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# Evidence of density currents with the potential to promote meromixis in ice-covered saline lakes

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ABSTRACT

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Ice covers all but the most saline of the Vestfold Hills' lakes for about 8–12 months of each year and precludes wind-induced turbulent mixing over the winter, when strong winds are most frequent. Nevertheless, the progressive growth of ice volume through the austral winter and spring months generates haline convection capable of mixing the water column to a depth at least as great as that achieved by wind-induced turbulence in the summer ice-free period. Further, cold and very saline brines may form at the shallow periphery of a lake and flow downslope, penetrating to the lake centre below the convectively mixed layer. Detailed temperature profiles of hypersaline Organic Lake provide the first evidence for these density currents in saline lakes of the Vestfold Hills. These data indicate a dynamic responsiveness to periods of relatively cold weather, and that the resulting density currents may be sufficiently small in volume to have little effect on the anoxia of bottom layers in these meromictic lakes.

Alternating periods of negative and positive water balance may also be significant in the formation and destruction of meromixis in these saline lakes, which lack outflow streams. If a lake has been through a period of negative water balance, becoming relatively more saline, and then begins to be diluted during a subsequent period of positive water balance, the winter haline convection will penetrate to progressively shallower depths and deeper layers may stagnate, marking the onset of meromixis. An increase in the water level of Organic Lake over ten years indicates the speed with which the Vestfold Hills' lakes may experience significant change in salinity despite the generally small catchments of these lakes.

## Introduction

The lakes that occupy valleys and depressions of the Vestfold Hills region of East Antarctica (68°35'S, 78°10'E) are a striking and varied feature of the landscape. The lake basins are the result of sheet glacial scouring over an area of low relief; many are devoid of loose material and reflect the relative weakness of underlying rock. Similar lake basins are known from the Hebrides and western Scotland, Norway, Finland and northern Canada (Hutchinson, 1957). The saline lakes of the Vestfold Hills formed following the end of the last period of glaciation ($\sim$8000 yr B.P.). The ice gradually retreated from the hills which were then partially flooded by the sea. Subsequently, isostatic readjustment cut off many basins filled with seawater, and these then developed according to their individual balance between evaporation and snowmelt (Adamson and Pickard, 1986).

Meromixis (year-round stratification) is unusually common in saline basins of the Vestfold Hills (Burton, 1981a, b). At least 20 such basins, ranging from marine embayments having year-round tidal exchange with the sea to fully isolated lakes, are known. The development of anoxia in the bottom waters of these basins establishes a vertical zona-

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tion of biota and a biochemically important interface between upper and lower water layers (Ferris et al., 1988). Further, the anoxia and stagnation of these bottom waters make them a particularly quiescent environment for the accumulation of sediment. Understanding the mechanisms by which meromixis is initiated and maintained in these basins has implications for any study of these lakes' biology and for the interpretation of their sedimentary history. We make use, here, of a detailed set of thermal data from meromictic Organic Lake to gain some understanding of the potential interaction between haline convective mixing, generated by ice forming on saline water, and lake basin shape. This interaction may explain the observed meromixis in saline waters of the Vestfold Hills. We also consider, hypothetically, what contribution long-term changes in water balance may make to the initiation of meromixis in lakes of this region.

## Materials and methods

Organic Lake was visited approximately weekly from August to December of 1987. Sampling sites are shown on a bathymetric map of the lake, Fig.1. The bathymetry, based on soundings made in 1978, does not take into account an increase in water level of about one metre since that time. The lake was ice-covered throughout this period and a Jiffy Ice-drill (Feldmann Engineering, Sheboygan Falls, Wisconsin, USA) was used to gain access to the water column. Detailed thermal profiles were measured using a Conductivity–Temperature–Depth (CTD) recorder (Platypus Engineering, Loyetea, Tasmania) which was factory-calibrated and accurate to $\pm 0.05$°C. The CTD, set to sample every five seconds, was lowered on a marked steel cable in steps of 0.1 m and held for 30 seconds at each depth. The full set of data is presented in Gibson et al. (1989). The 0 m depth in the figures refers to the water surface in the drill-hole which was $\sim$0.2 m below the ice surface, consequently, ice thicknesses are underestimated by this amount in Figs. 3–6. Supplementary temperature data were gathered using a mercury-in-glass thermometer positioned in a Van Dorn-type water sampler. Interpretation of the conductivity data was complicated by the fact that, to our knowledge, there are no published relationships between conductivity, temperature and density for marine-derived hypersaline lakes at very low temperatures. Algorithms which approximately define these relationships for saline lakes of the Vestfold Hills (Gibson et al., 1990) were used to correct conductivity to a constant temperature (0°C) as an indicator of salt concentration. Air temperature was monitored daily at Davis Station (16 km SW of the lake) by staff of the Australian Bureau of Meteorology.

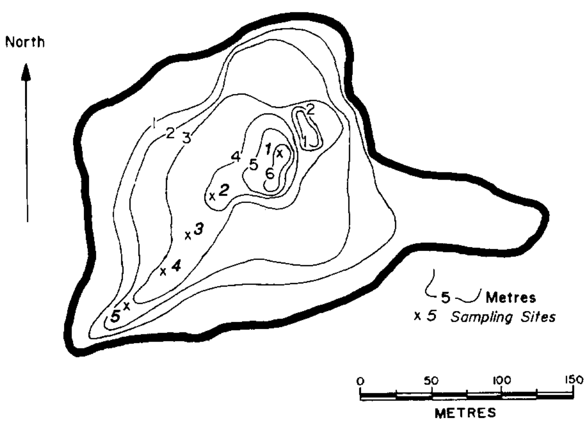


Fig.1. Organic Lake bathymetry (from 1978) and sampling sites.

## Results

Organic Lake had a maximum depth of $\sim$7.5 m in 1987. The lake is meromictic and usually remains ice-covered for the nine months from April to December of each year (Franzmann et al., 1987). The ice reaches a maximum thickness of $\sim$1.2 m in October.

Isotherms representative of the most commonly measured temperature profiles for the sampling period are shown in Fig.2. An isothermal layer, immediately beneath the ice, slowly cooled and increased in thickness until ice formation ceased in mid-October. Measurement of uniform conductivity in this isothermal layer shows that the layer was isohaline, while temperature-corrected conductivities indicate that the layer gradually increased in concentration over this period. At the time of its maximum development the layer was

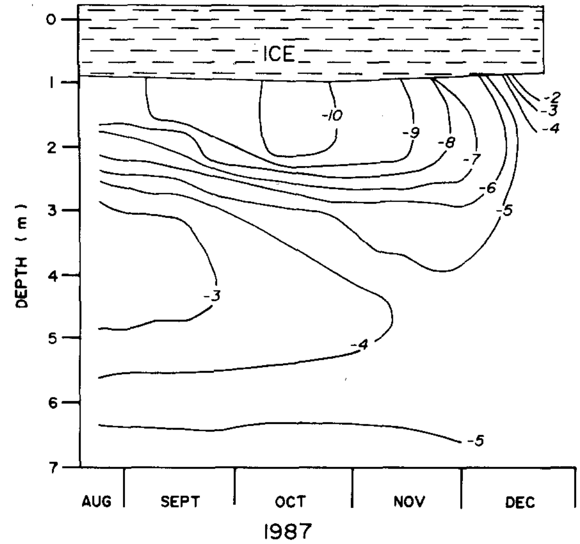


Fig.2. The pattern of thermal stratification (°C) in Organic Lake, August–December 1987.

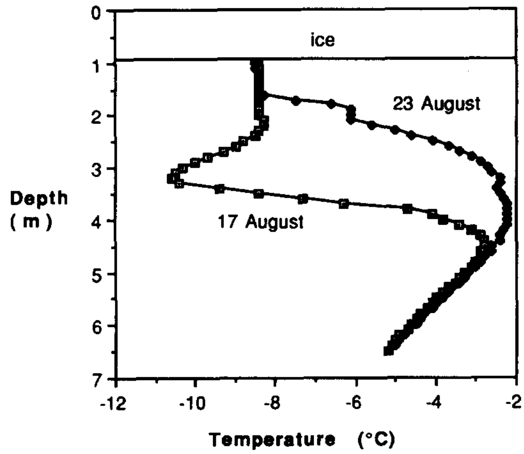


Fig.3. Temperature profiles in Organic Lake (Site 1), 17 and 23 August 1987.

~1 m thick, with a temperature of −10.1°C. Water sampled from this region was found to have a freezing point equal to the in-situ temperature. After ice formation ceased in mid-October, this layer warmed and became thermally stratified as solar radiation increased in November and December.

Beneath the isothermal layer, water temperature increased to a maximum of −2.2 °C at 3.8 m in August. This thermal maximum was evident in profiles taken throughout the sampling period but it gradually deepened to 5.0 m and cooled to −4.3°C by the end of December (Fig.2). Water sampled from this region had been as warm as +2°C in April. Below the thermal maximum, temperature decreased linearly with depth and this region showed very little change over the sampling period. Thermal profiles from various sites in Organic Lake were, except for the occasions discussed below, similar on any given day.

The pattern of thermal stratification (Fig.2) indicates a slow and smooth change of temperature with time, as might be expected in a lake covered by ice. However, anomalous thermal profiles were found on several occasions during the study. The first, is shown by comparison of profiles from site 1 for 17 and 23 August (Fig.3). The earlier profile was cooler between 1.6 and 4.3 m, with a maximum difference of 8.1°C at 3.2 m. Following this episode, other sites were monitored. During a period of extremely cold weather in early September, the air temperature at Davis dropped to −36°C. On 6 September, several thermal profiles measured at sites along the axis of a valley in the lake floor (sites *3*, *4* and *5*, Fig.1) contrasted markedly with a profile obtained closer to the centre of the lake (the valley mouth, site *2*). The shallower sites were colder below 1.7 m (Fig.4), with a maximum difference of 7.9°C at ~4.3 m (Fig.4). On 15 September the situation was reversed, with the deepest site (site *1*, Fig.5) showing a thermal profile similar to those found previously in the valley,

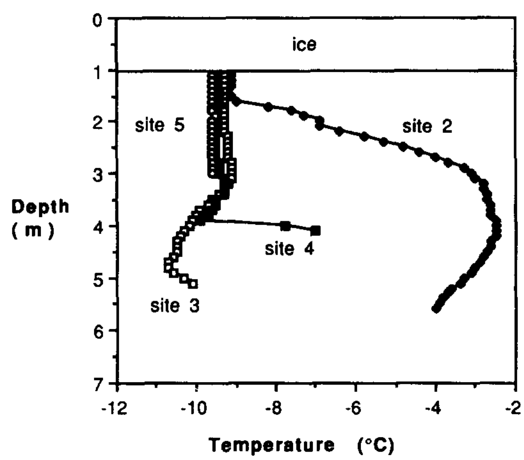


Fig.4. Temperature profiles in Organic Lake (Sites 2–5), 6 September 1987.

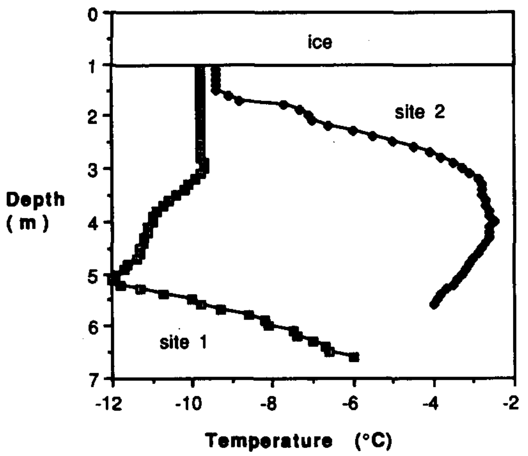


Fig.5. Temperature profiles in Organic Lake (Sites 1 and 2), 15 September 1987.

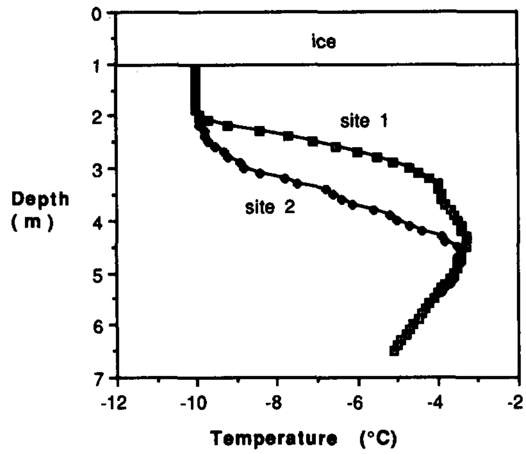


Fig.6. Temperature profiles in Organic Lake (Sites 1 and 2), 8 October 1987.

while more 'normal' profiles were found at the valley mouth (site *2*, Fig.5) and nearer to the lake's edge (sites *3* and *4*; Gibson et al., 1989). The greatest divergence between these profiles, taken about 60 m apart on the same day, was 8.6°C between 4 and 5 m (Fig.5). The water column was affected from a depth of 1.5 m to at least 5.6 m and probably to greater than 6 m. A third anomaly was recorded on 8 October, again as a contrast between temperature profiles obtained at sites 1 and 2. The maximum difference, 4.1 °C, occurred at 3.0 m but with the affected region extending from 2.0 to 4.6 m (Fig.6).

Periods of cold weather are evident from the five-day running mean of air temperature shown in Fig.7; the dates on which thermal profiles were measured are indicated on the figure. The thermal anomaly recorded at site *1* on 17 August followed

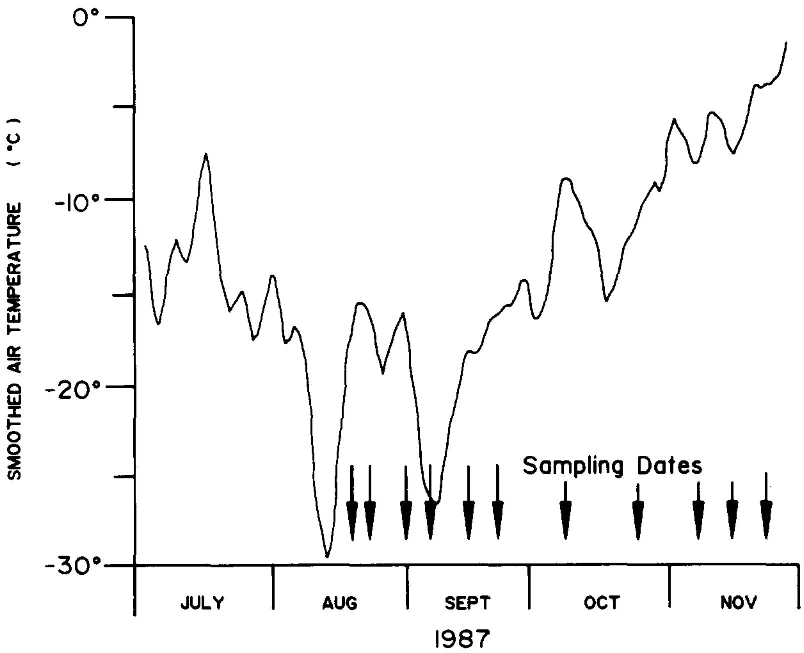


Fig.7. Five-day running mean of air temperature recorded at Davis Station. Sampling dates are indicated.

a period of cold weather centred on 12 August. Unusually cold water was found near the edge of the lake during a period of cold weather in early September and nine days later (15 September) an anomalous thermal profile was recorded close to the lake centre. The thermal anomaly found on 8 October followed a less pronounced cold period and was observed near to the lake centre about one week after the air temperature minimum. Apparently, temperature anomalies were related to periods of cold weather. Further, these anomalies were only found in Organic Lake in that period (July to October) when the mean air temperature usually remained below the minimum water temperature (−10.1°C), that is below the freezing temperature of the uppermost water in the lake.

There is some evidence that these thermally anomalous water masses were limited in cross-sectional area, in that 'normal' temperature profiles were sometimes recorded from water sampling profiles taken through a second drill-hole as little as 20 m away from the hole used for the CTD cast.

## Discussion

Exclusion of dissolved salts into the underlying water is an important process that attends ice formation. This is best documented in the oceanographic literature where brine exclusion has been discussed in detail (Lake and Lewis, 1970; Wakatsuchi and Ono, 1983). However, an increase in total alkalinity beneath ice forming on alkaline freshwater lakes has also been ascribed largely to exclusion of salts (Canfield et al., 1983). Seasonal variations in the concentrations of dissolved salts in Alaskan tundra lakes (Howard and Prescott, 1973) and in saline lakes of Saskatchewan (Hammer, 1986: Chapter 5) also result from this process.

The functional significance of brine exclusion in ice-covered saline waters is that it causes vertical convective mixing in the under-ice water column (Foster, 1968; Lewis and Walker, 1970; Gade et al., 1974; Wakatsuchi, 1982). Gallagher and Burton (1988) reported that haline convection completely mixed the inner basin of Ellis Fjord (Vestfold Hills) to its maximum depth of 117 m in August 1985. In confined, salt-stratified basins brine exclusion may significantly increase the salinity of the upper water layer as winter progresses (Burke and Burton, 1988; Gallagher and Burton, 1988). Consequently, the depth to which haline convective mixing penetrates will also increase throughout the period of ice growth, although the maximum extent of this mixing will obviously depend on the pre-existing density stratification. In waters more saline than 24.7‰ (Smith, 1974) the temperature of maximum density is less than the freezing temperature and haline convection will produce a certain depth of isohaline, isothermal water at a temperature essentially equal to its freezing temperature. This layer is evident in saline lakes of the Vestfold Hills (Gibson et al., 1989), developing throughout winter and achieving its maximum vertical extent in spring when the ice-cover is at its thickest. A clear example is seen in Organic Lake (Fig.2), where the winter mixed layer extended ~0.6 m beneath the ice on 23 August and was almost double that thickness on 25 October (~ 1 m; Fig.2). The mixed layer depth in this lake was constrained by a strong pycnocline between 2 and 3 m (Gibson et al., 1990). In less saline meromictic lakes, with less dramatic density gradients, the winter mixed layer can reach greater depths. Haline convective mixing in Ace Lake produced an isothermal layer approximately 4 m thick in 1979 (Burch, 1988). Burke and Burton (1988) reported a relatively sudden deepening of the mixed layer from 9 to 11 m, in Burton Lake, in August 1983. This event significantly lowered oxygen concentration throughout the mixed layer by incorporating anoxic water which had developed beneath a weak density gradient overlying the main pycnocline. In contrast to this winter mixing process, wind-driven mixing penetrates to a maximum depth of perhaps 5 m during the summer ice-free period in Burton Lake and Ace Lake, which are among the best studied lakes of this area (Burke and Burton, 1988; Hand and Burton, 1981; Burch, 1988)

Near the edges of saline water bodies, the exclusion of brine from forming ice involves the interaction between haline convective mixing and the basin sides. At some point close to the shoreline the convective layer is, inevitably, constricted. This contrast in the vertical extent of the mixed layer, and in the nature of the material underlying this layer, usually leads to some difference in physical properties between water in the shallows and at the basin centre (Gade et al., 1974). Assuming that the convectively mixed layer of Organic Lake is subject to a uniformly distributed flux of salt from its surface ice-cover, then shoreward of the point at which the sloping basin-side intersects the convectively mixed layer there will be a relative excess of salt compared to the basin centre where the salt is mixed more deeply and therefore into a greater volume of water. For temperature, assuming an evenly distributed loss of heat across the ice/water interface, the greater volume of convectively mixed water at the lake's centre compared to that in the shallows will lead to the formation of a relatively colder water mass near the periphery of the lake (cf. Imberger and Patterson, 1990: Differential cooling). If horizontal mixing in the upper water layer is insufficient to disperse this cold and relatively saline water, it will flow down the basin sides to a depth where its density coincides with that of the main body of water and move across the lake as a density current. In Organic Lake, where temperature and salinity (cf. Franzmann et al., 1987; Gibson et al., 1990) increase with depth below the convectively mixed layer, entrainment of underlying water may slightly reduce the difference in deep versus shallow water salinity and will tend to increase the temperature difference.

Temperature has the potential to provide a very good tracer of water movement in Organic Lake because salinity dominates temperature as a factor in density stratification. The persistence of an unstable thermal profile clearly shows this; the salinity gradient was sufficient to preclude mixing despite a destabilizing thermal gradient of up to 15°C $m^{-1}$. We interpret the anomalous temperature profiles recorded in Organic Lake as evidence of density currents. The results presented in Figs. 3, 5 and 6 clearly show the existence of cold water, at sites 1 and 2, deeper than either the isothermal layer (Fig.2) mixed by haline convection or the pycnocline between 2 and 3 m. The finding of thermally anomalous profiles near the lake edge (Fig.4) and only later in deeper water near to the lake's centre (Fig.5) is consistent with the view that the cold water was generated in the shallows and flowed towards the centre of the lake. The 'valley' that runs from the south-west extremity to the centre of the lake (Fig.1) could be expected to channel such flows. Temperature anomalies were transient features of the mid-lake thermal profile and were apparently of limited cross-sectional area, observations which indicate that individual currents were of comparatively small volume and may be difficult to detect by weekly sampling of a single site. The proposed currents, then, represent a dynamic interaction between short-lived periods of cold weather (Fig.7) and lake basin topography (Fig.1). Their effect is to contribute small parcels of water to the 3–5 m layer in the main body of the lake.

Density currents similar to those proposed for Organic Lake have not been reported from meromictic lakes of the Arctic region (Stewart and Platford, 1986; Ouellet and Pagé, 1987), nor have they been observed in any other saline lake in the Vestfold Hills. However, Burch (1988) speculated that such currents may have explained a deepening of the oxic/anoxic boundary from 9 to 10.5 m, which apparently occurred several metres below the maximum depth of the winter mixed layer (4–5 m) in Ace Lake during 1979.

That relatively dense water may be produced in the shallows and flow towards the basin centre has been shown in both fresh and saline water bodies. Hutchinson (1957) asserted that density currents arising from the warming of water at $< +4$°C in the shallow regions of ice-covered freshwater lakes was well established. More recently, Welch and Bergmann (1985) used rhodamine dye to trace such a downward flow in an ice-covered freshwater lake; they ascribed the movement to both brine exclusion and heating of water at $< +4$°C by the sediment. Imberger and Patterson (1990) described the flow generated by differential cooling in a freshwater, reservoir side-arm and reviewed the theoretical basis for understanding this process. Gade et al. (1974) concluded that hypersaline brines were formed in the extensive shallows of Cambridge Bay (Canadian Arctic Archipelago) and flowed downslope towards the basin centre, contributing to an active circulation of the whole bay beneath winter ice-cover. On a very large scale, this process is thought to form hypersaline water masses over parts of the Antarctic continental shelf which are the progenitors of Antarctic Bottom Water (Brennecke, 1921; Gill, 1973; Foster and Carmack, 1976). Evidently, currents generated by contrasts in the shallow and deep-water physical environments are recognized as agents which may initiate or maintain long-term stratification. In this context, they are of particular relevance to the general question: what has produced the 20 known meromictic basins of the Vestfold Hills ?

*Meromixis: formation and maintenance*

The formation and maintenance of meromixis in saline lakes and marine basins at high latitude is, as yet, imperfectly understood. Brine exclusion from developing ice is the process thought to generate the relatively saline waters found at the bottom of such basins. However, there is disagreement as to whether the annual formation of surface ice (see Goldman et al., 1967; Walker and Likens, 1975; Stewart and Platford, 1986; Gallagher et al., 1989) or the historical development of permafrost around a lake basin (Pagé et al., 1984) best explains the existence of these poorly mixed, anoxic layers.

Because the Vestfold Hills have been scoured repeatedly by the Antarctic ice sheet and have little surficial sediment or moraine, Gallagher et al. (1989) considered it unlikely that permafrost had played a significant role in the formation of hypersaline bottom waters in the meromictic lakes and fjords of the Vestfold Hills. However, there has been no study, to date, of permafrost history or distribution in the region. Consequently we cannot exclude the possibility that permafrost has played some role in the initiation of meromixis in lakes and fjords of this region.

The data we have presented for Organic Lake support the idea that the annual formation of surface ice is capable of generating density currents which contribute small parcels of cold, relatively saline water to the lower layers of meromictic lakes in the Vestfold Hills. From the evidence for Organic Lake it is also reasonable to suggest that oxygen transported by these currents need not have a lasting or widespread effect on the anoxia of the lower layers. A point that requires some consideration, however, is that the density currents (as indicated by thermal anomalies) did not penetrate to the greatest depth possible in Organic Lake. An explanation may lie in the observation that a number of lakes in the Vestfold Hills presently have a positive water balance. Surface levels are rising because the annual inflow exceeds the water loss through evaporation (Burton, 1981b; unpublished data). Organic Lake, for instance, has risen by about one metre since 1978. In this circumstance, haline convection and profile-bound density currents would be expected to have a progressively more superficial effect in the lake because the surface waters are being diluted.

Assuming that the changing water levels of lakes in the Vestfold Hills give some indication of the rate at which dilution (and concentration) may occur in these lakes, then several cycles of increasing and decreasing salinity may have occurred even over the comparatively brief period of their existence. According to Burton (1981a), various authors have suggested that cycles of negative and positive water balance have occurred in lakes of the Dry Valleys in Southern Victoria Land. This possibility invites extension of the surface ice hypothesis of generating meromixis to include the effects of changing water balance in closed basins.

During periods of negative water balance, and increasing salinity, haline convection induced by brine exclusion from the ice-cover would tend to penetrate more deeply. Ultimately, it is likely that convective mixing would occur throughout the water column and meromixis would cease. Periods of positive water balance, on the other hand, would impose a layer of fresher water over the saline lower water. Haline convection would tend not to penetrate so deeply, resulting in meromixis and anoxia in the deeper water layers. Therefore, dynamic change of water balance may lead to a cyclical interchange between meromixis and holomixis in some lakes. This has been very simply stated, and the existence of profile-bound density currents may maintain meromixis even during some concentration phases. Nevertheless, holomixis does occur in response to haline convection during winter in very shallow basins such as Rookery Lake and the Western Lobe of Burton Lake (Gibson et al., 1989).

## Conclusions

The picture presented here is one of dynamic water movement beneath the annually forming ice layer of saline lakes in the Vestfold Hills. The comparatively well known process of haline convection and the poorly studied interchanges between the shallow and deeper sections of these lakes appear capable of explaining the commonly observed meromixis. Changing water balance must interact with these processes, and may do so in a way that initiates meromixis during dilution phases such as the present period of rising water levels. Studies with greater spatial, and more especially temporal, resolution are required to gain a detailed understanding of the density currents in these lakes. Studies of individual lakes, representative of the full available salinity spectrum, offer the best prospect of understanding the interaction between annual processes and changing water balance. The relative importance of lake basin morphology remains to be established. These studies would be of significance in understanding the physical behaviour of ice-covered saline lakes generally.

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