

Running Head: Arctic hypersaline lakes

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**TWO HYPERSALINE LAKES IN THE CANADIAN HIGH
ARCTIC AND CONSIDERATION OF THEIR DEVELOPMENT**

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MANAGEMENT PERSPECTIVE

The Polaris lead-zinc mine at latitude 75°N is the world's most northerly mine. This mine discharges its tailings into Garrow Lake on Little Cornwallis Island. High concentrations of heavy metal sulfides accumulate in the stable bottom layer of the lake, although they appear to pose no problems for the life in the upper layer of the lake. Garrow Lake, and Sopha Lake on an adjoining island are interesting examples of two meromictic lakes, which we believe have developed their strong salinity gradients through differential freezing each year.

**ÉTUDE DE DEUX LACS HYPERSALÉS
DE L'ARCTIQUE SEPTENTRIONAL CANADIEN
ET DE LEUR FORMATION**

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PERSPECTIVE-GESTION

La mine Polaris de plomb et de zinc, située à 75°N de latitude, est la plus septentrionale du monde. On décharge ses résidus dans le lac Garrow de l'île Little Cornwallis. Des sulfures de métaux lourds s'accumulent ainsi en fortes concentrations dans la couche stable du fond du lac et cela ne semble pas entraver la vie aquatique des couches supérieures. Le lac Garrow et le lac Sophia, d'une île voisine, sont des exemples intéressants de lacs méromictiques dont le fort gradient de salinité est dû, selon nous, au gel différentiel chaque année.

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Abstract

The meromictic Sophia and Garrow Lakes are probably saline relicts of cutoff fjords on the uplifted Cornwallis and Little Cornwallis Islands in the high Canadian Archipelago. Sophia and Garrow have brackish (2-4 ‰) upper and hypersaline (55-90 ‰) lower waters with ion ratios (especially the lower waters) similar to that of the sea. Substantial oxygen extends well below the chemocline in Sophia. The stability of these lakes is among the highest known. Because of their size, depth, and unusually warm lower waters, it seems likely that an unfrozen "thermal chimney" extends beneath the lakes through the surrounding permafrost. We feel that the hypersaline gradients evolved primarily by descent of "salt fingers" during freeze out from above, and not by solute rejection from the ground during uplift and permafrost growth, or through taliks connected to the sea, as proposed by Page et al. (1984).

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Résumé

Les lacs méromictiques Sophia et Garrow sont probablement d'anciens fjords réséqués des îles soulevées Cornwallis et Little Cornwallis de l'archipel arctique canadien. Les couches supérieures de ces lacs sont saumâtres (2-4% et les couches inférieures hypersalées (55-90%); dans ces dernières surtout les rapports ioniques sont analogues à ceux de l'eau de mer. Dans le lac Sophia, on trouve de l'oxygène bien au-dessous de la chémocline. Ces lacs sont parmi les plus stables connus. En raison de leur étendue, de leur profondeur et de leurs eaux inférieures exceptionnellement chaudes, il semble probable que ces lacs soient reliés à des cheminées thermales non gelées qui percent le pergélisol. Nous pensons que le gradient hypersalé est principalement dû au gel de la surface qui forme des "doigts salés" et non pas à l'apport de substances en solution du sol lors du soulèvement et de la formation du pergélisol ni à des tabetisols reliant les lacs à la mer, comme le proposent Page et autres (1984).

Meromictic lakes, in which chemical gradients overwhelm temperature gradients in governing the stable density structure, are found from the tropics to the poles. This paper concerns two such unusual lakes in the High Arctic of the Canadian Archipelago. We examine here some comparative limnological data, mostly from 1982, and also consider the development of hypersaline gradients.

The study site and lakes

Sophia and Garrow Lakes are located on Cornwallis and Little Cornwallis Islands in the Northwest Territories (N.W.T.) at a latitude of about 75°N (Fig. 1). This treeless tundra region is characterized by a cold desert-like climate with a mean annual temperature of -16.2°C and precipitation of 13.0 cm as recorded at Resolute (Vowinckel and Orvig 1970). The regional glacial history (Blake 1964; Thorsteinsson 1958) suggests that the lakes are likely relict fjord basins that were separated from the sea following glacial retreat and isostatic rebound. Table 1 provides some morphometric comparisons. Both lakes have an outflow which is active only in the summer. The lake-ice thickness may exceed two meters. Sophia Lake is usually ice free for only about one month. In the years 1980, 1981, and 1982, Garrow Lake never completely lost its ice. This difference is a bit puzzling because the maximum and mean depths of both lakes are quite similar. However, the length, orientation to wind (Sophia lies east and west, Garrow north and south) and internal thermal structure differ slightly and those features may influence the extent and duration of open water.

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Methods

Water temperatures were measured on both lakes with a calibrated thermistor connected, via a coaxial cable, to a Keithley model 135 multimeter. Temperatures were easily resolved to ± 0.1 °C but, owing to minor uncertainties unknown to us during the field measurements, are now believed to be accurate to

only ± 1.0 °C.

Irradiance measurements were made with a Lambda Instruments model 185A meter and model 192S underwater quantum sensor in the photosynthetically active range (PAR) of 400-700 nm.

The 1982 sampling was done at a single station near the deep region of both lakes. Sophia Lake was ice free but approximately 3/5 of Garrow Lake was covered with drifting and broken ice in its southerly end. Sampling in Garrow was from the north edge of the loose ice pack.

Water samples from selected depths were collected with a 2.2 liter Van Dorn sampler. Dissolved oxygen was determined by the Winkler azide method (Am. Public Health Assoc. 1971). The major inorganic ions were determined as follows: sodium and potassium by flame photometry, magnesium and calcium by atomic absorption spectrometry, chloride by Mohr titration with silver nitrate, sulfate by MTB colorimetry, and alkalinity by infrared spectrometry of total carbon dioxide. The minor constituents were determined as follows: lead, zinc and iron by atomic absorption spectrometry, and selenium and arsenic by ion chromatography. The imprecision is 2 to 5 units in the last significant figure given in Table 2.

The ionic balance of the inorganic constituents agreed to within $\pm 3\%$, leading us to assign the same uncertainty to the major ion concentrations. Chloride, sodium, magnesium, sulfate, calcium, potassium and bicarbonate, in that order accounted for 99.9% of the equivalents present. The uncertainty in the heavy metal concentrations was about 10 ppb for the hypersaline lower waters. The more saline waters had to be diluted before analysis, thus accounting for the poorer precision. The arsenic and selenium values probably have detection limits of about 10 ppb. Some chemical and physical results for two strings of samples are given in Tables 2 and 3.

Salinities were determined both on the day of sampling by means of an AO

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Goldberg T/C model 10419 refractometer (0-160 ‰ range, ± 1 ‰) and, later, from pycnometric measurements of densities (Table 2) and the relation of the latter to salinity (Millero et al. 1976). Densities were estimated for two conditions for application to stability calculations. First, the relationship of Ichiye (1966) was used which states that density increases with salinity approximately $8 \times 10^{-4} \text{ g cm}^{-3}$ for each ‰ increase. As an example, sea water with a salinity of 32 ‰ would have a density of 1.0256 g cm^{-3} . The indirect refractometer determinations of densities were corrected for temperature variations in situ. Second, densities were also determined from 10 to 20°C by means of a pycnometer having an estimated precision of $\pm 0.0005 \text{ g cm}^{-3}$. This latter density was converted to the in situ σ_t value by means of the expression $\sigma_t = 10^3(\rho_t - 1)$; the in situ density was obtained by a short extrapolation of the laboratory density values to those at the water temperatures. The freezing points were determined with an Advanced Instruments, Inc. Osmometer and are precise to 0.001 K.

Total inorganic carbon (TIC), dissolved organic carbon (DOC), and particulate organic carbon (POC) were determined on an Oceanography International Corporation (O.I.C.) 0524B total carbon system (Oceanography International Corporation 1978). Samples from the field were prepared on the day of sampling for later analysis as follows. For TIC, 40 ml vials (Supelco with teflon lined caps) were filled to overflowing (no air bubbles). Later, Hamilton syringes were used to extract subsamples through the teflon cap for direct injection into the carbon analyzer. For DOC, samples were filtered through precombusted (2 hr at 400°C) Gelman glass fiber filters (which retain 99.9% of particles $> 0.3 \mu\text{m}$ in size) and acidified with 10% H_3PO_4 to convert all inorganic matter to CO_2 . For POC, the filters were placed in borosilicate glass ampules. After acidification of both DOC and POC samples, $\text{K}_2\text{S}_2\text{O}_8$ was added as

an oxidant, the ampules were purged, sealed, and autoclaved (4 hr at 130°C) to convert all organic matter to CO₂.

Results and discussion

Meromictic lakes are normally characterized by their lack of complete vertical mixing, a continuing absence of oxygen in the monimolimnion, and an increase in relative salinity and density with depth below the chemocline. In Sophia and Garrow Lakes, the temperature and oxygen concentrations peak at intermediate depths (Fig. 2). In both lakes the maximum oxygen concentration (supersaturated to ~227% in Sophia and 135% in Garrow) lies above the depths of maximum temperature. The intermediate peaking of temperature, found in other saline Arctic lakes that have been cut off from the sea (Hattersley-Smith et al. 1970; Jeffries et al. 1984), and in some Antarctic lakes (Hoare et al. 1964; Yoshida et al. 1975), has been attributed to solar heating through clear waters to a salinity gradient (Shirtcliffe and Benseman 1964; Ragotzkie and Likens 1964). Interestingly, this warm "lens" region is a common feature of heliothermal lakes at wide ranging latitudes within 80° of the equator (Sonnenfeld and Hudec 1980; Kirkland et al. 1983).

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The oxygen falls to zero at about the level of the chemocline in Garrow Lake but extends well below the chemocline in Sophia. Arctic regions are generally regarded as being organically depauperate (Remmert 1980). However, given the relatively large ratio of Sophia's catchment area to lake area (Table 1), and potential organic contributions to the highly saline zones with time, such extensive monimolimnetic quantities of oxygen in Sophia are puzzling and unusual for meromictic lakes generally. Oxygen contributions, particularly from descending saline plumes during freeze out, or generation in the lower transparent waters by photosynthetic pelagic and/or benthic flora, are possible mechanisms for enrichment. Subterranean contributions, as postulated for an Antarctic lake by Weand et al. (1975) and for Sophia Lake by Page et al. (1984),

seem questionable because such additions from the sea would likely have less oxygen and also lower salinity than the hypersaline lower waters of those lakes contain. It is curious that Page et al. (1984, their Table I) recorded no oxygen below 11 m in Sophia Lake. In light of our measurements on 26 August 1982 (Fig. 2), rechecked at selected depths on 30 August 1982, and the absence of detectable H_2S at depths < 35 m on either of those occasions, we now suspect that the lower water oxygen analyses of Page et al. for Sophia were in error. We also note an internal inconsistency (poor ion balance) in some other chemical data of Page et al. (1984, their Table 1).

The comparative semi-log plots of light decay (Fig. 3) show a marked change in slope and decrease in light transmission around 20 m for Garrow Lake. This probably reflects a turbid bacterial layer, (also noted previously by Fallis and Harbicht 1980). Sharp changes in light attenuation appear to be common features of lakes with bacterial layer and reductive zone associations (Takahashi and Ichimura 1968).

There is a marked increase of TIC from the mixolimnion to the monimolimnion in both lakes (Fig. 4) that generally parallels the corresponding salinity curves (Fig. 2). The particularly large rise in Garrow was also observed in 1980 by Dickman and Oueller (1983). In comparison, the relative constancy of the DOC and POC pools, as well as their mean DOC:POC ratios of roughly 6:1 or higher, is striking. Such constancy is a feature common to some temperate lakes and has been attributed (Wetzel 1983) to the lack of disturbance by external (man's) influence. If so, it will be interesting to see if the anthropogenic inputs (slurry tailings from a lead-zinc mine), being discharged into Garrow Lake since November 1981, will impact the carbon fractions in the future.

A weighted mean salinity was calculated for each lake by a summation of

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the products of salinities and volume fractions at ≤ 5 m intervals and assuming horizontal uniformity. Mean salinities were 26-29 ‰ for Sophia and 37 ‰ for Garrow Lake. These salinities are close to the salinity of the surrounding sea water (~ 32 ‰) and suggest an isolation from the surrounding sea some time in the past.

Stability

As might be expected, in spite of the obvious thermal instability (Fig. 2), the hypersaline chemical gradients (Table 2 and Fig. 2) prevent complete vertical mixing in either lake and produce a marked hydrostatic stability. Stability here refers to the amount of work required to mix the lake completely without loss or gain of heat. When defined in terms of a unit area (A) at depths (z), acceleration of gravity (g), and center of mass (z_g), (S) can be calculated from equation (1) as:

$$S = g A_0^{-1} \int_0^{z_m} (z - z_g) A_z (\bar{\rho} - \rho_z) dz \quad (1)$$

The equation and symbols are equivalent to those in Hutchinson (1957, p. 510, equation 37) except that we calculated a mean density ($\bar{\rho}$) for the dates of sampling and then substituted that $\bar{\rho}$ for the ρ of Hutchinson. This substitution makes the equation more universally applicable and is important when lake water densities exceed 1 g cm^{-3} , as is the case for Sophia and Garrow Lakes.

From the salinity relationships discussed earlier, stabilities were calculated from two separate sets of density determinations (Table 4). Other than the differences in numerical stability between the lakes, both approaches give similar results thus illustrating the overwhelming chemical component to the stability of the lakes. The stabilities are among the highest known and exceed those of some saline lakes in the Antarctic (Burton 1981), as well as

some tropical (Lewis 1984), and temperate (Hutchinson 1957) lakes.

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Interpretation of chemical results

The major ion data given in Table 2 can be most simply summarized by comparing them with sea water data. The surface waters (above the chemocline) in either lake appear to be diluted sea water; the waters below the chemocline appear to be concentrated sea water, with no major alteration in the ionic ratios such as would have resulted from differential mineral precipitation or intrusion of saline groundwater.

As a specific check we compared the similarity of cation milliequivalents in the Arctic Lakes with the ocean and with two Antarctic lakes (Table 5). The similarities are of course most obvious in the lower waters of both Sophia and Garrow (also noted in the latter by Fallis and Harbicht 1980). In detail, upper water calcium, especially in Sophia, shows the greatest difference from that of mean sea water. Given the somewhat calcareous nature of surficial material on Cornwallis Island (Cruickshank 1971), runoff contributions from the catchment basin could enhance those mixolimnetic differences over time.

In contrast, milliequivalent percentages in the Antarctic Lakes Vanda (particularly) and the two basins of Bonney suggest an older or more complicated history (Table. 5). Combinations of evaporation, fresh water flooding, and differential precipitation of sodium (first as mirabilite at about 4 times and then as hydrohalite at around 8 times sea water concentration) are believed to be responsible (Thompson and Nelson 1956, Matsubaya et al. 1979).

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Heavy metals (Garrow Lake)

The bottom waters of Garrow Lake contain up to 150 ppm of dissolved hydrogen sulfide. At the pH of the lake (seven to eight) the sulfide concentration should be about 10^{-9} M (Stumm and Morgan 1970). The heavy metal concentrations given in Table 4 correspond to $> 10^{-7}$ M for Pb, Zn and Fe. The

solubility products for the sulfides are about 10^{-27} , 10^{-20} and 10^{-19} respectively (Vogel 1951) so that the water is enormously oversaturated with the three sulfides. The Polaris mine, located roughly 3 km west of Garrow Lake, lies on one of the richest lead-zinc surface deposits in the world (Scales 1982). Therefore it would not be surprising to find particulate galena, sphalerite and pyrite in the bottom waters. An inspection of the vertical distribution of the heavy metals and sulfide in the water columns of the sampling site indicates that the water could become unsaturated with heavy metal sulfides above about 15 to 20 m depth, which is near the chemocline.

Permafrost and thermal chimney

On the basis of earlier temperature profiles, made through the deep permafrost by Cominco Ltd. at the Polaris lead-zinc mine on Little Cornwallis Island, Figure 5 has been prepared. Temperatures were measured in three (200-300 m) thermistor-rigged drill holes located in the mine area, ~3 km west of Garrow Lake, and in two shallower drilled holes, (50 m, of which only thermistors from 12 m upward functioned properly, and 91 m), located ~.9 km and .2 km respectively, from the south and southeast seaward side of the lake (Burns and Hamilton 1974). Considerable uncertainties in the extrapolated permafrost depth (Fig. 5) reflect both the limited number of profiles available and the difficulty of instrumenting holes much beyond depths at which drill hole fluid is lost (from > 200-300 m) and where temperatures have risen to ~-2°C. Drill hole fluid was lost in two of the three instrumented holes in the mine region. Because they are shallower, the loss of such fluid in the holes on the seaward side of Garrow had not yet been encountered. Linear extrapolation of the temperature profiles with depth provides an approximate 0°C permafrost depth.

Because the depth at which drill hole fluid is lost is reduced significantly as the sea coast is approached (Burns and Hamilton 1974), it is

interesting to speculate on whether there is permafrost beneath Sophia and Garrow Lakes. Lachenbruch (1968, p. 836) suggests that "if the minimum horizontal dimension of the water body is more than about twice as great as the local undisturbed permafrost depth, an unfrozen chimney generally occurs beneath the body of water... unless it was very recently formed". Some support for this rule of thumb comes from a study of two small lakes (roughly 6 ha area 1 m depth, and 3 ha area 6 m depth) in the Mackenzie River delta region of the N.W.T., Canada (Johnson and Brown 1961, 1966). The latter authors found no permafrost beneath the lakes proper to the depth of their drilling (~73 m in the shallower and ~98 m in the deeper lake) whereas permafrost was encountered within a few meters of the landward side of the lake edge and its thickness increased rapidly with distance from shore. Fig. 5
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Owing to their greater size, depth, and unusually warm lower waters, it would seem that Sophia and Garrow Lakes should have an unfrozen thermal chimney also. However, seismic and drilling data reveal that subsea permafrost from earlier times may extend many kilometers off shore in some Arctic regions (Hunter et al. 1976, Neave and Sellman 1982). This might be expected given the fairly rapid transgression of Arctic seas onto the land in some regions thus causing a slow degradation of the cold terrestrial permafrost (Lachenbruch et al. 1982). Granted, the temperature of the sea water (-1.7 ± 0.1 °C, Burns and Hamilton 1974) surrounding the Cornwallis Islands is markedly less than that of the lower lake waters, but it seems unlikely that permafrost would extend laterally well below the mud-water interface and effectively seal the hypersaline lakes. The age and rate of expanding (aggrading) or contracting (degrading) of deep permafrost on the Cornwallis Islands is uncertain - as is specific knowledge of possible earlier glacial and isostatic episodes. Consequently, until seismic or drill hole data are available from beneath the

lakes proper, it will be difficult to confirm the presence or absence of permafrost beneath Sophia and Garrow. Interestingly, as part of some initial geophysical exploration by the Cominco Ltd. lead-zinc mine, plans were made one year to drill through the center of Garrow Lake to check for permafrost beneath the lake. The lake ice became unsafe unexpectedly early that year and the project was never pursued (R. Burns, pers. comm.).

Evolution of hypersalinity

Based on the estimates of Andrews et al. (1971), shorelines that formed 4,000 years before present (y.B.P.) near Resolute on Cornwallis Island are now about 15 meters above sea level (m asl) (Fig. 6). This time and elevation estimate also fits within the emergence-curve envelopes of Washburn and Stuvier (1985), their Fig. 2). Washburn and Stuvier also showed that the uplift on Cornwallis Island has slowed dramatically from an initial rate of emergence of $8.3 \text{ m} \cdot (100 \text{ y})^{-1}$ for the first 75 m to about $0.5 \text{ m} \cdot (100 \text{ y})^{-1}$ for the last 40 m. Consequently, given the relative proximity of the lakes to Resolute, the current lake surface elevations (Table 1), and the shoreline thresholds near the outlet within 1 m of the lake elevation, we could estimate roughly that Garrow Lake separated from the sea ~ 2,500-3,000 years ago (Fig. 6). This period encompasses the estimates of 2,600 y.B.P. (Fallis and Harbicht 1980), 3,000 y.B.P. (Dickman and Ouellet 1983), and $2,580 \pm 260$ y.B.P. (Page et al. 1984, carbon dated sample of 1982 from 35 m in Garrow Lake) for the age of Garrow Lake. Though not available for this paper, the surface elevation of Sophia Lake is known (M. Dickman, pers. comm.) to be substantially less than that of Garrow Lake. Therefore, if the curve drawn from the data of Andrews et al. (1971) in Fig. 6 is valid, Sophia Lake should have separated from the sea more recently and be younger. No ^{14}C dates were included by Page et al. for Sophia but a higher percentage of modern carbon was found in its lower waters.

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Although the upper water values of the $\delta^{18}\text{O}$ isotope are fairly similar in

both lakes, as are comparative lower water values. Page et al. attribute the higher percent of modern carbon in the lower brines of Sophia Lake to recent seepage of seawater into the lake through taliks or seasonally unfrozen zones or underlake chimneys.

Further, Page et al. (1984) have recently suggested, on the basis of isotopic studies, that meromixis in Garrow Lake developed crenogenically. Specifically, they feel that the high salinity of the lower waters developed from brine production (i.e., solute rejection from the surrounding ground to the lake during uplift and permafrost growth). As evidence they cite the lower (more negative) values of the heavier $\delta^{18}\text{O}$ isotope in the mixolimnion and higher (less negative) values in the monimolimnion.

The case for hypersaline gradients by permafrost

The argument of Page et al. (1984) seems initially plausible because there is some slight enrichment ($\sim 3\%$) of the $\delta^{18}\text{O}$ isotope in the ice during freezing (Matsubaya et al. 1979; Page et al. 1984). Consequently, ice forming at the lake surface would tend to have less negative values than the saline water descending from brine exclusion during freeze out. Of course, isotopic enrichment in ice could gradually become isotopic impoverishment, as laboratory studies of Souchez and Jouzel (1984) have shown, if a huge volume fraction of a water body were to freeze. However, although the early details of the glacial climatic history of Cornwallis Islands are unknown, it seems unlikely that the present depth of freezing (roughly 2 - 2-1/2 m, $\geq 10\%$ of the lake volume) would at one time have been great enough (say 35 m, $> 90\%$ of the lake volume) to significantly alter the present isotopic profile.

Further, if the land were once covered by sea water, the ground water, at least near the sediment-water interface, should have a composition closer to that of the sea than ground water from land not so covered. Finally,

although many salts besides those of sea water will lower the freezing point, the fact that some bore hole fluid was lost in the drill holes when a temperature of ~ -2.0 °C was reached at least attests to some salts being present.

The case for hypersaline gradients by freeze out

The concentration of brines from sea water (Thompson and Nelson 1956) and development of hypersaline gradients in saline polar lakes (Goldman et al. 1967), have been attributed to the freezing out of salts and gases from the ice cover. Indeed, a much lower but significant increase in salts and gases during freeze out has been documented from freshwater lakes as well (Welch 1974; Barica 1972; Rigler 1978; Canfield et al. 1983).

The descent of brines excluded from sea ice does not take place merely by slow downward molecular diffusion because, even if one assumed an instantaneous uplift and separation (instead of a much more likely and slower separation during uplift), after the first or a few annual cycles in the two closed Arctic lakes, subsequent less dense saline layers would have to move against a density gradient. In fact, slow upward diffusion would be more likely from the more saline lower waters (Toth and Lerman 1975). However, hypersaline profiles could develop rapidly, even with a climate and ice thickness similar to the present, if there was a mechanism by which the brines formed during freeze out were concentrated. Such a mechanism occurs naturally and is well documented in mechanics, heat transfer, and oceanographic literature.

During the freezing of sea ice, there is rejection of concentrated brines in the form of narrow "salt fingers" (Lake and Lewis 1970; Federov 1972; Farhadieh and Tankin 1975) which easily lead to thermohaline convection (Grange et al. 1977). The salt is rejected through narrow brine channels in the ice matrix as the ice thickens. The salinity and density of the descending salt fingers vary with initial salinity and rate of sea ice

growth. Generally, the salinity increases at reduced rates of ice growth. Starting with sea water of 33 ‰, Wakatsuchi and Ono (1983) found that the salinity of the excluded brines, collected by positioning funnels within a few centimeters of the descending ice front, ranged from 42.3 ‰ to 92.7 ‰. It is noteworthy that the salinity of the sea water and that of the excluded brines is similar to the sea water surrounding the Cornwallis Islands and the monimolimnetic brines of the lakes respectively. Wakatsuchi and Ono (1983) and Wakatsuchi (1977) observed relatively little diffusion of the descending salt fingers into the sea water just below the ice. Whether or not the integrity of these long and relatively dense salt fingers could be maintained for several meters as they descend, either individually or in aggregated plumes to the bottom or to an equilibrium density, is unknown. However, the fact that hypersaline brines can be formed in one season, merely by freeze out from above, was documented by Schell (1973) and Coyle (1974) when they found salinities of ~40-72 ‰ in water below sea ice in some shallow (≤ 2.5 m) and restricted coastal waters of the Alaskan Beaufort Sea. In two extreme cases, Schell found salinities of ~126-183 ‰ where the ice was within a few centimeters of.....or on the bottom.

Prior to the time of lake-sea separation, there should have been lower $\delta^{18}O$ values throughout the lakes more similar to those of the connecting sea. During uplift and isolation, freeze out from above would have made the lower waters somewhat more negative than they were originally, while at the same time making them rapidly more saline and increasingly resistant to vertical mixing. Indeed, the ^{14}C value of 2.580 ± 260 y.B.P. of Page et al. (1984) suggests that the lower stable waters of Garrow Lake have mixed relatively little with the upper water since separation. As far as the more negative ($\delta^{18}O$) upper mixed waters are concerned, they are more simply explained by

meteoric contributions over time which can be added (by runoff and direct precipitation) or lost (outflow).

We feel the interpretation of Page et al. (1984) unnecessarily stresses bottom (permafrost) and lateral (talik) contributions to explain the hypersalinity. We do not discount all such possible contributions during the course of an unknown and complex history. However, we feel that freeze out from the surface is a more likely and dominant factor in the evolution of the hypersaline gradients in Sophia and Garrow Lakes. If freeze out were the process, it should be expected to impact every lake on either island. It does - but would tend to cause permanent hypersaline gradients in those very few lakes that were saline relicts (or cut-off fjords) initially. In contrast, if permafrost growth were the process by which salts were pushed into the lakes from below or laterally, it should also impact all the lakes on both islands and generate numerous hypersaline bodies above and beyond those that might have been saline relicts. However, this isn't the case. Therefore, freeze out leading to the development of a cryogenic meromixis (as in Goldman et al. 1967), not crenogenic meromixis (as in Page et al. 1984), is the most plausible mechanism.

The possible role of double-diffusive convection in either the early structuring or the present maintenance of thermal-salinity gradients in Lakes Sophia and Garrow is unknown. However, double-diffusive convection, i.e., where salt (diffusing about 100 times more slowly than heat, Terwilliger and Dizio 1970) and temperature make opposing contributions to the density, is known to play a role in the microstratification of the oceans (Gregg 1973; Huppert and Turner 1981) and in the density gradients of Lake Vanda in the Antarctic (Huppert and Turner 1972). Future measurements with greater spatial and temporal resolution may provide new insights into the possible significance of this intriguing phenomenon on density gradients in Lakes

Sophia and Garrow.

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References

- AMERICAN PUBLIC HEALTH ASSOCIATION, AMERICAN WATER WORKS ASSOCIATION AND WATER POLLUTION CONTROL FEDERATION. 1971. Standard methods for the examination of water and wastewater. 13th ed. Washington, DC. 874 p.
- ANDREWS, J. T., R. MCGHEE, and L. MCKENZIE-POLLOCK. 1971. Comparison of elevations of archeological sites and calculated sea levels in Arctic Canada. *Arctic* 24: 210-228.
- BARICA, J. 1977. Effects of freeze-up on major ion and nutrient content of a prairie winterkill lake. *J. Fish. Res. Bd. Can.* 34: 2210-2215.
- BLAKE, W. 1964. Preliminary account of the glacial history of Bathurst Island, Arctic Archipelago. *Geol. Surv. Can. Paper* 64-30. 8 p.
- BROECKER, W. S. 1974. Chemical oceanography. Harcourt Brace Jovanovich, Inc. New York, NY. 214 p.
- BURNS, R., and J. M. HAMILTON. 1974. Some geophysical and hydrological aspects of permafrost in the Cornwallis Island area, N.W.T. Presented at "Symposium on Permafrost-Hydrology and Geophysics", in Calgary, Can., 28 Feb 1974.
- BURTON, H. R. 1981. Chemistry, physics, and evolution of Antarctic saline lakes. *Hydrobiologia* 82: 339-362.
- CANFIELD, D. E., R. W. BACHMANN, and M. W. HOYER. 1983. Freeze-out of salts in hard-water lakes. *Limnol. Oceanogr.* 28: 970-977.
- COYLE, K. O. 1974. The ecology of the phytoplankton of Prudhoe Bay, Alaska, and the surrounding waters. M.S. Thesis. University of Alaska, Fairbanks, AK, 106 p.
- CRUICKSHANK, J. G. 1971. Soils and terrain units around Resolute, Cornwallis Island. *Arctic* 24: 195-209.
- DICKMAN M., and M. OUELLET. 1983. Limnological aspects of meromictic Lake Garrow. Quebec Univ. (INRS-Eau), Rep. 73. 25 p.

- FALLIS B. W., and S. M. HARBICHT. 1980. A preliminary study of the limnology and biology of Garrow Lake, N.W.T. Tech. Rep. Fish. Aquatic Sci., Dept. Fish. Oceans, Winnipeg, Manitoba. 76 p.
- FARHADIEH, R., and R. S. TANKIN. 1975. A study of freezing of sea water. J. Fluid Mech. 71: 293-304.
- FEDOROV, K. N. 1972. Thermochaline convection in the form of salt fingers and its possible manifestations in the ocean. Izv. Acad. Sci. USSR, Atmosph. Oceanic Physics 8: 122-130. (English edition).
- GOLDMAN, C. R., D. T. MASON, and J. E. HOBBIE. 1967. Two Antarctic desert lakes. Limnol. Oceanogr. 12: 295-310.
- GRANGE, B. W., R. VISKANTA, and W. H. STEVENSON. 1977. Interferometric observation of thermohaline convection during freezing of saline solution. Lett. Heat Mass Transfer 4: 85-92.
- GREGG, M. C. 1973. The microstructure of the ocean. Sci. Am. 228(2): 64-77.
- HATTERSLEY-SMITH G., J. E. KEYS, H. SERSON, and J. E. MIELKE. 1970. Density stratified lakes in northern Ellesmere Island. Nature 225: 55-56.
- HOARE, R. A., K. B. POPPLEWELL, D. A. HOUSE, R. A. HENDERSON, W. M. PREBBLE, and A. T. WILSON. 1964. Lake Bonney, Taylor Valley, Antarctica: A natural solar energy trap. Nature 202: 886-888.
- HUNTER, J. A. M., A. S. JUDGE, H. A. MACAULY, R. L. GOOD, R. M. GAGNE, and R. A. BURNS. 1976. Permafrost and frozen sub-seabottom materials in the southern Beaufort Sea. Beaufort Sea Proj. Tech. Rep. 22, Dept. of the Environ., Victoria, B. C. 174 p.
- HUPPERT, H. E., and J. S. TURNER. 1972. Double-diffusive convection and its implications for the temperature and salinity structure of the ocean and

- Lake Vanda. J. Phys. Oceanogr. 2: 456-461.
- HUPPERT, H. E., and J. S. TURNER. 1981. Double-diffusive convection. J. Fluid Mech. 106: 299-329.
- HUTCHINSON, G. E. 1957. A treatise on limnology. Vol. 1. John Wiley & Sons, Inc. New York, NY. xiv + 1015 p.
- ICHIYE T. 1966. Density, p. 229-230. In R. W. Fairbridge (ed.), The Encyclopedia of Oceanography. Reinhold. New York, NY.
- JEFFRIES, M. O., H. R. KROUSE, M. A. SHAKUR, and S. A. HARRIS. 1984. Isotope geochemistry of stratified Lake "A", Ellesmere Island, N.W.T., Canada. Can. J. Earth Sci. 21: 1008-1017.
- JOHNSON, G. H., and R. J. BROWN. 1961. Effect of a lake on distribution of permafrost in the Mackenzie River delta. Nature 192: 251-252.
- JOHNSON, G. H., and R. J. BROWN. 1966. Occurrence of permafrost at an Arctic Lake. Nature 211: 952-953.
- KIRKLAND, D. W., J. P. BRADBURY, and W. E. DEAN. 1983. The heliothermic lake - a direct method of collecting and storing solar energy. Arch. Hydrobiol./Suppl. 65, 1: 1-60.
- LACHENBRUCH, A. H. 1968. Permafrost, p. 833-839. In R. W. Fairbridge (ed.), The Encyclopedia of Geomorphology. Reinhold. New York, NY.
- LACHENBRUCH, A. H., J. H. SASS, B. V. MARSHALL, and T. H. MOSES Jr. 1982. Permafrost, heat flow, and the geothermal regime at Prudhoe Bay, Alaska. J. Geophys. Res. 87: 9301-9316.
- LAKE, R. A., AND E. L. LEWIS. 1970. Salt rejection by sea ice during growth. J. Geophys. Res. 75: 583-597.
- LEWIS, W. M. 1984. A five-year record of temperature, mixing and stability for a tropical lake (Lake Valencia, Venezuela). Arch. Hydrobiol. 99: 340-346.
- MATSUBYA, O., H. SAKAI, T. TORII, H. BURTON, and K. KERRY. 1979. Antarctic

- saline lakes - stable isotopic ratios, chemical compositions and evolution. *Geochim. Cosmochim. Acta* 43: 7-25.
- MILLERO, F. J., A. GONZALEZ and G. K. WARD. 1976. The density of seawater solutions at one atmosphere as a function of temperature and salinity. *J. Mar. Res.* 34: 61-93.
- NEAVE, K. G., and P. V. SELLMAN. 1982. Subsea permafrost in Harrison Bay, Alaska: an interpretation from seismic data. U. S. Army Cold Regions Research and Engineering Report 82-24. Hanover, NH. 62 p.
- OCEANOGRAPHY INTERNATIONAL CORPORATION. 1978. Operating procedures manual for 0524B total carbon system. College Station, TX. 74 p.
- PAGE, P., M. OUELLET, C. HILLAIRES-MARCEL, and M. DICKMAN. 1984. Isotopic analyses ($\delta^{18}\text{O}$, ^{13}C , ^{14}C) of two meromictic lakes in the Canadian Arctic Archipelago. *Limnol. Oceanogr.* 29: 564-573.
- RAGOTZKIE, R. A., and G. E. LIKENS. 1964. The heat balance of two Antarctic lakes. *Limnol. Oceanogr.* 9: 412-425.
- REMMERT, H. 1980. Arctic animal ecology. Springer-Verlag New York, Inc. Secaucus, NJ. 250 p.
- RIGLER, F. H. 1978. Limnology in the high Arctic: a case study of Char Lake. *Int. Ver. Theor. Angew. Limnol. Verh.* 20: 127-140.
- SCALES, M. 1982. High Arctic wizardry: Polaris mine on stream. *Can. Min. J.* 103(7): 24-41.
- SHELL, D. M. 1973. Seasonal variation in the nutrient chemistry and conservative constituents in coastal Alaskan Beaufort sea waters, p 217-281. In V. Alexander et al. (16 authors) Sea Grant Report 73-16. IMS Report R-74-1. University of Alaska, Fairbanks, Alaska.
- SHIRTCLIFFE, T. G. L., and R. F. BENSEMAN. 1964. A sun-heated Antarctic Lake. *J. Geophys. Res.* 69: 3355-3359.

- SONNENFELD, P., and P. P. HUDEC. 1980. Heliothermal lakes, p. 93-100. In A. Nissenbaum (ed.), Hypersaline brines and evaporitic environments. Developments in Sedimentology 28. Elsevier Scientific Publishing Company. New York, NY.
- SOUCHEZ, R. A., and J. JOUZEL. 1984. On the isotopic composition in δD and $\delta^{18}O$ of water and ice during freezing. J. Glaciol. 30: 369-372.
- STUMM, W., and J. J. MORGAN. 1970. Aquatic chemistry. Wiley-Interscience. New York, NY. 583 p.
- TAKAHASHI, M. and S. ICHIMURA. 1968. Vertical distribution and organic matter production of photosynthetic sulfur bacteria in Japanese Lakes. Limnol Oceanogr. 13: 644-655.
- TERWILLIGER, J. P., and S. F. DIZIO. 1970. Salt rejection phenomena in the freezing of saline solutions. Chem. Engng. Sci. 25: 1331-1349.
- THOMPSON, T. G., and K. H. NELSON. 1956. Concentration of brines and deposition of salts from sea water under frigid conditions. J. Sci. 254: 227-238.
- THORSTEINSSON, R. 1958. Cornwallis and Little Cornwallis Island, District of Franklin, Northwest Territories. Geol. Surv. Can., Mem. 294. 134 p.
- TOTH, D. J., and A. LERMAN. 1975. Stratified lake and oceanic brines: Salt movement and time limits of existence. Limnol. Oceanogr. 20: 715-728.
- VOGEL, A. I. 1951. A textbook of quantitative inorganic analysis. Longmans, Green. London. 918 p.
- VOWINCKEL, E., and S. ORVIG. 1970. The climate of the North Polar Basin, p. 129-252. In S. Orvig (ed.), World survey of climatology. 14. Climates of the polar region. Elsevier. New York, NY.
- WAKATSUCHI, M. 1977. Experiments on haline convection induced by freezing of sea water. Low Temp. Sci. Ser. A, 35, p. 249-258. (In Japanese with English summary).

- WAKATSUCHI, M., and N. ONO. 1983. Measurements of salinity and volume of brine excluded from growing sea ice. J. Geophys. Res. 88(C5): 2943-2951.
- WASHBURN, A. L., and M. STUVIER. 1985. Radiocarbon dates from Cornwallis Island area, Arctic Canada - an interim report. Can. J. Earth Sci. 22: 630-637.
- WELCH, H. E. 1974. Metabolic rates of arctic lakes. Limnol. Oceanogr. 19: 65-73.
- WEAND, B. L., R. D. FORTNER, R. C. HOEHN, and B. C. PARKER. 1975. Subterranean flow into Lake Bonney. Antarct. J. U. S. 10: 15-19.
- WETZEL, R. G. 1983. Limnology. Saunders College Publishing. Philadelphia, PA. 767 p. + R81 + I10.
- YOSHIDA, W., T. TORII, Y. YUSA, S. NAKAYA, and K. MORIWAKI. 1975. A limnological study of some lakes in the Antarctica. Bull. R. Soc. N.Z. 13: 311-320.

Table 1. Morphometric data of lakes. Note from elevation and depths that both lakes are cryptodepressions.

	Sophia Lake	Garrow Lake
Surface area (ha)	339	432
Area (catchment/lake)	20.1	2.5
Length (km)	4.8	3.2
Volume ($\text{m}^3 \times 10^6$)	75.8	99.1
Max depth (m)	50	49
Mean depth (m)	22.4	22.9
Elevation (m)	? but < Garrow	6.7

Table 1. Chemical and physical properties of Sophia and Arrow Lakes, August 1982.

Sample	Na ⁺	Mg ²⁺	Ca ²⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	TDS	o _T	o/oo	φ/K
S-0	0.32	0.042	0.037	0.009	0.725	0.07	< 0.01	1.2	0.5	1.3	0.069
S-5	0.32	0.043	0.037	0.009	0.730	0.07	< 0.01	1.2	0.5	1.3	0.069
S-10									0.5	1.3	0.069
S-12									35.0	45	2.533
S-15									35.5	45	2.560
S-20	16.5	2.0	0.74	0.52	28.8	4.3	(0.2)	53.1	39.5	50	2.906
S-30	18.4	2.3	0.75	0.60	29.8	4.8	(0.2)	56.8	40.5	52	3.051
S-33	17.6	2.1	0.72	0.58	31.0	4.6	(0.2)	56.8	43.2	52	3.163
S-40	17.7	2.2	0.73	0.58	31.6	4.6	(0.2)	57.6	43.4	55	3.211
G-0	1.02	0.134	0.078	0.031	2.02	0.25	(0.01)	3.5	2.5	4	0.201
G-5	1.25	0.164	0.091	0.036	2.40	0.30	(0.01)	4.2	3.0	4	0.230
G-10									5.7	6	0.490
G-15									37.3	45	2.614
G-20	20.1	2.7	0.88	0.51	35.3	5.7	(0.2)	65.4	49.5		3.634
G-30	24.5	3.1	1.01	0.74	42.9	6.3	(0.3)	78.8	60.5		4.37
G-40	28.2	3.5	1.12	0.90	49.5	7.2	(0.3)	90.6	69.8		5.23
G-CR	1.01	0.135	0.088	0.029	2.01	0.25	(0.01)	3.53	2.5		0.201
G-SW	10.0	1.22	0.40	0.32	17.8	2.8	(0.1)	32.6	25.5	32	1.740

Table 2: Chemical and physical properties of Sophia and Garrow Lakes, August 1982. (Continued)

Column	1:	S denotes Sophia Lake, G denotes Garrow Lake, suffix is sample depth in meters.
Columns	2-8:	Major ion concentrations in grams per kilogram of solution.
Column	8:	Estimated from $0.006 \times$ (chloride concentration) if below detection limit.
Column	9:	Total dissolved solids is sum of columns 2 to 8. This figure agrees within 3 % on average with a value calculated from $1.806 \times$ (chloride concentration), the conventional method for calculating sea water salinities.
Column	10:	The <u>in situ</u> water density in g cm^{-3} is given by $C_t = 1 + \sigma_t(10^{-3})$. The change in density on going from 0° to 20° is less than 0.5% for these waters.
Column	11:	Salinity calculated from the values in column 10 (from Millero et al. 1976).
Column	12:	Freezing point depression of the samples, in kelvins.

Last row in Table 2 is surrounding sea water and is the same as normal oceanic water of salinity $32 \text{ }^\circ/\text{oo}$

**Table 3 Stabilities (ergs cm⁻²) of lakes from
two separate sets of density determinations. Corrected
for in situ temperature**

Lake	I	II
	Density from relationship to salinity (as in Ichiye 1966)	Density from pycnometer
Sophia	40,800	40,990
Garrow	64,790	59,300

Table 4. Heavy metals (parts per billion) and related quantities

Concentrations	Sophia Lake		Garrow Lake	
	Above	Below	Above	Below
	Chemocline	Chemocline	Chemocline	Chemocline
Lead 1982	< 1	< 100	4	< 100
Zinc 1982	4	< 200	4	< 100
Iron 1982	3	< 200	3	< 200
Arsenic 1982	< 20	< 100	< 20	< 200
Selenium 1982	< 10	< 100	< 10	< 100

Table 5. Comparative milliequivalent percentages of dominant cations in the ocean and upper and lower waters of four hypersaline polar lakes. Determined from chemical data in: (1) Broecker 1974; (2) this paper 1982 data; (3) Matsubaya et al. 1979. Sophia and Garrow Lakes are in the Arctic and Lakes Bonney and Vanda are in the Antarctic. (Bonney W and Bonney E = west and east basins of Lake Bonney).

Water Body		Milliequivalent percentages				Reference
		Na	Mg	Ca	K	
Ocean		77.7	17.2	3.4	1.6	1
Sophia	5 m	71.3	18.1	9.4	1.2	2
	40 m	76.8	18.0	3.6	1.5	2
Garrow	5 m	74.2	18.4	6.2	1.3	2
	40 m	77.0	18.1	3.5	1.4	2
Bonney W	5 m	65.2	22.3	11.1	1.4	3
	W 29.5 m	63.6	31.3	3.4	1.7	3
	E 5 m	52.1	22.2	23.9	1.8	3
	E 29.5 m	47.7	49.2	1.4	1.7	3
Vanda	8 m	30.1	20.2	46.0	3.7	3
	60 m	11.5	27.8	60.0	0.6	3

FIGURE HEADINGS

- Fig. 1. A portion of the Canadian Archipelago showing the location of Sophia and Garrow Lakes.
- Fig. 2. Profiles of temperature, O_2 , and salinity in Sophia (26 Aug 1982) and Garrow (28 Aug 1982) Lakes.
- Fig. 3. Decay of PAR irradiance in Sophia (26 Aug 1982) and Garrow (28 Aug 1982) Lakes. Note rapid decrease in transmission in Garrow, at about 18-21 m, probably associated with a photosynthetic bacterial layer.
- Fig. 4. Profiles of TIC, DOC, and POC in Sophia (26 Aug 1982) and Garrow (28 Aug 1982) Lakes. The unknown value of DOC at 10 m reflects a single limited sample that was above the instrumental range.
- Fig. 5. A schematic representation of possible permafrost distribution along a hypothetical east-west transect through the middle of Garrow Lake. Vertical and horizontal scales are identical.
- Fig. 6. Elevation in meters above sea level of the former shoreline near Resolute on Cornwallis Island during 800 year stages (dark circles along curve) of the past 4000 years, from estimates of Andrews et al. 1971, in comparison to present lake surface elevations.

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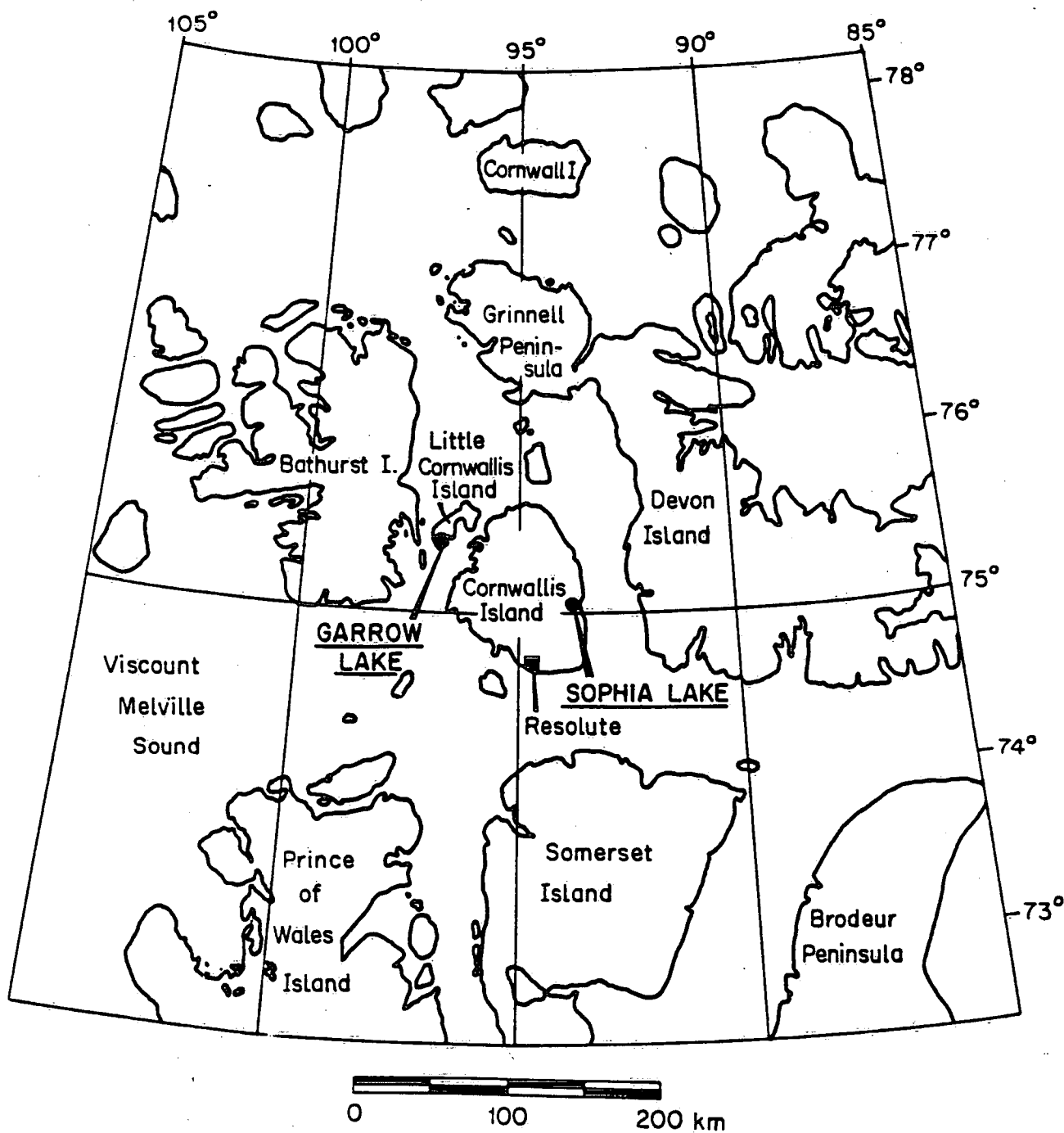


Fig. 1

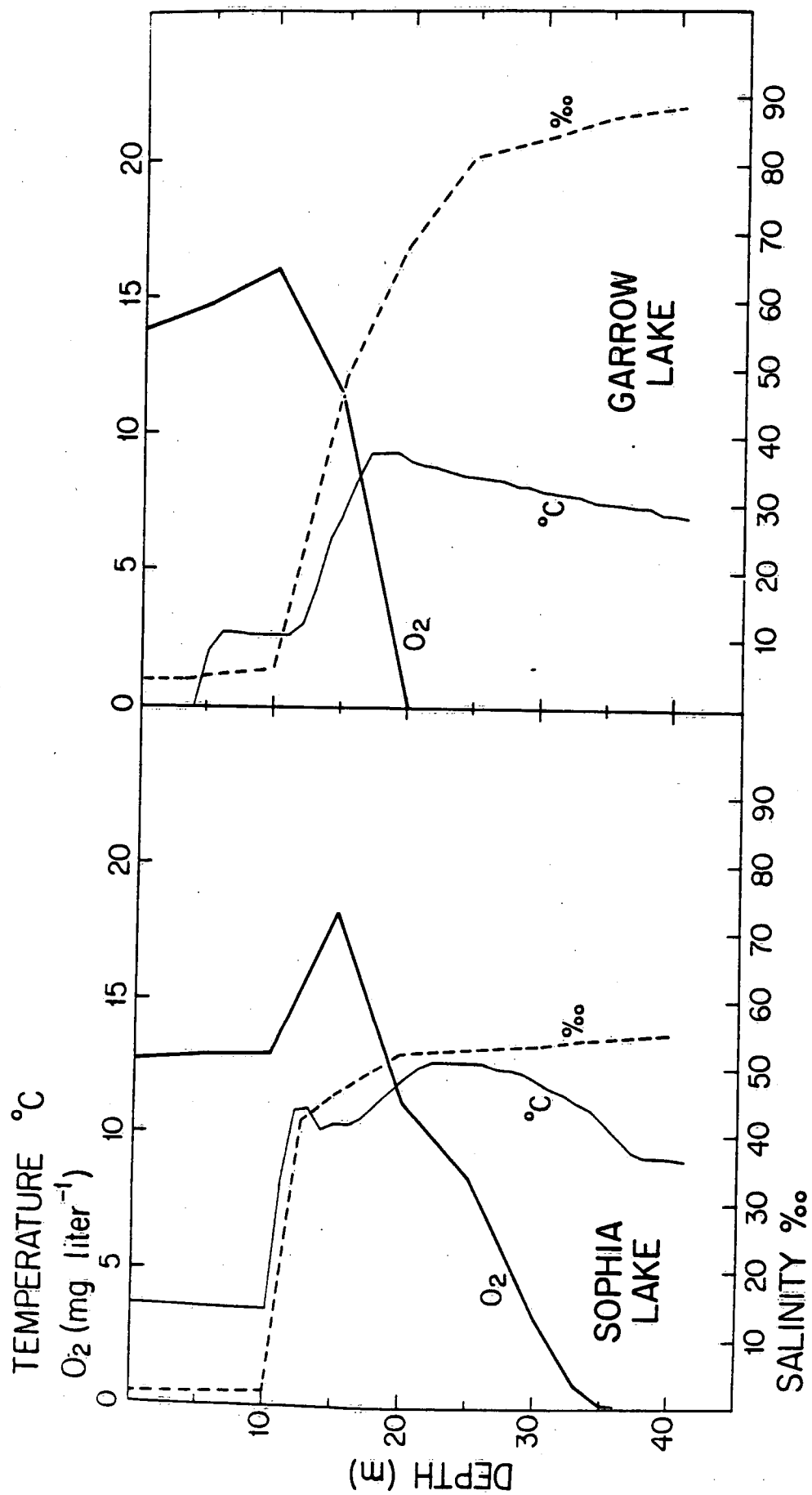


Fig. 2

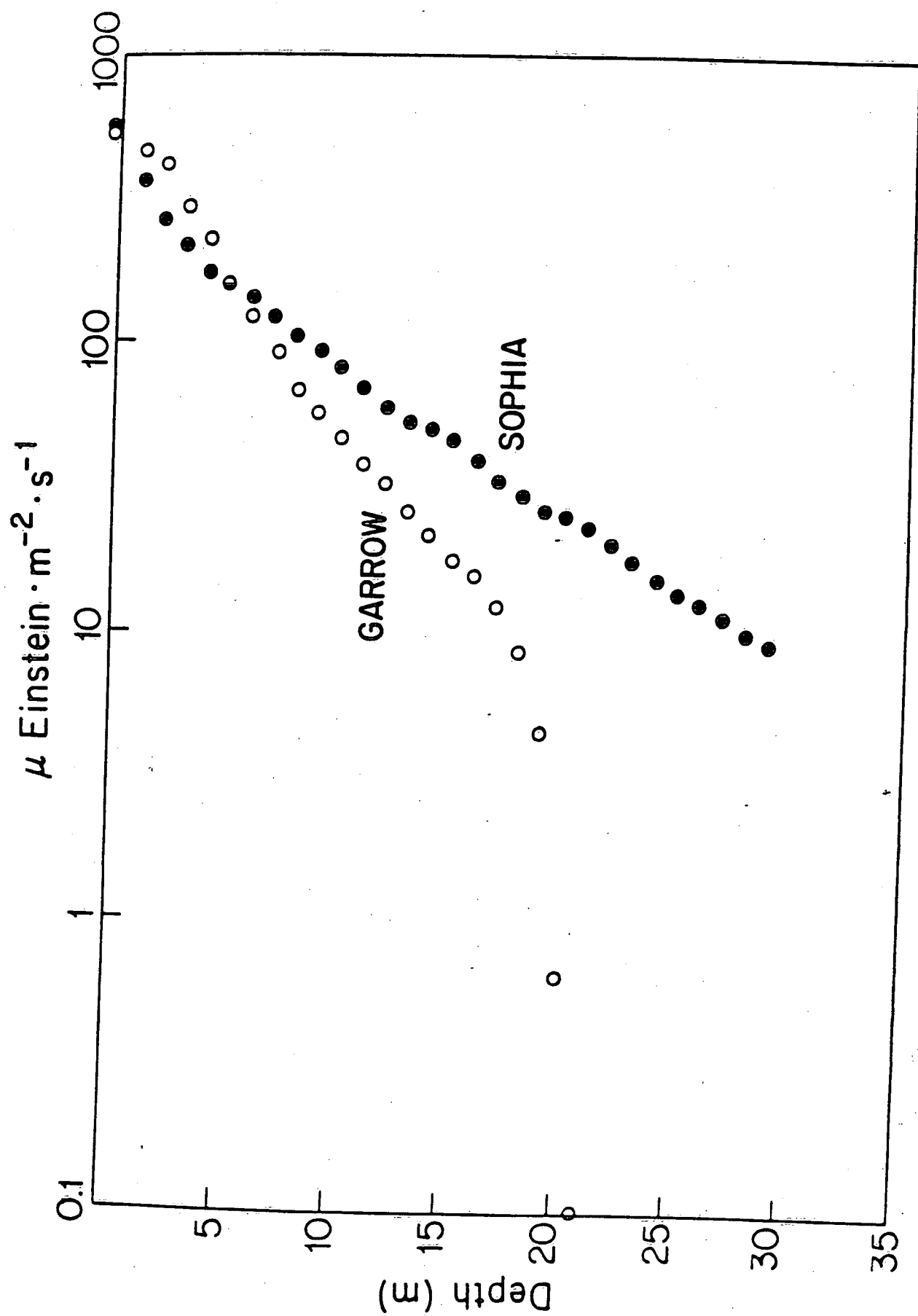


Fig. 3

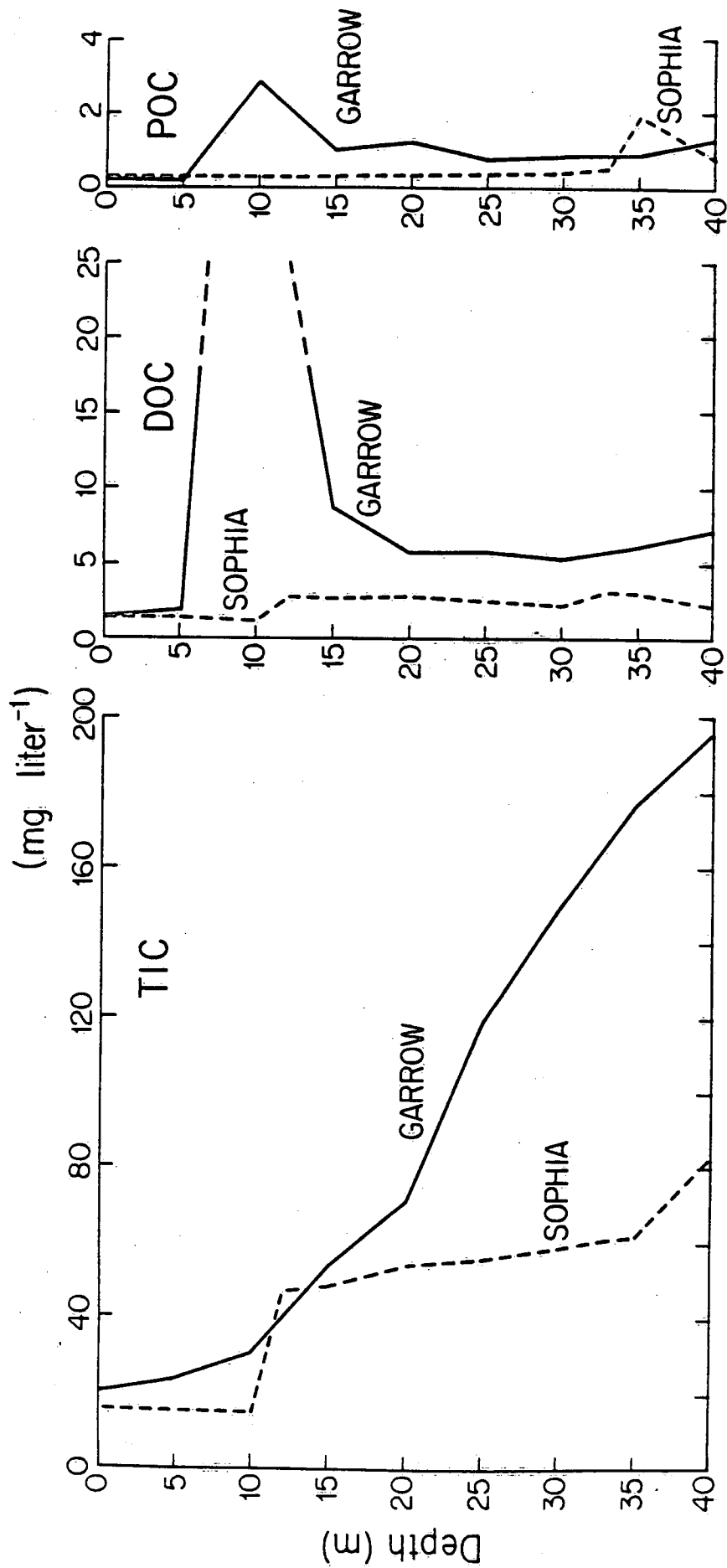


Fig. 4

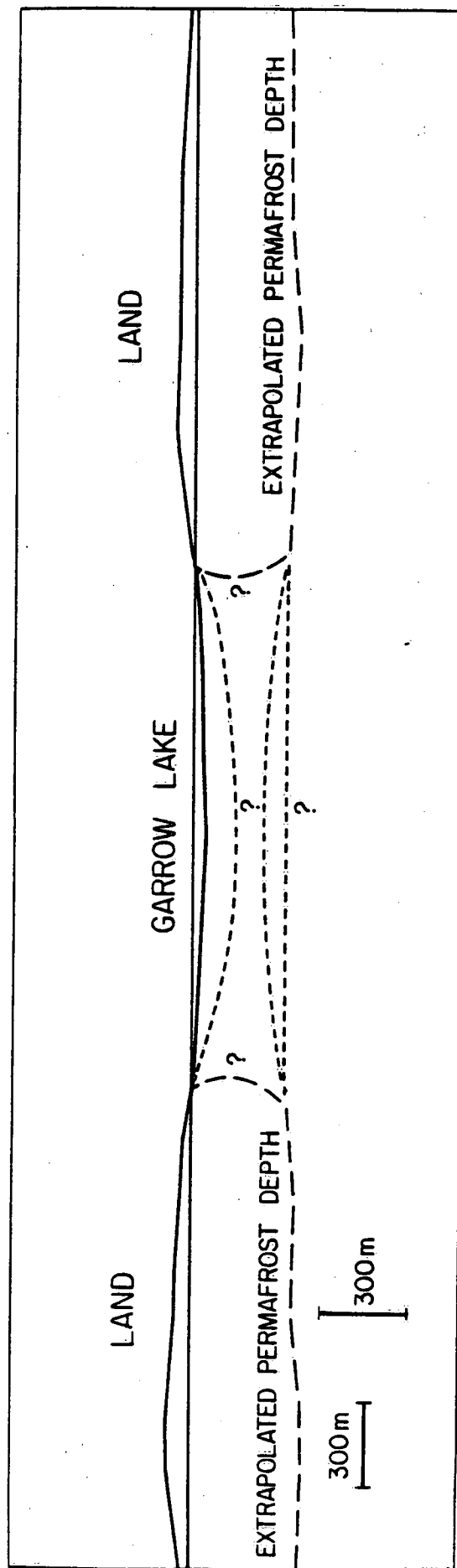


Fig. 5

Fig. 6

