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ARTICLE

# Physical processes and meromixis in pit lakes subject to ice cover

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**Abstract:** Understanding the physical limnology of pit lakes is essential to planning closure, managing water quality, and using pit lakes to address other water quality problems at mine sites. Pit lakes are generally deep, have relatively small surface areas sheltered by pit walls, and often contain saline water. As a consequence pit lakes are candidates for meromixis, where the salinity stratification is sufficiently strong to inhibit mixing between the surface and deep water. To illustrate a variety of processes that can act to disrupt meromixis, we examine data from six pit lakes at three different sites in northern Canada. In five of the six cases the deep water was disturbed by factors such as groundwater inflow, sludge deposition, wall failure, and water transfers as a result of mine site management. We also discuss a number of factors that enhance meromixis, including salinity, salt exclusion from ice, and runoff.

*Key words:* water-filled mine pit, pit lake, stratification, stability, meromixis.

**Résumé :** Il est essentiel de comprendre la limnologie physique des lacs de fosses à ciel ouvert pour en planifier la fermeture, gérer la qualité de l'eau et utiliser ces lacs pour aborder d'autres problèmes de qualité de l'eau aux sites miniers. Les lacs de fosses à ciel ouvert sont souvent profonds, ils ont une superficie relativement petite protégée par les murs de la fosse et contiennent souvent de l'eau saline. Il en résulte donc que ces lacs sont de bons candidats pour la méromixie, où la stratification de la salinité est suffisamment forte pour restreindre le mélange de l'eau de surface et l'eau en profondeur. Pour illustrer une variété de processus qui peuvent nuire à la méromixie, nous avons examiné des données provenant de six lacs de fosses à ciel ouvert à trois différents sites du Nord du Canada. L'eau en profondeur a été perturbée, dans cinq des six cas, par des facteurs tels que l'apport d'eau souterraine, la déposition de boues, l'effondrement d'un mur et les transferts d'eau découlant de la gestion du site minier. Nous discutons également de plusieurs facteurs qui contribuent à la méromixie, dont la salinité, l'exclusion du sel des glaces et le ruissellement. [Traduit par la Rédaction]

*Mots-clés :* fosse de mine à ciel ouvert remplie d'eau, lac de fosse à ciel ouvert, stratification, stabilité, méromixie.

## Introduction

On closure, an open pit mine typically fills with groundwater and surface inflow to form a pit lake that is very different from surrounding natural lakes (Castendyk and Eary 2009). The resulting pit lakes have been used for a variety of purposes, such as storing process water, sump water from underground workings, acid rock drainage (ARD), neutralization sludge, and excess water from tailings ponds (e.g., Gammons et al. 2009). In some cases pit lakes have been used to isolate poor quality water; in other cases they have been used as finishing ponds, where high quality water from the surface is discharged directly to the environment (e.g., Pelletier et al. 2009; Crusius et al. 2003). Pit lakes have also been used for in situ treatment such as ARD neutralization through the addition of lime, and biological remediation in which added fertilizer encourages phytoplankton to adsorb metals (e.g., Poling et al. 2003) or bacteria to oxidize cyanide (e.g., Chapman et al. 2007).

Effective management of a pit lake requires an understanding of its physical limnology: Under what conditions will water stored at depth remain isolated from the surface? How much deep water might come to the surface each year? What is the effect of ice cover? What role does groundwater inflow play on mixing? How much mixing is induced by stream flow, surface and sub-surface pipe inflow, sludge discharge, pit wall failure, and the cascading of water over pit-wall benches? What is the best way to engineer the stratification of a pit lake? The answers to these questions are surprisingly difficult to obtain as they depend on complicated turbulent mixing processes in a density stratified water body. In this paper we make use of observations from six Canadian pit lakes to examine some of these questions (Fig. 1).

Pit lakes differ from natural lakes in that they are typically brackish, and are usually deep relative to their surface area; as a consequence, pit lakes can evolve to a state of permanent stratification known as meromixis. Meromixis occurs when the deep water is sufficiently more saline than the surface water, so that mixing is inhibited. Salinity stratification can result from the exclusion of salt from ice-cover, or it can be engineered by adding a cap of fresh water.

A schematic defining the vertical structure of a meromictic lake is shown in Fig. 2*a*. The main feature that characterizes meromixis is a significant increase in salinity, traditionally called the chemocline (Hutchinson 1957; Wetzel 2001), but also referred to occasionally as the halocline (strong salinity gradient) or pycnocline (strong density gradient). The chemocline separates the mixolimnion (seasonally mixed surface water) from the monimolimnion (isolated deep water). The mixolimnion is further divided into the epilimnion and hypolimnion (Boehrer and Schultze 2008).

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**Fig. 1.** (*a*) Map showing location of the Equity, Colomac, and Faro mine sites. (*b*) Equity Main Zone (far) and Waterline (near) pit lakes. (*c*) Colomac Zone 2 Pit lake. At the Faro mine: (*d*) Vangorda pit lake just before ice-off; (*e*) Grum, and (*f*) Faro pit lakes. Photos courtesy of: (*b*) M. Aziz, (*c*) R. Pieters, (*d*), (*e*) Laberge Environmental Services, and (*f*) Google Earth.

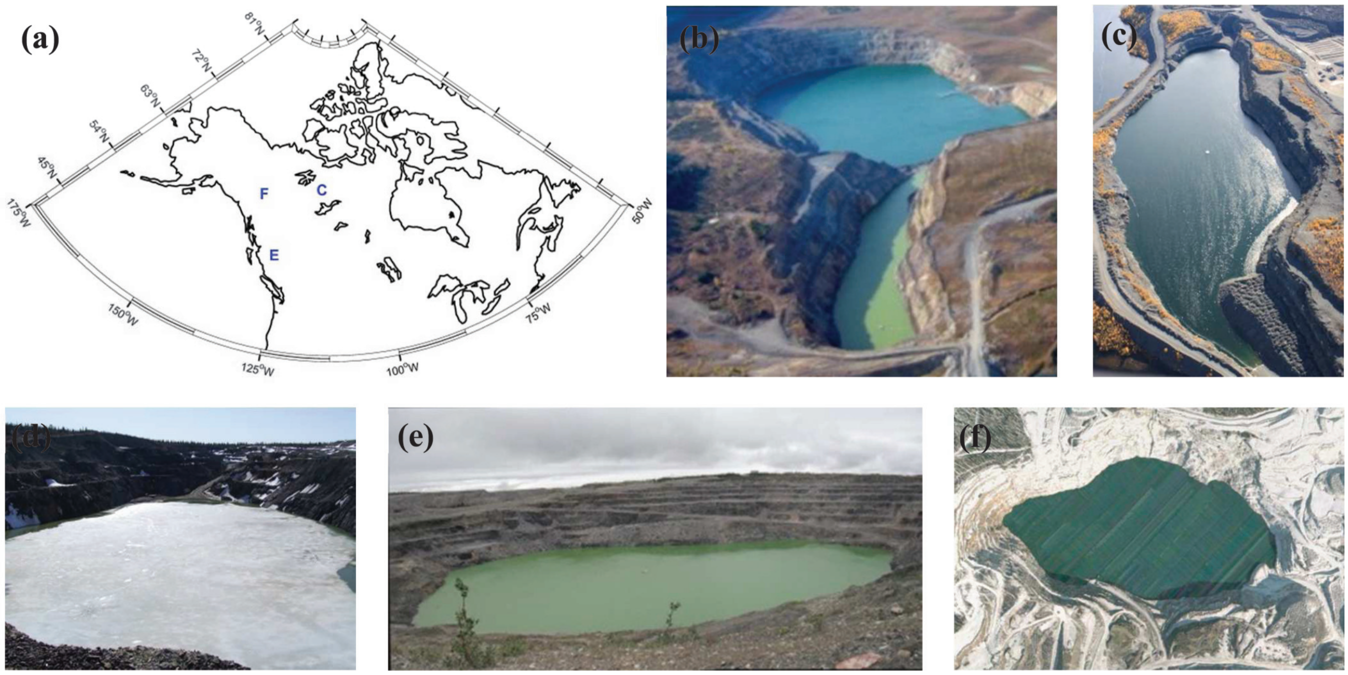



**Fig. 2.** (*a*), (*b*) Schematic of meromixis for a pit lake with ice cover. The chemocline separates the mixolimnion (surface water that mixes seasonally) from the monimolimnion (isolated deep water). (*c*) Water density as a function of temperature and salinity. The temperature of maximum density ($T_{MD}$) for $S$ = 0 is 3.98 °C. The increase in density from 0 to 4 °C is equivalent to adding $S$ = 0.165 g/L. The increase in density from $S$ = 0 to 1 g/L is equivalent to decreasing the temperature from 15 to 4 °C.

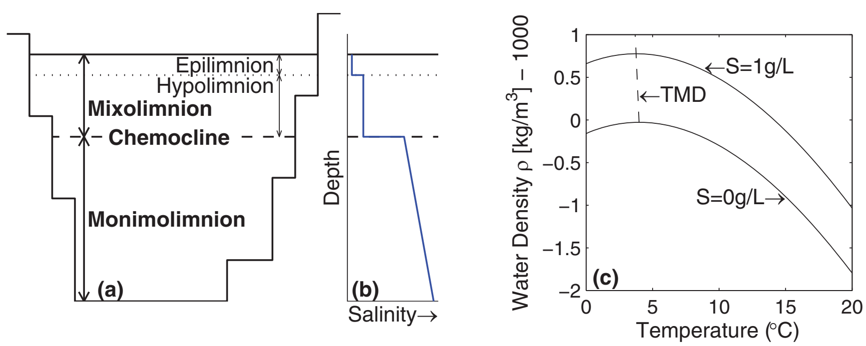



Figure 2*b* shows the salinity just after ice-off, when the epilimnion is fresher as a result of ice-melt and runoff. The epilimnion mixes downward, slowly in summer and more rapidly through fall, until, typically, the entire mixolimnion is included in the surface layer. Further deepening of the mixolimnion is resisted by the chemocline, leaving the monimolimnion isolated throughout the year.

Meromixis, however, does not necessarily preclude the transfer of water between the monimolimnion and the mixolimnion. This transport could occur, for example, by inflow of groundwater into the monimolimnion, and by subsequent erosion of the monimolimnion during fall cooling. There are varying degrees of meromixis: the most strongly meromictic pit lakes are characterized by a strong chemocline, and by a monimolimnion whose salinity and volume undergo little change over time, indicating negligible transport from the monimolimnion to the mixolimnion. At the other extreme are weakly meromictic pit lakes that are close to turnover, and transport between layers may be significant. We will examine indicators of the strength of meromixis.

We discuss six pit lakes with seasonal ice-cover from three different sites in northern Canada (Fig. 1): Faro, Grum, and Vangorda pit lakes located at the Faro mine, 200 km north of Whitehorse, in the Anvil Range, Yukon (62.353 N, 133.364 W); Waterline and Main Zone pit lakes located at the Equity Silver mine, 30 km southeast of Houston, B.C. (54.189 N, 126.263 W) (Crusius et al 2003; Leung 2003; Whittle 2004); and Zone 2 pit lake located at the Colomac mine, 250 km north of Yellowknife, NWT (64.397 N, 115.089 W). Characteristics of the pit lakes are given in Table 1.

The objectives of the present paper are to illustrate the unexpected variety of observed pit lake behaviour, and examine factors that promote or inhibit meromixis. After a brief description of methods, we discuss the seasonal evolution of meromixis in a pit lake subject to ice cover. We then examine data from the six pit lakes, and discuss factors that both favour meromixis (enhance stability) and oppose meromixis (induce mixing).

**Table 1.** Pit lake characteristics.

| | Faro | Grum | Vangorda | Waterline | Main Zone | Z2P |
|---|---|---|---|---|---|---|
| Water level (m ASL) | 1142 | 1185 | 1085 | 1265 | 1260 | 336 |
| Max. depth (m) | ~90 | ~50 | ~50 | 40 | 120 | 110 |
| Surface area (ha) | 51 | 9.5 | 5.9 | 2.6 | 20.5 | 17.3 |
| Volume ($Mm^3$) | ~30 | ~2 | ~1 | 0.48 | 9.7 | 8.4 |
| Average salinity (g/L) | 1.1 | 0.84 | 1.7 | 1.3 | 2.4 | 0.75 |
| Average pH | 7.0 | 7.9 | 6.0 | 7.5 | 7.5 | 7.9 |
| Relative depth (%) | 11 | 14 | 18 | 22 | 23 | 23 |
| Est. inflow ($m^3$/year) | $5.9\times10^4$ | na | $2.4\times10^6$ | $2\times10^5$ | $5\times10^5$ | $<2\times10^5$ |
| Bulk retention time (year) | 50 | na | <1 | 2.4 | 20 | >40 |
| Black ice thickness, $h_i$ (m) | 0.4–0.6 | 0.4–0.5 | 0.4–0.6 | ~0.9 | ~0.6 | 0.6–0.8 |
| Salt exclusion factor, $f_b$ | 0.93 | 0.97 | 0.98 | na | na | 0.87–0.99 |
| $\delta$* | ~10 | — | — | ~10§ | — | 1.7 (2004/05)<br>2.7 (2005/06) |
| Salinity stability, $St_S$* ($J/m^2$)† | ~700 | — | — | ~300 | — | ~200 |
| $\Delta St_S$ ($J/m^2$)‡ | ~20 | — | — | ~13 | — | ~25 |
| Observed mictic status | meromictic | uncertain | uncertain | meromictic | holomictic | intermittent |

**Note**: m ASL, is metres above sea level; Z2P, is Zone 2 Pit.
*Ratio of the salt deficit of the pit lake to the mass of salt excluded from the ice.
†Evaluated at 31 August.
‡Reduction in salinity stability from 31 August to ice-on.
§Calculated assuming $f_b = 0.95$.

## Methods

All vertical profiles were collected with a Sea-Bird Electronics SBE 19 or 19plus profiler. Temperature was accurate to 0.005 °C, and conductivity was calibrated in the laboratory against a Guildline Portasal salinometer with agreement to better than 0.2% throughout the study period. Conductivity was corrected for temperature, and converted to salinity following the method of Pawlowicz (2008). Density was calculated using Chen and Millero (1986). The profiler included a Wetlabs CStar transmissometer (660 nm, 0.25 m path length); from light attenuation $\kappa$ ($m^{-1}$), turbidity was calculated as $\kappa/0.8$ (NTU). All profiles are shown relative to the water surface elevation at the time the cast was collected. Oxygen was measured using Winkler titration.

## Examples of pit lake behaviour

In the following we examine temperature and salinity profiles from the six pit-lakes. We begin by examining the seasonal evolution of Faro, which has the strongest meromixis and best illustrates meromixis in a pit lake with ice cover. We then examine the effect of groundwater on Waterline and Zone 2 pit lakes, sludge disposal on Main Zone, wall failure on Grum, and water transfers on Vangorda.

### Faro

To illustrate the seasonal cycle of stratification, data from Faro pit lake are shown for June 2008 to April 2009 in Fig. 3. During spring, ice-melt and freshet runoff lowered the salinity of the epilimnion (0–4 m, Fig. 3*b*). The resulting difference in salinity between the epilimnion and the hypolimnion prevented mixing of the entire mixolimnion in spring. The epilimnion warmed quickly providing additional temperature stability throughout summer; on 11 June 2008, the epilimnion was between 8 and 11 °C (Fig. 3*a*) and by 6 August 2008 the temperature reached 13 °C (not shown).

In early fall the epilimnion had cooled to 10 °C and was deepened by wind mixing and penetrative convection to about 10 m (Fig. 3*c*, 3*d*). The epilimnion continued to cool and deepen; when it reached the temperature of maximum density, $T_{MD}$ = 3.7 °C, temperature variations were small and no longer contributed significantly to the stability. At this time the pit lake was most vulnerable to mixing, and the stability was maintained by the salinity stratification alone.

As the epilimnion cooled below $T_{MD}$, it became 'reverse' stratified: cold ($<T_{MD}$) and less-dense water formed a surface layer floating on the deeper, denser water nearer $T_{MD}$. It should be noted that the density difference provided by reverse stratification in winter is much less than that of typical thermal stratification in summer (Fig. 2*c*).

At Faro, ice cover generally occurs from late October to early June. The growth of black-ice through winter, which excluded a high proportion of the dissolved salt from the water, increased the overall salinity of the mixolimnion (under-ice profile of 29 April 2009; Fig. 3*f*). This is another time that the pit lake was vulnerable to mixing.

When ice begins to form, the epilimnion is reverse stratified with buoyant water at ~0 °C just under the ice (Fig. 3*e*). Because of the reverse temperature stratification, salt excluded from the ice will initially remain just under the ice. However, only a limited amount of salt can be stabilized by the reverse stratification, and eventually salt will be transported downward through the mixolimnion, either by episodic convection or double diffusion. In Faro, the salt excluded from the ice is not sufficient to raise the salinity of the mixolimnion to that of the monimolimnion, and salt driven mixing with the monimolimnion does not occur.

Ice-off, in early June, completes the annual cycle. Just after ice-off, the coldest point in the water column occurs in the lower part of the mixolimnion (e.g., 3.7 °C, 12–15 m, Fig. 3*a*). This minimum is a remnant of the reverse stratification from the previous winter and implies that the temperature minimum has been undisturbed either by mixing from above or by groundwater inflow from below. In other words, the temperature minimum confirms that spring turnover of the mixolimnion did not occur. This temperature minimum has been observed in Faro every year since data collection began in 2004 (Fig. 4*a*). It was also observed in Waterline (Fig. 5*a*), and, though not apparent in Fig. 6*a*, it also occurred occasionally in Zone 2 Pit.

Annual profiles from early in the open-water season are shown for Faro pit lake in Fig. 4. Each year there was an epilimnion (top 3–7 m) which was warm (>10 °C) and fresher than the water below as a result of ice melt and runoff. In the hypolimnion (7–20 m), temperatures below the $T_{MD}$ confirm that spring turnover did not occur. In the monimolimnion (below 20 m) the temperature was slightly above $T_{MD}$ and increased gradually with depth (inset), as did the salinity. Compared to the other pit lakes considered in the present study, there is a small annual increase in both the temperature (0.02 °C/year) and salinity (0.01 $g \cdot L^{-1} \cdot year^{-1}$) from 2004 to 2011. The cause of these gradual changes is unclear; the increase in temperature could result from geothermal heating from below

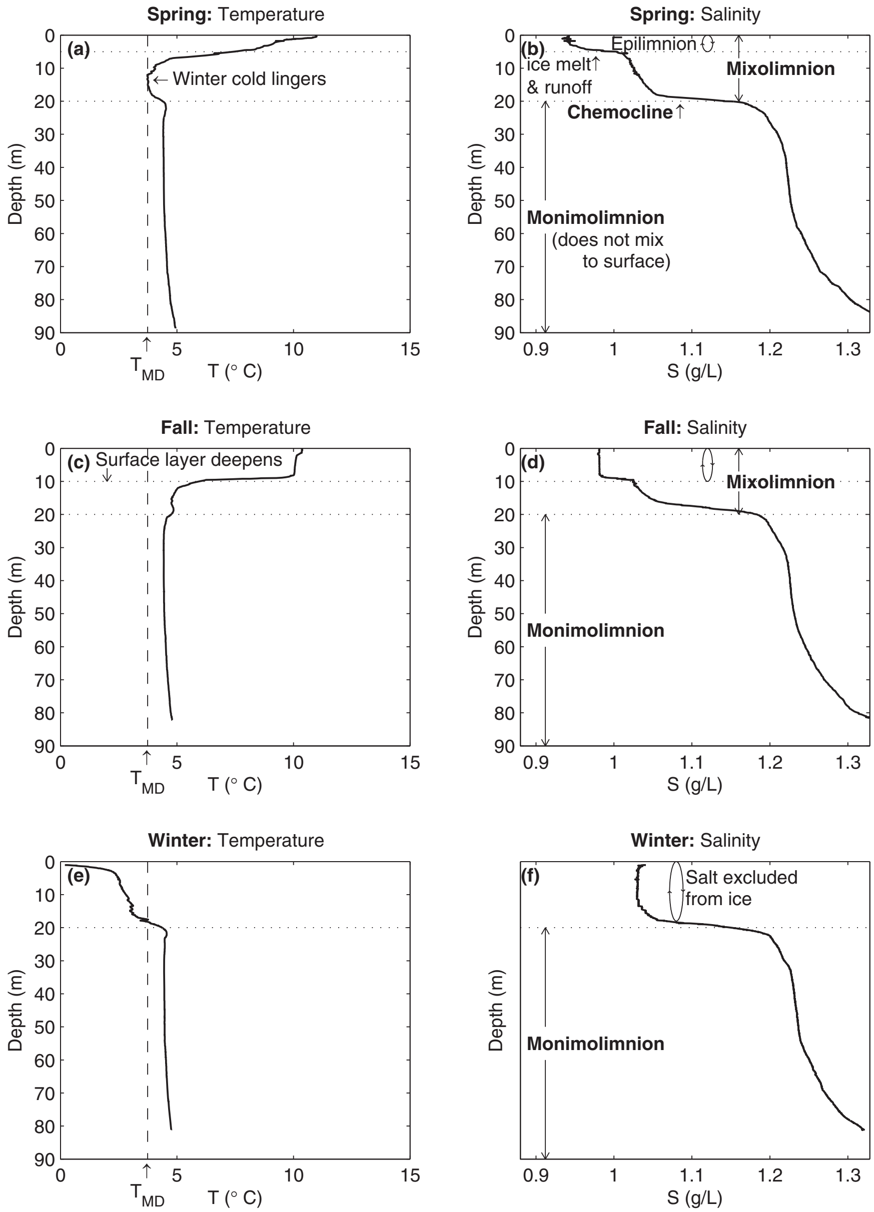



**Fig. 3.** Temperature and salinity for Faro pit lake. (*a*), (*b*) Spring after ice-off, 11 June 2008; (*c*), (*d*) Fall, 3 September 2008; and (*e*), (*f*) Under-ice, 29 April 2009.

(c.f. Hyndman 1976; Lewis et al. 1988; Scheifele 2013), and the increase in salinity in the deep water might result from remineralization (the decomposition of organic matter to inorganic forms). On the other hand a small inflow of groundwater might also account for the gradual change in temperature and salinity at depth.

The origin of the relatively large fresh water cap on Faro is not known; it may have been created inadvertently by the storage of less saline water in the pit. Regardless of its origin, it provides sufficient stability to avoid turnover in spring and fall, and sufficient salinity deficit in the mixolimnion to avoid under-ice mixing in winter.

## Waterline

We consider two pit lakes where deep inflow plays a role. The first is Waterline where temperature, salinity, and dissolved oxygen profiles over one year (21 June 2002 to 13 June 2003) are shown in Fig. 5*a*, 5*b*, 5*c*. Also shown are the two adits that connect Waterline to collapsed underground workings (Fig. 5*d*). Mixing is evident between 16 and 20 m depth, coincident with the upper adit (Fig. 5*e*). We speculate that internal seiching drives oscillating flow into and out of the adit resulting in mixing. Any mixing that might result at the lower adit (36 to 40 m depth) cannot be distinguished from that associated with the bottom boundary layer.

Below the upper adit (>20 m depth), the temperature and salinity remain relatively unchanged over time, which, along with the absence of dissolved oxygen (Fig. 5*c*), suggests that the lower adit does not contribute significantly to groundwater inflow and that water below 20 m is isolated. Above 16 m depth there are two layers (Fig. 5*e*). One is the surface layer that deepens gradually through summer and more rapidly during fall due to surface mixing processes. The other is a relatively uniform layer of temperature and salinity that appears to be driven by groundwater inflow from the top of the upper adit at about 16 m depth. The depth of the interface between these two layers is a balance between surface mixing processes and the inflow at 16 m.

**Fig. 4.** (*a*) Temperature and (*b*) salinity profiles, Faro pit lake, June 2004–2011. The chemocline is located at 20 m. A warm, fresh epilimnion can be seen in the top 3– 6 m. The cast in 2004 was near one side of the basin and reached a depth of only 50 m.

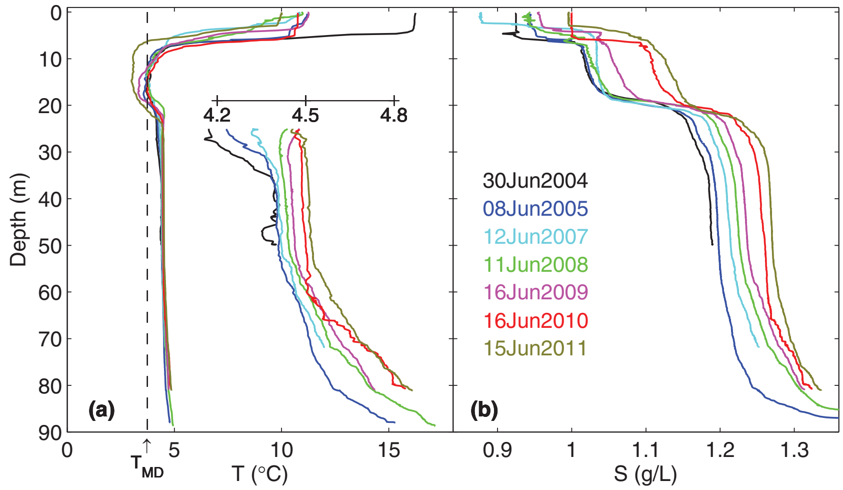
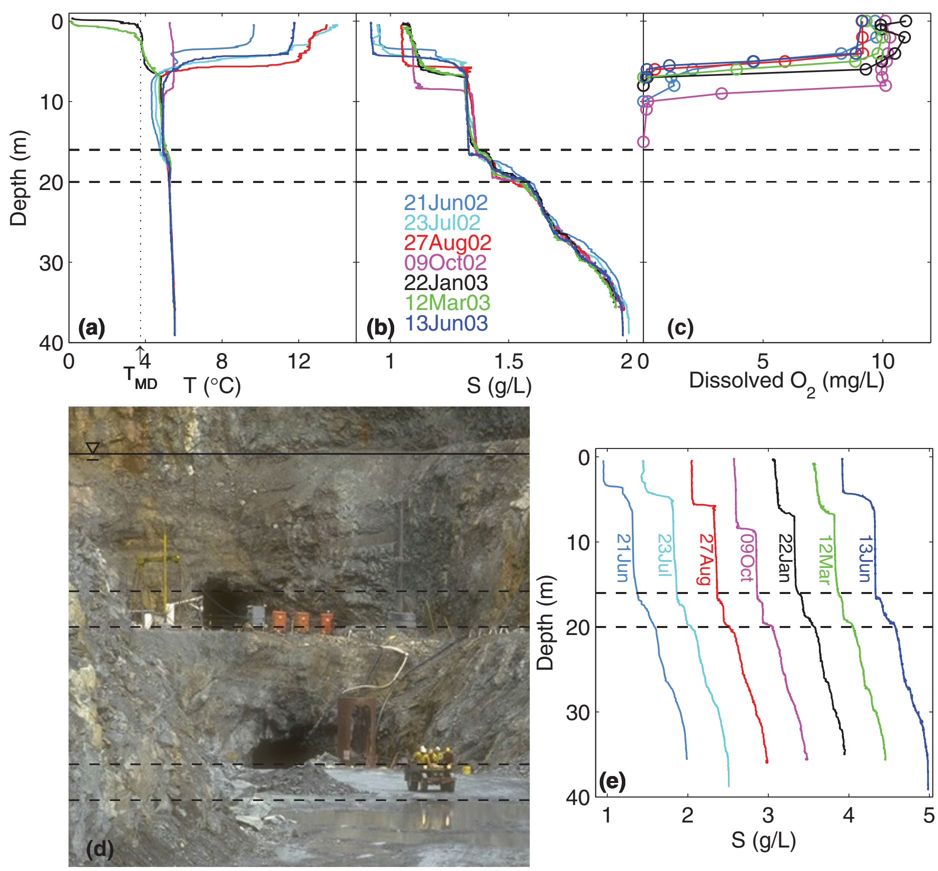



**Fig. 5.** (*a*) Temperature, (*b*) salinity, and (*c*) oxygen profiles, Waterline pit lake, 2002–2003. (*d*) Photo of Waterline before flooding showing the two 12 ft (3.7 m) high adits. The lower adit descends, and is lower than it appears from the entrance. Note that the bottom of Waterline was excavated deeper subsequent to the photo. Photo courtesy of M. Aziz. (*e*) Salinity profiles staggered by 0.5 g/L.

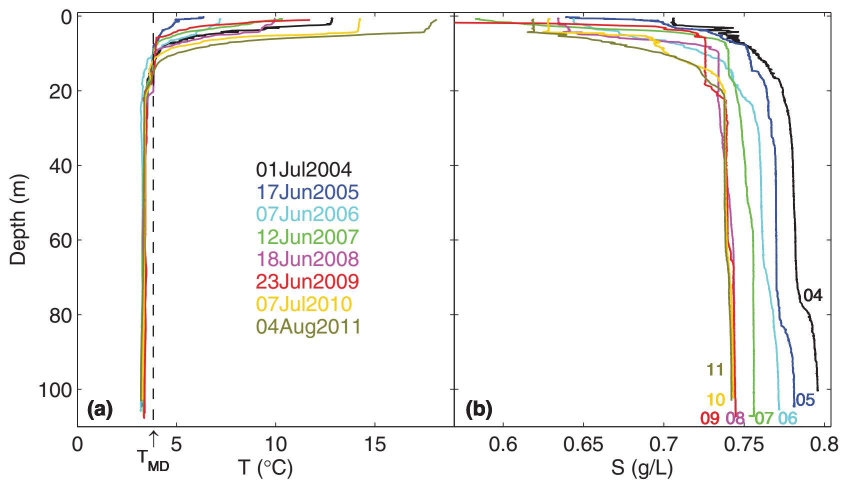



## Zone 2 Pit

Zone 2 Pit Lake provides a second example of deep inflow. Temperature and salinity profiles from 2004 to 2011 are shown in Fig. 6, during which time the pit lake was still filling. In each of these years, ice and snow melt, along with freshet inflow provided a fresh water cap that was sufficient to suppress both spring and fall turnover. Under-ice mixing was observed only once (see Discussion), and other than the intentional destratification of Zone 2 Pit by aeration in summer of 2006 and 2007 (Pieters et al. 2014*a*), this pit lake was otherwise meromictic.

Groundwater inflow to Zone 2 Pit was driven by the water level difference with the adjacent Baton Lake; as Zone 2 Pit filled, the water level decreased, and groundwater inflow declined. From 2004 to 2008, higher inflows of groundwater resulted in a significant decline in the salinity of the monimolimnion; after 2008 the decline slowed (Fig. 6*b*). Note that much of the groundwater en-

**Fig. 6.** (*a*) Temperature and (*b*) salinity, Zone 2 Pit lake, 2004–2011. Profiles are shown from the water surface which rose 5.1 m during this time. Note the pit lake was destratified by aeration at depth (12 July – 19 September 2006; 17 June – 21 September 2007), but restratified over winter.






tered at around 65 m depth, the elevation at which inflow of groundwater to the pit first became significant during mining, and accounts for the relatively uniform temperature and salinity from 30 m to 65 m depth (Fig. 6*b*).

### Main Zone

The Main Zone pit lake provides a contrast to the previous pit lakes as a result of ARD neutralization sludge that enters the surface of the pit and sinks to the bottom. This inflow effectively stirs the entire deep water of the pit as suggested by the relatively uniform profiles of temperature and salinity below 5 m (Fig. 7*a*, 7*b*). Besides mixing the deep water, the sludge also entrains water from the warm fresh surface layer and carries this surface water to depth. This weakens the summer stratification and results in the early onset of fall overturn. Because of fall overturn Main Zone is holomictic, meaning it mixes completely at least once a year (Pieters et al 2014*b*).

A signature of the sludge entering Main Zone can be seen in the turbidity (Fig. 7*c*), with increasing turbidity below 80 m. The height of this sludge 'cloud' above the bottom varied with the rate of sludge inflow. During breaks in sludge inflow, the sludge cloud would settle completely over a few days. Dissolved oxygen was also highest near the bottom, being carried to depth by the sludge (Fig. 7*d*).

### Grum

Profiles of temperature and salinity during open water are shown for Grum pit in Fig. 8. These profiles show a fresh layer due to ice melt and freshet runoff which warms in summer. However, below the surface layer the temperature and salinity are remarkably uniform from 7 m to the bottom. In addition, the temperature and salinity of the deep water increased significantly over the summer indicating that the deep water was not isolated. The warming is likely the result of transport of heat from above, but the cause of the salinity increase is unknown.

The similarity between these profiles (Fig. 8) and those from Main Zone (Fig. 7) suggests that a similar process may be at work. However, unlike Main Zone, the volume of water entering Grum was low, and the likely source of disturbance in Grum pit is the gradual failure of the east wall which is composed of till and shows signs of active creep. Ongoing and gradual slumping, either above or below the water surface, likely explains the significant mixing observed.

### Vangorda

Vangorda is used for storage of ARD and has a bulk retention time of less than a year. Three profiles over one year are shown in Fig. 9. The surface showed a fresh warm layer in summer and reverse stratification in winter. However, the temperature and salinity of the deep water varied significantly over the year. The evolution of Vangorda is unclear due to the fact that there are regular inflows and outflows as a result of mine site management.

## Discussion

### Indicators of meromixis

Meromixis occurs when the salinity stratification is sufficient to resist turnover in spring and fall and under-ice mixing in winter. Here we examine in detail the conditions for meromixis in fall and winter. Spring turnover has not been observed in any of the six pit lakes describe here; the conditions for ice melt and runoff required for the suppression of spring turnover are described in Pieters and Lawrence (2009*b*).

#### *Fall*

Increased salinity in the deep part of a pit lake makes the water column 'bottom heavy'; to mix the pit lake would require lifting the denser, more saline deep water to distribute it throughout the water column. The energy required to do this is given by the stability,

$$\text{St}_{\text{TOT}} = \frac{g}{A(0)} \int_0^h (\rho(z) - \bar{\rho})\, z\, A(z)\, \mathrm{d}z \; [\text{Jm}^{-2}] \tag{1}$$

where $z$ is the depth from the surface, $\rho(z)$ is the density, $\bar{\rho}$ is the mean density, $A(z)$ is the area of the pit, $h$ is the total depth, and $g$ is gravity. Both temperature and salinity contribute to the density, and hence, to the stability.

However, when the mixolimnion has cooled to $\sim T_{\text{MD}}$ in the fall, the remaining small temperature gradients in the chemocline and monimolimnion do not contribute significantly to density and the salinity alone resists further mixing. To remove the effect of temperature, eq. (1) can be evaluated at the mean temperature to give the salinity stability, $\text{St}_s$. The salinity stability gives the work needed to mix the entire pit lake at constant temperature (for further detail see Pieters and Lawrence 2009*a*).

To look at the stability in the fall, we start with the salinity stability of the pit lake on 31 August, $\text{St}_s^*$. This is relatively large for Faro, and smaller for Waterline and Zone 2 Pit (Table 1). Next we define $\Delta\text{St}_s$ as the decrease in salinity stability as the epilimnion is mixed deeper through the fall; the value of $\Delta\text{St}_s$ ranged from 13 to 25 J/m² (Table 1). If the decline in stability through the fall, $\Delta\text{St}_s$,

**Fig. 7.** (*a*) Temperature, (*b*) salinity, (*c*) turbidity, and (*d*) oxygen (bottle) data, Main Zone pit lake, 25 June 2001. The temperature and salinity are remarkably uniform between 8 and 118 m as shown on expanded scale (*a*, *b* inset); they are both close in slope to the dashed lines that mark the effect of pressure on water of a uniform temperature (*a*, inset) and salinity (*b*, inset). The steps in salinity result because the changes are near the resolution of the instrument (~0.001 g/L).

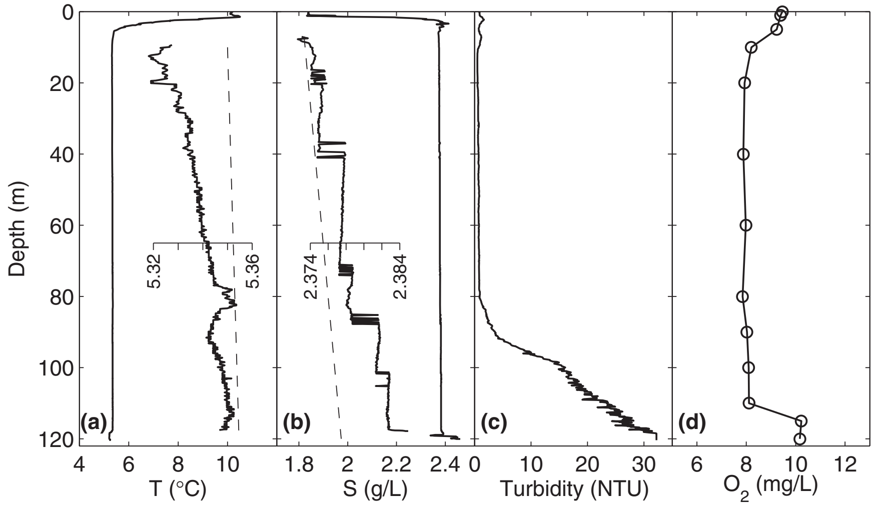
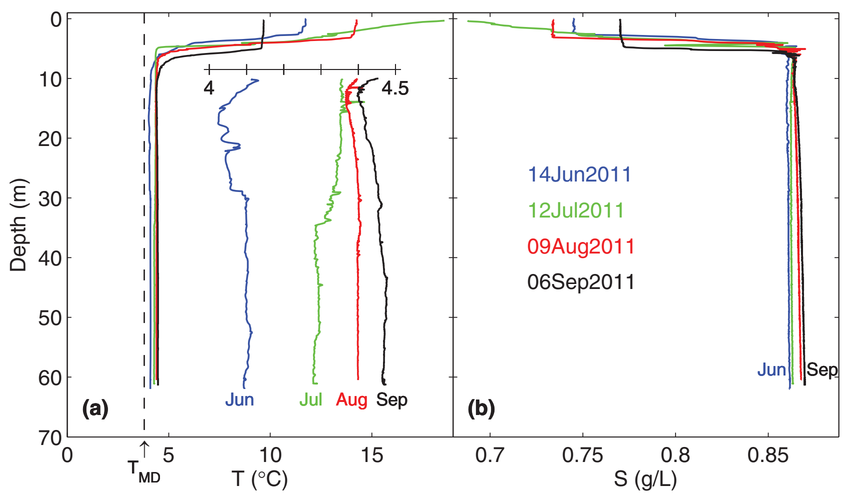



**Fig. 8.** (*a*) Temperature and (*b*) salinity in Grum pit lake, 2011. Note the relatively uniform temperature which on expanded scale (inset) shows noise suggestive of mixing.




is greater than the stability at the end of August, $St_s^*$, then fall turnover occurs, and a condition for meromixis is that the decline in stability through the fall be less than the stability on 31 August, $\Delta St_s < St_s^*$. We will use this relationship between $\Delta St_s$ and $St_s^*$ as an indicator of the degree of meromixis: for Faro, $St_s^* \gg \Delta St_s$ which suggests strong meromixis, while for Waterline and Zone 2 Pit meromixis is weaker.

### *Winter*

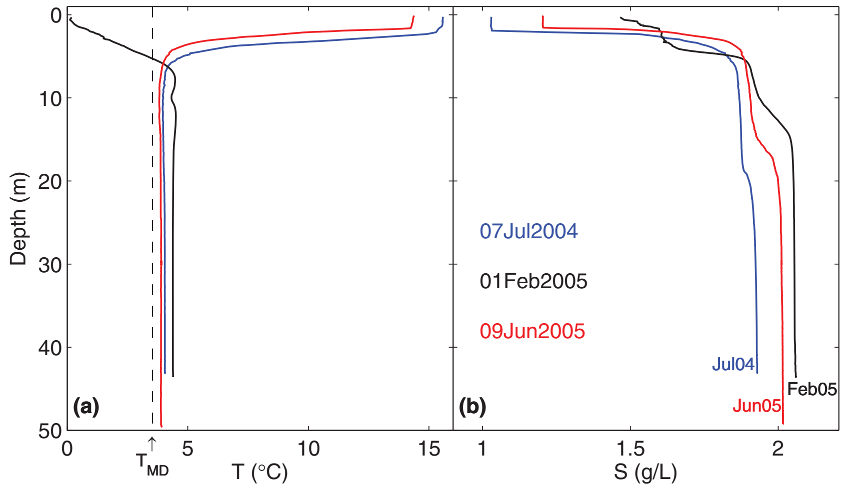
Salt excluded as ice forms can result in mixing of the water column under the ice (Solari and Parker 2013; Bluteau et al. 2014). We define the salt deficit to be the mass of salt needed to raise the salinity of the entire pit to the salinity at the bottom. An indicator of the importance of salt exclusion is the ratio of the salt deficit of the pit lake, $M_{DEF}$, to the mass of salt excluded from the ice, $M_{EXC}$

$$\delta = \frac{M_{DEF}}{M_{EXC}} = \frac{\int_o^h (S(h) - S(z))\, A(z) \mathrm{d}z}{h_i^*\, S(0)\, A(0)} \tag{2}$$

where $S(z)$ is salinity, and $A(z)$ is area as a function of depth, $z$, below the ice; $S(0)$ and $S(h)$ are the salinity at the surface and bottom, respectively; and $h_i^* = f_b h_i$ is the effective ice thickness, where $h_i$ is the thickness of black ice and $f_b$ is the fraction of salt excluded from black ice. The higher the mass of salt excluded from the ice, the lower the value of $\delta$, and the greater the potential for mixing. Values of $h_i$, $f_b$, and $\delta$ are given in Table 1.

For Faro and Waterline $\delta$ ~10 and it would take many times the observed effective ice thickness to initiate significant under-ice mixing. In Zone 2 Pit, $\delta$ was observed to vary from year to year: during the winter of 2004–2005, $\delta$ ~1.7 and under-ice mixing occurred throughout the water column; while in 2005–2006, during a mild winter with less ice and poor salt exclusion, $\delta$ ~2.7, and mixing was limited to the mixolimnion. This is an example of intermittent meromixis regulated by inter-annual variations in effective ice thickness. These observations highlight the dual role played by salt exclusion: while ice-melt contributes significantly to the salinity stratification that resists turnover each spring and fall, a winter with thick ice and high salt exclusion can result in under-ice mixing.

**Fig. 9.** (*a*) Temperature and (*b*) salinity in Vangorda pit lake, July 2004 – June 2005.






Note that if there are no sources of mixing, salinity gradients can persist in the monimolimnion (Fig. 2*b*). In Faro and Waterline the salinity from the top of the monimolimnion to the bottom increased by 200 and 500 μS/cm, respectively, while in the other pit lakes the increase was less than 20 μS/cm. Large gradients are also seen in the monimolimnion of natural lakes that are meromictic (Gibson 1999), though the mechanisms by which these gradients originate has not been detailed.

## Factors that enhance stability

### *Relative depth*

Most pit lakes are characterized by a small surface area relative to their maximum depth. This reduces the ability of wind stress and surface cooling to cause mixing. The relative depth is the maximum depth, $h_{max}$, divided by the equivalent diameter of the surface

$$h_r = \frac{h_{max}}{d_{eq}} \times 100 \quad (3)$$

and expressed as a percentage, where $d_{eq} = \sqrt{(4/\pi)A}$, and $A$ is the surface area. Most natural lakes have a small relative depth, $h_r < 2\%$, while natural lakes that are considered deep have $h_r > 4\%$ (Wetzel 2001). The relative depths of the pit lakes discussed here ranged from 11% to 23% (Table 1).

While relative depth is important, it does not predict meromixis. Rather, the key factor predicting meromixis is the salinity stratification that resists spring turnover, fall turnover, and under-ice mixing. If the salinity stratification is large enough, even a lake with a small relative depth can resist turnover and become meromictic.

### *Pit lake salinity and ice cover*

For most of the pit lakes discussed here, the primary source of salinity stratification is a combination of ice-melt and runoff. When the surface water freezes, the ice excludes a large proportion of the salt dissolved in the water. For example, at Colomac 87%–99% of salt was excluded from four water bodies ranging in salinity from 50 to 960 mg/L (Pieters and Lawrence 2009*b*). Because the proportion of salt excluded from ice is relatively high, pit lakes with higher salinity water have a larger density contrast between the resulting ice-melt and the deep water, and as a result, the stability increases with pit lake salinity. Stability also increases with the ice thickness, the fraction of black ice, and the proportion of excluded salt.

### *Inflow salinity and volume*

Runoff to the pit lake can also be important in establishing a fresh surface layer and can significantly increase stability (Pieters and Lawrence 2009*b*). However, the salinity of the runoff is important: most natural runoff is low in salinity, while drainage from waste rock piles, industrial areas, or tailings ponds can have elevated salinity. If the salinity of the runoff is lower than that of the epilimnion, then inflows reduce the salinity of the epilimnion, increasing stability, and reducing the likelihood of under-ice mixing. However, a more saline inflow may increase the salinity of the epilimnion, reducing the stability, and increasing the potential for under-ice mixing the following winter.

Like runoff, groundwater can also be a source of fresh or saline water. For example, in Zone 2 Pit, groundwater acted to reduce the salinity of the deep water. If groundwater flowing into the deep water were more saline than that in the pit, it would act instead to increase the stability. Note also that the possibility of simultaneous groundwater inflow and outflow from the monimolimnion can complicate the analysis of changes to the monimolimnion (Castendyk and Eary 2009).

## Factors that induce mixing

### *Wind and cooling*

During the open water season, the epilimnion deepens as a result of wind and surface cooling. Wind provides energy for turbulence, shear at the pycnocline, and upwelling, while surface cooling results in penetrative convection. All of these processes can act to deepen the epilimnion, through the mixolimnion and, if sufficiently strong, into the monimolimnion.

### *Ice*

The dual role of ice in both stabilizing and destabilizing meromixis has already been noted. Not only can the fresh ice-melt create meromixis, but under certain circumstances, salt excluded from the ice can induce mixing into the monimolimnion under the ice. As discussed, this would occur when sufficient salt was excluded from the ice to raise the salinity of the mixolimnion above that of the monimolimnion.

### *Other factors*

In addition to wind, cooling, and ice-cover, there are often additional natural and anthropogenic processes that can affect the stratification in pit lakes. The pit lakes examined here illustrate a wide variety of potential processes opposing meromixis, and the following summarizes these along with a few others:

- Active creep and subsidence of a till wall (Grum).
- Earthquakes (effects observed in Waterline, Fig. 10).
- Rock falls (observed in Zone 2 Pit; Brenda: Stevens and Lawrence 1998).
- Inflow of water through underground mine workings (Waterline) or conveyor shafts (Island Copper: Fisher and Lawrence 2006; Poling et al 2003).
- Groundwater inflow (Zone 2 Pit; Brenda).
- Restoration of diverted creek flow (considered for Faro and Grum).
- Water pumped out of the pit lake from a selected depth (Grum, Main Zone).
- Disposal of water from around the mine site (Faro, Grum, Vangorda, Main Zone).
- Disposal of dense sludge (Main Zone).
- Injection of ARD to depth (Island Copper: Fisher and Lawrence 2006; Pelletier et al 2009).
- Double-diffusion (Brenda: Hamblin et al. 1999; German mining lakes: von Rohden et al. 2010).
- Shoaling of internal seiches on pit lake benches (Island Copper: Stevens et al. 2005).
- Aeration (Zone 2 Pit: Pieters et al. 2014*a*).

**Isolation of the monimolimnion**

Determining whether a pit lake is meromictic is not sufficient for the purpose of environmental concerns, because even with meromixis, there can be significant transport of potentially undesirable water from the monimolimnion to the surface. We use two conditions for meromixis — one for fall turnover, and one for under-ice mixing — as indicators of the degree of meromixis. Note these indicators do not quantify the transport from the monimolimnion to the mixolimnion, but it is reasonable to assume that there is some relationship between the strength of the indicator and the vertical transport. Characterizing the vertical transport is beyond the scope of the present study.

Of the six pit lakes discussed in the present paper, Faro displayed the strongest meromixis; only Faro had the classic meromictic structure (Fig. 2*a*), and this was observed throughout the study period (Fig. 4); it also had the highest stability going into fall, $\mathrm{St}_s^*$ (Table 1), the largest resistance to under-ice mixing, $\delta$ (Table 1), and the largest salinity gradient in the monimolimnion. Nevertheless, there were small changes in the temperature and salinity of the monimolimnion over the observation period. If, as discussed, these changes in the deep water of Faro were due to geothermal heating and remineralization, then the deep water is more isolated than if those changes were due to groundwater inflow.

Groundwater inflow into the monimolimnion raises the chemocline; whereas surface mixing processes will lower it, bringing water from the monimolimnion to the mixolimnion. Whether or not transport into the mixolimnion is of environmental concern depends on such factors as the concentration of contaminants in the monimolimnion, the transport from the monimolimnion to the mixolimnion, the volume and flushing of the mixolimnion, and the acceptable contaminant concentration in the mixolimnion. If transport from the monimolimnion to the mixolimnion has negligible effect on the water quality of the mixolimnion then the deep water can be said to be effectively isolated.

## Conclusions

Of the six pit-lakes examined, Faro was the most strongly meromictic, displaying the classic structure of meromixis. Waterline was intermediate, with a reduction in volume of the monimolimnion due to inflow from an adit. Zone 2 was more weakly meromictic, with groundwater inflow acting to dilute the monimolimnion, and with under-ice mixing observed early in the study period, suggesting that the degree of meromixis can change over time both as a pit lake fills, and as local hydrological and meteorological conditions vary. Main Zone was holomictic with sludge inflow inducing fall turnover. The mictic status remains uncertain for Grum and Vangorda: Grum displays a uniform monimolimnion likely the result of gradual wall slumping, and the density structure in Vangorda is regularly disturbed by inflow and outflow as a result of mine site management. Monitoring in most of the pit-lakes is ongoing with the long-term goals of better understanding pit lake processes, and contributing toward improved hydrodynamic modelling.

Usage of the term "meromixis" often brings to mind systems with large salinity differences and vertical transport at rates not much higher than molecular diffusion in the monimolimnion (e.g., Sanderson et al. 1986; von Rohden and Ilmberger 2001). Such isolation of the deep water has not been observed in any of the six pit lakes examined in the present study. In these pit lakes, we observed a wide array of processes that resulted in varying degrees of vertical transport.

**Fig. 10.** The Alaska earthquake of 3 November 2001 (magnitude 7.9) as observed in the Waterline pit-lake. (*a*) Temperature at 35 and 37.5 m; note the temperature increases with depth, see Fig. 5*a*. (*b*), (*c*) Broken and dislodged ice cover after the earthquake. The temperature observations show that the earthquake generated internal seiching and some mixing. Waterline is located 1600 km to the southeast of the earthquake epicenter. Photos courtesy of M. Aziz.

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