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A GEOCHEMICAL STUDY OF LAKES BONNEY AND VANDA, VICTORIA LAND, ANTARCTICA[1]

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ABSTRACT

During Deep Freeze 61, highly saline water was found on the bottom of Lakes Vanda and Bonney, Victoria Land, Antarctica. These lakes, perennially ice-covered, have unusually warm waters for such cold environments. In December, 1960, the bottom 20-foot layer of Lake Vanda (217 feet ± 5 feet deep) had a temperature of 22° ± 2° C. and Lake Bonney (100 feet ± 5 feet deep) had an 8° C. thermal layer at the 40-foot level. As the average annual temperature in this region is approximately −17° C., the only reasonable explanation for the high temperature observed in these waters appears to be either an unusually high geothermal gradient or the influx of warm spring waters on the lake bottoms.

Analyses of water samples show abnormally high salinities, chlorinities, and conductivities. Interpretation of these data indicates that the lakes are meromictic. Investigation of the distribution of K^+, Na^+, Ca^{++}, Mg^{++}, $SO_4^=$ and other ions provides some information as to probable origin of these waters. A SO_4/Cl ratio of 0.010 for the highly saline bottom waters of Lake Vanda indicates a possible sea-water origin. Determination of Mg^{++}/Ca^{++} ratios indicates a probable salt water origin for the deeper waters (Mg/Ca = 23.6) of Bonney (elevation 38 m.) but not for Vanda (elevation 123 m.). The origin of these waters is not clear; however, present data suggest either a sea or thermal water origin for the monimolimnion of Lake Bonney. Whatever the origin of these saline bottom waters, many geologic and climatological implications are suggested.

INTRODUCTION

Other workers have reported the existence of small saline lakes in Antarctica (Ball and Nichols, 1960, and others); however, no detailed chemical data relating to the larger amictic (permanently ice-covered) lakes of this region are available. The Russian literature may contain information of this nature; but it is not known to the writers. The location of these lakes in relation to known landmarks of South Victoria Land is illustrated in figure 1.

A large ice-free area, 10–15 miles wide and approximately 100 miles long, exists in South Victoria Land on the west side of McMurdo Sound. The region, dominated by the mountains of Royal Society Range, is cut by alternating east trending ridges and valleys from which the polar ice cap has withdrawn (Péwé, 1960).

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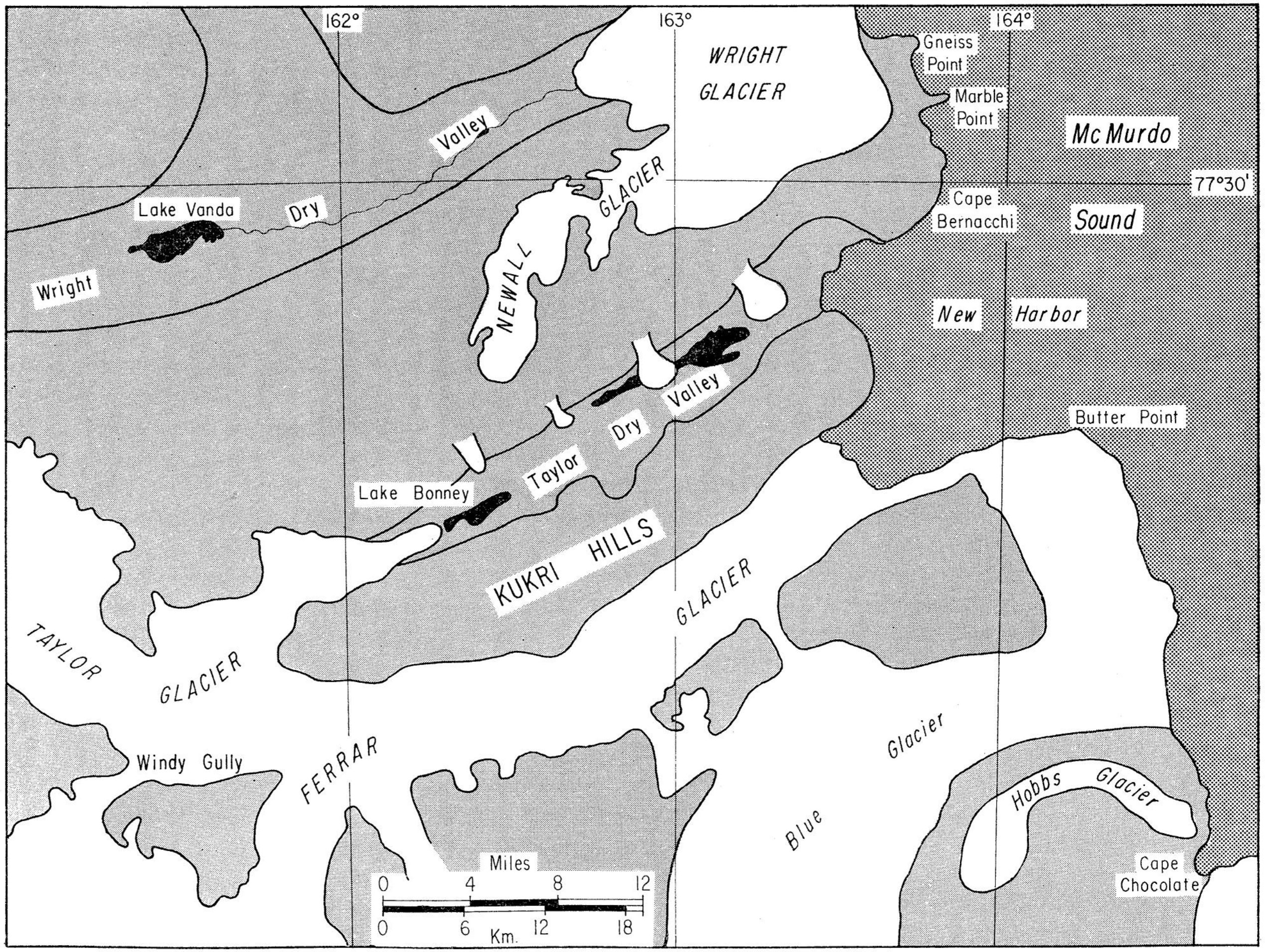

Fig. 1.—Index map of part of western coastal area of McMurdo Sound, South Victoria Land, Antarctica

Two of these valleys, Taylor and Wright, contain large amictic lakes, Lakes Bonney and Vanda, respectively. Both valleys are essentially snow-free. Prior to work conducted during 1960–61 Antarctic Field Season, no definite proof was available that any great amount of water lay beneath the ice cover of these lakes.

Lake Vanda, approximately 40 miles W.N.W. of Butter Point (see fig. 1), occupies the central part of Wright Dry Valley. Butter Point is about 40 miles of W.N.W. of Naval Air Facility, McMurdo. The lake is about 5.3 miles long and 1.5 miles wide at its widest point. Two ice corings made on different days and in different locations on the lake gave a mean ice thickness of 11.5 feet. The maximum measured depth of the lake was 217 ± 5 feet, including the ice.

Lake Bonney lies 18 miles southeast of Lake Vanda and 28 miles west from Butter Point. It occupies the upper reaches of Taylor Dry Valley. It is about 1.8 miles long and 0.3 miles wide at widest point. One ice core, taken near the center of the lake, indicated an ice thickness of 13.8 feet. Total depth (with ice) was 100 ± 5 feet.

CLIMATE

When considering these data it is pertinent to have in mind some knowledge of the climate of this area. The climate, characterized by low temperatures and extreme aridity, is rigorous. Incomplete data from IGY observations at NAF McMurdo indicate a mean annual air temperature at sea level of roughly −17° C. All months of the year have a mean temperature below 0° C. Considering the geographic positions of Lakes Vanda and Bonney, it seems reasonable to assume a mean annual air temperature in the vinicity of the lakes of −20° C.

Mummified seal carcasses found in vicinity of Lake Bonney yield C^{14} ages of 300–1,250 years (Olsen and Broecker, 1961), thereby suggesting that the climate has been cold and dry for at least 300 years. We can reasonably assume, therefore, that the lake waters and ice are essentially in equilibrium with the environment.

ANALYTICAL TECHNIQUES AND METHODS

Water samples were collected in Kemmerer bottles and then transferred to polyethylene bottles for transportation back to the laboratory. Temperature was measured by either a Whitney resistance thermometer or an ordinary glass mercury thermometer. A Beckman Model G pH meter determined the pH. Conductivity was measured with a dionic conductivity tube manufactured by the James G. Biddle Company of Philadelphia. Chlorinity was determined according to standard oceanographic techniques except that a standard sea-water sample was not used.

The Ca^{++} and Mg^{++} concentrations were evaluated by the disodium dihydrogen (ethylenedinitrilo) tetra-acetic acid method developed by Patton and Reeder (1956) using Eriochrome Black T as the indicator. The analysis involves two simple titrations (Welcher, 1958), one for total calcium and magnesium equivalents and one for magnesium equivalent alone. All chemical data in table 1 are the mean of two and in most instances three determinations.

Flame spectrophotometry (Zeiss PMQ-2 spectrophotometer) was employed to determine the Na^{+} and K^{+} contents of the water samples (Burriel-Marti and Ramirez-Munoz, 1957; Poluektov, 1961). All other chemical analyses followed procedures outlined in American Public Health Association (1955).

PHYSICAL DATA

Table 1 illustrates the general relations between chemical data as determined in the laboratory and physical data as measured in the field. The conductivity values are corrected to a standard temperature of 18° C. The waters of Lake Vanda were examined in greater detail than were those of Lake Bonney. Not the least important datum was the discovery of a warm (20°–22° C.) saline monimolimnion (Hutchinson, 1957) in the lower 20 feet of Lake Vanda and a cold (−2.4° C.) monimolimnion in Lake Bonney. The temperature profiles for the two lakes are shown in figure 2. Clearly the same processes do not seem to be at work in both lakes. An explanation of the thermal profiles of the lakes is not presently possible on the basis of the limited data on hand.

The high temperature of the monimolimnion of Lake Vanda leads immediately to speculation as to a possible heat source. Examination of the physical and chemical data available suggests a possible influx of thermal waters at depth. However, barring the equilibrium conditions postulated between the amount of glacial melt water entering the lake, sublimation from ice surface, and the suggested inflow of thermal waters at depth, it would seem that a large influx of warm waters would either raise the lake level or melt the ice cover. As neither of these latter two changes appear to be present, it would appear that an equilibrium condition is present. An inflow of some thermal water is not, however, eliminated.

A conservative estimate of heat available in this lower saline layer suggests the possibility of a higher than normal geothermal gradient for this area. The lake is included in the presently active Ross Sea volcanic province; consequently, this latter idea cannot be excluded from active consideration.

It would seem from the chlorinity and conductance data (table 1) that Cl^- is the main constitutent contributing to conductance. The pH data naturally reflect the combined interaction of the effects of temperature and ionic concentrations of waters found at the different depths.

TABLE 1

CHEMICAL ANALYSES*

Lake and Depth	Na^+ (p.p.m.)	K^+ (p.p.m.)	K/Na (p.p.m.)	Ca^{++} (p.p.m.)	Mg^{++}		Ca/Mg		Cl^- (Mg/1)	HCO_3^- (Mg/1)	$SO_4^=$ (Mg/1)	Cl/HCO_3	° C.	pH	Conductivity (Micromhos)
					e.p.m.	p.p.m.	e.p.m.	p.p.m.							
Vanda:															
20...	28	10	0.36	46	2.3	9	.7	3.3	150	......	......	......	4.2	8.5	450
37...	34	11	.32	......	......	......	......	......	200	41.5	7	6.0	.....	8.3	540
40...	41	9	.22	69	3.4	17	1.4	2.4	250	......	......	......	5.5	8.3	660
60...	100	32	.32	148	7.4	48	3.9	1.9	700	......	......	......	7.2	7.9	1,600
80...	26	9	.35	43	2.2	11	.9	2.4	150	......	......	......	5.0	8.5	450
100...	29	10	.34	47	2.4	11	.9	2.7	200	......	......	......	4.8	8.6	460
110...	103	30	.29	189	9.4	47	3.9	2.4	650	......	......	......	7.5	7.8	1,600
120...	120	40	.33	190	9.5	47	3.9	2.4	600	......	......	......	7.5	7.9	1,600
130...	40	9	.23	50	2.5	10	.8	3.1	150	......	......	......	5.0	8.4	480
140...	142	39	.27	413	20.6	......	......	......	950	......	......	......	8.0	7.7	2,500
150†..	151	44	.29	298	14.9	77	6.3	2.4	1,900	......	......	......	8.0	7.7	2,500
152†..	183	45	.25	320	......	......	......	......	1,600	85.4	40	18.7	.....	7.4	4,400
160...	185	80	.43	1,070	53.4	293	24.1	2.2	3,350	......	......	......	9.6	7.2	10,000
180†..	38	12	.32	61	3.1	15	1.3	2.4	300	......	......	......	5.0	7.7	550
200...	5120	690	.13	20,534	1,024.7	7,039	579.0	1.8	64,500	......	......	......	20.6	6.3	195,000
217...	6,761	766	.11	24,254	1,210	7,684	632	1.9	75,869	126	770	602.1	22.0	6.1	250,000
Bonney:															
37†..	1,500	180	.12	45	2.2	43	3.5	0.6	750	87.8	127	8.5	8.0	8.5	2,000
100‡..	43,333	3,000	0.069	1,109	55.3	26,253	2,159	0.03	143,333	378	525	379	−2.4	7.8	135,000

* Conversion factors for parts per million (p.p.m.) to equivalents per million (e.p.m.) can be found in Hem, 1959, p. 32.

† Equivalents do not add; insufficient water sample to recheck analyses.

‡ Density of bottom water = 1.2.

CHEMISTRY

The origin of these waters and the exact mechanism of their concentration are problematical. The high Mg^{++}, Na^+, and Cl^- content of the monimolimnoin of Lake Bonney suggests either a sea-water origin or salt-water contamination. It is also possible that the waters are a magnesian brine resulting from extensive past concentration either by a freezing mechanism or evaporation. Péwé (1960) suggests that Lake Bonney may be the remnant of a large glacial lake. It is reasonable to assume that, if the concentration is due to a freezing process, then the concentration has probably been going on for at least 300 years.

The high K^+ content of Lake Bonney is somewhat enigmatic. The upper waters of Lakes Vanda and Bonney are low in dissolved solids (table 1) and, as pointed out by

Hem (1959), in such waters the ratio of Na/K may approach 1:1. The condition is common in waters associated with sialic igneous rocks. Such rocks are common in the vicinity of these lakes. If the lower waters are essentially saturated with respect to Na^+, then their Na/K ratio can be also explained in another manner. An X-ray diffraction study of material crystallizing out of waters of the monimolimnion of Bonney, after the waters were allowed to stand for 30 days in the laboratory at room temperature, gave a characteristic NaCl pattern. Small amounts of mirabilite were also indicated to be present (note the temperature difference involved). Similar results were also obtained at 0° C. If Na^+ is taken out of solution, the K^+ and Mg^{++}, owing to greater solubility of their compounds, would tend to remain in solution and become more concentrated. This process would also change the Na/K ratio.

The extremely low Ca/Mg ratio (e.p.m.) again suggests either a possible sea-water origin or sea-water contamination (Hem, 1959). As Hem points out, however, a low ratio may result in some instances from precipitation of $CaCO_3$, just before collection

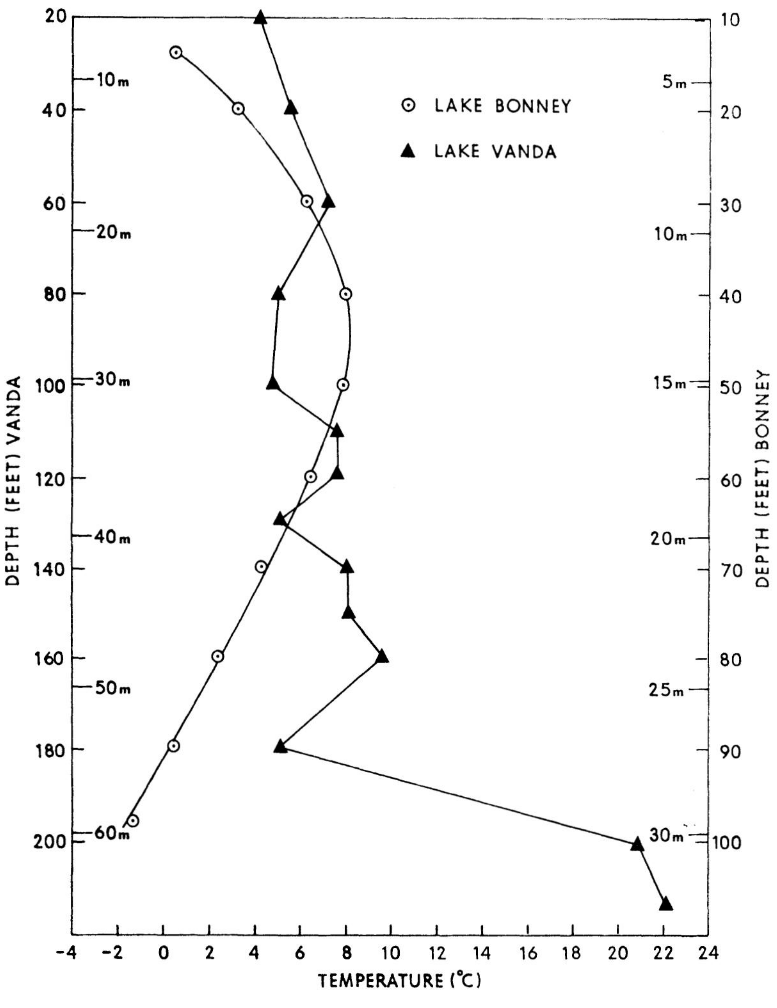

Fig. 2.—Temperature versus depth profile of lake waters. Inner scale indicates depth in meters

of the sample. In addition the X-ray diffraction pattern for precipitated salts mentioned previously reveals presence of significant amounts of $CaSO_4 \cdot 2H_2O$. Removal of Ca^{++} ion would also lower the Ca/Mg proportion in the water. The low SO_4/Cl ratio is a further suggestion of a possible sea-water origin for the bottom waters of Lake Bonney. As the surface of Lake Bonney is about 38 m. above present sea level, such an origin is not precluded. From the above discussion, it seems as if the monimolimnion of Lake Bonney may be of sea-water origin. It should be emphasized here, however, that such an origin is by no means proved by the data.

A sea-water origin for monimolimnion of Lake Vanda (elevation 123 m.) is not considered likely. The rather high Ca^{++} and Mg^{++} concentrations of these waters can be reasonably explained. The area, though an enclosed basin, is drained by moderate sized meltwater streams flowing from the Wilson Piedmont Glacier. These streams cross a series of vertical dolomitic marble beds which are a part of bedrock floor of the valley (Bull, 1960). The streams are intermittent, flowing only during the short Antarctic summer (2 to 2.5 months). Assuming the concentration process to have been operating for a long time, the presence of these marble beds would easily explain the high concentration of Ca^{++} and Mg^{++} in the lower saline layers of Lake Vanda.

The low Ca/Mg ratios (in e.p.m.) for the upper waters of Lake Vanda also suggest that dolomite rocks are being attacked by waters draining into the lake (Hem, 1959).

X-ray diffraction studies of the salts crystallizing from samples of lower waters of Lake Vanda allowed to stand at room temperature (20° C.) for 30 days again reveal characteristic peaks of NaCl intermixed with very small amounts of $Na_2SO_4 \cdot 10H_2O$. Evidence for $CaSO_4$ was no more than suggestive. As room temperature is similar to that prevailing in monimolimnion of Lake Vanda, it is quite possible that these salts are actually precipitating *in situ*. Bottom sediment to be collected during next field season will help to clarify this point.

The Cl^- concentrations present some problems, especially in the case of Lake Bonney. Assuming an influx of thermal waters now or at some time in the past, then the high Cl^- values are explainable. Other than extensive evaporation or concentration by a prolonged freezing mechanism, the only reasonable alternative is sea-water contamination. This argument applies to both lakes. The rocks in the area are, for the most part, igneous and metamorphic, both of which are minor sources of Cl^- in natural waters (Hem, 1959). Evidence of recent evaporation in these lakes is lacking. The most logical concentration mechanism appears to be by freezing.

Data on $SO_4^=$ and $HCO_3^=$ are incomplete. They were determined only for the few samples indicated in table 1 and are included for comparison. The data show a regular increase of these ions with depth in both lakes. The chloride-bicarbonate (Cl/HCO_3) ratios for Lakes Bonney and Vanda, 379.0 and 602.1, respectively, are suggestive of admixture of recent or fossil sea water (Revelle, 1941). However, it should be strongly emphasized that other processes besides sea-water contamination can raise the Cl/HCO_3 ratio. There was a strong odor of H_2S from the sample at 217 feet from Lake Vanda. Iron, ammonia, and nitrate were not detected in any of the water samples from monimolimnia of either lake.

Application of White's ratios (1957) to analytical data suggests that some of lower waters of Lake Bonney and Vanda may be of thermal origin. Such an inflow would also be a reasonable heat source.

SUMMARY AND CONCLUSIONS

Both lakes are meromictic as evidenced by the highly saline water in the bottom of each. Probably the meromixis in both lakes was initiated ectogenically. Both lakes lie in closed basins, and the monimolimnia may have formed by evaporation. Lake Bonney may be remanent of an earlier Glacial Lake Llano (Péwé, 1960). A fresh-water source is probable; however, the likelihood of either a