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3.3 The Chemical Characteristics of Antarctic Lakes and Ponds, with Special Emphasis on the Distribution of Nutrients

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Summary: This paper reviews Japanese limnological studies mainly in the McMurdo and Syowa oases, with special emphasis on the nutrient distribution. Generally, the chemical composition of the major ionic components in the coastal lakes and ponds is similar to that in seawater, while that in inland Dry Valley lakes and ponds of the McMurdo Oasis is abundant in calcium, magnesium and sulfate ions. The former can be explained by the direct influences of sea salts, while the latter is mainly attributable to the accumulation of atmospheric salts.
Most saline lakes are meromictic. Dissolved oxygen concentrations in the upper layers are saturated or supersaturated, but the bottom layers are anoxic and often hydrogen sulfide occurs. The concentrations of nutrients vary largely not only among the lakes but also with depth. Silicate-Si, which is generally abundant in all freshwater and saline lakes, may be due to erosions of soils and rocks. Nitrite-N concentrations in both freshwater and saline lakes are generally low. Nitrate-N concentrations in the oxic layers of the inland saline lakes in the McMurdo Oasis are often high, but not high in the coastal saline lakes of the Syowa and Vestfold oases. The abundance of phosphate-P and ammonium-N in the bottom stagnant layers of saline lakes can be explained by the accumulation of microbially released nutrients due to the decomposition of organic substances. Nutrients are supplied mainly from meltstreams in the catchment areas, and are proved to play an important role in primary production.

Zusammenfassung: Eine Übersicht über japanische limnologische Studien in den eisfreien Gebieten der McMurdo Dry Valleys und der Syowa-Oase im Hinblick auf die Nährstoffverteilung wird dargestellt. Im allgemeinen ähnelt die Ionenzusammensetzung in küstennahen Stehgewässern der des Seewassers, während Kalzium, Magnesium und Sulfationen in dne Gewässern des Binnenlandes angereichert sind. Ersteres beruht auf dem unmittelbaren Einfluß des Ozeans, letzteres auf Akkumulation von Salz durch Verdunstung.
Die meisten Seen sind meromiktisch. In oberflächennahen Schichten liegt die Sauerstoffkonzentration im Sättigungsbereich oder darüber, während in bodennahen Schichten Sauerstoffarmut herrscht und Schwefelwasserstoff vorkommt. Nährstoffgehalte variieren nicht nur in den einzelnen Seen sondern auch mit der Seetiefe. Silikat-Si ist in allen Seen reichlich vorhanden und stammt von der Erosion von Gestein und Böden. Nitrat-N kommt allgemein nur in niedrigen Konzentrationen vor. Nitrat-N-Konzentrationen sind in den sauerstoffhaltigen Schichten der Seen in den McMurdo Dry Valleys hoch, doch nicht in den Salzseen bei Syowa und in den Vestfold Hills. Die großen Mengen von Phosphat-P und Ammonium-N in den ruhigen tiefen Schichten von Salzseen sind wohl auf die Anhäufung mikrobiell erzeugter Substanz und die Ablagerung organischen Material zurückzuführen. Nährstoffe weden vor allem von Schmelzwasserströmen des Einzugsbereichs der Gewässer eingetragen und spielen eine bedeutende Rolle für die Primärproduktion.

1. INTRODUCTION

There are a large number of ice-free areas, so-called oases, in and around the coastal regions of Antarctica (Fig. 1). Many lakes and ponds, fed by local snow and glacial meltwaters, are located in depressions in ice-free regions or in drainage basins enclosed by glaciers. Since the International Geophysical Year (1957—58), many investigators of the SCAR nations have studied lakes and ponds in the oases and other ice-free regions from the limnological and geochemical points of view. These studies have revealed interesting physicochemical properties of lake waters, such as unusual temperature profiles, origin and evolutional processes of lake itself, and of the major ionic components and trace metals, features of organic constituents that account for the absence of vascular plants, and unique microbial communities in harsh environments. This paper reviews mainly Japanese limnological studies on physical, chemical and some biological features in lakes and ponds of the McMurdo Oasis (McMurdo Dry Valleys or Ross Desert) and Syowa Oasis in Antarctica, with special emphasis on the distribution of nutrients in relation to their sources, controlling factors and photosynthetic activity (Figs. 1 and 2).

2. GENERAL CHARACTERISTICS OF ANTARCTIC LAKES AND PONDS

Lakes and ponds in the oases are distributed usually at altitudes between –60 m below sea level and 1450 m above sea level. Saline pond at the highest elevation (1450 m) was found at the foot of Mount Bastian of the upper Victoria Valley in the McMurdo Oasis (MURAYAMA et al. 1983). Generally, saline lakes in the coastal regions

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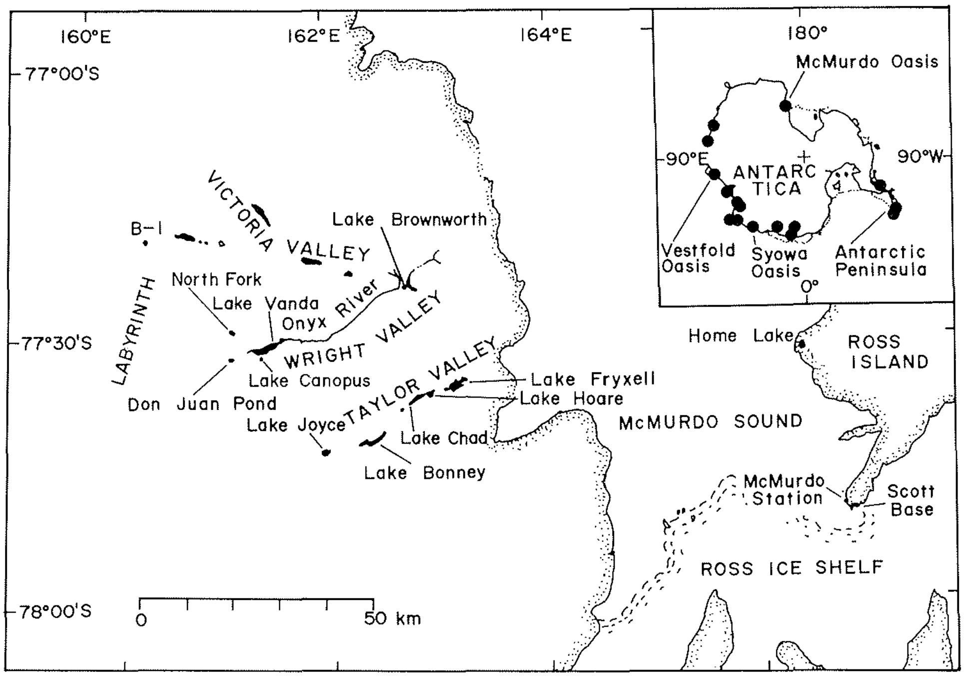

Fig. 1: Lakes and ponds in the McMurdo Oasis of southern Victoria Land in Antarctica. ●: Oases.

are found below sea level, while those in the inland Dry Valley regions of the McMurdo Oasis are situated above sea level. Lakes and ponds in the oases contain a large variety of dissolved salts in chlorinity ranging from near snow meltwater to 13 times higher than that of seawater. In general, inland Dry Valley lakes are covered with thick ice throughout the year, and thus not influenced with wind-induced turbulance, although some coastal saline lakes and small ponds often melt completely during the austral summer. However, hypersaline Don Juan Pond in the McMurdo Oasis and Deep Lake in the Vestfold Oasis are often fre of ice cover throughout the year. Usually saline lakes have no outlets and the lake levels are balanced between the supply of snow and glacial meltwaters and the evaporation of lake waters.

The stable isotopic ratios of hydrogen and oxagen for the coastal and inland freshwater lakes and ponds are similar to those for local snow and glacial meltwaters, and fit with the metoric water relationship line (MATSUBAYA et al. 1979, TORII et al. 1988). They indicate that these water bodies are directly supplied from local snow and glacial meltwaters. However, the stable isotopic ratios for some saline lakes and ponds are deviated from the meteoric water relationship line due to the isotopic fractionation during the fractional freezing or evaporation of lake and pond waters.

Most saline lakes are meromictic. Thus physical, chemical and biological properties in the water column differ remarkably not only among the lakes but also with depth. For instance, the water temperature in Lake Vanda of the McMurdo Oasis rises stepwise with increasing depth and reaches the maximum of about 25° C in the bottom layer (Fig. 3). YUSA (1975) interpreted this unusually high water temeprature based on a simple and quasisteady thermal model. The model leads to a possible conclusion that water temperatures up to 25° C can be attributed to solar heating. Also the water temperature in Lake Nurume of the Syowa Oasis has two maxima at depths of 3.5 and 12 m (SANO et al. 1977). In general, the heat source of high water temperatures in the meromictic lakes is believed to be the penetrating solar energy. The dissolved oxygen in the upper layers is usually saturated or super-saturated but the bottom layers are anoxic, and often hydrogen sulfide occurs (e. g. Fig. 3). In some cases, dissolved oxygen concentrations are extremely high, over 4 times higher than the saturation (e. g. TORII et al. 1975, MATSUMOTO et al. 1982, 1985, WHARTON et al. 1987). For the high dissolved oxygen concentrations,

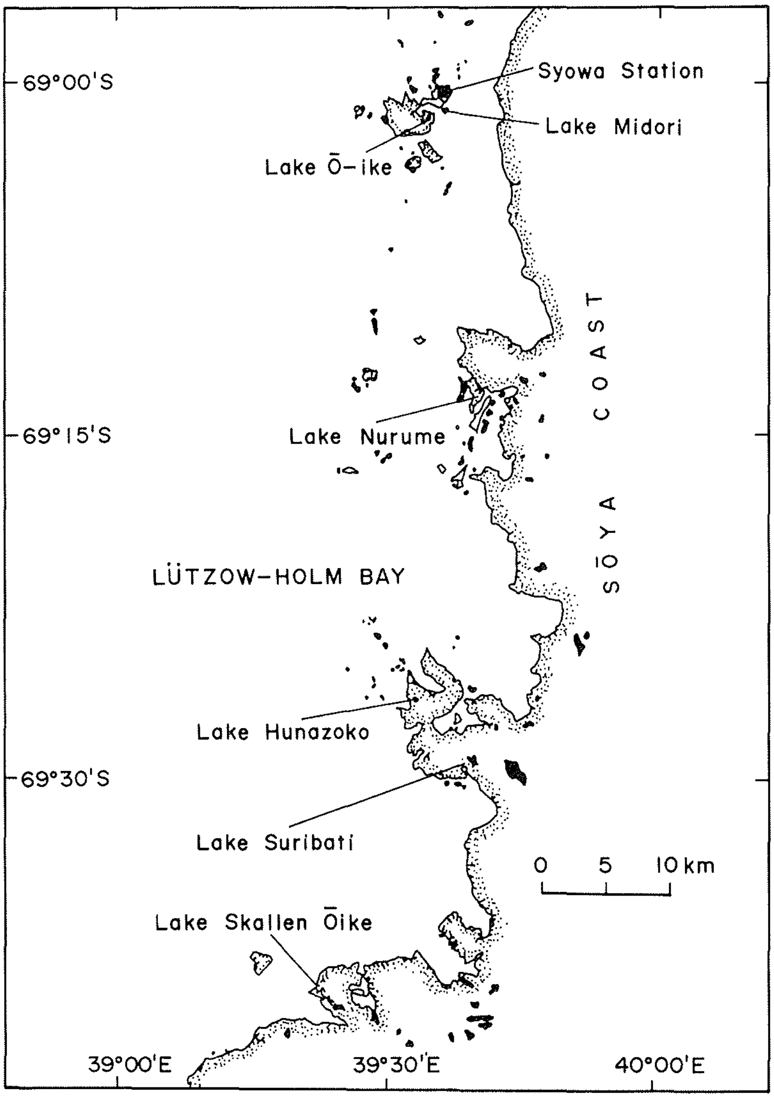

Fig. 2: Lakes and ponds in the Syowa Oasis of Enderby Land, Antarctica.

WHARTON et al. (1987) suggested that this super-saturation resulted from the exclusion of oxygen during the freezing of aerated meltstream water at the bottom of the ice cover. pH values of lake waters in the oxic layers showed neutral or alkaline, but those of the anoxic layers indicated sometimes acidic.

More than 60 small freshwater and saline ponds are distributed in high elevted areas of 600—1000 m above sea level, viz., in the Labyrinth of the upper Wright Valley of the McMurdo Oasis. High concentrations of dissolved oxygen, together with high pH values (>10) were observed in certain ponds in the Labyrinth (MATSUMOTO et al. 1985, TORII et al. 1988). This can be explained by the intensive photosynthesis since extensive cyanobacterial mats were observed at the pond edges.

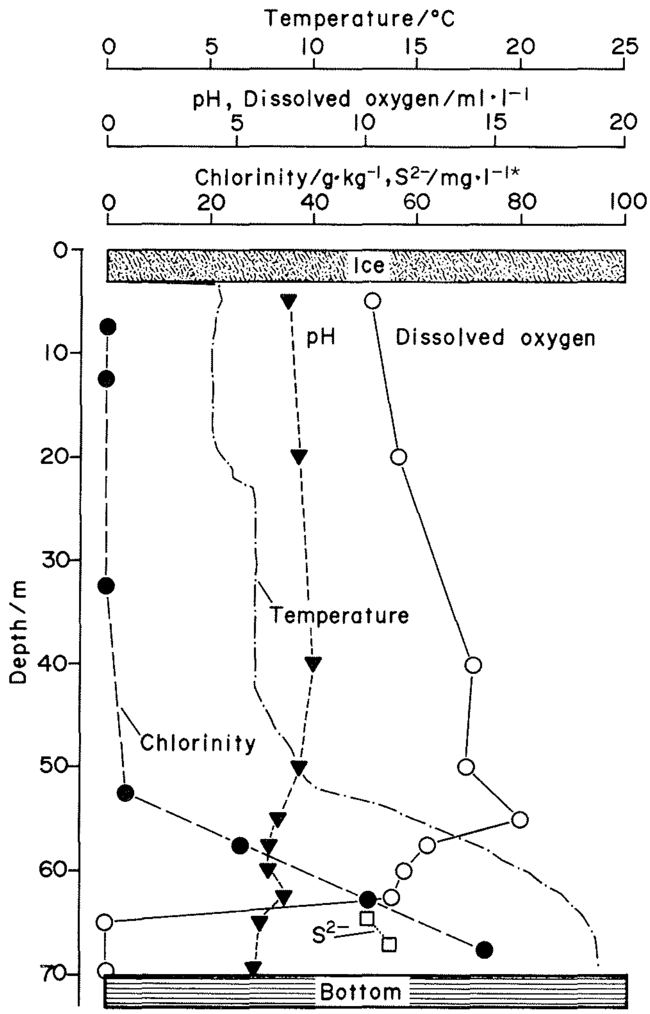

Fig. 3: Vertical distribution of physicochemical properties in Lake Vanda of the McMurdo Oasis. *Data from NAKAI et al. (1975).

3. MAJOR IONIC COMPONENTS AND TRACE METALS

The composition of the major ionic components in freshwater lakes and ponds in both the coastal and inland Dry Valley regions is generally similar to that of local snow and glacial meltwaters in the catchment areas (Tab. 1, Fig. 4). Most saline lakes and ponds are of chloride-type, meromictic and are chemically stratified, having a layer of freshwater underneath an ice cover and the deeper water increasing in salinity with depth (e. g. Fig. 3). The composition of the major ionic components of the saline lakes and ponds in the coastal regions is similar to that of seawater, while that of the inland Dry Valley saline lakes and ponds is markedly different among the lakes and ponds, although these lakes are generally abundant in calcium, magnesium and sulfate ions (Tab. 2 and 3, Fig. 4). Equivalent percentages of calcium ions in total cations (sodium, potassium, calcium and magnesium ions) for Don Juan Pond and Lake Vanda are 97 and 58%, respectively. Those of magnesium ions for the east lobe of Lake Bonney and L-1 Pond (unnamed pond in the Labyrinth) are approximately 40% (TORII & YAMAGATA 1981). Torii and his coworkers (TORII & YAMAGATA 1981, TORII et al. 1981, 1988) explained the formation of these unusual dissolved salts as follows: Freshwaters originated from local snow and glacial meltwaters are concentrated in lakes and ponds by freezing and evaporation of waters, accompanied by the fractionation of dissolved salts

Sample	Na	K	Ca	Mg	Cl	SO_4	References
McMurdo Oasis							
Lake Brownworth	3.85	0.47	1.90	0.6	4.9	6.2	TORII et al. (1975)
Lake Canopus	35.9	2.01	4.10	5.8	44.0	38.0	ibid.
L-12 Pond*	60.3	1.3	25.8	17.5	78.3	99.6	TORII et al. (1987)
L-20 Pond*	42.5	1.3	4.5	10.0	93.6	15.0	ibid.
NF-1 Pond**	17.0	0.65	4.4	6.4	16.1	13.8	TORII et al. (1975)
NF-2 Pond**	20.0	0.66	5.7	7.2	18.5	15.2	ibid.
Syowa Oasis							
Lake Midori	8.5	0.2	3.2	1.7	17.3	6.8	MURAYAMA(1977)
Lake O-ike	60	3.0	5.9	9.6	120	12	ibid.
Lake Skallen Oike	48	3.4	9.4	9.5	85	10	ibid.

Tab. 1: Chemical composition of freshwater lakes and ponds (mg·kg^{-1}). * Unnamed ponds in the Labyrinth. Unnamed ponds in the North Fork.

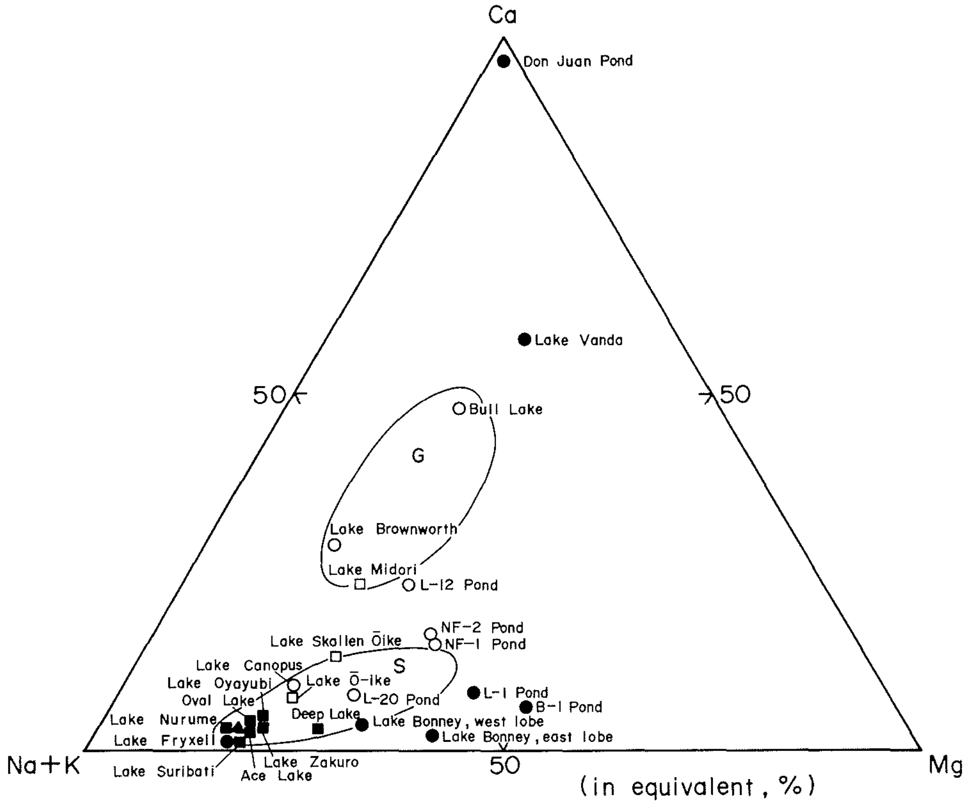

Fig. 4: Triangular diagram showing major cation composition of the bottom waters of lakes and ponds in the McMurdo, Syowa and Vestfold oases.
G: Glacial meltwater. S: Snow. ▲: Seawater. ❑ and ■: Coastal freshwater and saline lakes and ponds, respectively. ○ and ●: Inland freshwater and saline lakes and ponds, respectively.

under frigid conditions, as delineated by THOMPSON & NELSON (1956).

MASUDA et al. (1982, 1984) analyzed trace metals, Al, Co, Cr, Cs, Cu, Fe, Mn, Ni, Rb, Sb, Sr, Th and Zn, in the water samples from Lakes Canopus, Fryxell and Vanda, Don Juan Pond, L-4 Pond (unnamed pond in the Labyrinth), Onyx River and glacier ice. Three possible origins of these metals, i. e. connate seawater, rock weathering and tropospheric aerosol particles, were investigated. The correlations of trace metals between tropospheric aerosol particles and lake and pond waters indicate that the trace metals in the Dry Valley lakes and ponds may have been derived from tropospheric aerosol particles. For Lake Vanda they concluded the pathway

		Syowa Oasis						Vestfold Oasis	
		Lake Hunazoko	Lake Nurume	Lake Oyayubi	Lake Suribati	Lake Zakuro	Ace Lake	Deep Lake	Oval Lake
Sampling date		10/06/67	10/12/69	10/05/72	11/11/72	10/06/72	11/29/74	12/02/74	04/30/74
Lake level (m)		–25	–0.5	0	–33	–6	7.6	–56	–27
Maximum depth (m)		9.3	16.6	5.2	31.2	4.6	21	36	–
Sampling depth (m)		2.5	15	5.0	30.0	4.1	15	30	0
Temperature (° C)		–15.7	9.4	–6.0	–5.5	–15.0	–	–13.0	–9.0
pH		7.26	6.80	7.2	7.1	7.1	–	7.44	7.63
Specific gravity		1.146 (25° C)	1.040 (25° C)	1.070 (20° C)	1.141 (20° C)	1.142 (20° C)	1.022 (20° C)	1.175 (20° C)	1.105 (20° C)
Na	($g \cdot kg^{-1}$)	58.2	15.1	34.0	69.0	60.0	10.2	59.1	44.9
K	($g \cdot kg^{-1}$)	2.4	0.66	1.2	2.5	2.5	0.36	3.95	0.79
Ca	($g \cdot kg^{-1}$)	2.22	0.77	1.1	1.2	2.5	0.24	2.19	1.91
Mg	($g \cdot kg^{-1}$)	7.87	2.00	3.5	8.5	8.4	1.31	12.2	5.52
Cl	($g \cdot kg^{-1}$)	116.6	29.90	53.0	130	130	18.04	137.4	80.43
SO_4	($g \cdot kg^{-1}$)	2.47	3.81	8.3	8.1	4.0	0.85	2.50	2.36
$\delta^{18}O$	(‰)	–9.9 (7 m)	–29 (16 m)	–4.2	–10.9 (17 m)	–11.0	–17.3	–12.7 (34 m)	–14.2
δD	(‰)	–137 (7 m)	–83 (16 m)	–74	–146 (17 m)	–137	–145	–141 (34 m)	–141
Refernces*		a	a	b	b	b	a	a	a

Tab. 2: Chemical composition of saline lakes in the coastal region. *a: TORII (1986). b: MURAYAMA (1977).

		B–I Pond (unnamed)	Lake Bonny east lobe	Lake Bonny west lobe	Don Juan Pond	Lake Fryxell	Lake	Labyrimth JoyceL–I pond (unnamed)	Lake Vanda
Sampling date		12/21/82	01/04/72	01/09/72	01/06/65	12/20/72	12/18/76	01/03/77	12/09/72
Lake level (m)		1450	56	56	122	12	330	930	93.6
Maximum depth (m)		–	33.4	30.2	0.1	18	34.8	4	68.5
Sampling depth (m)		0.5	32.5	29.5	surface	16	30.4	0.15	64.6
Temperature (° C)		–0.2	–2.4	–4.6	10.4	1.6	–0.1	4.0	24.3
pH		8.32	6.51	5.73	4.6	7.07	6.59	7.54	5.45
Spec. grafity (25° C)		1.034	1.203	1.102	1.386	1.00	1.00	1.017	1.092
Na	($g \cdot kg^{-1}$)	9.96	56.9	32.1	1.63	2.98	1.06	4.13	6.11
K	($g \cdot kg^{-1}$)	0.052	2.30	1.47	0.26	0.203	0.07	0.025	0.59
Ca	($g \cdot kg^{-1}$)	1.07	1.22	1.48	137	0.027	0.25	0.531	24.4
Mg	($g \cdot kg^{-1}$)	5.86	21.7	8.34	1.80	0.331	0.14	1.92	7.40
Cl	($g \cdot kg^{-1}$)	17.1	162	78.1	251	3.71	1.45	7.58	74.3
SO_4	($g \cdot kg^{-1}$)	1.90	2.94	4.45	0.00	0.253	1.08	2.13	0.615
$\delta^{18}O$	(‰)	–25.3	–25.2	–40.5	–13.9	–31.8	–	–12.7	–29.7 (64 m)
δD	(‰)	–225	–252	–318	–186	–254	–	–174	–237 (64 m)
References*		a	b	b	c	b	d	a	b

Tab. 3: Chemical composition of saline lakes in the Dry Valley region. *a: TORII et al. (1987). b: TORII et al. (1975). c: TORII et al. (1977). d: TORII (1986).

of these trace metals as follows: Tropospheric aerosol particles — precipitation — glacier — glacial meltwater — Lake Vanda. This result supports a view that the dissolved salts in the Dry Valley lakes were derived from atmospheric salts.

4. NUTRIENTS

4.1 *Distribution*

Many investigators have studied nutrients, i. e. silicate-Si, phosphate-P, nitrate-N, nitrite-N and ammonium-N, in lake and pond waters in the three geographical regions, McMurdo, Syowa and Vestfold oases. Nutrient concentrations vary largely among the lakes and ponds, although they also differ considerably by investigators (e. g. FORTNER et al. 1976). Especially, earlier researches for hypersaline water samples are generally underestimated. Table 4 summarizes some selected nutrient concentrations for freshwater and saline lakes and ponds in the three regions. Also examples of vertical nutrient distributions in an inland meromictic Lake Vanda and a coastal meromictic Lake Suribati are shown in Figures 5 and 6, respectively.

S i l i c a t e — The silicate-Si concentrations in Lakes Fryxell, Joyce and Vanda in the McMurdo Oasis rise with

Lake or pond	Depth (m)	SiO_2–Si (µg–at·l⁻¹)	PO_4–P (µg–at·l⁻¹)	NO_3–N (µg–at·l⁻¹)	NO_2–N (µg–at·l⁻¹)	NH_4–N (µg–at·l⁻¹)	Lake** type	References
McMurdo Oasis								
Lake Bonney east lobe	4–26	NR	0.0761–6.61	4.5–156	0.41–42.4	1.60–430	HS	FORTNER et al. (1976)
ibid.	4–25	NR	<0.003–3.29	6.4–246	0–44.6	0–1270	HS	WEAND et al. (1977)
ibid.	5.4–33.4	6.5–220	0.0	16–210	0.25–40	2–58	HS	MATSUMOTO ET al. (1982)
Lake Bonney west lobe	5.4–30.2	47–250	0.0–0.7	0.0–24.4	0.01–0.37	0–190	HS	ibid.
Lake Conopus	NR	18.7	0.17	51	0.60	1.32	F	TORII et al . (1975)
Lake Chad	Various depths	NR	NR	0.35#		0.490	F	PARKER & SIMMONS (1985)
Lake Fryxell	4–16	14–175	0.02–50.2	ND	0.01–1.3	ND–293	S	TORII et al. (1975)
ibid.	Various depths	NR	0.042–1.281?	0–0.32#		0.10–>7	S	PARKER & SIMMONS (1985)
ibid.	5.0–18.5	64–650	0.24–77	<1	0.0–0.60	0.0–800	S	TORII et al. (unpubl.)
Lake Hoare	Various depths	NR	0.0250–0.126	0–3.53#		0–>7	F	PARKER & SIMONS (1985)
Home Lake	surface	240	190	5.6	3.1	36	S	MATSUMOTO et al. (1982)
Lake Joyce	5.4–30.4	39–500	0.0–3.2	0.8–570	0.0–0.55	0–66	S	ibid.
NF-1 Pond*	surface	73.5	0.27	107	2.68	ND	F	TORII et al. (1975)
NF–2 Pond*	surface	65.0	NR	129	2.70	NR	F	ibid.
NF–3 Pond*	surface	73.5	NR	455	4.33	NR	F	ibid.
NF–4 Pond*	surface	458	ND	24800	20.0	0.81	S	ibid.
NF–5 Pond*	surface	25.2	NR	535	15.0	ND	F	ibid.
Lake Vanda	3.25–67.5	NR	<0.01–8.15	<1.0–233	<0.1–1.90	0.1–1747	HS	VINCENT et al. (1981)
ibid.	5.1–68.6	176–714	0.0–10.2	2.80–153	0.04–0.70	0–2200	HS	MATSUMOTO et al. (1985)
ibid.	5.0–69.5	180–1200	0.0–11	<1–270	0.0–0.78	0–1700	HS	TORII et al (unpubl.)
Syowa Oasis								
Lake Hunazoko	0–7	155–227	0.25–0.45	1.0–1.9	0.2–0.5	1.7–6.0	HS	FUKUI et al. /1985)
Lake Nurume	0–15	4–426	0.04–156	<0.1–1.8	0.0–0.3	0–2420	S	ibid.
Lake Õ-ike	0–7.5	23	0.01–0.11	<0.1	0.0	0–0.1	F	ibid.
Lake Skallen Õike	0–8	88–93	0.04	<0.1	0.0–0.2	0–0.3	F	ibid.
Lake Suribati	0–29	105–244	0.05-68.1	0	0.0–0.1	0–575	HS	ibid.
Vestfold Oasis								
Ace Lake	5.0	95	3.2	ND	ND	ND	S	HAND & BURTON (1981)
ibid.	22.0	NR	326.0	ND	ND	49.3	S	BARKER & BURTON (unpubl.)
Deep Lake	0–34	99.9–163	<0.03–1.48	3.8–6.2	0.093–0.36	NR	HS	KERRY et al. (1977)
Seawater from Antarctic Ocean	NR	21.3	1.15	12.4	0.19	NR		EL-SAYED (1970) BURTON (1981)

Tab. 4: Ranges of nutrient concentrations in Antarctic lakes and ponds. * Unnamed ponds in the North Fork of Wright Valley. **F: Freshwater. S: Saline. HS: Hypersaline. # Nitrate + nitrite. NR: Not reported. ND: Not detected.

increasing depth and attain the maximum values of 650, 500 and 1200 µg-at/l, respectively in the bottom layers (TORII et al. 1975, NAKAYA et al. 1977, MATSUMOTO et al. 1982, 1985, TORII et al. unpubl. results). These profiles are also found in Lakes Nurume, Hunazoko and Suribati in the Syowa Oasis (TOMINAGA & FUKUI 1981, FUKUI et al. 1985). However, those in the east and west lobes of Lake Bonney have the maximum values of 220 and 250 µg-at/l in the middle layers, 15.4 and 13.4 m, respectively (MATSUMOTO et al. 1982). Further, high silicate-Si concentrations were found in waters from a meromictic Ace Lake (HAND & BURTON 1981) and a hypersaline Deep Lake (KERRY et al. 1977) of the Vestfold Oasis. Generally, silicate-Si concentrations in freshwater lakes and ponds are similar to those in seawater from the Antarctic Ocean, but those in saline lakes are much higher. Extremely high silicate-Si values were found in the bottom waters of Lakes Vanda and Fryxell.

P h o s p h o r o u s — Phophate-P concentrations in freshwater lakes are generally considerably low and similar to those in the oxic layers of meromictic Lakes Bonney, Fryxell, Joyce and Vanda in the McMurdo Oasis (TORII et al. 1975, FORTNER et al. 1976, HOEHN et al. 1977, NAKAYA et al. 1977, WEAND et al. 1977, VINCENT et al. 1981, MATSUMOTO et al. 1982, 1985), and Lakes Nurume and Suribati in the Syowa Oasis (MURAYAMA et al 1981, 1984, TOMINAGA & FUKUI 1981, FUKUI et al. 1985, Tab. 4). In these meromictic lakes, phosphate-P concentrations increased with depth and reached the maximum values in the bottom layers. The extremely high phosphate-P concentrations were found in the bottom waters of Ace Lake (326 µg-at/l, BURTON 1981), Lake Nurume (156 µg-at/l, TOMINAGA & FUKUI 1981, FUKUI et al. 1985) and Home Lake (190 g-at/l, MATSUMOTO et al. 1982). Phosphate-P concentrations in the water column of the east lobe of Lake Bonney showed seasonal variation in the 1973—75 austral summers (HOEHN et al. 1977, WEAND et al. 1977). They suggested that these variations are attributable to the supply of subsurface water.

WEAND et al. (1977) reported considerable amounts of condensed (acid hydrolyzable) phosphate in the mixolimnion of Lake Bonney. The concentrations are about 3 times higher than those of phosphate-P. This may be interesting in relation to primary productivity limitation.

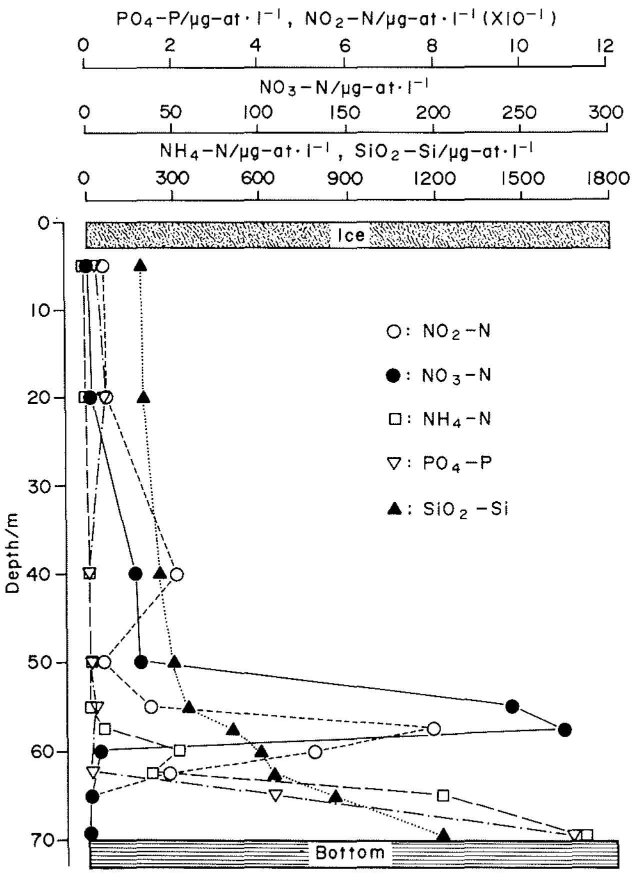

Fig. 5: Vertical distribution of nutrients in Lake Vanda of the McMurdo Oasis.

I n o r g a n i c n i t r o g e n c o m p o u n d s — Nitrate-N, nitrite-N and ammonium-N concentrations in freshwater lakes and ponds are generally considerably lower than those in saline lakes. Nitrite-N concentrations in both freshwater and saline lakes from the three oases were generally low, but relatively higher nitrite-N concentrations (31—40 µg-at/l) were found between depths of 25.4 and 33.4 m in the east lobe of Lake Bonney (MATSUMOTO et al. 1982).

In the oxic layers of Lakes Bonney, Joyce and Vanda, considerably high concentrations of nitrate-N were detected, but those in Lake Fryxell were near zero (TORII et al. 1975, unpubl. results, NAKAYA et al. 1977, MATSUMOTO et al. 1982, 1985). The low nitrate-N and nitrite-N concentrations were also found in freshwater lakes, Õike and Skallen Õike as well as saline lakes, Lakes Hunazoko, Nurume and Suribati in the Syowa Oasis (MURAYAMA et al. 1981, 1984, TOMINAGA & FUKUI, 1981, FUKUI et al. 1985), and Ace and Deep Lakes in the Vestfold Oasis (KERRY et al. 1977, HAND & BURTON 1981). These lakes are all located near the coast and considered to have the character of coastal lakes.

Ammonium-N was largely concentrated in the anoxic layers of the meromictic lakes. Ammonium-N concentrations in the bottom waters of Lakes Fryxell and Vanda of the McMurdo Oasis (TORII et al. 1975, NAKAYA et al. 1977, WEAND et al. 1977, VINCENT et al. 1981, MATSUMOTO et al. 1982, 1985) and Lakes Hunazoko, Nurume and Suribati (TOMINAGA & FUKUI, 1981, FUKUI et al. 1985) exceed 200 µg-at/l. The extremely high ammonium-N concentrations were detected in the bottom waters of Lakes Nurume (2420 µg-at/l) and Vanda (2200 µg-at/l). HOEHN et al. (1977) and WEAND et al. (1977) observed that nitrate-N, nitrite-N and ammonium-N concentrations in the water column of the east lobe of Lake Bonney varied significantly with sampling date

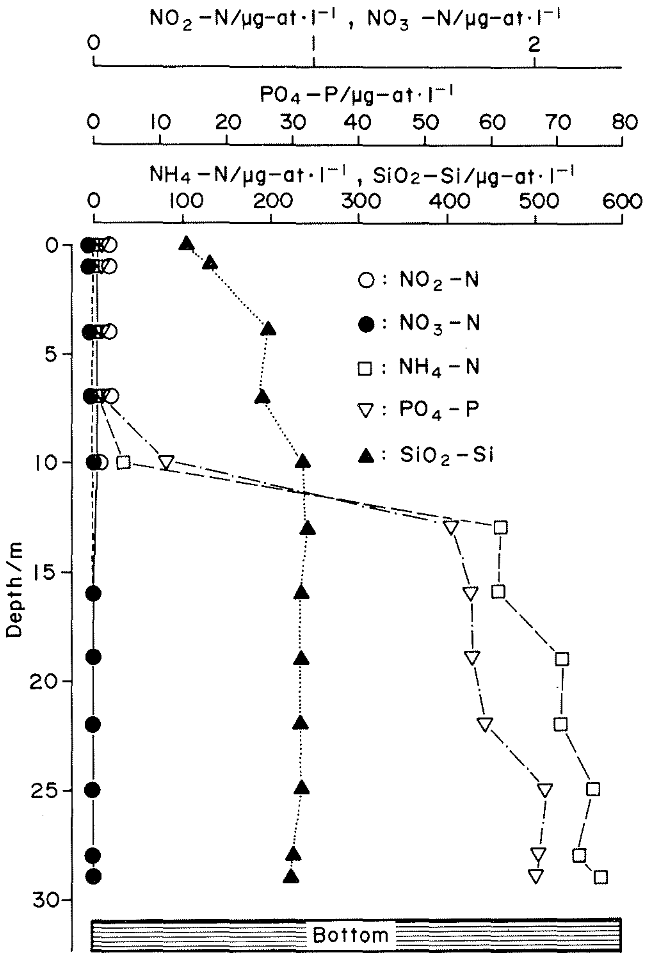

Fig. 6: Vertical distribution of nutrients in Lake Suribati of the Syowa Oasis.

as in the results on phosphate-P.

4.2 *Sources and Controlling Factors of Nutrient Distribution*

Saline lakes and ponds have no outflows. Thus non-volatile substances, such as dissolved salts, including nutrients supplied from local snow and glacial meltwaters accumulate in the water bodies over a long period of time. Therefore, local snow and glacial meltwaters through surface meltstream and subsurface flow can be considered to be important nutrient sources.

TORII et al. (1975) reported nutrients in meltstreams in the Wright Valley of the McMurdo Oasis, and found appreciable amounts of silicate-Si, phosphate-P, nitrate-N and ammonium-N (Tab. 5). Measurements of the Sollas-Lacroix Glacier and Taylor Glacier meltstreams flowing into Lake Bonney indicated that phosphate-P and nitrate-N were relatively abundant (TORII et al. 1975, WEAND et al. 1977). Silicate-Si and phosphate-P can be supplied mainly by erosion of soils and rocks in the catchment areas, although atmospheric salts are also possible sources. For example, WEAND et al. (1977) found that the bulk of phosphate-P from Sollas-Lacroix meltstreams contributed to Lake Bonney was delivered during the first two weeks of flow, and suggested that weathering processes in the stream bed during the long winter produced phosphate-P that was easily leached during the early stages of meltflow.

Meltstream	SiO_2–Si (µg–at·l^{-1})	PO_4–N (µg–at·l^{-1})	NO_3–N (µg–at·l^{-1})	NO_2–N (µg–at·l^{-1})	NH_4–N (µg–at·l^{-1})	References
Onyx River-1	12.0	0.04	0.36	0.00	0.00	TORII et al. (1975)
Onyx River-2	54.0	1.00	NR	0.36	0.72	ibid.
Onyx River-3	97.0	0.25	4.50	0.38	0.00	ibid.
Onyx River	60	0.3	8.9	0.41	0	MASUMOTOet al. (1982)
Sollas-Lacroix Glacier	95.5	0.58	21.8	0.33	ND	TORII et al. (1975)
Taylor Glacier	91.0	0.81	15.5	0.74	ND	ibid.
Wright Lower Glacier	3.0	0.43	1.79	ND	4.88	ibid.
Sollas-Lacroix Glacier	NR	0–23	0.71–22.1	0–1.1	0–16	WEAND et al. (1977)

Tab. 5: Nutrient concentrations in meltstreams from the McMurdo Oasis. ND: Not detected. NR: Not reported

Distribution of dissolved nitrogen gas in the anoxic layers of the west lobe of Lake Bonney exhibited the highest d15N values (1.5—2.5‰) among those observed in the anoxic layers of various aquatic environments (WADA et al. 1984). It revealed that denitrification of nitrate took place at temperatures lower than 0° C. This process may be important for the losses of inorganic nitrogen compounds. Nutrients losses are also due to the deposition into the lake bottom as well as the fixation by benthic organisms (PARKER & SIMMONS 1985).

PARKER et al. (1978) reported that ice core and fresh snow samples from the South Pole contained considerable amounts of nitrate-N and ammonium-N, and explained that these inorganic nitrogen compounds were due to auroral activity. These inorganic nitrogen compounds should be largely responsible for the distribution of nutrients in lakes and ponds in Antarctic oases. $\delta^{15}N$ values of nitrate in soils from the Dry Valleys region showed extremely low values (–23.4 to –11.5‰) as compared with other areas of the world (WADA et al. 1981, 1984). This result supports the hypothesis proposed by PARKER et al. (1978).

For the concentration of silicate-Si, phosphate-P and ammonium-N in the anoxic bottom layers of most meromictic lakes discussed above can be explained as follows: Nutrients derived from meltstreams are first used by primary producers, including diatoms, followed by precipitation of some dead plankton towards the lake bottom, and then undergo microbial degradation. Bacterial numbers determined by the acridine orange epifluorescence direct count method showed a marked increase in the anoxic bottom layers of Lakes Vanda and Fryxell (TAKII et al. 1986, KONDA et al. 1987, unpubl. results). Thus, the nutrients released by microbial degradation of organic substances are accumulated in the stagnant lake bottom layers over a long period of time. High abundance of refractory organic substances in the bottom anoxic layers of Lakes Fryxell and Vanda supports this contention (MATSUMOTO et al. 1984, 1987, 1988). However, the abundance of phosphate-P in Home Lake can be explained by the influences of penguins and skuas nesting around the lake (MATSUMOTO et al. 1982).

4.3 *Influences on Primary Productivity*

These unique nutrient distributions may reflect the distribution of photosynthetic plankton and decomposers, such as bacteria in the lakes and ponds. ANGINO & ARMITAGE (1963) suggest that inorganic nitrogen may limit primary production in Lake Bonney. Later detailed studies of nutrients in the lake have shown that inorganic nitrogen is abundant and not growth-limiting (HOEHN et al. 1977, WEAND et al. 1977). Phosphate-P is present in much lower concentrations than inorganic nitrogen, and may be growth-limiting to phytoplankton in the mixolimnion in the early austral summer of the year (HOEHN et al. 1977), whilst WEAND et al. (1977) determined condensed-P concentration in the mixolimnion which is three times that in the concentration of phosphate-P and concluded that phosphrous does not limit productivity in the lake. GOLDMAN et al. (1967) reported that the addition of nitrate stimulated carbon fixation in Lake Vanda littoral and pelagic waters, but the addition of phosphate for the littoral waters did not. Further study on phosphate-P concentration levels and ^{33}P uptake experiments have demonstrated that phosphorous is a major limiting nutrient to the primary producers in the lakes of the McMurdo Oasis (SIMMONS et al. 1979). This degree of limitation appears to follow the order: Lake Vanda = Lake Joyce > Lake Hoare > Lake Bonney (west lobe) > Lake Fryxell > Lake Miers. VINCENT (1981) studied production strategies in Lake Fryxell and suggests that nutrient supply, rather than in situ light or temperature, determines the large lake-to-lake and depth variation in primary productivity, viz. nutrient availability appears to control algal biomass. For Lake Skallen Õike in the Syowa Oasis, TOMINAGA (1977) reported that the addition of nitrate-N stimulated primary production, but that of phosphorous did not. HAND & BURTON (1981) suggest that inorganic nitrogen inputs may limit primary production in Ace Lake, but phosphate may be limiting it in Clear Lake of the Vestfold Oasis. These results reveal that phosphorous or nitrogen nutrient is limiting primary productivity in most Antarctic lakes and ponds. Virtually the absence of nutrient cycling leads to oligotrophic status of Antarctic meromictic lakes and ponds (AKIYAMA 1985, PARKER & SIMMONS 1985).

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