-saturated with dissolved oxygen down to 13 m where the temperature shows a maximum, then decreases quickly as in the case of the west lobe, but still from 1 to 2 mg/l of oxygen is present at the bottom. This indicates a condition in which denitrification cannot occur. The chlorinity of 161.5 g/kg is 8.5 times that of sea-water and the total solid content is the largest among the lakes in the Dry Valleys except for Don Juan Pond which shows 246 g/kg. (Fig. 6)

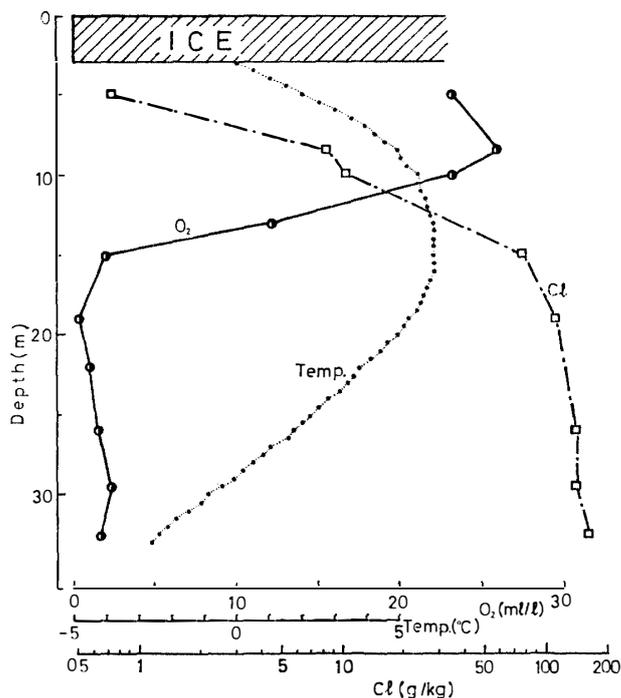Fig. 6.   Vertical distribution of temperature, O_2 and Cl in
Lake Bonney, east lobe.

4. Distribution of Inorganic Nutrient Matters

The distribution of inorganic nutrient matters in each lake is summarized and some general interpretations of them are given below.
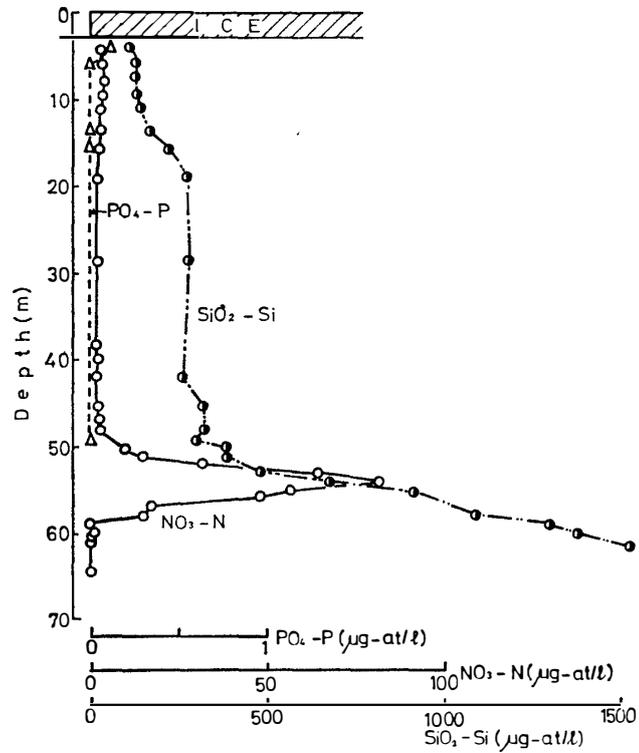
Fig. 7. Vertical distribution of nutrient matters in Lake Vanda.
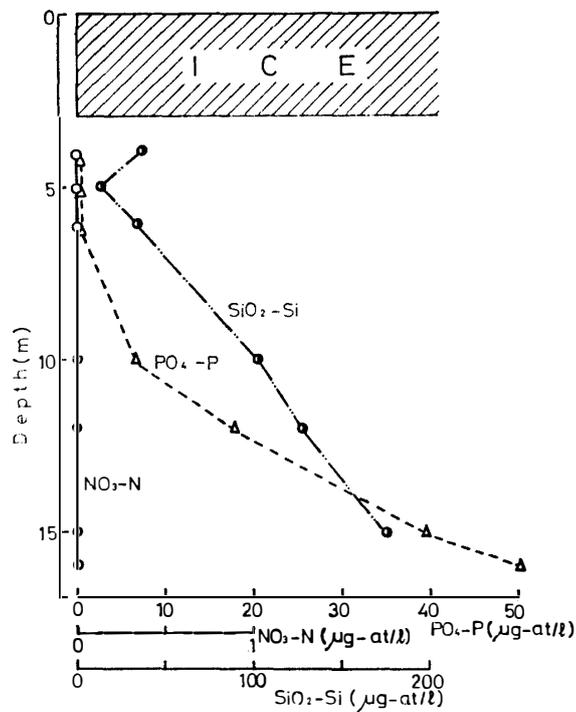
Fig. 8. Vertical distribution of nutrient matters in Lake Fryxell.

4.1. Lake Vanda

Lake Vanda is characterized by the absence of phosphate except in the eastern part where the Onyx River supplies inflow-water, 0.3-1 μg-at phosphate-P/l in summer. Silicate-Si shows large values in the proximity of the bottom. Nitrate-N is 2-3 μg-at/l in the upper layers but increases with depth becoming very high below 50 m depth. The maximum value was observed at 54 m. This trend is similar to the case of nitrite-N. The decrease of nitrate at the bottom can be attributed to the activity of sulphate reducing bacteria in an anaerobic state. Dissolved oxygen of less than 0.2 ml/l in the bottom waters was recorded, suggesting the denitrification producing nitrogen gas with ammonia (Fig. 7).

4.2. Lake Fryxell

The phosphate concentration in Lake Fryxell is abnormally high at the bottom and this might be caused by the influence of animals or birds such as the skua and by dissolution of bottom sediment. The absence of nitrate in this lake reflects a high consumption rate of nitrate and coincides with the absence of dissolved oxygen. Silicate-Si increases with depth as in Lake Vanda (Fig. 8).

4.3. Lake Bonney

In the west lobe of Lake Bonney, the distribution pattern is rather unstable during the summer because of a large supply of inflow-water from the Taylor
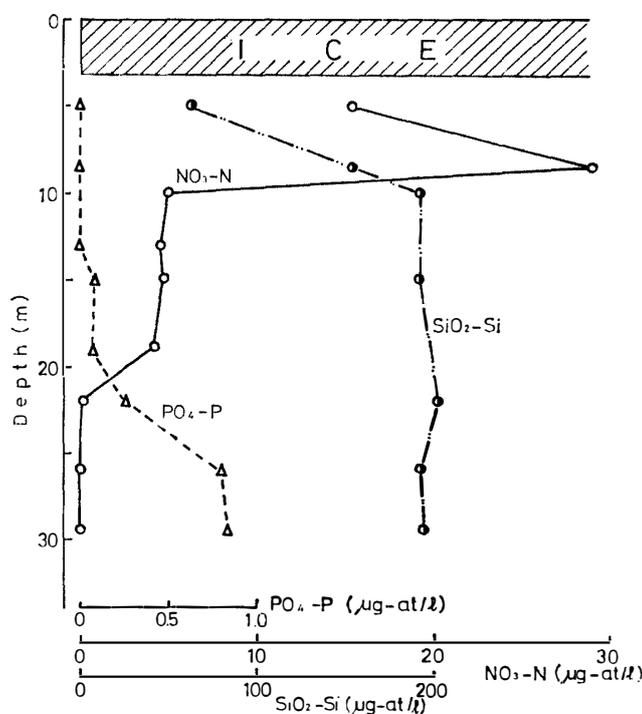
Fig. 9.   Vertical distribution of nutrient matters in Lake Bonney, west lobe.
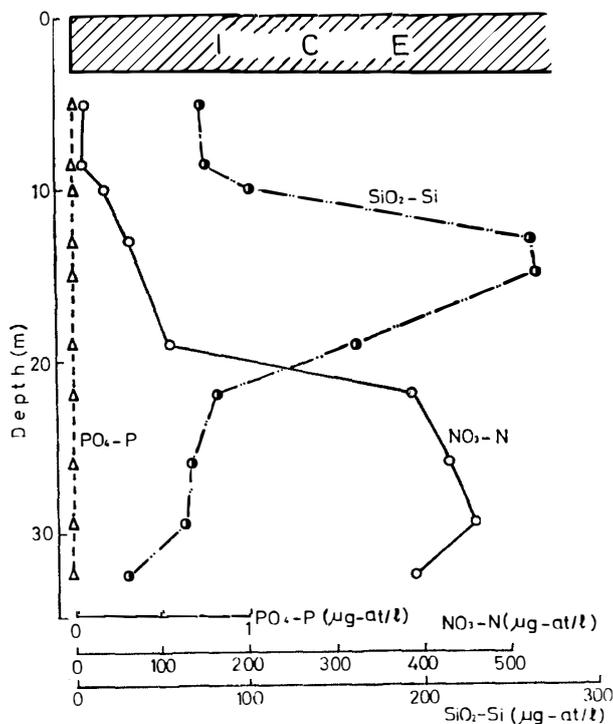
Fig. 10. Vertical distribution of nutrient matters in Lake Bonney,
east lobe.

Glacier. Phosphate-P is present in the lower layer. Nitrate-N is abundant in the
upper layer but absent in the lower layer. The distribution of dissolved oxygen
also indicates the reducing activity of organisms in the middle and lower layers.
The high concentration of silicate-Si in the upper layer should be attributed to
the inflow-water from the Taylor Glacier (Fig. 9).

In the east lobe, phosphate-P is absent in contrast to the west. Nitrate-N
increases with depth, showing a maximum of 400μg-at/l which is the largest value
among the lakes in the Dry Valleys. A maximum of silicate-Si was observed in
the middle layer which has the maximum temperature ($6°C$ at 13–15 m) as well,
and decreases with depth. This is an exceptional phenomenon among these lakes
(Fig. 10).

4.4. Distribution patterns of nitrogen compounds

Figure 11 indicates the vertical distribution of nitrogen compounds in Lake
Vanda. The right figure shows the percentage compositions of nitrate-N, nitrite-
N and ammonia-N, and the left figure indicates the total inorganic nitrogen con-
centration.

At the depth of 54 m, where nitrate and nitrite attain the maximum concen-
trations, the total inorganic nitrogen shows a peak and then decreases with depth.
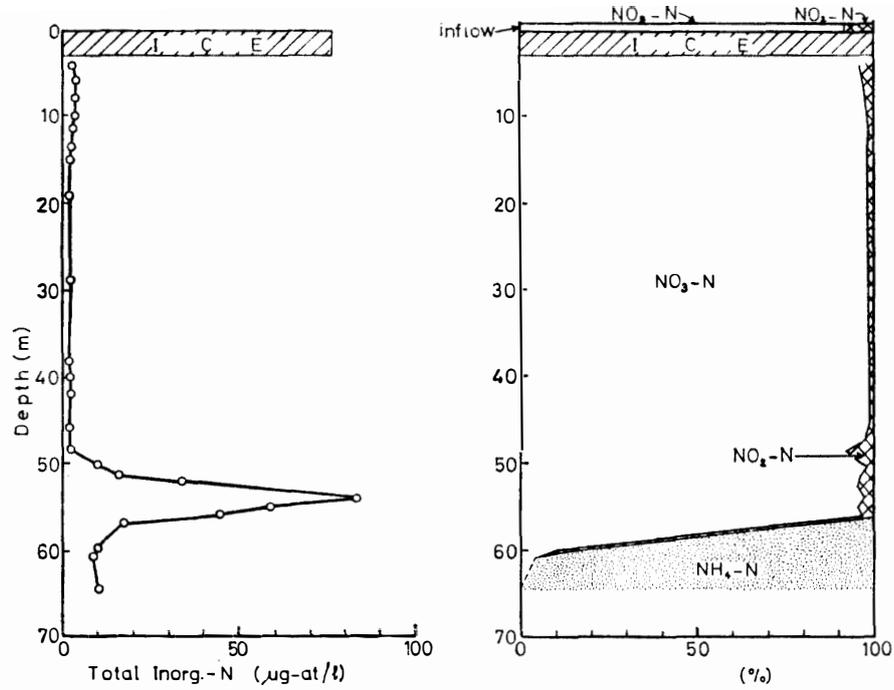
Fig. 11.   Vertical distribution of N-compounds in Lake Vanda.
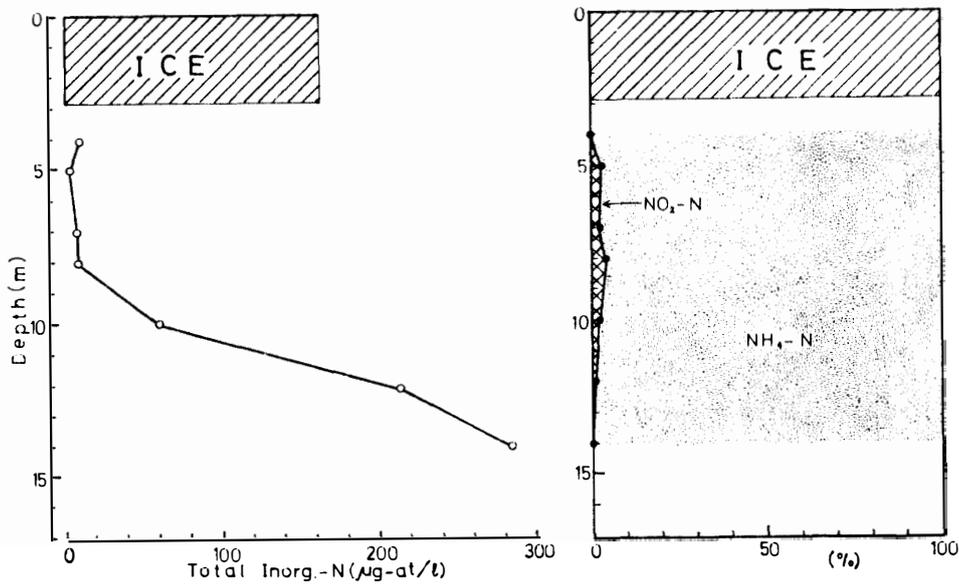
Fig. 12.   Vertical distribution of N-compounds in Lake Fryxell.

This can be attributed to the occurrence of denitrification as stated earlier. These observations lead to the assumption that the supply of nitrogen compounds comes from the bottom of the lake. It is clearly shown in Fig. 11 that the nitrate is reduced to ammonia in the bottom layer.

Lake Fryxell is characterized by the absence of nitrate and the high concentration of ammonia in the bottom. The latter condition in tandem with the high concentration of phosphate may suggest decomposition of organic materials in the sediment. The presence of a nitrite maximum in the middle layer may be due to the occurrence of nitrification from ammonia as a result of biological activity as is often the case with ordinary lakes. The total inorganic nitrogen compounds increase with depth and the majority of this is ammonia at the bottom layer (Fig. 12).

As stated earlier, the distribution patterns of nitrogen compounds in the east and west lobes of Lake Bonney drastically differ from each other, demanding further study from microbiological points of view.

In the west lobe, the distribution patterns of dissolved oxygen and nitrate indicate that the nitrate is reduced by organic activity, and disappears completely from the 26 m depth down. While it is not clear whether or not denitrification can occur even below the freezing point, the complete absence of dissolved oxygen in the bottom layer indicates a possible condition of denitrification. The total inorganic nitrogen shows a maximum in the mixolimnion and decreases in the lower layer (Fig. 13).

The east lobe is characterized by a large amount of nitrate in the bottom waters. The concentration of dissolved oxygen is higher than 1 ml/l even in the bottom layer. This suggests that denitrification cannot occur. If productivity becomes larger, ammonia in the bottom layer should increase until the distribution pattern of nitrogen compounds approaches that in the west lobe. The present state of the east lobe is considered to be marginal for denitrification showing a balanced state among different nitrogen compounds (Fig. 14).
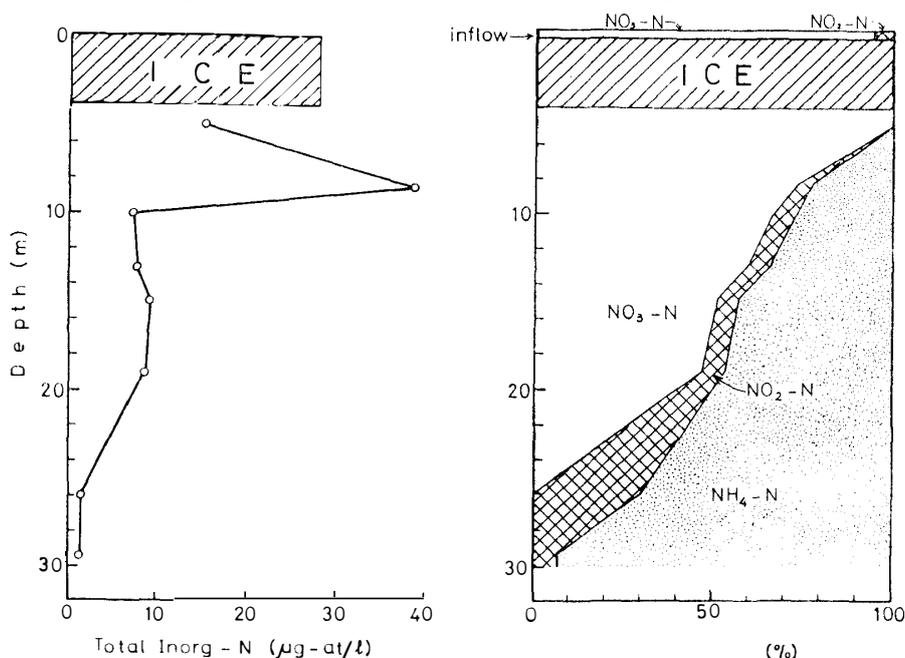
Fig. 13.   Vertical distribution of N-compounds in Lake Bonney, west lobe.
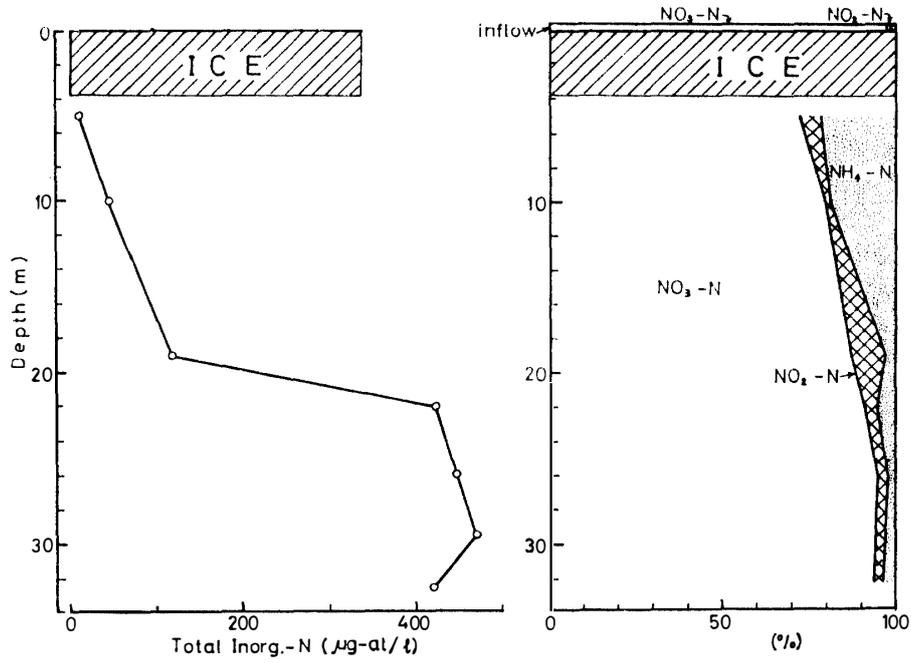
Fig. 14. Vertical distribution of N-compounds in Lake Bonney, east lobe.
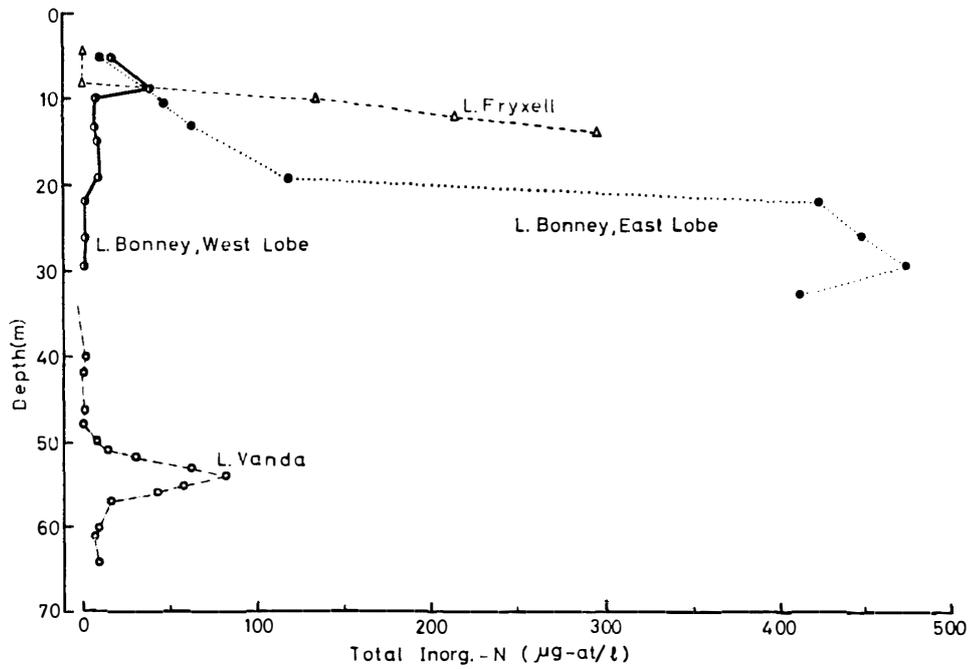
Fig. 15. Vertical distribution of total inorganic-N in the saline lakes.

5. The Source of Nitrogen Compounds

One of the characteristic features of the saline lakes in the Dry Valleys is the high concentration of nitrogen compounds. Figure 15 gives an overall comparison of the distribution patterns of nitrogen compounds in these lakes. It shows that the east lobe of Lake Bonney has the highest nitrogen content among these lakes. According to Johanneson (1962) and Morikawa (1974), the evaporites and soils around the lakes also have large contents of nitrate compounds. Canopus Pond located south of Lake Vanda contained 51 μg-at/l and Don Quixote Pond in the North Fork contained 24800 μg-at/l of NO_3-N. The general presence of nitrogen compounds was also discovered throughout this and other areas (Jensen, 1916; Claridge et al., 1968). The nitrate and nitrite contents in the core samples from the drilling at Lake Vanda and the adjacent ground waters are also very high (Table 9). In fact, a large amount of nitrogen compounds is present in the soil etc. in this valley as a whole.

The abundant distribution of these nitrogen compounds together with silicate and other major elements support the view that they come from bottom sediments.

6. The Geochemical History of Lake Bonney and Its Bearings on the Distribution of the Nutrient Matters

The hydrogen and oxygen isotopic ratios of Antarctic saline lakes have extensively been studied by Matsubaya (1974) and Ambe (1974). Their results are reproduced in Fig. 16 showing the vertical isotopic profiles of the two lobes of
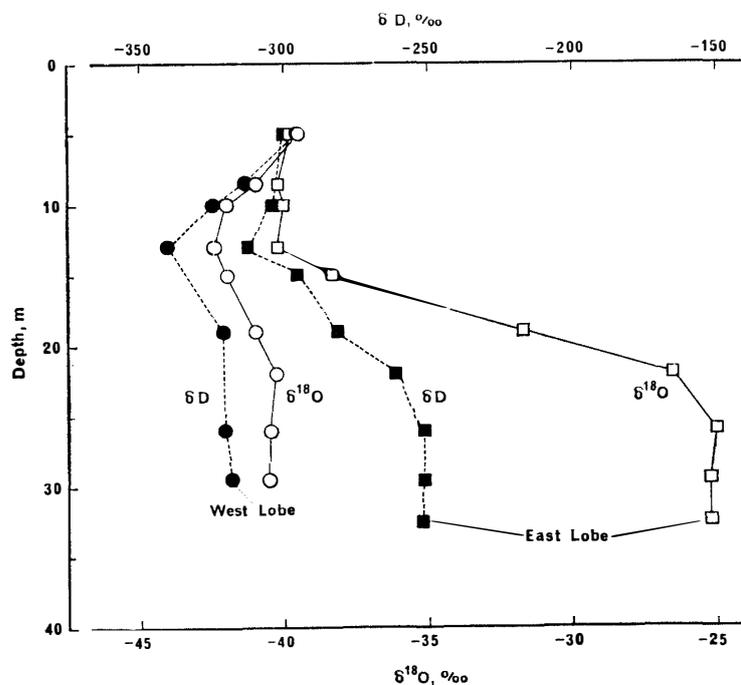
Fig. 16.   Vertical distribution of δD and δ^{18}O in Lake Bonney.

Lake Bonney. In order to explain the distribution patterns of both isotopes and major elements in each lobe and their differences between the two lobes, MATSUBAYA and others (1974) have proposed the following model of formation of Lake Bonney:

Initially, dry salt deposits were present in each of the lobes (stage 1 in Fig. 17). Then, melt water of approximately $\delta D = -300$ and $\delta^{18}O = -40‰$ from inland flowed into the west basin forming a saline lake. At the same time, a brine lake was formed in the east basin by melt water from coast side, having approximately $\delta D = -250$ and $\delta^{18}O = -32‰$. In the west lobe, the rate of the inflow was high enough to form a stratified lake with brine at the bottom and fresh water in the upper layer. The fresh water was no doubt covered with ice soon after the formation. On the other hand, the east lobe kept a shallow brine lake of uniform concentration, because the inflow rate was not high enough to overcome mixing by diffusion (stage 2 in Fig. 17). During this stage, evaporation of the east brine lake resulted in an enrichment of ^{18}O of the water. After the west lobe was gradually filled, the surface melt water started to flow into the east lobe through the channel (stage 3 in Fig. 17). Finally, stage 4 (Fig. 17) or the present stage, of the lake begins when water levels of the east and west lobes became equal. In this stage, surface water still moves from west to east, because of the higher inflow rate of melt water at the west lobe.

This model suggests that the stratified distribution of the isotopes and major
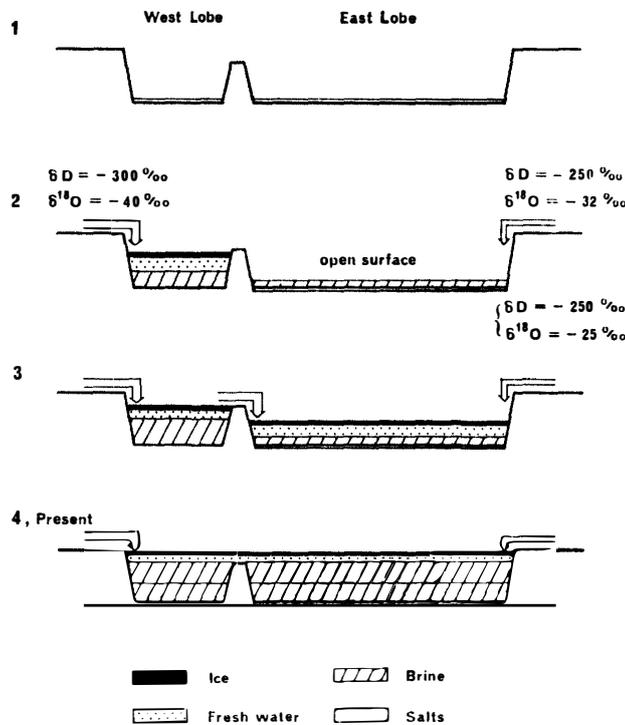
Fig. 17. Scheme of the formation of Lake Bonney.

elements in the east lobe started only after stage 3 and that it has a younger history than the west lobe. The distribution pattern of the nutrient matters in the east lobe also is premature in that denitrification has not started in the bottom water. However, the biogenic activity is controlled not only by the concentration of nutrient matters but also by many other factors such as salinity, chemical composition and temperature. Furthermore, the time constant of biogenic activity should be much faster than that of geologic events. Note that sharp concentration of inorganic nitrogen at 54 m of Lake Vanda could only be explained by such fast biogenic activity. Therefore, we feel that further study is required before any connection between the geochemical and biochemical features of the lakes can be suggested. Obviously needed is more detailed information on the biogenic and biochemical processes which take place in cold saline brines.

The difference of the chemical composition between the two lobes (Table 10) and the presence of the halite deposit at the bottom of the east lobe (WILSON *et al.*, 1974 ; YAMAGATA *et al.*, 1967) would also give some supporting points on this line.

Acknowledgments

References

AMBE, M. (1974): Deuterium content of water substances in Antarctica. Part II. Geochemistry of deuterium of lake waters in Victoria Land. Antarct. Rec., 48, 100-109.

ANGINO, E.E., K.B. ARMITAGE and J.C. TASH (1962): Chemical stratification in Lake Fryxell, Victoria Land, Antarctica. Science, 138 (3536), 34-35.

BARGHOORN, E.S. and R.L. NICHOLS (1961): Sulfate-reducing bacteria and pyritic sediments in Antarctica. Science, 134 (3437), 190.

BAKER, H.H. and I.M. KOLTHOFF (1928): A specific reagent for the rapid gravimetric determination of sodium. J. Am. Chem. Soc., 50, 1625-1631.

CLARIDGE, G.G.C. and I.B. CAMPBELL (1968): Origin of nitrate deposits. Nature, 219 (5127), 428-430.

CRAIG, H. (1966): Origin of the saline lakes in Victoria Land, Antarctica. Trans. Am. Geophys. Union, 47 (1), 112-113.

DOMASK, W.G. and K.A. KOBE (1952): Mercuric determination of chlorides and water-soluble chlorohydrines. Anal. Chem., 24, 989-991.

GAST, J.A. and G. THOMPSON (1958): Determination of the alkalinity and the borate concentration of sea water. Anal. Chem., 30, 1949-1951.

IWASAKI, I., S. UTSUMI, K. HAGINO and T. OZAWA (1956): A new spectrophotometric method for the determination of small amounts of chlorine using the mercuric thiocyanate method. Bull. Chem. Soc. Jap., 29, 860-864.

IWASAKI, I., S. UTSUMI, K. HAGINO, T. TARUTANI and T. OZAWA (1957): Spectrophotometric metod for the detrmination of small amounts of sulfate ions. Bull. Chem. Soc. Jap., 30, 847-851.

JAPAN METEOROLOGICAL AGENCY (1970): The manual of Oceanographic Observation. The Oceanographical Society of Japan, Tokyo.

JENSEN, H.I. (1916): Report on Antarctic soils. Rep. Sci. Invest. Br. Antarct. Exped. 1907–1909, Geol., 2 (9).

JOHANNESSON, J.K. and G.W. GIBSON (1962): Nitrate and iodate in Antarctic salt deposits. Nature, 194 (4828), 567-568.

KAPLAN, D. and I. SCHNERB (1958): Semimicrodetermination of bromides application to physiological fluids. Anal. Chem., 30, 1703-1705.

MATSUBAYA, O., S. NAKAYA, H. MURAYAMA, T. TORII and H. SAKAI (1974): Oxygen and hydrogen isotopic ratios and major element compositions of Antarctic saline lakes. 1974 Annual Meeting of Geochemical Society of Japan.

MORIKAWA, H., I. MINATO, J. OSSAKA and T. HAYASHI (1974): The distribution of secondary minerals and evaporites at Lake Vanda, Victoria Land, Antarctica. Mem. Natl. Inst. Polar. Res., Special Issue, 4, 45-59.

MORRIS, A.W. and J.P. RILEY (1963): Determination of nitrate in sea water. Anal. Chim. Acta, 29, 272-279.

NAKAI, N. (1974): Stable isotope studies of the salt, water, and ice from Ross Island core and Lake Vanda. DVDP Bull., 4, 46-47.

NISHIMURA, M., N. MATSUNAGA and H. KANZAWA (1969): Conditions for coloration of nitrite with Giess-Romijin reagent and elimination of interferences of sulfur compounds and iodide. Jap. Anal., 18, 1372-1376.

RAGOTZKIE, R.A. and I. FRIEDMAN (1965): Low deuterium content of Lake Vanda, Antarctica. Science, 148 (3674), 1226-1227.

RICHARDS, F.A. and R.A. KLETSCH (1964): The spectrophotometric determination of ammonia and rabile amino compounds in fresh and sea water by oxydation to nitrite. Ken Sugawara Festival Volume. Recent Researches in the Fields of Hydrosphere, Atmosphere and Nuclear Geochemistry, Maruzen, Tokyo, 65-81.

SIMONOV, I.M. (1971): The oases of eastern Antarctica. Hydrometeorological Press, Leningrad.

STRICKLAND, J.D.H. and T.R. PARSONS (1968): A Practical Handbook of Sea Water Analysis. Fisheries Research Board of Canada, Ottawa.

WILSON, A.T. and C.H. HENDY (1974): McMurdo Dry Valley lakes sediments—A record of cenozoic climatic events. DVDP Bull., 4, 34.

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.

APPENDIX

Table 1. Chemical composition of Lake Vanda (sampling date: 9 December 1972).

Depth (m)	Sp. Gr.	Na (g/kg)	K (g/kg)	Ca (g/kg)	Mg (g/kg)	Sr (g/kg)	Cl (g/kg)	SO$_4$ (g/kg)	Br (g/kg)	HBO$_2$ (g/kg)
3.9		0.031	0.008	0.042	0.005	0.00024	0.154	0.012	0.00003	
5.8		0.066	0.015	0.057	0.013	—	0.186	0.013	0.00006	0.00005
7.7		0.057	0.013	0.061	0.015	0.00034	0.204	0.013	0.00006	0.00005
11.6		0.057	0.008	0.071	0.017	0.00035	0.234	0.018	0.00006	0.00005
13.5		0.075	0.011	0.092	0.022	0.00039	0.302	0.020	0.00012	0.0001
28.6		0.116	0.016	0.172	0.043	0.00064	0.548	0.031	0.00012	0.0001
41.9	1.001	0.140	0.032	0.275	0.073	0.00091	0.880	0.034	0.00022	0.00015
50.3	1.009	0.719	0.071	2.30	0.667	—	7.11	0.074	0.0022	0.0011
52.2	1.018	1.40	0.125	5.09	1.48	0.0194	15.43	0.130	0.0048	0.0024
54.1	1.023	2.20	0.212	8.30	2.43	—	24.95	0.199	0.007	0.0038
55.1	1.039	2.78	0.224	10.16	3.15	0.0370	30.87	0.246	0.009	0.0049
57.9	1.060	3.92	0.413	15.56	4.82	—	46.94	0.396	0.013	0.007
59.9	1.070	5.55	0.415	18.07	5.66	0.0676	54.04	0.473	0.015	0.009
64.6	1.092	6.11	0.590	24.40	7.40	0.0938	74.28	0.615	0.020	0.012

Table 2. Chemical composition of Lake Fryxell (sampling date: 20 December 1972).

Depth (m)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Cl (mg/l)	SO$_4$ (mg/l)	Br (mg/l)	HBO$_2$ (mg/l)
4	85	12.6	25.3	16	195	27.2	0.4	0.4
5	135	15.3	29.0	17	199	30.8	—	0.8
6	348	36.0	21.1	40	480	57.0	1.2	1.2
8	1110	91.5	31.6	124	1450	165	4.3	2.4
10	1670	134	35.2	184	2160	214	6.3	4.4
12	1950	172	31.0	248	2845	240	8.4	7
15	2700	192	43.5	311	3510	244	10.5	8
16	2980	203	26.8	331	3710	253	11.1	9

Table 3. Chemical composition of Lake Bonney.

Location	Depth (m)	Sp. Gr.	Na (g/kg)	K (g/kg)	Ca (g/kg)	Mg (g/kg)	Cl (g/kg)	SO$_4$ (g/kg)	Br (g/kg)	HBO$_2$ (g/kg)
West lobe	5	1.001	0.376	0.014	0.056	0.068	0.733	0.114	0.0036	0.0008
W-1	8.5	1.037	8.25	0.433	0.803	3.00	28.23	2.748	0.135	0.027
5 January	10	1.063	21.3	0.813	1.18	5.05	48.69	4.056	0.228	0.050
1972	15	1.078	28.2	0.996	1.56	6.27	60.26	4.521	0.284	0.061
	22	1.094	33.0	1.26	1.46	7.97	74.41	4.332	0.360	0.075
	29.5	1.102	32.08	1.47	1.48	8.34	78.12	4.453	0.375	0.078
East lobe	5	1.001	0.298	0.018	0.119	0.067	0.769	0.111	0.0039	0.0008
E-1	8.5	1.011	3.87	0.134	0.323	0.948	8.67	0.292	0.058	0.007
9 January	10	1.011	3.85	0.152	0.566	0.914	9.08	0.533	0.055	0.007
1972	15	1.100	21.6	1.36	0.797	15.25	79.32	2.507	0.775	0.059
	19	1.143	34.3	2.01	0.990	22.37	113.7	2.510	1.107	0.090
	26	1.181	43.9	2.74	1.35	27.27	143.4	2.748	1.340	0.137
	29.5	1.177	43.5	2.69	1.11	23.70	141.3	2.854	—	—
	32.5	1.203	56.9	2.30	1.22	21.71	161.5	2.936	1.239	0.108

Table 4. Nutrient matters in Lake Fryxell (sampling date: 20 December 1972).

Depth (m)	Conductivity ($\mu\sigma$/cm at 18°C)	pH	Temp. (°C)	Dissolved oxygen (ml/l)	Alkalinity (meq/l)	NO$_2$-N (μg-at/l)	NO$_3$-N (μg-at/l)	NH$_4$-N (μg-at/l)	SiO$_2$-Si (μg-at/l)	PO$_4$-P (μg-at/l)
4	5.93×10^2	7.00	0.2	17.5	3.26	0.0	nil	11.2	37	0.05
5	1.73×10^3	8.16	1.2	18.3	3.55	0.1	nil	nil	14	0.02
6	3.60×10^3	7.98	1.6	28.8	7.44	0.1	nil	nil	34	0.10
8	5.27×10^3	7.50	1.9	9.8	20.5	0.1	nil	2.94	102	0.14
10	7.56×10^3	7.40	1.7	nil	29.8	1.3	nil	60.0	128	6.78
12	9.04×10^3	7.40	1.6	nil	38.3	0.7	nil	214	175	18.2
15	1.03×10^4	7.10	1.6	nil	47.5	0.1	nil	293	—	39.5
16	1.07×10^4	7.07	1.6	nil	51.3	0	nil	—	—	50.2

H$_2$S : 8 m 6.8 mg/l, 15 m 22.6 mg/l.

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Table 5. Nutrient matters in Lake Vanda (sampling date : 9 December 1972).

Depth (m)	Conductivity ($\mu\sigma$/cm at 18°C)	pH	Temp. (°C)	Dissolved oxygen (ml/l)	Alkalinity (meq/l)	NO₂-N (μg-at/l)	NO₃-N (μg-at/l)	NH₄-N (μg-at/l)	SiO₂-Si (μg-at/l)	PO₄-P (μg-at/l)
3.9	471	7.11	4.7	12.2	0.64	0.11	2.9	nil	111	0.1
5.8	514	7.59	4.8	12.2	0.71	0.09	3.28	nil	123	0.0
7.7	529		4.7	11.2	0.78	0.07	3.56		127	nil
9.7	587	7.99	5.2	13.9	0.79	0.06	3.29		127	nil
11.6	609	7.90	5.9		0.86	0.04	3.01		136	nil
13.5	770	7.62	6.6	15.5	0.91	0.04	2.9	nil	164	0.0
15.3	1040		7.2	15.9	1.12	0.04	2.2	nil	217	0.0
19.0	1530		7.7	15.3	1.24	0.02	1.4		268	nil
28.6	1530	7.40	7.6	14.8	1.31	0.01	1.3	nil	268	0.0
38.1	1.53×10^3	7.30	7.6	15.6	1.30	0.01	1.22	nil		nil
40.0	1.54×10^3		7.7	15.0	1.34	0.01	2.0			nil
41.9	1.82×10^3	7.01	8.0	16.9	1.46	nil	1.9	nil	255	nil
45.6	2.64×10^3		9.5	14.3	1.48	0.01	2.1	nil	318	nil
47.5	3.09×10^3	6.52	10.0	13.8	1.48	0.05	2.2	nil		nil
48.4	3.90×10^3	6.72	10.6	13.1	1.49	0.19	2.1	nil	323	nil
49.4	5.66×10^3	6.90	11.4	12.1	1.67	0.11		nil	296	nil
50.3	1.09×10^4	6.75	12.8	11.0	1.71	0.12	9.5	nil	387	nil
51.3	1.54×10^4	6.62	14.0	11.5		0.58	14.9		384	nil
52.2	2.11×10^4	6.46	14.8	12.6	1.88	1.48	31.4	nil		nil
53.2	2.59×10^4		16.0	12.3	2.15		64.6	nil	475	nil
54.1	3.97×10^4	6.40	17.1	12.7		1.83	81.1	nil	669	nil
55.1	4.88×10^4	6.46	18.1	15.4	2.43	2.27	56.4	nil	911	nil
56.0	5.75×10^4	6.38	19.3	10.5	2.63	1.18	42.9	nil	919	nil
57.0	6.63×10^4	5.95	20.3	4.7	2.99	0.32	17.0			nil
57.9	7.57×10^4		21.2	2.6	3.09	0.36	15.4		1090	nil
58.9	8.29×10^4	5.80	21.9	0	3.75		0.8		1310	nil
59.9	8.97×10^4		22.7	0	3.84	0.3	1.1	8.66	1370	nil
60.8	1.00×10^5		23.2	0	4.54		0.3	8.24	1520	nil
61.7	1.07×10^5		23.7	0	4.74	0	0.2		2100	nil
64.6	1.23×10^5	5.45	24.3	0	4.73	0	0	10.1	1690	nil

H_2S (mg/l): 58.9 m 2.98, 60.8 m 3.11, 61.7 m 21.4, 64.6 m 40.0.

Table 6. Nutrient matters in Lake Bonney.

West lobe (sampling date: 5 January 1973)

Depth (m)	Conductivity ($\mu\mho$/cm at 18°C)	pH	Temp. (°C)	Dissolved oxygen (ml/l)	Alkalinity (meq/l)	NO_2-N (μg-at/l)	NO_3-N (μg-at/l)	NH_4-N (μg-at/l)	SiO_2-Si (μg-at/l)	PO_4-P (μg-at/l)
5	2.85×10^3	6.87	1.7	21.4	1.32	0.2	15.4	—	63	—
8.5	5.66×10^4	6.30	1.9	23.9	44.1	0.3	28.9	9.6	153	—
10	8.42×10^4	5.98	1.0	0.71	71.7	0.5	4.9	2.0	193	—
13	9.43×10^4	5.88	−0.8	0.39	79.8	0.5	4.6	2.7	—	—
15	9.81×10^4	5.99	−1.8	0.24	82.9	0.5	4.7	4 0	191	0.08
19	1.02×10^5	5.80	−3.1	—	85.6	0.5	4.1	4.1	—	0.08
22	1.10×10^5	5.70	−3.7	0	90.8	—	0.1	2.2	203	0.26
26	1.16×10^5	5.72	−4.3	0	98.4	0.5	nil	1.2	193	0.80
29.5	1.15×10^5	5.78	−4.6	0	99.7	0.1	nil	1.6	194	0.84
30.2 (bottom)										

East lobe (sampling date: 9 Janury 1973)

Depth (m)	Conductivity ($\mu\mho$/cm at 18°C)	pH	Temp. (°C)	Dissolved oxygen (ml/l)	Alkalinity (meq/l)	NO_2-N (μg-at/l)	NO_3-N (μg-at/l)	NH_4-N (μg-at/l)	SiO_2-Si (μg-at/l)	PO_4-P (μg-at/l)
5	2.77×10^3	5.50	2.0	23.0	1.40	0.6	7.1	2.2	72.9	nil
8.5	1.72×10^4	6.90	4.9	25.9	3.46	0.2	5.6	—	75.9	nil
10	2.24×10^4	6.95	5.5	23.2	5.26	0.3	37.1	9.4	101	nil
13	7.32×10^4	6.89	6.0	12.1	10.8	1.1	61.8	—	262	nil
15	1.18×10^5	6.40	6.0	1.9	16.4	5.4	—	—	265	nil
19	1.56×10^5	6.00	5.3	0.34	12.4	11.9	104	4.1	162	nil
22	1.55×10^5	6.51	3.8	0.81	10.3	13.2	384	26.5	82.0	nil
26	1.51×10^5	6.81	1.8	1.4	8.21	13.2	425	10.2	68.2	nil
29.5	1.44×10^5	6.72	−0.5	2.2	7.72	12.7	459	—	64.0	nil
32.5	1.45×10^5	6.51	−2.4	1.5	3.70	8.8	388	16.2	31.4	nil
33.4 (bottom)										

Table 7.   Chemical composition of small ponds and inflow waters.

Location	Na (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Sr (mg/kg)	Cl (mg/kg)	SO₄ (mg/kg)	Br (mg/kg)	HBO₂ (mg/kg)
Canopus Pond (29 December 1971) Pond water	35.9	2.01	4.10	5.8	—	44.0	38.0	—	—
Inflow from glacier	19.6	1.86	24.2	8.0	—	20.7	23.6	—	—
North fork, Wright Valley(17 December 1971) Pond No. 1	17.0	0.65	4.4	6.4	—	16.1	13.8	—	—
Pond No. 2	20.0	0.66	5.7	7.2	—	18.5	15.2	—	—
Pond No. 3	29.0	1.04	15.7	24.5	—	36.3	40.3	—	—
Pond No. 4	5.91*	0.189*	0.815*	2.6*	4.1	10.9*	223	—	—
Pond No. 5	31.8	1.04	11.9	21.4	—	57.2	8.3	—	—
Melt water from Wright Lower Glacier (26 December 1972)	2.77	0.36	1.90	0.58	—	5.0	0.86	—	—
Lake Wright (26 December 1972)	3.85	0.47	1.90	0.58	—	4.9	6.17	—	—
Onyx River from Lake Wright (26 December 1972)	2.50	0.52	2.47	0.71	—	5.8	2.31	—	—
Onyx River, weir (26 December 1971)	6.90	1.27	9.40	1.60	0.02	7.5	3.7	—	—
Onyx River, weir (17 January 1973)	5.54	1.28	8.66	1.54	—	7.5	12.6	0.00	0.00
Lake Bonney Inflow from west (5 January 1973)	12.6	1.16	19.0	4.0	—	12.0	10.7	0.03	0.00
Inflow from east (9 January 1973)	25.6	3.84	20.0	6.0	—	25.0	29.1	0.05	0.00

*   g/kg.

Table 8.   Nutrient matters of small ponds and inflow waters.

Location	Temp. (0°C)	pH	Alkalinity (meq/l)	NO$_2$-N (μg-at/l)	NO$_3$-N (μg-at/l)	NH$_4$-N (μg-at/l)	SiO$_2$-Si (μg-at/l)	PO$_4$-P (μg-at/l)
Canopus Pond (29 December 1971) Pond water	2.5	9.40	0.53	0.60	51	1.32	18.7	0.17
Inflow from glacier	4.6	7.62	1.03	—	—	—	—	—
North fork,Wright Valley(17 December 1971) Pond No. 1	1.3	9.53	1.11	2.68	107	nil	73.5	0.27
Pond No. 2	1.5	9.29	1.63	2.70	129	—	65.0	—
Pond No. 3	3.0	9.11	1.44	4.33	455	—	73.5	—
Pond No. 4	8.7	8.70	6.64	20.0	24,800	0.81	458	nil
Pond No. 5	2.8	9.43	0.93	15.0	535	nil	25.2	—
Melt water from Wright Lower Glacier (26 December 1972)	0.0	—	—	nil	1.79	4.88	3.0	0.43
Lake Wright (26 December 1972)	0.2	—	—	0.04	1.59	3.27	3.0	0.37
Onyx River from Lake Wright (26 December 1972)	9.4	—	—	0.00	0.36	0.00	12.0	0.04
Onyx River, weir (26 December 1972)	5.0	7.19	0.38	0.36	—	0.72	54.0	1.10
Onyx River, weir (17 January 1973)	4.8	7.22	—	0.38	4.50	0.00	97.0	0.25
Lake Bonney								
Inflow from west (5 January 1973)	2.3	—	0.2	0.74	15.5	nil	91.0	0.81
Inflow from east (9 January 1973)	—	—	1.77	0.33	21.8	nil	95.5	0.58

Table 9. Composition of nutrient matters in various phases of Lake Vanda.

Item		Lake water (64.6 m)	Ground water No. 1 (72.2 m)	No. 2 (75.7 m)	Water soluble part of core sample (72 m)
Specific gravity		1.095	1.121	1.141	—
NO_2-N	(μg-at/l)	0	8.2	7.8	46*
NO_3-N	〃	0	0	0	0
NH_4-N	〃	10.1	47	19.6	160*
SiO_2-Si	〃	1690	6700	8550	50800*
PO_4-P	〃	0	10.2	10.3	19*
Na	(g/kg)	6.11	7.82	8.75	1.30
K	〃	0.59	0.98	1.08	0.18
Ca	〃	24.4	28.9	33.2	3.83
Mg	〃	7.40	9.03	10.5	1.15
Cl	〃	74.28	94.24	108.7	12.03
SO_4	〃	0.615	0.463	0.284	0.204
Br	〃	0.020	0.025	0.028	0.003
I	〃	<0.001	<0.001	<0.001	—
HBO_2	〃	0.012	0.016	0.018	0.003
Na/Cl	(%)	8.23	8.30	8.05	10.8
K/Cl	〃	0.79	1.04	0.99	1.50
Ca/Cl	〃	32.85	30.67	30.58	31.84
Mg/Cl	〃	9.96	9.58	9.66	9.56
SO_4/Cl	〃	0.828	0.491	0.261	1.70
Br/Cl	〃	0.027	0.027	0.026	0.025
I/Cl	〃	<0.001	<0.001	<0.001	—
HBO_2/Cl	〃	0.016	0.017	0.017	0.025

* μg-at/kg core sample.   500 ml leachate of 50 g core sample was analyzed.

Table 10. Chemical composition of the bottom water in west and east lobes of Lake Bonney.

Item	West lobe (29.5 m)	East lobe (32.5 m)
Temperature (°C)	−4.6	−2.4
pH	5.78	6.51
Alkalinity (meq/l)	99.7	3.70
Conductivity ($\mu\eth$/cm, 18°C)	1.15×10^5	1.45×10^5
Dissolved oxygen (ml/l)	0	1.5
Specific gravity	1.102	1.203
NO$_2$-N (μg-at/l)	0.1	8.8
NO$_3$-N ″	0	388
NH$_4$-N ″	1.6	16.2
SiO$_2$-Si ″	194	31.4
PO$_4$-P ″	0.84	0
Na (g/kg)	32.08	56.94
K ″	1.47	2.30
Ca ″	1.48	1.22
Mg ″	8.34	21.71
Cl ″	78.12	161.5
SO$_4$ ″	4.453	2.936
Br ″	0.375	1.239
HBO$_2$ ″	0.078	0.108