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GEOCHEMICAL CHARACTERISTICS OF ANTARCTIC LAKES AND PONDS

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Abstract: General characteristics of lakes and ponds, distributions, changes and sources of major ionic components (Na, K, Mg, Ca, Cl and SO_4), nutrients and organic components in lake and pond waters and/or sediments of the McMurdo and Syowa Oases, Antarctica have been discussed from a geochemical viewpoint. Chloride ion contents of lake and pond waters range from 0 17 to 251100 mg/kg Total salt contents show bimodal distributions presumably reflecting the presence and absence of outflows, respectively. Generally, the relative abundances of Na, K, Ca, Mg and SO_4 decrease with increasing Cl contents, indicating that these ionic components deposit during concentration of dissolved salts in lakes and ponds through fractional freezing and/or evaporation of waters

Although contents of nitrate in the coastal lakes and ponds of the Syowa and Vestfold Oases are generally low, those in the oxic zones of the inland lakes and ponds of the McMurdo Oasis are often high Nitrite concentrations in freshwater and saline lakes and ponds are generally low Ammonium, phosphate and/or silicate released by the degradation of settled plankton are generally highly concentrated in the anoxic bottom layers of meromictic lakes because of the paucity of circulation.

Total organic carbon or dissolved organic carbon contents in the anoxic layers of meromictic lakes are considerably high, and correlated with Cl contents. Organic matter and dissolved salts are concentrated in the bottom waters due to evaporation and/or freezing concentration of waters Long-chain *n*-alkanes and *n*-alkanoic acids ($>C_{19}$), and C_{29} sterols are often predominant components in lake and pond water and/or sediment samples in spite of the absence of vascular plants in the areas studied, and indicate that microorganisms are important sources of these compounds. As expected a series of phenolic acids relating to vascular plants are not detected in any Antarctic lake samples

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1. Introduction

Although Antarctica is mostly covered with an ice-sheet with an average of 2450 m thickness, SIMONOV (1971) reported 16 ice-free areas, so-called "oasis" in the coastal regions of the continent (Fig. 1). Many lakes and ponds are scattered in the depressions of the oases. Antarctica is extremely harsh for biological activity, and vascular plants are absent except in the Antarctic Peninsula. So, the continent can be expected to be a suitable field for the study of microbial biomarkers. Also, Antarctica is located in the farthest region from industrialized areas of the Northern Hemisphere, and is believed to be least polluted continent. Hence, Antarctica is the most favorite field for the background study of human activity.

Since the International Geophysical Year 1957–58, limnological and geochemical studies of lakes and ponds have been carried out by many scientists of the SCAR nations. These studies have shown interesting characteristics of Antarctic lakes and ponds, such as unusual temperature profile, stable and radio isotope ratios, origin and evolution of lakes, distributions and sources of major ionic components and trace metals, inorganic nutrients, and primary productivity as well as organic components for the absence of vascular plants. Also, these extensive studies are now providing many analytical data of Antarctic lakes and ponds. Here we discuss general characteristics of lakes and ponds, distributions and sources of the major ionic components and trace metals, inorganic nutrients in relation to sources and primary productivity, and organic components in lakes and ponds of the McMurdo and Syowa Oases in Antarctica based on these analytical data (*e g* , TORII *et al* , 1975, 1989; MURAYAMA, 1977; MATSUBAYA *et al* , 1979; MATSUMOTO *et al.*, 1985; MIYOSHI *et al.*, 1988).

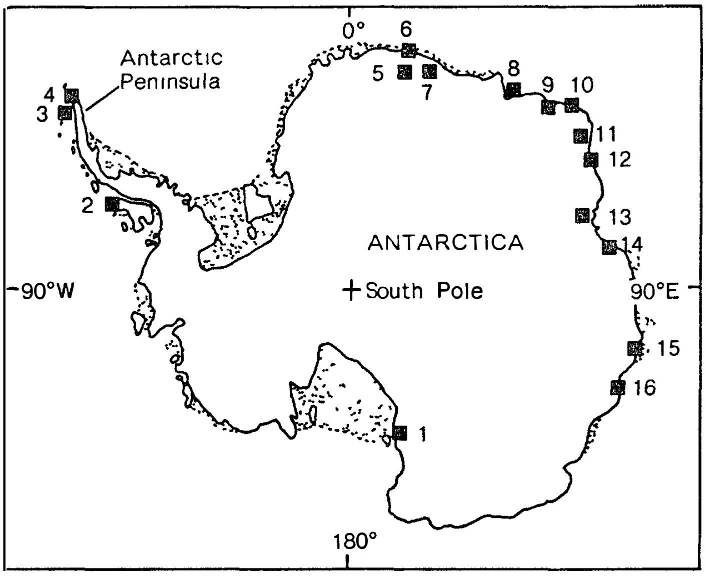

Fig 1. Antarctic ice-free areas (oasis, after SIMONOV, 1971) 1, McMurdo, 2, Alexander, 3, Bellingshausen, 4, Snow Hill, 5, Zimmerman, 6, Schirmacher, 7, Insel, 8, Syowa; 9, Molodezhnaya, 10, Thule, 11, Øygarden, 12, Stefansson, 13, Amery, 14, Vestfold Hills; 15, Bunger, 16, Greason.

Table 1. Chloride ion and total salt (Na, K, Ca, Mg, Cl and SO_4) contents in lake and pond waters of the McMurdo Oasis, Antarctica.*

Lake, Pond**	Sampling date	Sampling depth (m)	Cl (mg/kg)	Total salts (mg/kg)
Victoria Valley				
B1 Pond	21/12/'82	0.1	17080	35870
Balham Lake	08/01/'82	2.8	1350	4518
Wright Valley				
L00 Pond (ice)	21/12/'85	0.9	32.4	191.6
L01 Pond	21/12/'85	0.95	20400	47080
L02 Pond	23/12/'85	0.65	3080	23720
L1 Pond	03/01/'77	Surface	7580	16300
L4 Pond	14/12/'84	Surface	37200	67840
L7 Pond	04/01/'83	Surface	15790	33110
L8 Pond	22/12/'85	Surface	1040	2192
L9 Pond	22/12/'85	0.40	7170	14730
L11 Pond	05/01/'82	0.12	5890	11530
L12 Pond	28/12/'83	Surface	78.3	281.5
L13 Pond	22/12/'85	0.83	1510	4549
L14 Pond	05/01/'82	0.15	10400	23320
L15 Pond	04/01/'83	Surface	5020	27510
L16 Pond	24/12/'83	Surface	169.0	382.2
L17 Pond	22/12/'85	1.38	13.6	34.1
L19 Pond	24/12/'83	Surface	26700	57890
L20 Pond	27/12/'83	Surface	93.6	165.6
L22 Pond	17/12/'83	Surface	231.0	460.5
L25 Pond	22/12/'85	Puddle	20.3	62.2
L26 Pond	27/12/'85	0.10	134.0	363.1
L27 Pond	27/12/'85	0.05	941.0	2389
L28 Pond	27/12/'85	Surface	743.0	1845
L29 Pond	27/12/'85	Surface	53.6	146.2
L30 Pond	27/12/'85	0.10	8.76	21.3
L31 Pond	27/12/'85	Surface	75.5	145.1
L32 Pond	27/12/'85	0.20	15.7	58.6
L33 Pond	27/12/'85	0.40	8.94	39.4
L34 Pond	27/12/'85	0.15	11500	89160
L35 Pond	27/12/'85	0.06	14500	30300
L36 Pond	28/12/'85	0.05	1500	3272
L37 Pond	28/12/'85	0.05	8570	17320
L38 Pond	28/12/'85	0.05	1430	3163
L39 Pond	28/12/'85	0.05	5140	11530
L40 Pond	28/12/'85	0.10	103.0	370.8
L42 Pond	31/12/'85	0.05	5120	12540
L43 Pond	31/12/'85	0.05	66.7	289.3
L44 Pond	31/12/'85	0.20	10600	19580
L45 Pond	31/12/'85	0.10	1010	2238
E1 Pond	24/12/'85	0.79	19100	40380
E3 Pond	24/12/'85	No data	392.0	4557
E4 Pond	24/12/'85	0.40	10.3	34.1
E5 Pond	28/12/'85	No data	14400	30370
E7 Pond	17/12/'84	No data	48.1	104.1
E9 Pond	24/12/'85	0.73	9.3	34.5

Table 1 (continued)

Lake, Pond**	Sampling date	Sampling depth (m)	Cl (mg/kg)	Total salts (mg/kg)
E10 Pond	28/12/'85	0 10	3030	6682
SF0 Pond	31/12/'85	Surface	82 0	355
SF1 Pond	30/12/'85	Surface	62 9	259
NF1 Pond	17/12/'71	No data	16 1	58 4
NF2 Pond	17/12/'71	No data	18 5	67 3
NF3 Pond	17/12/'71	No data	36 3	146 8
NF4 Pond	17/12/'71	No data	10900	20640
NF5 Pond	17/12/'71	No data	57 2	131 6
Don Juan Pond	06/01/'65	No data	251100	391700
Lake Canopus	29/12/'71	No data	44 0	129 8
Lake Vanda	09/12/'72	64 6	74280	113500
Lake Brownworth	26/12/'71	No data	4 9	17 9
Taylor Valley				
Lake Bonney (East)	09/01/'73	32 5	161500	246600
Lake Bonney (West)	05/01/'73	29 5	78120	125900
Lake Fryxell	20/12/'72	16	3710	7504
Pearse Valley				
Lake Joyce	18/12/'76	30 4	1450	4050

* Refernces TORII *et al* (1975, 1989, unpublished results), MATSUMOTO *et al* (1985), TAKAMATSU *et al* (1988), MIYOSHI *et al* (1988).

** Locations of lakes and ponds are shown in TORII *et al* (1989) B1, L01–L45, E1–E10, SF, and NF1–NF5 ponds are unnamed ponds in the upper Victoria Valley or Wright Valley

2. General Characteristics of Lakes and Ponds

Principally, freshwater lakes and ponds have outflows, but saline lakes and ponds have not. Most saline lakes and ponds are meromictic, composed of the upper freshwater layer of mixolimnion, and the lower saline layer of monimolimnion Highly saline lakes and ponds (Cl content is greater than seawater of 19000 mg/kg) in the coastal regions of the Syowa and Vestfold Oases are generally located below sea level, while those in the inland McMurdo Oasis are situated above sea level (*e. g* , MCLEOD, 1964; MURAYAMA, 1977; TORII *et al.*, 1986). A saline pond (B1 Pond) containing Cl of 17080 mg/kg is discovered in a high elevated area (1450 m above sea level) of the upper Victoria Valley in the McMurdo Oasis (MURAYAMA *et al*, 1983). Chloride ion contents of lake and pond waters vary largely from 0 17 to 251100 mg/kg which is 13 times greater than seawater (Tables 1 and 2) The highest Cl content is found in Don Juan Pond where a new mineral, antarcticite ($CaCl_2 \cdot 6H_2O$) is present (TORII and OSSAKA, 1965).

Total salt (Na, K, Mg, Ca, Cl and SO_4) contents in 62 lakes and ponds in the McMurdo Oasis reveal bimodal distributions maximizing at about 320 (log 2.5) and 3200 mg/g (log 4 5; Fig. 2; MATSUMOTO, 1992). Also, the total salt contents in 49 lakes and ponds of the Syowa Oasis show bimodal distributions maximizing at about 100 (log 2.0) and 32000 mg/kg (log 5.5), respectively. The first freshwater lake peak presumably reflects the presence of outflows, while the second saline lake peak could be explained by the absence of outflows (MATSUMOTO, 1992). Freshwater lakes and

Table 2. Chloride ion and total salt (Na, K, Ca, Mg, Cl and SO_4) contents in lake and pond waters of the Syowa Oasis, Antarctica (data from MURAYAMA, *1977).*

Lake, Pond*	Sampling date	Sampling depth (m)	Cl (mg/kg)	Total salts (mg/kg)
Cape Hinode				
No. 1**	07/01/'72	Surface	2.0	7.6
No. 2**	07/01/'72	Surface	<0.5	21.5
No. 3**	05/01/'72	Surface	30	59.5
No. 4**	06/01/'72	Surface	43	78.4
No. 5**	06/01/'72	Surface	71	134
No. 6**	04/01/'72	Surface	10.7	98.7
No. 7**	04/01/'72	Surface	365	642.7
East Ongul Is.				
Lake Midori	23/03/'72	0.6	17.3	37.7
Lake Kamome	23/03/'72	1.0	45.3	113.2
Lake Taratine	24/03/'72	0.35	2050	3666
Mizukumi-ike**	31/01/'72	Surface	84.4	187.2
Aragane-damu**	31/01/'72	Surface	59.9	128.8
West Ongul Is.				
Yumi-ike**	14/03/'72	5.3	7.7	23.8
Ura-ike**	07/03/'72	10.5	38.0	92.9
Higasi-ike**	15/03/'72	4.5	36.0	97.9
Nisi-ike**	15/03/'72	5.5	57.0	76.4
Lake Ō-ike	18/11/'72	10.5	125	220.1
Naka-ike**	14/03/'72	4.2	341	507.9
Langhovde				
Lake Higasihamuna	25/11/'72	22.0	2.7	7.8
Lake Nisihamuna	04/10/'72	15.5	6.8	14.2
Hyoga-ike**	30/09/'72	4.5	7.7	20.0
Amanokama**	24/11/'72	2.0	6.8	21.2
Lake Yukidori	23/11/'72	6.0	10.4	29.8
Nakanotani-ike**	04/10/'72	17.0	40	75.5
Lake Kamigama	24/11/'72	2.0	23	74.8
Lake Higasiyukidori	23/11/'72	15.5	53	125.5
Lake Akebi	07/10/'72	5.0	7700	15090
Lake Nurume	07/10/'72	16.0	29000	52070
Lake Oyayubi	05/10/'72	5.0	53000	101100
Lake Zakuro	06/10/'72	4.1	130000	207400
Lake Itiziku	08/02/'73	0.2	210000	322240
Breidvagnipa				
Bouzu-ike**	15/11/'72	17.0	1.3	3.0
Tankobu-ike**	14/11/'72	13.0	2.1	4.9
Lake Hiroe	22/11/'72	8.5	3.2	8.5
Skarvsnes				
Kamino-ike**	23/10/'72	11.0	1.3	7.3
Dojou-ike**	25/10/'72	4.5	17	61.0
Namazu-ike**	25/10/'72	19.0	36	80.7
Lake Oyako	27/10/'72	7.5	400	760.0
Naga-ike**	27/10/'72	9.0	780	1351.8
Hyotan-ike**	26/10/'72	9.5	850	1468.0
Hama-ike**	21/10/'72	2.5	8600	17550
Kobati-ike**	26/10/'72	8.5	15000	24377

Table 2 (continued)

Lake, Pond*	Sampling date	Sampling depth (m)	Cl (mg/kg)	Total salts (mg/kg)
Lake Suribati	11/11/'72	30 0	130000	219300
Lake Hunazoko	27/10/'72	8 5	140000	224000
Skallen				
Kabuto-ike**	07/11/'72	5 5	23	47 9
X-ike**	06/11/'72	7 5	26	69 6
Lake Dairi	08/11/'72	0 8	7 4	85 2
6-ban-ike**	08/11/'72	2 0	48	88 7
Lake Skallen Ōike	07/11/'72	8 5	86	165 3

* Locations of lakes and ponds are shown in MURAYAMA (1977).

** Tentative name

ponds, and saline lakes and ponds in the McMurdo and Syowa Oases are 42 and 69%, and 58 and 31%, respectively Sixteen and 12% of the lakes and ponds in the McMurdo and Syowa Oases contain salts greater than seawater, respectively. Chloride ion distributions are similar to the total salts (Fig. 2). The correlation coefficient between

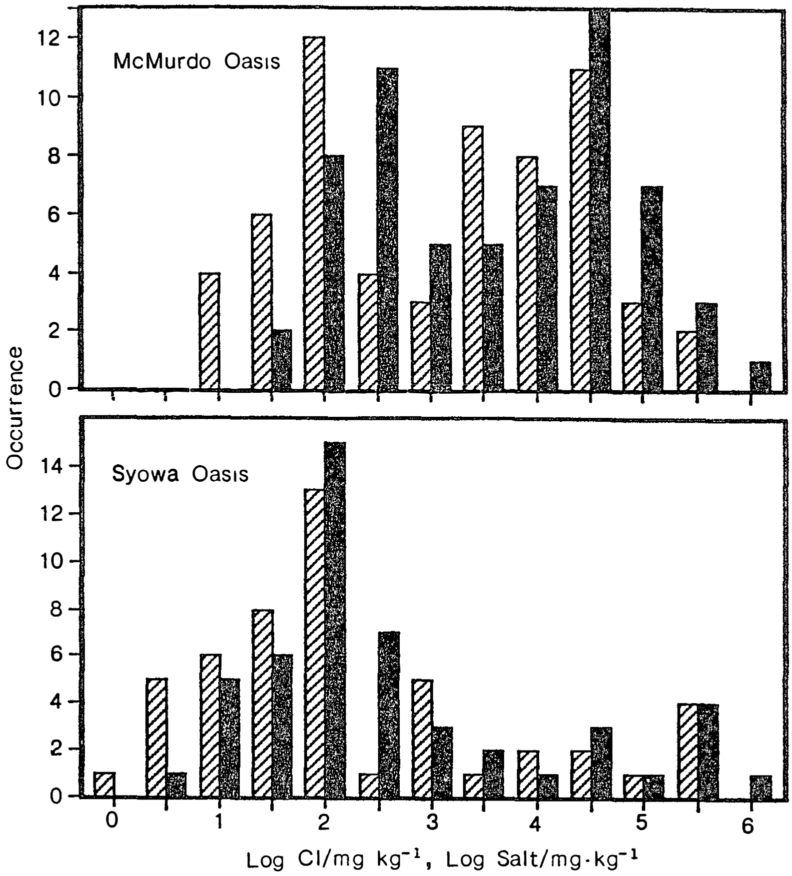

Fig 2 Distributions of total salts (Na, K, Ca, Mg, Cl and SO$_4$, black bar) and chloride ion (oblique lines bar) contents in lake and pond waters of the McMurdo and Syowa Oases. The highest chloride ion content of the bottom water was used for the estimation of each lake or pond

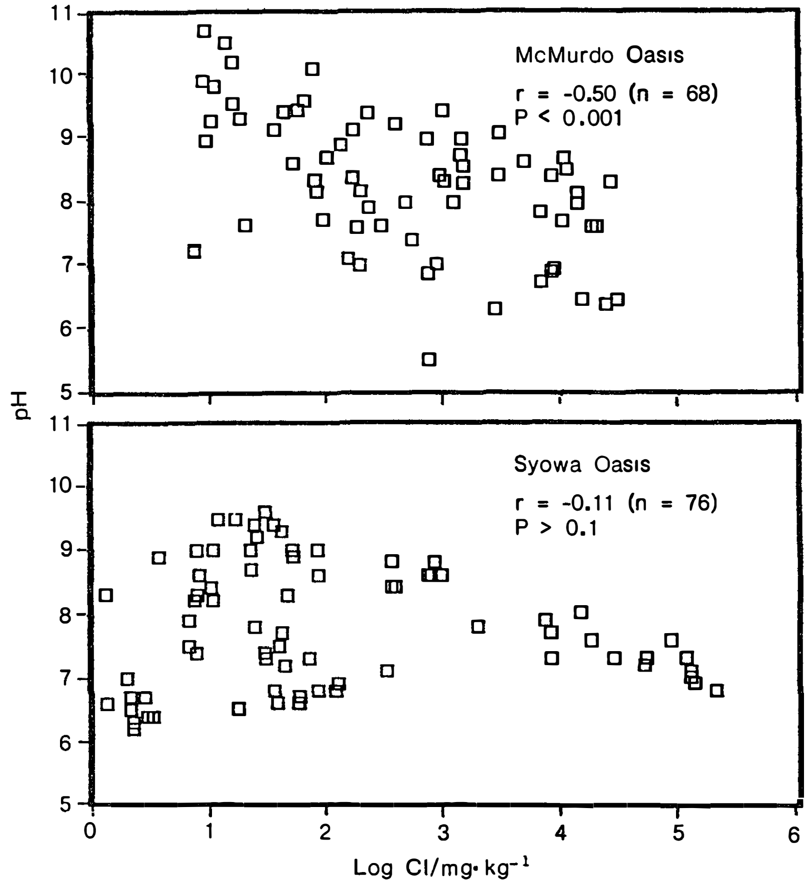

Fig 3 Distributions of pH in lake and pond waters of the McMurdo and Syowa Oases. Anoxic bottom water samples of Lakes Vanda, Fryxell and Joyce in the McMurdo Oasis were excluded.

the Cl and total salt contents in the lakes and ponds of the McMurdo and Syowa Oases is calculated to be +0.99 ($n=111$)

In the McMurdo Oasis, pH values ranging from 5.5 to 10.8, with an average of 8.3 are generally considerably high (Fig. 3). Generally, pH values decrease with increasing Cl contents, with a correlation coefficient of −0.50 ($p<0.001$ by t-test, $n=68$) These results are probably attributed to the intense photosynthetic activity under continuous sunlight in the austral summer. Photosynthetic activity consumes dissolved carbonate and thus causes high pH values in ponds of low chloride ion contents where buffer capacity is small (MATSUMOTO, 1992) However, no clear relationships between pH and Cl contents were observed in lakes and ponds of the Syowa Oasis ($r=-0.069, p>0.1$, $n=75$), although pH values are generally high ranging from 6 2 to 9.6 with an average of 7 8 (Fig. 3). These results are probably due to the absence of ice-cover in lakes and ponds of the Syowa Oasis during the austral summer. Thus, carbon dioxide may be easily supplied from atmosphere, and compensates the pH.

Dissolved oxygen (DO) contents except for the anoxic layers of meromictic lakes (Vanda, Bonney, Fryxell and Joyce) in the McMurdo Oasis vary largely ranging from 5.5 to 35.0 ml/l, with an average of 15.1 ml/l, which is much higher than satura-

Table 3 Concentrations and enrichment factors (EF_M) of the major ionic components for lake and pond waters in the McMurdo and Syowa Oases, Antarctica**.*

	Number of data	Concentration (mg/kg)		EF_M	
		Range	Average	Range	Average
McMurdo Oasis					
Na	125	0 051–69700	4560	0 012–10 9	1 25
K	93	0 024–2740	212	0 033–18 2	2 78
Mg	123	0 017–27270	1950	0 098–19 7	3 01
Ca	126	0 031–137100	2830	0 34–84 3	12 2
Cl	126	0 170–251100	14900	—	—
SO_4	123	0 00–13100	1070	0 00–47 5	4 80
Syowa Oasis					
Na	75	0 40–69000	7090	0 10–11 2	1 33
K	75	0 10–2900	267	0 24–480	9 45
Mg	75	0 20–48000	1480	0 82–10 0	2 56
Ca	75	0 40–2500	214	0 05–626	15 9
Cl	75	0 50–210000	15400	—	—
SO_4	75	0 60–15000	923	0 15–109	3 9

* $EF_M=[(M/Cl)_{sample}/(M/Cl)_{seawater}]$ M Cation or anion

** References Torii *et al* (1975, 1989, unpublished results), Murayama (1977), Takamatsu *et al* (1988), Miyoshi *et al* (1988)

tion. Wharton *et al.* (1987) suggests that the super-saturation of DO and N_2 results from the exclusion of air during freezing of aerated meltstream water at the bottom of the ice cover. Also, high DO contents may be responsible for the DO evolution by intense photosynthetic activity under continuous sunlight in the austral summer (Matsumoto, 1992) In contrast, DO contents in saline lakes of the Syowa Oasis are generally not super-saturated (*e g*, Fukui *et al*, 1985). It is consistent with the absence of ice-cover in the austral summer

3. Major Ionic Components and Trace Metals

The major ionic components (Na, K, Mg, Ca, Cl and SO_4) in lake and pond waters of Antarctic oases are studied by many researchers. Also, some workers report trace metals in these water bodies (*e. g* , Boswell *et al.*, 1967; Masuda *et al.*, 1982; Green *et al*, 1989) The contents of Na, K, Ca, Mg and SO_4 vary largely among the lakes and ponds as well as depth in both the McMurdo and Syowa Oases (Table 3; Torii *et al*, 1975, 1989; Hirabayashi and Ossaka, 1977; Murayama, 1977; Matsubaya *et al*, 1979; Miyoshi *et al*, 1988) Generally, the compositions of the major ionic components in the coastal and inland freshwater lakes and ponds are similar to those in local snow and glacial meltwaters, while those in highly saline lakes and ponds of the coastal regions are similar to those in seawater (*e. g* , McLeod, 1964; Hirabayashi and Ossaka, 1977; Murayama, 1977; Watanuki *et al*, 1977; Torii and Yamagata, 1981). In contrast, the major cation compositions in the inland saline lakes and ponds of the McMurdo Oasis vary markedly among the lakes and ponds (Torii *et al*, 1989; Torii and Yamagata, 1981) For instance, equivalent

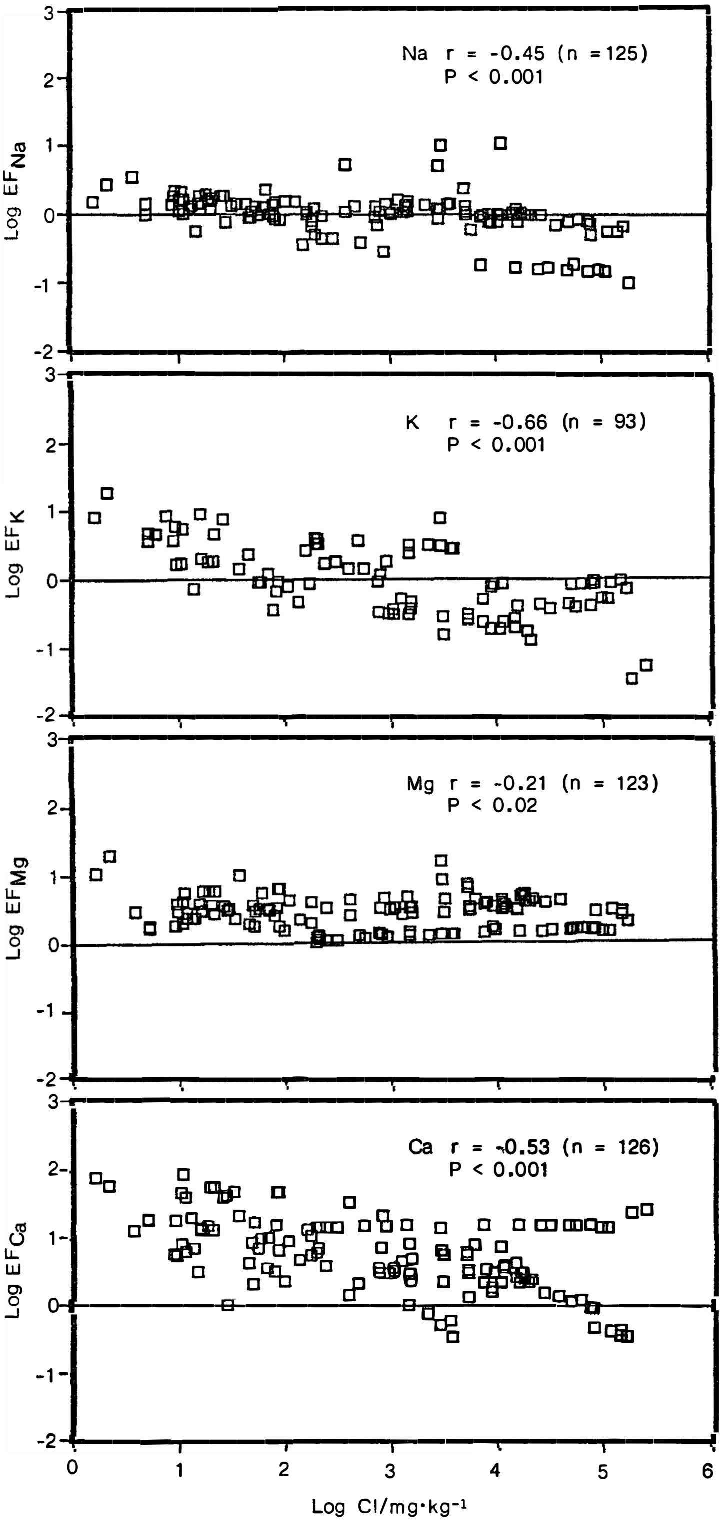

Fig. 4. *Relationships between enrichment factors* (EF_M)* *for cations and chloride ion contents in lake and pond waters of the McMurdo Oasis.* $*EF_M=[(M/Cl)_{sample}/(M/Cl)_{seawater}]$. *M = Cation, r, Correlation coefficient.*

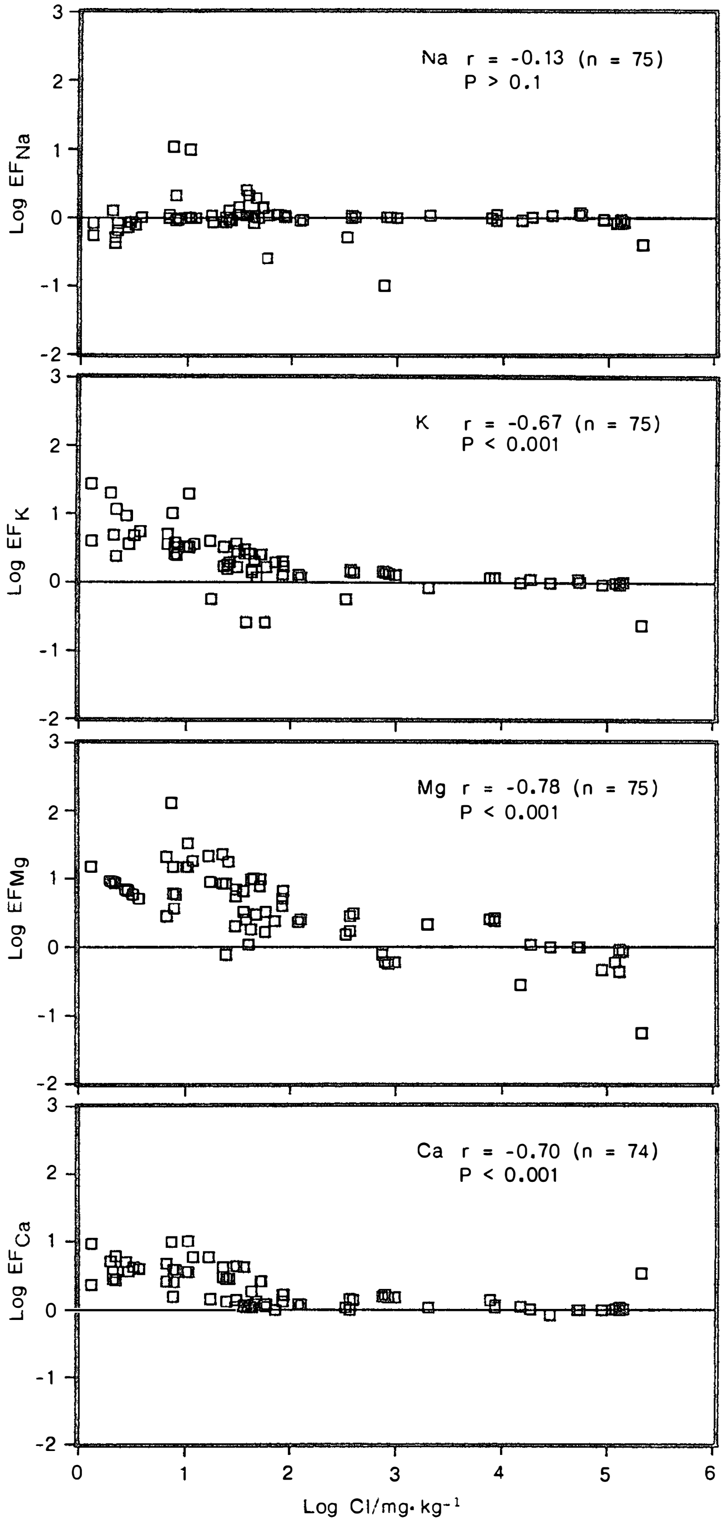

Fig 5 Relationships between enrichment factors (EF_M)* *for cations and chloride ions in lake and pond waters of the Syowa Oasis* *$EF_M = [(M/Cl)_{sample}/(M/Cl)_{seawater}]$ M= *Cation, r, Correlation coefficient*

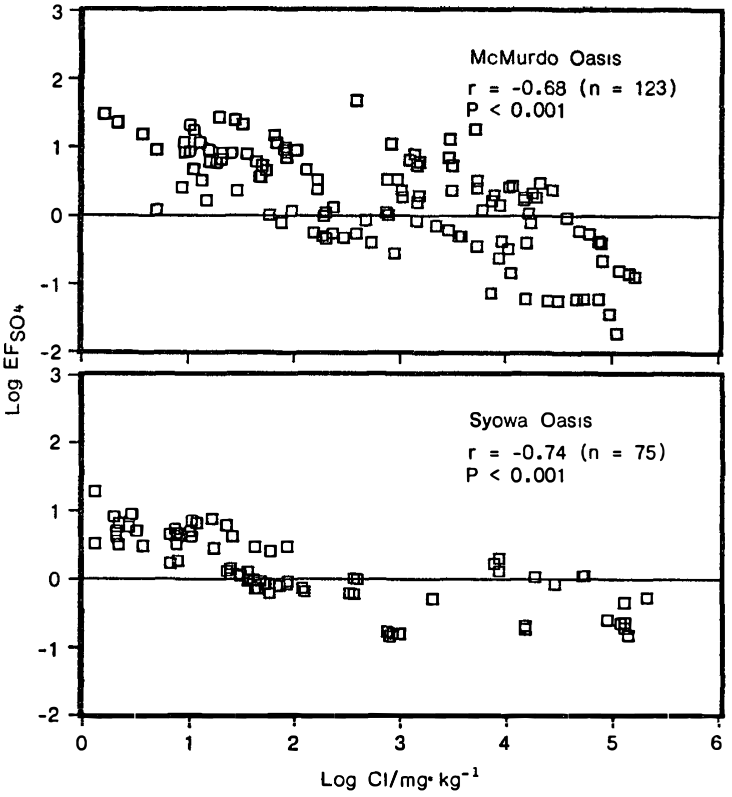

Fig. 6. *Relationships between enrichment factors (EF_{SO_4})* for sulfate ions and chloride ion contents in lake and pond waters of the McMurdo and Syowa Oases. *$EF_M = [(M/Cl)_{sample}/(M/Cl)_{seawater}]$. $M = SO_4$, r, Correlation coefficient.*

cation percentage of Ca for Don Juan Pond is 97%, and for Lake Vanda is 58%. That of Mg for the east lobe of Lake Bonney is about 40% (Torii and Yamagata, 1981).

Enrichment factor (EF_M) defined as follows is useful for the characterization of chemical components, such as the major ionic components in natural water systems:

$$EF_M = [(M/Cl)_{sample}/(M/Cl)_{seawater}]$$

where, M is cation or anion.

The EF_M values change markedly among lake and pond water samples. That is, in the McMurdo Oasis, EF_{Na}, EF_K, EF_{Mg}, EF_{Ca} and EF_{SO_4} range from 0.012 to 10.9 with an average of 1.25, 0.033 to 18.2 with an average of 2.78, 0.098 to 19.7 with an average of 3.01, 0.34 to 84.3 with an average of 12.2, and 0.00 to 47.5 with an average of 12.2, respectively (Table 3). Interestingly, these values in lakes and ponds of the Syowa Oasis are generally similar to those in the McMurdo Oasis. These EF_M values reveal that the former components of the ion pairs of K>Na, Ca>Mg, SO_4>Cl are more enriched than the latter, and are consistent with those found in Ross Island and Ongul Islands (Yamagata *et al.*, 1967). Although generally the EF_{Na} values are close to unity, and are similar to that in seawater, K, Mg, Ca and SO_4 are much abundant in these water bodies, as evidenced by the high EF_M values. These results suggest that similar processes of the distributions of the major ionic components have occurred in both the McMurdo and Syowa Oases (Figs. 4–6). However, these salt distributions are largely deviated from Gibbs plot (Gibbs, 1970) of world water systems (Ma-

TSUMOTO *et al.*, unpublished results).

There are a number of hypothesis on the salt sources in lakes and ponds of the inland McMurdo Oasis, *i e.*, atmospheric salts, glacial and snow meltwaters, rock weathering, groundwater, hydrothermal activity, and relict seawater (*e.g.*, TORII and YAMAGATA, 1981) However, no one has fully discussed on the salt sources in lakes and ponds of the Syowa Oasis, except for highly saline lakes.

In the coastal regions, dissolved salts in the highly saline lakes, such as Deep Lake of the Vestfold Oasis (*e. g.*, MCLEOD, 1964) and Lakes Hunazoko, Nurume and Suribati of the Syowa Oasis (*e. g.*, WATANUKI *et al.*, 1977), are attributed to relict seawater because of the similarity of the major ionic components. In contrast, for the formation of a saline pond (Ll Pond; Na content=4300 mg/kg) in the Labyrinth of the upper Wright Valley of the McMurdo Oasis, TORII *et al.* (1979) reported that the age of the pond is calculated to be 56000 years by salts in snow only. Also, MASUDA *et al.* (1982) found that trace metals (Al, Co, Cr, Cs, Eu, Fe, Hf, Mn, Ni, Rb, Sb, Sr, Th and Zn) in certain lakes of the McMurdo Oasis are attributed to atmospheric salts. Thus, atmospheric salts including sea salts are important sources of dissolved salts in lakes and ponds of the McMurdo Oasis (*e. g.*, TORII and YAMAGATA, 1981; TORII *et al.*, 1989). Especially, the abundances of K and SO_4 may be largely attributed to atmospheric salts. However, the predominance of Ca and Mg in lakes and ponds cannot be explained by atmospheric salts only.

Calcium salts are distributed in all rock types of the McMurdo Oasis. Also, Mg can be attributed to chemical weathering of dolerite and volcanic rocks and soils (CLARIDGE and CAMPBELL, 1977; KEYS and WILLIAMS, 1981; CAMPBELL and CLARIDGE, 1987). The abundance of Ca and Mg in lakes and ponds of the McMurdo Oasis can be explained by these contributions Also, GREEN *et al* (1989) reported that trace metals (Cd, Co, Cu, Fe, Mn and Ni) in meltstreams in the Lake Fryxell basin have originated from chemical weathering of local rocks and soils.

However, extremely high abundance of $CaCl_2$ in Don Juan Pond and Lake Vanda is difficult to explain by these salt sources YOSHIOKA *et al.* (1970) hypothesized that the calcium chloride-type water is formed through an active water-rock interaction in the underground of the Matsushiro area in Japan. TAKAMATSU *et al.* (1988) reported that the EF_{Li} values in the water bodies of Don Juan Pond (166) and Lake Vanda (47) are extremely high, and suggested the occurrence of hydrothermal activity. Geochemical studies of secondary minerals (NISHIYAMA, 1975) and mercury (KOGA, 1977) support the presence of hydrothermal activity in the past in the Don Juan and Vanda basins. Hence, $CaCl_2$ in the water bodies of Don Juan Pond and Lake Vanda are probably supplied by hydrothermal activity in the past through groundwater systems (*e. g.*, TOMIYAMA *et al.*, 1983).

The McMurdo Oasis is very dry and evaporation rates of water exceed precipitation. Thus, water containing salts by chemical weathering of rocks and soils should be moved from subsurface (groundwater) to the ground surface through capillary siphoning in the austral summer (MATSUMOTO, 1992). This process is probably most important for the formation of various evaporites found in the oasis, in addition to atmospheric salts. These salts may be occasionally washed by snow and glacial meltwaters, and can be responsible for the dissolved salts in lakes and ponds. Highly saline lakes in the Syowa Oasis are distributed below sea level, indicating that the dry climatic conditions are prevailed in recent years. Therefore, similar processes controlling salt distributions are probably occurring in lakes and ponds of the Syowa Oasis.

Generally, the EF_{Na}, EF_{K}, EF_{Mg}, EF_{Ca} and EF_{SO_4} values of lake and pond waters of the McMurdo and Syowa Oases decrease with increasing Cl contents (Figs. 4–6). These data reveal that Na, K, Mg, Ca and SO_4 are removed from water bodies during the concentration of dissolved salts. According to THOMPSON and NELSON (1956), when seawater is concentrated under frigid conditions, calcium carbonate crystallize first, followed by mirabillite at —8.2°C, halite at —22.9°C, a mixture of magnesium chloride dodecahydrate and potassium chloride at —36°C, calcium chloride only remains in the final solution at —54°C. TORII and his co-workers explained salt distributions in lakes and ponds of the McMurdo Oasis based on this fractional freezing (TORII and YAMAGATA, 1981; TORII *et al.*, 1989) These results support that fractional freezing and/or evaporation of waters occurred in lakes and ponds of the McMurdo and Syowa Oases. However, the Na/Ca and Mg/Ca ratios in the lakes and ponds of the McMurdo Oasis tend to increase with increasing Cl contents, while the K/Ca ratios show no clear tendency (MATSUMOTO, 1992). Hence, Ca may be deposited as carbonate salts, but further fractional freezing of Ca may have not taken place in these Antarctic lake and pond water systems.

Consequently, a large variety of distributions of the major ionic components and trace metals in Antarctic lakes and ponds are explained by the contributions of common sources of atmospheric salts, and local sources of chemical weathering of rocks and soils, relict seawater and hydrothermal activity. Furthermore, relative abundances of Na, K, Mg, Ca and SO_4 decrease with the concentration of dissolved salts through fractional freezing and/or evaporation.

4. Nutrients

Inorganic nutrients (silicate, phosphate, nitrate, nitrite and ammonium) are important for the estimation of primary production of lakes and ponds. TORII *et al.* (1988) summarized distributions and significance of inorganic nutrients in lake and pond waters of the McMurdo, Syowa and Vestfold Oases. The concentrations of nutrients change largely among the lakes and ponds, and with depth as well as investigators (*e g.*, FORTNER *et al.*, 1976; TORII *et al.*, 1988). Ranges of nutrient concentrations in lakes and ponds of the McMurdo and Syowa Oases are summarized in Table 4 (TORII *et al.*, 1975; FORTNER *et al.*, 1976; NAKAYA *et al.*, 1977; VINCENT *et al.*, 1981; MATSUMOTO *et al*, 1982a; MURAYAMA *et al.*, 1984; FUKUI *et al.*, 1985). Silicate concentrations in both freshwater and saline meromictic lakes and ponds are generally higher than those in Antarctic and Subantarctic Oceans (EL-SAYED, 1970). Especially, silicate concentrations in the bottom anoxic layers of meromictic lakes are extremely high (*e. g.*, TORII *et al*, 1975, 1988). Nitrite concentrations in freshwater and saline meromictic lakes are generally low, but nitrate concentrations in the oxic layers of the saline lakes in the McMurdo Oasis are often high. Unusually, high nitrate concentrations are observed in unnamed ponds in the Labyrinth and North

Table 4 Ranges of nutrient concentrations in lake and pond waters of the McMurdo and Syowa Oases, Antarctica, and Antarctic and Subantarctic Oceans (μg-at Si, P or N/l)**.*

	Freshwater lake	Saline lake
McMurdo Oasis		
SiO_2-Si	14–73.5	14–1200
PO_4-P	0.17–0.90	0.0–190
NO_3-N	0–535	0.8–24800
NO_2-N	0–15.0	0–44.6
NH_4-N	0–16	0–2200
Syowa Oasis		
SiO_2-Si	12–108	4–426
PO_4-P	0.01–0.6	0.04–156
NO_3-N	0.00–1.4	0.00–4.8
NO_2-N	0.0–0.2	0.0–0.5
NH_4-N	0.0–1.3	0–2420

* Antarctic and Subantarctic Oceans (EL-SAYED, 1970). SiO_2-Si, 21.5, PO_4-P, 1.16, NO_3-N, 12.3, NO_2-N, 0.19. NH_4-N, No data.

** References. TORII *et al.* (1975), FORTNER *et al.* (1976), NAKAYA *et al* (1977); VINCENT *et al* (1981), MATSUMOTO *et al* (1982a), MURAYAMA *et al.* (1984), FUKUI *et al* (1985); TORII *et al* (1988), MATSUMOTO (1992).

Fork up to 24.8 mg at-N/l of the McMurdo Oasis (TORII *et al.*, 1975; MATSUMOTO, 1992). Ammonium and phosphate concentrations in the oxic layers of the meromictic lakes are low, but are considerably high in the anoxic bottom layers (*e.g.*, FUKUI *et al.*, 1985; VINCENT *et al.*, 1981; TORII *et al.*, 1988).

Meltstreams in the Wright and Taylor Valleys of the McMurdo Oasis contain appreciable amounts of silicate, phosphate, nitrate and ammonium, with some exception. Silicate and phosphate can be mainly supplied by chemical weathering of soils and rocks in the catchment areas (WEAND *et al.*, 1977). PARKER *et al.* (1978) suggested that auroral activity is the main sources of nitrate and ammonium in ice core and fresh snow samples at the South Pole. WADA *et al* (1981, 1984) found that δ^{15}N values of nitrate in soils from the McMurdo Dry Valleys are extremely low as compared with other areas in the world, supporting that nitrate is derived from atmospheric fallout, including auroral activity. However, the paucity of inorganic nitrogen in the lakes and ponds of the Syowa Oasis is not clear.

For the concentrations of silicate, phosphate and ammonium in the anoxic bottom layers of meromictic lakes can be explained as follows: Nutrients derived from meltstreams are first used by primary producers, including diatoms, followed by some dead plankton precipitating towards the lake bottom, and then undergo microbial degradation. Thus, released nutrients accumulate in the stagnant bottom layers of meromictic lakes over a long period of time. Denitrification, deposition as well as the fixation by benthic organisms are important processes for the losses of inorganic nutrients (*e.g.*, TORII *et al.*, 1988; GREEN *et al.*, 1989; MATSUMOTO, 1992).

The addition of phosphate or nitrate frequently stimulates carbon fixation. Hence, phosphorous and often nitrogen nutrients are limiting primary productivity in most Antarctic lakes and ponds (*e.g.*, GOLDMAN *et al*, 1967; HOEHN *et al*, 1977;

WEAND *et al*, 1977; AKIYAMA, 1985). In the lakes of the McMurdo Oasis, SIMMONS *et al.* (1979) concluded based on the ^{33}P uptake experiments that the degree of phosphorus limitation appears to be as follows: Lake Vanda=Lake Joyce>Lake Hoare> Lake Bonney (west lobe)>Lake Fryxell>Lake Miers. Also, VINCENT (1981) reported that nutrient supply, rather than *in situ* light or temperature, determines primary productivity in lakes of the McMurdo Oasis. The paucity of nutrient cycling leads to oligotrophic status of Antarctic meromictic lakes (PARKER and SIMMONS, 1985; TORII *et al.*, 1988).

5. Organic Carbon

Total organic carbon (TOC) and dissolved organic carbon (DOC) contents in lake and pond waters change largely among the lakes and ponds as well as with depth, as in the case of other chemical components. Generally, the high TOC and DOC contents are found in the anoxic layers of meromictic lakes. Extremely high values are found in the bottom waters of Lakes Bonney (28.0 mg C/l), Fryxell (29.1 mg C/l) and Vanda (63.8 mg C/l) of the McMurdo Oasis (*e. g.*, PARKER *et al.*, 1974, 1977; MATSUMOTO *et al*, 1979), Lakes Nurume (30 mg C/l), Hunazoko (186 mg C/l) and Suribati (130 mg C/l) of the Syowa Oasis (TOMINAGA and FUKUI, 1981; FUKUI *et al.*, 1985), and Ace (>60 mg C/l) and Deep (50 mg C/l) Lakes of the Vestfold Oasis (BURTON, 1981).

TOMINAGA and FUKUI (1981) found a good correlation between Cl and DOC contents in the lakes of the Syowa Oasis. In the McMurdo Oasis, however, no good correlation between them was found for whole water samples, but a relatively good correlation was obtained for the Labyrinth ponds and each lake. These results reveal the occurrence of similar concentration processes between Cl and TOC. The slopes of regression lines between Cl and TOC decrease from Lake Fryxell>Labyrinth ponds>Lake Vanda>Lake Bonney, indicating that the concentration rates of organic matter decrease with this order. These results probably reflect the amounts of primary production (MATSUMOTO, 1992).

The sources and concentration of organic matter in lake and pond waters are summarized as follows: Organic matter and salts supplied from snow and glacial meltwaters are concentrated by freezing and/or evaporation of waters. Besides, *in situ* photosynthetic activity produces organic matter. At the same time, microbial degradation of labile organic matter has taken place in lakes and ponds. For the meromictic lakes, sinking dead plankton is degraded by microbial activity. Hence, refractory organic matter is concentrated in the anoxic bottom layers, along with dissolved salts during a long period of time (MATSUMOTO, 1992).

6. Organic Components

Various organic components, including hydrocarbons, fatty acids, hydroxy acids, sterols and phenolic acids are distributed in Antarctic lake waters and sediments (*e. g.*, MATSUMOTO *et al.*, 1979; VOLKMAN *et al.*, 1986; MATSUMOTO, 1989). These organic groups are widely distributed in biological and environmental samples of the

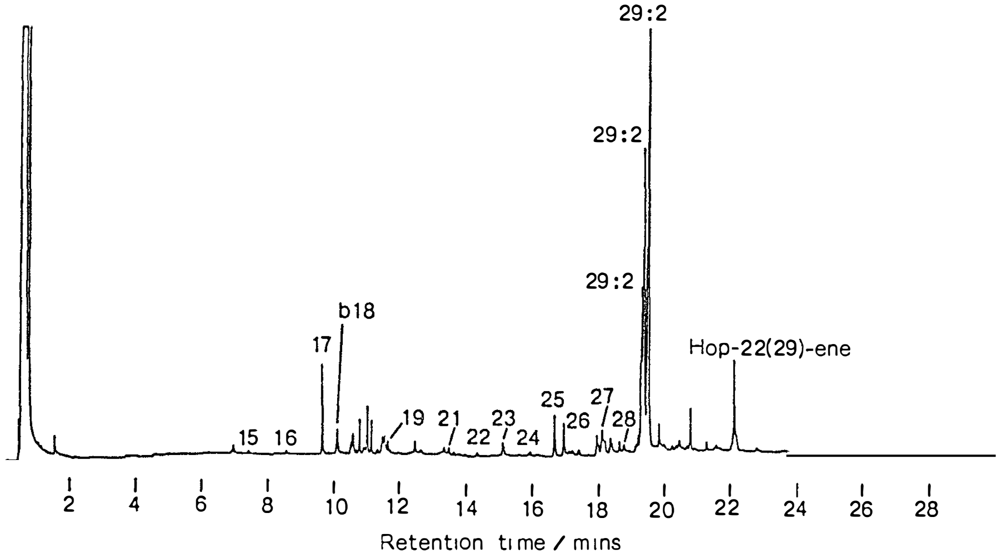

Fig. 7. Capillary gas chromatogram of the hydrocarbon fraction from a sediment sample of Lake Fryxell in the McMurdo Oasis, Antarctica Arabic figures on the peaks denote carbon chain length of n-alkanes, except for b18 and 29 2 b=Branched, 29 2=Carbon chain length number of double bonds

world The concentrations of these organic components in Antarctic lake waters and sediments are generally low in spite of the high concentrations of TOC or DOC. It is explained by the fact that TOC components are composed mainly of humic substances, as discussed above (MATSUMOTO, 1989)

Short-chain *n*-alkanes and *n*-alkenes are mainly distributed in algae and cyanobacteria, whereas long-chain *n*-alkanes ($>C_{19}$) with a predominance of odd-carbon numbers are distributed in the waxes of vascular plants, and are generally accepted as a biomarker of vascular plants Although short-chain *n*-alkanes and *n*-alkenes are the major hydrocarbons in Antarctic cyanobacterial mats, unusually a suite of long-chain *n*-alkanes are detected with a predominance of odd-carbon numbers in the sediment sample of Lake Vanda of the McMurdo Oasis (MATSUMOTO *et al*, 1987), and Lakes Ō-ike and Nurume of the Syowa Oasis (MATSUMOTO *et al.*, 1981)

It is unusual that long-chain *n*-alkenes are the major hydrocarbons in lake sediments of Lakes Bonney, Fryxell and Joyce in the McMurdo Oasis (MATSUMOTO *et al.*, 1979, 1989) and Ace Lake of the Vestfold Oasis (VOLKMAN *et al*, 1986). For instance, capillary gas chromatogram of the hydrocarbon fraction obtained from a sediment sample of Lake Fryxell is shown in Fig 7 The major hydrocarbons are *n*-$C_{29\ 2}$ alkenes After hydrogenation these peaks gave *n*-C_{29} alkane (MATSUMOTO *et al*, 1989) Thus these alkene peaks are due to *cis*- and *trans*-isomers These alkenes may be derived from cyanobacteria and microalgae (MATSUMOTO *et al.*, 1979; VOLKMAN *et al*, 1986; MATSUMOTO, 1989)

Of special interest is the occurrence of 2, 6-dimethylhexadecane and 2, 6, 10-trimethylhexadecane (tentative identification) in a sediment sample of Lake Vanda (MATSUMOTO *et al.*, 1987) These compounds have not yet been found in any environmental samples other than the McMurdo Oasis. Certain unknown microor-

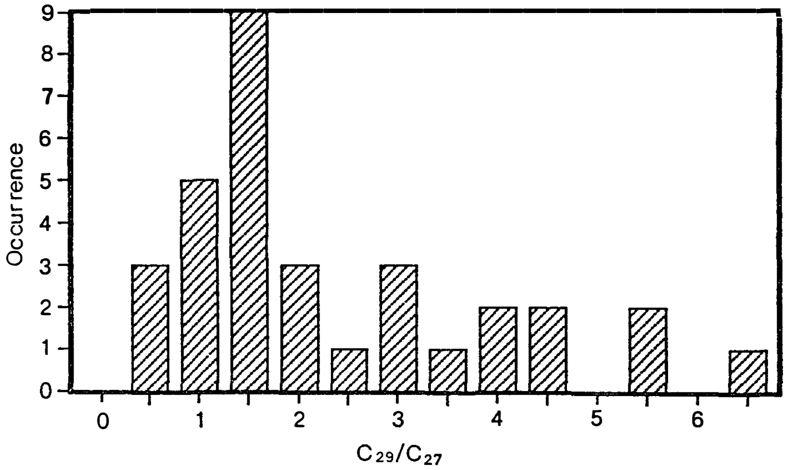

Fig. 8 C_{29}*/C_{27}** *sterol ratios for Antarctic lake and pond samples *24-Ethylcholest-5-en-3β-ol, 24-ethylcholesta-5, 22-dien-3β-ol and 24-ethyl-5α-cholestan-3β-ol **Cholest-5-en-3β-ol and 5α-cholestan-3β-ol Data from* MATSUMOTO *(1989).*

ganisms in the lake bottom may produce these compounds.

Short-chain *n*-alkanoic acids are widely distributed in every organism except for Archaebacteria, while long-chain *n*-alkanoic acids are abundant in the waxes of vascular plants, and are believed to be a biomarker of vascular plants. Although short-chain *n*-alkanoic and *n*-alkenoic acids are generally major fatty acids in water and sediment samples of Antarctic lakes and ponds, a suite of long-chain *n*-alkanoic acids are abundant in sediment samples from Lakes Joyce and Vanda in the McMurdo Oasis, Lakes Ō-ike, Itiziku and Skallen Ōike of the Syowa Oasis (*e. g.*, MATSUMOTO *et al.*, 1979, 1981; MATSUMOTO, 1989), and Ace Lake (VOLKMAN *et al.*, 1988). Also, in the Lake Vanda sediment, uncommonly long-chain *n*-alkenoic acids are predominant fatty acids which are not detected in any other environmental samples in the world (MATSUMOTO *et al.*, 1987). Their source organisms are not yet clear.

Various hydroxy acids, 2-, 3-, (ω-1), -and dihydroxy acids are found in lake waters and/or sediments of the McMurdo Oasis. Although short-chain 3-hydroxy acids derived from microorganisms, including microalgae and cyanobacteria, are generally major components in water and sediment samples of Antarctic lakes and ponds, interestingly, long-chain 3-hydroxy acids, *e. g.* *n*-C_{24} and *n*-C_{26}, are predominant in the Lake Vanda sediment (MATSUMOTO *et al.*, 1988, 1989). Again, their source organisms are not yet clear.

In natural environment, C_{27} sterols, such as cholest-5-en-3β-ol are generally derived from phyto- and zooplankton, while C_{28} sterols (24-methylcholest-5-en-3β-ol and 24-methylcholesta-5, 22-dien-3β-ol) are abundant in certain diatoms. C_{29} sterols (24-ethylcholest-5-en-3β-ol and 24-ethylcholesta-5, 22-dien-3β-ol) are predominant in vascular plants, and generally accepted as their biomarker. Unexpectedly, C_{29} sterols are frequently abundant in Antarctic samples, and thus the C_{29}/C_{27} sterol ratios are much higher than unity, ranging from 0.33 to 7.2 with an average of 2.2 (Fig. 8; MATSUMOTO, 1989). These sterols are mainly derived from cyanobacteria and green algae (*e. g.*, MATSUMOTO *et al.*, 1982b; MATSUMOTO, 1989). On the contrary, these results strongly suggest that cyanobacteria and microalgae are important sources of C_{29} sterols in environmental samples from the mid and lower latitudes.

As expected, only *p*-hydroxybenzoic acid originated from cyanobacteria and microorganisms is the prominent phenolic acid in Antarctic samples, although lake and river water and sediment samples from Japan contain a series of phenolic acids, *i e.* *p*-hydroxybenzoic, vanillic, syringic, *p*-coumaric and ferulic acids (MATSUMOTO, 1989) Thus, *p*-coumaric acid/*p*-hydroxybenzoic acid ratios (PCA/PHA) demonstrate the relative contribution of vascular plants for the environmental samples For instance, the water and sediment samples of Japan show a wide range of variation, whereas those in the Antarctic samples are all zero (MATSUMOTO, 1992). Thus, the PCA/PHA ratios must be a good indicator of the contribution of vascular plants in environmental studies.

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