# Physical Processes and Meromixis in Pit Lakes

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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. We look at data from six Canadian pit lakes from three different sites in northern Canada to illustrate a variety of pit lake mixing processes.

Meromixis (permanent stratification) occurs when a chemocline is sufficiently strong to inhibit mixing between the surface and deep water. Pit lakes are candidates for meromixis because they are generally deep, have relatively small surface areas sheltered by pit walls, and often contain saline water. However, strong meromixis, with isolated deep water, does not occur as often as might be expected. We discuss a number of factors that affect meromixis, including salinity, salt exclusion from ice, runoff, groundwater, sludge inflow and wall failure.

Key Words: water-filled mine pit, pit lake, stratification, stability, meromixis

## Introduction
On closure, an open pit mine typically fills with water from 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, ARD, neutralization sludge and excess water from tailings ponds (cf. 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 2003). Pit lakes have also been used for in-situ treatment such as ARD neutralization through the addition of lime, or biological remediation in which added fertilizer encouraged phytoplankton to adsorb metals (e.g. Poling et al. 2003) or bacteria to oxidize cyanide (e.g. Chapman, 2007).

To assess the potential use 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 fall of water from pit-wall benches? How best to engineer the stratification as a pit lake fills? Many of these questions are surprisingly difficult as they depend on complicated turbulent mixing processes in a density stratified water body. In this paper we make use of observations from six pit lakes with ice-cover to look at some of these questions.

Natural temperate lakes are typically dimictic (twice mixing), with turnover after ice-off in spring, a cap of warm surface water in summer (temperature stratification), and finally turning over again before ice-on in fall. In contrast, meromixis (permanent stratification) occurs when the deep water is sufficiently more saline than the surface (salinity stratification), 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 Figure 1a. The main feature that defines meromixis is the large increase in salinity, traditionally called the chemocline (Hutchinson

1957, Wetzel 2001), 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 (Castendyk and Eary, 2009). Figure 1b shows the salinity just after ice-off, in which 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 relatively isolated throughout the year.

The term meromictic is used to describe lakes that 'do not undergo complete circulation' (Wetzel 2001) and are 'not completely mixed' (Walker and Likens 1975). However, the absence of complete mixing does not preclude the transfer of water between the monimolimnion and the mixolimnion. This transport may occur, for example, by inflow of groundwater into the monimolimnion, or by eroding the top of the monimolimnion during fall cooling or under-ice mixing. It is useful to consider varying degrees of meromixis: we use the term "weak meromixis" to describe cases where complete mixing is absent, but there is some degree of transport of deep water to the mixolimnion (water above the chemocline), and "strong meromixis" to describe cases where the monimolimnion is more isolated.

The meromictic status can also change over time as local hydrological and meteorological conditions vary. We provide an example of a pit lake which displayed intermittent meromixis, where meromixis occurred in one year and not in another.

We discuss six pit lakes with seasonal ice-cover from three different sites in northern Canada: 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, BC (54.189 N, 126.263 W), (Crusius et al 2003, Leung 2003, and 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. All vertical profiles were collected with a Sea-Bird Electronics SBE 19 or 19plus profiler. Temperature is accurate to 0.005ºC and conductivity to 2 μS/cm. Conductivity is a measure of salinity, S[mg/L]~0.7 C25[μS/cm].

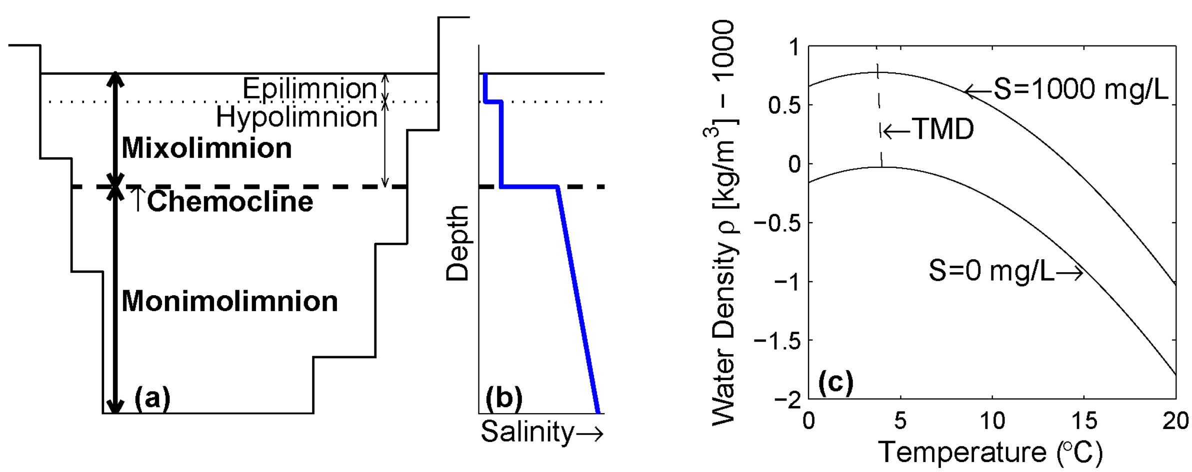


Figure 1. (a,b) Schematic of meromixis for a pit lake with ice cover. The chemocline separate the mixolimnion (surface water that mixes seasonally) from the monimolimnion (isolated deep water). (c) Water density as a function of temperature and salinity (Chen and Millero 1986). The temperature of maximum density (TMD) is near 4 ºC. The increase in density from 0 and 4ºC is equivalent to adding S = 165 mg/L. The increase in density from S=0 to 1000 mg/L is equivalent to increasing the temperature from 4 to 15ºC.

Table 1. Pit lake characteristics

| PIT | Faro | Grum | Vangorda | Waterline | Main Zone | Z2P |
|---|---|---|---|---|---|---|
| Water level (m ASL) | 1066 | 1185 | 1089 | 1265 | 1260 | 336 |
| Max. depth (m) | ~90 | ~50 | ~50 | 40 | 120 | 110 |
| Surface area (m2) | 510,000 | 95,000 | 59,000 | 26,000 | 205,000 | 173,000 |
| Volume (Mm3) | ~30 | ~2 | ~1 | 0.48 | 9.7 | 8.4 |
| Relative depth (%) | 11 | 14 | 18 | 22 | 23 | 23 |
| Est. inflow (m3/y) | $5.9 \times 10^4$ | - | $2.4 \times 10^6$ | $2 \times 10^5$ | $5 \times 10^5$ | $<2 \times 10^5$ |
| Bulk retention time (y) | 50 | - | 0.4 | 2.4 | 20 | >40 |
| White ice thickness (m) | ~0.1 | ~0.1 | ~0.1 | - | - | 0.04-0.16 |
| Black ice thickness (m) | 0.4-0.6 | 0.4-0.5 | 0.4-0.6 | total ~0.9 | total ~0.6 | 0.6-0.8 |
| $f_b$[(a)] | 0.93 | 0.97 | 0.98 | - | - | 0.87-0.99 |
| $\delta$[(b)] | 11 | 1 | 1.4 | 3 | na | 0.9 (04/05)<br>1.4 (05/06) |
| $St_s^*$ ($J/m^2$)[(c)] | 700 | - | - | 200 | - | 150 (2004)<br>200 (2011) |
| Mictic status | moderately to strongly meromictic | uncertain | uncertain | moderately meromictic | holomictic | weakly meromictic |

[a] Fraction of salt excluded from black ice.
[b] Ratio of the ice-thickness that induces mixing to the measured ice thickness. For $\delta<1$ excluded ice may induce under-ice mixing with the deep water.
[c] Salinity stability at maximum heat content.

We first discuss the seasonal circulation of Faro pit lake, which is meromictic. We then examine profiles from the other five pit lakes, examining the effect of groundwater, sludge disposal, wall failure and inflows on mixing. To conclude, we discuss the factors that both favour meromixis (enhance stability) and oppose meromixis (induce mixing).

## Seasonal Evolution Of Meromixis With Ice-Cover

The seasonal cycle of stratification for Faro pit lake is shown in Figure 2 for June 2008 to April 2009. During spring (11 Jun 2008, Figure 2a,b), ice-melt and freshet runoff lowered the conductivity of the epilimnion (0 to 5 m, Figure 2b). The resulting difference in conductivity 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 11ºC (Figure 2a) and by 06 August, 2008 the temperature reached 13ºC (not shown).

In early fall (Figure 2c,d) the epilimnion had cooled to 10ºC and was deepened by wind mixing and penetrative convection to about 10 m. The epilimnion continued to cool and deepen until it reached the temperature of maximum density (near 4ºC, Figure 1c). At this point the epilimnion would have been isothermal and included all the mixolimnion. It is at this time that the pit lake would have been most vulnerable to mixing; there would have been no temperature stratification and the stability would have been maintained by the chemocline alone.

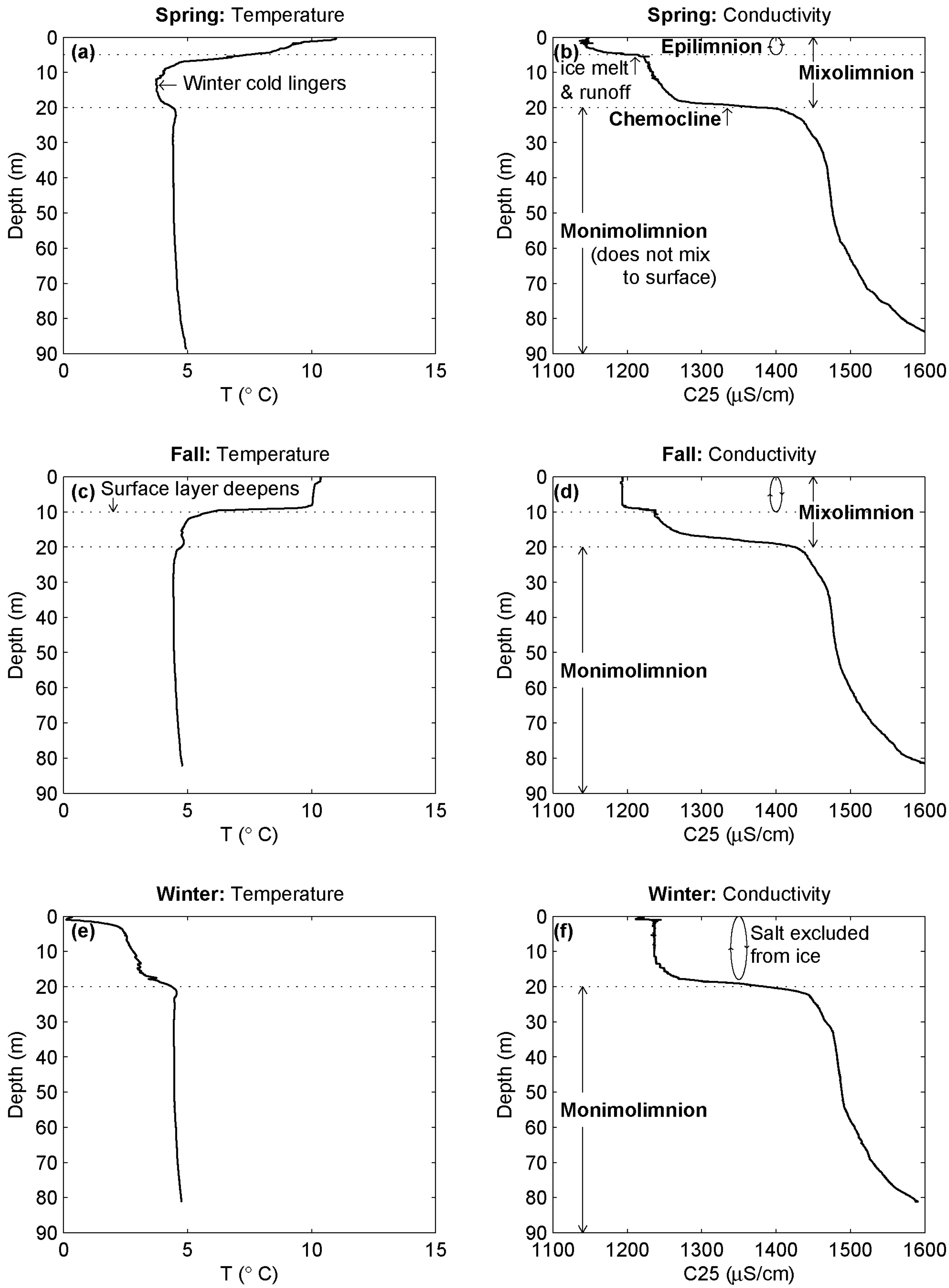


Figure 2. Temperature and conductivity for Faro pit lake, Yukon. (a,b) Spring, after ice-off, 11 June 2008; (c,d) Fall, 03 September 2008; and (e,f) Under-ice, 29 April 2009.

As the epilimnion cooled below 4ºC, it became 'reverse' stratified: cold (< 4ºC), less-dense water formed a surface layer floating on the deeper, denser water nearer 4ºC. 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 (Figure 1c).

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; Figure 2e,f). This is another time that the pit lake is vulnerable to mixing.

When ice begins to form, the temperature of the epilimnion is reverse stratified with buoyant water at ~0ºC just under the ice (Figure 2e). Because of the reverse temperature stratification, the salt excluded from the ice will initially remain just under the ice. However, only a limited amount of salt can be sustained by the reverse stratification, and eventually salt will be transported downward through the mixolimnion, either by double diffusion or episodic convection. In Faro, the salt excluded from the ice is not sufficient to raise the conductivity 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., 3.7ºC, 12-15m; Figure 2a). 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 was observed in Faro since data collection began in 2004 (Figure 3a). It was also observed in Waterline (Figure 4a), and, though harder to see, it also occurred occasionally in Zone 2 Pit (Figure 5a).

The first profiles of each open-water season in Faro pit lake for 2004-2011 are shown in Figure 3. While there is little discernable change in temperature and conductivity in the monimolimnion during any given year, there is a small, gradual increase in both temperature (~0.02ºC/yr) and conductivity (~14 µS/cm/yr) from 2004-2011. The causes of these increases are not known, but possibilities include groundwater inflow, geothermal heating, and remineralization (decomposition of organic matter to inorganic forms).

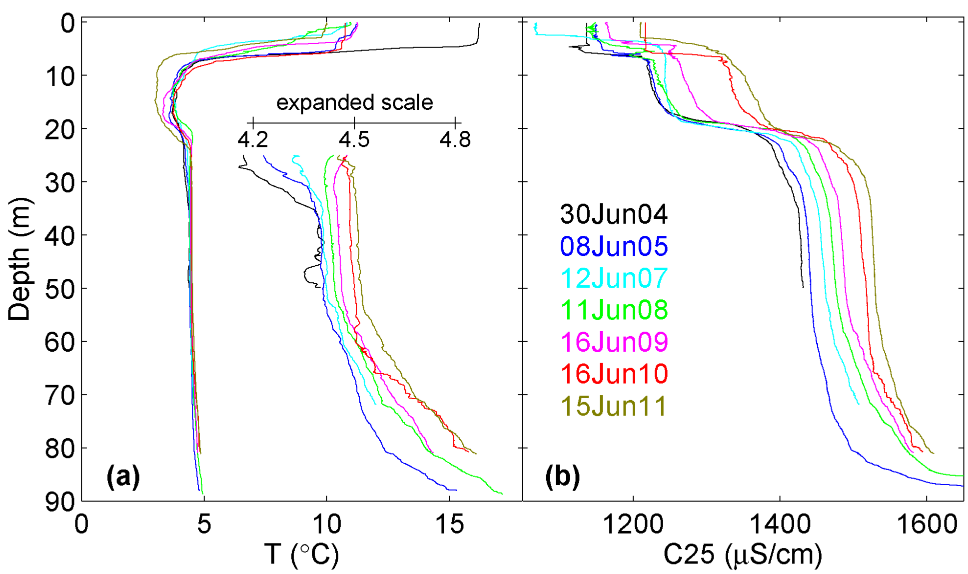


Figure 3. (a) Temperature and (b) conductivity profiles, Faro pit lake, spring and early summer, 2004-2011. The chemocline is located at 20 m. A warm, fresh epilimnion can be seen in the top 5 m.

## Examples Of Pit Lake Behaviour

The following section describes profiles from the other five other pit lakes of varying stability, Table 1.

### Groundwater

We consider two pits where groundwater inflow into the monimolimnion plays an important role. The first is the Equity Waterline where there is a chemocline at 19 m (Figure 4). The spring profiles show a warm fresh surface layer (0-4 m) and a temperature minimum below the surface layer, from 8-15 m. Isolation of the monimolimnion is suggested by relatively constant temperature and conductivity and by the absence of dissolved oxygen (not shown). Note that the stratification in Waterline is influenced by groundwater inflow at 17 m and possibly 32 m depth from adits connected to collapsed underground mine workings.

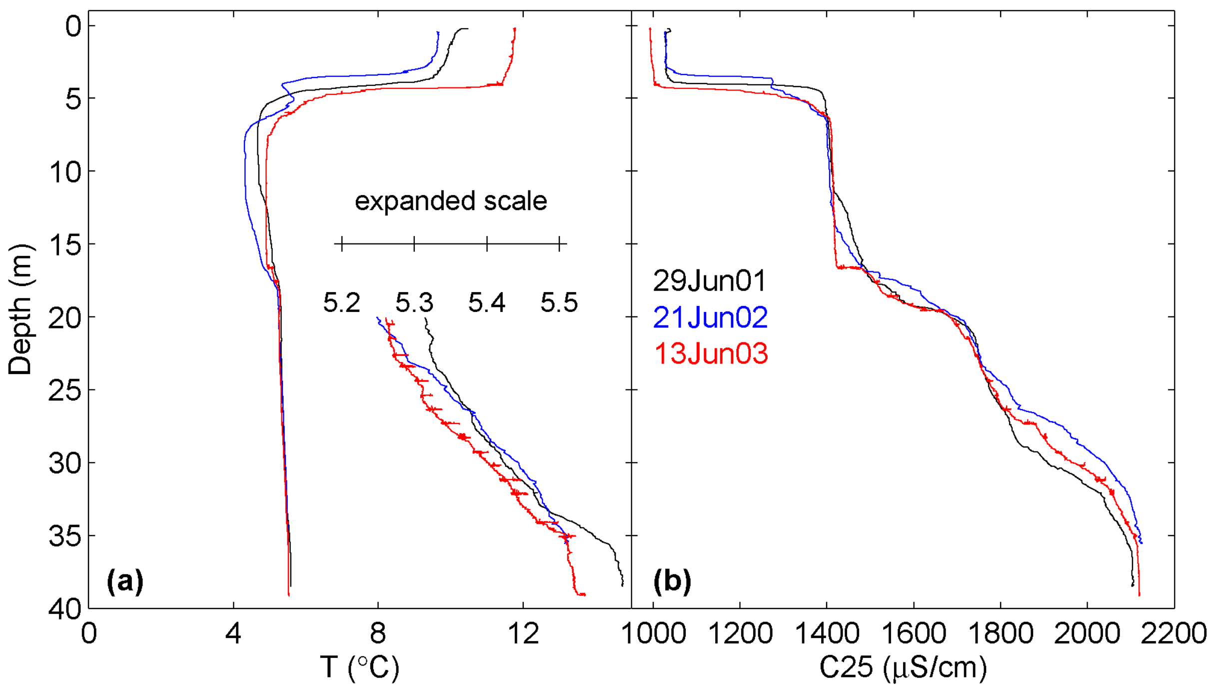


Figure 4 (a) Temperature and (b) conductivity, Waterline pit lake, 2001-2003

From 2004 to 2011, the Colomac Zone 2 Pit has been filling with precipitation, runoff and groundwater inflow. In each of these years, ice melt and freshet inflow provided a fresh water cap that was sufficient to suppress both spring and fall turnover. However, as the pit has filled, the conductivity of the entire pit lake declined from 2004 to 2008 (Figure 5), and groundwater inflow at depth prevented Zone 2 Pit from developing strong meromixis during that time. For example, the 2004 and 2005 profiles suggest inflow of groundwater around 70 m depth, accounting for the small step below this depth and relatively uniform temperature profiles from 70m up to 40 m depth (Figure 5). Around 70 m is also the depth where inflow of groundwater to the pit was first encountered during mining. As the pit has approached its ultimate water level, the inflow of groundwater has declined and the conductivity of the pit has changed less rapidly from 2008 to 2011. Though difficult to see, a small chemocline may be developing near 20 m.

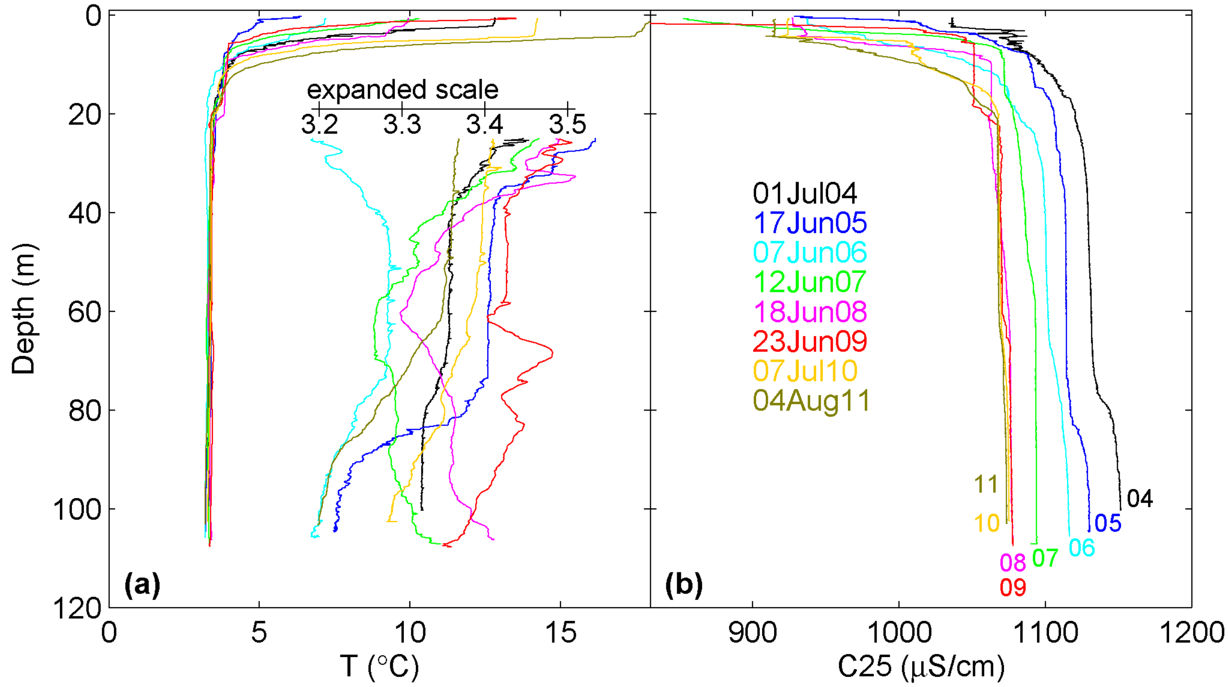


Figure 5 (a) Temperature and (b) conductivity, Colomac Zone 2 pit lake, 2004-2011

**Sludge inflow**

The Equity Main Zone pit lake provides a startling 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 conductivity (Figure 6a,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.

A signature of the sludge entering Main Zone can be seen in the light transmission (Figure 6c), with highly reduced transmission 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 as a result of being carried to depth by the sludge (Figure 6e).

**Wall failure**

Profiles from Grum pit appear to be similar to those from Main Zone and suggest that a similar process may be at work (Figure 7). While the volume of water flowing into Grum was low, the likely source of disturbance in Grum pit is the gradual failure of the east wall which is composed of till and which shows signs of active creep. Ongoing slumping, either above or below the water surface, likely explains the significant mixing observed.

Like Main Zone, the spring profiles in Grum show a fresh, warm surface layer but no chemocline (Figure 7b). Also like Main Zone the temperature and conductivity profiles are relatively uniform with noise suggestive of active mixing. In addition, the temperature and conductivity of the deep water increased significantly over the summer suggesting that the deep water was not isolated.

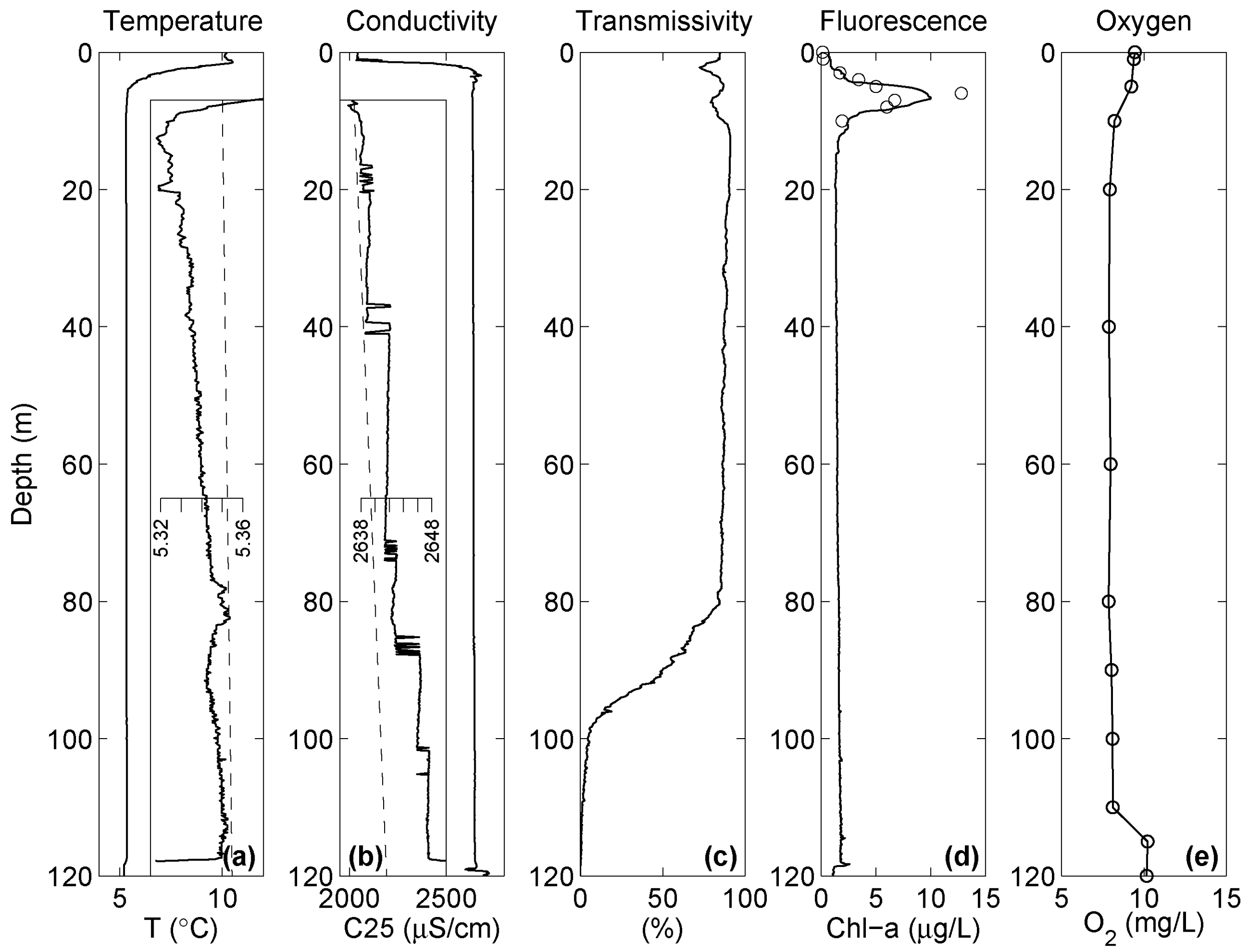


Figure 6. Characteristics of the Main Zone pit lake, June 25, 2001. Conductivity and temperature in the monimolimnion are replotted on expanded scales. Chl-a, and oxygen data are described in Whittle (2004).

**Inflows**

Vangorda is used for storage of ARD from around the mine site and has a small bulk retention time of 5 months. While Vangorda has a chemocline at 13 to 18 m, the location of the chemocline, along with the temperature and conductivity of the monimolimnion, varied significantly over the year (data not shown). The processes that lead to these changes in Vangorda are not known, but we suspect they result from the large inflows and outflows, as Vangorda is used to store water from around the mine site.

**Earthquakes**

The Alaska earthquake of 03 November 2001 was observed in the Waterline pit-lake in central BC, 1600 km to the southeast of the earthquake epicenter. The earthquake resulted in internal waves (Figure 8a), and broke the ice cover (Figure 8b), but did not change the overall stratification significantly.

## Indicators of Meromixis

Here we briefly look at three indicators of meromixis. The first and primary indicator is the chemocline. The additional salinity in the deep part of the 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,

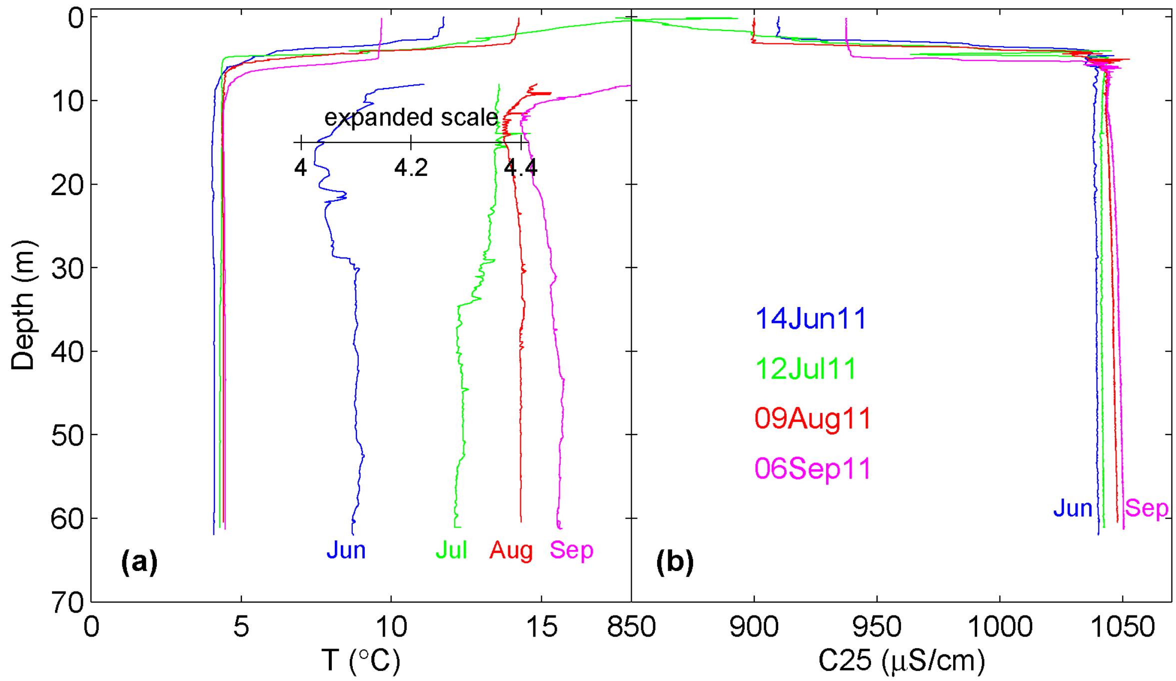

Figure 7 (a) Temperature and (b) conductivity in Grum pit lake, 2011

$$St_{TOT} = \frac{g}{A(0)} \int_0^h (\rho(z) - \bar{\rho})\, z\, A(z)\, dz \quad [\mathrm{J\ m^{-2}}] \tag{1}$$

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 constant temperature 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, equation (1) can be evaluated at constant temperature to give the salinity stability, $St_S$. The salinity stability gives the work needed to mix the entire pit lake at constant temperature, namely the work done against the salinity stratification (for further detail see Pieters and Lawrence, 2009a).

For the first indicator of meromixis, we look at the stability in the fall. We start with the salinity stability of the pit lake at the time of maximum heat content (generally in August), $St_S^*$. This is larger for Faro, and smaller for Waterline and Zone 2 Pit (Table 1). The salinity stability in Zone 2 Pit increased slightly from 2004 to 2011 as the pit has approached full pool. The value of $St_S^*$ can be compared to the decrease in salinity stability as the epilimnion is mixed deeper through the fall, $\Delta St_S$, which has been observed to be on order of 20 J/m$^2$ (Pieters and Lawrence, 2009a). For Faro, $St_S^* >> \Delta St_S$ which suggests strong meromixis, while for Waterline and Zone 2 Pit meromixis is weaker.

The second indicator of meromixis is the size of the conductivity step at the chemocline compared to the amount of salt excluded from the ice. We ask what thickness of black ice would be needed to make the mixolimnion as saline as the top of the monimolimnion. This is the point at which mixing into the monimolimnion could begin. We define δ to be the ratio of the ice thickness needed to initiate mixing divided by the observed ice thickness. Values of δ are given in Table 1.

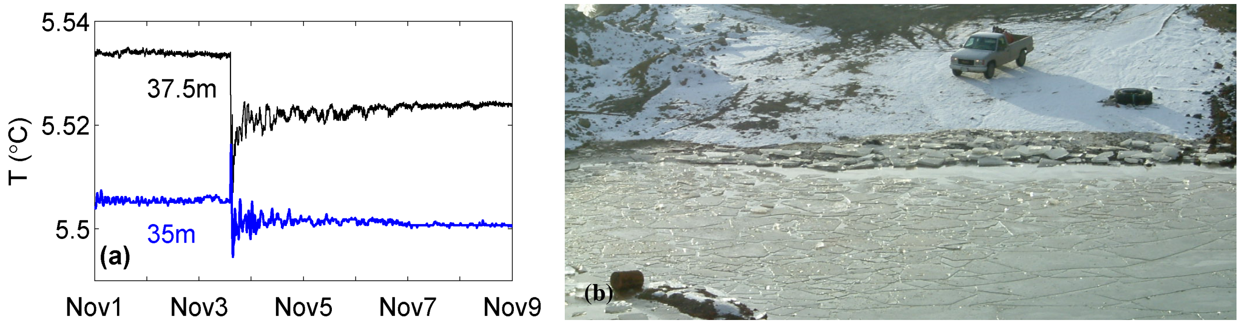

Figure 8. (a) Temperature fluctuations in Waterline pit lake as a result of the Alaska earthquake of 3 November 2001 (magnitude 7.9). (b) Pit lake surface after the earthquake (photo courtesy of M. Aziz).

For Faro δ>>1 and it would take many times the observed ice thickness to initiate mixing into the monimolimnion during winter. In contrast, while for Zone 2 Pit in 2004-2005 there was sufficient salinity stability to oppose fall turnover (the epilimnion depth at ice-on was 20 m), during the winter, δ was 0.9 and under-ice mixing occurred between the mixolimnion and the monimolimnion. However, for the subsequent winter of 2005-2006, which was milder, with less ice and poorer salt exclusion, δ was 1.4, and no mixing with the monimolimnion occurred. This is an example of intermittent meromixis regulated by inter-annual variations in ice thickness.

A third indicator of meromixis is the salinity gradient throughout the monimolimnion (Figure 1b). In Faro and Waterline the conductivity 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 seen in natural lakes that are meromictic (Gibson 1999), though the origin of these large gradients is unclear.

## 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,

$$h_r = \frac{h_{\max}}{2\sqrt{A/\pi}} \cdot 100$$

where $A$ is the surface area and expressed as a percentage 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 11-23% (Table 1).

While relative depth is important, it does not predict meromixis. Rather, the key factor predicting meromixis is the strength of the chemocline. If the salinity difference is large enough, even a lake with a small relative depth is meromictic. Conversely, a high relative depth, such as those of pit lakes, would require a comparatively weak chemocline for meromixis to occur.

### Pit lake Salinity and Ice Cover

For most of the pit lakes discussed here, the primary source of the chemocline 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 2009b). 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. 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. However, the salinity of the runoff is important. Most natural runoff is low in salinity; however, 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, if the salinity of the inflow is higher than that of the epilimnion, the inflow will increase the salinity of the epilimnion, reducing the stability, and increasing the potential for under-ice mixing the following winter.

## 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, current 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 special 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 to that of the monimolimnion ($\delta \leq 1$).

### Other Factors

In addition to wind, cooling, and ice-cover, there are often additional natural and anthropogenic processes which can also 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 and a few others:

- Active creep and subsidence of a till wall (Grum).
- Earthquakes (observed in Waterline).
- Rock falls (observed in Zone 2 Pit).
- 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 pit-lake: Stevens and Lawrence 1998).
- Restoration of diverted creek flow (planned 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).

Of the six examples discussed only Faro pit lake displays a potential for strong meromixis. The origin of the large fresh water cap on Faro is not known; perhaps it was 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.

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