Report No. 4

Laboratory for Isotope Geology and Geochemistry

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THE ISOTOPE COMPOSITION OF STRONTIUM AND CATION CONCENTRATIONS OF LAKE VANDA AND LAKE BONNEY IN SOUTHERN VICTORIA LAND, ANTARCTICA

by

Lois M. Jones and G. Faure

June, 1969

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PREFACE

This report has been prepared for the benefit of our colleagues who are interested in the results of research in Antarctica or who may have a special interest in the ice-free valleys of southern Victoria Land. The objective of this report is to communicate scientific data whose availability may be limited because of delays in publication. The tentative conclusions and interpretations presented here have not yet been thoroughly evaluated and are therefore not final. We would welcome discussion and critical comments on any part of this report. Because this is a preliminary report we ask that anyone wishing to quote data or conclusions contained in it obtain our prior approval. This report is available free of charge by request to the undersigned.

Lois M. Jones
G. Faure
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I. INTRODUCTION

The ice-free valleys of southern Victoria Land are located in the Transantarctic Mountains west of Ross Island, Antarctica. In these valleys, the average annual temperature is well below the freezing point of water and precipitation is extremely low. Nevertheless, lakes are present and soils have begun to form since deglaciation. These lakes and soils are characterized by high concentrations of salts. The salinity of some lakes, such as Lake Vanda and Don Juan Pond in Wright Valley and Lake Bonney in Taylor Valley, is several times greater than that of sea water. In addition, salts occur as surface efflorescences and as lenses and cement within the soil.

The origin of the salts in the lakes and soils of the ice-free valleys is controversial. Possible sources that have been suggested include: (1) trapped sea water; (2) wind-transported marine salts; (3) volcanic activity and associated hot springs; and (4) chemical weathering of local soil and bedrock. Previous attempts to explain the origin of the salts have resulted in conflicting conclusions because the parameters which were used (chemical composition, isotope composition of the water) have been modified by chemical or physical processes occurring in the lakes.

In order to determine the origin of the salts, a new parameter is needed that can unambiguously identify a specific source for the salts. The isotopic composition of strontium in the salts meets the necessary requirements because: (1) the isotopic composition of strontium of each of the possible sources is distinctive and differs significantly from that of the other sources, and (2) the isotopes of strontium are not measureably fractionated in natural processes such as are occurring in the ice-free valleys. The objective of this study was to ascertain the usefulness of strontium isotopes as natural tracers, and to identify thereby the source(s) of the salts in the lakes and soils of the ice-free valleys in Antarctica.

Lakes Vanda and Bonney were studied in detail because they are the largest and most unusual of the Antarctica lakes. Both lakes are perennially ice-covered and are meromictic. At depth the water is highly saline and has surprisingly high temperatures. Lake Vanda has a maximum density of 1.10 g/ml at a depth of 67 m, and a maximum recorded temperature of +28°C at the bottom of the lake. Lake Bonney has a maximum density of 1.20 g/ml at a depth of 32 m, and reaches a temperature of +8°C at about the middle of the depth profile.

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In order to determine the origin of the salts in the two lakes, measurements were made of the isotopic composition of strontium in water samples collected at different depths from the surface to the bottom of the lakes. The results of these analyses were then compared to isotopic compositions of strontium in sea water, basalts of the McMurdo volcanic province, and the strontium in water-soluble salts from the soils in Wright and Taylor Valleys. From these comparisons the principal sources of the strontium in the two lakes can be clearly identified.

In addition to measurements of the isotopic composition of strontium in the lakes, chemical analyses of the brines have been made to provide information that can be used with the isotopic studies to develop a model for the geochemical evolution of the lakes. The combination of isotopic and chemical analyses of the brines in Lakes Vanda and Bonney permits the formulation of a better model than has been possible before.

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II. THE CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES
OF WATER IN LAKE VANDA

Introduction

Lake Vanda occupies a closed bedrock basin in the western portion of Wright Valley, about 47 km from the coast, as shown in Figure 1. It is about 8.5 km long, 2.4 km wide, and attains a maximum depth of about 67 m (Angino, et al., 1965; and Torii, et al., 1967). The lake is perennially covered by ice whose thickness ranges from 3.4 m (Armitage and House, 1962) to about 4.2 m (Angino, et al., 1965).

Water samples used in this study were collected by Dr. Derry D. Koob (Department of Botany, The Ohio State University) during the 1965-1966 austral summer using a Van Dorn sampling apparatus. The samples were obtained near the center of the main lobe of the lake at different depths below the surface.

Density of the Water Samples

Density of the water samples from Lake Vanda was determined by weighing known volumes of water. All densities were normalized to 20°C for comparison within the series of samples and are listed in Table 1. A density-depth profile for Lake Vanda is shown in Figure 2.

Inspection of Figure 2 shows that Lake Vanda is strongly density stratified. The water immediately below the ice to a depth of about 14 m has a constant density identical to that of pure water. At 14 m, the density increases slightly, but remains constant to a depth of about 44 m. A second small increase in density occurs between 44 and 50 m. The density then increases continually to 60 m, the bottom of the lake, where it reaches a value of 1.08 g/ml.

Temperature of the Water

A temperature profile of Lake Vanda is shown in Figure 3, based on measurements reported by Torii and others (1967). Two sharp thermoclines are indicated, one beneath the ice cover and the other at a depth of about 50 m. A third, less pronounced, thermocline occurs at 14 m. Although a minor temperature change at 66 m was reported by Angino and others (1965), its presence has not been confirmed by later investigators (including Hoare, 1966; Ragotzkie and Likens, 1964; Torii, et al., 1967; and Wilson and Wellman, 1962). The temperature of the uppermost thermocline is about 2°C, the intermediate one is about 7°C, and the lowermost, about 15°C. Locations of the thermoclines closely correspond to those of the density-layer boundaries. Temperature data obtained from early spring to late summer suggest that the thermal stratification remains constant throughout the year. Despite the inverted temperature

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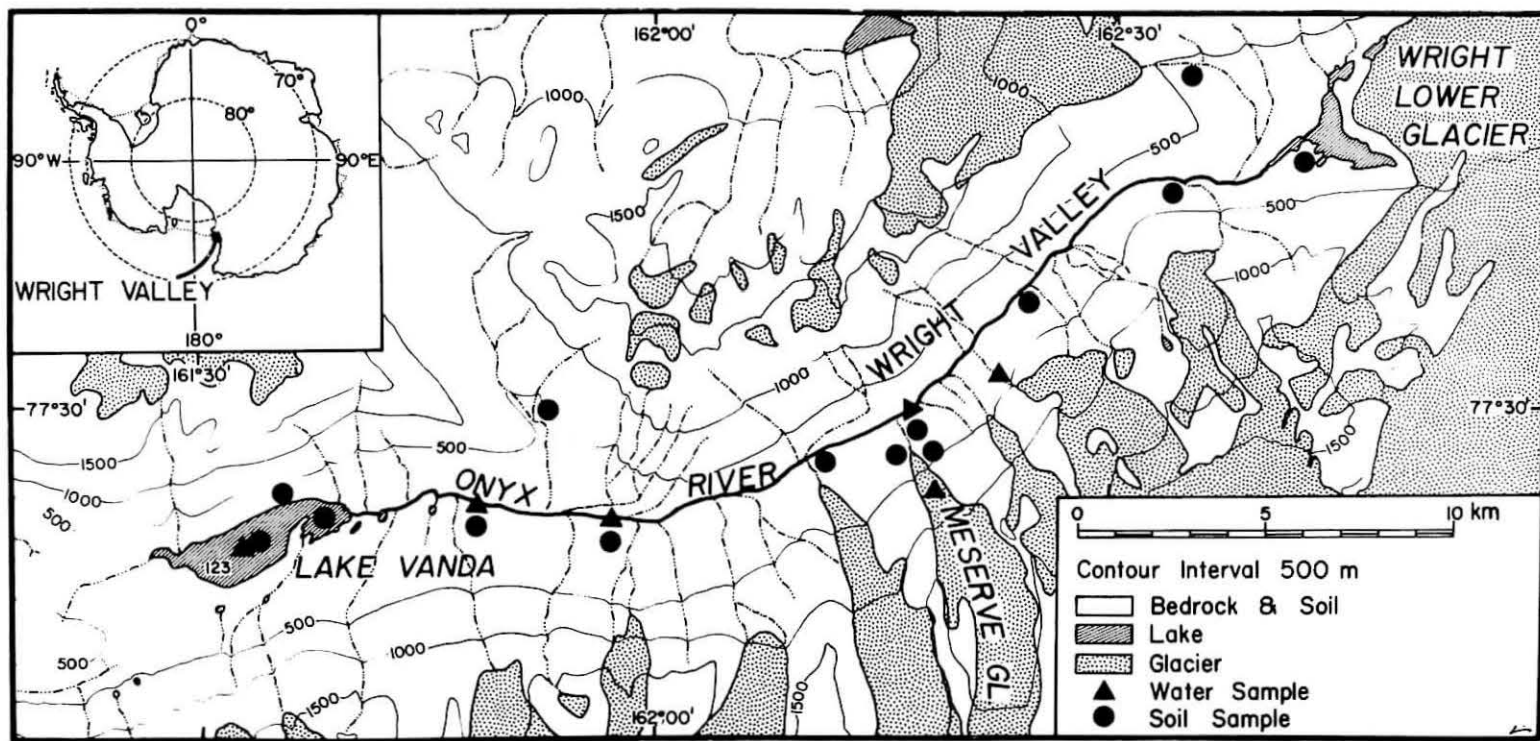
Figure 1. Location of water, ice, and soil samples in Wright Valley.

Table 1. Density profile of Lake Vanda,
          Wright Valley

Depth below surface, m	Density, g/ml at 20°C
4	0.9983
	0.9981
5	0.9986
6	0.9978
7	0.9987
8	0.9984
9	0.9986
10	0.9981
11	0.9984
12	0.9985
13	0.9982
14	0.9991
15	0.9990
20	0.9987
25	0.9990
30	0.9988
35	0.9985
40	0.9992
44	1.0001
46	0.9996
48	1.0009
50	1.0227
52	1.0306
54	1.0490
56	1.0636
58	1.0737
60	1.0835
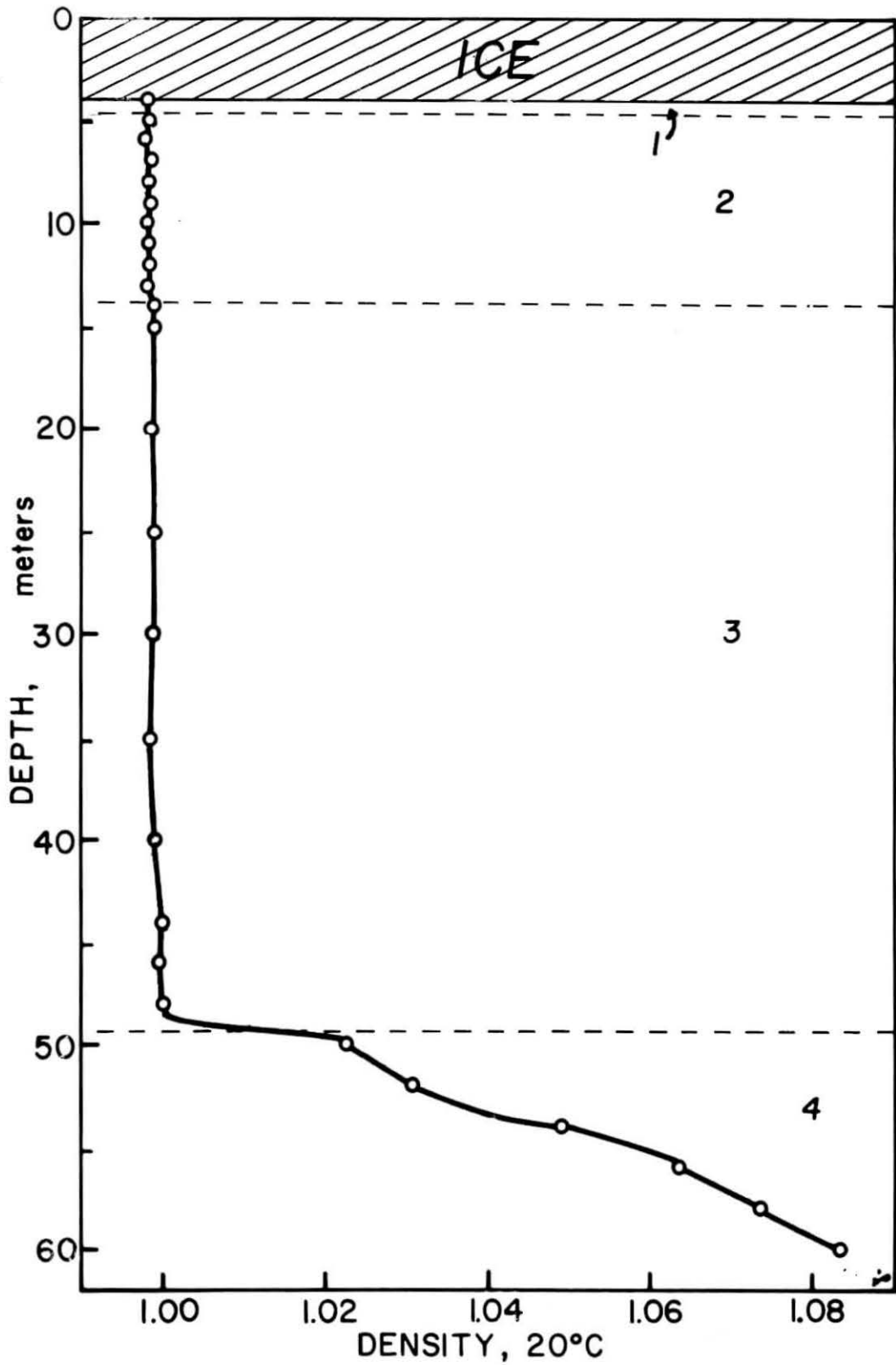
Figure 2.   Density-depth profile of Lake Vanda.
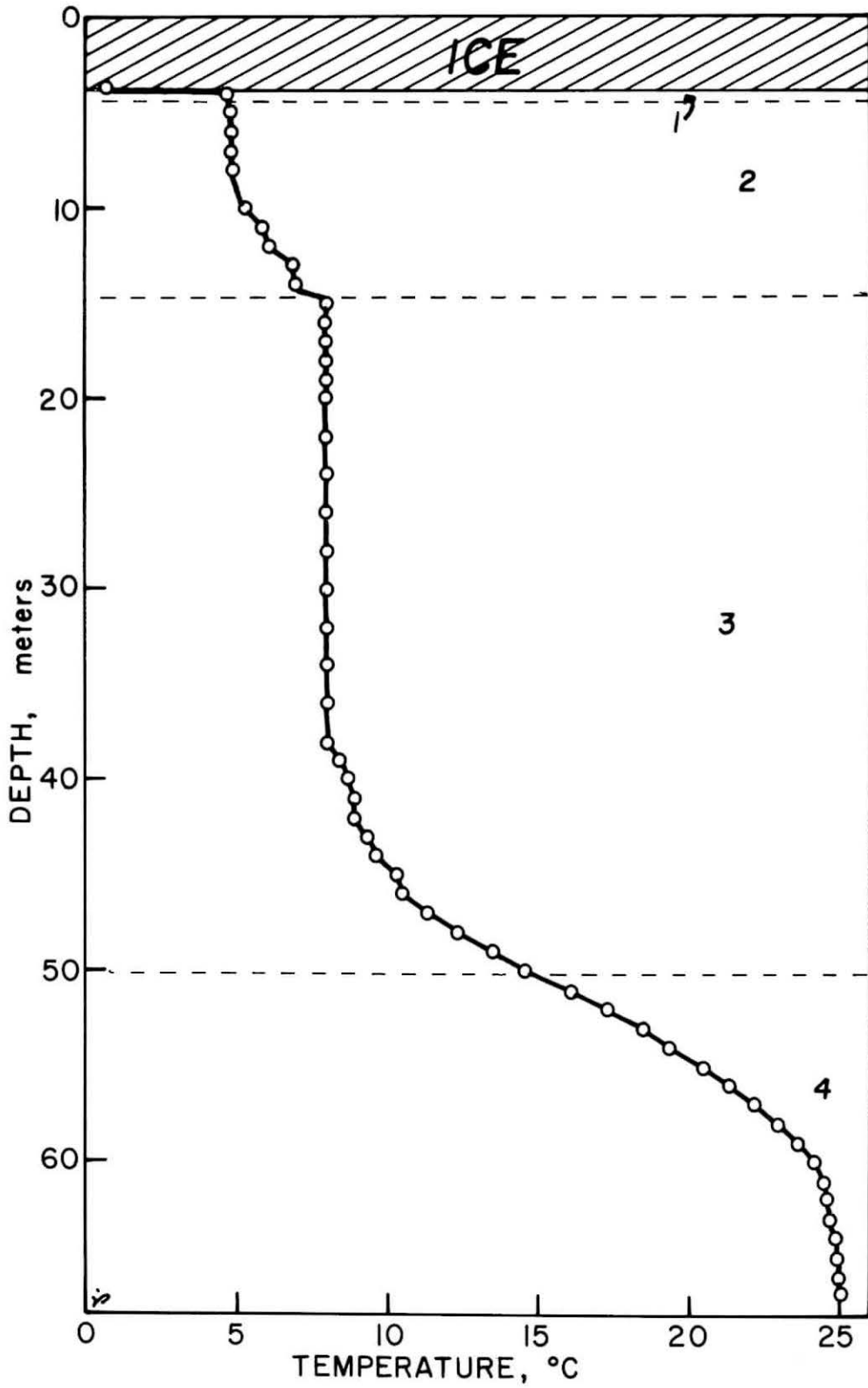
Figure 3. Temperature-depth profile of Lake Vanda (from Torii, et al., 1967).

structure (i.e., temperature increasing with increasing depth), the brine layers are dynamically stable because of the increasing salinity and density of the water with depth.

The Chemical Composition of Water in Lake Vanda

New analyses for calcium, strontium, sodium, and potassium are reported here for water samples collected at intervals from the surface to the bottom of the lake. Concentrations of major ions and trace elements reported by other investigators have been included to provide a more complete summary of the chemical composition of the lake. Calcium was determined by titration with EDTA at pH 12, using Hydroxy Naphthol Blue as indicator. Strontium was anslyzed by isotope dilution using Sr^{86}-enriched spike. Both sodium and potassium were determined by flame photometry. The results of these analyses are compiled in Table 2. Similar data taken from the literature are shown in Table 3. Figures 4, 5, and 6 are concentration-depth profiles constructed by plotting the logarithm of the concentration versus depth in meters on a linear scale.

The results of our analyses confirm the conclusions of earlier investigators who reported that the concentrations of the major cations increase with depth. Figures 4, 5 and 6 show that the concentrations of sodium, potassium, and calcium exhibit pronounced changes at certain depths indicating the presence of chemoclines. These chemoclines are boundaries separating layers of brine of more or less homogeneous chemical composition. Using the data in Tables 2 and 3 it can be shown that the concentrations of the major cations as well as the anions fit the same pattern consisting of layers of brine separated by transition zones. Therefore, we suggest that Lake Vanda may be subdivided into four layers of brine separated by three chemoclines which occur at 4.5, 14 and 50 m below the surface. It should be noted that these chemoclines coincide very closely with the thermoclines described earlier and with density changes. The resulting four layers are numbered 1 to 4 from the top of the lake downward. Each layer is characterized by (1) concentrations and relative proportions of major elements, (2) temperature, and (3) density.

Layer 1 is the uppermost layer, extending from the base of the ice cover to a depth between 4 and 5 m. This is the thinnest layer, being less than 1 m in thickness. In Layer 1, temperature and salt content are increasing, and density varies only with the ambient temperature since the salinity is too low to cause a detectable change within this layer.

Layer 2 extends from a depth of less than 5 m to 14 m. This layer is characterized by constant density (0.998-0.999 g/ml at 20°C) and by relatively constant concentrations of the principal ions. From about 5 to 10 m, the concentrations and temperatures remain constant, but between 10 and 14 m, a slight increase in both parameters was noted.

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Table 2. Concentration in ppm of calcium, strontium, sodium, and potassium in Lake Vanda, Wright Valley.

Depth below surface	Ca^{+2}	Sr^{+2}	Na^+	K^+
4 m	38.5	0.141	31.9	9.98
5	64.5	0.226	45.1	12.5
6	66.6	0.228	45.5	12.6
7	67.7	-	45.8	12.8
8	68.0	0.228	46.0	14.1
9	68.6	-	47.0	15.7
10	76.2	0.256	49.5	16.1
11	78.3	-	57.5	17.8
12	89.2	0.298	62.8	17.9
13	106.2	-	69.5	19.2
14	169.4	-	108	33.1
15	170.4	0.536	101	31.4
20	172.6	0.539	105	29.2
25	170.8	0.552	105	28.5
30	171.3	0.553	102	29.5
35	172.2	0.553	104	26.9
40	275.0	0.886	147	37.8
44	448.0	1.283	183	40.7
46	600.1	1.655	220	41.1
48	815.0	2.281	223	39.6
50	6,680	18.50	1,550	276
52	8,890	-	1,920	309
54	13,850	39.16	3,100	421
56	17,690	50.90	3,900	459
58	20,140	58.97	5,100	570
60	22,180	67.05	5,420	684

Table 3. The chemical composition of Lake Vanda, Wright Valley. Data from Angino and others (1965); values in parentheses () from Yamagata and others (1967). Concentrations are in ppm.

Depth below surface	Mg^{+2}	Ca^{+2}	Na^+	K^+	Cl^-	$SO_4^=$	HCO_3^-
(3.6)m	(1.7)	(6.4)	(2)	(1.8)	(21.4)	(2.2)	-
4.5	4	17	6	2	<28	0	10
(5)	(8.5)	(32.7)	(19)	(7.2)	(105)	(10)	-
6	12	44	30	9	134	4	39
9	12	46	30	10	149	8	39
12	13	54	35	11	164	8	41
15	22	83	51	15	260	16	49
(15.5)	(15.8)	(66.1)	(34)	(13.4)	(210)	(17)	-
18	47	181	99	29	564	12	66
21	49	182	99	30	578	24	77
24	48	182	100	30	576	24	78
27	50	182	100	30	584	28	77
30	50	182	100	30	586	24	78
(31.5)	(44.3)	(184)	(64)	(28.8)	(573)	(24)	-
33	47	181	101	30	571	32	74
36	48	182	100	30	577	32	77
39	50	182	100	30	576	44	77
42	70	264	127	35	827	36	79
(42)	(30.8)	(123)	(33)	(13.0)	(199)	(16)	-
45	95	345	150	40	1,060	40	81
48 m	173	614	228	53	1,910	80	84
51	915	2,730	746	142	8,590	200	88
(52)	(2,329)	(7,918)	(1,655)	(406)	(23,650)	(187)	-
54	2,190	7,150	1,610	281	21,500	400	116
57	3,780	11,700	2,450	389	36,600	770	139
60	6,190	16,700	3,750	515	51,000	1,880	182
(63.5)	(3,137)	(10,120)	(1,794)	(419)	(30,680)	(288)	-
66	7,684	24,254	6.761	766	75,870	770	126

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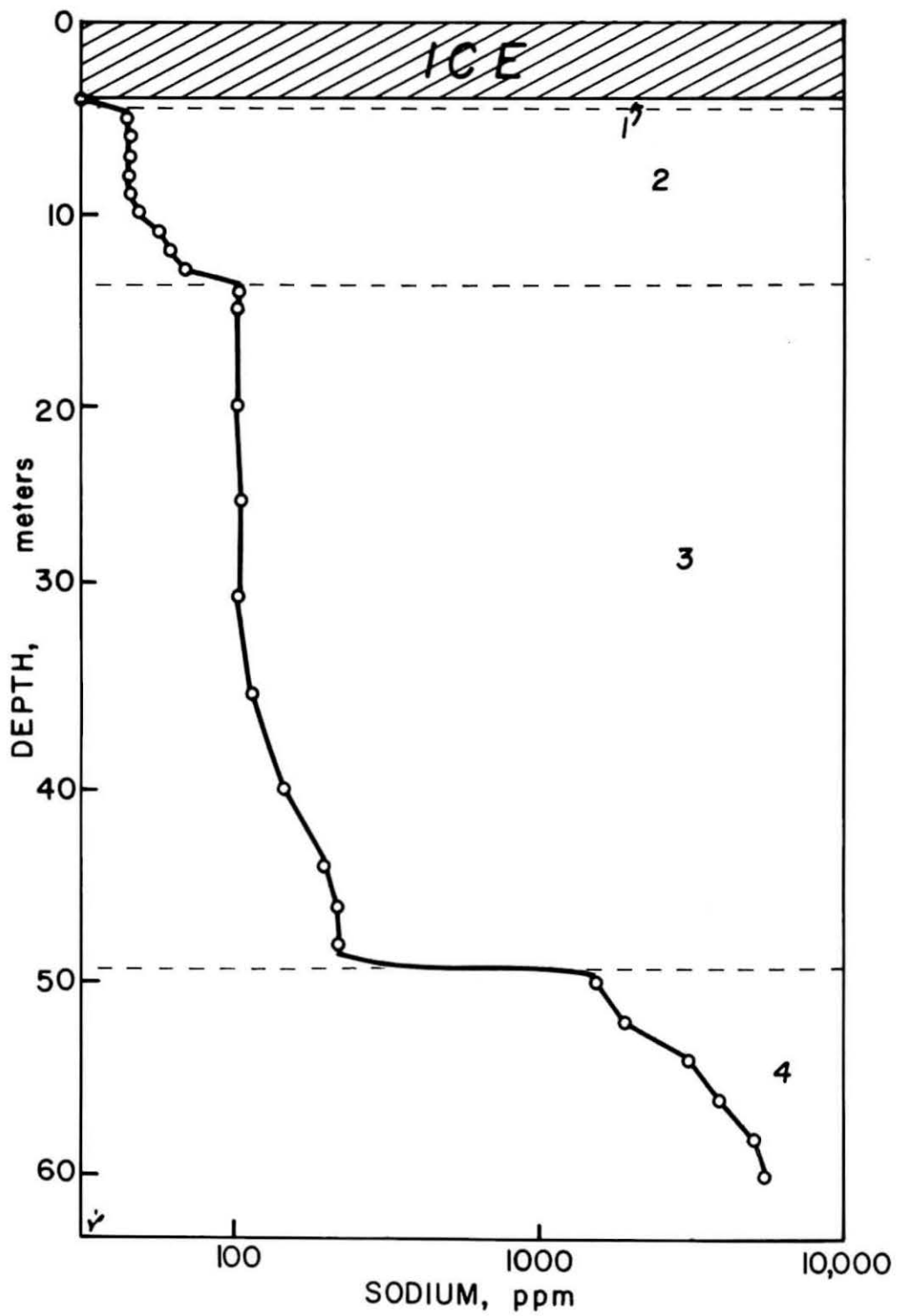
Figure 4. Variation of the sodium concentration with depth in Lake Vanda.
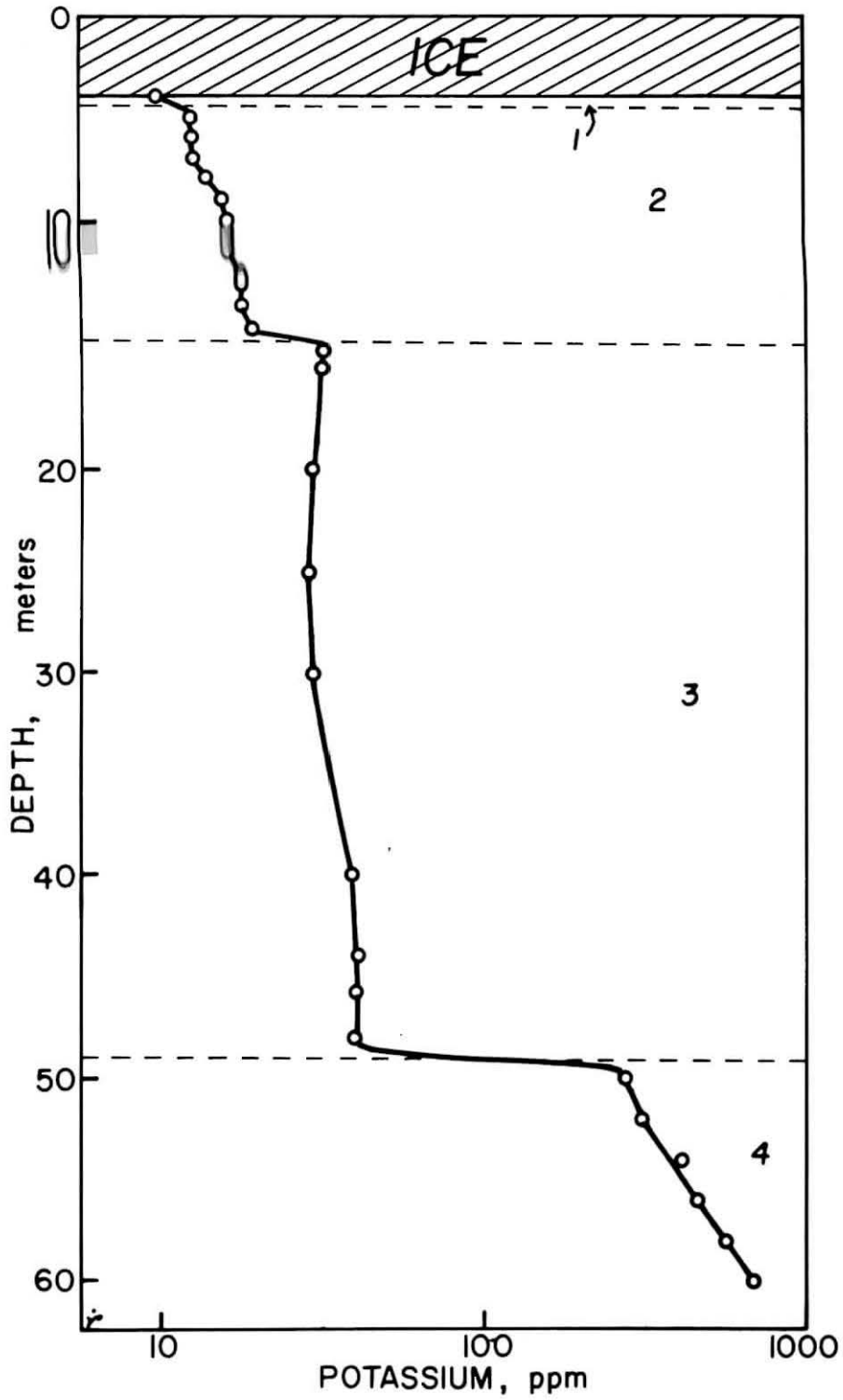
Figure 5. Variation of the potassium concentration with depth in Lake Vanda.
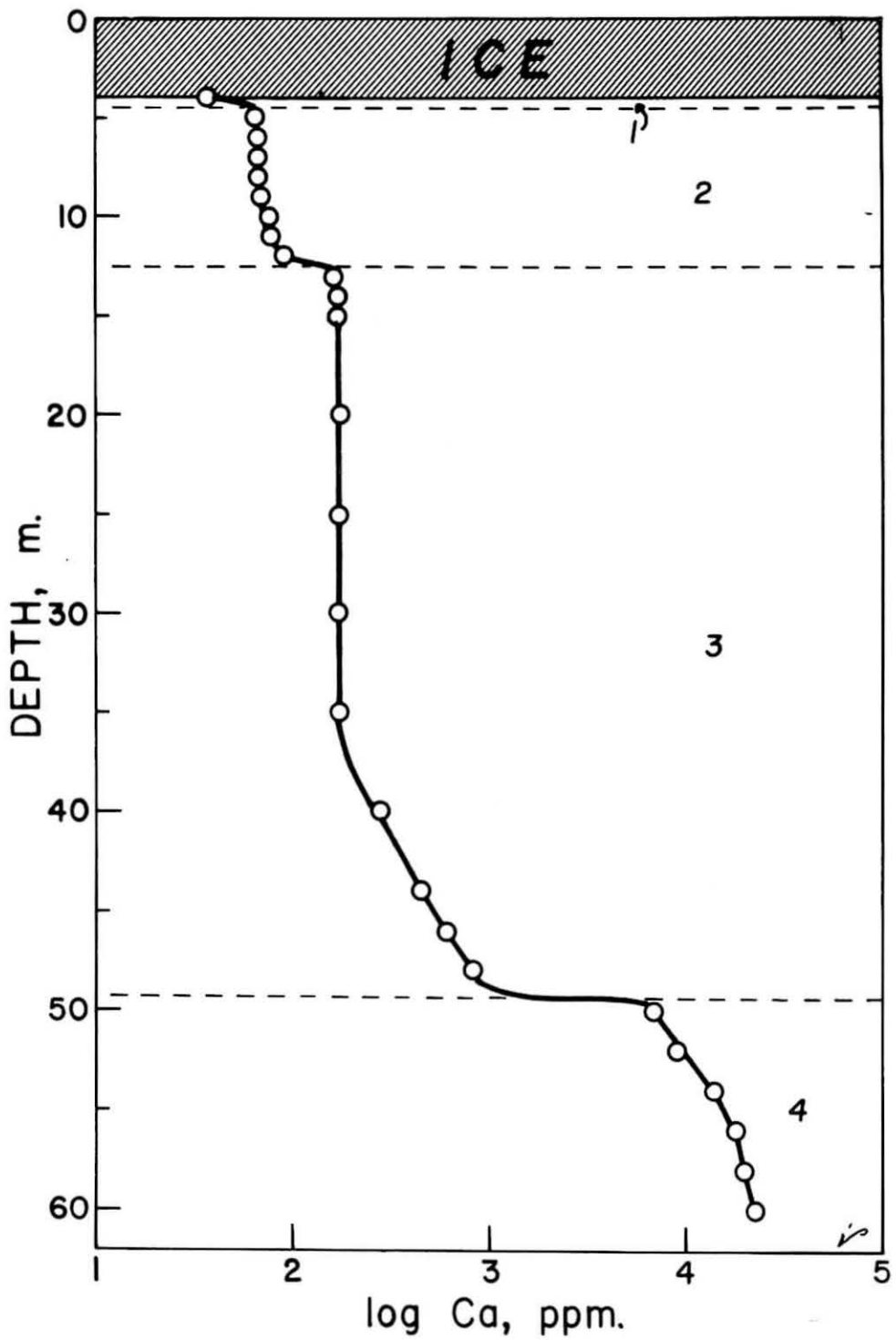
Figure 6. Variation of the calcium concentration with depth
in Lake Vanda.

Because this change is small compared to the full range of concentrations and temperature throughout the profile, Layer 2 does not warrant further subdivision.

Layer 3 occupies a depth interval from 14 to 50 m. In this region, profiles for temperature, major ion concentration, and density are similar. In crossing the boundary at 14 m from Layer 2 to Layer 3, there is a relatively small but abrupt increase in these parameters. Below 15 m, numerical values of these three parameters remain essentially constant down to a depth of about 38 m. There is a gradual increase between 38 and 40 m of density, temperature, and ion concentrations until a depth of about 50 m, which has been taken as the base of Layer 3.

Layer 4 has been assigned to depths between about 50 m and the bottom of Lake Vanda. The top of this layer has been identified mainly on the basis of the shape of the density and concentration profiles, where a very abrupt increase in density and salt content occurs. This increase is of greater magnitude than that observed at the boundary between Layers 2 and 3. The major thermocline is also located at the upper boundary of Layer 4.

The nature of the boundaries between layers is not yet well established. Layer 4 is considered to be non-convective, while Layers 2 and 3 are thought to be convective (Hoare, 1966, 1968; Wilson, 1964; and Wilson and Wellman, 1962). Layer 1 may be the result of recent discharge of the Onyx River. The transition from Layer 3 into the denser Layer 4 may have been modified by upward diffusion of ions (Wilson and Wellman, 1962). However, Craig (1966) has stated that the chemocline at 50 m cannot result primarily from diffusion. He maintained that the concentration gradient is the same for the principal ions in Lake Vanda, although their diffusion coefficients are quite different. Therefore, he concluded that the chemocline represents mixing "by convection and turbulent diffusion".

The relative importance of diffusion and physical mixing between Layers 3 and 4 can be studied by plotting concentrations of ions in water samples taken across the chemocline. If diffusion of ions upward from Layer 4 into Layer 3 is important, a concentration-concentration plot of two dissimilar ions should deviate significantly from a straight line. On the other hand, if physical mixing is occurring at the boundary, a linear plot of concentrations should be found. However, two similar ions (same charge, similar size) which diffuse at the same rate could also generate a linear concentration plot. Therefore, linearity is not necessarily an indication that mixing is occurring, while significant deviation from linearity seems to require the conclusion that diffusion is the dominant process whereby ions are transported across the chemocline from Layer 4 into Layer 3.

Three such diagrams have been prepared and are shown in Figures 7, 8 and 9. Figure 7 is a plot of the concentration of Ca^{+2} versus the
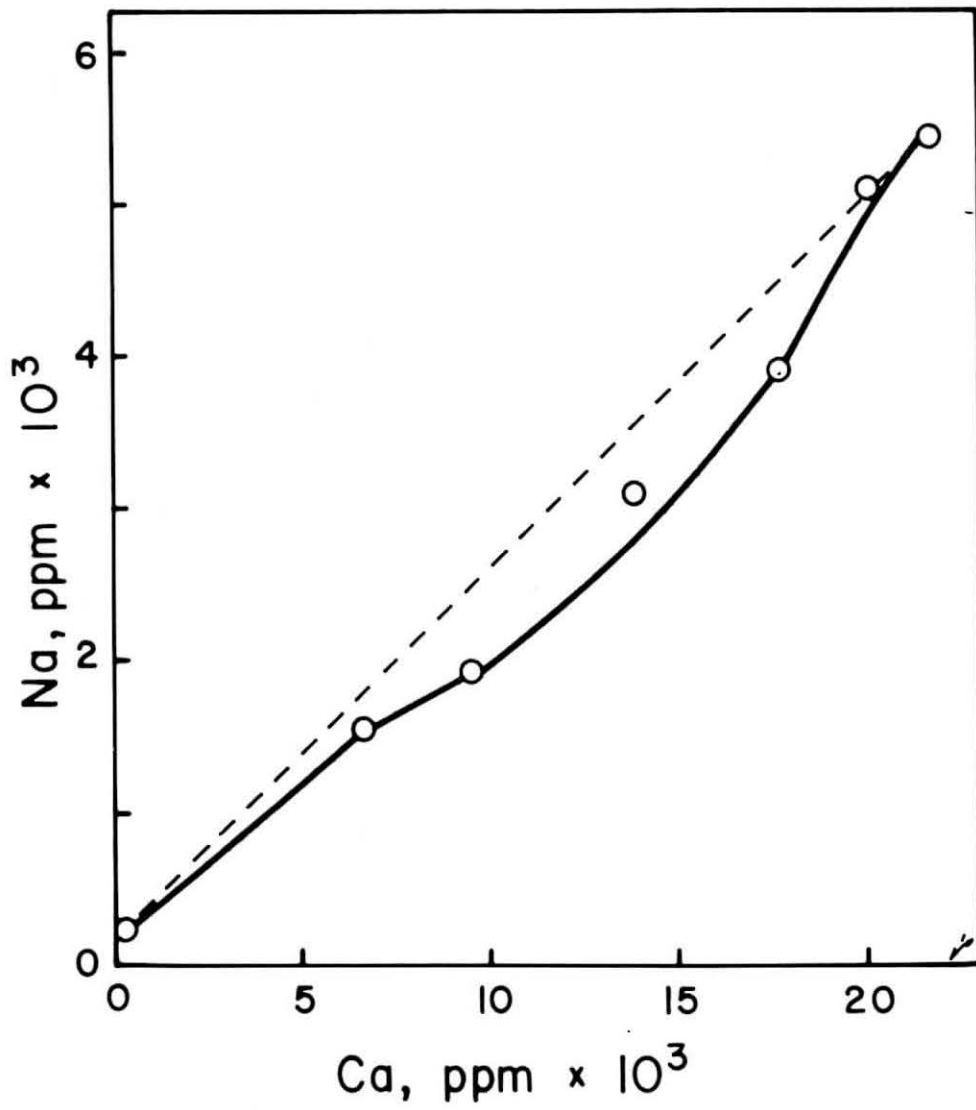
Figure 7. Variation of the concentrations of sodium and calcium between Layers 3 and 4 in Lake Vanda.
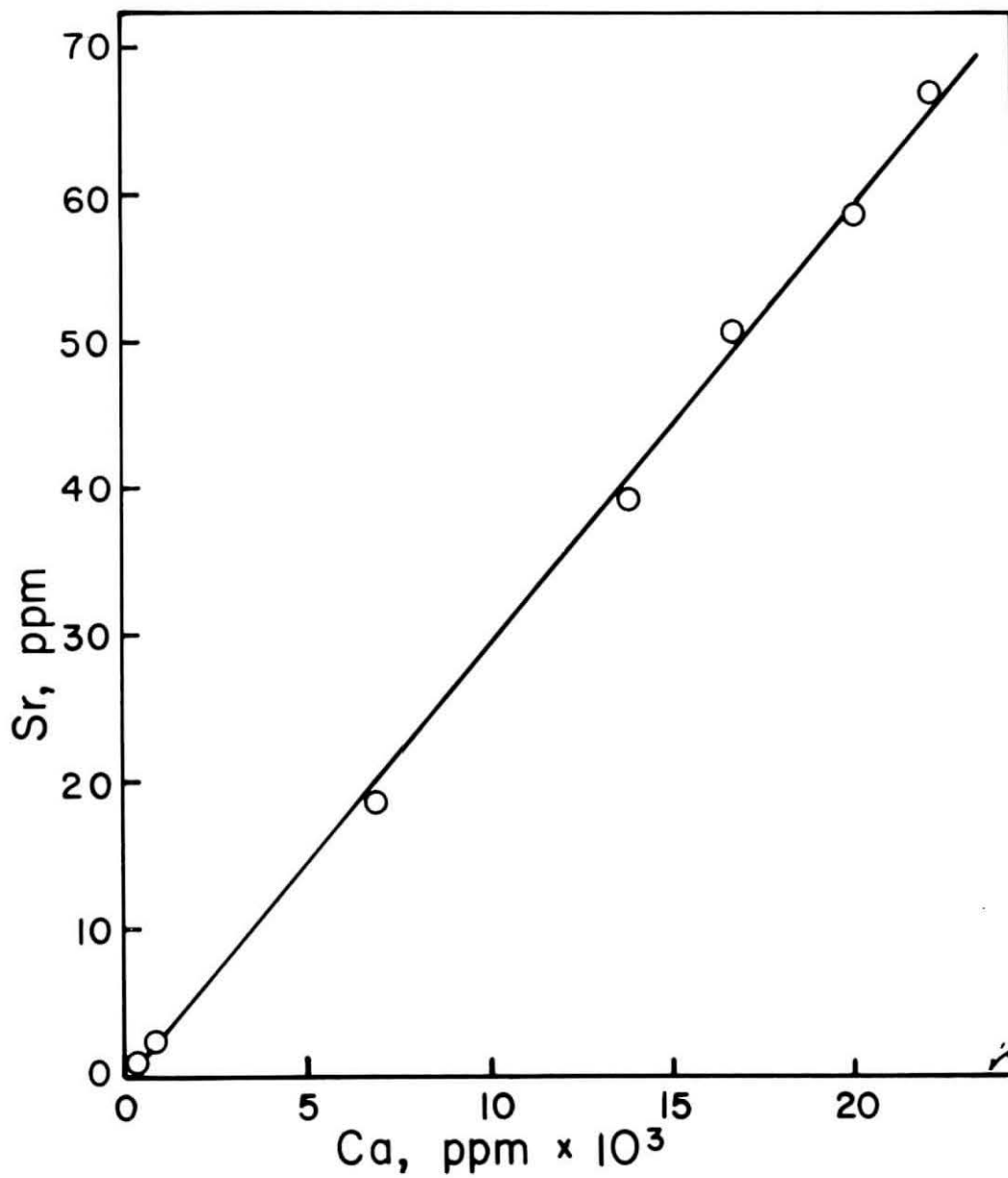
Figure 8. Variation of the concentration of calcium and
strontium between Layers 3 and 4 in Lake Vanda.
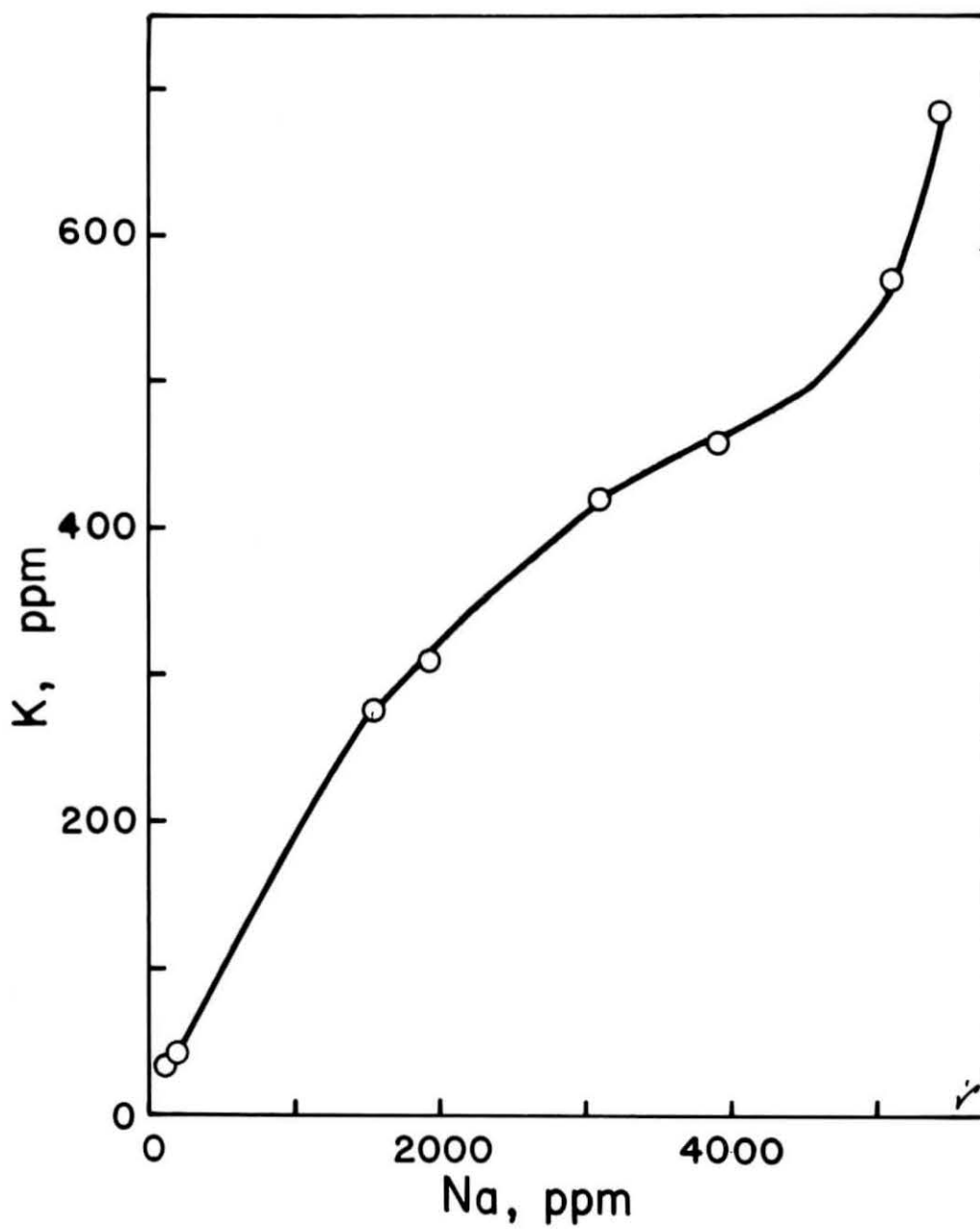
Figure 9. Variation of the concentration of sodium and
potassium between Layers 3 and 4 in Lake Vanda.

concentration of Na$^+$. It is clear that the samples form a curve rather than a straight line suggesting thereby that diffusion plays an important role in determining the concentrations of Na$^+$ and Ca^{+2} in the lower part of Layer 3. On the other hand, Figure 8 illustrates the relationship of concentrations of Ca^{+2} and Sr^{+2}. Evidently this relationship is linear. If diffusion is in fact the determining process, the linearity of this plot suggests that the diffusion coefficients of Ca^{+2} and Sr^{+2} have similar values or, that the two ions are diffusing at the same rate. Figure 9 is a plot of concentrations of Na$^+$ and K$^+$ which are also not linearly related, in spite of the fact that both ions have the same charge and similar chemical properties. Figure 9 suggests that the diffusion rates of Na$^+$ and K$^+$ are different while Figure 8 seems to show that Ca^{+2} and Sr^{+2} are diffusing at essentially the same rate. A possible explanation of this anomaly may be the fact that the ionic radii of Na$^+$ and K$^+$ differ more than the ionic radii of Ca^{+2} and Sr^{+2}. According to Pauling, the ionic radius of K$^+$ is 40% larger than that of Na$^+$, while the radius of Sr^{+2} is only 14% larger than that of Ca^{+2}. These differences in size may be sufficient to explain why Na$^+$ and K$^+$ appear to diffuse at different rates while Ca^{+2} and Sr^{+2} diffuse at nearly the same rate.

The model used by Wilson (1964) to establish the age of Lake Vanda on the basis of diffusion of chloride ion from Layer 4 into Layer 3 is supported by these observations which suggest that diffusion, rather than physical mixing, is the principal process acting across this chemocline.

The layers of fresh water and brine in Lake Vanda can be distinguished from each other not only on the basis of temperature, density and concentrations of ions, but also on the basis of the composition of the salts. Figure 10 shows the variation of the composition of the salts expressed as mole per cent of the major cations as a function of depth. It is evident from Figure 10 that Na$^+$ is the dominant cation in Layers 1 and 2 and in the upper part of Layer 3. At a depth of about 33 m the proportion of Ca^{+2} exceeds that of Na$^+$ and continues as the most abundant cation to the bottom of the lake. The proportions of K$^+$ and Mg^{+2} exhibit similar changes as a function of depth. It is clear therefore that the chemical composition of each layer varies with depth and that each brine layer can be distinguished from the others on the basis of its chemical composition as well as on the basis of differences in concentration. According to analyses published by Angino and others (1965), chloride is the principal anion, ranging from 84.7 mole per cent in Layer 2 to 99.6 mole per cent at the bottom of the lake. The only other anions present in appreciable proportions relative to Cl$^-$ are HCO$_3^-$ and SO$_4^=$.

The pronounced stratification of the concentrations of the major ions and the systematic variation of the proportions of these ions with depth in the lake would seem to rule out convection in Layers 3 and 4. Physical mixing processes may, however, play an important role in the upper part of the water column, particularly between Layers 1 and 2. This will be discussed in a later section of this report.

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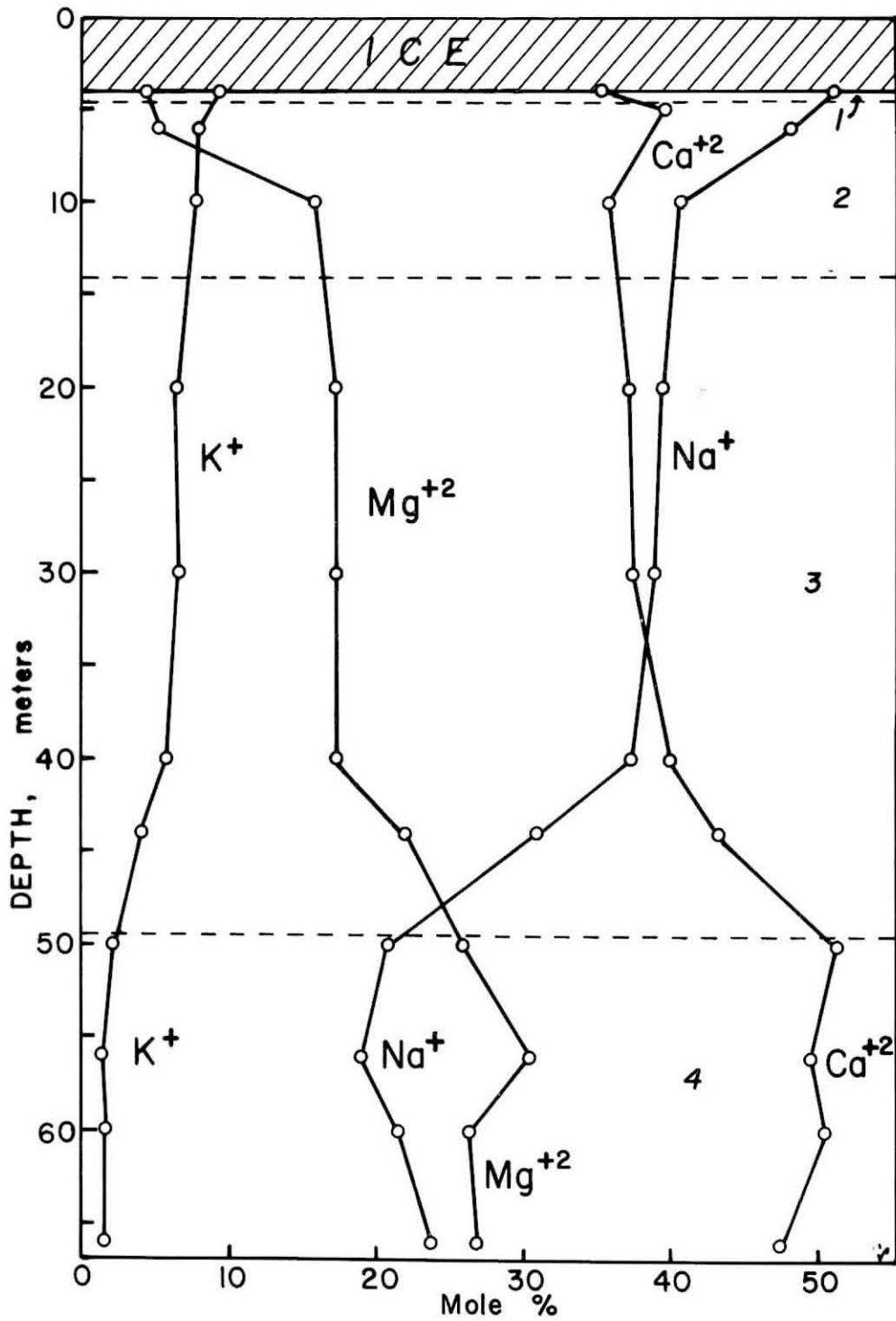
Figure 10. Variation of the cation composition as a function
of depth in Lake Vanda.

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III. THE CHEMICAL COMPOSITION OF THE ONYX RIVER AND
MELTWATER IN WRIGHT VALLEY

The Onyx River is the major supply of water to Lake Vanda. It flows intermittently and only during the warmest part of the summer, from early December to mid-January. Partial chemical analyses of five samples of water from the Onyx River are given in Table 4. The sample locations are shown in Figure 1.

Concentrations of the principal ions in the Onyx River vary by as much as an order of magnitude. An extensive chemical study of the Onyx River has not yet been carried out; therefore, the seasonal variation of concentrations of major ions in the water is not known. On the basis of available data, the concentration of the major ions appear to increase downstream. However, since the samples were collected over a period of several days, this characteristic has not been definitely established.

It seems probable that Layers 1 and 2 in Lake Vanda are derived from the discharge of the Onyx River. Therefore, it will be of interest to compare the concentrations of the major cations in the Onyx River between Bull Pass and Lake Vanda (DV-66-016 in Table 4) with those of the water in Layer 1 of Lake Vanda. Reference to the data in Table 4 shows that the concentrations of Ca^{+2}, Mg^{+2}, Na^+ and K^+ of the Onxy River differ in all cases by less than 40% from those of Layer 1 in Lake Vanda. The agreement for Ca^{+2} and Mg^{+2} is better than it is for the alkali metals. Nevertheless, considering the limited number of samples from the Onyx River and the variation of concentrations of the Onyx River along its length, the similarity in concentrations is reasonably good.

The Na/K ratio in the Onyx River varies systematically along its length from a value of 13 below Denton Glacier to a low value of 7.2 between Bull Pass and Lake Vanda. The variation of this ratio is illustrated in Figure 11 which shows a profile of the Na/K ratio along the course of the Onyx River. It can be seen that the Na/K ratio approaches that of Layer 1 in Lake Vanda but that a discrepancy remains. The Na/K ratio in Layer 1 is 3.2 while that of the Onyx River near its mouth is 7.2. If this difference is real, it suggests that potassium is being concentrated in Layer 1 relative to sodium. A possible mechanism for fractionating the alkali metals may be formation of ice which may incorporate the smaller Na^+ ion in preference to the larger K^+ ion.

An important parameter in the evaluation of the chemistry of the lakes in the ice-free valleys is the chemical composition of the snow and ice of the glaciers which are providing meltwater to Lake Vanda. For this reason a series of ice and névé samples from the Meserve Glacier were analyzed.

The Meserve Glacier lies about midway in the drainage basin of Lake Vanda, as shown in Figure 1. Since the amount of salts in snow

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Table 4. Partial chemical analyses of meltwater from Wright Valley. Concentrations are given in ppm.

Sample No.	Date, 1966	Location	Ca	Mg	Sr	Na	K
DV-66-002	Nov. 18	Foot, Lower Wright Glacier	2.5	0.21	-	2.3	0.72
DV-66-012	Dec. 5	Onyx River, below Denton Glacier	2.8	0.19	-	7.6	0.59
DV-66-013	Dec. 5	Onyx River, between Denton and Goodspeed Glaciers	4.2	0.78	-	9..7	0.99
DV-66-009	Dec. 1	Onyx River, below Meserve Glacier	15.7	1.15	0.0194	30.2	3.50
DV-66-010	Dec. 4	Onyx River, below Bull Pass	38.1	3.07	-	30.5	4.30
DV-66-016	Dec. 7	Onyx River, between Bull Pass and Lake Vanda	43.0	3.05	-	44.6	6.20
DV-66-005	Nov. 25	Bartley Glacier	3.3	0.30	-	3.4	0.48
DV-66-006	Nov. 28	E. Lake Vanda, pond on ice	2.1	-	-	2.18	1.03
DV-66-007	Nov. 28	N. Lake Vanda, pond on ice	2.3	-	-	2.80	1.08
DV-66-011	Dec. 5	Stream below Clark Glacier	6.2	-	-	10.2	0.95
DV-66-017	Dec. 12	Stream, Meserve Glacier	5.3	1.38	-	8.3	0.80
DV-66-025	Dec. 19	Stream, Meserve Glacier	2.2	0.47	-	4.3	0.72
2-GH	(1968)	Stream, Meserve Glacier	3.51	-	-	1.21	0.44
V-4	Jan. 18	Lake Vanda, 4 m depth	38.5	2.97	0.141	31.9	9.98
V-5	Jan. 18	Lake Vanda, 5 m depth	64.5	5.01	0.226	45.1	12.5
-	-	Rivers, World Average[*]	15	4.1	-	6.3	2.3

[*]Livingstone, 1963.
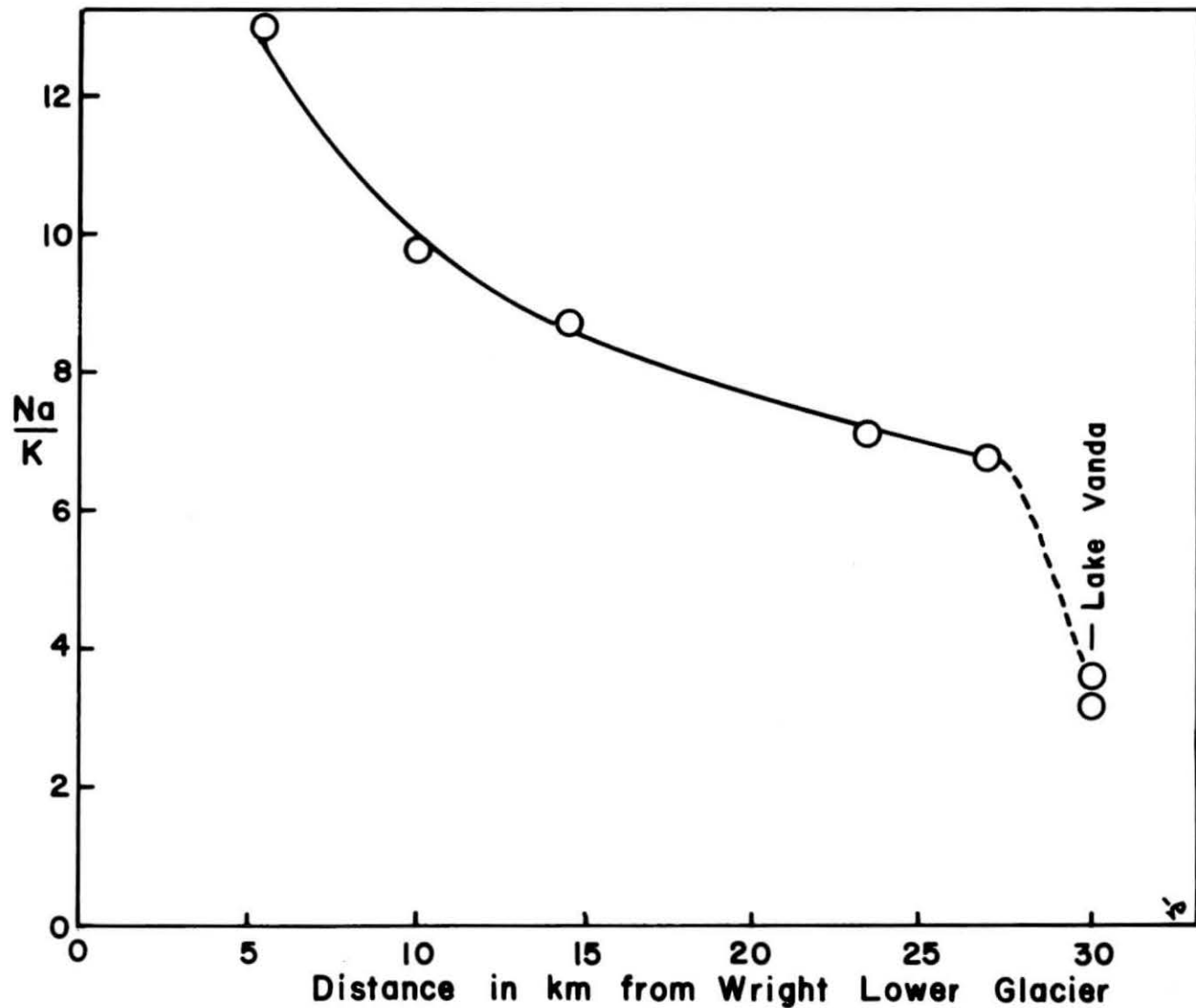
Figure 11.   Variation of the Na/K ratio in the Onyx River compared to the values of
this ratio in Layer 1 of Lake Vanda.

tends to decrease inland, the chemical composition of the ice from the upper surface of the Meserve Glacier might be considered to represent to a first approximation an average composition of ice and snow in the drainage basin of the lake. A series of samples of meltwater, névé, and ice from the Meserve Glacier were obtained from G. Holdsworth. Névé samples were collected within the accumulation basin of the glacier.

A tunnel 54 m in length has been excavated normal to the eastern edge of the Meserve Glacier about 300 m above the snout. Horizontal drifts were cut normal to the main tunnel at the 20, 48, and 54m positions. At the base of the glacier is a layer of "dirty" ice, designated the "amber" layer by Holdsworth. Its thickness is fairly uniform, varying between 45 and 60 cm. At the entrance to the tunnel, there is a wedge of clear ice under the amber layer, about 40 cm thick at the outside edge. It narrows under the glacier until it disappears approximately 10 m from the cliff edge. Bands of dirty ice within the clear ice overlying the amber layer were encountered during the tunneling, and some of these bands were sampled in addition to the basal amber layer and clear ice. Samples were also selected from the surface, from clear ice at depth, and dirty bands. Meltwater samples were collected near the tunnel entrance from a stream that flows near the base of the glacier during the summer.

The results of partial chemical analyses of these samples are compiled in Table 5. The concentrations of Ca^{+2}, Na^+ and K^+ in névé and ice from the surface of the Meserve Glacier are uniformly low compared to the meltwater discharged at the front of this glacier. A certain proportion of this increase in concentrations is probably due to sublimation of ice. However, the principal reason for the higher solute content of the meltwater is that the dirty ice at the base of the glacier and the soil below it contain soluble salts. These salts evidently are leached by meltwater and thereby contribute significantly to the solute content of meltwater discharged at the base of the Meserve Glacier, and also by other alpine valley glaciers in Wright Valley. The salt accumulations present in the soil and basal ice of the Meserve Glacier presumably formed before the glacier occupied its present position. The significance of the presence of salt in the soil below the base of the Meserve Glacier will be discussed in the final section of this report.

Table 5. Partial chemical analyses of névé, ice, and meltwater from the Meserve Glacier. Concentrations are in ppm.

Sample No.	Description	Ca	Mg	Na	K
1	Névé, accumulation basin	0.29	–	0.61	0.15
14	Névé, accumulation basin	0.48	–	0.54	0.45
N-11	Névé, accumulation basin	0.29	–	0.79	0.29
DV-66-017	Stream, base of glacier	5.3	1.38	8.3	0.80
DV-66-025	Stream, base of glacier	2.2	0.47	4.3	0.72
2-GH	Stream, base of glacier	3.51	–	4.4	0.55
3	Ice, surface of glacier	0.30	–	1.21	0.44
M-T	Ice, surface of glacier	0.38	0.24	0.43	0.15
10	Ice, clear, base	0.36	–	0.96	0.34
11	Ice, clear, base	0.33	–	1.40	0.85
12	Ice, clear, base	1.03	–	1.64	0.36
48-100-150	Ice, clear, base	0.33	–	0.33	0.01
5	Ice, clear, near amber layer	1.48	–	1.32	0.41
13	Ice, clear, near amber layer	0.91	–	0.80	0.13
M-B	Ice, amber layer	1.9	0.66	4.36	0.69
A-3.4	Ice, amber layer	2.43	0.66	8.20	1.24
6	Ice, amber layer	5.08	–	9.6	1.50
7	Ice, amber layer	6.76	–	10.0	1.82
8	Ice, amber layer	6.94	–	7.7	1.68
9	Ice, amber layer	4.90	–	5.3	1.50
48-0-20	Ice, amber layer	5.19	–	9.1	1.65
48-20-45	Ice, amber layer	5.20	–	3.8	1.50

IV. THE ISOTOPIC COMPOSITION OF STRONTIUM OF LAKE VANDA
AND OF SOLUBLE SALTS IN THE SOIL OF WRIGHT VALLEY

Isotope Geochemistry of Strontium

Naturally-occurring strontium consists of four stable isotopes: Sr^{84}, Sr^{86}, Sr^{87}, and Sr^{88}. At this mass range, the isotopes are not measureably fractionated by natural processes. Thus, variations in the isotopic composition of strontium result exclusively from the beta decay of naturally-occurring Rb^{87} to Sr^{87} according to the reaction:

$$_{37}Rb^{87} \rightarrow {}_{38}Sr^{87} + \beta^- + \nu + 0.27 \text{ Mev}$$
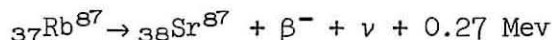
where β^- is a negatively charged beta particle emitted from the nucleus and ν is a neutrino.

The equation for radioactive decay

$$N = N_0 e^{-\lambda t} \qquad (1)$$

states that the number of parent atoms N remaining from an initial number of parent atoms N_O is a function of the decay constant λ and the length of time t that the system has been closed. From equation (1), the number of radiogenic Sr^{87} atoms resulting from decay of a given number of Rb^{87} atoms within a system closed since time t is:

$$*Sr^{87} = Rb^{87}(e^{\lambda t}-1) \qquad (2)$$

where λ is the decay constant of Rb^{87}. The decay constant of Rb^{87} most often used has been determined by Aldrich and others (1956), who obtained a value of 1.39×10^{-11} yrs^{-1}. Not all Sr^{87} in a sample is radiogenic; some Sr^{87} is inherited. Thus, the total amount of Sr^{87} can be represented by

$$Sr^{87}_{total} = Sr^{87}_O + *Sr^{87} \qquad (3)$$

where Sr^{87}_O represents the amount of Sr^{87} inherited in the system and $*Sr^{87}$ is the amount of radiogenic Sr^{87} formed within the system. Substituting equation (2) into equation (3), the total Sr^{87} content in a sample is represented by

$$Sr^{87}_{total} = Sr^{87}_O + Rb^{87}(e^{\lambda t}-1) \qquad (4)$$

This equation relates the total amount of Sr^{87} in a closed system to the amount that was inherited and the amount formed since the system became closed t years ago.

It is more convenient to measure isotope ratios, and since the number of Sr^{87} atoms does not change in a closed system, equation (4) can be stated with respect to Sr^{86}:

$$\left(\frac{Sr^{87}}{Sr^{86}}\right)_{total} = \left(\frac{Sr^{87}}{Sr^{86}}\right)_{o} + \frac{Rb^{87}}{Sr^{86}}\left(e^{\lambda t}-1\right) \qquad (5)$$

Thus, the total Sr^{87}/Sr^{86} ratio in a sample is a function of the initial Sr^{87}/Sr^{86} ratio, the Rb/Sr ratio, and the length of time the system has been closed.

The isotopic compositions of strontium of the McMurdo volcanics, the Ross Sea, and granitic rocks of Precambrian and Paleozoic age of the basement complex of Wright Valley are quite different and can be readily distinguished from one another. Therefore the isotopic composition of strontium in Lake Vanda was expected to identify its principal source unambiguously and thereby contribute to the solution of the basic problem which is to determine the origin of the salts and to explain the history of the lakes in the ice-free valleys. For this reason Sr^{87}/Sr^{86} ratios were measured for a suite of samples of bedrock and salts of Wright Valley, McMurdo volcanics from Ross Island and Victoria Land, and in a series of water and ice samples from the Onyx River, the Ross Sea, and Meserve Glacier. These ratios were then compared to the average Sr^{87}/Sr^{86} ratio of Lake Vanda to ascertain the principal source of the salts in the lake.

Lake Vanda

The isotopic composition of strontium in Lake Vanda was determined for 13 samples of brine collected by D. D. Koob in January, 1966. Two samples were analyzed in duplicate. The results are listed in Table 6 and plotted in Figure 12. The column labelled "$\bar{\sigma}$" includes values for the standard deviation of the mean for a number of sets of mass scans made during the course of measurement of the isotopic ratio. The concentrations of strontium in Lake Vanda are also listed in Table 6 and are shown in Fig. 12. The concentration of strontium, like that of other major ions varies with depth, ranging from 0.141 ppm under the ice cover of the lake to 67.05 ppm for a bottom sample 60 m below the surface. Chemoclines for strontium occur at depths identical to those of the other principal ions, i.e., at depths of 4.5, 14, and 50 m.

On the other hand, the isotopic composition of strontium was found to be constant within experimental error throughout the entire depth of Lake Vanda. The average Sr^{87}/Sr^{86} ratio for the lake is 0.7149 ± 0.0003 at the 99% confidence level. The fact that the strontium is isotopically homogeneous is consistent with the interpretation that the source of the strontium in each of the layers of Lake Vanda has remained the same during the lifetime of the lake.

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Table 6. The isotopic composition and concentration of strontium from a depth profile of Lake Vanda, Wright Valley.

Depth below surface	Sr^{87}/Sr^{86}*	σ	Sr, ppm
4 m	0.7149	0.0002	0.141
5			0.226
6			0.228
8			0.228
9	0.7150	0.0001	
10			0.256
12			0.298
14	0.7149	0.0004	
15			0.536
20	0.7151	0.0002	0.539
25	0.7146	0.0002	0.552
30	0.7147	0.0003	0.553
35	0.7149	0.0006	0.553
40	0.7147	0.0004	0.886
44	0.7150	0.0002	1.283
46			1.655
48	0.7150	0.0002	2.281
	0.7150	0.0003	
50			18.50
52	0.7148	0.0003	
54			39.16
56	0.7149	0.0006	50.90
58			58.97
60	0.7154	0.0002	67.05
	0.7150	0.0002	

Average = 0.7149 ± 0.0001

*Normalized to Sr^{86}/Sr^{88} = 0.1194.
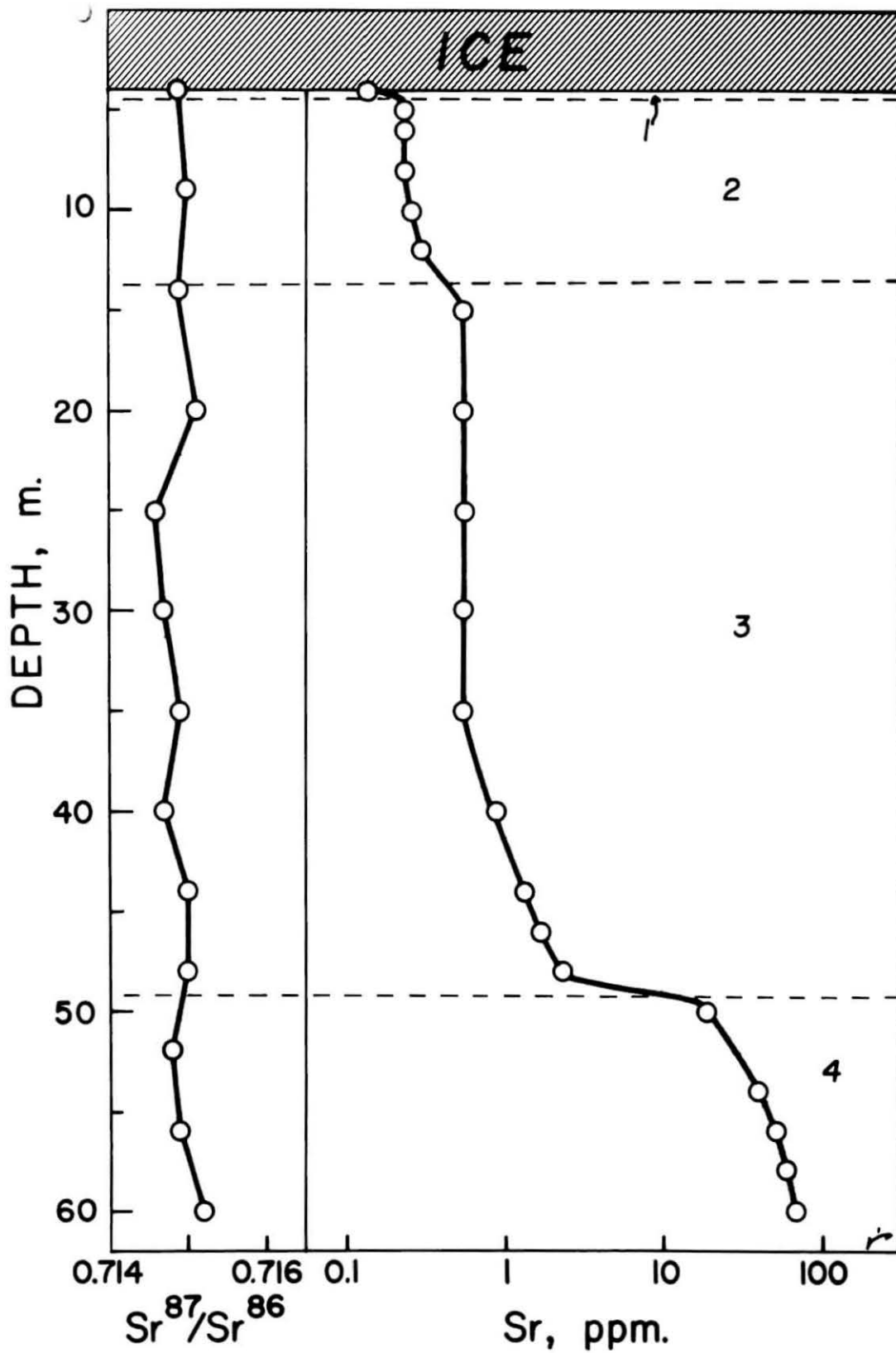
Figure 12.   The isotope composition and concentration of strontium
in Lake Vanda.

Onyx River

The isotopic composition of strontium was determined on three samples of water from the Onyx River and for one sample from the "Goodspeed Stream," a tributary of the Onyx River. All four samples were collected during the 1966-1967 field season; the sample locations are shown in Figure 1. The Sr^{87}/Sr^{86} ratios of the Onyx River and "Goodspeed Stream" samples are listed in Table 7. The average Sr^{87}/Sr^{86} ratio for these four samples is 0.7146 ± 0.0002. All four values are identical to each other within experimental limits. The average Sr^{87}/Sr^{86} ratio for these meltwater streams is very similar to the average Sr^{87}/Sr^{86} ratio of the strontium dissolved in Lake Vanda (0.7149).

On the basis of these data, it is apparent that the Onyx River is presently supplying to the lake strontium of the same isotopic composition as that found throughout the lake.

Ross Sea

If Lake Vanda and the Onyx River contain strontium predominantly derived from a marine source, then the isotopic composition of the strontium should be identical to that of sea water. The Sr^{87}/Sr^{86} ratios of two samples of water from the Ross Sea (McMurdo Sound) and one from Lyttleton Harbor, New Zealand, were measured. The results are given in Table 8. The average isotopic composition of strontium of the samples from the Ross Sea (0.7094) and Lyttleton Harbor (0.7095) agree with previous analyses of marine strontium from other localities (Faure, et al., 1967; Faure, et al., 1965; and Murthy and Beiser, 1968).

When the average Sr^{87}/Sr^{86} ratio of Lake Vanda (0.7149) is compared to the average Sr^{87}/Sr^{86} ratio of water from McMurdo Sound (0.7094), it is clear that the lake contains strontium whose isotopic composition is significantly different from that of the sea and that strontium in Lake Vanda contains more radiogenic Sr^{87} than does sea water.

Because on-shore winds prevail in the eastern part of Wright Valley during certain periods of the day, it is possible that marine salt is being transported inland by these winds. To ascertain whether or not marine strontium is being transported into Wright Valley, the Sr^{87}/Sr^{86} ratio was determined for a sample of ice from the Meserve Glacier. Approximately 10 kg of ice from the upper surface of the glacier was obtained from G. Holdsworth. The Sr^{87}/Sr^{86} ratio for this sample is 0.7090, and is therefore identical within experimental limits to the average Sr^{87}/Sr^{86} ratio of the Ross Sea (0.7094). Thus, strontium in the ice on the surface of the Meserve Glacier was probably transported into Wright Valley from the Ross Sea by easterly winds. This is the only marine strontium in Wright Valley that can be identified by its characteristic isotope composition. Its concentration in the ice is less than 0.22 ppb and is therefore so low that when the meltwater comes

Table 7. Isotopic composition of strontium in meltwater from Wright Valley.

Sample No.	Description	Sr^{87}/Sr^{86*}	$\bar{\sigma}$
DV-66-009	Water, Onyx River	0.7148	0.0004
DV-66-010	Water, Onyx River	0.7144	0.0004
DV-66-016	Water, Onyx River	0.7147	0.0005
DV-66-015	Water, Goodspeed stream	0.7145	0.0005
		Average = 0.7146 ± 0.0002	

*Corrected for fractionation assuming $Sr^{86}/Sr^{88} = 0.1194$.

Table 8. Isotopic composition of strontium in the Ross Sea, Meserve Glacier, and Lyttleton Harbor, New Zealand.

Sample No.	Locality	Sr^{87}/Sr^{86}*	$\bar{\sigma}$
DV-66-001	McMurdo Sound	0.7095	0.0001
DV-66-026	Cape Evans	0.7093	0.0003
	Average =	0.7094 ± 0.0001	
DV-67-002	Ice, upper surface, Meserve Glacier	0.7090	0.0005
DV-67-001	Lyttleton Harbor	0.7095	0.0003

*Corrected for fractionation assuming $Sr^{86}/Sr^{88} = 0.1194$.

in contact with salts in the soil, the marine strontium is mixed with such large quantities of strontium from the soil that this marine component looses its identity.

This observation can be extended to the whole of Wright Valley. Marine strontium may exist throughout the valley, transported inland mainly by easterly winds, but can only be identified in snow and ice that has not come into contact with the water-soluble salts of the bedrock and soil. Although some strontium of marine origin is dissolved in the meltwater, it is completely masked by strontium derived by weathering of silicate minerals.

McMurdo Volcanics

Wright Valley is located within the McMurdo volcanic province. Volcanic activity is indicated in the valley by the presence of cinder cones near the Bartley and Meserve Glaciers and near the Loop Morain. The possibility that volcanic activity has been an important source of the strontium in Lake Vanda can be tested by comparing the Sr^{87}/Sr^{86} ratios of the volcanics to the average Sr^{87}/Sr^{86} ratio of the lake.

Sr^{87}/Sr^{86} ratios were measured for 31 volcanic rocks, mainly basalts, from the McMurdo volcanic province of Victoria Land. Samples were collected from Ross Island and from the Transantarctic Mountains, as far north as Cape Hallett and southward to Brown Peninsula. Basalts from Wright and Taylor Valleys have been dated by the K/Ar method, with dates ranging from about 2 to 3.9 m.y. (Armstrong, et al., 1968; and Denton and Armstrong, 1968). A K/Ar date of 0.68 ± 0.14 m.y. has been obtained on anorthoclase from a kenyte flow on Ross Island (Treves, 1967).

The Sr^{87}/Sr^{86} ratios for these volcanic rocks are listed in Table 9. The strontium concentrations in ppm for these volcanics are also listed. The average Sr^{87}/Sr^{86} ratio is 0.7040. This value is in good agreement with analyses of strontium isotopes in basaltic rocks from other localities (Faure and Hurley, 1963; Hedge, 1966; and Powell, et al., 1965). It is clearly seen that the Sr^{87}/Sr^{86} ratio of the McMurdo volcanics (0.7040 ± 0.0003 at the 99% confidence level) is significantly lower than the Sr^{87}/Sr^{86} ratio for Lake Vanda (0.7149). This excludes the possibility that the bulk of the strontium in Lake Vanda could have had a local volcanic source.

Soil and Bedrock

Since the bulk of strontium in Lake Vanda has not been derived from either a volcanic or marine source, local soil and bedrock in Wright Valley was considered as a possible source. The isotopic composition of strontium was determined for 16 samples of soils from the valley. These were collected mainly from or near the valley floor

Table 9. Isotopic composition and concentration in ppm of strontium of McMurdo volcanics, Victoria Land.

Sample No.	Locality	Sr^{87}/Sr^{86*}	$\bar{\sigma}$	Sr ppm
257	Ross Island	0.7045	0.0002	747.5
258	Ross Island	0.7040	0.0004	1011
259	Ross Island	0.7042	0.0004	1009
263	Wright Valley	0.7043	0.0003	722.0
268	Cape Hallett	0.7037	0.0003	1150
269	Cape Hallett	0.7042	0.0003	1301
270	Cape Hallett	0.7054	0.0003	646.6
272	Ross Island	0.7045	0.0003	596.4
273	Ross Island	0.7045	0.0006	712.0
275	Dailey Islands	0.7047	0.0004	832.6
277	Ross Island	0.7028	0.0003	433.6
281	Ross Island	0.7044	0.0005	1276
282	Ross Island	0.7032	0.0003	782.7
287	Ross Island	0.7044	0.0003	940.9
288	Inaccessible Island	0.7047	0.0005	908.8
301	Mount Overlord	0.7044	0.0004	577.9
302	Mount Overlord	0.7047	0.0002	100.7
304	Lower Campbell Gl.	0.7034	0.0003	738.0
305	Lower Campbell Gl.	0.7041	0.0005	1135
327	Taylor Valley	0.7048	0.0003	1090
341	Dromedary Platform	0.7032	0.0003	1215
342	Howchin Glacier	0.7033	0.0003	810.3
343	Taylor Valley	0.7038	0.0002	775.0
344	Taylor Valley	0.7035	0.0004	972.4
346	Taylor Valley	0.7039	0.0005	1077
21001	Brown Peninsula	0.7036	0.0003	912.4
21058	Brown Peninsula	0.7044	0.0003	1146
21248	Black Island	0.7037	0.0003	1004
DV-66-106	Wright Valley	0.7035	0.0003	673.4
DV-66-170	Taylor Valley	0.7035	0.0002	1005
DV-66-182A	Wright Valley	0.7042	0.0003	708.4

Average = 0.7040

*Corrected for fractionation assuming Sr^{87}/Sr^{86} = 0.1194.

between Lake Vanda and Wright Lower Glacier; the sample localities are shown in Figure 1. In some of the samples, two Sr^{87}/Sr^{86} ratio measurements were made: one analysis on the salt removed by a water or dilute acid leach, and the other on the total salt-free soil. The water leach is to be preferred because (1) water leaching does not attack the unweathered silicates, and (2) it simulates conditions likely to occur in the environment of the ice-free valleys when meltwater flows through the soil.

The Sr^{87}/Sr^{86} ratios for the salts and total soils are given in Table 10. Three facts are immediately evident by examination of data in the table. First, all the Sr^{87}/Sr^{86} ratios of samples along the floor of Wright Valley are concentrated within a very narrow range, 0.7141-0.7149, with only two exceptions. These two samples (DV-66-203 and WVM-24-7-36) are not included in the average; they were collected in the "Clark Valley" and from a locality high on the south wall of Wright-Valley, respectively. These samples are probably not as representative of the bedrock of Wright Valley as samples collected from the valley floor and have been omitted for this reason. Second, the average Sr^{87}/Sr^{86} ratio is 0.7146. This value is identical to the average Sr^{87}/Sr^{86} ratio of the Onyx River (0.7146) and Lake Vanda (0.7149). Third, the Sr^{87}/Sr^{86} ratios of water-soluble salts are identical to those of the total salt-free soil, within the precision of the measurements.

Two samples of sediment from Lake Vanda were dissolved and their Sr^{87}/Sr^{86} ratios were measured. One sample, V-62, was collected in the center of the main lobe of the lake at a depth of about 62 m. This is the same locality where the series of water samples was collected for this study. The other sample, DV-68-201, was collected from the smaller eastern lobe at 30 m depth by D. Greegor in February, 1968. The Sr^{87}/Sr^{86} ratios of these two sediment samples were found to be 0.7148 and 0.7149 for samples V-62 and DV-68-201, respectively. The isotope composition of strontium in the sediments is identical to that of strontium in the water of Lake Vanda, within experimental limits.

The isotope composition of strontium was measured on suites of samples from most of the major units of the bedrock in Wright Valley as shown in Table 11. The selection of these samples was biased to provide the greatest possible range in chemical composition (and thus the Sr^{87}/Sr^{86} ratio) within each suite. Therefore, these analyses do not represent what could be considered an average value for each rock type, but rather should be regarded as an indication of the range of the Sr^{87}/Sr^{86} ratio within each unit. In spite of the biased sampling, it is noteworthy that of the 23 Sr^{87}/Sr^{86} ratios given in Table 11, 16 samples are in the range 0.712-0.718. It is reasonable to conclude from these measurements that a value of 0.715 represents an average of the Sr^{87}/Sr^{86} ratios for the bedrock of Wright Valley.

The observation that the Sr^{87}/Sr^{86} ratio of the water-soluble salts is identical to the Sr^{87}/Sr^{86} ratio of the total salt-free samples is

Table 10. Sr^{87}/Sr^{86} ratios of salts and soils from the floor of Wright Valley.

Sample No.	Location	Sr^{87}/Sr^{86*}	$\bar{\sigma}$	Remarks
DV-66-201-V9	18 m from N edge, L. Vanda	0.7144	0.0004	water leach
DV-66-201-V16	100 m from N edge, L. Vanda	0.7148	0.0005	water leach
DV-66-202	E side, Meserve Glacier	0.7144	0.0003	water leach
DV-66-203	Clark Valley	0.7119	0.0002	water leach
DV-66-204	E. Wright Valley	0.7145	0.0002	water leach
DV-66-205	E. Wright Valley	0.7145	0.0004	water leach
DV-66-206	near Onyx River, between L. Vanda and Bull Pass	0.7144	0.0003	HCl leach, pH 3-4
DV-66-207	near Onyx River, east of Bull Pass	0.7148	0.0003	HCl leach, pH 3-4
DV-66-207	"	0.7145	0.0003	HCl leach, 0.5 $\underline{N}$
DV-66-207	"	0.7148	0.0003	Total soil
DV-66-208	near Onyx River, below Bartley Glacier	0.7141	0.0002	HCl leach, pH 3-4
V-62	Sediment, L. Vanda, 62 m	0.7148	0.0004	total sample
DV-68-201	Sediment, L. Vanda, 30 m	0.7149	0.0003	total sample
WLG-0-12	base, Wright Lower Glacier	0.7149	0.0003	water leach
WLG-0-12	"	0.7144	0.0004	total sample
BP-0-12	Bull Pass	0.7148	0.0003	water leach
WVM-9-2-12	near Meserve Glacier	0.7145	0.0003	water leach
WVM-23-2-9	"	0.7142	0.0003	water leach
WVM-23-9-19	"	0.7142	0.0004	water leach
WVM-24-7-36	"	0.7157	0.0003	water leach

*Corrected for fractionation assuming $Sr^{86}/Sr^{88} = 0.1194$.

Table 11. Sr^{87}/Sr^{86} ratios of the major units of the bedrock, Wright Valley.

Unit	Sample No.	Sr^{87}/Sr^{86}*	$\bar{\sigma}$
Olympus Granite-Gneiss	DV-66-108	0.7171	0.0007
	DV-66-126	0.7207	0.0002
	DV-66-135	0.7146	0.0003
	DV-66-138	0.7155	0.0003
Dais Granite	DV-66-115	0.7174	0.0004
	DV-66-118	0.7185	0.0003
	DV-66-123A	0.7285	0.0003
	DV-66-123B	0.7280	0.0004
	DV-66-134	0.7154	0.0003
	DV-66-154	0.7235	0.0005
Vida Granite	DV-66-136	0.7147	0.0002
	DV-66-142	0.7161	0.0003
	DV-66-148A	0.7146	0.0003
	DV-66-148B	0.7149	0.0003
	DV-66-149	0.7145	0.0003
	DV-66-157A	0.7232	0.0004
	DV-66-157B	0.7205	0.0002
Ferrar Dolerite	310[a]	0.7121	0.0007
	368	0.7134	0.0003
	DV-66-105	0.7116	0.0002
	DV-66-155	0.7125	0.0002
	DV-66-160	0.7118	0.0003
Asgard Formation marble	DV-66-177	0.7088[b]	

*Corrected for fractionation assuming $Sr^{86}/Sr^{88} = 0.1194$

[a]Sample from Taylor Valley

[b]ratio determined by R. J. E. Montigny

unexpected. A difference in the Sr^{87}/Sr^{86} ratios would be expected due to differences in susceptibility to weathering of various minerals. The more resistant minerals, such as mica and potassium feldspar, have high Rb/Sr ratios and contain strontium with a relatively high Sr^{87}/Sr^{86} ratio. More readily weathered minerals, such as carbonates, pyroxenes, and plagioclase, have low Rb/Sr ratios and therefore have correspondingly lower Sr^{87}/Sr^{86} ratios. The similarity of the isotopic composition of strontium in the bedrock and the soil compared to that of the water-soluble salts in the soil suggests that chemical weathering releases strontium into solution in surface water whose isotope composition is similar to that of the strontium present in the rocks. These observations agree with recent results reported by Dasch (1969), who studied the isotope composition of strontium in several weathering profiles. On the other hand, Dasch and others (1966) and Hart and Tilton (1966) have shown that deep sea sediments and the sediment at the bottom of Lake Superior are not in isotopic equilibrum with the strontium in solution in the water. The apparent discrepancy in the weathering behavior of sediment in contact with water is not yet understood, and will be discussed more fully in the last section of this report.

Conclusions

The isotopic composition of strontium of Lake Vanda is compared with those of the possible sources of salts in Figure 13. It is readily seen that the water in the lake contains more radiogenic strontium-87 than does sea water or the McMurdo volcanics. On the other hand, Sr^{87}/Sr^{86} ratios of water-soluble salts from the floor of Wright Valley and the total soil material are identical to the average Sr^{87}/Sr^{86} ratio of Lake Vanda.

These observations justify the conclusions that (1) strontium in the salts in Wright Valley has been derived by chemical weathering of local soils and bedrock and (2) strontium in these salts is dissolved in meltwater and is transported to Lake Vanda by the Onyx River.
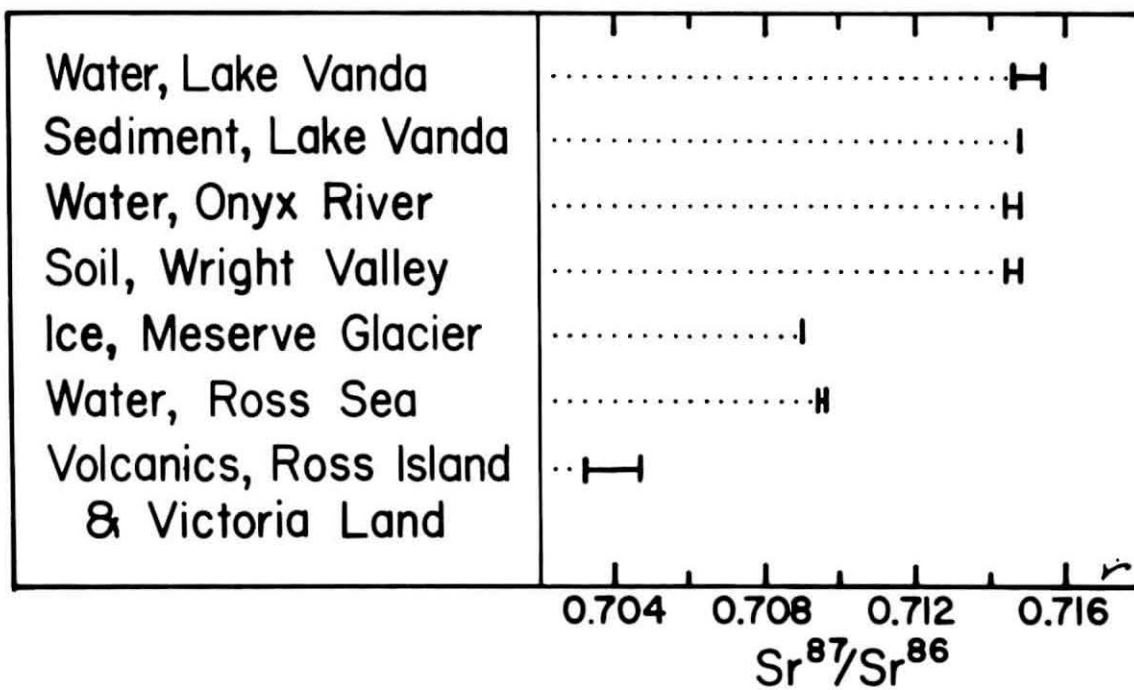
Figure 13. The isotope composition of strontium in Wright Valley.

V. THE CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES
OF WATER IN LAKE BONNEY

Introduction

Lake Bonney is situated in an enclosed basin in the westernmost part of Taylor Valley, about 30 km from the coast. The lake occupies the lowest part of the valley. The altitude of the surface of the lake is probably less than 100 m above sea level, but the exact altitude is in question at the present time. Reported altitudes include values of 38 m (Angino, et al., 1964), 56 m (Yamagata, et al., 1967), and 98 m (U. S. G. S., Taylor Galcier topographic map). Lake Bonney extends almost 6 km in an east-west direction; the western end of the lake reaches almost to the eastern end of the Taylor Glacier shown in Figure 14. Although scientific investigations in Taylor Valley began during the first Antarctic expedition of Scott in 1901, the first limnological reconnaissance of Lake Bonney was carried out during the summer of 1961-1962 by Armitage and House (1962).

Lake Bonney is composed of two lobes separated by the Bonney Riegel. From measurements taken during the 1961-1962 Antarctic summer (Angino, et al., 1964), the western lobe is about 2.0 km in length and 612 m wide. The eastern lobe is 3.8 km long and 864 m wide. Maximum recorded depths of the lake are 21 m for the western lobe and 33 m for the eastern lobe (Yamagata, et al., 1967). The size of the lake in the past was much more extensive, as indicated by strand lines that surround the lake. These strand lines represent high water levels of a much larger proglacial lake dammed to the east by a glacier that moved inland from McMurdo Sound. Lake Bonney may be a remnant of this larger, older lake, whose strand lines can be traced as far as the eastern end of Taylor Valley.

Lake Bonney appears to be increasing in size since the turn of the century. In 1903 the width of the channel connecting the two lobes was only 5.2 m, while in 1964, it was 42.3 wide (Shirtcliffe, 1964). This increase in channel-width corresponds to an increase of 9.2 m in the lake level between 1903 and 1964.

The lake is perennially ice-covered except for a narrow moat about the edge that forms during the warmest part of the summer. The average thickness of the ice-cover is about 4 m, ranging from 3.5 to 4.3 m (Ragotzkie and Likens, 1964), similar to the thickness of ice on Lake Vanda. Angino and others (1964) suggest that this thickness of ice represents a state of equilibrium between thermal conductivity of the ice, rate of sublimation, and temperature of the ice-free valleys. Meltwater is supplied to Lake Bonney during summer mainly from Taylor Glacier and from alpine galciers surrounding the lake basin to the north and south.
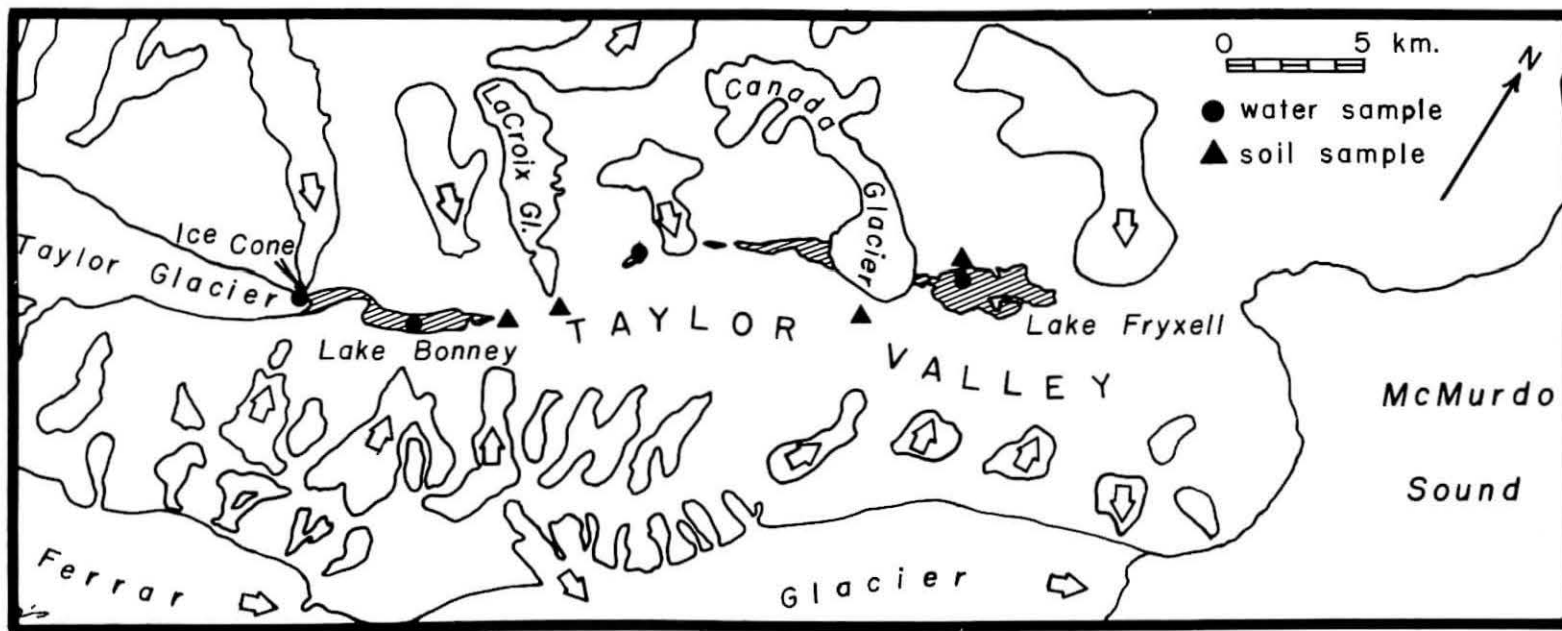
Figure 14. General map of Taylor Valley showing sample locations

The chemical, physical, and isotopic measurements reported here
were obtained from a series of water samples collected by D. D. Koob
during the 1965-1966 field season close to the center of the eastern
lobe of Lake Bonney. Some additional data of other investigators have
been included to provide more complete documentation of the chemical
and physical properties of the lake. These data are acknowledged in
the text and tables.

Density of Water Samples

Density determinations for Lake Bonney are given in Table 12 and
are plotted in Figure 15. The density increases with depth in such a
way that five discrete layers can be recognized. These layers are
shown in Figure 15 and have been numbered 1 through 5 from the top down.

Layer 1 extends from the ice-water interface at an average depth
of 4 m below the surface of the lake and extends to a depth of 8 m.
The density of this layer is 0.999 g/ml and is similar to that of dis-
tilled water at the same temperature. Layer 2 extends from above 9 m
to a depth of about 10.5 m. The density of this layer is 1.008 g/ml.
Layer 2 is only 2 m thick. The density difference between it and
Layer 1 is small, but is significant. For this reason, and because
previous investigators collected samples at larger depth intervals,
the presence of this layer has not been previously reported. Layer 3
extends from a depth of 10.5 m to 17.5 m. This layer is transitional
between Layers 2 and 4 and consequently its density varies from a little
more than 1.008 g/ml to about 1.155 g/ml at a depth of about 17.5 m.
Layer 4 extends from a depth of 17.5 m to about 28 m. The density of
brine in this layer increases downward only slightly, from about 1.115
g/ml at the top of the layer to 1.182 g/ml at the base. Layer 5 extends
from about 28 m to the bottom of Lake Bonney. In this layer, the den-
sity increases from 1.182 g/ml to 1.193 g/ml. Where the lake has been
sampled to a depth of 32 m, a density of 1.20 g/ml has been reported
(Yamagata, et al., 1967).

The density stratification of Lake Bonney is apparently permanent.
Boundaries of the major density layers determined by several investi-
gators over the past few years have been identical within the limits
of measurement. The increase of density with depth is directly related
to the amount of salts dissolved in the water. On the basis of con-
ductivity measurements by Angino and others (1964), density layering
throughout the lake is horizontal, except at the edges where seasonal
temperature variations are encountered.

Temperature of the Water

The temperature profile for the eastern lobe of Lake Bonney is
shown in Figure 16, based on data obtained by D. D. Koob and tabulated

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Table 12. Density profile of Lake
Bonney, Taylor Valley.

Depth below surface	Density, g/ml at 20°C
4 m	0.9992
5	0.9987
6	0.9994
7	0.9994
8	1.0023
9	1.0080
10	1.0075
11	1.0283
12	1.0559
13	1.0775
14	1.1103
15	1.1259
16	1.1410
17	1.1509
18	1.1613
19	1.1643
20	1.1699
21	1.1703
22	1.1744
23	1.1744
24	1.1750
25	1.1787
26	1.1764
27	1.1791
28	1.1820
29	1.1820
30	1.1932
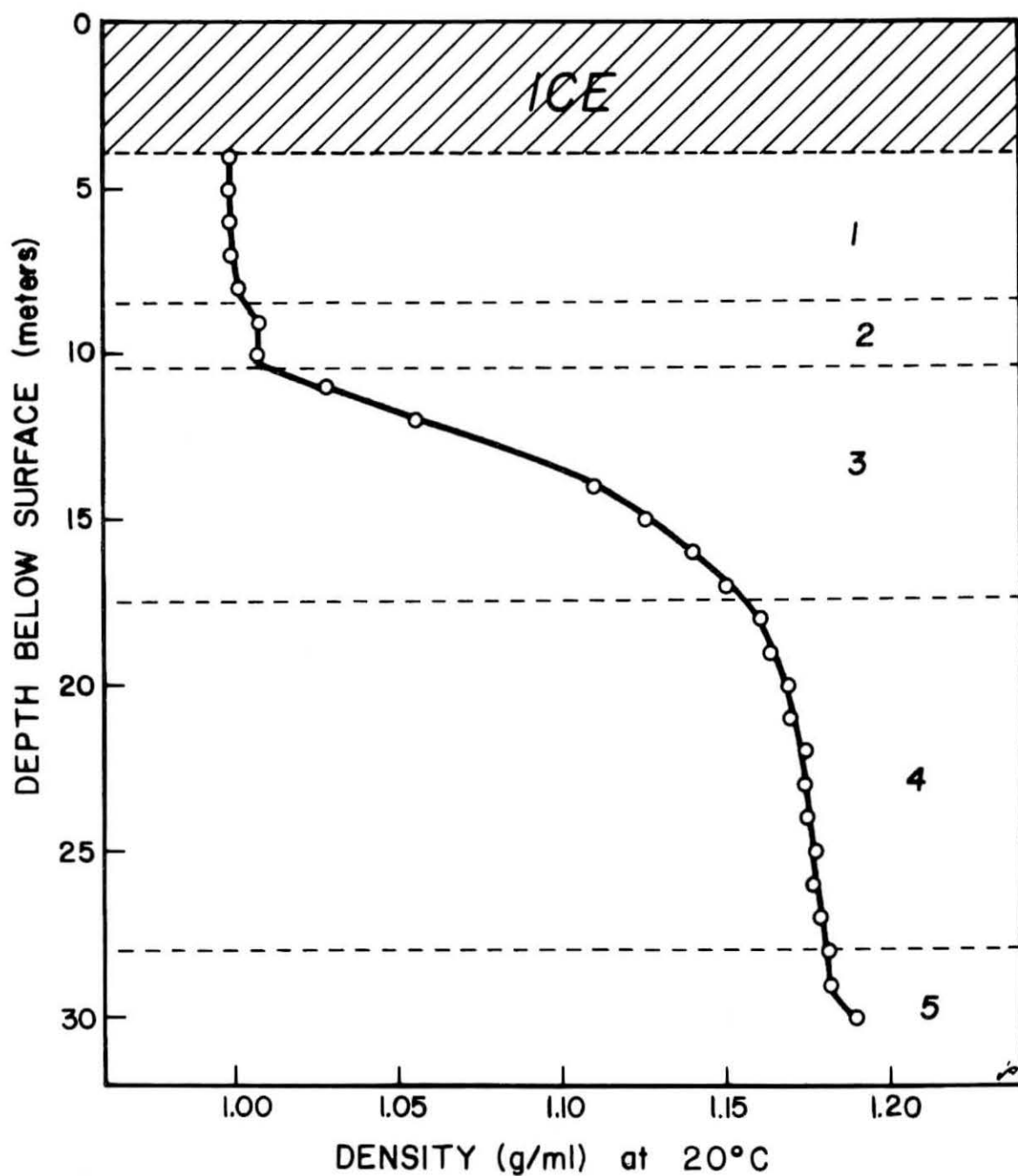
Figure 15. Variation of density with depth in Lake Bonney.
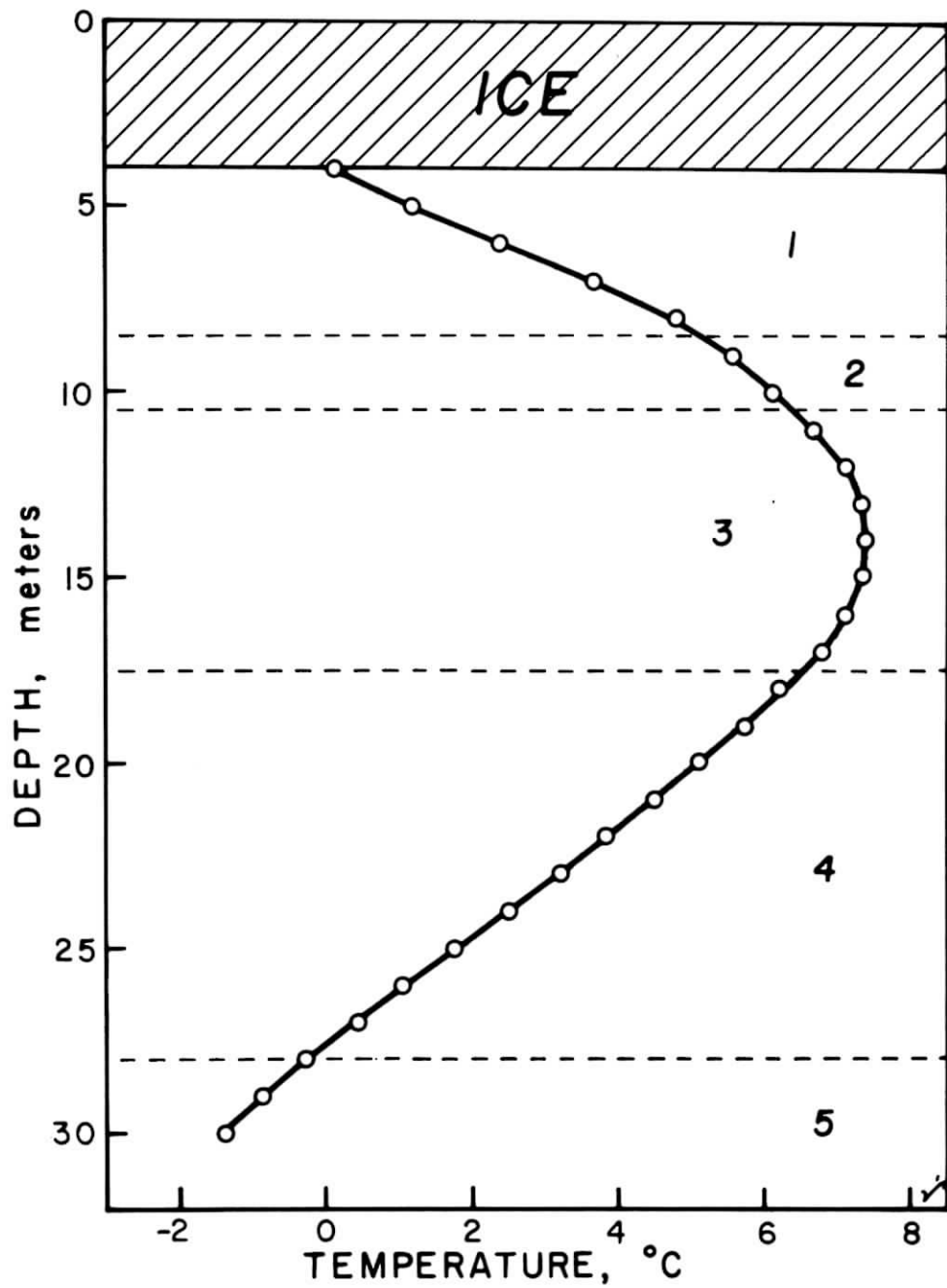
Figure 16. Variation of temperature with depth in Lake Bonney.

Table 13.   Temperature profile of Lake
            Bonney, Taylor Valley.*

Depth below surface	Temperature °C
4 m	0.11
5	1.17
6	2.39
7	3.67
8	4.78
9	5.56
10	6.11
11	6.67
12	7.11
13	7.33
14	7.39
15	7.33
16	7.11
17	6.78
18	6.22
19	5.72
20	5.11
21	4.50
22	3.83
23	3.22
24	2.50
25	1.77
26	1.05
27	0.44
28	-0.28
29	-0.89
30	-1.39

*Measurements made by
D. D. Koob, 1966.

in Table 13. Temperatures were measured using a Precision Scientific oxygen analyzer equipped with a thermometer.

The temperature of water in contact with the base of the ice-cover is +0.11°C and increases to a maximum of +7.39°C at a depth of about 14 m below the surface. Below 14 m the temperature decreases continually to -1.39°C at the bottom of the lake. The maximum temperature occurs in the middle of Layer 3 in which the density is rapidly changing. Hoare and others (1964), Shirtcliffe (1964) and Shirtcliffe and Benseman (1964) have shown that the temperature distribution in Lake Bonney can be accounted for on the basis of entrapment of solar radiation by the stratified brines existing at depth in the lake.

The Chemical Composition of Water in Lake Bonney

Concentrations of Mg^{+2}, Ca^{+2}, Sr^{+2}, Na^+ and K^+ have been determined for a suite of water samples from Lake Bonney by the methods outlined earlier. The data are compiled in Table 14 and are plotted as a function of depth in Figures 17, 18, 19 and 20. The geochemistry of strontium in Lake Bonney will be discussed elsewhere in this report.

Comparison of the concentration-depth profiles for the major cations shows that they are very similar to the density gradient in the lake and that the zonation of the water proposed on the basis of density is confirmed by the variation of the solute content with depth. Table 15 includes previous analyses of water from Lake Bonney taken from the literature which are presented here for the sake of completeness.

The zonation of Lake Bonney suggested by the concentration and density gradients differs somewhat from that of Lake Vanda. Lake Bonney contains essentially two layers of water: a very dense brine at the bottom (Layers 4 and 5) overlain by a layer of fresh water (Layers 1 and 2). The fresh water grades downward into the dense brine through a transition layer (3) which is approximately 7 m thick. The transition zones between the brine layers in Lake Vanda appear to be thinner and are all less than one meter in thickness. Zone 5 in Lake Bonney occupies the basal portion of Layer 4. This zone is characterized by a marked increase in density and sodium concentration, while the concentrations of Ca^{+2}, Mg^{+2} and Sr^{+2} decrease.

The variation of the composition of the solute content of the water in terms of mole per cent with depth is shown in Figure 21. The relative proportions of the major cations below a depth of about 15 m appear to be constant to a first approximation. Na^+ is the dominant species, followed by Mg^{+2} and Ca^{+2}. Near the bottom the proportion of Na^+ increases slightly while that of Mg^{+2} decreases. Above 15 m the proportions of Na^+ and Mg^{+2} change with depth. Na^+ is dominant, but decreases from about 83 mole per cent at a depth of 6 m to about 55 mole per cent at 15 m. Mg^{+2}, on the other hand, increases from 10 to

Table 14. Concentrations in ppm of the principal cations in Lake Bonney, Taylor Valley.

| Depth below surface	Mg^{+2}	Ca^{+2}	Sr^{+2}	Na^+	K^+
4 m	80.5	77.3	0.7345	452	29.5
5	42.1	86.6	0.5827	268	22.6
6	92.2	56.9	0.5949	473	52.2
7	135.5	79.7	0.8124	689	44.9
8	367.2	125	1.750	1,550	90.3
9	902	250	3.026	3,410	210
10	1,085	220	3.502	3,130	245
11	4,288	458	7.066	7,460	504
12	8,629	855	12.28	13,700	900
13	12,660	858	15.95	17,800	1,180
14	18,200	1,142	21.84	23,200	1,410
15	20,680	1,346	24.98	25,800	1,620
16	22,870	1,373	33.69	30,100	1,990
17	24,030	1,470	-	32,100	2,150
18	25,180	1,471	37.19	34,600	2,510
19	25,550	1,478	-	36,200	2,430
20	26,000	1,489	38.89	37,700	2,570
21	26,070	1,477	-	38,100	2,510
22	26,550	1,461	38.70	39,600	2,650
23	26,400	1,524	39.37	39,000	2,570
24	26,520	1,514	38.93	38,900	2,670
25	26,860	1,527	39.92	40,500	2,720
26	26,690	1,545	39.02	40,000	2,620
27	26,750	1,529	39.41	40,000	2,620
28	26,850	1,512	38.21	41,900	2,840
29	26,150	1,459	37.02	43,400	2,710
30	25,790	1,434	35.88	47,300	2,690
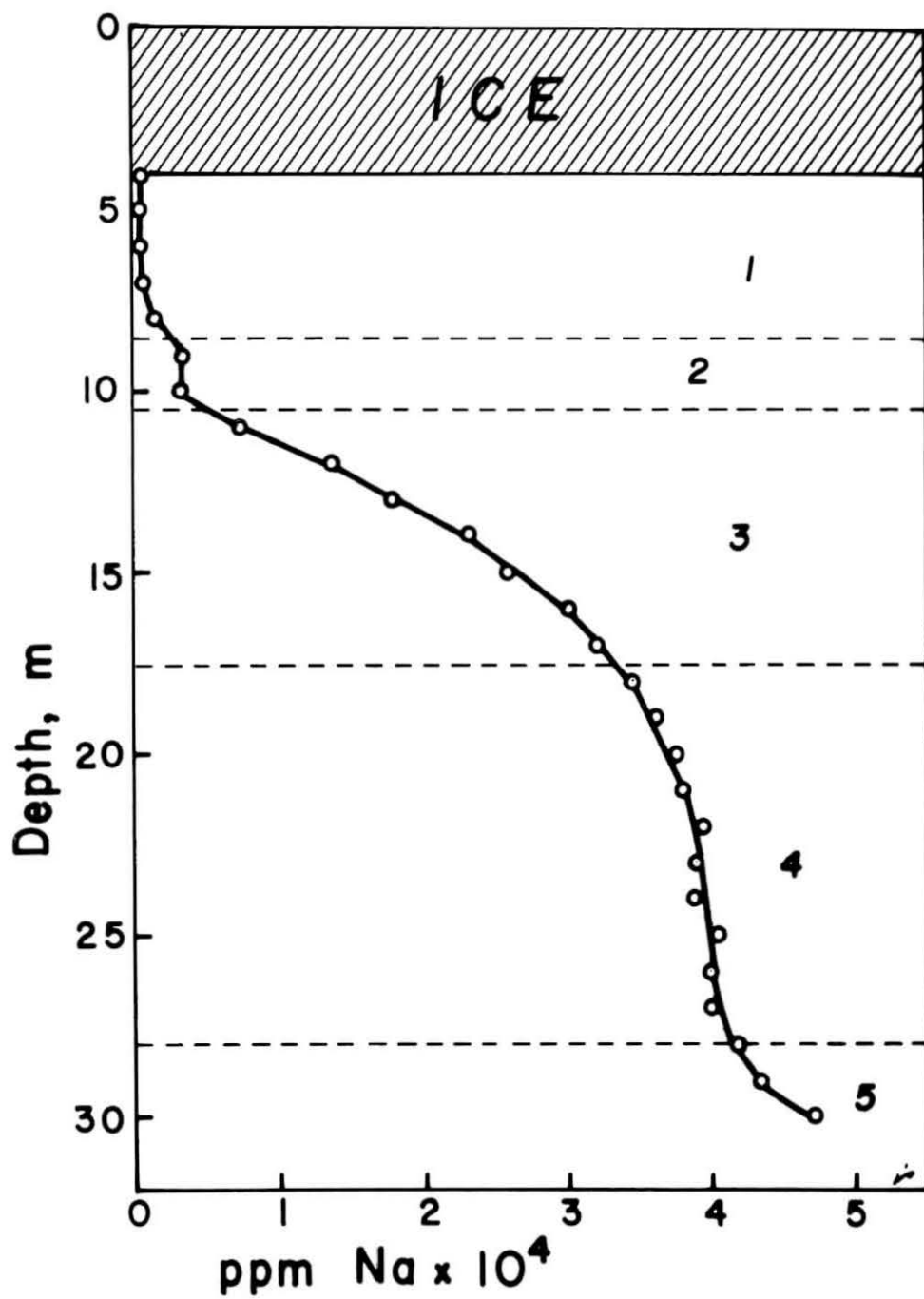
Figure 17. Variation of the sodium concentration with depth
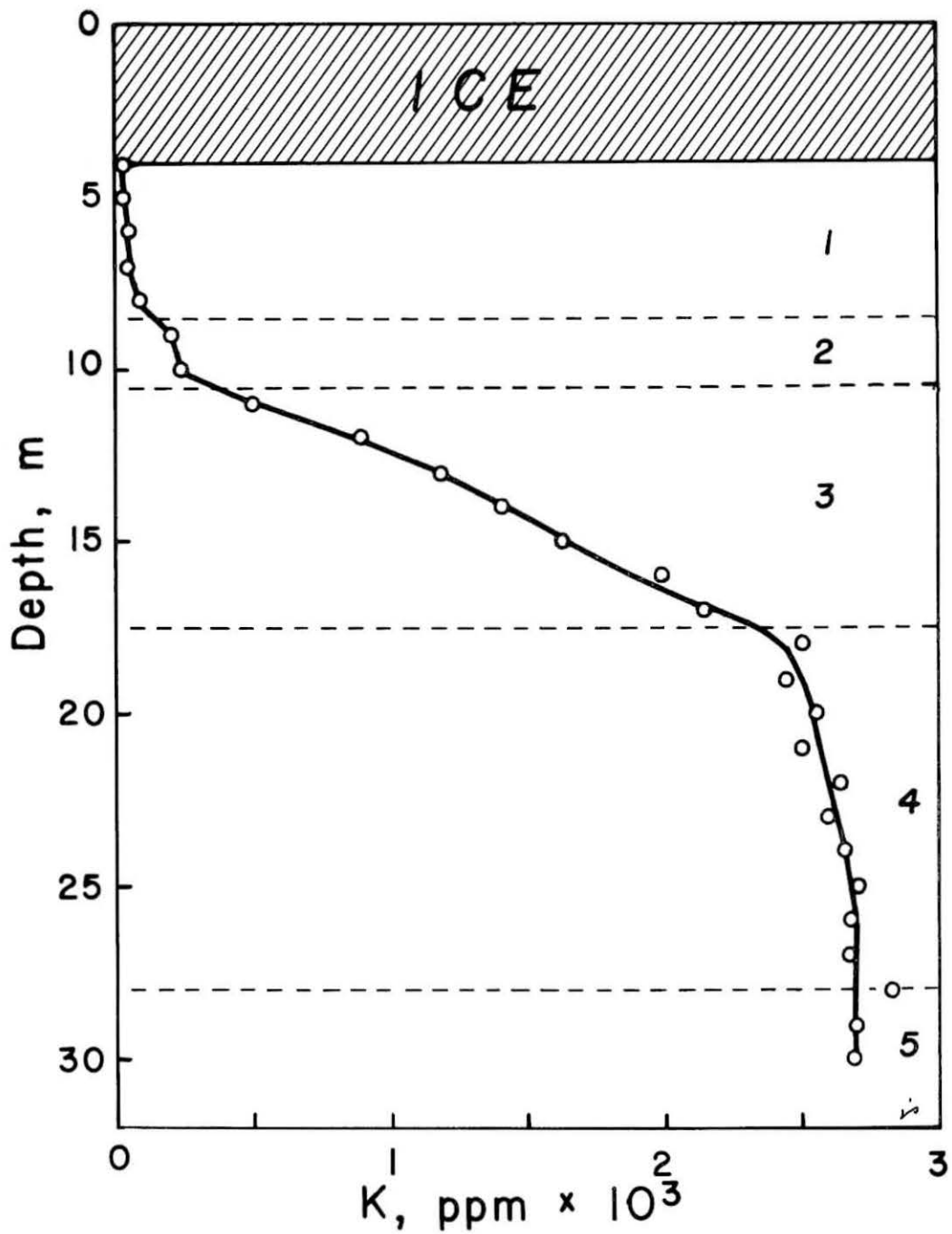in Lake Bonney.

Figure 18.   Variation of the potassium concentration with
depth in Lake Bonney.
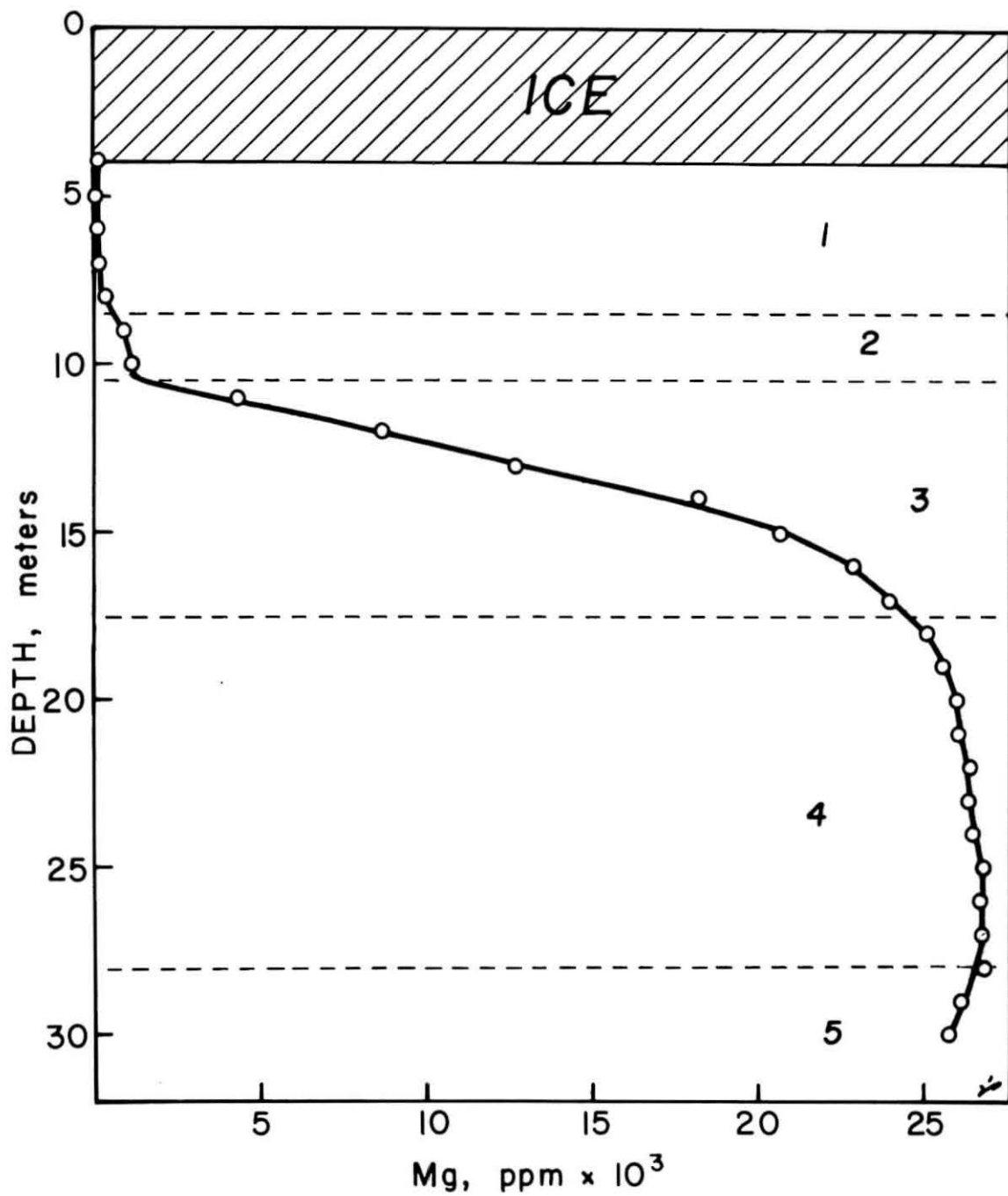
Figure 19. Variation of the magnesium content with depth in Lake Bonney.
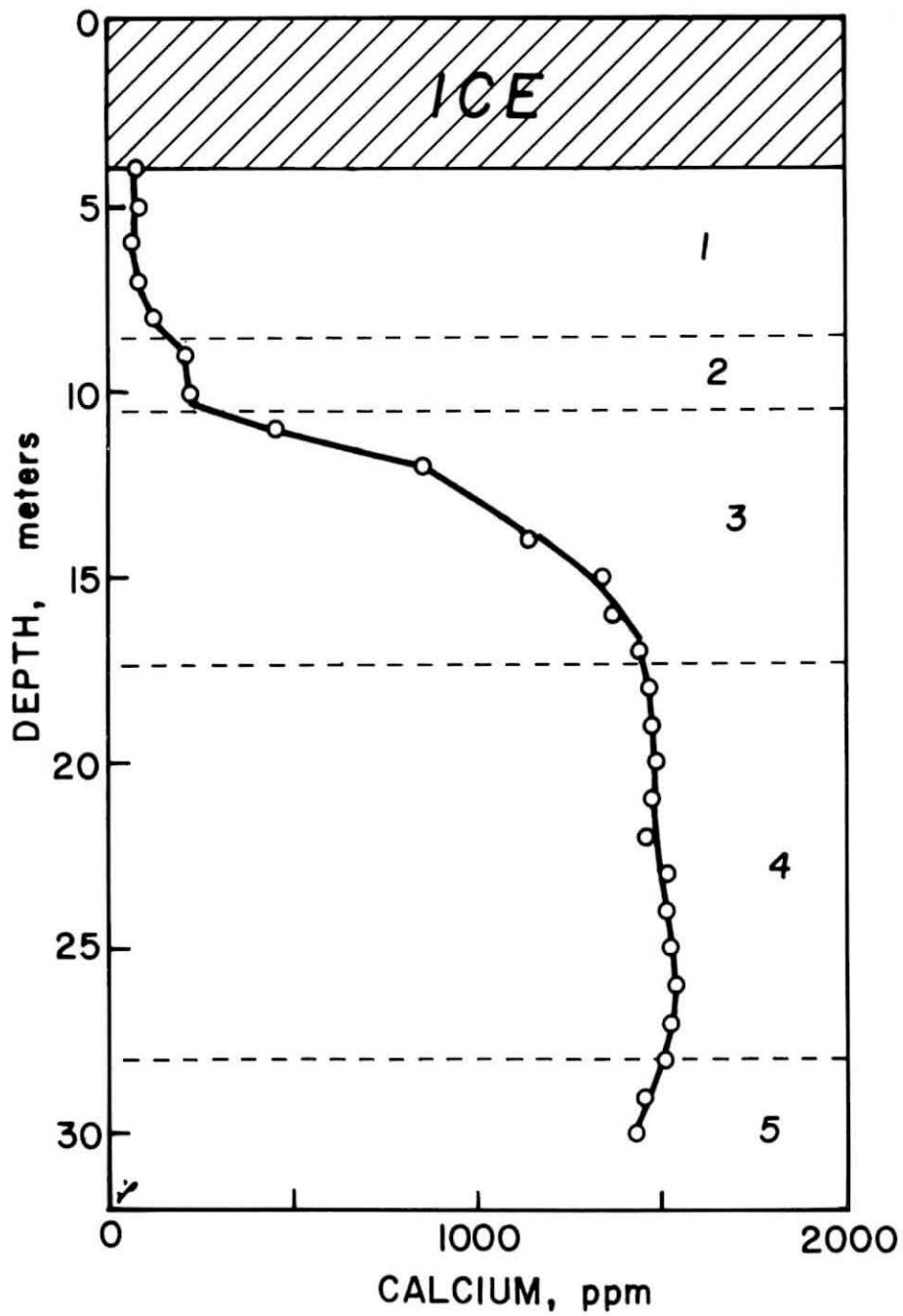
Figure 20. Variation of the calcium concentration with depth in Lake Bonney.

Table 15. Concentrations in ppm of the principal ions in Lake Bonney, Taylor Valley*.

Depth below surface	Mg^{+2}	Ca^{+2}	Na^+	K^+	Cl^-	$SO_4^=$	HCO_3^-
5 m	52	68	284	22	592	200	36
	(64.4)	(74.4)	(335)	(25.6)	(734)	(160)	
8	163	80	740	54	1,660	120	60
(10.5)	(1,762)	(343)	(3,920)	(417)	(12,420)	(473)	
11	909	250	2,880	231	7,540	380	168
14	12,800	1,190	16,600	1,300	66,200	925	656
(14.5)	(16,700)	(1,260)	(16,780)	(1,540)	(82,470)	(2,480)	
17	24,600	1,470	32,100	2,360	124,000	868	382
(19)	(25,470)	(1,430)	(33,300)	(2,950)	(129,700)	(2,560)	
20	25,500	1,520	35,100	2,610	134,000	3,090	290
(22)	(25,290)	(1,430)	(32,600)	(2,750)	(131,600)	(2,480)	
(25)	(27,270)	(1,600)	(38,800)	(3,730)	(142,800)	(2,710)	
26	27,000	1,640	39,300	2,930	144,600	3,140	143
(28.5)	(26,970)	(1,810)	(33,900)	(3,090)	(144,500)	(2,760)	
29	26,300	2,310?	41,200	2,900	143,000	3,380	133
32	24,200	1,650	51,400	2,840	162,000	3,320	100
	(26,030)	(1,540)	(36,000)	(2,870)	(154,500)	(2,950)	

*Data are from Angino and others (1964b) and, in parentheses, Yamagata and others (1967).

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Figure 21. Variation of the cation composition with depth in Lake Bonney.

42 mole per cent in the same interval. The chloride ion is by far the most abundant anion ranging from 86 mole per cent at 5 m to 99 mole per cent at 32 m. The sulfate ion is important only in the upper 5 m of water, where it ranges from about 11 per cent to less than 2 per cent. The bi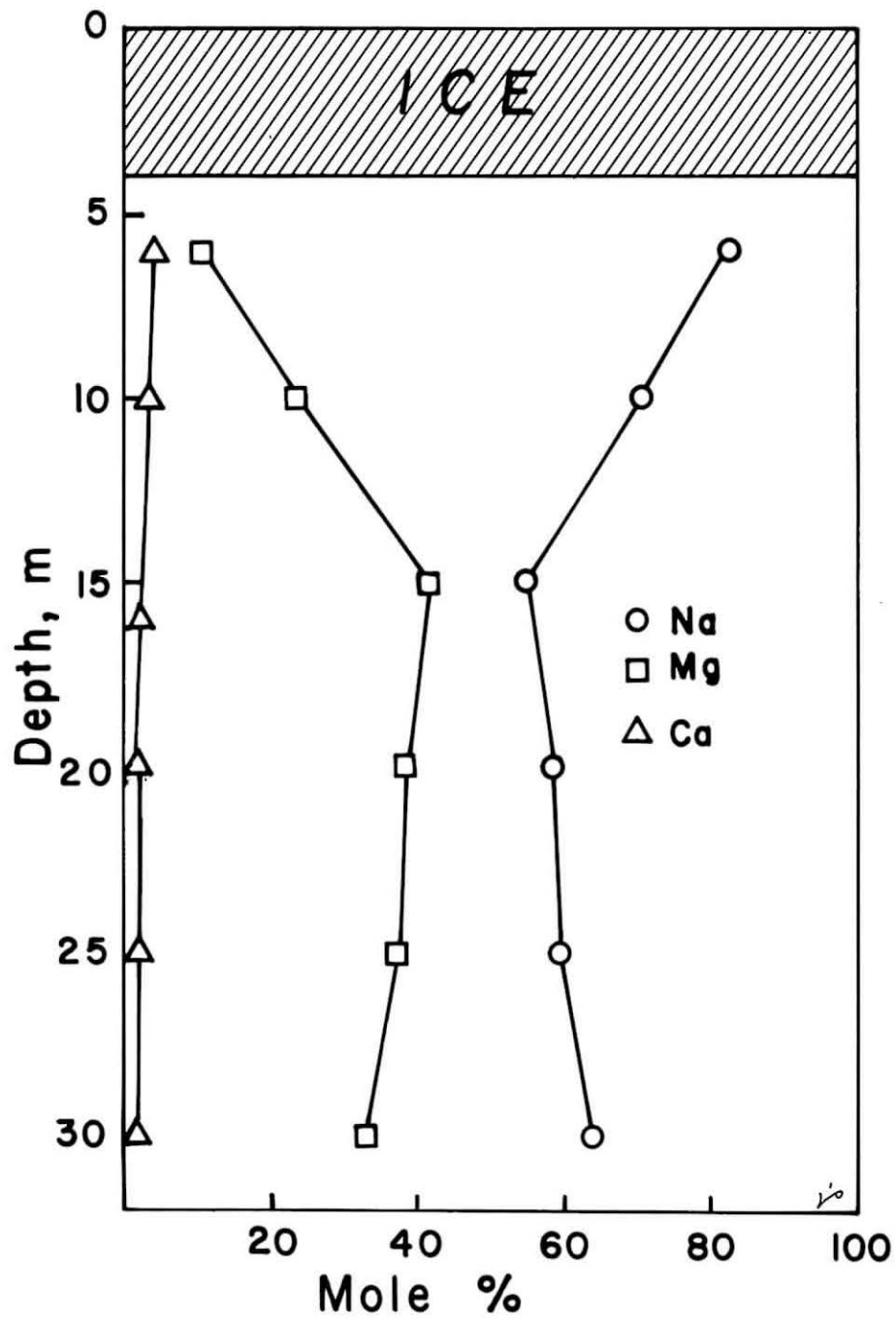carbonate ion is similarly restricted to the upper 6 m of water (3 to 1 per cent) and makes up less than one per cent below a depth of 11 m. The salts in Lake Bonney therefore consist primarily of chlorides of sodium and magnesium. Calcium chloride, which is the most abundant salt in Lake Vanda, is much less important in Lake Bonney.

The nature of the transition zone (Layer 3) between upper, relatively fresh water and the bottom brines is of interest. Shirtcliffe (1964) and Shirtcliffe and Benseman (1964) assumed that it is a diffusion boundary. In order to ascertain whether this transition zone is governed by diffusion or mixing processes, concentration-concentration curves were plotted. Figure 22 shows the relationship between concentrations of Mg^{+2} and K^+ in the transition zone. The concentrations of these two ions are obviously not linearly related, suggesting that diffusion rather than physical mixing is occurring between the brine of Layer 4 and the water in Layer 2. The relationship between concentrations of Sr^{+2} and Ca^{+2} is shown in Figure 23. An interesting discontinuity occurs here for water samples taken from depths below 15 m. In the upper part of the transition zone the Sr^{+2} concentration appears to be a linear function of Ca^{+2} concentration. The water below 15 m appears to be depleted in Ca^{+2} relative to Sr^{+2}. This change in the Ca/Sr ratio may be caused by the precipitation of $CaSO_4$.
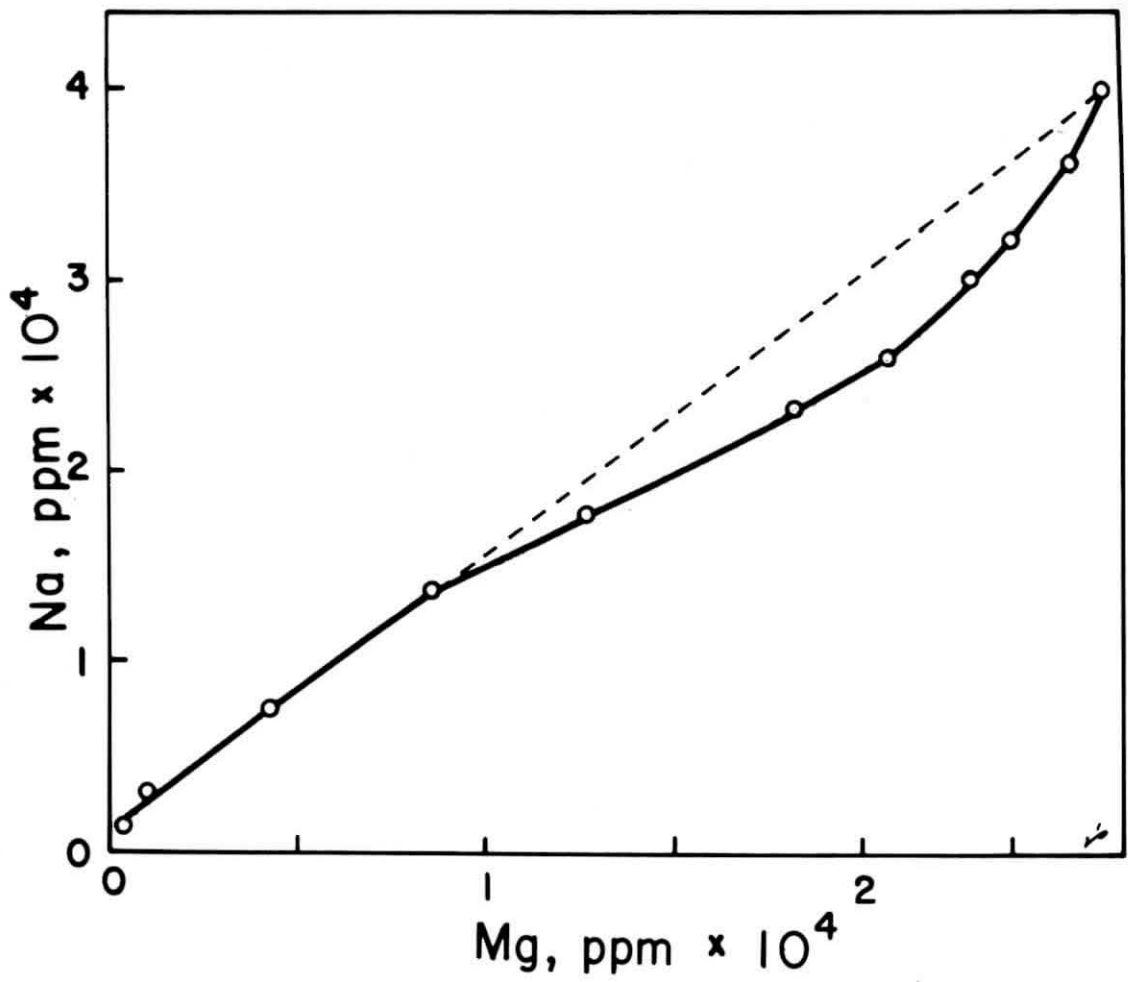
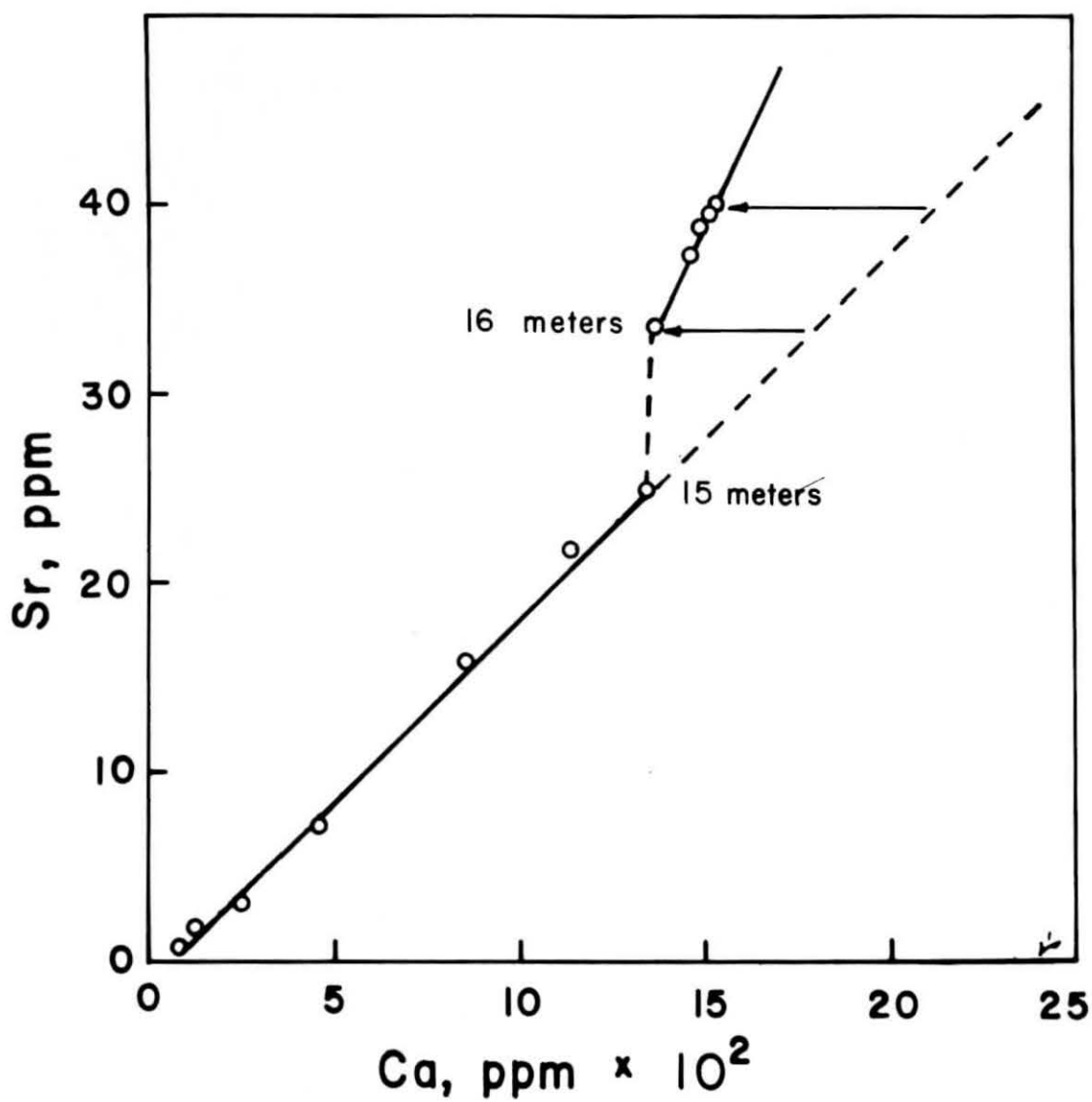Figure 22. Relationship between concentration of sodium and magnesium in Layer 3 of Lake Bonney.

Figure 23. Relationship between concentrations of strontium and calcium in Layer 3 of Lake Bonney.

VI. THE ISOTOPIC COMPOSITION OF STRONTIUM OF LAKE BONNEY
AND OF SOLUBLE SALTS IN SOILS OF TAYLOR VALLEY

Lake Bonney

The isotopic composition of strontium of Lake Bonney was measured in a series of water samples collected at different depths. Unfortunately, the suite of soil samples from Taylor Valley was not as complete as that of Wright Valley. Only four samples were available for analysis. These soils represent the entire length of Taylor Valley of which only one pertains specifically to the drainage basin of Lake Bonney. No samples of meltwater from streams discharging into Lake Bonney were available. The sample locations are shown in Figure 24 and the Sr^{87}/Sr^{86} ratios are compiled in Tables 16 and 17.

The concentration of strontium, like that of the other major ions varies with depth, as shown in Figure 14, ranging from 0.735 ppm at a depth of 4 m to a maximum of 39.9 ppm at a depth of 25 m. The strontium content then decreases to 35.9 ppm at the bottom of the lake at a depth of 30 m below the surface.

In contrast, the isotopic composition of strontium is constant within experimental error throughout the entire depth profile of Lake Bonney. The average Sr^{87}/Sr^{86} ratio for Lake Bonney is 0.7130 ± 0.0002. Therefore, although the lake is compositionally and density stratified, it is homogeneous with respect to strontium isotopes. The fact that the strontium is isotopically homogeneous is consistent with the interpretation that the source of strontium of Lake Bonney has remained the same during the lifetime of the lake.

"Taylor Red Melt"

The isotopic composition of strontium in salts of the "Taylor Red Cone" was of particular interest because of the possibility that this phenomenon may be contributing significant amounts of salts to Lake Bonney. One sample of the meltwater from the "Taylor Red Cone" was available for analysis, and the Sr^{87}/Sr^{86} ratio was found to be 0.7136 (Table 17). This ratio is very similar to the average Sr^{87}/Sr^{86} ratio for Lake Bonney (0.7130). Although the Sr^{87}/Sr^{86} ratio for the "Taylor Red Melt" is slightly higher than the average value for the lake, the difference is probably not significant and, for the present, the isotopic composition of strontium from the cone may be considered identical to that in Lake Bonney.

"Suess Pond"

The isotopic composition of strontium was measured for water from a pond between the Suess and LaCroix Glaciers. (The name "Suess Pond"
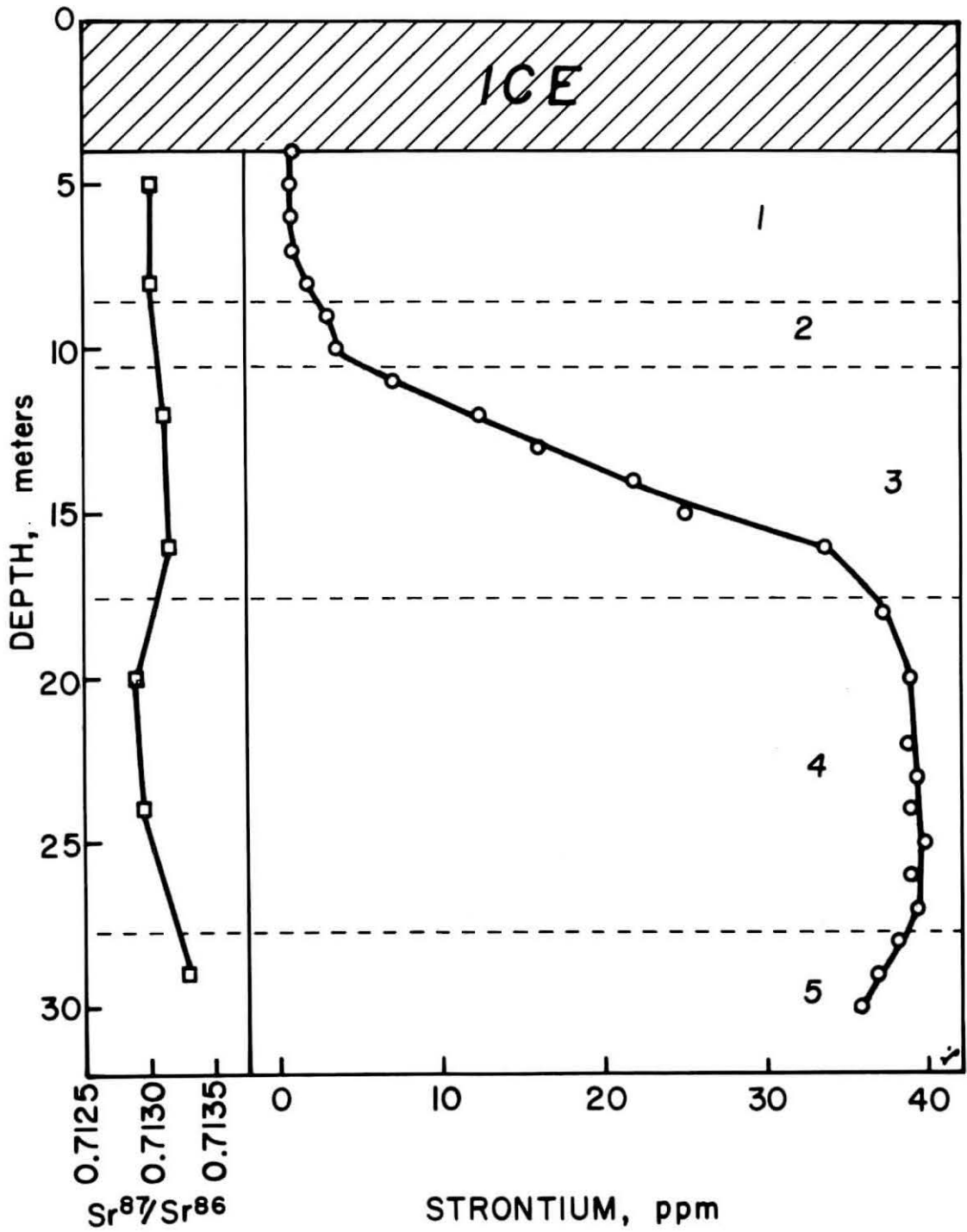
Figure 24. Variation of the isotope composition and concentration of strontium with depth in Lake Bonney.

Table 16. The isotopic composition and concentration
of strontium from a depth profile of
Lake Bonney.

Depth below surface	Sr^{87}/Sr^{86}*	$\bar{\sigma}$	Sr, ppm
4 m			0.7345
5	0.7130	0.0003	0.5827
6			0.5949
7			0.8124
8	0.7130	0.0002	0.7150
9			3.026
10			3.502
11			7.066
12	0.7131	0.0004	12.28
13			15.95
14			21.84
15			24.98
16	0.7130	0.0002	33.69
	0.7133	0.0002	
18			37.19
20	0.7129	0.0002	38.89
	0.7129	0.0005	
22			38.70
23			39.37
24	0.7130	0.0003	38.93
	0.7129	0.0005	
25			39.92
26			39.02
27			39.41
28			38.21
29	0.7133	0.0002	37.02
30			35.88

average = 0.7130

*Corrected for fractionation assuming
$Sr^{87}/Sr^{86} = 0.1194$.

Figure 17. Sr^{87}/Sr^{86} ratios of "Taylor Red Cone," "Suess Pond," Lake Fryxell, and water-soluble salts from soils of Taylor Valley.

Sample No.	Description	Sr^{87}/Sr^{86}*	
TRM-1	Water, "Taylor Red Cone"	0.7136	0.0002
DV-66-019	Water, "Suess Pond"	0.7112	0.0003
DV-68-001	Water, Lake Fryxell	0.7090	0.0004
DV-68-201	Soil, near Lake Bonney, water leach	0.7136	0.0003
DV-68-201	Soil, near Lake Bonney total salt-free soil	0.7136	0.0003
DV-68-202	Soil, near LaCroix Glacier, water leach	0.7125	0.0003
DV-68-203	Soil, near Canada Glacier, water leach	0.7101	0.0003
DV-68-204	Soil, near Lake Fryxell, water leach	0.7089 0.7092	0.0003 0.0006

*Corrected for fractionation assuming Sr^{86}/Sr^{88} = 0.1194.

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is unofficial, but it serves to identify it for this purpose.) The
Sr^{87}/Sr^{86} ratio was found to be 0.7112 (Table 17). This ratio is inter-
mediate between the Sr^{87}/Sr^{86} ratio of Lake Bonney (0.7130) and that of
the Ross Sea (0.7094). Therefore, this pond is probably receiving salts
from a source that is not the same as that of Lake Bonney, nor has the
bulk of the strontium been derived from a marine source.

Lake Fryxell

The isotopic composition of strontium was determined for a sample
of water collected from the moat at the edge of Lake Fryxell. The $Sr^{87}/$
Sr^{86} ratio was 0.7090 (Table 17) and is significantly different from
that of Lake Bonney (0.7130), but essentially identical to that of the
Ross Sea (0.7094).

The altitude of Lake Fryxell is only about 22 m above sea level
(Henderson, et al., 1966) and the lake is less than 5 km from McMurdo
Sound. Although the saline waters in Lake Fryxell could represent the
remnants of Glacial Lake Llano (Péwé, 1966), it is also reasonable to
expect that much of the salt in the lake could be of marine origin.
The highest strand lines at nearby Marble Point are about 20 m above
present sea level (Nichols, 1965, 1966). Thus, it is possible that the
eastern portion of Taylor Valley has been flooded by the sea. Salts in
Lake Fryxell may also be derived from the sea by wind transport, since
onshore winds prevail at the eastern end of the valley.

The Sr^{87}/Sr^{86} ratio of water from Lake Fryxell indicates that the
bulk of the strontium could have been derived directly or indirectly
from the sea. This conclusion can be extended to include most of the
calcium, magnesium, and chloride ion, as well as sodium and potassium.
Differences in ratios of major ions from those of sea water are probably
a result of precipitation of insoluble compounds such as alkaline earth
carbonates and sulfates.

Soil

Four samples of soil were collected from Taylor Valley by
K. R. Everett and R. E. Behling. These were obtained from (1) the area
east of Lake Bonney; (2) the valley floor at the base of the LaCroix
Glacier; (3) near the foot of the Canada Glacier; and (4) near the edge
of Lake Fryxell. Water-soluble salts were removed from these soils and
the Sr^{87}/Sr^{86} ratios were measured (Table 17).

The Sr^{87}/Sr^{86} ratio for the water-soluble fraction of salts in the
soil sample from the vicinity of Lake Bonney was found to be 0.7136.
The Sr^{87}/Sr^{86} ratio for the total salt-free soil was also 0.7136. This
value is similar to the average Sr^{87}/Sr^{86} ratio of Lake Bonney (0.7130).
The strontium in the water-soluble salt is significantly different from

strontium found in the Ross Sea (0.7094) and McMurdo volcanics (0.7040). Therefore, the bulk of the strontium appears to have been derived from a source other than the sea or volcanic activity. Since strontium in Lake Bonney has a higher radiogenic Sr^{87} content that that of either the Ross Sea or McMurdo volcanics, it is probable that the bulk of the strontium in the lake has been derived from local bedrock.

A soil sample was collected near the foot of the LaCroix Glacier, located to the east of Lake Bonney. Meltwater of this glacier discharges into Lake Bonney. The Sr^{87}/Sr^{86} ratio of water-soluble salts in this soil was 0.7125. This value is not significantly different from the Sr^{87}/Sr^{86} ratio of Lake Bonney. Strontium of this composition is probably being transported to Lake Bonney by meltwater streams.

Water-soluble salt from a soil sample collected near the foot of the Canada Glacier has a Sr^{87}/Sr^{86} ratio of 0.7101. This strontium is significantly less radiogenic than that in Lake Bonney. Meltwater from this glacier does not enter Lake Bonney. Instead, it enters Lake Fryxell to the east and Lake Chad to the west.

While strontium in salts of most of the previously discussed soils in Taylor and Wright Valleys had Sr^{87}/Sr^{86} ratios similar to that of the parent material, it is possible that most of the strontium in the soils in the eastern part of Taylor Valley have been derived from the sea.

The fourth soil sample was collected near Lake Fryxell. Duplicate determinations of the water-soluble material gave Sr^{87}/Sr^{86} ratios of 0.7089 and 0.7092. The isotopic composition of strontium in salts and soils near Lake Fryxell is therefore identical to strontium in both the lake and the Ross Sea. This suggests that salts found in both the soil and Lake Fryxell have been derived from a marine source.

Conclusions

The Sr^{87}/Sr^{86} ratios for samples of the lakes and soils of Taylor Valley decreases from the western end of the valley to the east. The Sr^{87}/Sr^{86} ratios for Lake Bonney, soil from the lake basin, and "Taylor Red Cone" were found to be 0.7130, 0.7136, and 0.7136, respectively. A few kilometers to the east, salt near the LaCroix Glacier has a Sr^{87}/Sr^{86} ratio of 0.7125. "Suess Pond," east of the LaCroix Glacier, contains strontium with a Sr^{87}/Sr^{86} ratio of 0.7112. Salts in soil from near the Canade Glacier, still farther to the east, contain strontium with a Sr^{87}/Sr^{86} ratio of 0.7101. Finally, farthest to the east and nearest to McMurdo Sound, the strontium in Lake Fryxell and salts in the nearly soil had the lowest Sr^{87}/Sr^{86} ratios measured, 0.7090 and 0.7091, respectively. This gradual change in the Sr^{87}/Sr^{86} ratio is shown graphically in Figure 25. The Sr^{87}/Sr^{86} ratio decreases as McMurdo Sound is approached. By the time Lake Fryxell is reached, all the strontium in the soluble salts is identical to marine strontium.
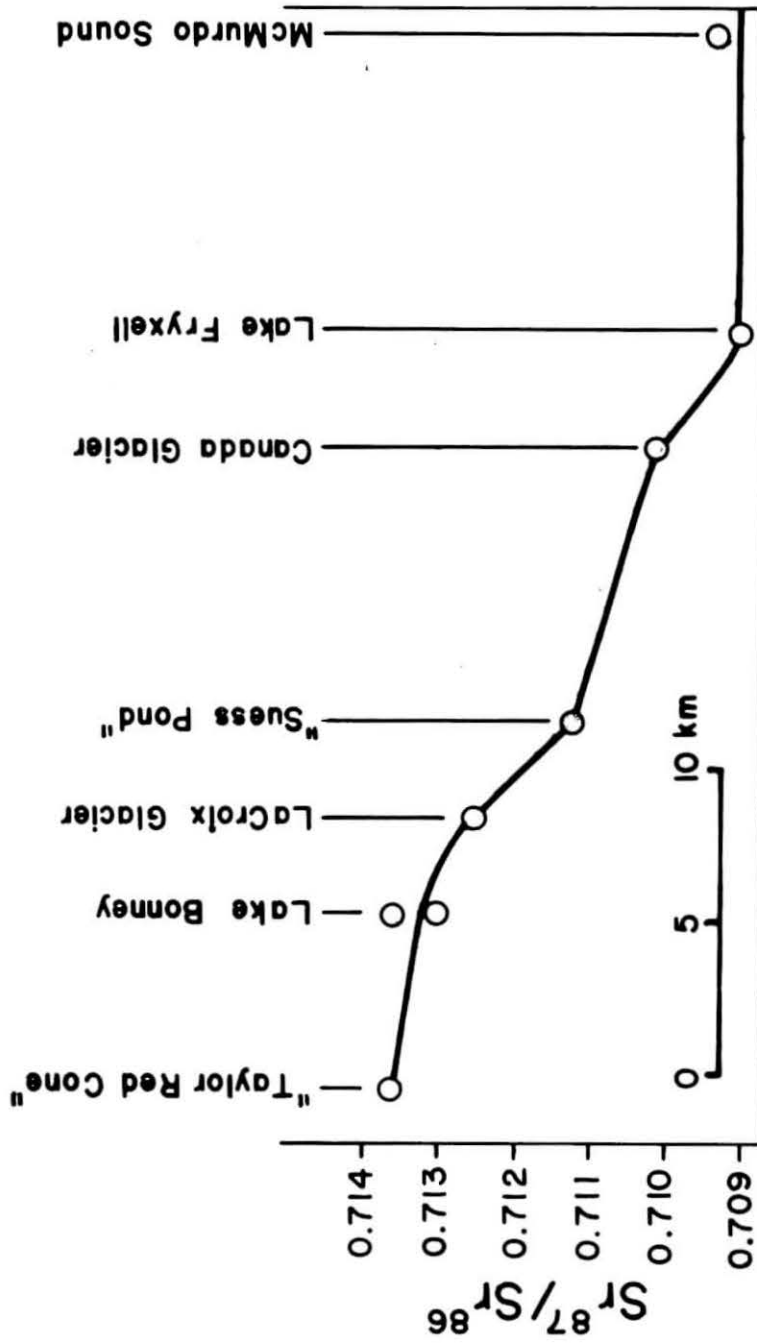
Figure 25. Profile of the Sr^{87}/Sr^{86} ratio of salts in soil samples collected along the bottom of Taylor Valley.

VII.   THE GEOCHEMICAL EVOLUTION OF LAKE VANDA AND LAKE BONNEY

The data presented in the previous sections of this report are consistent with the following conclusions:

1.   The isotope composition of strontium in both lakes is not compatible with that of sea water or the volcanic rocks of the McMurdo volcanic province.

2.   The strontium in both lakes is very similar isotopically to strontium in meltwater streams and soluble soil salts and could have been derived by chemical weathering of bedrock and soil in the valleys.

3.   The water in both lakes is strongly and permanently stratified with respect to the concentrations of the major ions. In each lake a number of discrete brines can be recognized on the basis of their characteristic salinity and chemical composition.

4.   In spite of strong concentration gradients, the isotope composition of strontium in both lakes is constant and invariant with depth. This indicates that the strontium entering the lakes has had the same isotope composition and was probably derived from the same general source.

On the basis of these conclusions a model can be outlined which describes the geochemical evolution of the lakes. This model is based on the following assumptions:

1.   The lakes were formed and are maintained by discharge of glacial meltwater.

2.   The salts dissolved in the lakes originated as the solute content of glacial meltwater and are derived as weathering products of local bedrock and soil, supplemented by salts of marine origin which are transported inland by air masses and precipitated in snow.

3.   The salinity of the water under the ice-cover increases as the result of freezing of water and exclusion of ions.

4.   Water is lost from the lakes primarily by sublimation of ice at the surface.

5.   The salinity of the brine layers in the lakes is determined by the balance between sublimation of ice and discharge of meltwater and is therefore a sensitive indicator of past climatic conditions in the ice-free valleys.

With these assumptions which define the proposed model, the formation of brines in the lakes can be outlined as follows: under stable climatic conditions diluted meltwater enters the lakes each summer and

forms a thin layer of fresh water overlying the dense water at depth. Water in this layer freezes, leading to a concentration of the solute content accomplished by an increase in density. The denser water then sinks until its density matches that of the deeper water it displaces. This process is repeated annually and gradually leads to the formation of a brine of uniform density and chemical composition.

Depending on the balance of discharge of meltwater and the rate of sublimation of ice, three modes of operation of this process can be defined.

1. Discharge exceeds loss by sublimation: If more meltwater enters the lake each year than is lost by sublimation, the lake level will rise and the freezing-out of the salts will produce a layer of dilute brine of uniform density and chemical composition whose thickness will increase annually, but whose salinity will remain constant.

2. Discharge equals loss by sublimation: When discharge and the rate of sublimation are in balance, the lake level will fluctuate seasonally but will show no net gain or loss. The brine layer being formed under the ice will not increase in thickness, but its salinity will rise each year as new salt is added to it. Local differences in salinity of this brine will tend to be eliminated by sinking of denser water and the brine will remain homogeneous throughout.

3. Loss of ice by sublimation exceeds discharge: If less meltwater enters the lake each year than is lost by sublimation of ice at the surface, the lake level will drop. Since more water freezes than is added to the lake, the brine layer under the ice will decrease in thickness, but its salinity will rise annually. Eventually its density may exceed that of the underlying brine and mixing will occur by sinking of the heavier brine. As the process continues, the volume of brine is reduced while its salinity and density rise. Eventually only a single residual brine layer will remain whose freezing point may be depressed by its salinity to the point where ice can no longer form except during unusually low temperatures in the winter. Don Juan Pond in Wright Valley may be at this stage of development, since it appears to remain ice-free even in the winter. During the terminal stage, water may be lost primarily by evaporation until the lake dries up completely, leaving only a deposit of salts behind. Precipitation of salts from the brine may occur as its salinity increases whenever the activity product of a salt is exceeded. Formation of salts will lead to a corresponding change in the chemical composition of the brine and will tend to concentrate those ions whose salts are most soluble.

There is no direct evidence that either Lake Vanda or Lake Bonney have dried up completely in the past. However, the dense brines present at the bottoms of both lakes could represent residual liquids from earlier periods when loss of water may have periodically exceeded discharge of meltwater.

On the basis of the model outlined above, the layered structure of the brines in Lakes Vanda and Lake Bonney can be regarded as a record of past climatic changes. If at some time the imbalance between discharge and sublimation is reversed such that more meltwater enters a lake than is lost, a new, more dilute, layer of brine would accumulate on top of the older, denser, layers. The boundaries between brine layers are subsequently modified by diffusion of ions upwards leading to an increase in the salinity and density in the basal portion of the younger brine as shown clearly near the bottom of Layer 3 in Lake Vanda. If diffusion proceeds uninterrupted, eventually the salinities of the two brines will become approximately equal across a broad transition zone such as Layer 3 in Lake Bonney. The length of time required to approach homogenization of two brine layers depends on the temperature and chemical gradients which govern the rates of diffusion.

Some information about the evolution of Lake Bonney since the turn of the century can be derived from measurements of the width of the channel connecting the two lobes of the lake. According to Shirtcliffe (1964) the width of this channel increased from 5.2 m in 1903 to 31 m in 1911 and 42.3 m in 1964. The widening of the channel is plotted as a function of time in Figure 26. It coincides with an increase in lake level of 9.2 m between 1903 and 1964. The increase in lake level may be represented by the dilute water of Layers 1 and 2 in Lake Bonney which, according to the model proposed here, were formed in response to a sudden increase in discharge relative to the rate of sublimation. The rate of change of the channel-width suggests that the imbalance between discharge and sublimation favored discharge more strongly in the early part of this century than it does now. However, the channel appears to be widening and the lake level may still be rising at a slow rate.
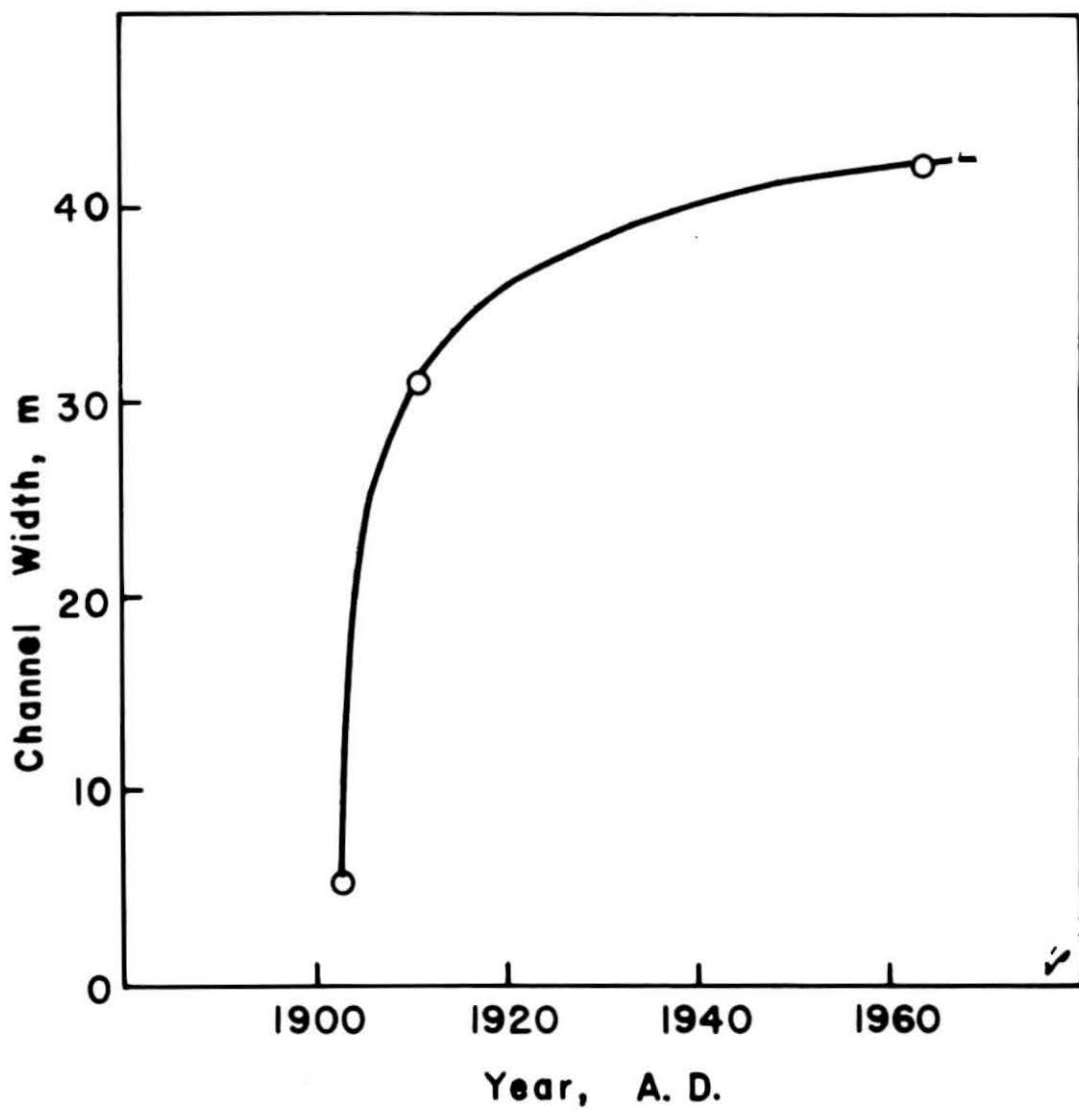
Figure 26. Widening of the channel connecting the eastern and western lobes of Lake Bonney.

VIII. THE CASE FOR CHEMICAL WEATHERING IN WRIGHT VALLEY

Introduction

Evidence was cited in an earlier part of this report for the occurrence of chemical weathering in Wright Valley. This was based on the observation that the isotopic composition of strontium of the water-soluble salts within the soil is essentially identical to that of the parent material. This appears to be unpredicted on the basis of present knowledge of chemical weathering. Therefore, a more extensive study of the isotopic composition of strontium in salts was undertaken This study was centered around the Meserve Glacier for three reasons: (1) the lithology of the soils varies greatly, ranging wholly or partially from basalt to dolerite to granite and schist; (2) the area of study is located more than 500 m above the valley floor, thereby decreasing the possibility of mixing of the salts by meltwater; and (3) a large number of soil samples were made available for analysis by R. E. Behling and K. R. Everett.

Salt Accumulation, Chemical Weathering and Age of the Salts

Large accumulations of salts are present in the ice-free valleys. These occur as lenses and cement within the soil and as encrustations on the surfaces of pebbles. From a study of the isotopic composition of strontium in the salts along the floor of Wright Valley and in Lake Vanda, it was concluded that most of the strontium, calcium, and possibly the magnesium were derived from the local bedrock, while most of the chlorine and perhaps sodium are of marine origin.

The most common soils of the ice-free regions are ahumic, structureless, and coarse-textured. Because of the arid conditions, Antarctic soils are desert types. Most soils are saline, the pH is relatively high (8-9), and, where sufficient water has been available, migration of salts has taken place (Ugolini and Bull, 1965). Soil profiles are weakly developed in some ice-free areas (e.g., Claridge, 1965; and McCraw, 1967).

Early investigators had considered physical weathering to be the predominant process of soil formation. A study of a quartz diorite at Marble Point east of Wright Valley suggests that physical processes may predominate over chemical weathering (Kelley and Zumberge, 1961). Although the diorite appeared to be strongly chemically weathered, the bulk chemical and mineralogical composition of material from various "stages" remained essentially constant throughout the observed weathering sequence. Since the climate at Marble Point is different from that of Wright Valley and the diorite samples were collected near the shore of McMurdo Sound, the conclusions of Kelley and Zumberge (1961) cannot be extrapolated to weathering phenomena in Wright Valley.

More recent studies, however, indicate that chemical weathering has been or is now occurring at a rate greater than was originally believed (Claridge and Campbell, 1968; Tedrow and Ugolini, 1966). Many investigators cite the occurrence of salts on and within the soils as evidence of chemical weathering (e.g., Campbell and Claridge, 1967; Claridge, 1965; Claridge and Campbell, 1968; McCraw, 1967; Tedrow and Ugolini, 1966). Clay minerals are present in the soils of the ice-free valleys. Claridge (1965) concluded that clays are actively forming at the present time and that they are derived by slow hydration of micas. Many soils contain up to 1-2% clay, consisting principally of vermiculite, montmorillonite, and some chlorite.

Chemical weathering has undoubtedly been responsible for the release of some elements from the local bedrock. However, the age of these salts is controversial. Two possibilities exist: (1) the salts are "fossil salts" formed during a period when the climate in Wright Valley was more amenable to chemical weathering; or (2) the salts are young, possibly forming at the present time but at a slow rate.

G. Faure (personal communication) considered it likely that the salts in the ice-free valleys are a relict feature of a former warmer and more humid environment, perhaps during the Tertiary Period. Part of his argument is based on the presence of salt accumulations in till underlying the Meserve Glacier and in the basal layers of ice, where chemical weathering is not occurring at the present time because the ice temperature is less than 0°C at all times. If glaciation of the Antarctic continent were initiated about 20 million years ago (Rutford et al., 1968) and has been continuous since that time, then these salts, if they are "fossil salts," may be at least 20 million years old.

From studies of the mass balance of the Meserve Glacier, Bull and Carnein (1968) have shown that "an advance of 400 meters (by the glacier) ... could be produced very quickly by a very slight (increase) in the annual accumulation (rate)." The glacier advances by a dry-calving process, which tends not to destroy or rework debris and salts previously exposed on the surface. Thus, it is possible that the salts presently observed under the ice have been overridden in relatively recent times.

Sorting studies of unconsolidated material under the Meserve Glacier by G. Holdsworth (1969, personal communication) indicated that this material has been wind-blown. These data suggest that the Meserve Glacier has retreated a distance at least as far as the position of the tunnel (the sampling sites). Since one of the materials studied was McMurdo basalt, the glacier appears to have retreated before the volcanics were erupted. Then, with readvance of the glacier, the wind-blown material was overriden, presumably by the dry-calving mechanism described by Bull and Carnein (1968).

There is evidence in the ice-free valleys of a former, wetter, and probably warmer, climate. For example, the lakes were at higher levels, as indicated by elevated strand lines. Glaciers have been more extensive than present as indicated by their moraines. Geomorphic investigations by Calkin (1964) in Victoria Valley revealed the presence of many mud-flows in addition to much larger solifluction lobes, which transported more material than those now active in the area. Mercer (1968a) cited evidence from lake sediments and solifluction flows in the Reedy Glacier area in the Transantarctic Mountains about 1200 km south of Wright and Taylor Valleys, that the climate was approximately 6 to 10°C warmer than present. Mercer (1968b) suggested that a high sea level, dated at about 120,000 years B. P., represents the most recent time that this increase in temperature is likely to have occurred.

A series of three well-defined moraines surround the Meserve Glacier as shown in Figure 27. (For reference, these will be referred to as the "outer" (oldest), "middle," and "inner" (youngest) moraines.) The moraines on the west side are darker due to the presence of McMurdo basalt. This basalt has originated from two cinder cones in the accumulation basin of the glacier. It has been suggested that additional cones exist under the ice (R. E. Behling; G. H. Denton, 1969; R. J. E. Montigny, 1967; personal communications).

On the east side of the Meserve Glacier, McMurdo volcanics are incorporated within only the two inner moraines. Thus, these inner moraines have been deposited since the basalt was erupted. All the McMurdo volcanics that have been dated in Wright and Taylor Valleys fall within the limits of 2-4 million years (Armstrong, et al., 1968; Denton and Armstrong, 1968). Although basalt from the area surrounding the Meserve Glacier has not been dated, it is reasonable to suggest that the age of 2-4 million years would also apply to these volcanics. Then, the age of the outer moraine is greater than 2-4 million years, and the inner moraines are younger than 2-4 million years. Basalt incorporated within one of the inner moraines has apparently undergone chemical decomposition (K. R. Everett and R. E. Behling, 1968, personal communication). Thus, chemical weathering has occurred since that moraine was deposited, i.e., sometime since the basalt was erupted, perhaps 2-4 million years ago.

Chemical Weathering in Wright Valley

In Wright Valley there is isotopic equilibrium of the strontium between water in the Onyx River and water-soluble salts and parent material from the valley floor. This conclusion has been confirmed by Dasch (1969), who also found that the isotopic composition of strontium in weathering products is largely unaffected by weathering processes. It is interesting that the materials analyzed by Dasch (1969) did not originate in a polar desert enviornment like that of the ice-free
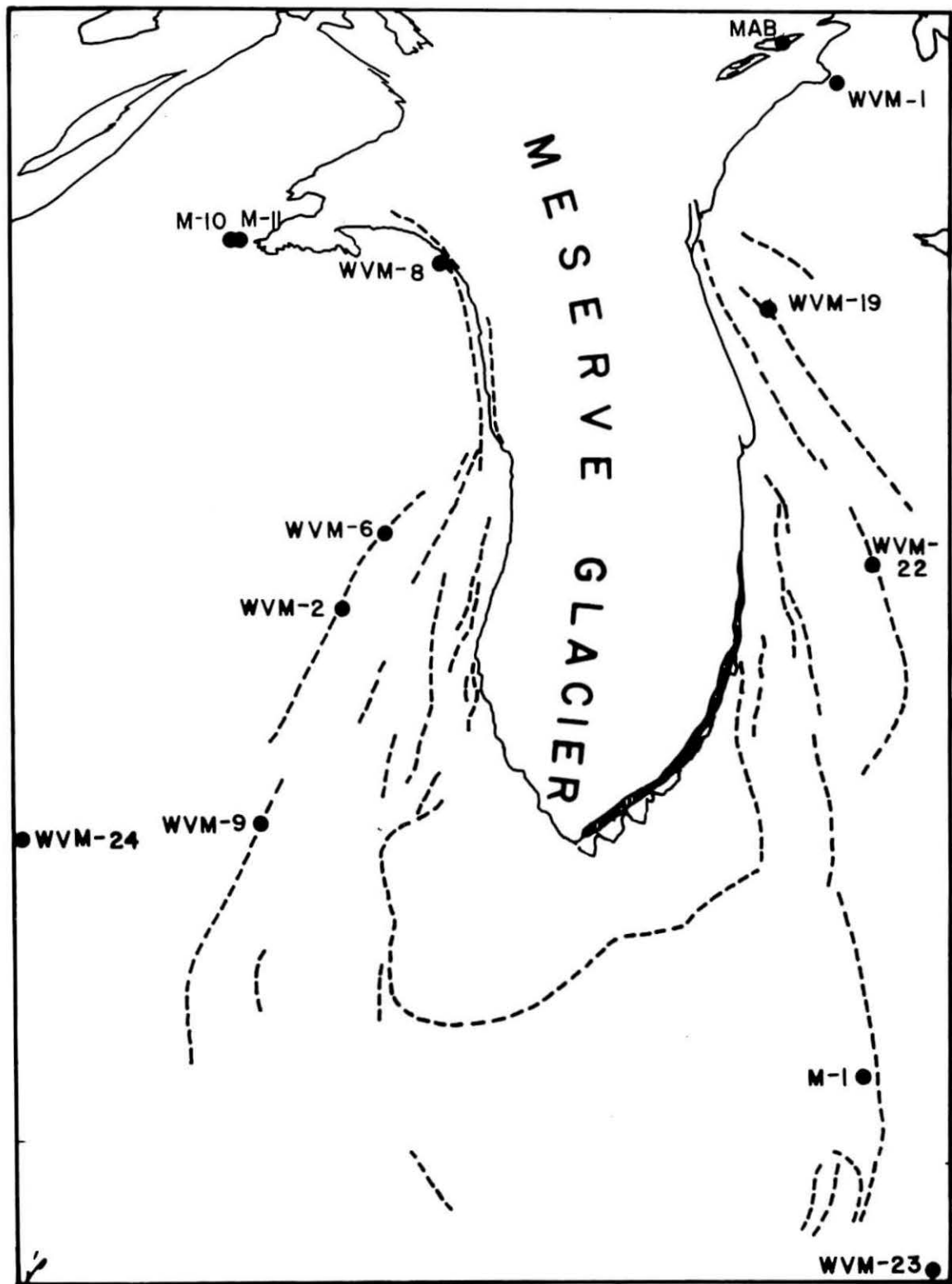
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Figure 27.   Terminal moraines associated with the Meserve Glacier of
Wright Valley.

valleys. Instead, his samples were collected in warmer, more humid regions such as Hong Kong, Connecticut, New Hampshire, and Georgia.

The isotopic composition of strontium was measured during this study for sediment and water from Lake George, Ontario. One sample of each was collected during the summer, 1968. The Sr^{87}/Sr^{86} ratio of the water was 0.7184, while that of the sediment was 0.7288. The strontium in the water is clearly not in isotopic equilibrium with strontium in the sediment. This isotopic disequilibrium between the water and sediment may be due to differential weathering of those minerals which have low Rb/Sr ratios.

Hart and Tilton (1966) have analyzed the isotopic composition of strontium in sediment and water from Lake Superior. The Sr^{87}/Sr^{86} ratio of the sediment was 0.739, while that of the water was 0.718. The strontium in this water is clearly not in equilibrium isotopically with strontium in the sediment, a conclusion identical to the results obtained for Lake George. They attributed this difference in the Sr^{87}/Sr^{86} ratios to differences in susceptibility to weathering of various minerals. The more resistant minerals, such as mica and potassium feldspar, have high Rb/Sr ratios and contain strontium with a relatively high Sr^{8}/Sr^{8} ratio. More readily weathered minerals, such as carbonate, pyroxene, and plagioclase, have low Rb/Sr ratios and therefore have correspondingly lower Sr^{87}/Sr^{86} ratios.

A suite of samples was selected from the moraines of the Meserve Glacier to provide a wide range of lithology. The sample locations are shown in Figure 27 and the lithology of these samples represented by pebbles greater than 1/4 inch diameter is given in Table 18. The salts were removed by water leaching. Two samples (WVM-22 and WVM-23) were analyzed at two different horizons. For many of the samples, the Sr^{87}/Sr^{86} ratio was also determined on the salt-free material.

Three observations may be made by inspection of Table 18. (1) The Sr^{87}/Sr^{86} ratio of the soluble salt and lithology appear to be essentially constant within a given profile (WVM-22 and WVM-23). (2) The Sr^{87}/Sr^{86} ratio of the water-soluble salt is generally similar to the Sr^{87}/Sr^{86} ratio of the salt-free soil. (3) The Sr^{87}/Sr^{86} ratio of both the water-soluble salt and the parent material reflect the lithic composition of the till (i.e., soils with a high basalt content have somewhat lower Sr^{87}/Sr^{86} ratios than soils of low basaltic content).

Because the Sr^{87}/Sr^{86} ratios of the water-soluble salts are similar to the ratios of the parent material, it is reasonable to conclude that these salts have formed in situ. If the salts were derived from a source that is not local, or if they are relict salts, then the strontium would be more isotopically homogeneous.

Since the salts appear to have formed during the moraines of the Meserve Glacier was deposited, then it follows that chemical weathering has occurred during and since deposition, i.e., in the case of the

Table 18. Sr^{87}/Sr^{86} ratios of water-soluble salts and total salt-free soil, and the lithologic composition of moraine samples, Meserve Glacier, Wright Valley.

Sample (cm depth)	Sr^{87}/Sr^{86}[a] salt	Sr^{87}/Sr^{86}[a] salt-free soil	Per cent Composition[b]		
			basalt	dolerite	basement
WVM-1 (2-4)	0.7121	0.7127	0.0	100.0	0.0
WVM-2 (5.5-27.5)	0.7146	0.7152	0.0	6.2	93.8
WVM-6 (3-16)	0.7137	0.7137	0.0	5.2	94.3
WVM-8 (2-12.5)	0.7130	0.7138	5.2	7.7	87.1
WVM-9 (2-12)	0.7145	-	2.2	2.0	95.8
WVM-19 (15-20)	0.7091	0.7046	89	10	1
WVM-22 (8-28) (106-109)	0.7080 0.7066	- 0.7047	77[c] [d]	20[c] [d]	3[c] [d]
WVM-23 (2-9) (9-19)	0.7142 0.7142	- -	9.9 15.0	13.8 6.1	76.3 78.9
WVM-24 (9-36)	0.7157	-	0.0	12.7	87.3
MAB	0.7099	0.7107	34.3	65.7	0.0

[a]Corrected for fractionation assuming $Sr^{86}/Sr^{88} = 0.1194$

[b]Pebbles greater than 1/4 inch diameter

[c]Pebble count approximate

[d]Pebble count not available at present time; sample highly indurated, but appears to consist of basalt with some dolerite

inner two moraines, sometime following eruption of the McMurdo basalts Although the age of the basalts in the vicinity of the Meserve Glacier is not known at present, basalts from near the neighboring Bartley Glacier have K-Ar ages of 3.7 m.y. (Denton and Armstrong, 1968). All K-Ar dates presently available for these basalts in Wright and Taylor Valleys are within the interval 2 to 4 million years, making it reasonable to suppose that the basalt at the Meserve Galcier is of similar age. The salts in these moraines, therefore, have formed in relatively recent times.

Further evidence of relatively recent chemical weathering can be obtained from the Sr^{87}/Sr^{86} ratios of salt encrustations of glacially-dropped boulders. These surficial salt deopsits are fragile and probably could not have survived glacial transport. Therefore, these salts were undoubtedly deposited on the boulders after they were dropped by the ice. Four Sr^{87}/Sr^{86} ratio analyses of these salt encrustations are given in Table 19. Samples M-10 and M-11 are boulders of Ferrar dolerite and schist or gneiss, respectively. These bounders are located near the entrance to the accumulation basin of the Meserve Glacier and occurred about 30 cm from each other (K. R. Everett, 1968, personal communication). The Sr^{87}/Sr^{86} ratio of the salt from the dolerite boulder (M-10; 0.7136) is identical to that of dolerite collected nearby (0.7134). The Sr^{87}/Sr^{86} ratio of the salt from the gneissic boulder (M-11; 0.7160) is similar to the values obtained for many samples of the basement complex. Because of the proximity of the boulders to each other, the salts probably have not been brought from an outside source, but have formed in situ since the bounders were dropped by the glacier. No relative age can presently be given for the time these boulders were deposited.

The Sr^{87}/Sr^{86} ratios for salts from the surfaces of Boulder A and ST-1 further suggest the possibility of local formation of salts. Both of these boulders were located under the Meserve Glacier about 54 m from the edge of the ice cliff. They were located about one meter from each other in a cavity formed by bedrock and till. Boulder A was composed of dolerite, which is reflected by the Sr^{87}/Sr^{86} ratio of 0.7138 for the salt encrustation. ST-1 is a salt sample from a boulder of granite-gneiss. The Sr^{87}/Sr^{86} ratio of this salt (0.7195) is similar to the isotopic composition of strontium measured for the Olympus granite-gneiss and other basement rocks.

Conclusions

On the basis of the Sr^{87}/Sr^{86} ratio measurements of salts in the moraines and on boulders in the vicinity of the Meserve Glacier, it is concluded that most of these salts have formed in situ. By extrapolation of age determinations of nearby basalts similar to those in the region of the Meserve Glacier, it is further concluded that these salts have formed within the last 2-4 million years and are possibly forming at the present time.

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Table 19. Sr^{87}/Sr^{86} ratios of salt encrustations from boulders
in the vicinity of the Meserve Glacier, Wright Valley.

Sample No.	Sr^{87}/Sr^{86}*	$\bar{\sigma}$	Rock Type
M-10	0.7136	0.0003	Ferrar dolerite
M-11	0.7160	0.0003	schist or gneiss
Boulder A	0.7138	0.0004	Ferrar dolerite
ST-1	0.7195	0.0004	Granite-gneiss

*Corrected for fractionation assuming $Sr^{86}/Sr^{88} = 0.1194$

REFERENCES

Aldrich, L. T., Wetherill, G. W., Tilton, G. R., and Davis, G. L., 1965, Half-life of Rb[87]: Phys. Rev., v. 103, p. 1045-1047.

Angino, E. E., Armitage, K. B., and Tash, J. C., 1965, A chemical and limnological study of Lake Vanda, Victoria Land, Antarctica: Univ. Kansas Sci. Bull., v. 45, p. 1097-1118.

--------, Armstrong, K. B., and Tash, J. C., 1964, Physicochemical limnology of Lake Bonney, Antarctica: Limnol. Oceanogr. v. 9, p. 207-217.

Armitage, K. B., and House, H. B., 1962, A limnological reconnaissance in the area of McMurdo Sound, Antarctica: Limnol. Oceanogr., v. 7, p. 36-41.

Armstrong, R. L., Hamilton, W., and Denton, G. H., 1968, Glaciation in Taylor Valley, Antarctica older than 2.7 million years: Science, v. 159, p. 187-189.

Bull, C., and Carnein, C. R., 1968, The mass balance of a cold glacier: Meserve Glacier, south Victoria Land, Antarctica: manuscript.

Calkin, P. E., 1964, Geomorphology and glacial geology of the Victoria Valley system, southern Victoria Land, Antarctica: The Ohio State University, Institute of Polar Studies Report No. 10, 66 pp.

Campbell, I. B., and Claridge, G. G. C., 1967, Site and soil differences in the Brown Hills region of the Darwin Glacier, Antarctica: New Zealand Jour. Geol. and Geophys., v. 10, p. 567-577.

Claridge, G. G. C., 1965, The clay mineralogy and chemistry of some soils from the Ross Dependency, Antarctica: New Zealand Jour. Geol. and Geophys., v. 8, p. 186-220.

--------, and Campbell, I. B., 1968, Soils of the Shackleton Glacier region, Queen Maud Range, Antarctica: New Zealand Jour. Geol. and Geophys., v. 11, p. 171-218.

Craig, H., 1966, Origin of the saline lakes in Victoria Land, Antarctica (abstract): Trans. American Geophys. Union, v. 47, p. 112-113.

Dasch, E. J., 1969, Strontium isotopes in weathering profiles, deep-sea sediments, and sedimentary rocks: Ph.D. dissert., Yale Univ., 94 pp.

--------, Hills, F. A., and Turekian, K. K., 1966, Strontium isotopes in deep-sea sediments: Science, v. 153, p. 295-297.

Denton, G. H., and Armstrong, R. L., 1968, Glacial geology and chrono-
        logy of the McMurdo Sound region: Antarctic Jour. of the
        U. S., v. 3, 99-101.

Faure, G., Crocket, J. H., and Hurley, P. M., 1967, Some aspects of the
        geochemistry of strontium and calcium in the Hudson Bay and
        the Great Lakes: Geochim. et Cosmochim. Acta, v. 31, p. 451-
        461.

--------, and Hurley, P. M., 1963, The isotopic composition of strontium
        in oceanic and continental basalts: Application to the origin
        of igneous rocks: Jour. Petrology, v. 4, p. 31-50.

--------, Hurley, P. M., and Powell, J. L., 1965, The isotopic composi-
        tion of strontium in surface water from the North Atlantic
        Ocean: Geochim. et Cosmochim. Acta, v. 29, p. 209-220.

Hart, S. R., and Tilton, G. R., 1966, The isotope geochemistry of
        strontium and lead in Lake Superior sediments and water, in
        J. S. Steinhart and T. S. Smith, Editors, The earth beneath
        the continents, American Geophys. Union, Geophys. Monograph
        No. 10, p. 127-137.

Hedge, C. E., 1966, Variations in radiogenic strontium found in volcanic
        rocks: Jour. Geophys. Res., v. 71, p. 6119-6126.

Henderson, R. A., Prebble, W. M., Hoare, R. A., Popplewell, K. B.,
        House, D. A., and Wilson, A. T., 1966, An ablation rate for
        Lake Fryxell, Victoria Land, Antarctica: Jour. Glaciology,
        v. 6, p. 129-133.

Hoare, R. A., 1966, Problems of heat transfer in Lake Vanda, a density
        stratified Antarctic lake: Nature, v. 210, p. 787-789.

--------, 1968, Thermohaline convection in Lake Vanda, Antarctica:
        Jour. Geophys. Res., v. 73, p. 607-612.

--------, Popplewell, K. B., House, D. A., Henderson, R. A., Prebble,
        W. M., and Wilson, A. T., 1964, Lake Bonney, Taylor Valley,
        Antarctica: a natural solar energy trap: Nature, v. 202,
        p. 886-888.

Kelly, W. C., and Zumberge, J. H., 1961, Weathering of a quartz diorite
        at Marble Point, McMurdo Sound, Antarctica: Jour. Geology,
        v. 69, p. 433-446.

Livingstone, D. A., 1963, Chemical composition of rivers and lakes,
        Chapter G, Data of Geochemistry, Sixth Edition, U. S. Geol.
        Survey Prof. Paper 440-G, 64 pp.

McCraw, J. D., 1967, Soils of Taylor Valley, Victoria Land, Antarctica, with notes on soils from other localities in Victoria Land: New Zealand Jour. Geol. and Geophys., v. 10, p. 498-539.

Mercer, J. H., 1968a, Glacial geology of the Reedy Glacier area, Antarctica: Geol. Soc. America Bull., v. 79, p. 471-486.

--------, 1968b, Antarctic ice and Sangamon sea level: Internat. Assoc. Scientific Hydrology Publ. No. 79, p. 217-225.

Murthy, V. R., and Beiser, E., 1968, Strontium isotopes in ocean water and marine sediments: Geochim. et Cosmochim. Acta, v. 32, p. 1121-1126.

Nichols, R. L., 1965, Antarctic interglacial features: Jour. Glaciology, v. 5, p. 433-449.

--------, 1966, Geomorphology of Antarctica, in J. C. F. Tedrow, Editor, Antarctic Soils and Soil Forming Processes, American Geophys. Union, Antarctic Research Series, v. 8, p. 1-46.

Péwé, T. L., 1966, Quaternary climatic variations in Antarctica as suggested by glacial fluctuations, in Symp. Pleistocene and Post-Pleistocene Climatic Variations in the Pacific Area, Bishop Museum Press, p. 57-82.

Powell, J. L., Faure, G., and Hurley, P. M., 1965, Strontium-87 abundance in a suite of Hawaiian volcanic rocks of varying silica content: Jour. Geophys. Res., v. 70, p. 1509-1513.

Ragotzkie, R. A., and Likens, G. E., 1964, The heat balance of two Antarctic lakes: Limnol. Oceanogr., v. 9, p. 412-425.

Rutford, R. H., Craddock, C., and Bastien, T. W., 1968, Late Tertiary glaciation and sea-level changes in Antarctica: Palaeogeography, Palaeoclimatology, and Palaeoecology, v. 5, p. 15-39.

Shirtcliffe, T. G. L., 1964, Lake Bonney, Antarctica: cause of the elevated temperatures: Jour. Geophys. Res., v. 69, p. 5257-5268.

--------, and Benseman, R. F., 1964, A sun-heated Antarctic lake: Jour. Geophys. Res., v. 69, p. 3355-3359.

Tedrow, J. C. F., and Ugolini, F. C., 1966, Antarctic soils, in J. C. F. Tedrow, Editor, Antarctic Soils and Soil Forming Processes, American Geophys. Union, Antarctic Research Series, v. 8, p. 161-177.

Torii, T., Yamagata, N., and Cho, T., 1967, Report of the Japanese
    Summer Parties in dry valleys, Victoria Land, 1963-1965.
    II. General description and water temperature data for the
    lakes: Antarctic Record (Japan), No. 28, p. 2225-2238.

Ugolini, F. C., and Bull, C., 1965, Soil development and glacial events
    in Antarctica: Quaternaria (Rome), v. 7, p. 251-269.

Wilson, A. T., 1964, Evidence from chemical diffusion of a climatic
    change in the McMurdo dry valleys 1,200 years ago: Nature,
    v. 201, p. 176-177.

--------, and Wellman, H. W., 1962, Lake Vanda: and Antarctic lake:
    Nature, v. 196, p. 1171-1173.

Yamagata, N., Torii, T., and Murata, S., 1967, Report of the Japanese
    Summer Parties in dry valleys, Victoria Land, 1963-1965. V.
    Chemical composition of lake waters: Antarctic Record (Japan),
    No. 29, p. 2339-2361.