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The meromictic lakes and stratified marine basins of the Vestfold Hills, East Antarctica

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Abstract: Thirty-four permanently stratified water bodies were identified in a survey of the Vestfold Hills. Of these, 21 were lakes, six were seasonally isolated marine basins (SIMBs), and seven were marine basins with year round connection to the open ocean. The basins varied markedly in salinity (4 g l^{-1} to 235 g l^{-1}), temperature (-14°C to 24°C), depth (5 m to 110 m), area (3.6 ha to 146 ha) and surface level (-30 m to 29 m above sea level). The stratification in all the basins was maintained by increases in salinity. During winter, a thermohaline convection cell was present in all lakes and SIMBs directly beneath the ice cover. These cells were the result of brine exclusion from the forming ice, and increased in density throughout winter, penetrating progressively deeper into the lake. Minimum stability, and therefore the maximum likelihood of turnover, occurred at the time of maximum ice formation in spring. At the end of the period of ice formation, the convection cell broke down, and stratification of the surface water occurred. When the ice melted completely, lenses of relatively fresh water capped the lakes, which reduced the effect of wind mixing. Net meltwater input increased the stability of the meromictic basins, while periods of lower water level resulted in deeper penetration of the thermohaline convection cell, increasing the possibility of turnover and destratification.

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Key words: climate change, meromictic, salinity, stratification, temperature, Vestfold Hills

Introduction

Meromictic lakes are those in which some water remains unmixed with the bulk of the lake at any time of the year (Hutchinson 1957). Such lakes are characterized by an upper mixolimnion, which mixes at some stage of the year, and the lower, stagnant, monimolimnion, which does not mix with the surface waters. The two layers are typically separated by a steep density gradient, or pycnocline, which provides a physical barrier to mixing. Walker & Likens (1975) provided a list of *c.* 150 known meromictic lakes and, even though many more such lakes have been identified in the intervening years, this class of lake continues to be of both theoretical and practical interest. For example, the sediments of meromictic lakes are particularly useful in the study of Quaternary history and climate change, as the quiescent water results in the formation of well-defined varves, and the permanent anoxia precludes bioturbation by benthic organisms (Skei 1983). The microbial ecology of meromictic lakes, particularly the stratification of microbiota living in the unusual chemical environments found within such lakes, has also attracted a great deal of interest (e.g. Franzmann & Dobson 1993, Overmann 1997).

Meromictic lakes are spread throughout the world, but are most common at high altitude and in the polar regions (Walker & Likens 1975). In particular, a significant proportion of the world's total occurs in Antarctica (Burton 1981a), where they are found in the McMurdo Dry Valleys (Spigel & Priscu 1998), Ross Island (Goldman *et al.* 1972), the Vestfold Hills (Burke & Burton 1988a) and the Syowa Oasis (Tominaga & Fukui 1981) (Fig. 1). The lakes of the McMurdo Dry Valleys have been studied for over thirty years, and the characteristics of Lakes Vanda, Fryxell, Bonney and Hoare are well known (Spigel & Priscu 1998). Meromictic lakes appear to be absent from other major Antarctic lake regions, including the Bunger Hills (Kaup *et al.* 1993), Larsemann Hills (Ellis-Evans *et al.* 1998), and the Schirmacher Oasis (Kaup 1994). Permanently stratified marine basins, which are similar to meromictic lakes but which retain contact with the ocean and are thus tidal, are also known from many regions of the world, including the Red Sea (Hartmann *et al.* 1998), the Cariaco Trench, the Black Sea, Scandinavia (Skei 1983, Lindholm 1996) and Antarctica (Gallagher & Burton 1988, Gallagher *et al.* 1989).

The greatest concentration of stratified water bodies in Antarctica, and possibly the world, is found in the Vestfold Hills, where both meromictic lakes and permanently stratified marine basins occur (Burton 1981b, Burke & Burton 1988a, Gallagher *et al.* 1989). The Vestfold Hills is an ice-free oasis of *c.* 400 km^2 which lies on the eastern side of Prydz Bay (Fig. 1). Following the retreat of the continental ice sheet *c.* 10 000 years ago, isostatic rebound occurred at a faster rate than sea level rise, and the land emerged from the ocean. The resulting landscape is dotted with hundreds of lakes ranging in size from small ponds to large lakes up to 140 m deep (e.g. Crooked Lake). Those lakes closer to the ice sheet are

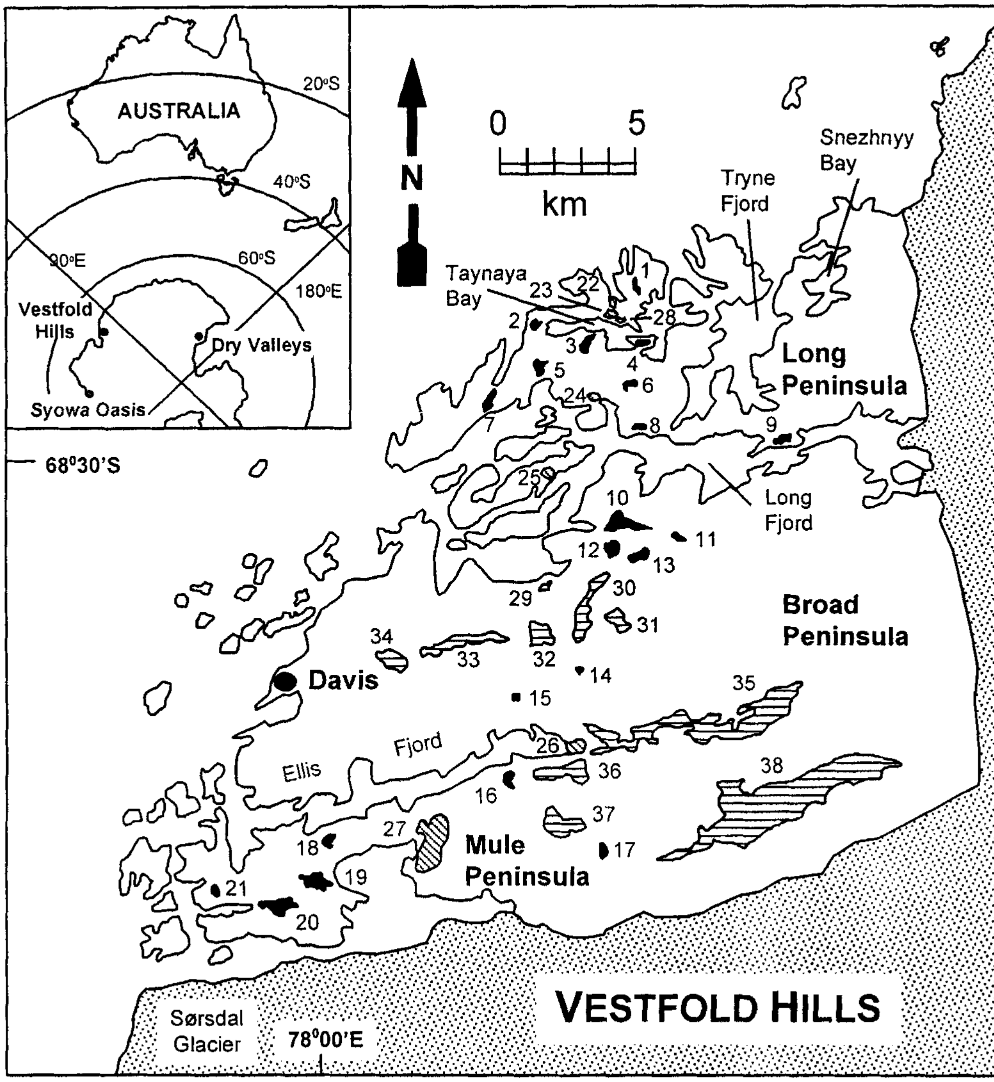


Fig. 1. Locations of the meromictic lakes (numbered 1–21, solid fill) and SIMBs (numbered 22–27, diagonal fill) of the Vestfold Hills. Other lakes mentioned in the text are numbered 28–38 (horizontal fill). The lakes and basins are: 1. unnamed lake 2; 2. Organic Lake; 3. Pendant Lake; 4. Glider Lake; 5. Ace Lake; 6. unnamed lake 1; 7. Williams Lake; 8. Abraxas Lake; 9. Johnstone Lake; 10. Ekho Lake; 11. Lake Farrell; 12. Shield Lake; 13. Oval Lake; 14. Ephyra Lake; 15. Scale Lake; 16. Lake Anderson; 17. Oblong Lake; 18. Lake McCallum; 19. Clear Lake; 20. Laternula Lake; 21. South Angle Lake; 22. Bayly Bay; 23. Lake Fletcher; 24. Franzmann Lake; 25. Deprez Basin; 26. 'Small Meromictic Basin', Ellis Fjord; 27. Burton Lake; 28. Burch Lake; 29. Tassie Lake; 30. Club Lake; 31. Lake Jabs; 32. Deep Lake; 33. Lake Stinear; 34. Lake Dingle; 35. Lake Druzhby; 36. Watts Lake; 37. Lebed' Lake; 38. Crooked Lake. All lake and basin names are official except for 'Small Meromictic Basin' and the unnamed lakes. The stippling indicates continental ice.

typically fresh (Laybourn-Parry & Marchant 1992, Bronge 1996), and this portion of the oasis must have been above sea level when the ice cap retreated. In contrast, lakes nearer to the coast are often saline or hypersaline (Burke & Burton 1988a), and result from the entrapment of seawater in depressions as the land rose out of the sea. The salt in some of these initially marine lakes has subsequently been flushed out by fresh meltwater (Pickard *et al.* 1986, Bird *et al.* 1991). Up until now, no complete inventory or description of the stratified water bodies of the Vestfold Hills has been made. This paper describes all known meromictic lakes and stratified marine basins in the region, and examines aspects of their unusual physical limnology.

Methods

Water temperature and electrical conductivity profiles of all saline lakes (> 3 g l^{-1} salt, and identified as such on the 1:100 000 map of the Vestfold Hills, Australian Division of National Mapping 1983) were recorded on at least one occasion between November 1992 and March 1995. Previously identified stratified marine basins in Ellis Fjord and Taynaya

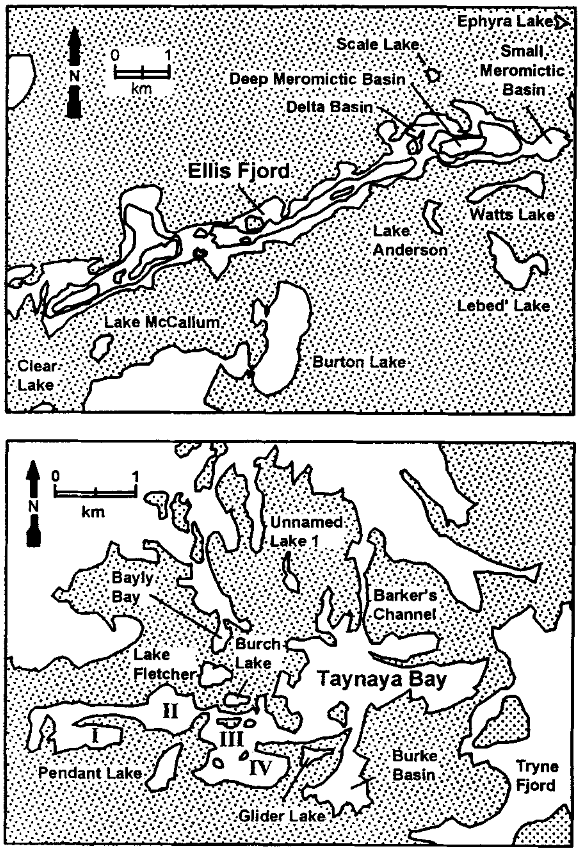


Fig. 2. Locations of stratified basins of **a.** Ellis Fjord ('Small Meromictic Basin', 'Deep Meromictic Basin', Delta Basin) and **b.** Taynaya Bay (Basins I, I, III, and IV, Burke Basin). Also shown for Ellis Fjord are the 40 m and 80 m bathymetric contours, as well as small section of the 20 m contour in the vicinity of Delta Basin. The extents of the stratified basins in Taynaya Bay are unknown. 'Delta Basin' and 'Deep Meromictic Basin' are unofficial names. Lakes and SIMBs mentioned in the text are also shown.

Bay (Gallagher & Burton 1988, Burke & Burton 1988a) were also visited, and a survey of the other major basins of Taynaya Bay (Fig. 2) carried out. All semi-enclosed bays (e.g. Snezhnyy Bay, Tryne Fjord: Fig. 1) were also visited to check for stratification. Profiles were recorded at the deepest point of the few lakes and basins for which the bathymetry is well known, and for the others near the centre of the lake or basin, which was not necessarily the deepest point. If the lakes and basins were ice covered, a hole was drilled through the ice with an auger to allow access to the water column. When the basins were ice-free profiles were recorded from a small boat. Locations and selected morphometric details of the meromictic lakes and stratified marine basins are given in Table I.

In situ temperature and conductivity were measured using a Platypus Submersible Data Logger (SDL) (Platypus Engineering, Hobart, Australia), which was attached to a marked line and lowered into the water column in steps of between 0.1 and 5 m depending on the depth of the lake or basin. If ice were present, the zero metre mark was taken to be the piezometric water level in the ice hole. The SDL was kept at each depth for at least 40 s to allow stabilization of the temperature and conductivity outputs. The precision of the temperature function was ± 0.01°C. Calibration of the conductivity function of the SDL was carried out using seawater of known salinity. The precision of the conductivity function was less than for temperature, with output varying by ± 0.05 mS cm^{-1} when the SDL was placed in seawater at constant temperature.

Three conductivity or salinity curves were determined for each basin: *in situ* conductivity uncorrected for temperature (C_{is}), conductivity corrected to a standard temperature of 15°C (C_{15}), and salinity calculated using the equation of state for seawater (Fofonoff & Millard 1983), and converted to units of g l^{-1}. Details of the calculations of the latter two curves are given in Appendix 1. The calculated salinity underestimates true salinity above *c.* 75 g l^{-1}. Selected temperature and C_{is} data can be obtained from

http://aadc-db.antdiv.gov.au/dataaccess/lake_search

No attempt was made in this study to calculate lake stability due to the problems with calculation of salinity and density discussed in Appendix 1.

Results

Thirty four separate basins were identified as permanently stratified during the survey of the Vestfold Hills (Figs 1 & 2). Of these, 21 were true lakes, six were seasonally isolated marine basins (SIMBs) which had exchange (in some cases very limited) with the ocean during summer, but which were isolated by ice during winter, and the other seven were marine basins which probably remained tidal year-round. Temperature, C_{is}, C_{15} and salinity (g l^{-1}) profiles for all the basins are given in Figs 3–5. These figures are plotted with common horizontal scales in order to highlight the range of meromictic environments in the Vestfold Hills. Further details of the basins are given in Table I.

All the profiles (excepting those of Laternula Lake and small meromictic basin, Ellis Fjord) were recorded in late winter, spring or early summer, when water temperatures were near their annual minima, ice thickness was close to the annual maximum, summer meltwater input from melting of the lake ice and local snow banks had not yet affected the salinity profile to any significant degree, and lake stability was at a minimum. Stratification was identified by a number of criteria, including an increase of C_{15} (a proxy for *in situ* density) with depth; significantly higher water temperatures at depth in the water column compared to the surface; and the presence of anoxia. Studies undertaken over a number of years (Burton 1981b, Burke & Burton 1988a, Gibson *et al.* 1989, Gibson, unpublished data) of all except three of the lakes (Ephyra, Oblong, unnamed 2) and three of the marine basins (Ellis Delta, Taynaya III and Taynaya IV) confirm that the observed stratification is 'permanent', i.e. continuous over the time scale of years to decades. Profiles from a single year only are available for the other basins. Of these basins, Ephyra and unnamed 2 lakes, and the marine basins are undoubtedly permanently stratified, as there are marked increases in C_{15} with depth in the water column. Oblong Lake, which is anoxic at depth, has relatively warm bottom waters which are associated, however, with only a relatively slight increase in C_{15}. It is most likely that this lake does not mix completely during the year, and thus it has been included in the list. Further profiles and water samples are needed to confirm the meromictic status.

Discussion

Geographical groupings

The meromictic lakes can be divided into five different geographical groups. Long Peninsula (Fig. 1), with nine meromictic lakes, is the area of greatest concentration in the Vestfold Hills. These lakes are generally small, and in many cases shallow (<10 m). Three larger lakes in areas of greater relief – Ace, Pendant and Abraxas – attain depths of over 20 m. All the lakes are surrounded by marine terraces (Peterson *et al.* 1988), indicating that they occupy basins in which sea water was trapped when Long Peninsula rose from the ocean during isostatic uplift approximately 5000 years ago (Adamson &

Table I. Location, selected morphometric parameters and water levels of the lakes, SIMBs and stratified marine basins of the Vestfold Hills. The numbering scheme is the same as used in Fig. 1.

	Lake or Basin	Abbrev.	Group	Latitude °S	Longitude °E	Area ha	Perimeter km	Surface[a] level m	Month/ year measured	Max recorded depth, m	Estimated max salinity $g\ l^{-1}$
8	Abraxas	ABR	Long	68.489	78.287	7.7	1.44	12.685	2/97	24	24
5	Ace	ACE	Long	68.473	78.189	18.0	2.44	8.733	2/97	25	43
16	Anderson	AND	Ellis	68.608	78.170	11.9	1.99	3.328	2/97	21	160
19	Clear	CLE	Mule	68.639	77.988	35.6	3.12	-8.444	2/97	62	14
10	Ekho	EKH	Broad 1	68.522	78.270	44.4	4.41	-1.960	3/97	43	165
14	Ephyra	EPH	Broad 2	68.576	78.233	4.7	1.46	29	Est 1997[b]	9	33
11	Farrell	FAR	Broad 1	68.529	78.311	5.3	1.12	-0.153	3/97	10	224
4	Glider	GLI	Long	68.462	78.287	5.2	1.09	-1.174	2/97	9	168
9	Johnstone	JOH	Long	68.495	78.407	7.5	1.37	-4.523	3/97	12	216
20	Laternula	LAT	Mule	68.649	77.973	36.3	3.91	-3.377	2/97	9	220
18	McCallum	MCC	Mule	68.649	78.121	11.6	1.50	-2.750	2/97	28	25
17	Oblong	OBL	Ellis	68.627	78.238	18.5	1.80	-3.582	2/97	15	233
2	Organic	ORG	Long	68.458	78.190	4.7	1.02	1.837	2/97	7	230
13	Oval	OVA	Broad 1	68.533	78.284	18.2	1.97	-29.180	3/97	16	228
3	Pendant	PEN	Long	68.463	78.240	12.4	1.69	2.790	2/97	23	120
15	Scale	SCA	Broad 2	68.585	78.175	3.8	0.72	15	Est 1997[b]	10	34
12	Shield	SHI	Broad 1	68.530	78.265	20.3	1.95	-7.466	3/97	39	172
21	South Angle	SOU	Mule	68.644	77.911	7.9	1.19	-0.835	2/97	16	235
7	Williams	WIL	Long	68.482	78.157	17.1	2.20	0.617	2/97	7	150
6	unnamed no 1	UN1	Long	68.477	78.265	6.6	1.84	7.81	1/89	5	140
1	unnamed no 2	UN2	Long	68.443	78.279	7.1	1.78	7.95	1/89	5	175
22	Bayly	BAY	SIMB	68.449	78.257	6.1	1.14			8	120
27	Burton	BUR	SIMB	68.626	78.100	145.9	6.15			18	45
25	Deprez	DEP	SIMB	68.505	78.203	10.6	1.30			10	120
23	Fletcher	FLE	SIMB	68.453	78.255	9.3	1.31			12	110
24	Franzmann	FRA	SIMB	68.483	78.251	6.3	1.14			9	140
26	'Small Meromictic Basin', Ellis Fjord	ESM	SIMB	68.597	78.228	21.4	2.16			13	45
	'Deep Meromictic Basin', Ellis Fjord	EDM	MB[d]	68.596	78.184	825.0[c]	27.89[c]			110	50
	Delta Basin, Ellis Fjord	EDE	MB[d]	68.594	78.167					38	45
	Taynaya Bay I	TA1	MB[d]	68.459	78.221	404.9[c]	38.57[c]			12	45
	Taynaya Bay II	TA2	MB[d]	68.457	78.246					80	95
	Taynaya Bay III	TA3	MB[d]	68.461	78.261					55	75
	Taynaya Bay IV	TA4	MB[d]	68.465	78.268					20	50
	Burke Basin, Taynaya Bay	TAB	MB[d]	68.466	78.294					35	52

[a]All SIMBs and marine basins are at sea level.
[b]Estimated
[c]The area and perimeters given are for the entire Ellis Fjord (including 'Small Meromictic Basin') and Taynaya Bay.
[d]Marine basin

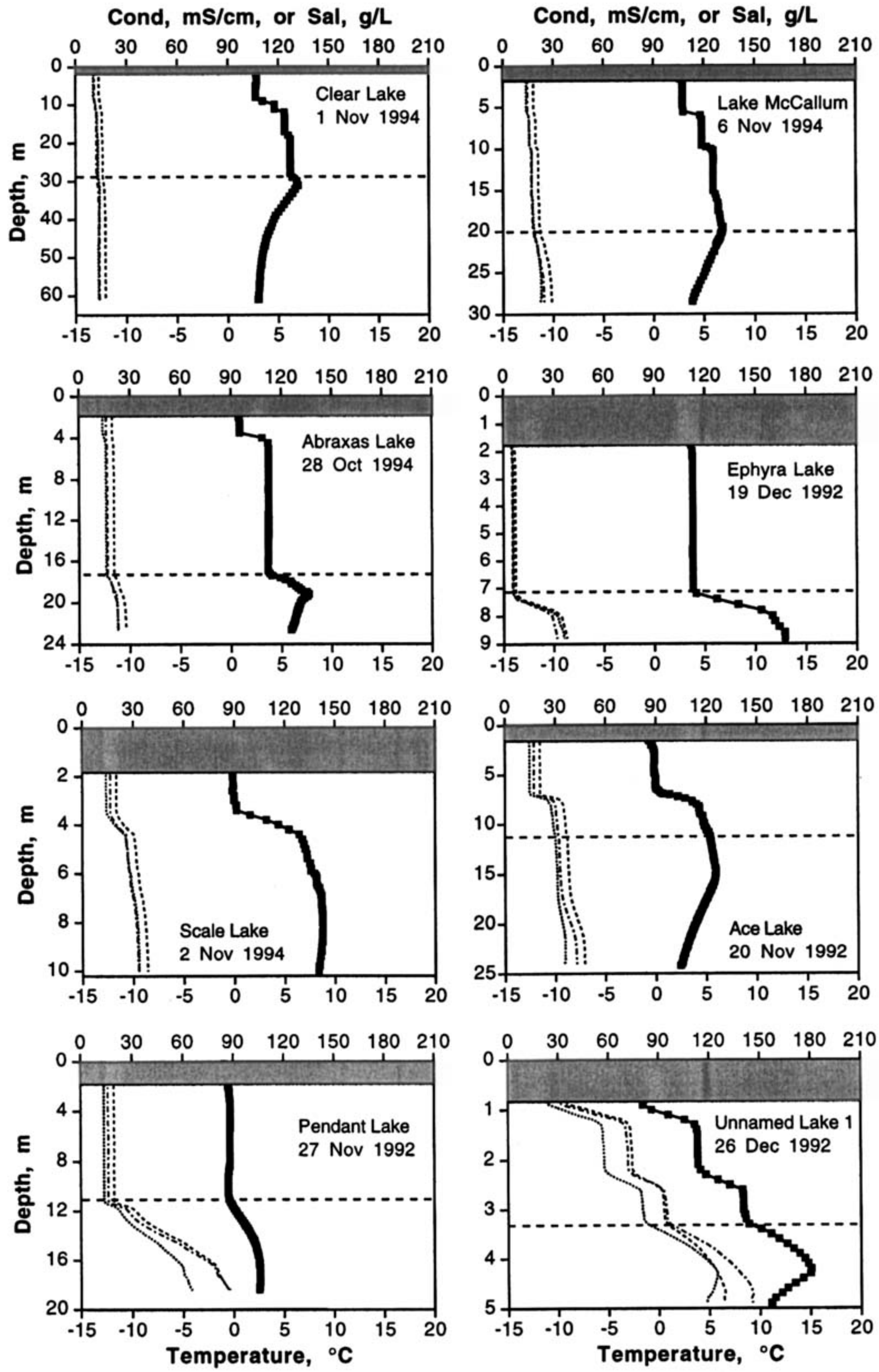


Fig. 3. Temperature (°C; solid line and squares, which indicate depths at which data were recorded), C_{is} (mS cm^{-1}; dotted line), calculated C_{15} (mS cm^{-1}; dashed line) and calculated salinity (g l^{-1}; dot-dash line) profiles of the meromictic lakes. The dashed horizontal line indicates the approximate position of the oxic-anoxic interface if known. The shaded area indicates ice thickness. The lakes are ordered in terms of increasing maximum salinity. All temperature, conductivity and salinity data are plotted at the same horizontal scales to highlight the varied nature of the meromictic lakes in the Vestfold Hills. Figure 9 shows temperature, conductivity and salinity profiles for Ace and McCallum lakes on expanded horizontal scales.

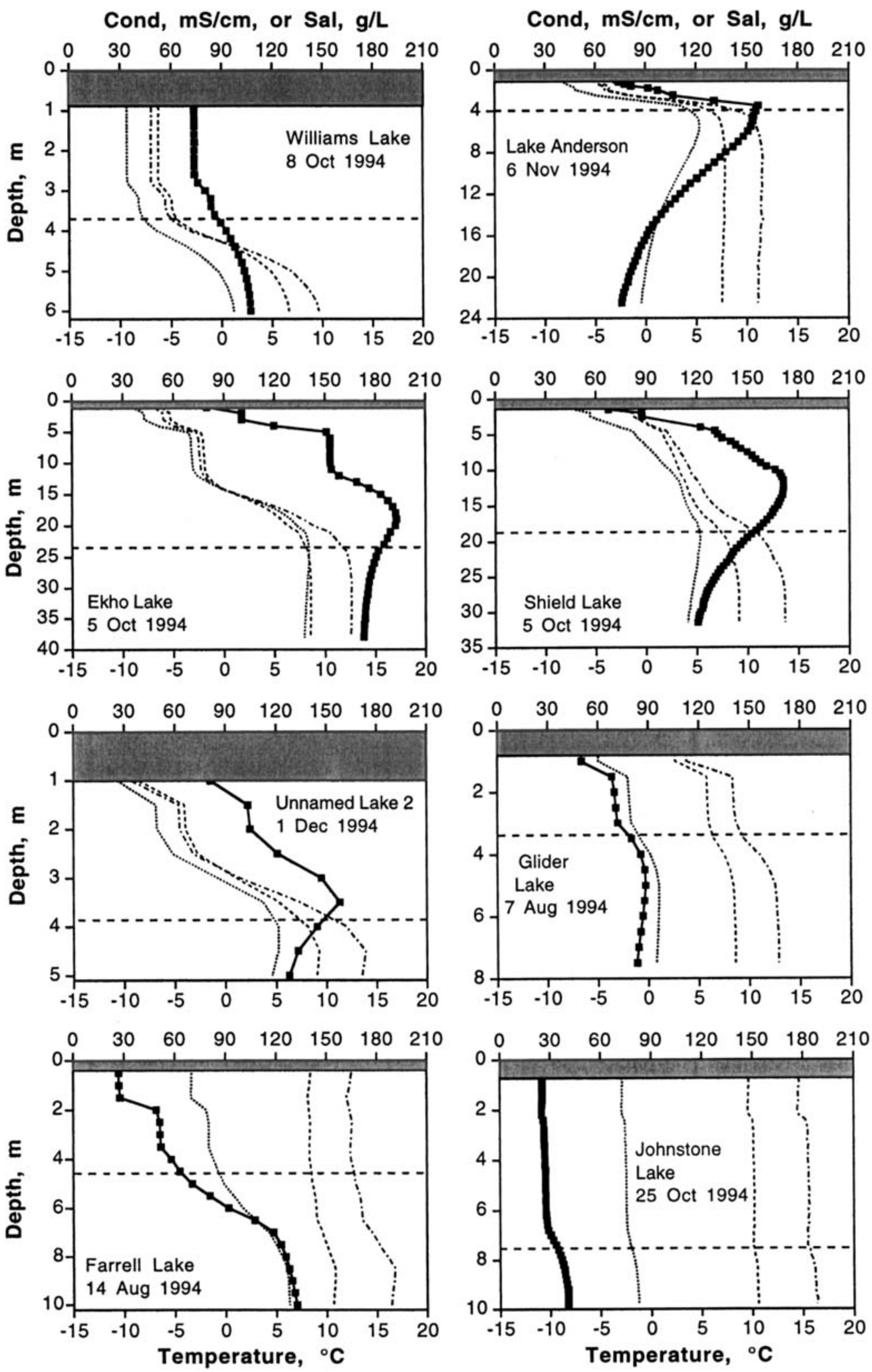
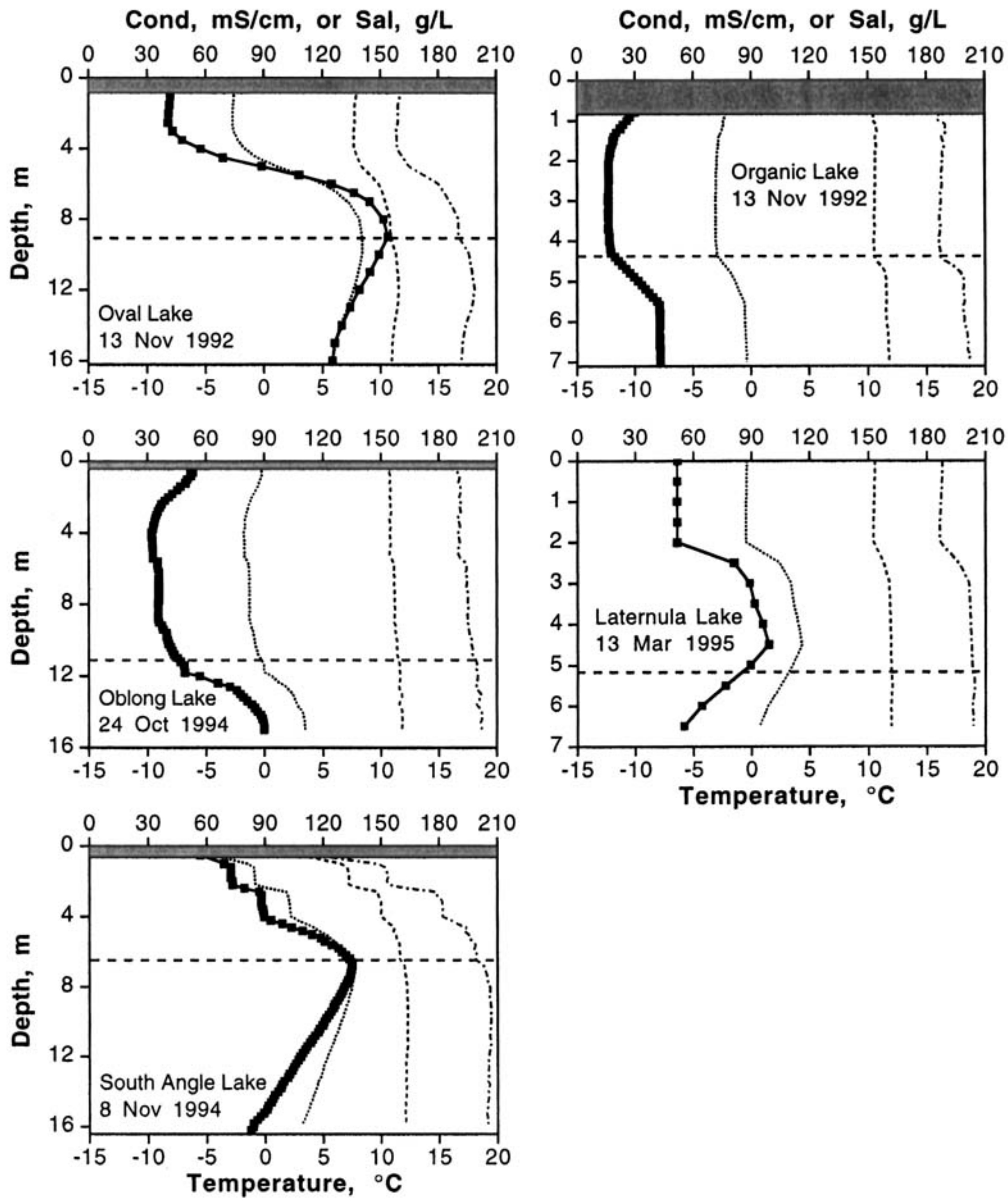


Fig. 3. (cont.) Temperature (°C; solid line and squares, which indicate depths at which data were recorded), C_{is} (mS cm^{-1}; dotted line), calculated C_{15} (mS cm^{-1}; dashed line) and calculated salinity (g l^{-1}; dot-dash line) profiles of the meromictic lakes. The dashed horizontal line indicates the approximate position of the oxic-anoxic interface if known. The shaded area indicates ice thickness. The lakes are ordered in terms of increasing maximum salinity. All temperature, conductivity and salinity data are plotted at the same horizontal scales to highlight the varied nature of the meromictic lakes in the Vestfold Hills. Figure 9 shows temperature, conductivity and salinity profiles for Ace and McCallum lakes on expanded horizontal scales.



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Pickard 1986, Bird *et al.* 1991, Zwartz *et al.* 1998). The salinity of the lakes ranges from some of the least saline of the meromictic lakes in the Vestfold Hills to hypersaline (Fig. 6). The volume-weighted average salinities of the three deepest lakes are significantly lower than seawater, indicating that either partial flushing of the salt from the lakes by meltwater has occurred, or that only partial invasion of an initially freshwater lake by seawater took place. The surface levels of the lakes are generally within a few metres of sea level, and all the lakes, except for the two unnamed lakes, occur in cryptodepressions (Fig. 6). All the lakes are within 1 km of the current coastline.

Broad Peninsula contains two distinct groups of meromictic lakes (Fig. 1). Members of the first group (Ekho, Shield, Oval and Farrell lakes) are part of a well-defined series of lakes that lie in depressions that were once part of an extensive fjord-like system which subsequently was isolated from the ocean by isostatic rebound (Adamson & Pickard 1986, Peterson *et al.* 1988). Three of the four lakes are comparatively large and deep, with surfaces ranging from a few metres beneath sea

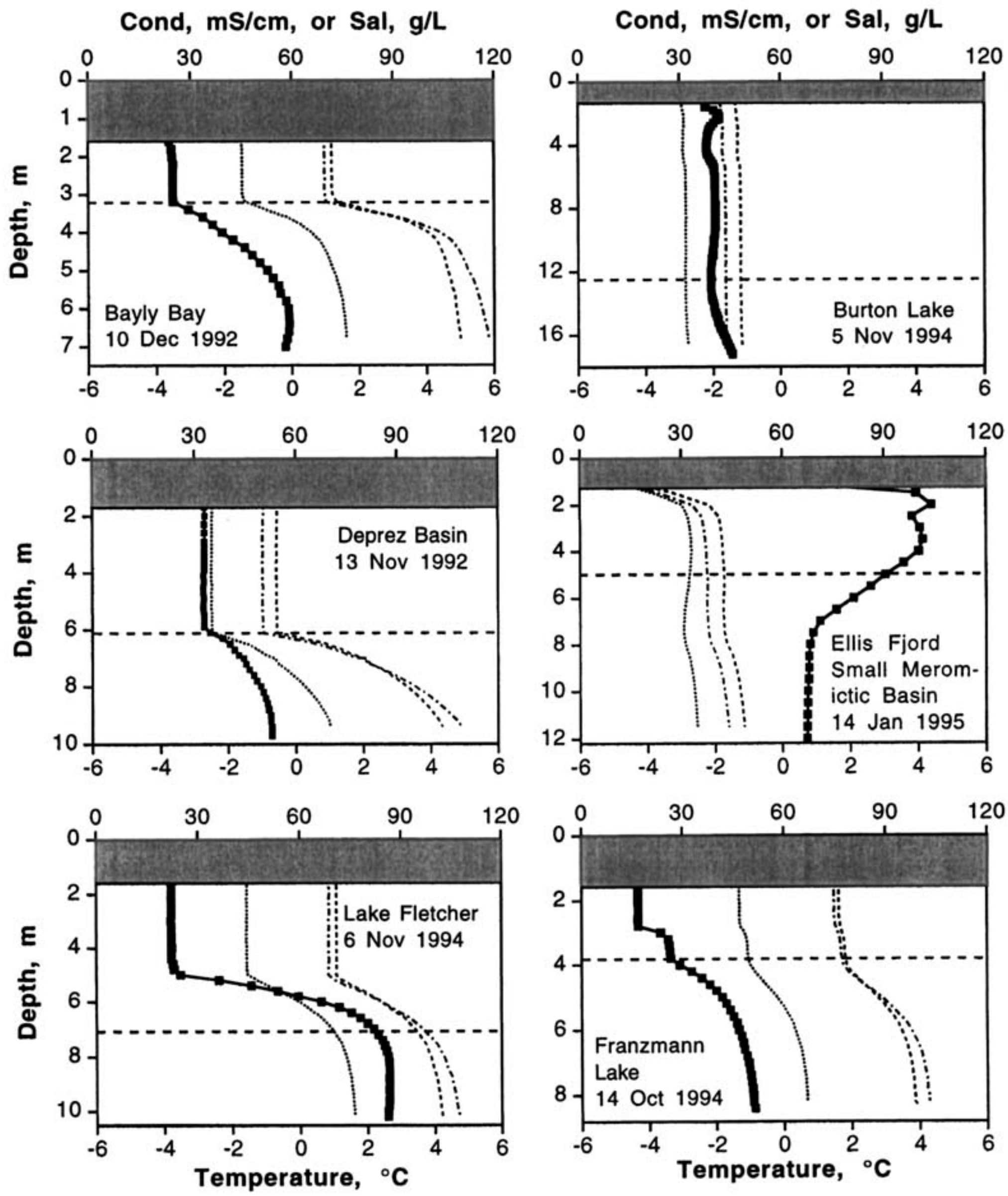

Fig. 4. Temperature (°C; solid line and squares, which indicate depths at which data was obtained), C_{is} (mS cm^{-1}; dotted line), calculated C_{15} (mS cm^{-1}; dashed line) and calculated salinity (g l^{-1}; dot-dash line) profiles of the SIMBs. The dashed horizontal line indicates the approximate position of the oxic-anoxic interface.

level (Farrell and Ekho lakes) to over 30 m beneath sea level (Oval Lake). All are surrounded by marine terraces (Peterson *et al.* 1988) and are hypersaline, reflecting evaporation of the water after the connection with the ocean was severed and presumably limited input of freshwater from the retreating ice sheet. Many other large, hypersaline, but apparently monomictic lakes (e.g. Deep, Dingle, Club, Jabs and Stinear lakes) occur in same system.

The second group of meromictic lakes on Broad Peninsula consists of Scale and Ephyra lakes. Both of these lakes are small, and are the two meromictic lakes with surface levels highest above sea level (Fig. 6); most lakes in the Vestfold Hills with surfaces this far above sea level are fresh or only slightly brackish. Neither of these lakes is surrounded by marine terraces (Peterson *et al.* 1988), indicating a non-marine origin. It is probable that the salt in the lakes was blown into them from hypersaline lakes located directly upwind which remain unfrozen for most, if not all, of winter (e.g. Deep and Club lakes). Both Scale and Ephyra lakes are characterized by relatively fresh surface waters and sharp salinity increases towards the base of the water column.

Anderson and Oblong lakes, which make up the fourth group, were isolated from an extended Ellis Fjord (Fig. 1) during isostatic rebound (Pickard *et al.* 1986, Roberts &

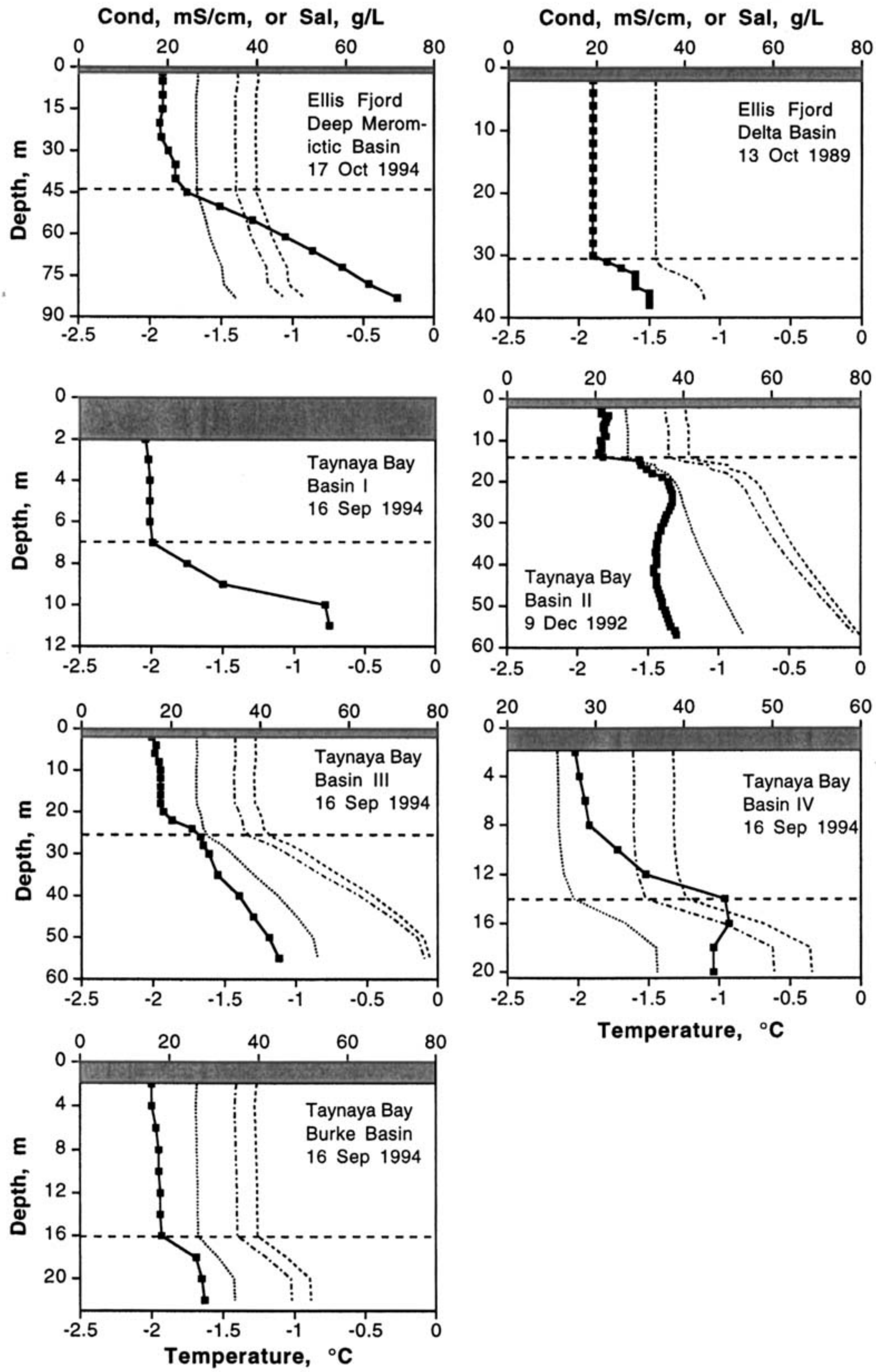

Fig. 5. Temperature (°C; solid line and squares, which indicate depths at which data was obtained), C_{is} (mS cm^{-1}; dotted line), calculated C_{15} (mS cm^{-1}; dashed line) and calculated salinity (g l^{-1}; dot-dash line) profiles of the stratified marine basins. The dashed horizontal line indicates the approximate position of the oxic-anoxic interface. The shaded area indicates ice thickness.

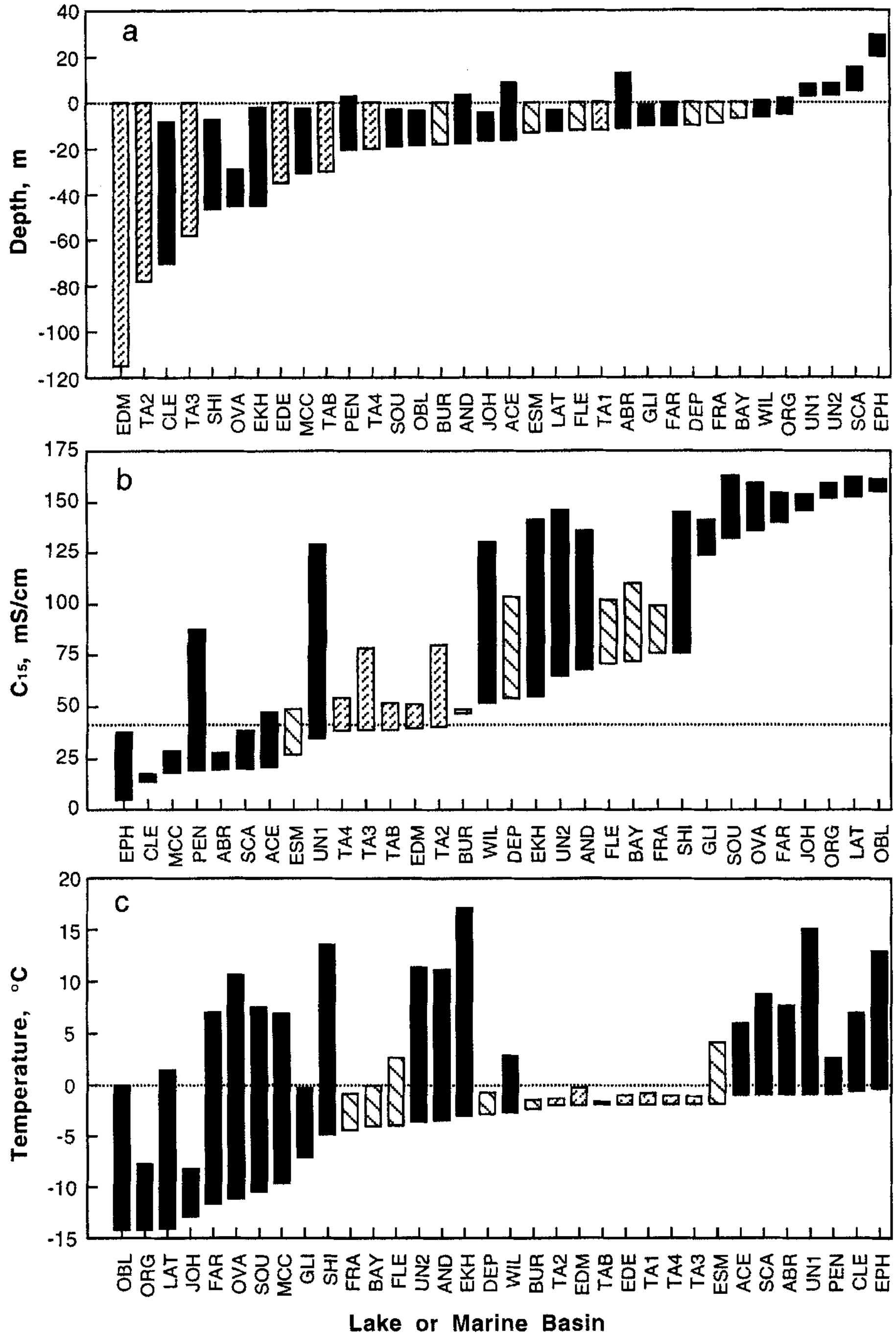

Fig. 6. Attributes of the meromictic lakes (black), SIMBs (diagonal lines) and stratified marine basins (diagonal dashes). **a.** Maximum recorded depth and surface height. The horizontal line is at sea level, **b.** C_{15} range. The horizontal line is the approximate C_{15} of seawater; and **c.** Temperature range. The minimum temperatures were calculated from the estimated late winter maximum salinities, and the maximum temperatures are those in the plots in Fig. 3. Warmer temperatures occur during summer in most of the water bodies. The horizontal line is drawn at 0°C. The abbreviations used for the lakes and basin names are given in Table I.

McMinn 1997). Both lakes have surfaces below sea level, are hypersaline, and are in a chain of lakes that also includes monomictic Lebed' Lake, which is one of the most saline lakes in the Vestfold Hills, and Watts Lake, from which most of the salt has been flushed (Pickard *et al.* 1986). Lake Anderson is quite close to Ellis Fjord, but Oblong Lake is at the landward end of the marine-influenced area, and is at present over three kilometres from the nearest marine water.

The last group of meromictic lakes is located at the western end of Mule Peninsula. These lakes are quite diverse, ranging from small (South Angle) to large (Laternula) in area, and from low (Clear and McCallum) to high salinity (Laternula and South Angle). Clear Lake is the deepest meromictic lake in the Vestfold Hills, whereas nearby Laternula Lake is one of the shallowest. The former has been shown to have a history involving an initial freshwater stage followed by partial invasion of seawater (Adamson & Pickard 1986). All of this group of lakes are within a few hundred metres of the coastline, have surfaces beneath sea level, and are surrounded by marine terraces (Peterson *et al.* 1988).

The six SIMBs are scattered throughout the Vestfold Hills (Fig. 1). All these basins are connected to the ocean during summer (though this connection is particularly tenuous in the case of Lake Fletcher (Eslake *et al.* 1991)), but are isolated by ice dams for extended periods during autumn, winter and spring when they effectively become lakes. The surface levels of the SIMBs are close to the high tide mark during winter, but during summer they rise and fall with the tides (Bayly 1986, Gallagher & Burton 1988). All these basins exhibit evidence of the marine influence, including higher nutrient concentrations than the generally oligotrophic lakes as a result of input of relatively high nutrient marine water (J. Gibson, unpublished results), overwintering populations of mesozooplankton (Bayly 1986, Eslake *et al.* 1991), and a greater diversity of phytoplankton species. The salinity of the SIMBs ranges up to 120 g l^{-1}, indicating that net importation of salt into the basins has occurred during summer water exchange, and that isolation from the ocean is not required for formation of hypersaline waters. If the land were to rise another metre or two, it would be expected that all these basins would become completely isolated from the ocean, but that other, currently mixed marine basins might become stratified. It has recently been suggested that Williams Lake is also subject to occasional marine inputs (Perris & Laybourn-Parry 1997), but I have observed no physical, chemical or biological evidence for this.

Stratified marine basins occur in both Ellis Fjord and Taynaya Bay (Fig. 1). These inlets have narrow and shallow entrances, which reduce water exchange with the open ocean (and thus the tidal range), and facilitate the retention of the stratification (Gallagher & Burton 1988). Ellis Fjord contains at least three stratified basins (Fig. 2), with 'Deep Meromictic Basin' probably having the greatest volume of anoxic water of any basin or lake in the Vestfold Hills. The occurrence of the relatively small Delta Basin suggests that other, similar basins might occur near the head of the fjord. 'Small Meromictic Basin' is cut off from the rest of the fjord by ice for approximately six months of the year (Gallagher & Burton 1988), and is, thus, the most 'marine' of the SIMBs. The bathymetry of Taynaya Bay is only poorly known. Five meromictic basins have been identified in the bay, though the intricate coastline suggests that more might occur. The basin at the entrance to Barker's Channel appears to be mixed.

The list of lakes, SIMBs and marine basins given here may not be complete, as it is possible that deeper points than the profiling site were present in some of the lakes considered to be mixed, and that permanent stratification does in fact exist. Furthermore, meromixis is not a truly permanent state; as discussed below, it is possible for lakes to lose their meromictic status due to changes in water level, and for other lakes to be become stratified. Stratification occurs in some lakes for shorter periods (1–2 years), and these have not been included here.

The ranges of areas and depths of the lakes (3.8–44.4 ha, average 14.5 ha, and 5–62 m, average 14.6 m, respectively) are similar to those of the meromictic lakes of the coastal Syowa Oasis (Tominaga & Fukui 1981) (Fig. 1), which were also formed from the isolation of shallow marine basins during isostatic rebound. The surfaces of the lakes of the Syowa Oasis are also close to sea level. These coastal, marine-derived lakes contrast sharply with the meromictic lakes of the McMurdo Dry Valleys (Spigel & Priscu 1998), which are much larger (900–7080 ha) and generally deeper (20–75 m). The Dry Valley lakes are also much further away from the ocean (9–47 km) than those in the coastal oases, and have surfaces well above sea level (18–325 m). These lakes have had longer and more involved histories than those in the coastal oases (Burton 1981a, Doran *et al.* 1994, Lyons *et al.* 1998).

Stratification

Stratification in the lakes, SIMBs and marine basins is maintained in all cases by an increase in salinity, and thus *in situ* density, with depth. In some basins this increase is quite marked, and the water column is highly resistant to vertical mixing, but in others the increase is only slight. All the water bodies have a zone in which temperature increases with depth (Figs 3–5), which would be expected to destabilize the water column. However, the increase in density resulting from a concomitant increase in salinity outweighs this effect. Similar mid-water temperature maxima have been recorded for the meromictic lakes in the McMurdo Dry Valleys (Spigel & Priscu 1998), the Syowa Oasis (Tominaga & Fukui 1981, Murayama *et al.* 1988) and in western and northern Canada (Hall & Northcote 1986, Ouellet *et al.* 1987, 1989, Ludlam 1996).

Figure 7 shows the generalized vertical structure of the lakes. Ice is present on all the lakes for between 8 and 11 months of the year, and reaches a thickness of *c.* 2 m on the

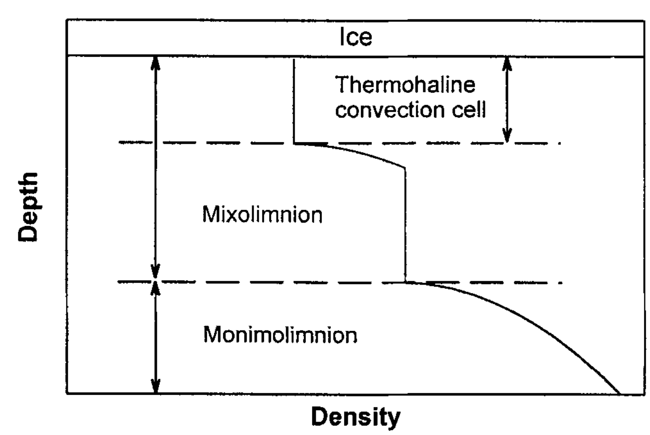

Fig. 7. Generalized structure of the meromictic lakes of the Vestfold Hills in winter. Beneath the ice cover is a layer which undergoes thermohaline convection. The depth to which this cell penetrates increases during active ice formation, reaching a maxium in spring that defines the extent of the mixolimnion. Beneath this boundary is the monimolimnion, in which no vertical mixing occurs.

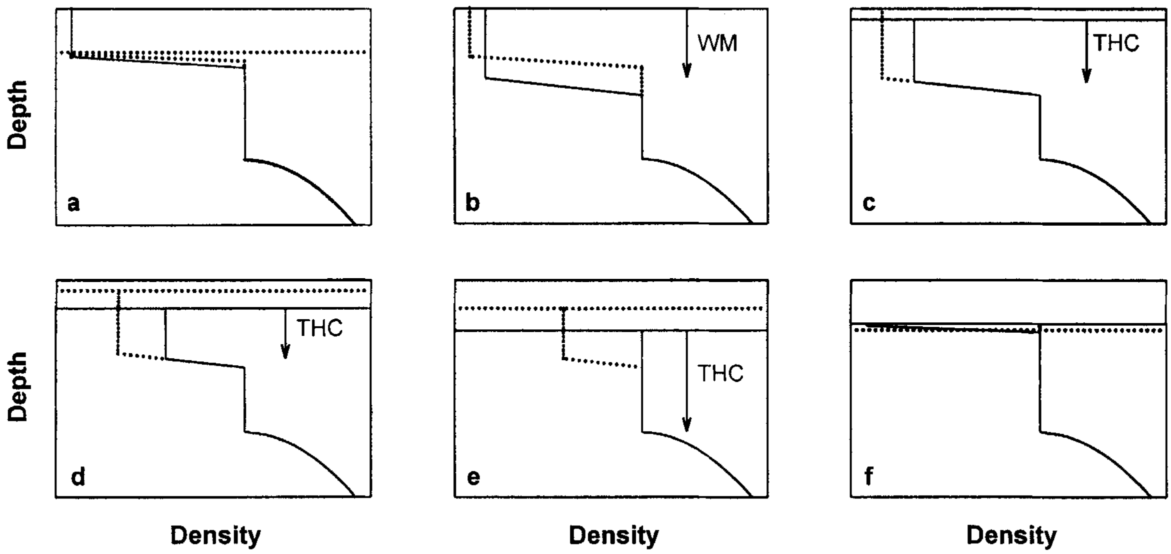

Fig. 8. Seasonal changes in density in the near surface waters of a typical meromictic lake **a.** immediately after ice melt out, **b.** late summer after wind mixing, **c.** early winter, **d.** mid-winter, **e.** at the end of ice formation, and **f.** during early ice melt. The dotted lines in each panel show the density profile and ice thickness indicated by the horizontal line in the preceding panel. The zones of wind mixing (WM) and thermohaline convection (THC) are also indicated.

least saline of the lakes, but only 0.4 m on some of the most saline (e.g. Johnstone, Oblong and Laternula lakes). The shortest periods of ice cover occur on the lakes with thinnest ice, and the longest for lakes with surface salinities near 20 g l^{-1} (e.g. Ace Lake, which in some summers remains ice-covered). Fresher lakes generally melt out earlier than these moderately saline lakes (J. Gibson, unpublished observation). The differences in timing of melt out between lakes appears to be a balance between the inverse relationship between under ice salinity and ice thickness (Gibson *et al.* 1989), and the warming of under ice water by solar radiation through the more transparent ice of the low salinity lakes.

Beneath the ice is the mixolimnion, which by definition is that part of the lake which undergoes vertical mixing on at least one occasion during the year (Hutchinson 1957). The seasonal development of the convection cell which is responsible for mixing the mixolimnion is shown in Fig. 8. In the first panel, the ice has just melted out, resulting in the formation of a cap of relatively fresh water at the surface. This water is fresher than that below due to the exclusion of salt during ice formation. During the ice-free period some wind mixing occurs (Fig. 8b), though this mixing rarely penetrates the lake to any great depth (Ferris & Burton 1988, J. Gibson, unpublished data), in part because of the sharp pycnocline that results from ice melt. Evaporation from the lake surface during the ice-free period increases surface salinity, but this is counteracted by freshwater input from meltwater streams.

When ice formation begins in February or March, a thermohaline convection cell is set up under the ice in which the water is at its freezing point (as it is effectively in contact with the ice) (Fig. 8c). The mixing results from the exclusion of brine from the forming ice, which increases salinity and density directly under the ice, and which leads to downward mixing, and transfer of heat to the base of the cell from deeper, warmer water, which leads to warming and a decrease in density and thus upward mixing. This cell is particularly apparent in the profiles of Deprez Basin and Lake Fletcher (Fig. 4). The depth to which mixing occurs is determined by the pre-existing density profile. As the ice thickens, the depth to which mixing occurs increases, as the greater salinity (and density) of the layer allows the convection cell to penetrate deeper into the lake (Fig. 8d). The depth of mixing and the salinity of the mixolimnion will continue to increase until ice formation ceases (Fig. 8e). The mixed layer is at this time at its most saline and coldest, and extends to the base of the mixolimnion (unless deeper convection cells occur). Temperatures as low as -14.1°C have been measured under the ice in Organic Lake (Gibson & Burton 1996). Water column stability is also at a minimum at this time, as the lake is closest to having uniform density.

The maximum depth of penetration of the convection cell (Z_c) may or may not be the same depth to which mixing occurred during the previous winter; situations in which the Z_c changes between years are discussed below. Once active mixing of the convection cell ceases, the water will again become stratified as absorption of solar radiation occurs near the surface and a lens of fresher water from melting of the ice forms (Fig. 8f). This process had occurred by the time the Organic Lake profile was recorded (Fig. 3). Eventually the ice will melt, and the cycle will be repeated.

At the base of the mixolimnion there is a pycnocline, often sharp (e.g. Ace Lake, Fig. 9), which is characterized by an increase in both temperature and salinity. As mentioned above, the effect of salinity on density outweighs the

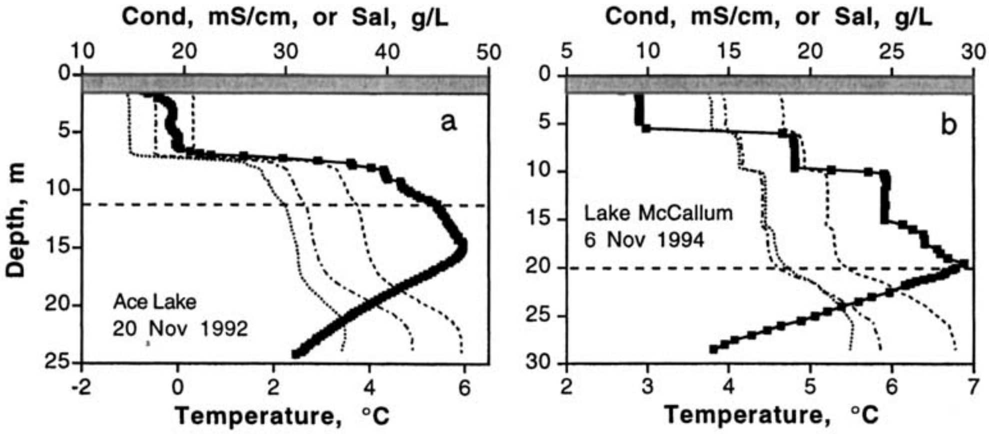

Fig. 9. Temperature, conductivity and salinity profiles for **a.** Ace Lake and **b.** Lake McCallum with expanded horizontal scales. The line styles used are the same as in Fig. 3.

destabilizing influence of increasing temperature. Further vertical mixing occurs at depth in a number of lakes (Clear, Ekho, McCallum, unnamed no. 1 and Abraxas) which contain one or more thermohaline convection cells separated from the under ice cell and from each other by thin, apparently unmixed, layers. Figure 9 shows a detailed profile of Lake McCallum, which clearly shows a series of such cells. These mid-water cells are equivalent to those observed in Lake Vanda in the McMurdo Dry Valleys (Hoare 1968, Spigel & Priscu 1998). The convection cells are permanent features of these Vestfold Hills lakes and have had essentially constant salinity since first identified, though temperatures vary both inter- and intra-annually (J. Gibson, unpublished data).

The monimolimnion in all the stratified basins is characterized by increasing salinity and (initially at least) temperature. In some basins (e.g. Basin II, Taynaya Bay) salinity increases steadily with depth, whereas in others (e.g. Lake Anderson) it is near constant beneath a strong halocline. The monimolimnion in many lakes (e.g. Ace Lake, Ekho Lake) is characterized by having C_{15} profiles which exhibit a number of distinct steps. These steps are typically sharper closer to the surface, and more rounded towards the bottom of the water column. Similar profiles are well known for lakes in the McMurdo Dry Valleys (Spigel & Priscu 1998) and northern Canada (Ludlam 1996). Gibson & Burton (1996) suggested that these steps were the result of the penetration of the under ice convective cell to greater depths in the past. The lower boundaries of the older, deeper palaeocells (e.g. at *c.* 18 m in Ace Lake: Fig. 9) are more rounded than those higher in the water column as there has been more time for ionic diffusion to smooth the initially sharp gradients.

For most, but not all, of the basins, temperature increases in the monimolimnion to a mid-depth maximum, and then decreases to the bottom of the lake. The particular shape of the temperature curve is a function of heat gain during summer and heat loss via conduction through the ice cover during winter. Most of the lakes are heliothermal, as are the meromictic lakes of the McMurdo Dry Valleys (Shirtcliffe & Benseman 1964, Spigel & Priscu 1998) and the Syowa Oasis (Tominaga & Fukui 1981). The highest recorded temperature in the lakes of the Vestfold Hills is 24.8°C, at 5 m in Lake Anderson on 14 February 1991 (N. Roberts, unpublished data), though the lake cools to *c.* 12°C at this depth by the end winter. Ekho Lake, which maintains temperatures of 16–18°C at 20 m throughout the year, is perennially the warmest lake.

All of the lakes are anoxic at depth, though not all lakes contain H_2S. In Organic, Johnstone, Laternula, and probably Oblong and South Angle lakes, the salinity of the water beneath the oxic-anoxic interface (OAI) is too high to support sulphate-reducing bacteria, and H_2S is absent (Franzmann *et al.* 1987, Gibson *et al.* 1991). Nearly all of the OAIs are coincident with a jump, in some cases only slight (e.g. Ace Lake, Fig. 9), in C_{15} and salinity. The position of the OAI is controlled in part by the depth of under ice thermohaline convection. In some of the basins (e.g. Pendant and Ephyra lakes) the OAI is coincident with the base of the current mixolimnion. In these lakes the winter thermohaline convection distributes dissolved oxygen throughout this zone, and reduces the likelihood of the onset of anoxia resulting from the oxidation of organic material produced during spring and summer. In lakes in which the OAI is deeper than the base of the current mixolimnion, I suggest that greater penetration of the under ice convective cell in the past resulted in oxygenation of water to the depth of the current OAI. Thus, Ace Lake was mixed to a depth of *c.* 12 m, and, therefore, oxygenated at some time, though the water beneath this depth, as now, remained anoxic. Subsequently, freshwater inflow reduced the salinity in the surface waters, resulting in the present salinity regime. Even though there is no active mixing of dissolved oxygen resulting from photosynthesis or melt stream input at the surface to beneath 7 m in this lake at the present time, the phytoplankton and algal mat communities in the zone between 7 and 12 m (Burch 1988, Rankin *et al.* 1997) are able to maintain the oxygenated status. The water between the base of the mixolimnion and the OAI can be considered physically stagnant, but oxygenated.

An increase in the depth of penetration of the convection cell to beneath the OAI can also lead to near anoxia in the surface waters, as hydrogen sulphide-containing monimolimnetic water is entrained into the oxygenated surface layer. An example of this process was observed in Burton Lake, which has perhaps the most variable of the OAIs. A

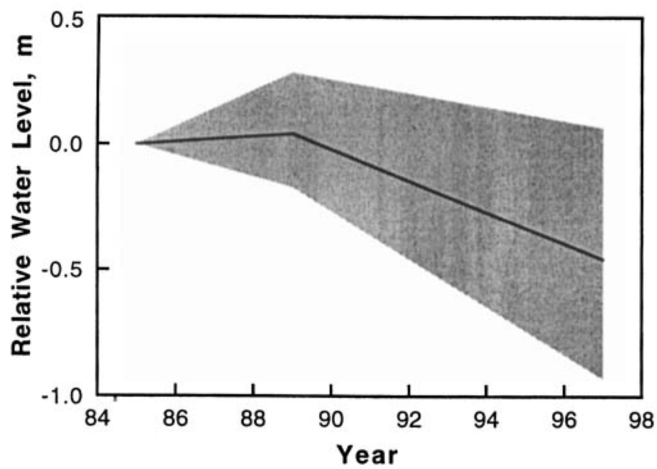

Fig. 10. Average (line) and range (shaded) changes in water level for 15 meromictic lakes between January 1985 and January 1989, and between January 1989 and January 1997.

sharp increase in the mixing depth in Burton Lake during the winter of 1981 resulted in an abrupt drop in the oxygen concentration in the surface water from 10 – 11 mg l^{-1} to less than 1 mg l^{-1} (Burke & Burton 1988b, C. Burke, unpublished data). More recently, sulphidic water has been recorded at a depth of 2 m in this SIMB during winter (J. Gibson, unpublished data). In many lakes the position of the OAI has not appeared to change with respect to the bottom of the lake over the last 20 years.

The meromictic lakes are in nearly all cases situated in closed, rocky basins. Water input into the lakes is from melting snow banks (which develop in winter in the lee of the surrounding hills) during summer, and direct capture of precipitation when ice free. Water loss is by direct sublimation and physical abrasion of the ice, and evaporation when ice free. On only one occasion has water been observed flowing from a lake to the ocean (Williams Lake; 23 January 1988), and it is unlikely that such a flow would occur from any other basin at current water levels. This observation was made during a period of historically high water level in many of the lakes of the Vestfold Hills. Groundwater flow both into and out of the lakes is likely to be near zero, as the rocky basins and permafrost preclude such flows. The water level in the lakes are, therefore, sensitive indicators of changes in local water balance (Gibson & Burton 1996). Accurate surveys of the surface levels of many of the lakes have been undertaken on three occasions (January 1985, January 1989 and February 1997). Water level in some lakes fell between the first two measurements whereas others rose (Fig. 10), but the surface level of all lakes fell between the second and third surveys. These general trends were consistent with more regular data collected for Deep Lake (H. Burton, unpublished data) and Organic Lake (Gibson & Burton 1996) in which water level rose to a maximum in late 1980s before beginning to fall. Similar changes in water level have been recorded for the lakes of the McMurdo Dry Valleys, where lake levels rose steadily from the 1960s until the early 1990s (Chinn 1993), though in the last few years the rate of increase has slowed or stopped (P. Doran, personal communication 1998). As pointed out by Gibson & Burton (1996), the processes controlling meltwater input to lakes of the two regions are quite different. Dry Valleys lakes are fed by glaciers, and the production of meltwater each year is controlled by the radiation balance at the ice face. In the Vestfold Hills, however, the lakes are fed by relatively small snow banks which generally melt completely during summer, and the annual hydraulic loading is thus a function of precipitation and the frequency of storm events which transport the snow into the basins.

Variations in water level have significant effects on the mixing within the lake. An increase in level adds little salt to the lake, and therefore the surface waters are diluted. Assuming

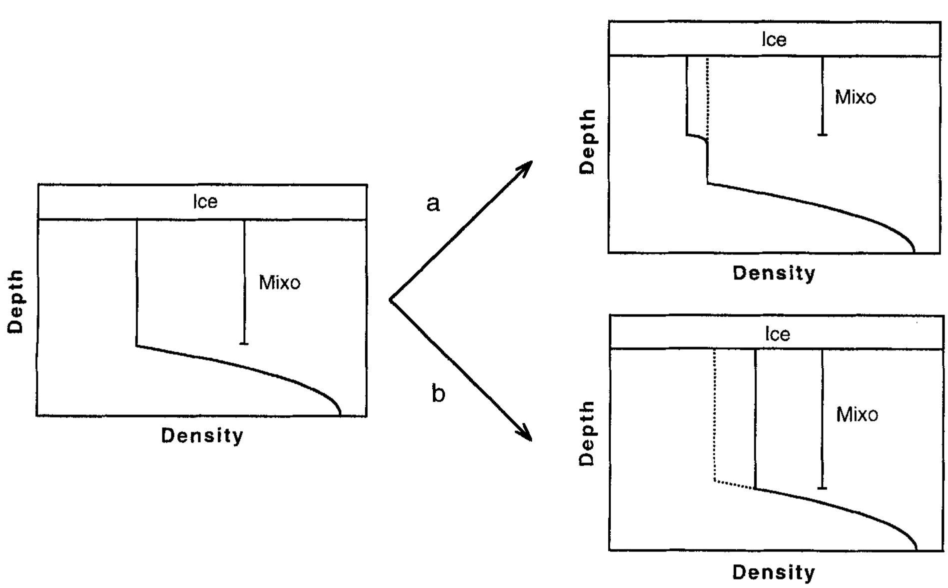

Fig. 11. The effect of increasing or decreasing water level and maximum ice thickness on the penetration of the under ice thermohaline convection cell at the end of ice formation, and therefore extent of the mixolimnion: **a.** an increase in water level or a decrease in maximum ice thickness, **b.** a decrease in water level or an increase in maximum ice thickness. The extent of the mixolimnion is indicated in each case.

an equivalent amount of ice formation, the maximum *in situ* density (ρ_{is}) reached in the mixolimnion will therefore be less, and mixing will not penetrate as deeply into the lake (Fig. 11). In contrast, when water levels decrease, maximum ρ_{is} increases as the quantity of salt remains constant, and Z_c increases. These processes were clearly observed in Organic Lake between 1978 and 1994 (Gibson & Burton 1996). Between 1978 and 1987 the lake level increased, the maximum winter salinity of the mixolimnion decreased, the minimum mixolimnion temperature increased, and Z_c decreased. From 1987–94, all these trends were reversed as the surface level of the lake fell.

The changes in Z_c play an important role in structuring of the lakes. As the water level drops maximum ρ_{is} increases, and deeper penetration of the mixolimnion will remove steps evident in the profiles (Fig. 11). If water level continues to drop, the lake stability in late winter will eventually decrease to zero, and convective mixing will extend to the bottom of the lake. The meromictic status of the lake will thus be lost. Such a process occurred between 1987 and 1994 for two Vestfold Hills lakes – Tassie Lake and Burch Lake (Fig. 1) – which were stratified at the end of winter in the earlier year, but which had lower surface levels and were holomictic in late winter in the latter. At least two of the currently meromictic lakes – Anderson and South Angle lakes – appear to have been totally mixed in the relatively recent past. In both of these lakes, a few metres of fresher water overlie many metres of essentially isohaline water. If the bathymetry of the lake is known, the water level decrease required to mix the lake can be calculated For Ace Lake, water level would have to drop by about 6 m (Gibson & Burton 1996). Considering that the lake has increased in water level by *c.* 2 m in the last 20 years, such a decrease is not unreasonable.

Changes in maximum winter ice thickness will have a similar, though less intense, effect to varying water level (Fig. 11). During colder winters more ice is formed, which is functionally equivalent to a decrease in water level, as the salt is concentrated into a smaller volume of water beneath the ice. The opposite occurs during warmer winters, when Z_c may not reach that of previous years.

The situation in the SIMBs is similar, but with the major difference that the mean water level is constant. The volume of the basin therefore is also constant, but in contrast to the lakes the amount of salt varies. Import of salt from or export to the ocean occurs during summer, when there is a connection between the water bodies. The net amount of salt transferred will depend on the both the volumes of water flow into and out of the basin through the connection, and the salinities of these flows. Net importation is more likely to occur when meltwater input from snow banks into the basin is low, decreasing the total outflow and salt export. Conversely, export of salt will be more likely to occur when the volume of outflow is higher. During periods when there is a net importation of salt into the basin, maximum ρ_{is} and Z_c will increase, and during net exportation, the opposite will occur. The similarity between the cycles of salt importation and exportation and water levels in the lakes without marine connections is clear in data from Lake Fletcher, as under ice salinity decreased from 1978–87 (when the under ice salinity was 54 g l^{-1}; Eslake *et al.* 1991), but has subsequently increased (Fig. 4). These variations parallel observations for many of the lakes over the same time period. Thus, the high salinity at the base of the SIMBs is a result of the same general processes that occur in the lakes: periods of lower meltwater input result in higher salinities and vice versa.

The sources of the hypersaline waters in Ellis Fjord and Taynaya Bay are less clear, but are most likely due to the formation of brine flows in shallows during periods of intense ice formation (Gallagher *et al.* 1989). Similar flows have been identified in Organic Lake (Ferris *et al.* 1991), but are probably of limited importance in the lakes. The hypersaline waters of 'Deep Meromictic Basin', Ellis Fjord, have been estimated to have been formed 4–6000 years ago (Gallagher *et al.* 1989).

It is clear from the occurrence of the SIMBs that stratification can begin before a basin is isolated from the ocean. However, there is no necessity for this, as Scale and Ephyra lakes, which apparently did not have a marine phase, are meromictic. Furthermore, as discussed above, it is likely (though not necessary) that the lakes have mixed at some time in their post-isolation histories. Therefore, there are probably two mechanisms for the formation of meromictic lakes: isolation of an already stratified marine basin as a result of decreasing water level, or input of fresh meltwater to mixed lakes. It is clear that net input of fresh water and higher water levels is important not only in the formation but also in the maintenance of meromixis in the lakes, as it leads to an increase in annual minimum stability. In contrast, net loss of water decreases minimum stability, and can lead to the loss of meromixis.

Conclusions

The Vestfold Hills contains a wide variety of meromictic lakes and permanently stratified marine basins. These range in depth (from 5–110 m), in area (3–150 ha), in salinity (from brackish to hypersaline), in temperature (from frigid to relatively warm), and in many other attributes. The list of meromictic lakes will not be constant, as environmental change will lead to either stratified lakes mixing, and thus losing their meromictic status, or other, presently mixed, lakes becoming stratified. The lakes provide sensitive indicators of local climate change, and, therefore, monitoring of the physical characteristics of these lakes should be continued. Along with the SIMBs and stratified marine basins, they provide a particularly clear continuum in the isolation and development of polar marine-derived lakes unparalleled in any other region of the world.

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Appendix 1

Converting *in situ* conductivities, which are highly temperature dependent, to salinities or densities for saline and hypersaline waters is fraught with difficulties (Hall & Northcote 1986, Spigel & Priscu 1996). The ionic ratios of the major components of the Vestfold Hills saline lakes are generally close to those in seawater (Burton 1981a, Masuda *et al.* 1988), so it would be expected that relationships derived for seawater should be applicable. The equation of state for seawater was developed for salinities beneath 42 (Fofonoff & Millard 1983), and this relationship can be used with reasonable confidence for lakes up to this salinity (Spigel & Priscu 1996). Problems are created at higher salinity by ion-pair formation and alteration of ionic ratios by precipitation of salts (particularly mirabilite, $Na_2SO_4.10H_2O$, which precipitates from Vestfold Hills lakes of salinity greater than about 150 g l^{-1}). Two other sets of equations have been developed specifically for Antarctic lakes. Gibson *et al.* (1989) gave relationships between *in situ* conductivity and density for lakes of the Vestfold Hills, but is has since been found that these equations underestimate density in hypersaline waters. Spigel & Priscu (1996) developed equations to predict density and salinity for Lake Bonney in the McMurdo Dry Valleys, but these equations again underestimate both these parameters for hypersaline lakes of the Vestfold Hills.

Given below are details of the algorithms used in this study for the calculation of C_{15} from C_{is} and *in situ* temperature, and conversion of salinities calculated using the equations of Fofonoff & Millard (1983) to units of g l^{-1}.

Calculation of C_{15}

Gibson *et al.* (1990) measured the electrical conductivity of water samples from the lakes of the Vestfold Hills as a function of temperature. Equations fitted to these data can be used to calculate C_{15} from C_{is} and temperature. Gibson *et al.* (1990) fitted quadratic equations to the temperature/conductivity curves:

$$C_{is} = L + MT + NT^2 \qquad (1)$$

where T is the temperature in degrees celsius and L, M and N are constants for each particular water sample. Plotting the values of M against L for different water samples indicated that these parameters were linearly related:

$$M = 2.7907 \times 10^{-2}L \qquad (2)$$

Similarly, a plot of N against L indicated a quadratic relationship between these parameters:

$$N = 1.3215 \times 10^{-6}L^2 \qquad (3)$$

Substituting equations 2 and 3 into equation 1 and rearranging gives:

$$0 = ((1.3215 \times 10^{-6}T)^2)L^2 + (2.7907 \times 10^{-2}T+1)L - C_{is} \qquad (4)$$

Solving this equations for L results in:

$$L = (-(2.7907 \times 10^{-2}T +1) + ((2.7907 \times 10^{-2}T +1)^2 + 4 \times C_{is} \times (1.3215 \times 10^{-6}T)^2)^{0.5})/(2 \times (1.3215 \times 10^{-6}T^2)) \qquad (5)$$

Equation 5 can now be used to calculate L, which is in effect the conductivity at 0°C. The equation is in fact not defined at T = 0; but from Equation 1 it is clear that at this temperature $L = C_{is}$. C_{15} can then be calculated by substituting the value of L into equation 4, along with T = 15.

Calculation of salinity

Fofonoff & Millard (1983) gave equations for the calculation of the salinity of seawater (units: 'practical salinity units', assumed here to be equivalent to g kg^{-1}) from electrical conductivity, pressure and temperature. In the present study, salinities in units g kg^{-1} (i.e. parts per thousand by mass) were converted to g l^{-1} (i.e. parts per thousand by volume) using the following equations derived experimentally for Vestfold Hills lakes samples (S. Stark, personal communication 1994):

$$S_L = ((2880.9 - (2880.9^2 - 2956.88 \times (S_k + 2140.6)^{0.5})/1478.44) \times S_k \qquad (6)$$

where S_L is the salinity in units g l^{-1}, and S_k is the salinity in g kg^{-1}.