Physical processes and meromixis in pit lakes with ice cover, Part 1

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University of British Columbia

22nd Annual BC MEND ML/ARD Workshop   Dec 3, 2015

Zone 2 Pit
Faro
Grum
Vangorda
Main Zone
Waterline
RUSSIA
ARCTIC OCEAN
Norwegian Sea
Chukchi Sea
Arctic Circle
GREENLAND
ICELAND
Reykjavik
Beaufort Sea
Baffin Bay
Yukon
Anchorage
Godthab
Gulf of
Whitehorse
Great Bear Lake
Iqaluit
Juneau
Yellowknife
Great Slave Lake
CANADA
Prince Rupert
Hudson Bay
St. John's
Edmonton
OCEAN
Lake Winnipeg
Victoria
Vancouver
Calgary
Regina
Charlottetown
Seattle
Spokane
Winnipeg
Quebec
Fredericton
Portland
Helena
Lake Superior
Ottawa
Montreal
Halifax
Augusta
Bismarck
Missouri
Concord
Boise
ATLANTIC
Lake Huron
Lake Ontario
Boston
St. Paul
Lake Michigan
Minneapolis
Toronto
Hartford
Milwaukee
Providence
OCEAN
Buffalo
Salt Lake City
Chicago
Detroit
Lake Erie
New York
Cheyenne
Cleveland
Philadelphia
Omaha
Pittsburgh
San Francisco
Baltimore
Denver
Indianapolis
U. S. A.
Washington D. C.


Laberge Environmental Services


M. Aziz


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- Laberge Environmental, SRK and others

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- CRD, AAND Canada; SRK and others

  Ron Breadmore, Bill Coedy, and many others
- NSERC

Outline

1. Illustrate Meromixis

   Faro seasonal cycle

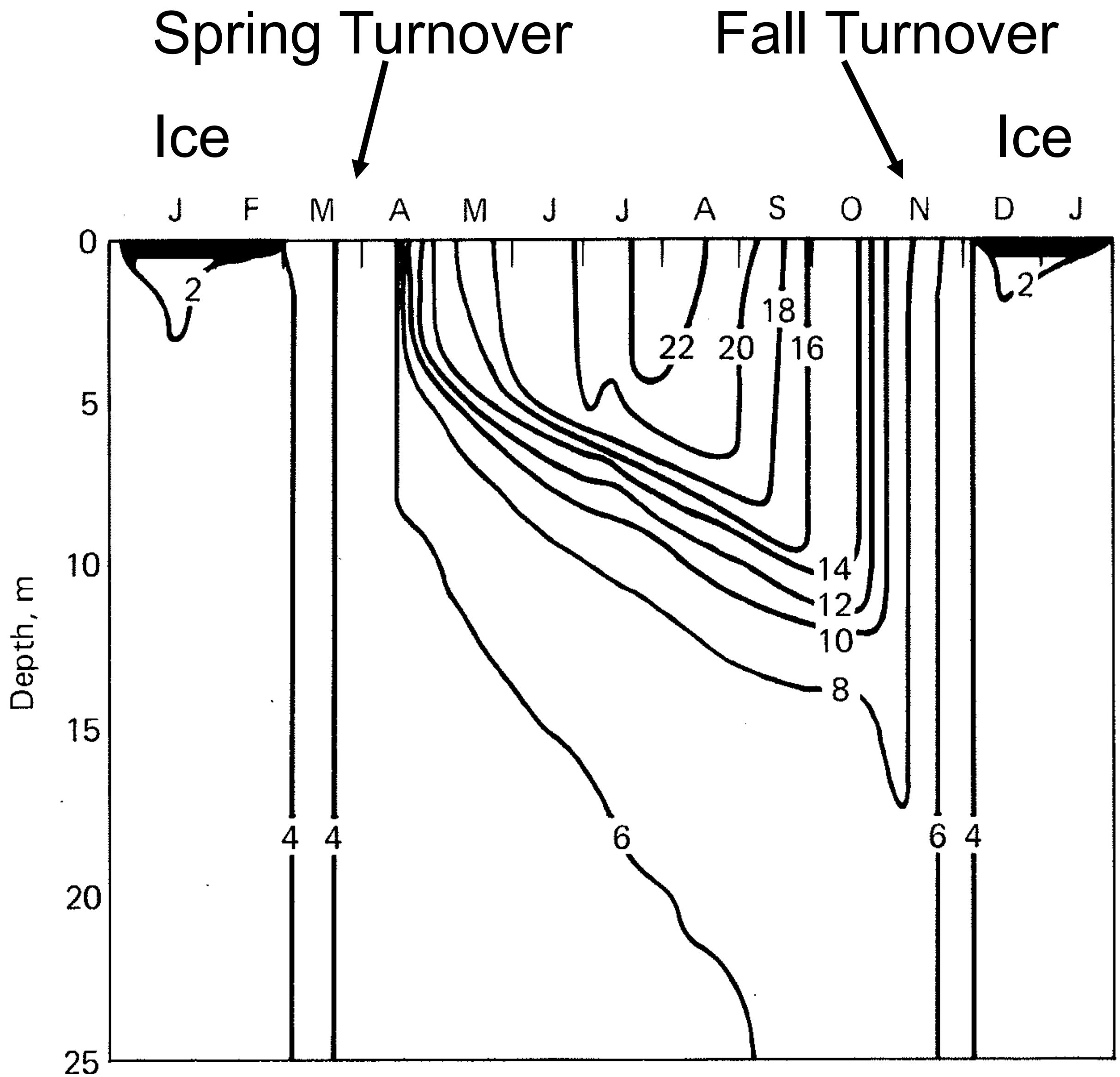
2. Factors that enhance meromixis

   Simplified equation

3. Factors that work against meromixis

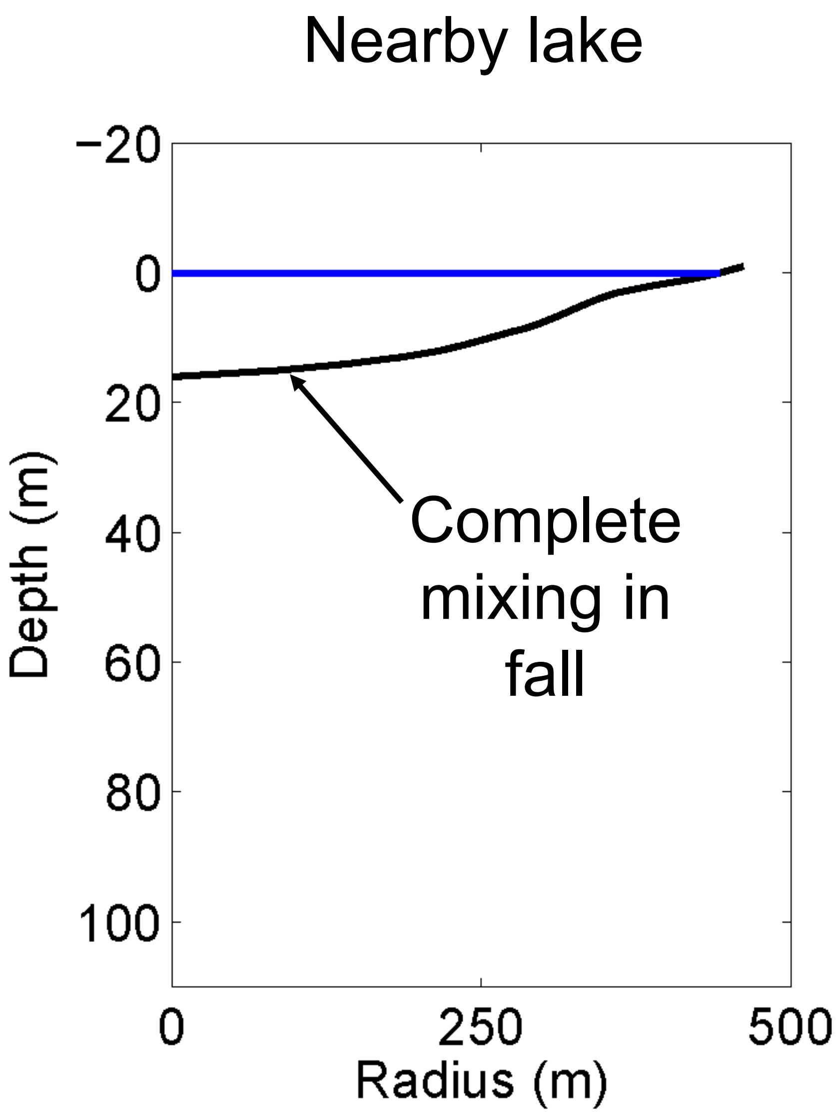
   Illustrate six processes

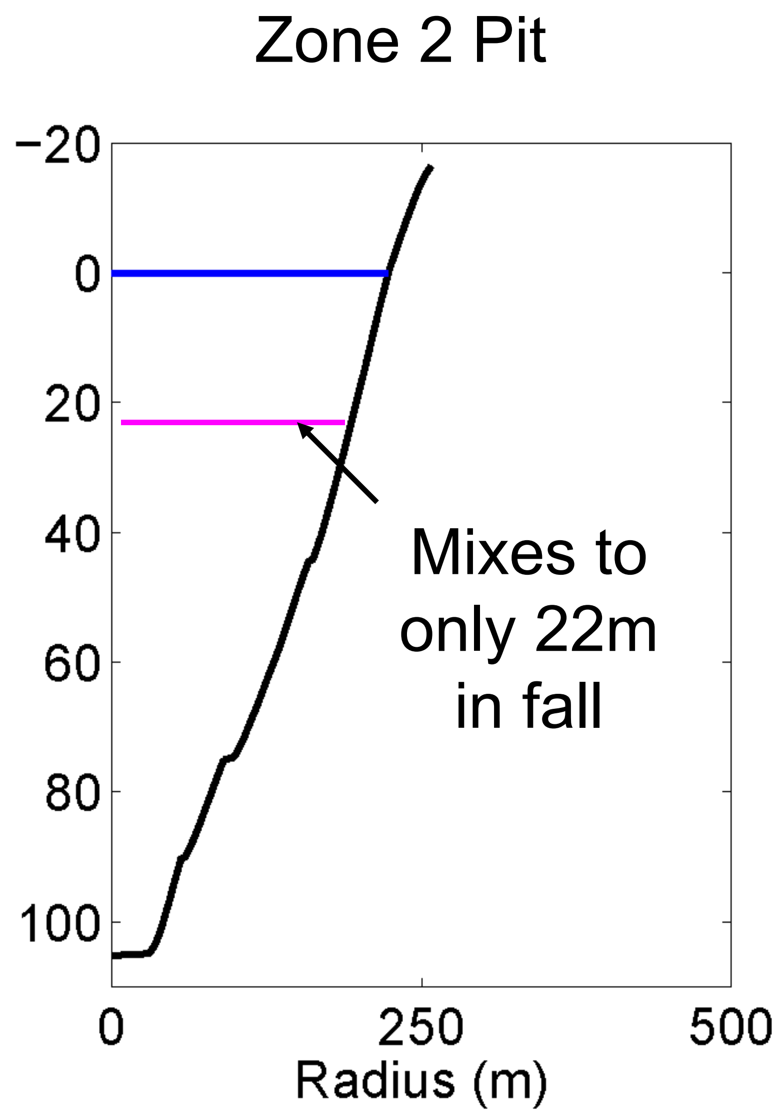
Dimictic Lake



Mountain Lake, Virginia (Horne)

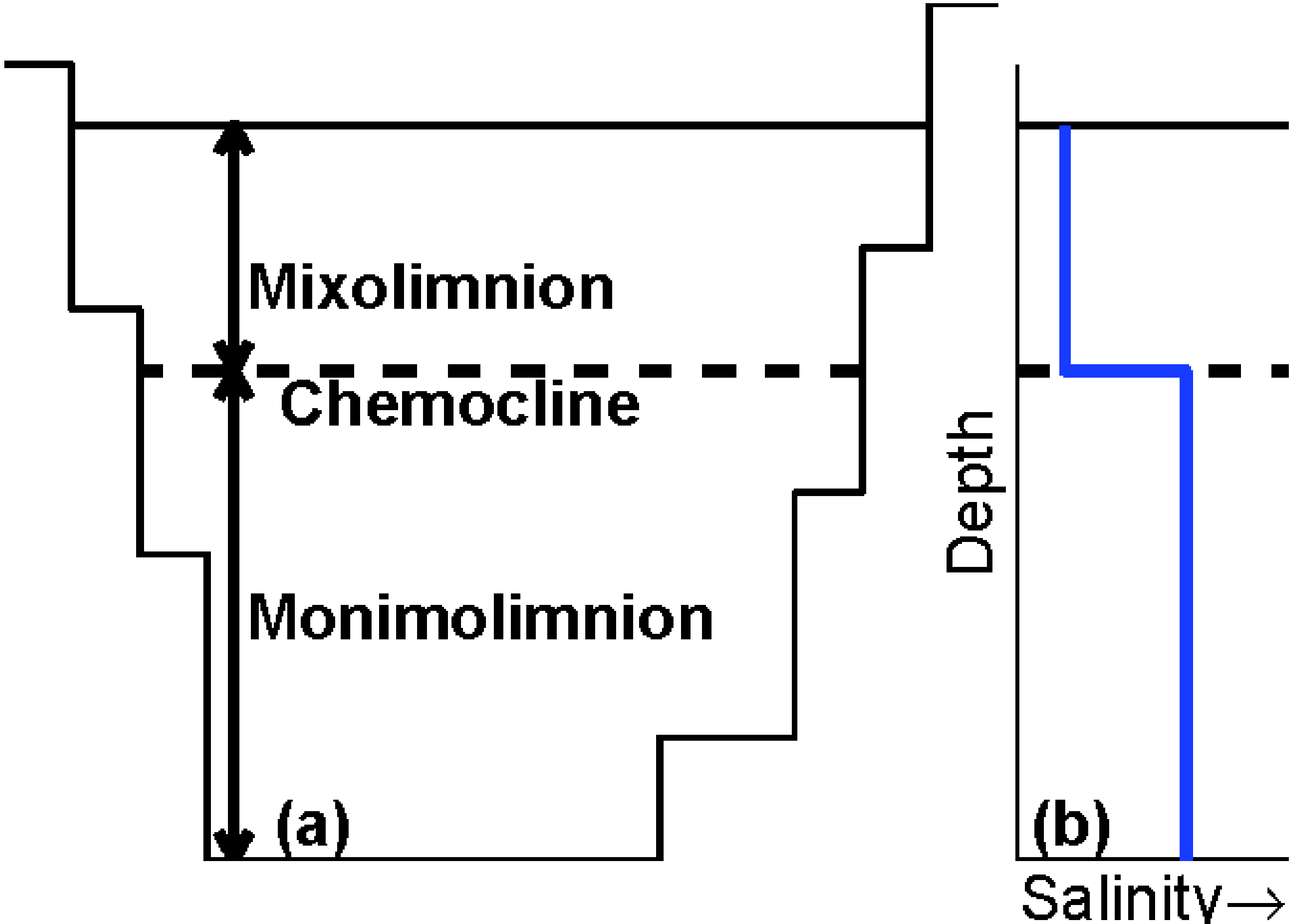
Lake vs. Pit-Lake





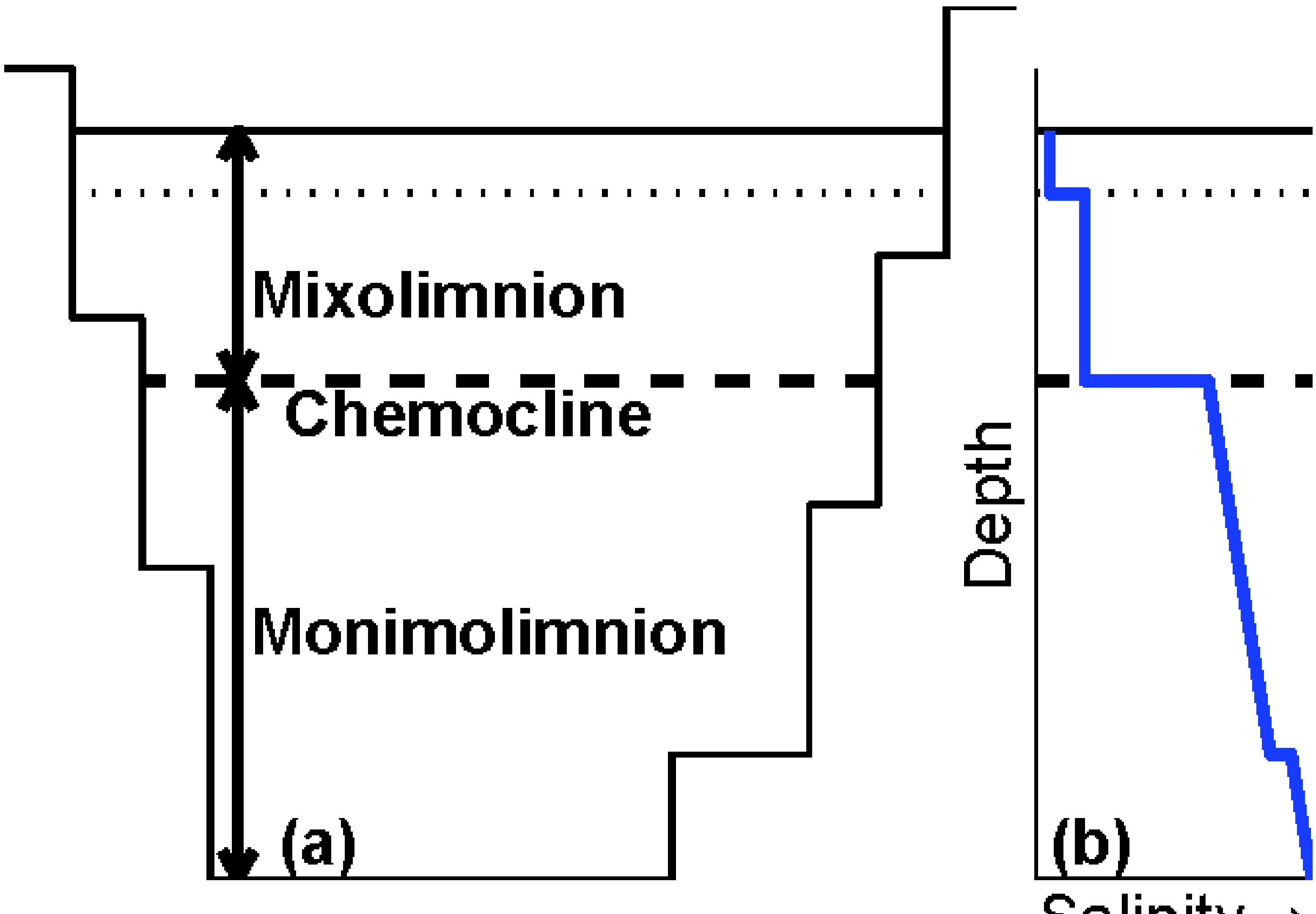
MEROMIXIS

Turnover inhibited by salinity stratification

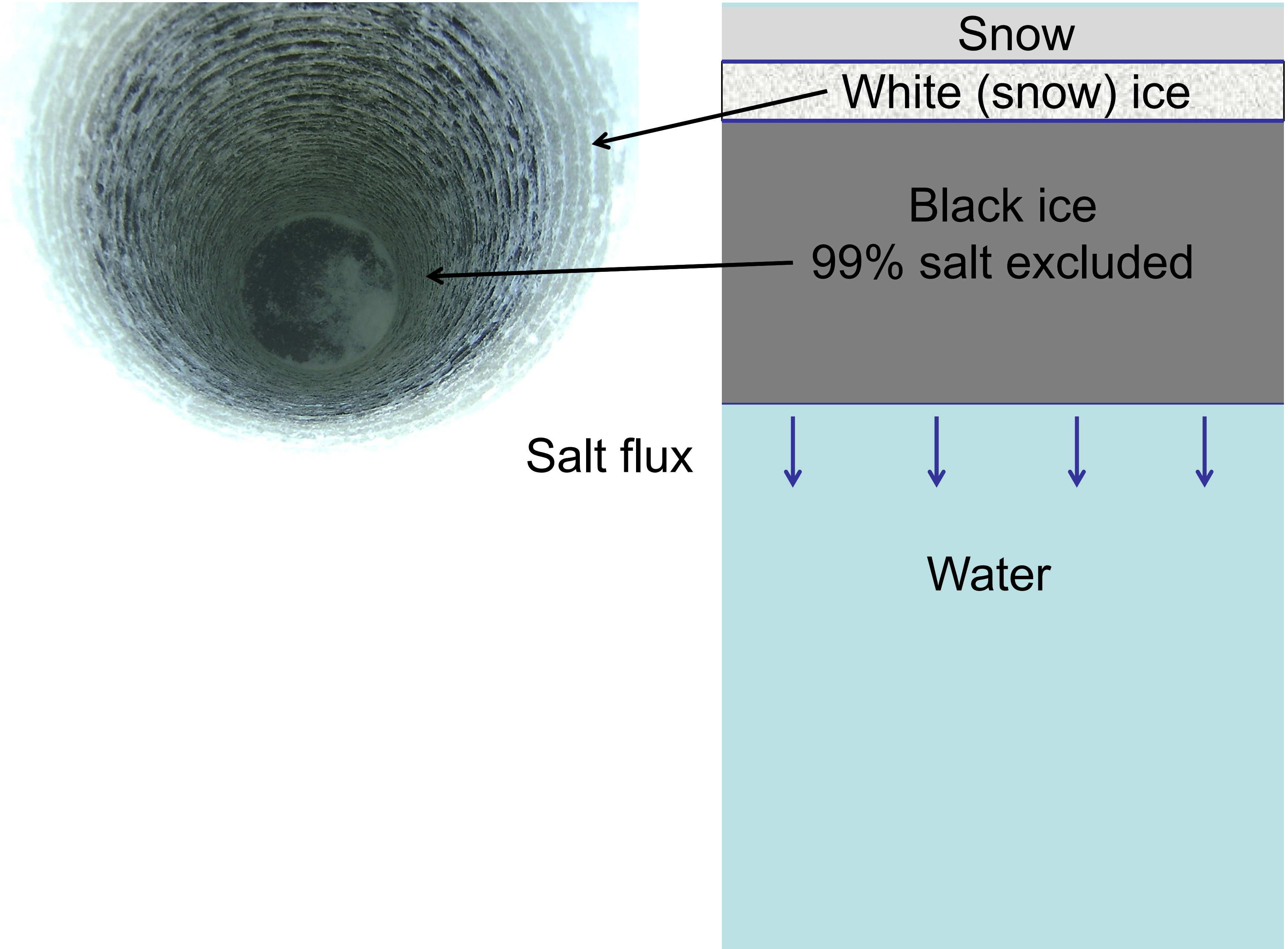


MEROMIXIS

Turnover inhibited by salinity stratification



Salt exclusion from ice



Seasonal cycle of meromixis: Faro pit-lake

Faro

SPRING

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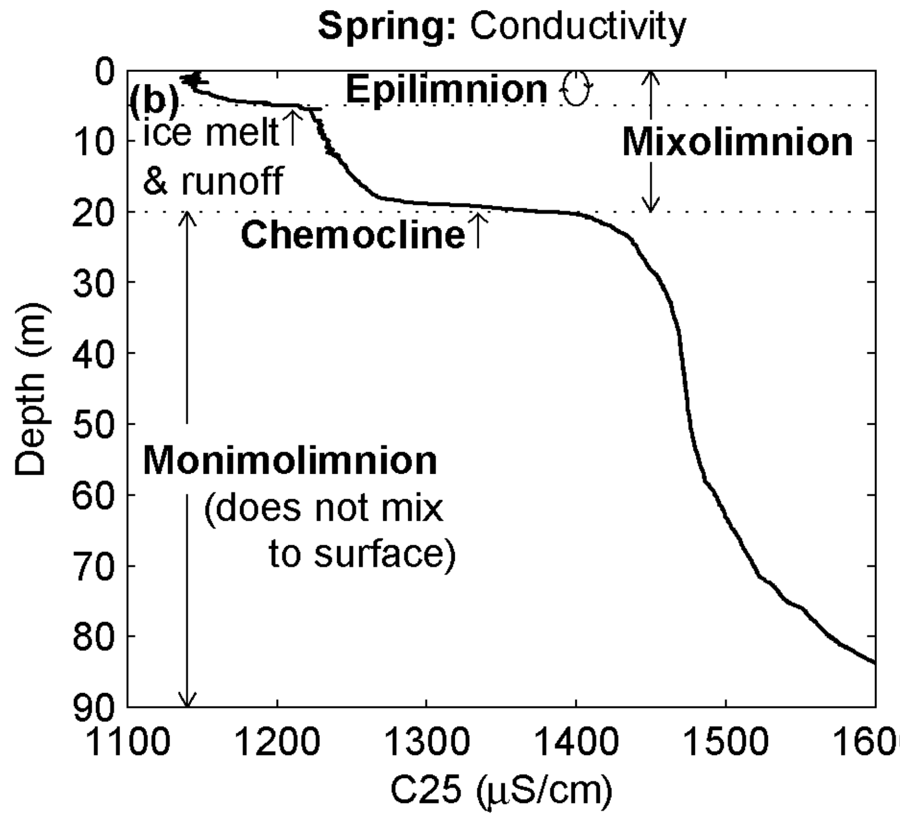
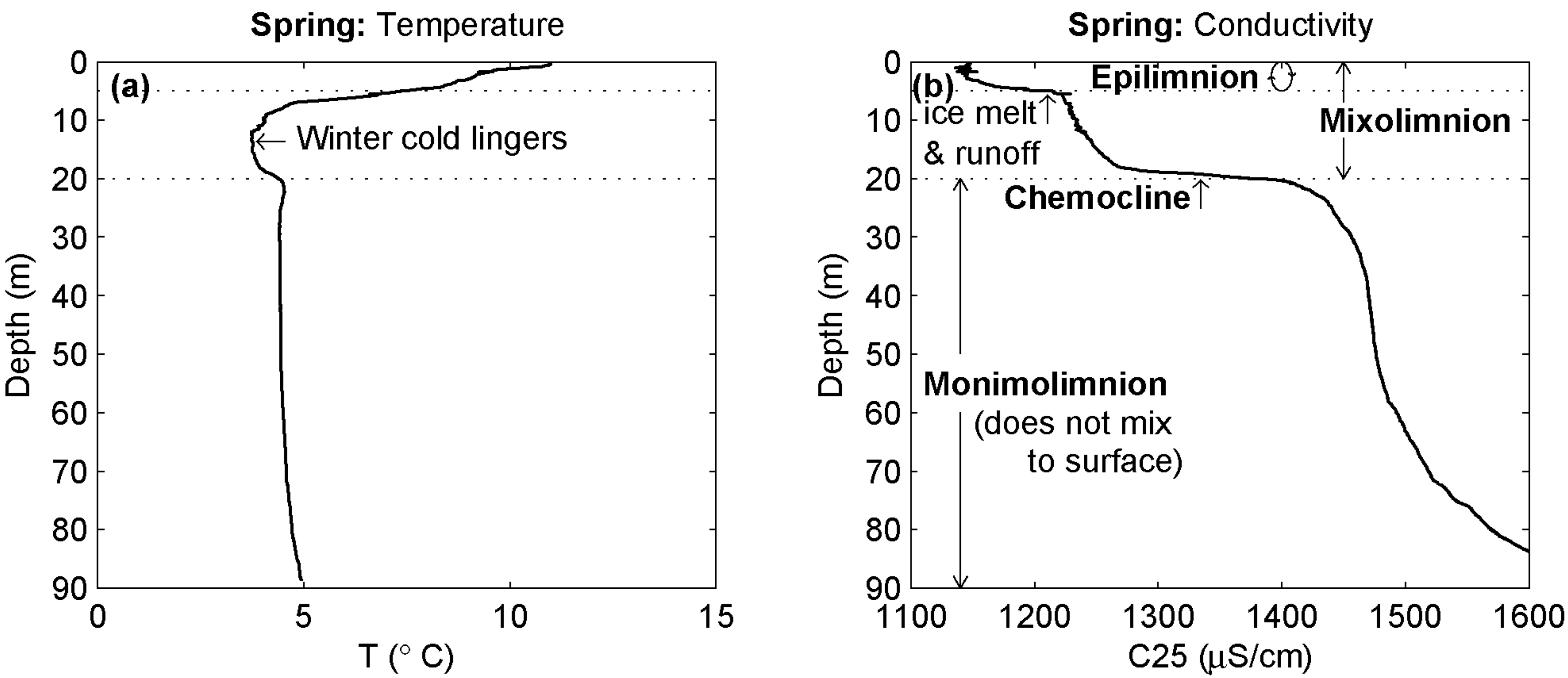


1 S (g/L) 1.3

1000 TDS (mg/L) 1300

Faro

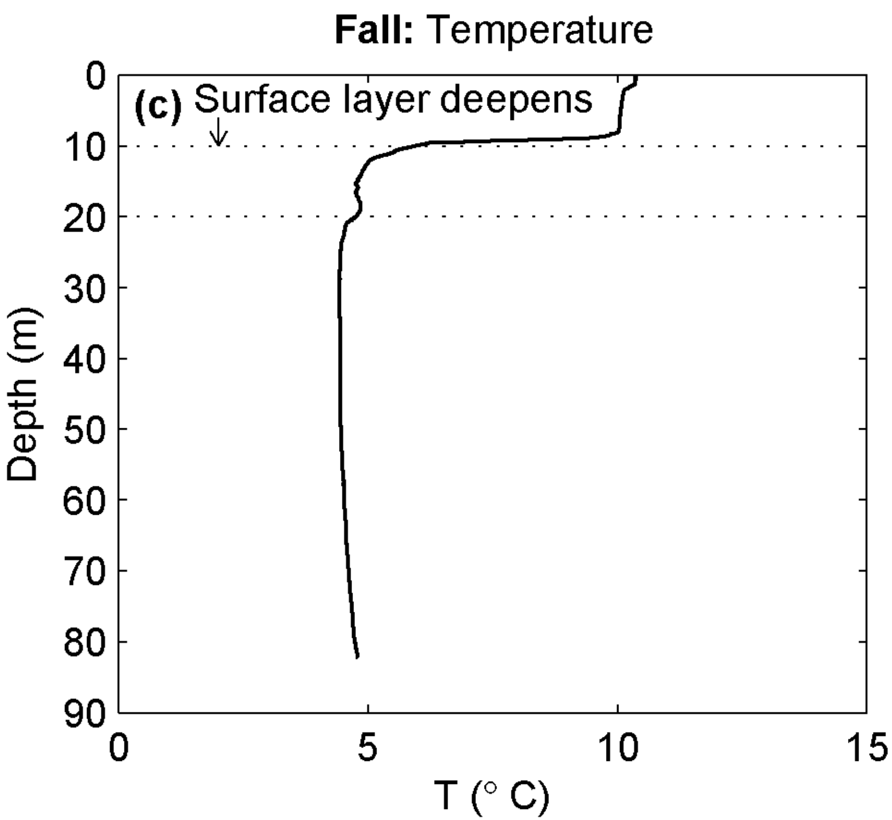
SPRING



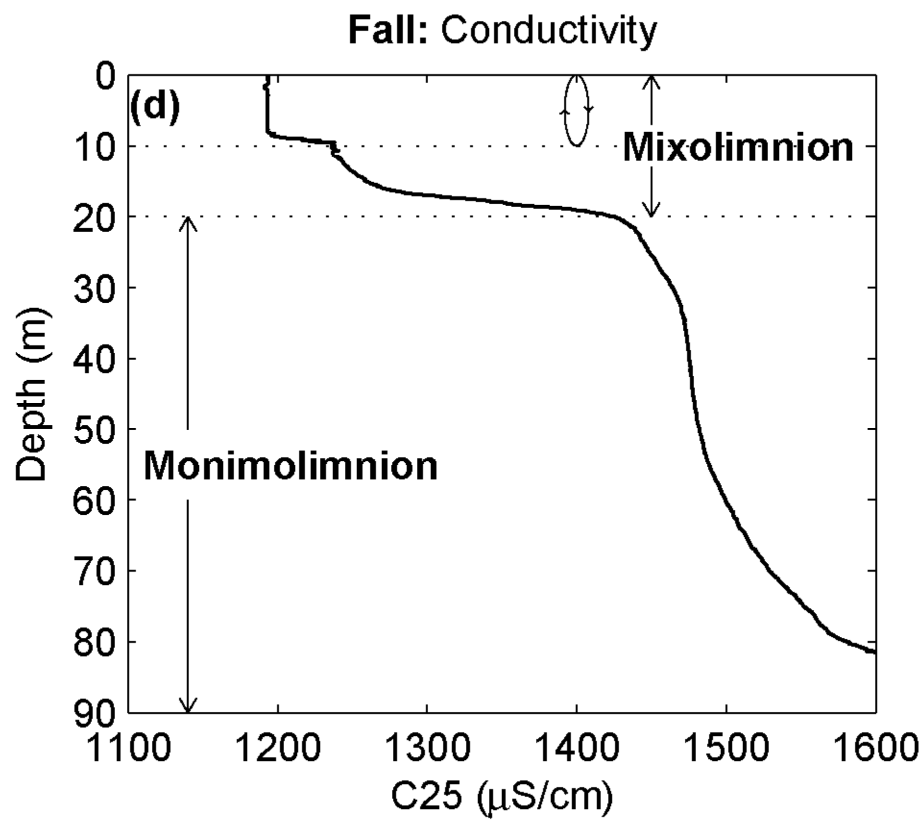
Spring: Temperature
(a)
Winter cold lingers
Depth (m)
T (° C)
0
10
20
30
40
50
60
70
80
90
0
5
10
15
Spring: Conductivity
(b)
Epilimnion
ice melt
& runoff
Mixolimnion
Chemocline
Monimolimnion
(does not mix
to surface)
Depth (m)
C25 (µS/cm)
1100
1200
1300
1400
1500
1600

Faro

FALL



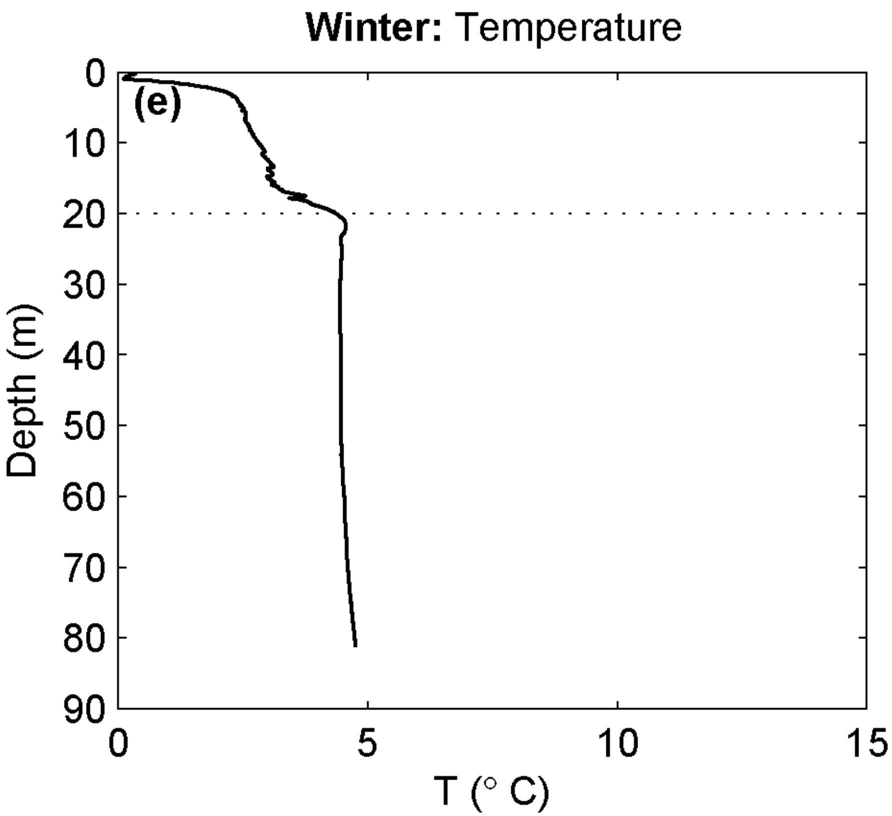
Fall: Temperature
(c) Surface layer deepens
Depth (m)
T (° C)
0
10
20
30
40
50
60
70
80
90
0
5
10
15



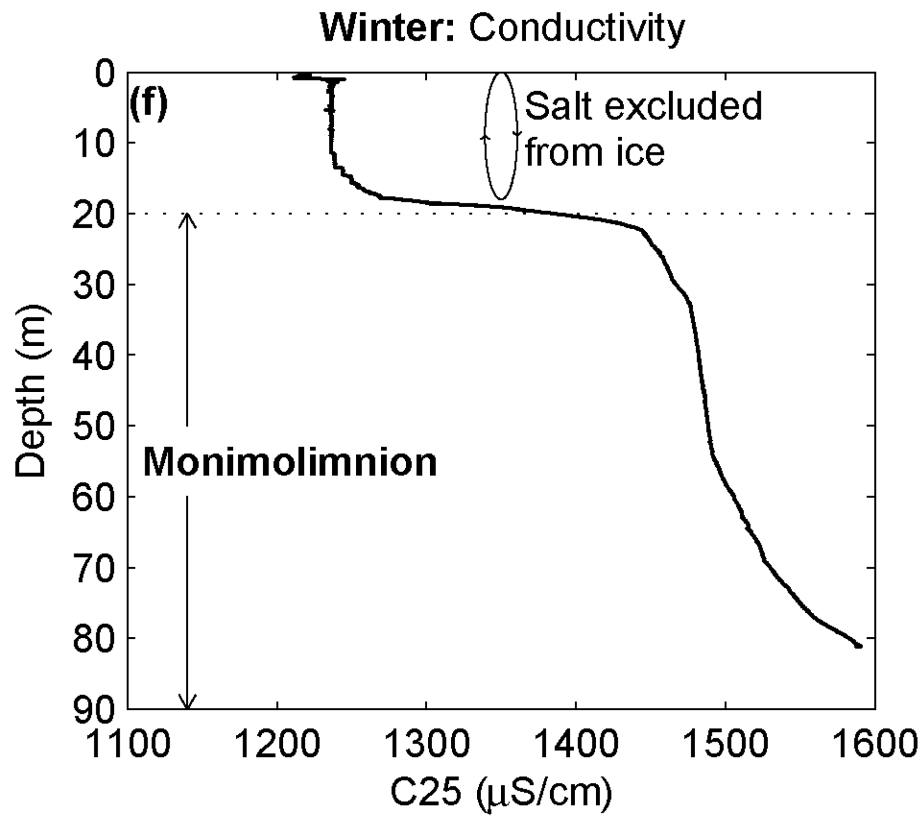
Fall: Conductivity
(d)
Mixolimnion
Monimolimnion
Depth (m)
C25 (µS/cm)
0
10
20
30
40
50
60
70
80
90
1100
1200
1300
1400
1500
1600

Faro

WINTER

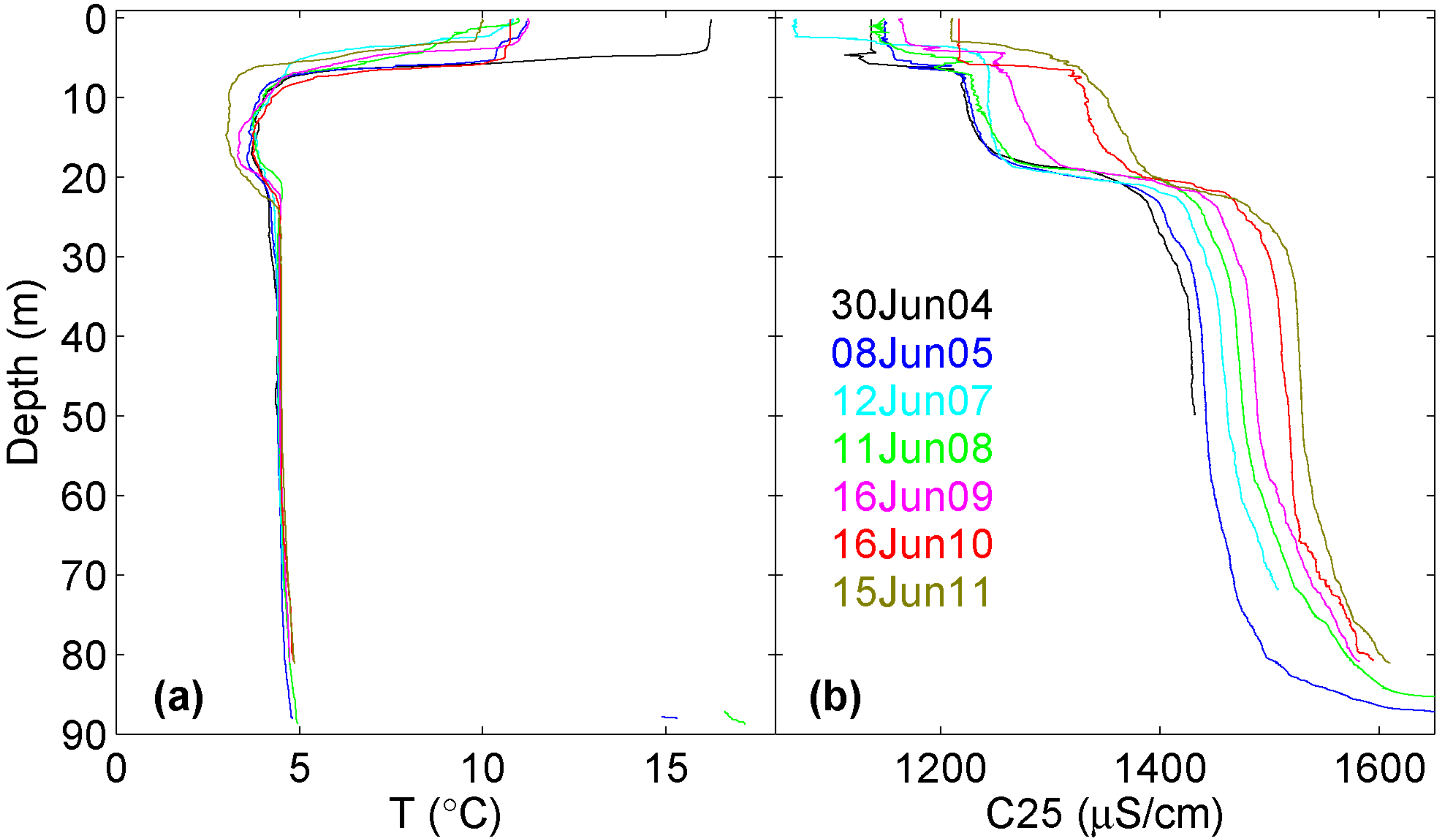


Winter: Temperature
(e)
Depth (m)
T (° C)
0
10
20
30
40
50
60
70
80
90
0
5
10
15



Winter: Conductivity
(f)
Salt excluded from ice
Monimolimnion
Depth (m)
C25 (µS/cm)
0
10
20
30
40
50
60
70
80
90
1100
1200
1300
1400
1500
1600

Faro 2004-2011



1.1g/L

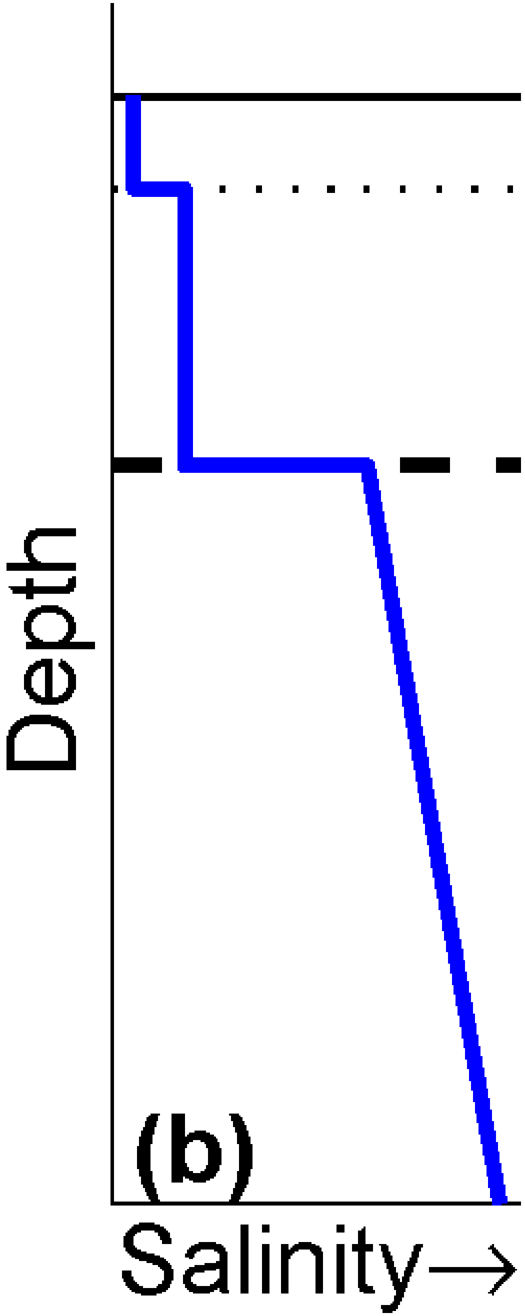
1.4g/L

2. FACTORS THAT ENHANCE MEROMIXIS

- Depth
- Small surface area
- Initial saline water
- Salt exclusion from ice
- Fresh surface inflow

} chemocline (Initial saline water, Salt exclusion from ice, Fresh surface inflow)

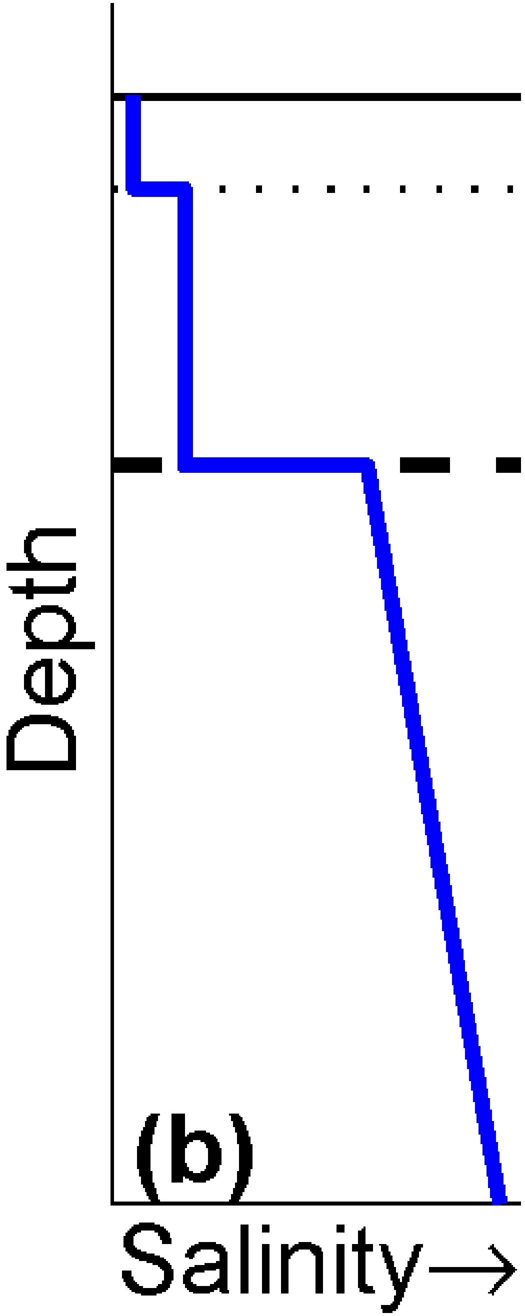
Stability



potential energy needed to mix [J/m^2]

$$St = \frac{g}{A_0}\int_0^h (\rho(z) - \overline{\rho})\, z\, A(z)\, dz$$

Stability



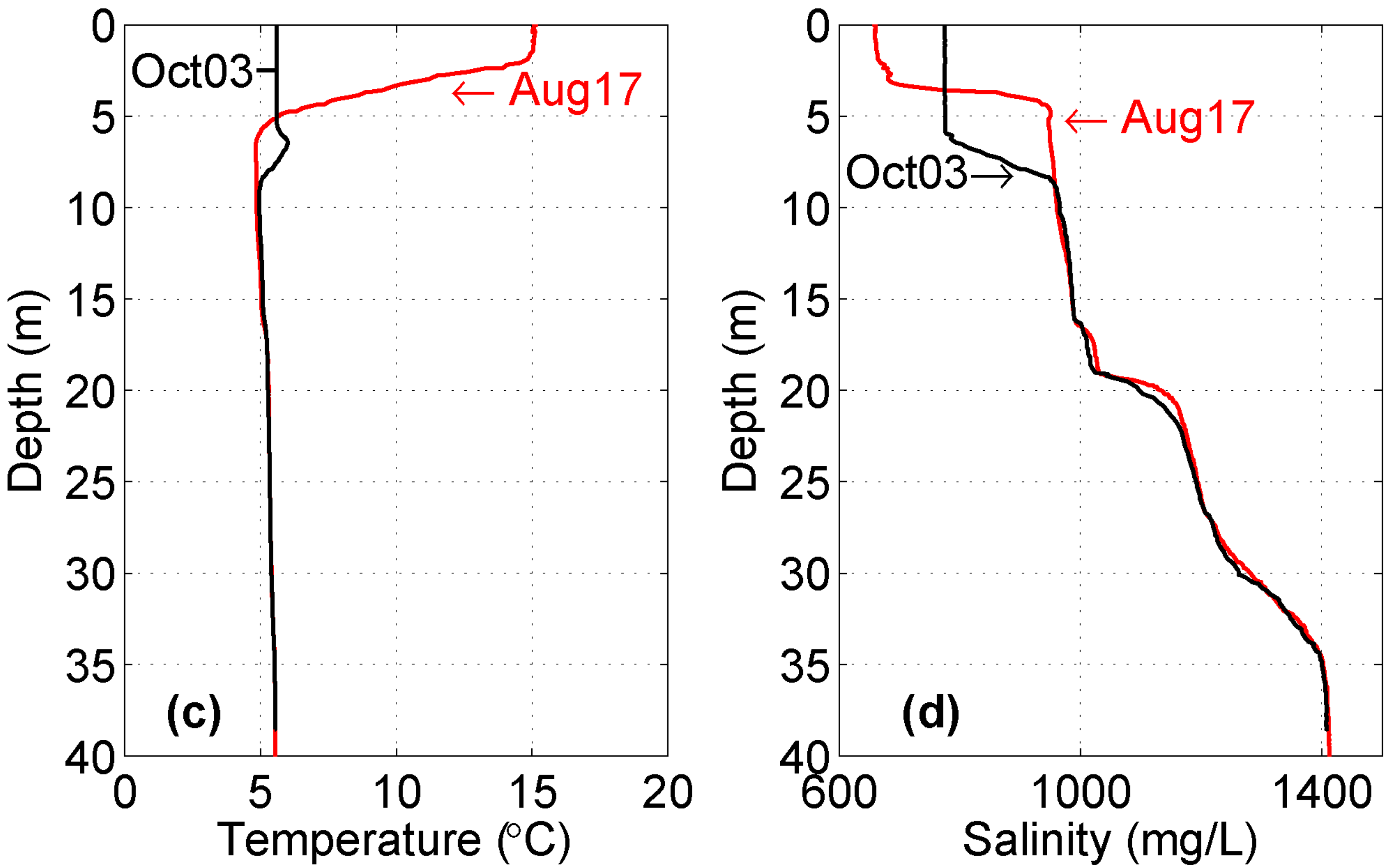
potential energy needed to mix [J/m^2]

$$St_S \cong \frac{g\,\Delta\rho\,h_1\,h_{\max}}{\alpha+1}$$

Increase salinity stability with:

- density difference, $\Delta\rho$
- surface layer depth, h_1
- maximum depth, h_{max}
- More deep volume, small α

Change in salinity stability during fall



$$\text{Aug } St_S^* = 200 \text{ J/m}^2$$

$$\underline{\text{Oct } St_S = 187 \text{ J/m}^2}$$

$$\Delta St_S = 13 \text{ J/m}^2$$

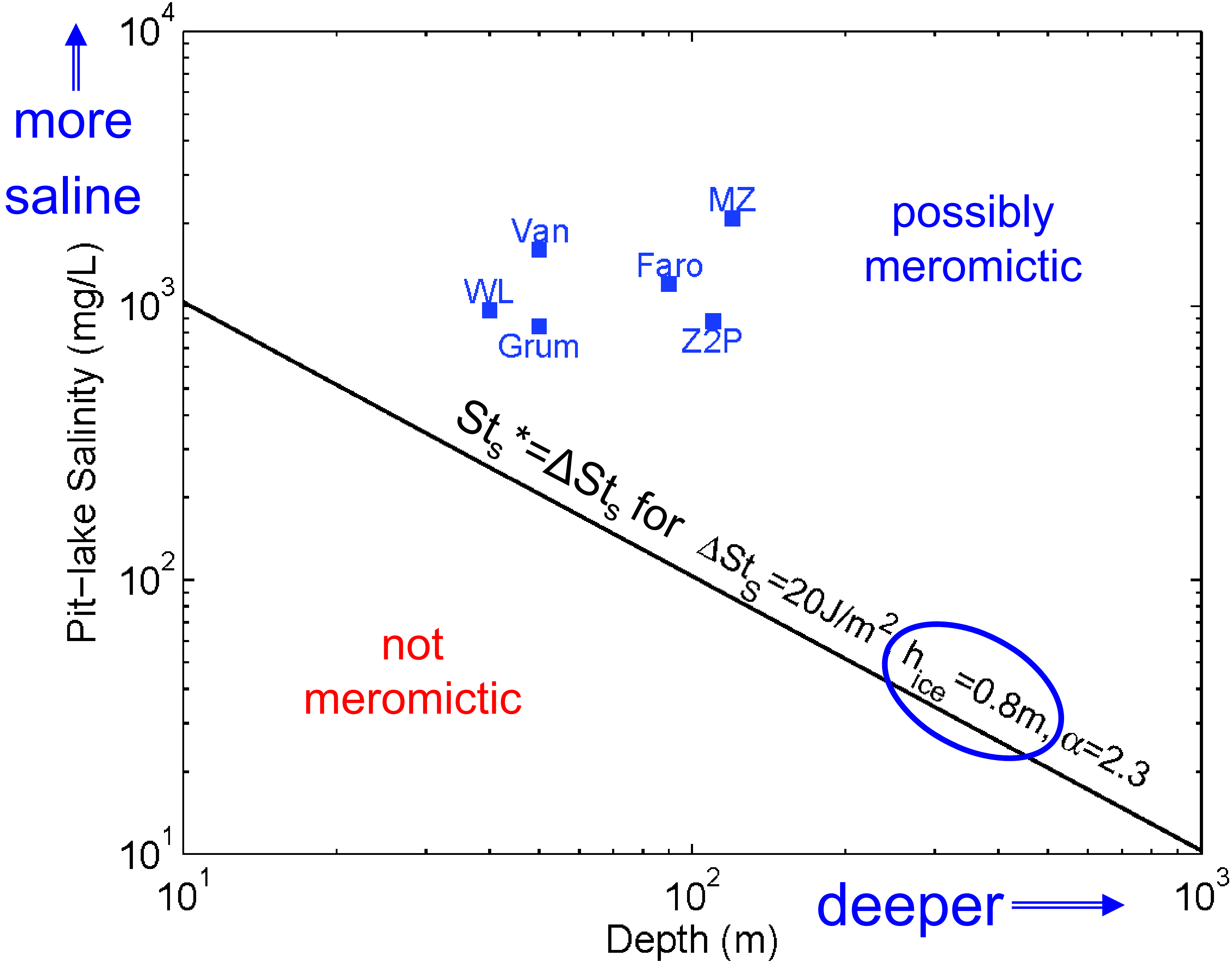
Meromixis likely when:

$$St^* \gg \Delta Sts$$

Salinity stability at max heat content (Aug) → St^*

Change in salinity stability through fall → ΔSts

Site	Mictic Status	Year	St_S^* (J/m^2)	ΔSt_S (J/m^2)	Ratio: $St_s^*/\Delta St_s$
Z2P	**weakly meromictic**	**2004**	**140**	**25**	6
		2005	**145**	**~19**	8
Waterline	**meromictic**	**2001**	**200**	**13**	15
Faro	**meromictic**	**2004**	**700**	**~20**	35



more saline
possibly meromictic
not meromictic
deeper
Van
MZ
Faro
WL
Grum
Z2P
$St_s^* = \Delta St_s$ for $\Delta St_S = 20 J/m^2$, $h_{ice} = 0.8 m$, $\alpha = 2.3$
Pit-lake Salinity (mg/L)
Depth (m)
10^1
10^2
10^3
10^4

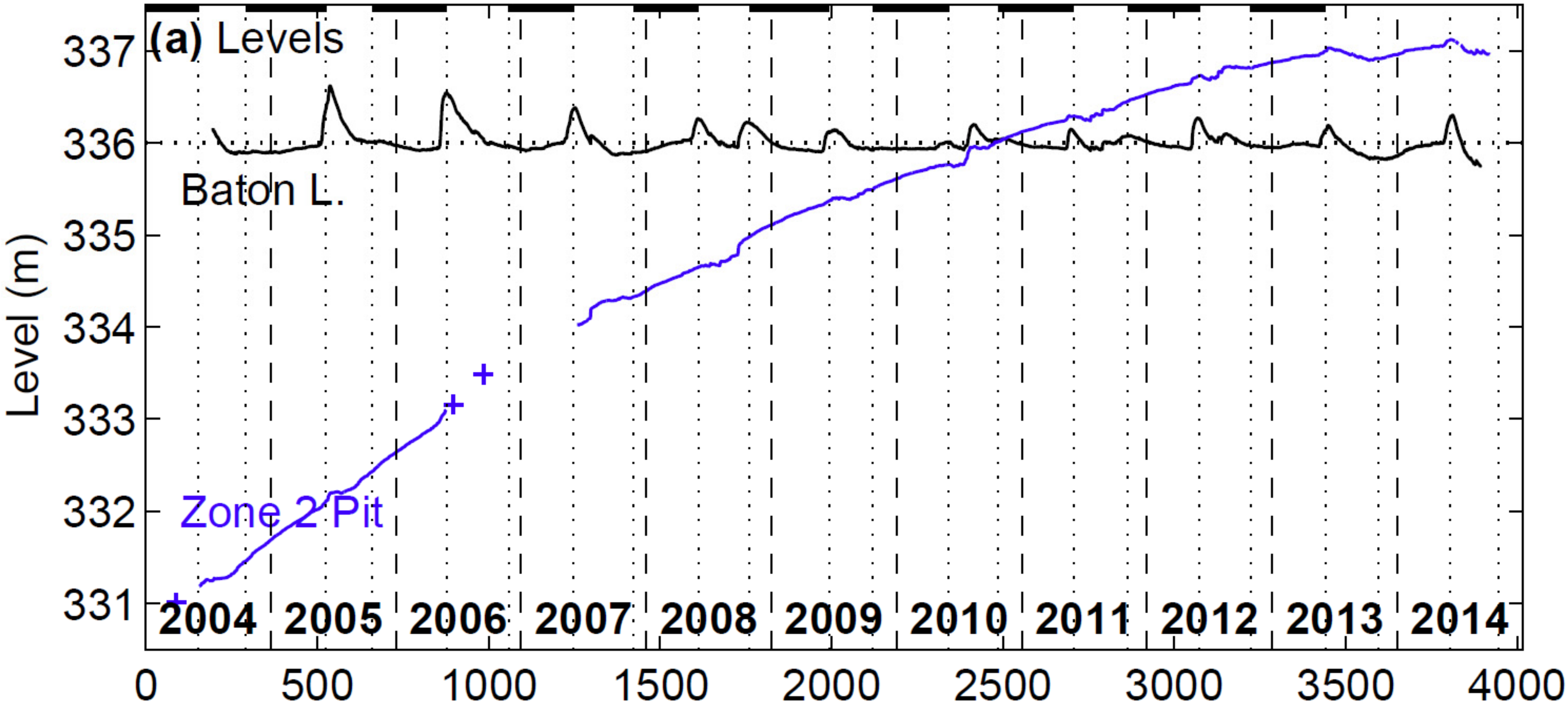
3. FACTORS THAT WORK AGAINST MEROMIXIS

- Groundwater
- Underground workings
- Earthquake
- Sludge inflow
- Wall creep
- Inflow and outflow
- Aeration

Groundwater

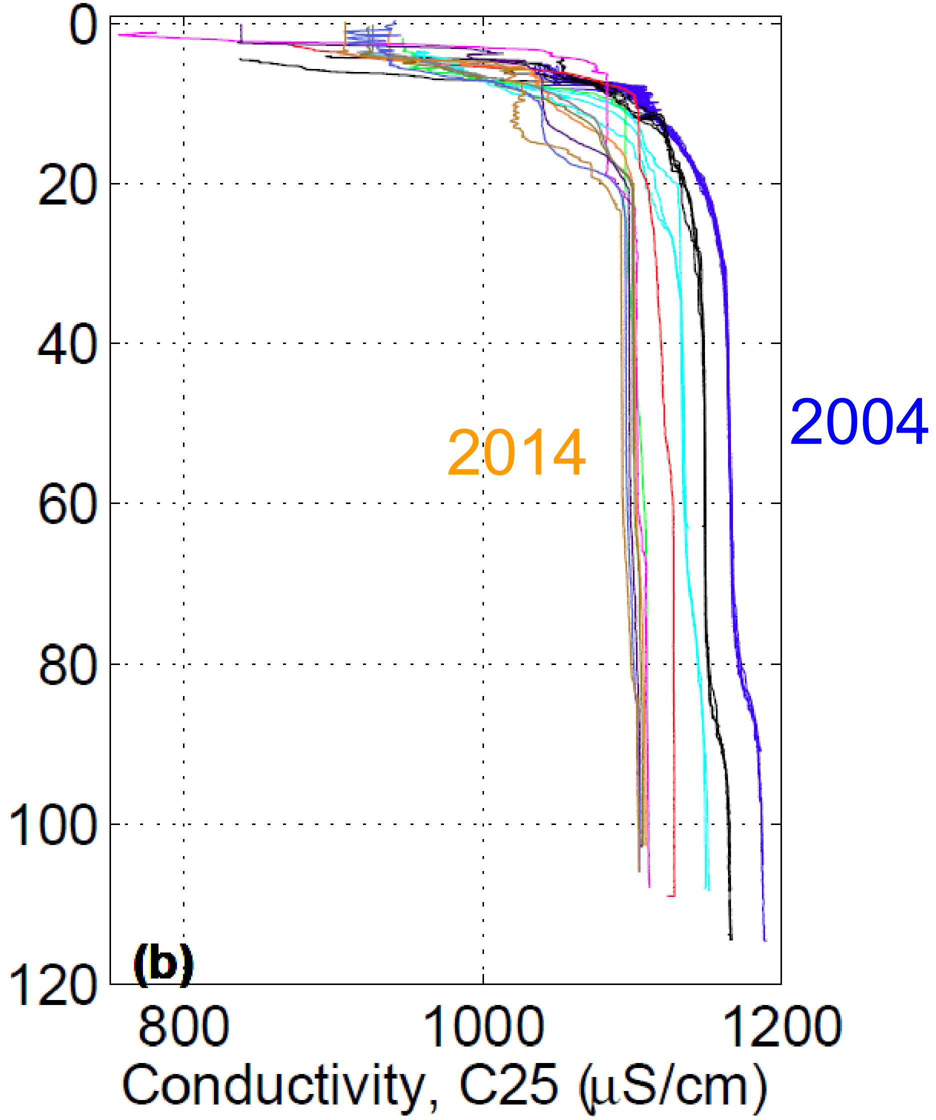
Zone 2 Pit

Figure 2 Water level and estimated grounwater inflow, 2004−2014



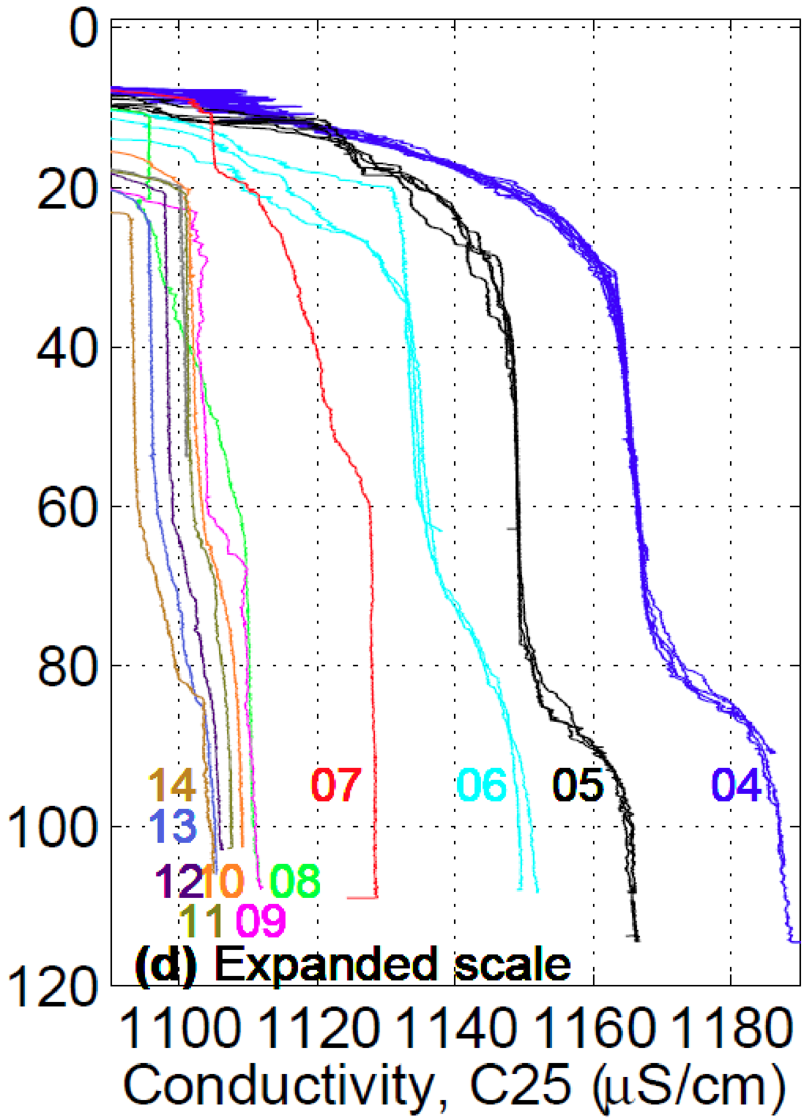
Groundwater

Zone 2 Pit



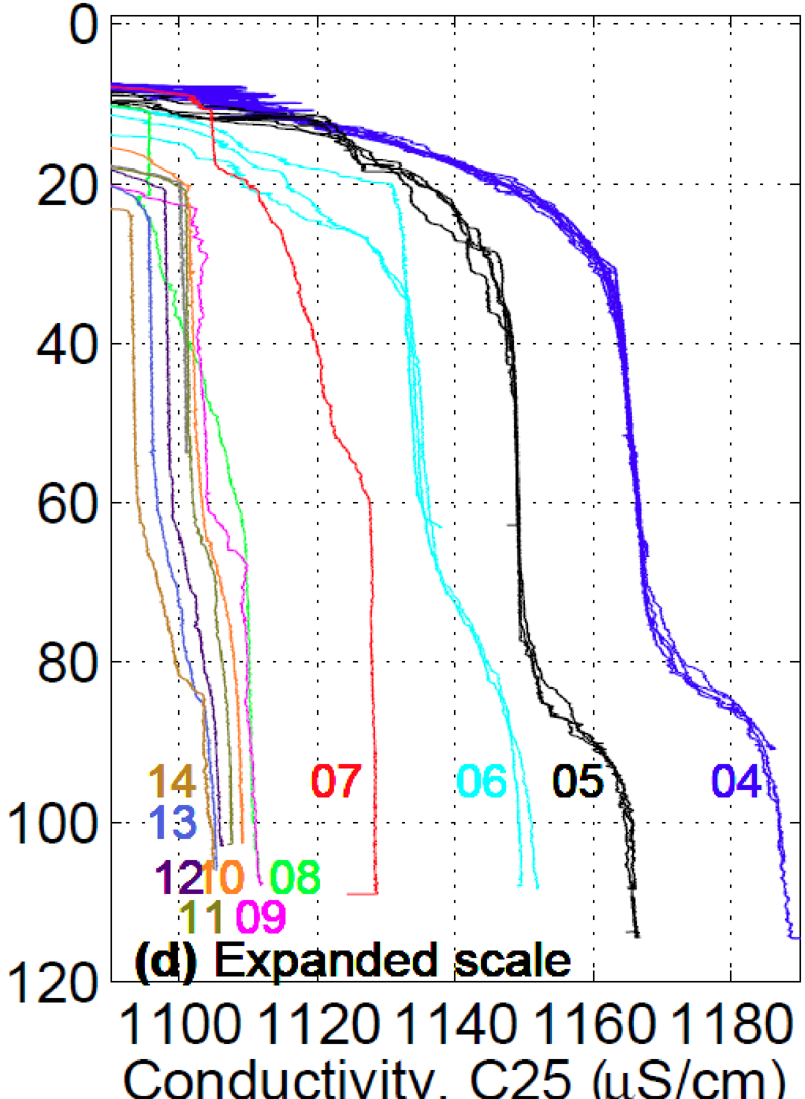
Groundwater

Zone 2 Pit

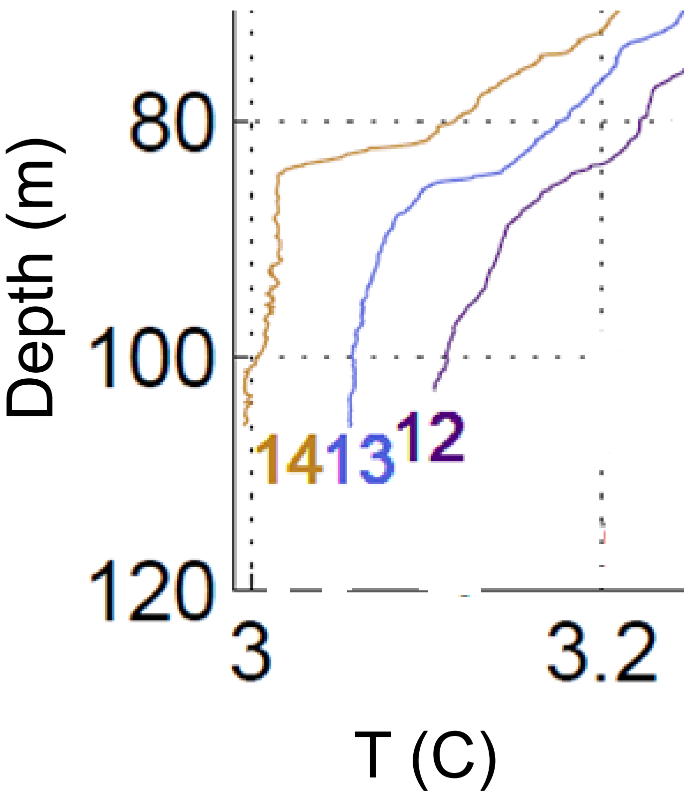


Expanded scale for deep water

Groundwater
Zone 2 Pit

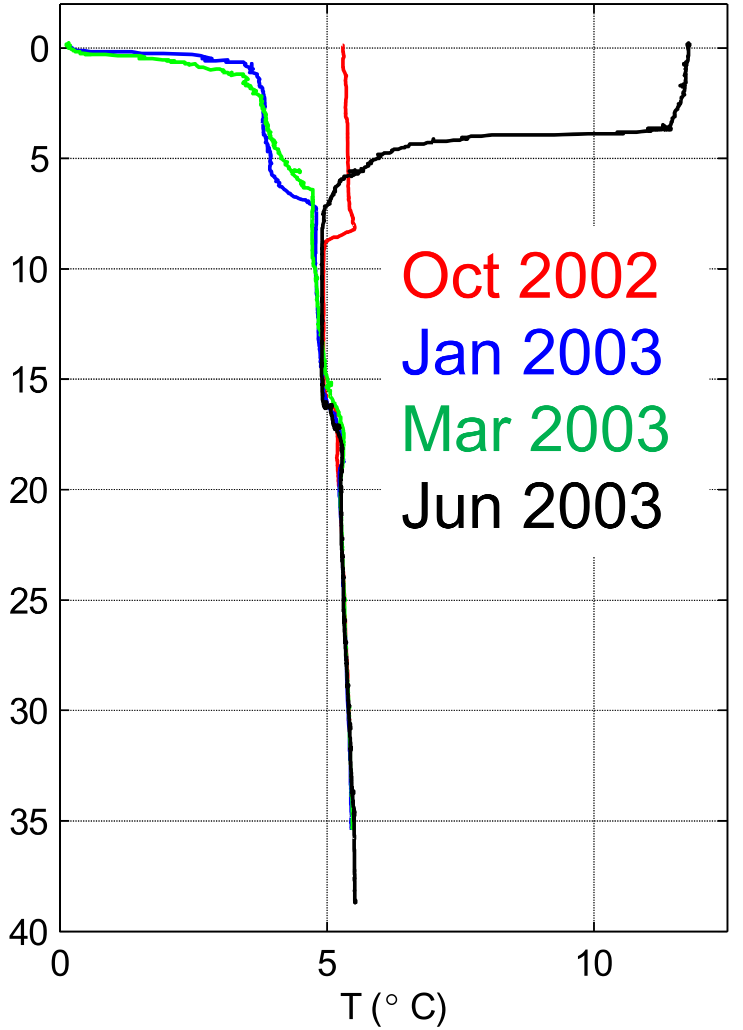


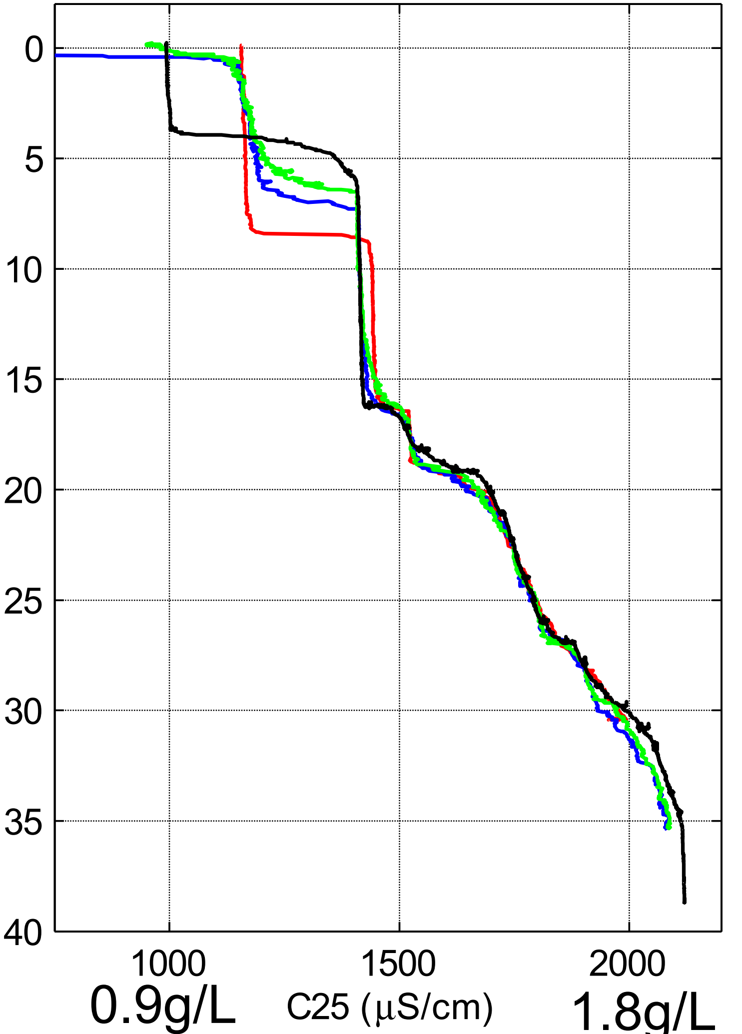
DEEP TEMPERATURE



Inflow from Adits

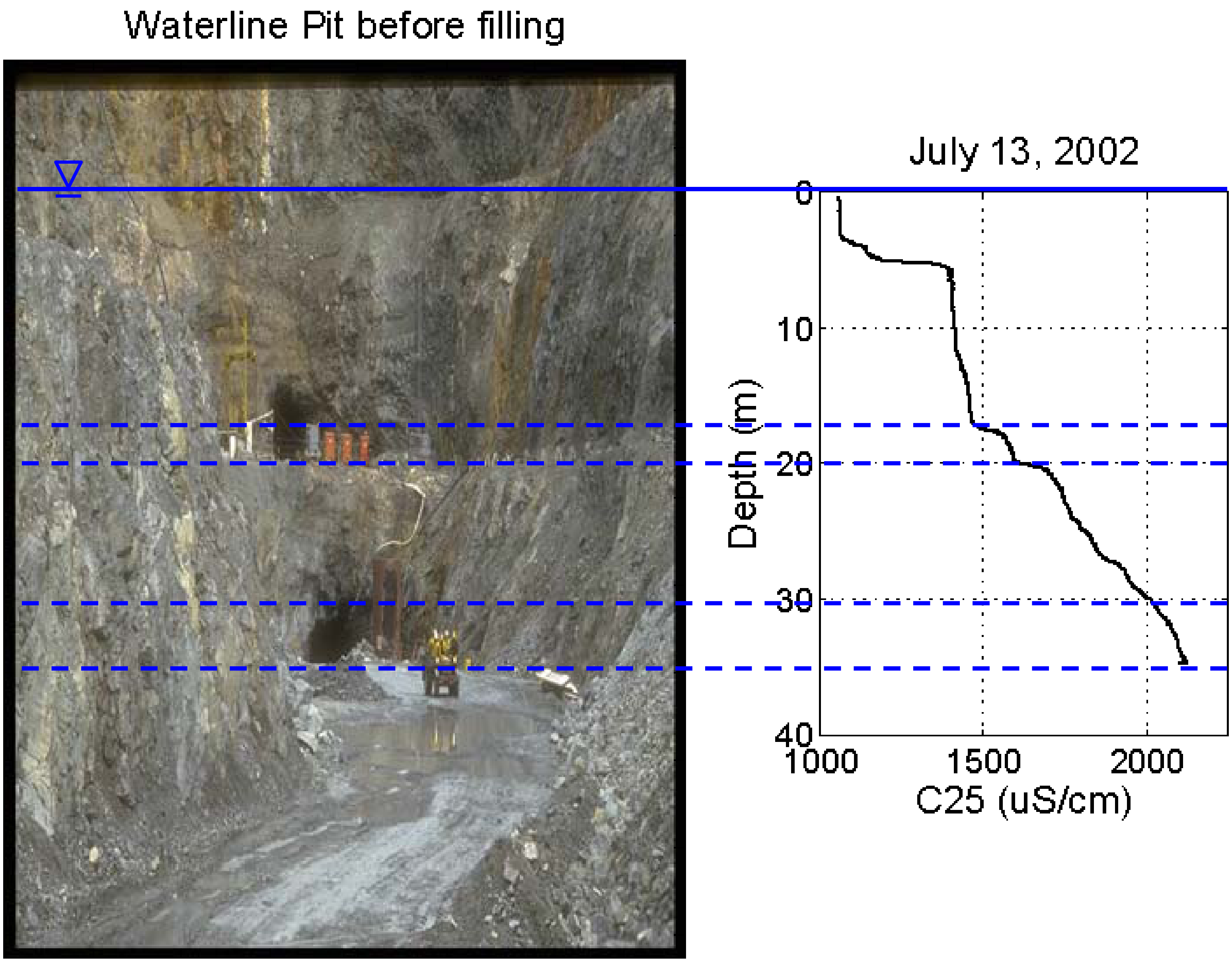
Equity Waterline





Equity Waterline Adits

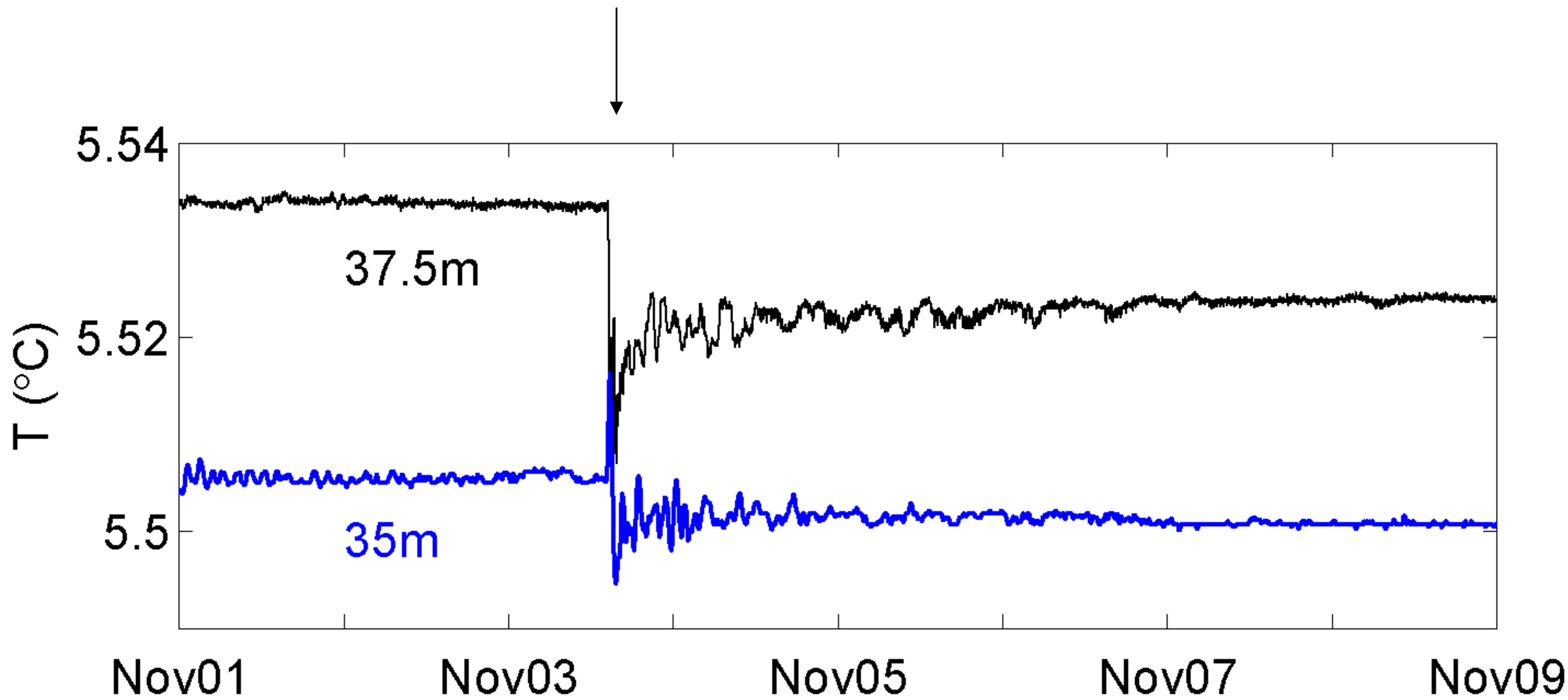
Waterline adit inflow



Earthquake

Denali Alaska to Waterline BC

Nov 3, 2002 1:12 PM PST Mag 7.9

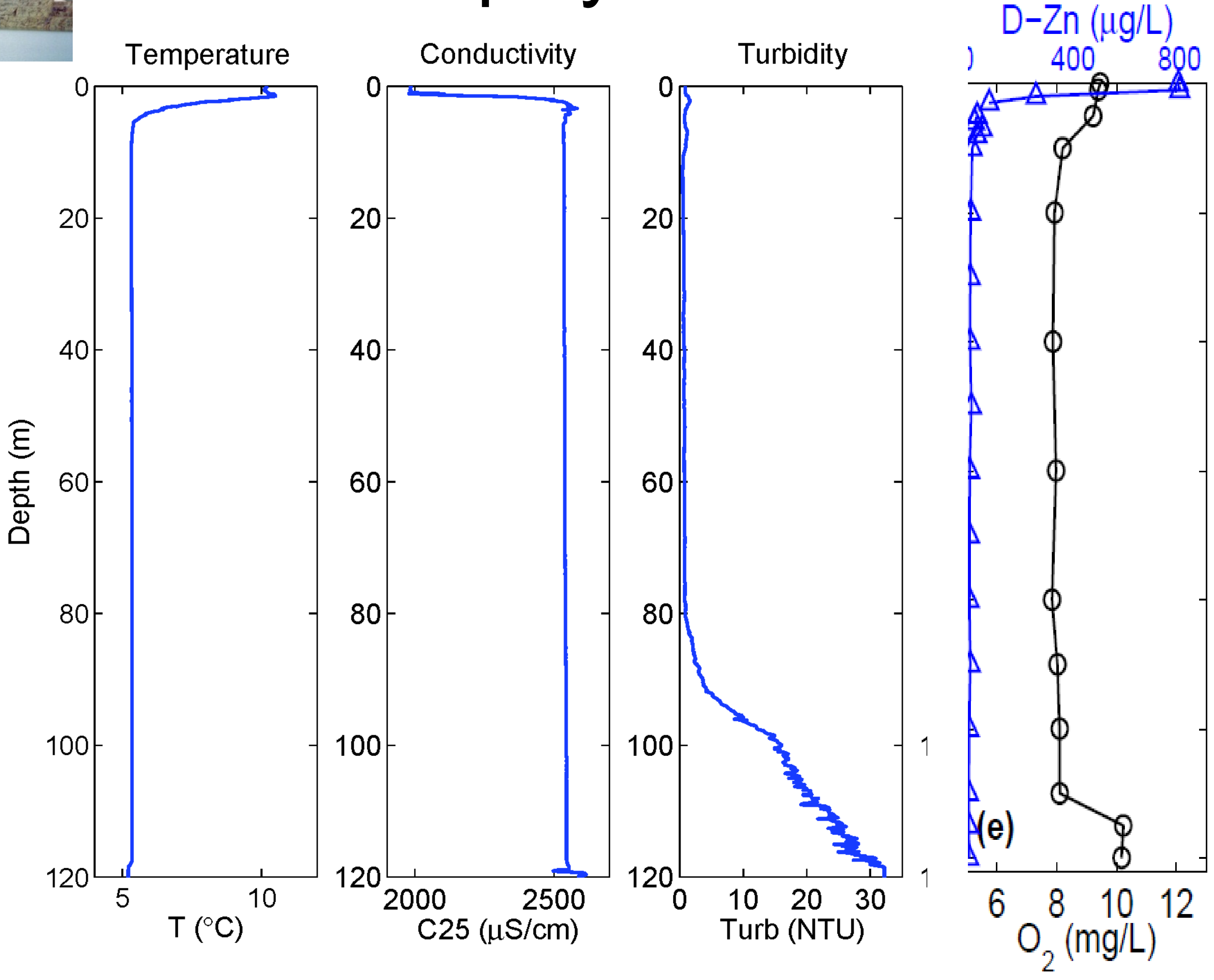



Distant Earthquake…
Photo Mike Aziz

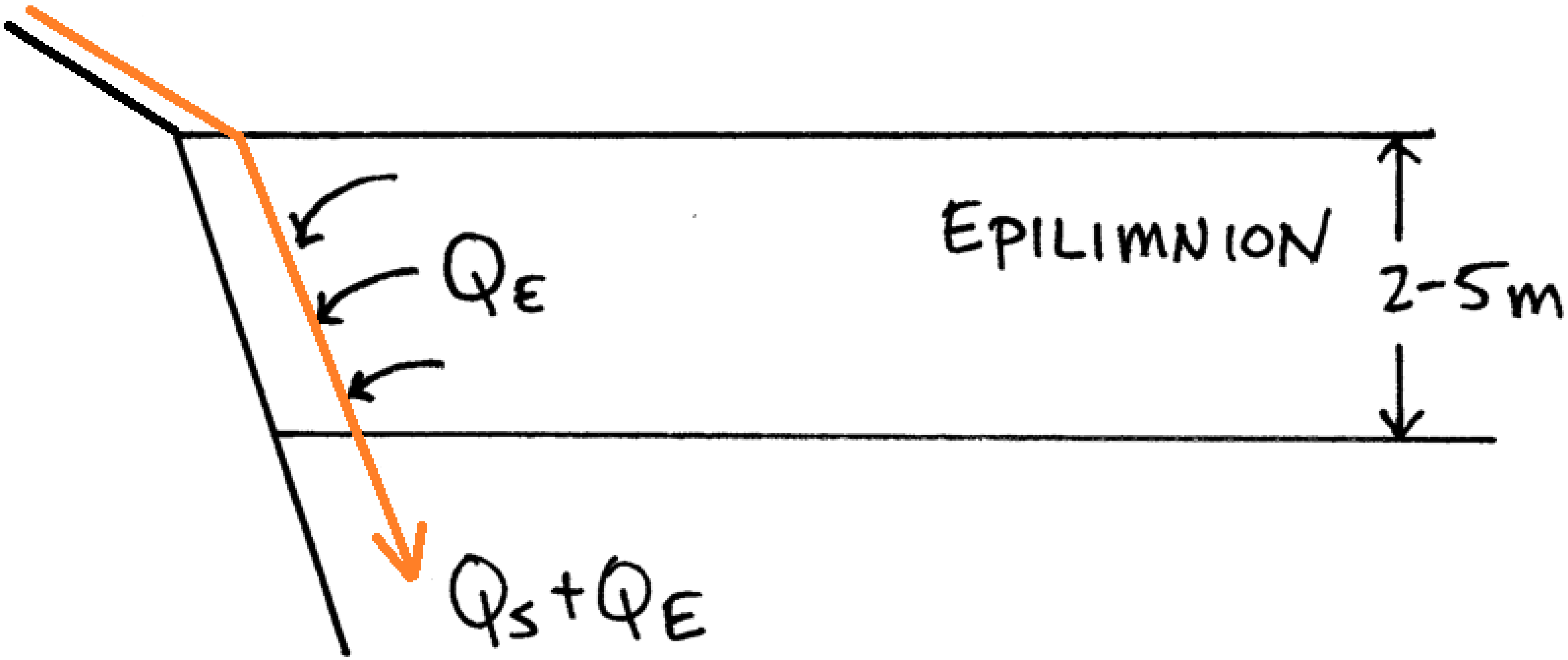
Photo Mike Aziz

Sludge inflow: Equity Main Zone

Equity Main Zone



Removal of surface layer



$Q_E/Q_s = 5\text{-}20$

Creep of till wall: Grum

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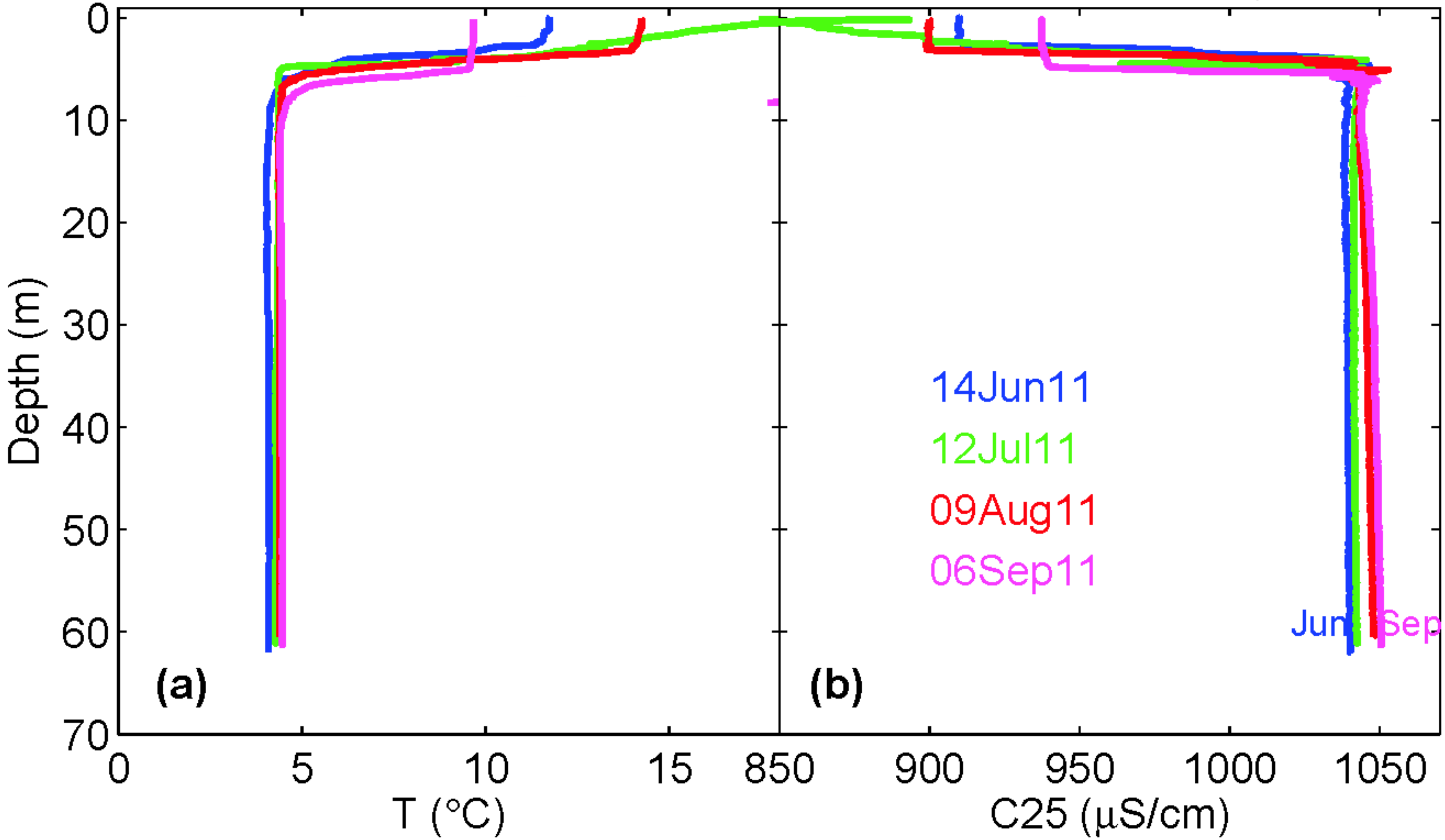
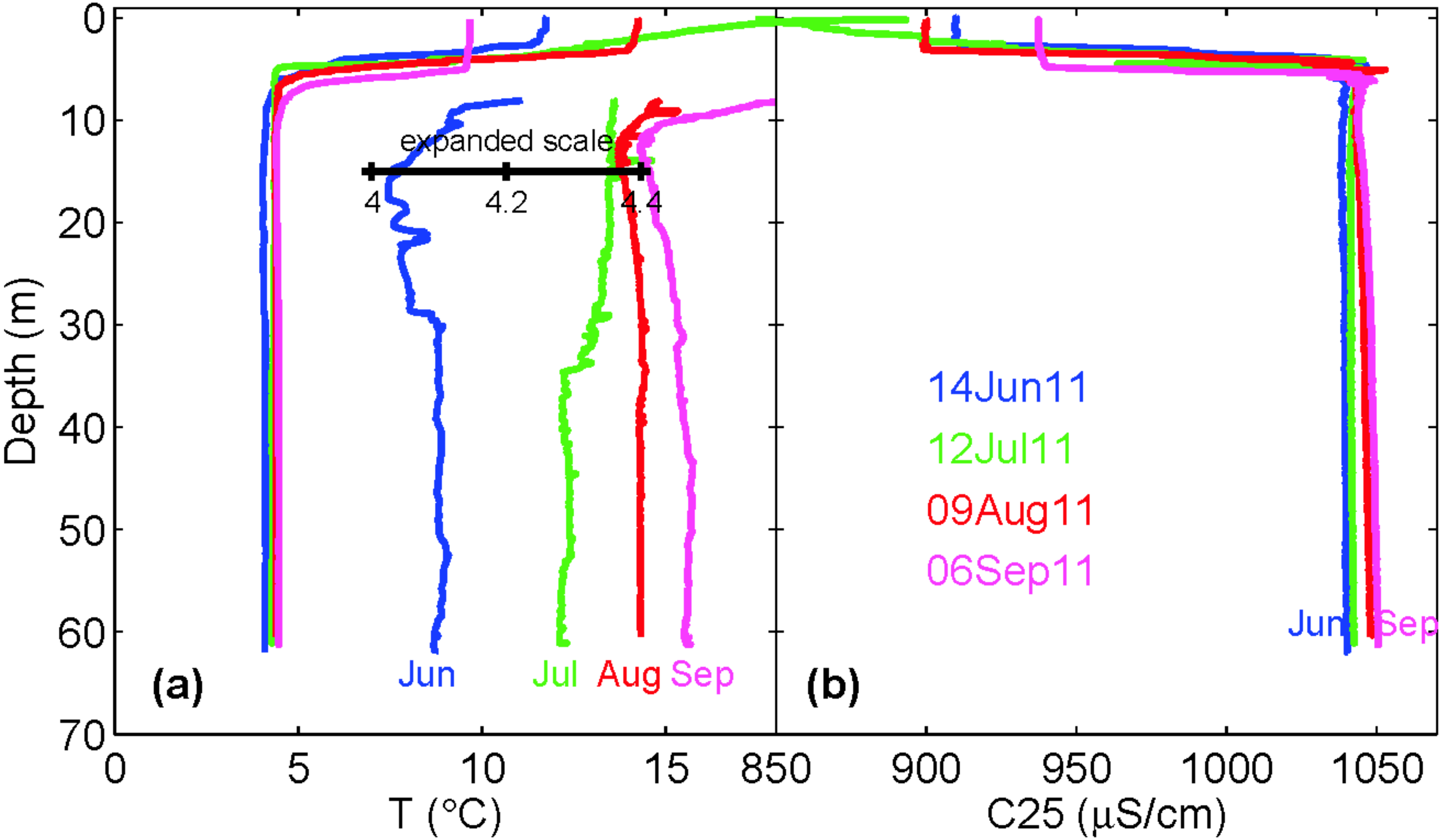


Creep of till wall Grum



High inflows & outflows

(temporary storage)

Vangorda

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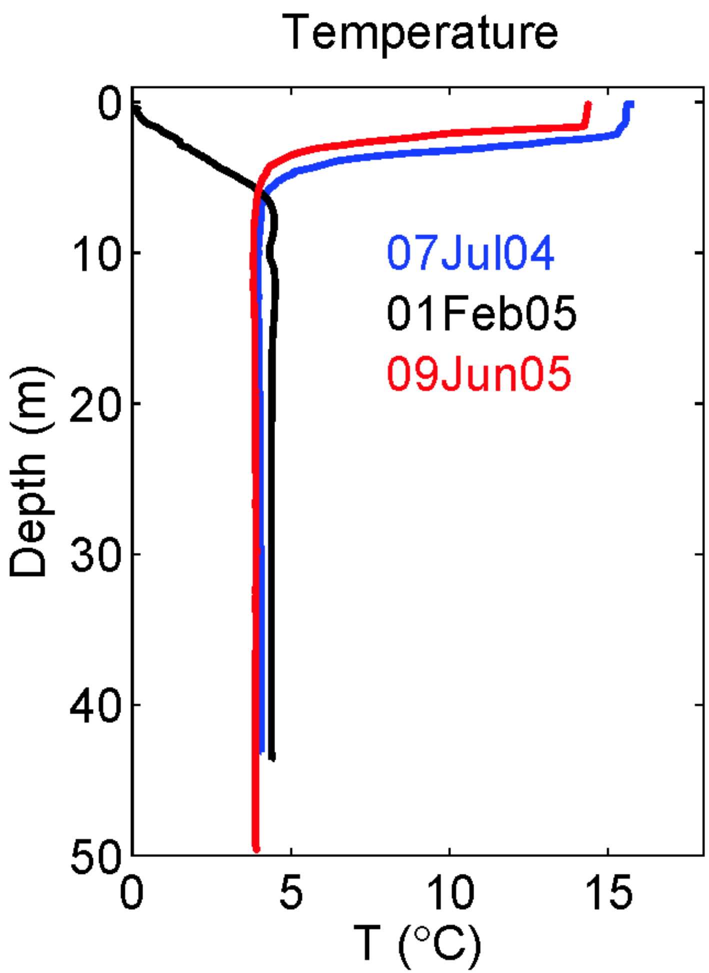
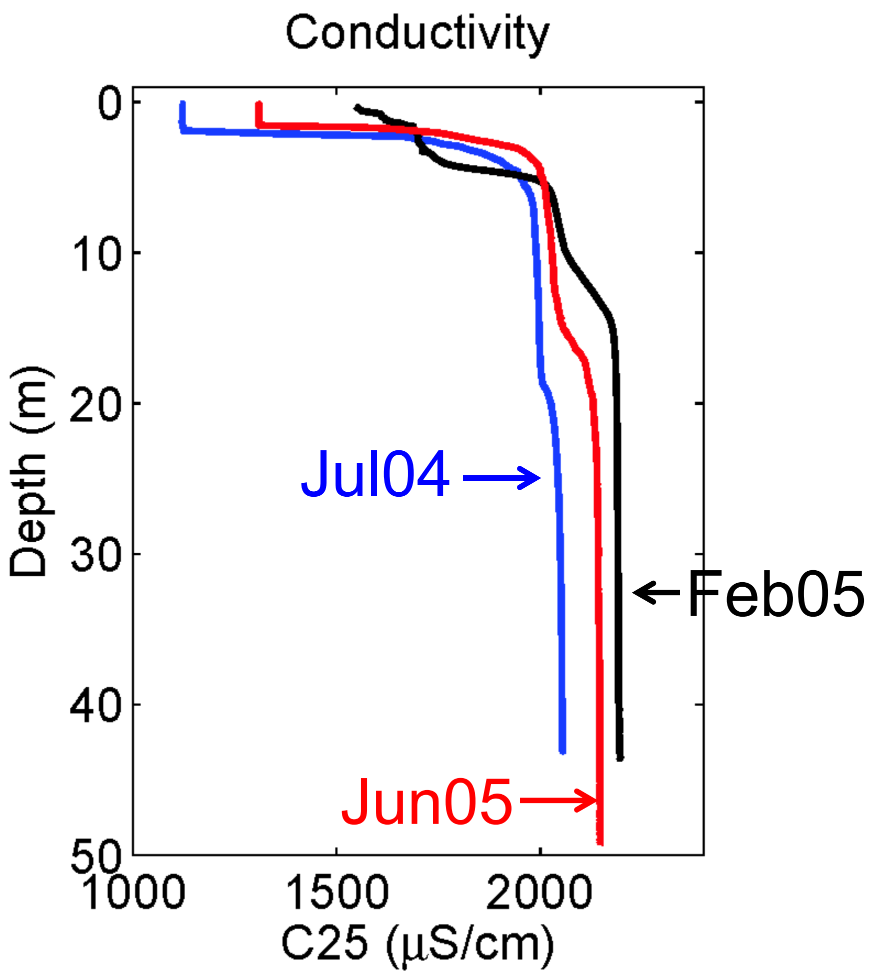
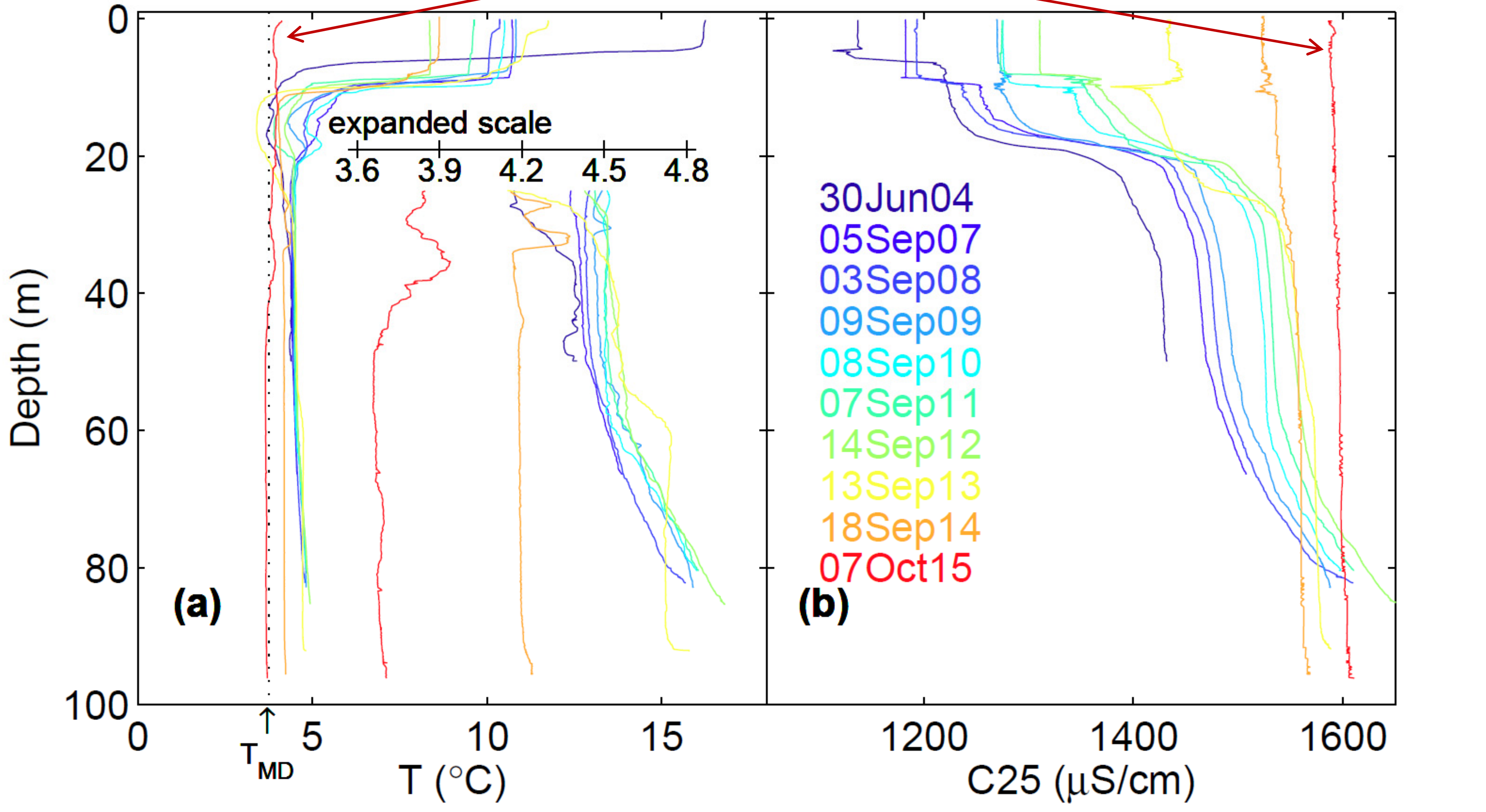




Another example of inflows:

Faro: destratification in 2015



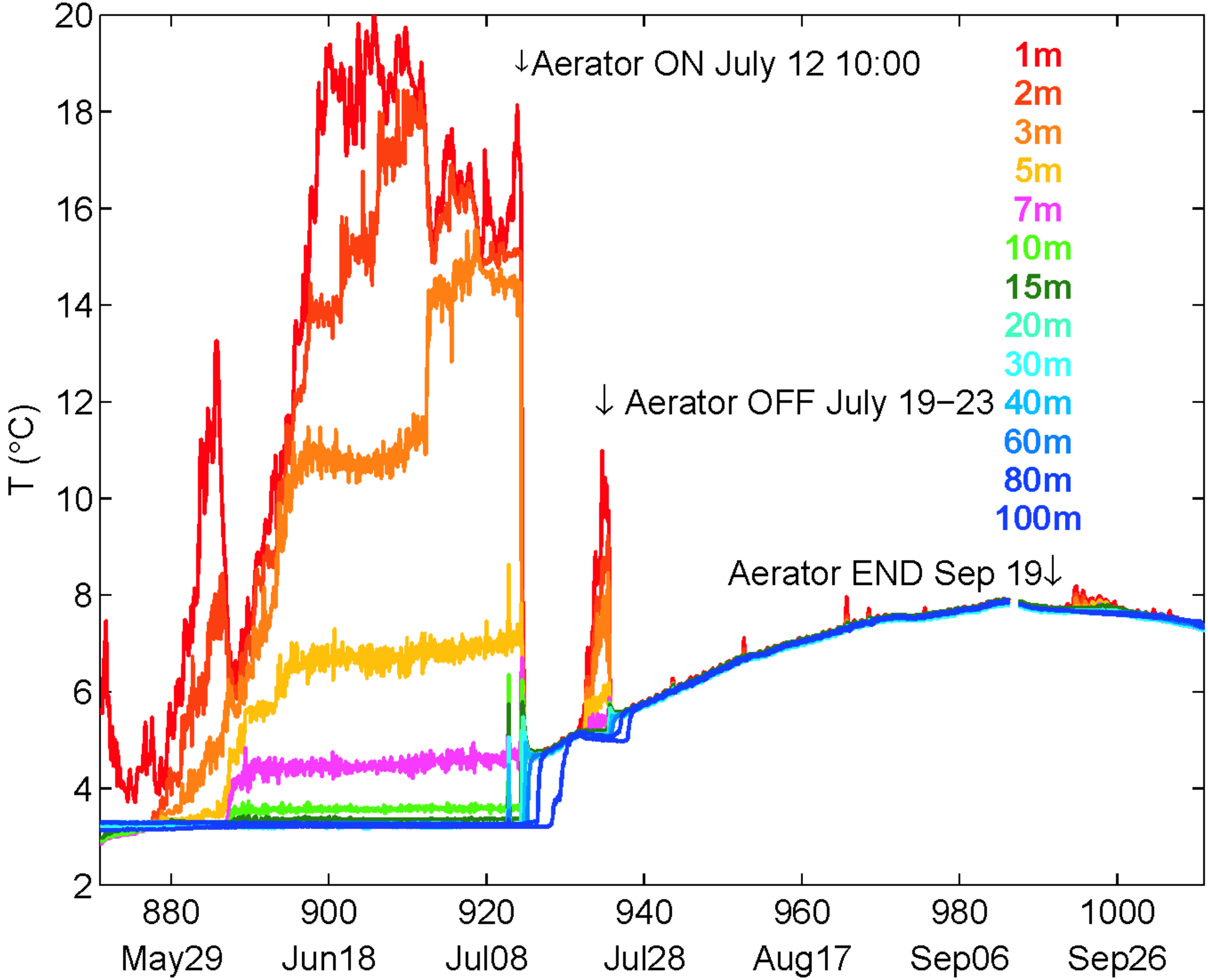
Intentional destratification:

Aeration Zone 2 Pit 2006-07


Photo Bill Coedy

July 12, 2006 startup

Summer 2006 with aeration:



•CONCLUSIONS

- •Factors that enhance meromixis
  - •bathymetry – deep, large deep volume (low α)
  - •enhance chemocline – salinity, ice cover, inflow
  - •reduced mixing, ΔSt_s – wind sheltering, quick freeze up

- •Factors that disrupt meromixis
  - •Groundwater (Z2P)
  - •Unflow from Adits (WL)
  - •Earthquake (WL)
  - •Sludge inflow (MZ)
  - •Wall Creep (Grum)
  - •Inflow/outflow for temporary storage (Vangorda,Faro)
  - •Aeration (Z2P)

- Observe a range of meromictic behaviour

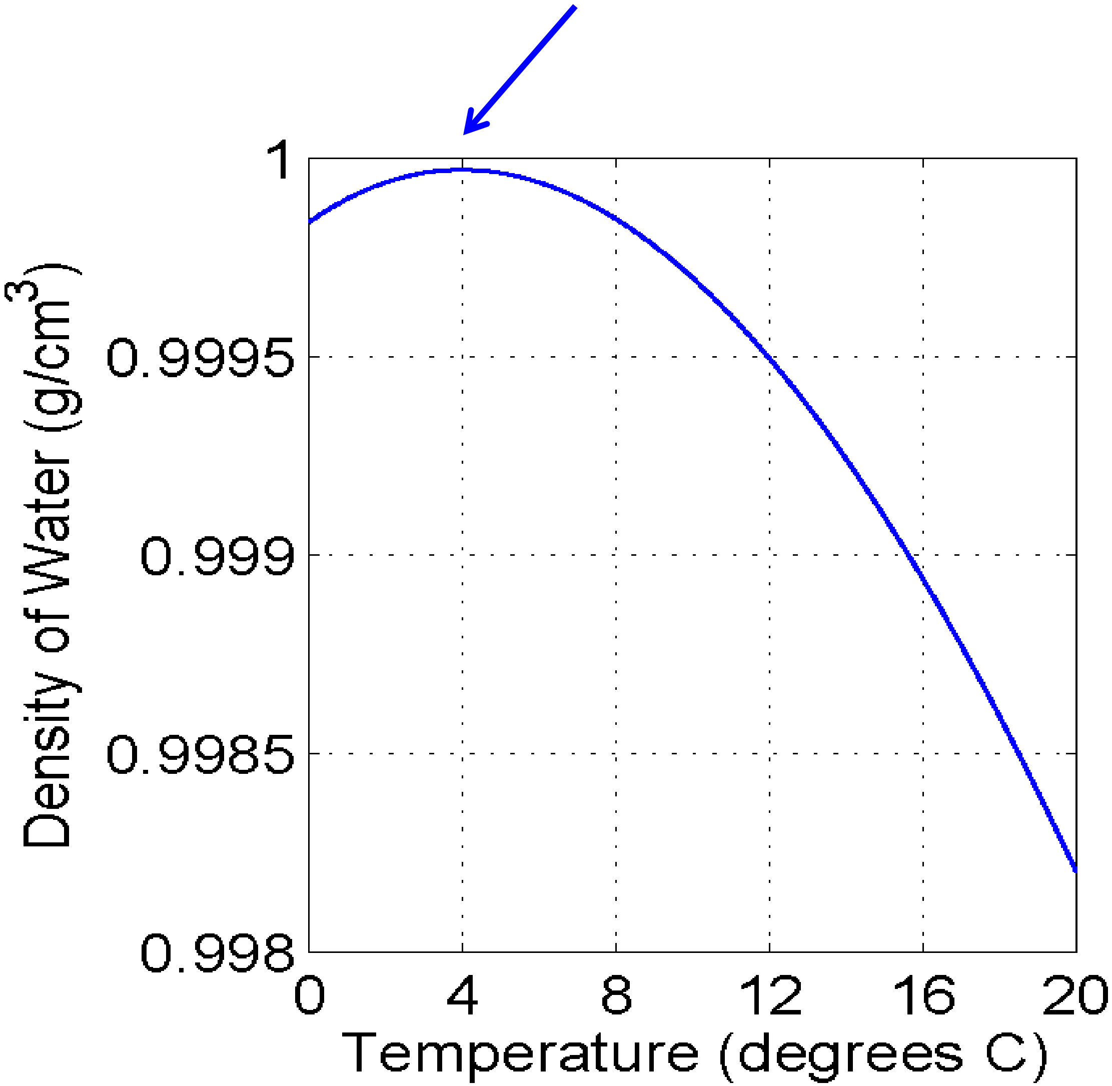
Outstanding questions

- How much deep water mixed into the surface?
- Winter: can excluded salt enhance meromixis?
- Stratification that is not two layers

Questions?

Density of water

Maximum freshwater density: 4 ºC



Salt excluded from ice