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MODELING THE THERMAL STRATIFICATION OF WATER-FILLED MINE PITS

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Modeling the Thermal Stratification of Water-Filled Mine Pits

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ABSTRACT

Closure and reclamation of open pit mines in British Columbia will allow pits to fill with runoff and groundwater. Some pit waters contain elevated heavy metals concentrations and eventual overflows may pose a risk to aquatic resources. For this reason, Environment Canada asked the authors to examine hydrodynamic mixing of pit waters, using as a model, the very large Brenda Pit in south central British Columbia.

This paper provides an analysis of the hydrodynamics of a deep, temperature and salt-stratified filled pit. Bulk parameters suggest that vertical entrainment of a deep layer is unlikely but that horizontal wind mixing might be important. Modelling shows that the water column should undergo 'overturn'; a feature not shown in the observations of dissolved oxygen. Field observations also show a persistent deep warm salty layer for which an explanation is offered.

RÉSUMÉ

La fermeture et la restauration des mines à ciel ouvert en Colombie-Britannique permettra leur remplissage par les eaux de ruissellement et l'eau souterraine. L'eau de certaines mines contient des concentrations élevées en métaux lourds et les débordements éventuel pourraient représenter un danger pour les ressources aquatiques. Pour cette raison, Environnement Canada a demandé aux auteurs d'analyser le mélange hydrodynamique des eaux contenues dans les mines, en utilisant comme modèle, la très grande mine Brenda située dans le centre-sud de la Colombie-Britannique.

Ce rapport documente une analyse de l'hydrodynamique d'une mine profonde remplie de couches d'eau, stratifiées par des températures et salinités différentes. Les paramètres du modèle indiquent que l'entraînement vertical d'une couche profonde est improbable mais que le mélange horizontal par le vent pourrait être important. La modélisation montre que la colonne d'eau devrait subir un <<renversement>>, une caractéristique non révélée par les observations de l'oxygène dissous. Les observations sur le terrain indiquent également une couche salée chaude persistant en profondeur pour laquelle une explication est présentée.

CONTENTS

§1. Introduction

The Brenda Mines Pit near Peachland in the Okanagan region was closed in 1990 and the main pit area has been gradually filling with water to the point where it now contains approximately 20×10^6 m^3 of water in a pit lake that is over 120 metres deep. If the present filling strategies are maintained the pit will overflow sometime in around 10-20 years, releasing pit water into the local stream system.

There is a need to quantify the vertical stability of the water in the mine pit. This knowledge serves two purposes; (i) it identifies the likelihood of the water presently at the bottom of the pit being mixed to the surface and (ii) it allows projection of different conditions to estimate whether a layer can be injected into the base of the water column in such a way that is protected from surface energy fluxes and consequently be effectively capped.

§2. Review

Physical limnology, that is, the study of the physical behaviour of lakes and other inland waters, is a relatively new and sparsely populated field of research. The early work that provides broad classification of the thermal structure and mixing in lakes (Wetzel 1983) must now be adjusted to incorporate new understanding (Imberger and Patterson 1990).

Wetzel (1983) states that

> a number of lakes do not undergo complete circulation and the primary water mass does not mix with a lower portion. Such lakes are termed meromictic. In meromictic lakes, the deeper stratum of water that is perennially isolated is the *monimolimnion*... The two strata are separated by a steep salinity gradient which is called the chemocline.

Thus, it is expected that it is desirable that a water filled mine pit be *meromictic*. Other studies of relevance to the topic include those concerning nearby Mahoney Lake (Northcote and Hall 1983, Ward *et al.* 1990), a shallow meromictic lake that has its strong stability maintained by salinity. In addition, and possibly more relevant, is the study of the Berkeley Pit in Montana, described by Davis and Ashenberg (1989). This pit has remarkably similar dimensions to the Brenda Pit, however the density stratification is totally dominated by dissolved salts, whereas temperature appears to play a significant role in the stratification of the Brenda Pit (Stevens *et al.* 1994).

The physical mechanisms of importance in the epilimnion are often described by "mixed layer" models (Imberger 1985) whilst transport in in the hypolimnion in more typically described by quasi-empirical descriptions (Hondzo and Stefan 1993), although the mixed layer models do tend to rely heavily on coefficients from observations also. The energy fluxes in and out of the water column are often not emphasized enough in field studies (Fig. 1). The difficulties encountered when modeling Ice-cover are described by (Patterson and Hamblin 1988) and Rogers (1992).

§3. Site Description and Available Data

The Brenda Mines pit is at present around 130 metres deep allowing for debris settlement (Fig. 2). The pit has an averaged radius near 130 metres at the base and around 350 metres at the surface. Comparison with other meromictic lakes in the Pacific Northwest (Walker 1974, Northcote and Hall 1983, Ward *et al.* 1990) reveals that it is much deeper than the natural lakes surveyed. The shoreline formed by the old pit walls rises quite steeply providing in the order of 100 metres of sheltering on most sides.

The Brenda Mines company have been collecting monthly data for the majority of the period running from mid 1992 to the present. These data include temperature and dissolved Oxygen profiles at 10 metre intervals throughout the water column (Fig. 3). In addition there are analyses of the chemical composition from these profiles and some wind observations from a nearby observation post. This data-set forms one of the more extensive compilations for this type of water body.

Data for the Brenda Mines Pit and other mines around the Province and in neighbouring provinces is collated in Appendix iii (c/- R. McCandless).

In addition to this data the Environmental Fluid Mechanics Group in the Department of Civil Engineering at the University of British Columbia recorded Conductivity-Temperature-Depth profiles in March and May of 1994. This instrument records rapidly giving sub-metre scale spatial resolution in the vertical. It provides a more complete picture of the density structure (Fig. 4). The profile definitely indicates a pool of warmer water right at the very base of the pit. Because of the bathymetry it does not represent a large volume; however its existence is puzzling and means that the physics and possibly chemistry of the pit lake is not as simple as it might "normally" be. More complete information from the profiler is included in Appendicies iv and v. The comparison between the two profiles is discussed in Appendix vi.

In terms of providing a sound basis for numerical modeling the greatest deficit in the data lies in the lack of weather data specific to the pit. This is of more importance than the temperature and oxygen structure in many ways because it is used to drive the simulations whereas the vertical stratification data is used simply as a check.

§4. Parametrization

Here we consider non-dimensional parameters based on the scales of the Brenda Pit to infer its likely behaviour.

4.1 Wind circulation above the water surface

The steep walls of the unfilled portion of the pit suggest a certain degree of protection from the wind; however on-lake visual observations clearly indicate that there is substantial wind energy transferred to the surface waters, with reasonable chop developing over the 700 metre maximum fetch. To categorise the wind behaviour we may consider the air in the pit above the water to form a cavity. A Reynold's

Number based on cavity length (1000 metres) and typical air speed during a period of mixing (say 10 m/s) may form part of a Reynolds Number, Re, to indicate the nature of the flow. Hence

$$Re = \frac{UL}{\nu_a} \tag{1}$$

where ν_a is the kinematic viscosity of air ($16 \times 10^{-6} \mathrm{m}^2\mathrm{s}^{-1}$) and results in $Re \approx 6 \times 10^8$. This is four orders of magnitude greater than laboratory experiments described by Koseff and Street (1985) (comparisons must be made with their high Richardson's Number experiments) and even at their reduced Re they encountered highly turbulent flow; we would expect the same at the water surface. It is reasonable to expect that it is attenuated in magnitude however it is difficult to say by how much without measurement. Systematic directionality is unlikely.

The average effective wind speed at the water surface will decrease as the aspect ratio H_w/L is increased, where H_w is the height of the wall. However substantial decreases are only likely to be felt when $H_w/L \approx 1$ as the cavity flow should split into a series of cells of similar dimension. The Brenda Pit has an aspect ratio of closer to 0.1.

4.2 Vertical Entrainment

An entrainment velocity may be estimated. This value describes the mean downwards velocity of the thermocline region under the action of stirring.

The experiments of Kranenburg (1985) and earlier have been compiled to provide a model for deepening of a recirculating wind driven surface layer. One of the greatest difficulties with laboratory simulations has been the surface layer to basin length aspect ratio $A = h_1/L$. In lakes this ratio is typically of order 0.001 however laboratory experiments rarely achieve values less than 0.01. The Brenda Pit, due to its small fetch, is actually more relevant to this entrainment literature than the applications for which it was intended! It has an aspect ratio of around 0.014.

The entrainment law is given by

$$u_e = C_1 \frac{u_*}{Ri} \tag{2}$$

where the Richardson Number Ri is an indicator of stability

$$Ri = \frac{g' h_1}{u_*^2}, \tag{3}$$

and

$$g' = \frac{\Delta\rho}{\rho_0} g$$

is the modified gravitational acceleration. The density difference, $\Delta\rho$ between the epilimnion and the hypolimnion is required as is the thickness of the upper layer h_1 and the friction velocity at the surface u_*. The friction velocity is given by

$$u_* = \sqrt{C_D \frac{\rho_a}{\rho_0}} U, \tag{4}$$

u_s is the surface drift velocity, the drag coefficient is given by $C_D = 1.3 \times 10^{-3}$ and the density of air may be taken as $\rho_a \approx 1.2$ kgm^{-3}. The experimental coefficient C_1 is generally assumed to hold a value of 0.23.

Substitution of conservative (in the sense of describing more energetic events than would be the norm) summer time values ($U = 10 m/s$, $\Delta\rho = 1$ kgm^{-3}, $h_1 = 10$ m) gives a $u_* = 12$ mms^{-1}, $Ri \approx 700$ and hence $u_e = 4 \times 10^{-6}$ m/s. This suggests vertical penetrations of 0.3 of a metre in a 24 hour period. It can be imagined that this small value is significant if the U were to persist for say a month. This persistence is unlikely.

4.3 Upwelling

In recent years it has become apparent that much of the "vertical mixing" in lakes is due, not solely to vertical turbulent transport, but also to horizontal motions generated at the same time. These motions can bring the hypolimnion to the surface at one end of the lake, exposing it to the wind and resulting in enhanced mixing. To parametrize this behaviour the Richardson number described by (3) is combined with the surface layer aspect ratio A in a factor termed the Wedderburn Number

$$W = Ri.A. \tag{5}$$

A $W \gg 1$ represents stability whilst $W \ll 1$ represents a high probability of mixing. Values around unity represent transition where the timescales of internal waves must be examined before the mixing can be anticipated (Stevens 1992).
Here we find that W, for the selected conditions is approximately equal to 10 which suggests that perhaps some consideration should be given to internal waves; the fundamental internal seiche is around 1.3 hours at the selected conditions. This implies that even the highly variable wind conditions in the pit might still have sufficient time to generate upwelling mixing. None of the numerical models known to the authors includes this effect.

4.4 Buoyancy Inflows

Here we will consider two different buoyancy inflows; the first is that of the pumped Tailings Pond water; in 1993 alone 2.6×10^6 m^3 of water was pumped into the pit (H. Larratt, pers. comm.). The second buoyancy inflow is that which has been observed to occur during some storm events. The storm generates waves which in turn break on the shore and create a silt laden flow. This has, in one instance, been observed to sink and samples taken at 70 metres indicated a band of silt laden water. The interesting point is that while the storm driven plume is observed to sink, the Tailings Pond water spreads out over the surface in the manner of a positively buoyant plume. This occurs even though the Tailings Pond water is injected into the pit by running it down the steep pit walls. Presumably the walls in the region of the pumping are now relatively clean and thus these inflows do not entrain significant levels of silts.
The tailings pond is relatively shallow (only a metre or so) and thus is likely to

heat up substantially more than the deeper pit lake; this is partially because of the depth limiting the volume which is being heated. If we assume an inflowing density difference $\Delta\rho_i = 0.2$ kgm^{-3} (roughly 2 degrees) enters the lake with a given velocity we can use a parameter equivalent in form to (3) but now related to $\Delta\rho_i$, the inflow velocity u_i and the inflow thickness, δ. The latter two are difficult to infer but if we assume the inflowing layer is 0.01 m deep then assuming it occurs over 1/4 the circumference of the pit then $u_i = Q/(\text{circum.} \times \delta)$ where Q is the flow rate. Assuming the volume stated above is injected over 4 months $Q = 0.25$ m^{3}s^{-1}, circum=550 metres then $u_i = 4.5 \times 10^{-2}$ ms^{-1}. Consequently the inflow $Ri_i = \Delta\rho_i\delta/u_i^2$ has a value of around 10^{-3} indicating that it will mix vigorously upon entering the epilimnion. Thus, the inflow can be expected to form a bulk flux to the entire epilimnion without forming a near-surface layer.

§5. Modeling

Here we describe an energy based approach as outlined by Fisher *et al.* (1979) and partially described by Ward *et al.* (1990). The diffusion based model described in Stevens *et al.* (1994) is still under development. The energy approach calculates the amount of potential energy in the water column; an increase in the thickness of the surface layer represents an increase in the overall potential energy of the water column and this energy comes from the heat fluxes across the surface or the wind stirring.

The parametrization described in §4 indicates entrainment of any existing lower layer at depths of around 80 metres or more into the surface layer, is unlikely. Furthermore any moderately saline layer deep in the water column should remain intact. Consequently the heat and wind inputs we have employed can be considered very coarse and conservative.

5.1 The model structure

The model is a mixed layer model in that it considers a layer of thickness h_1

overlying the rest of the pit lake. This layer is $\Delta\rho$ lighter than the underlying fluid (Fig. 5).

A heat loss from the surface, $\hat{H}$ (W/m^2) results in thermally driven plumes that fall with a velocity

$$u_f = \left(\frac{\alpha g h_1 \hat{H}}{c_p \rho_0} \right)^{1/3}, \tag{6}$$

where α is the coefficient of thermal expansion and c_p is the specific heat of water. This plume impacts on the thermocline region making its energy available for an increase in potential energy of the water column. So that

$$\Delta E_p \text{per unit area } = \rho_0 C_k u_f^3 \Delta t, \tag{7}$$

where ΔE_p is the change in potential energy per unit area, C_k is an empirical coefficient from experiments and Δt is the time over which the plumes are generated. Two points are worth noting here; the area A that is assumed is that of the depth of the thermocline h_1. By maintaining this as a function of depth gives the model a quasi-second dimension.

Now we are able to calculate what change in h_1 is required to match this ΔE_p. This is calculated as

$$\Delta h = 2 \frac{\Delta E_p}{\Delta \rho g h_1}, \tag{8}$$

which through conservation of mass generates a new density difference of

$$\Delta \rho h_1 / (\Delta h + h_1)$$

. This however is not the total change in density at the thermocline as the surface cooling leads to a decreased $\Delta\rho$ by directly decreasing the temperature as well as through entrainment of the hypolimnion. This change in density is given by

$$\Delta \rho' = \frac{\alpha \hat{H}}{c_p h_1}.$$

If we now reverse the situation and apply surface heating it is assumed that this does not affect h_1 but via subsequent mixing it increases the averaged surface layer temperature and thus decreases $\Delta\rho$.

The effect of wind mixing is not parametrized as suggested by Ward et al. (1990) but rather we have chosen to use (2). This simply provides a Δh for a known time step.

The lack of meteorological information has led us to select model distributions that broadly suggest the Spring-Summer-Autumn cycle. The coarse calculations for (3) have already suggested *vertical* wind mixing is likely to be of minor importance. The model runs for 6 months with 12 hour time steps. The model provides a surface layer depth and temperature. It is possible to add a conservative tracer. In all cases, but the final case, described here the model starts with conditions similar to those found in the pit at the beginning of June (Fig. 6). That is a 10 metre deep surface layer 10 degrees warmer than that beneath. Inputs include heat fluxes across the surface, wind forcing and volumetric buoyancy inputs.

Run 2.1: Expected Heat Fluxes

The only input in this run was typical heating that might be expected; that is a mean nighttime cooling of 80 W/m^2 and a mean daytime "heating" of - 20 W/m^2, so that positive "heating" is actually a net loss of heat from the pit lake. The temporal variations are meant to represent enhanced cooling as winter approaches. The surface layer deepens less than expected (Fig. 7) although the actual surface layer temperature is acceptable.

Run 2.2: Enhanced Heat Fluxes

Here (Fig. 8) the heat fluxes have been boosted well above reasonable levels in an attempt to match the observations. However this results in marginal "improvement" as the temperatures in run 2.1 were already close; any asymmetric change in the heating, as required to deepen more rapidly, affects the temperature.

Run 2.3: Expected Heat Fluxes Plus Wind

Now (Fig. 9) we add in a fortnightly wind of 10 ms^{-1} which is an extreme situation. The results do not show any particularly enhanced deepening but it does lead to a slightly more rapid cooling. This in turn leads to the equivalent of "fall overturn" around day 170. Essentially the surface layer becomes more dense than that beneath. The curves after this day cannot be considered as representative of reality.

Run 2.4: Expected Heat Fluxes Plus Inflow

This run (Fig. 10) has no wind but does include the significant bouyancy inflow generated by the Tailings Pond Water. It provides results very similar to the observations (Fig. 6). This indicates that the thermal structure is significantly affected by this inflow.

Run 2.5: Deep Layer in Winter

The final run (Fig. 11) has no wind nor inflow. It has only the surface heat fluxes. This run was designed to see if the falling plumes from winter time cooling would impinge on a deeper (80 m) layer. In this parametrization this does not appear to happen - the winter cooling serves to only cool the upper layer. The upper layer is so thick that the parametrization has insufficient energy to provide any increase in potential energy. Consequently it does not matter too greatly what salinity is used to represent the lower layer if the energy does not penetrate this deeply.

§6. Discussion

The crude modeling indicates that the Tailings Pond water is crucial to the development of the surface layer. In addition the modeling indicates that overturning should occur.

Three major questions remain; how far does "overturning" penetrate? There is no data for deepening by thermal penetrative convection on this scale in the absence of horizontal motion. We have no way of knowing how deep the falling plumes will penetrate. The second question is how did the temperature profile of Fig. 4 evolve? Is it transient or permanent? An additional CTD profile recorded in May 1994 helps to answer this. It suggests that it is a transient effect and thus represents an unknown mechanism for vertical transport (see Appendix Vi). The final question regards the effect of seiches. The Wedderburn number described by (5) suggests that the possibility of internal waves cannot be ignored. Significant enhancement of mixing rates can occur if seiches are generated; data at positions across the lake are required to determine if this is the case.

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FIGURES

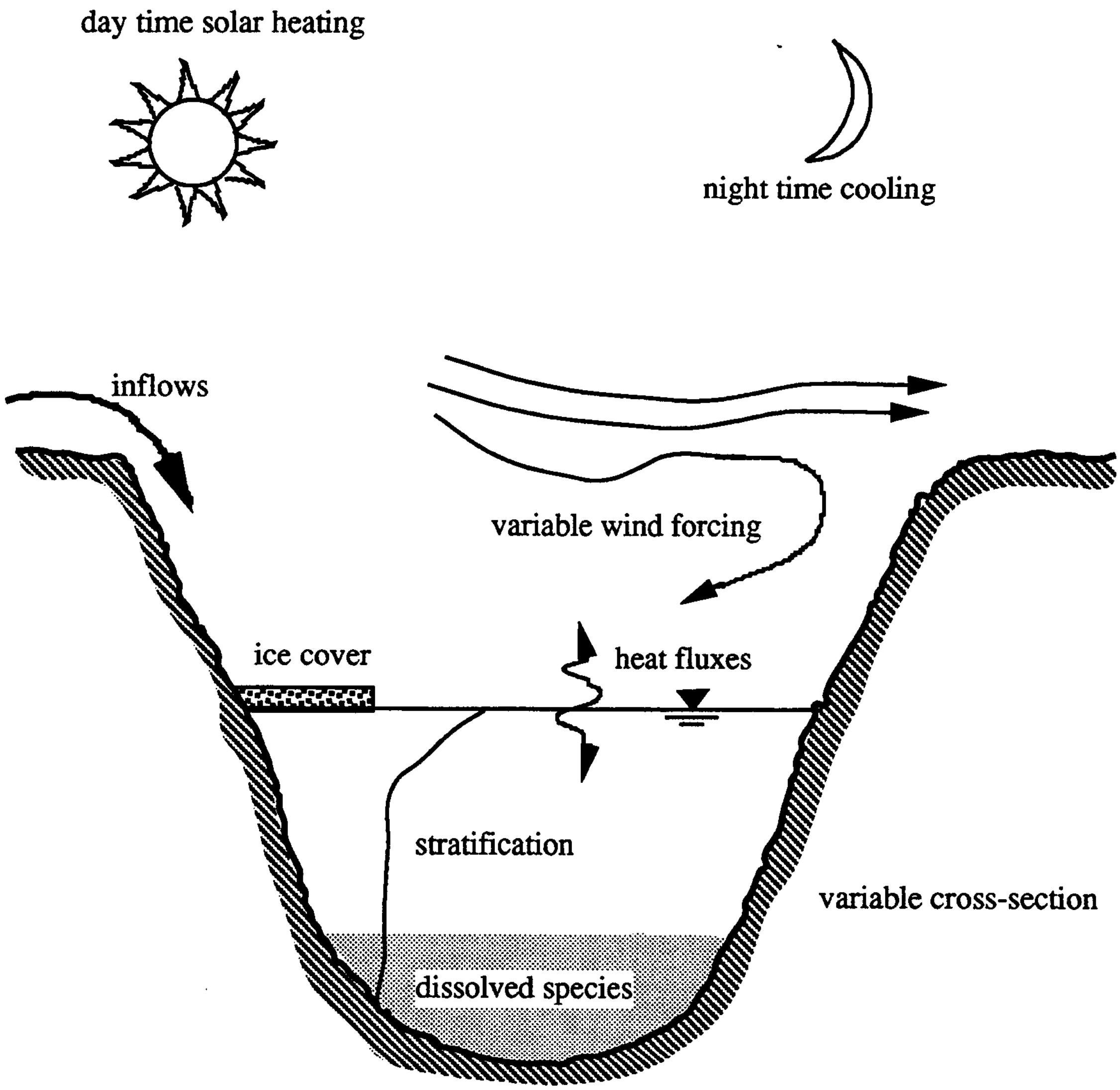
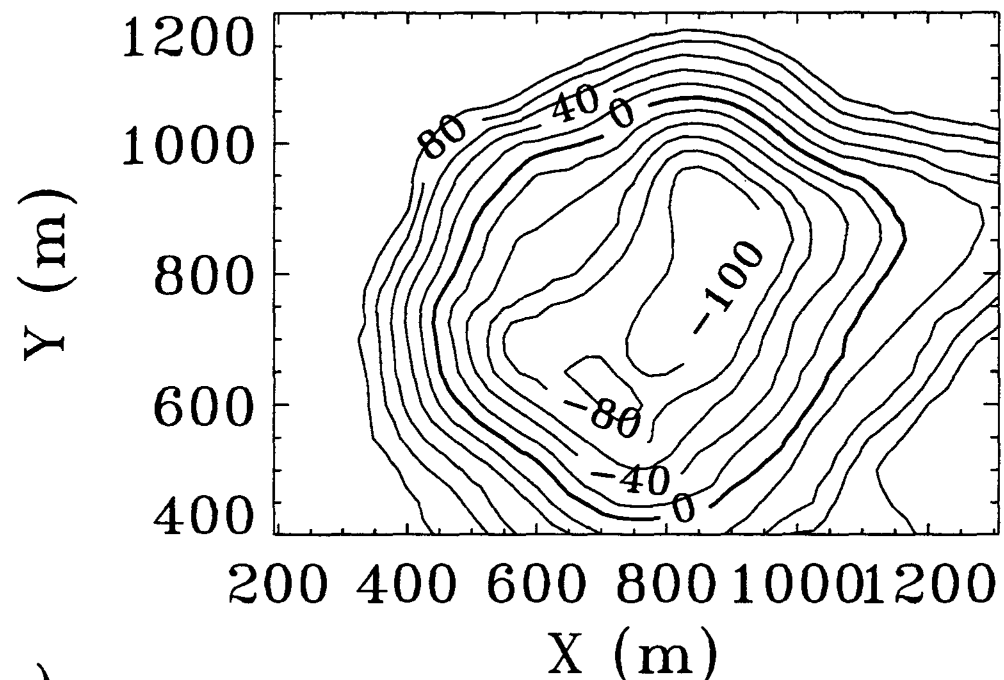
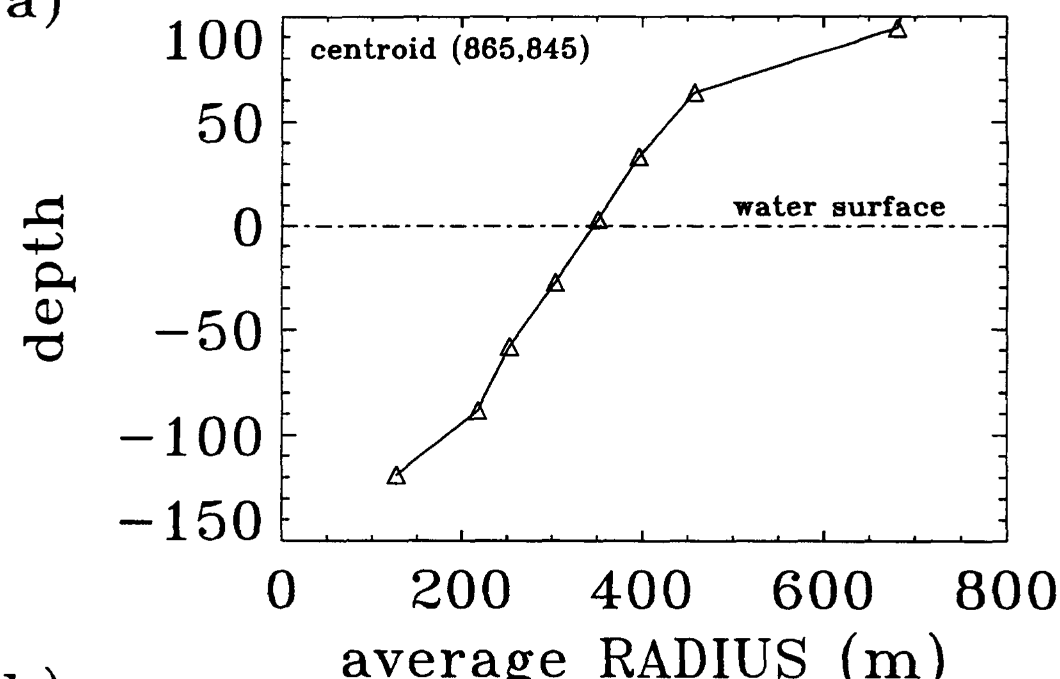

day time solar heating
night time cooling
inflows
variable wind forcing
ice cover
heat fluxes
stratification
variable cross-section
dissolved species

fig 1

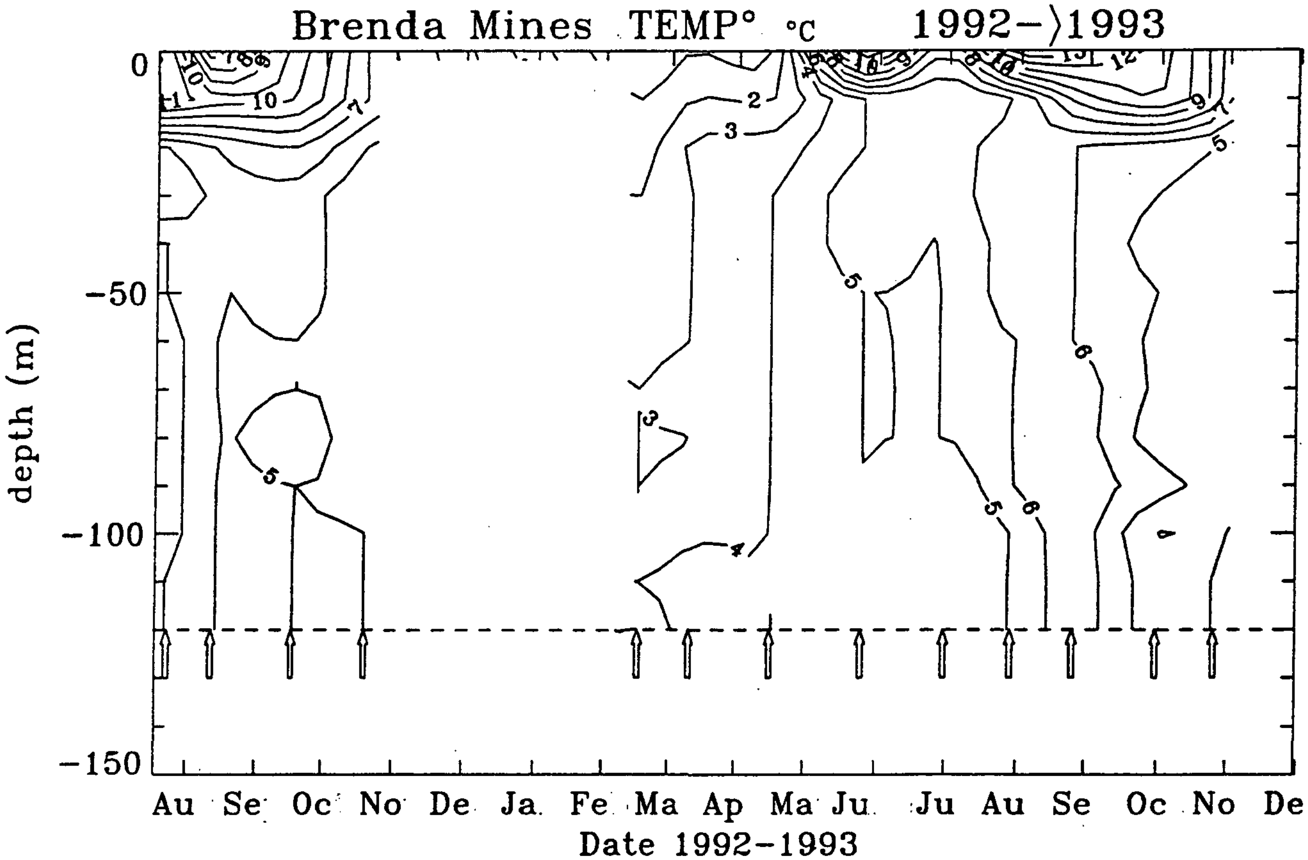

1200
1000
800
600
400
Y (m)
200 400 600 800 1000 1200
X (m)
80
40
0
-100
-80
-40
0

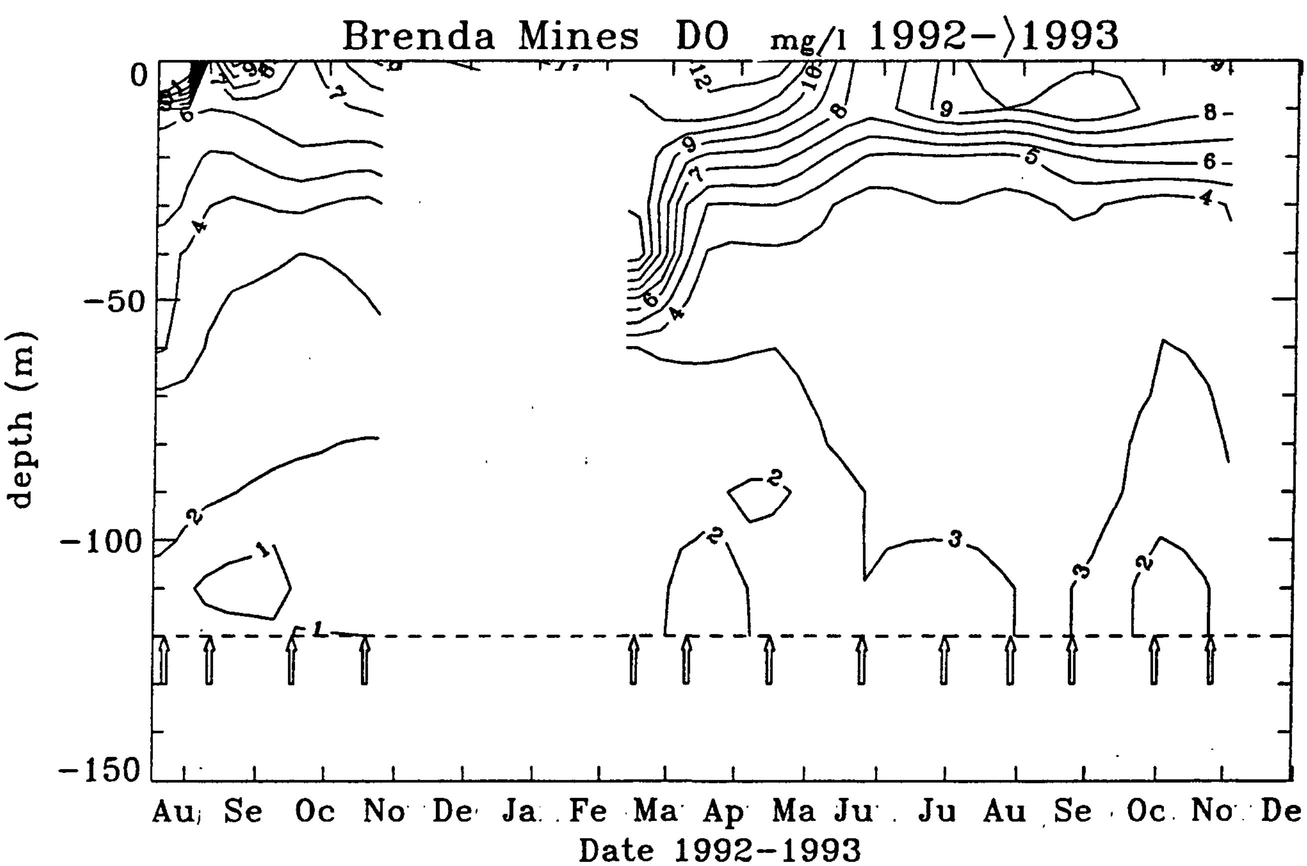
(a)


100
50
0
-50
-100
-150
depth
centroid (865,845)
water surface
0 200 400 600 800
average RADIUS (m)

(b)

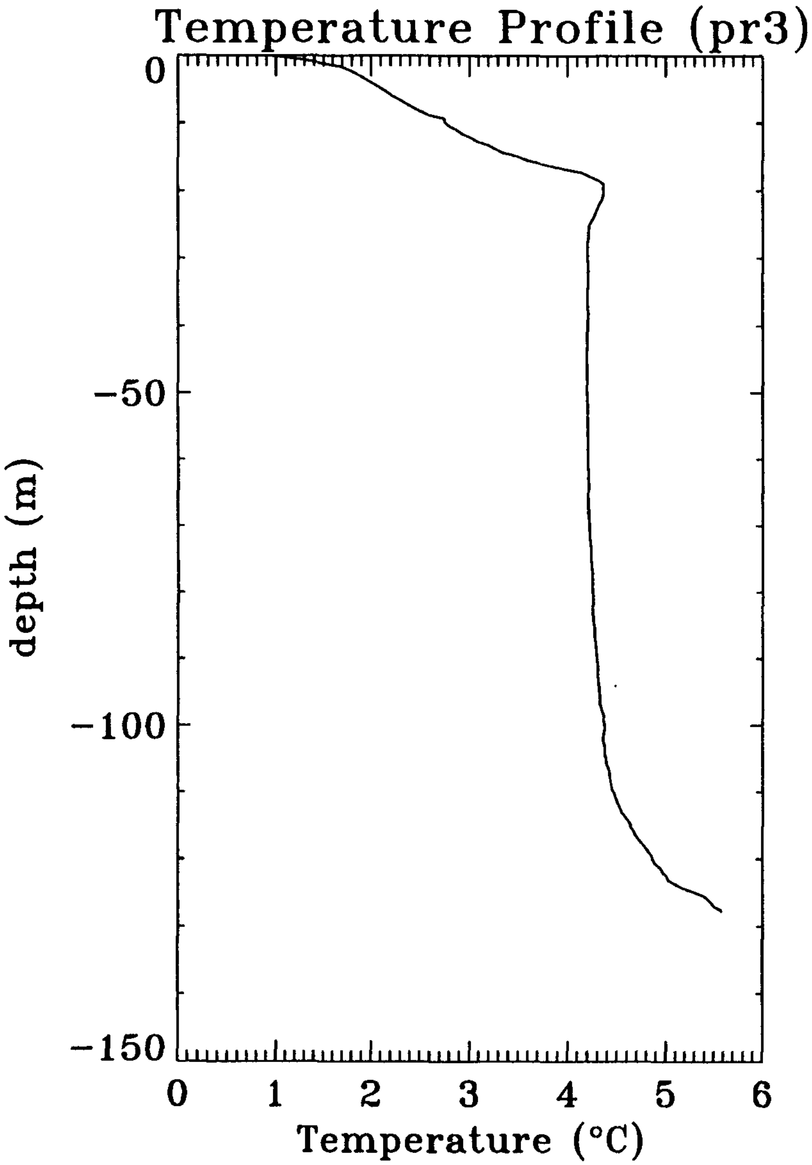
2

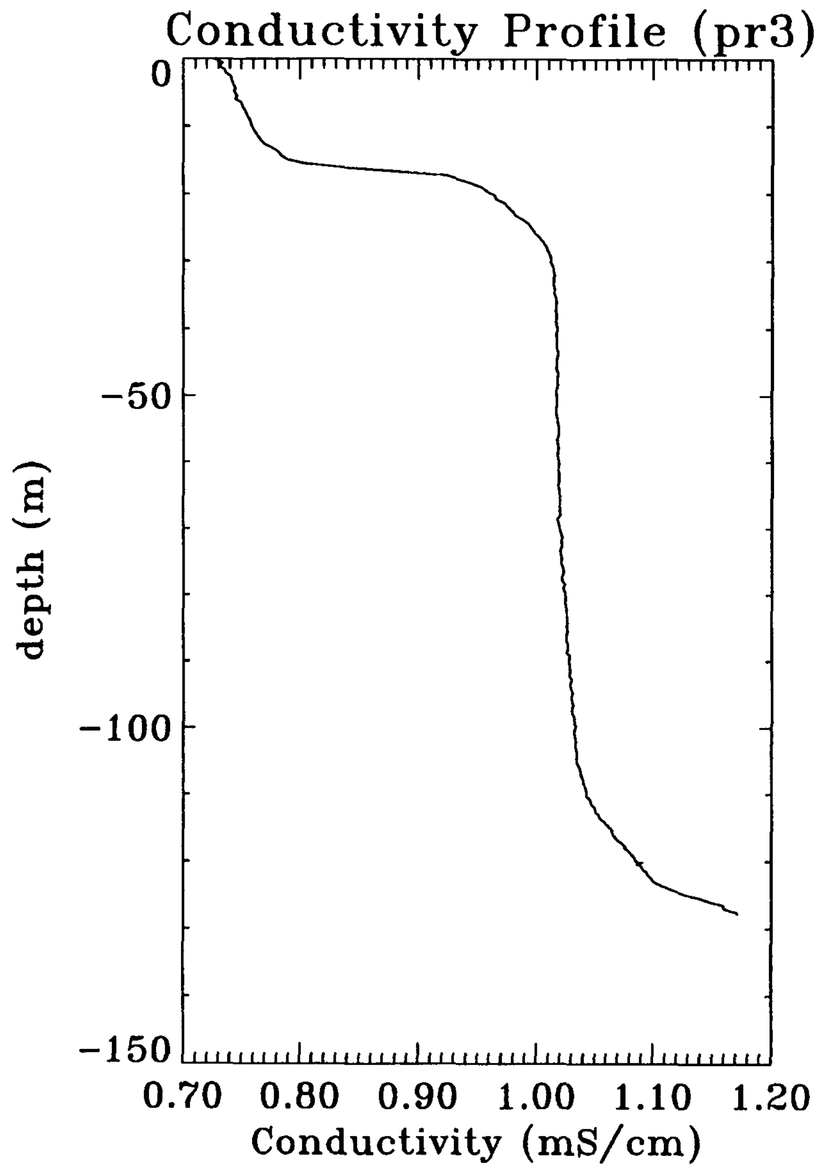




3

(STEVENS ET AL., 1994)





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4

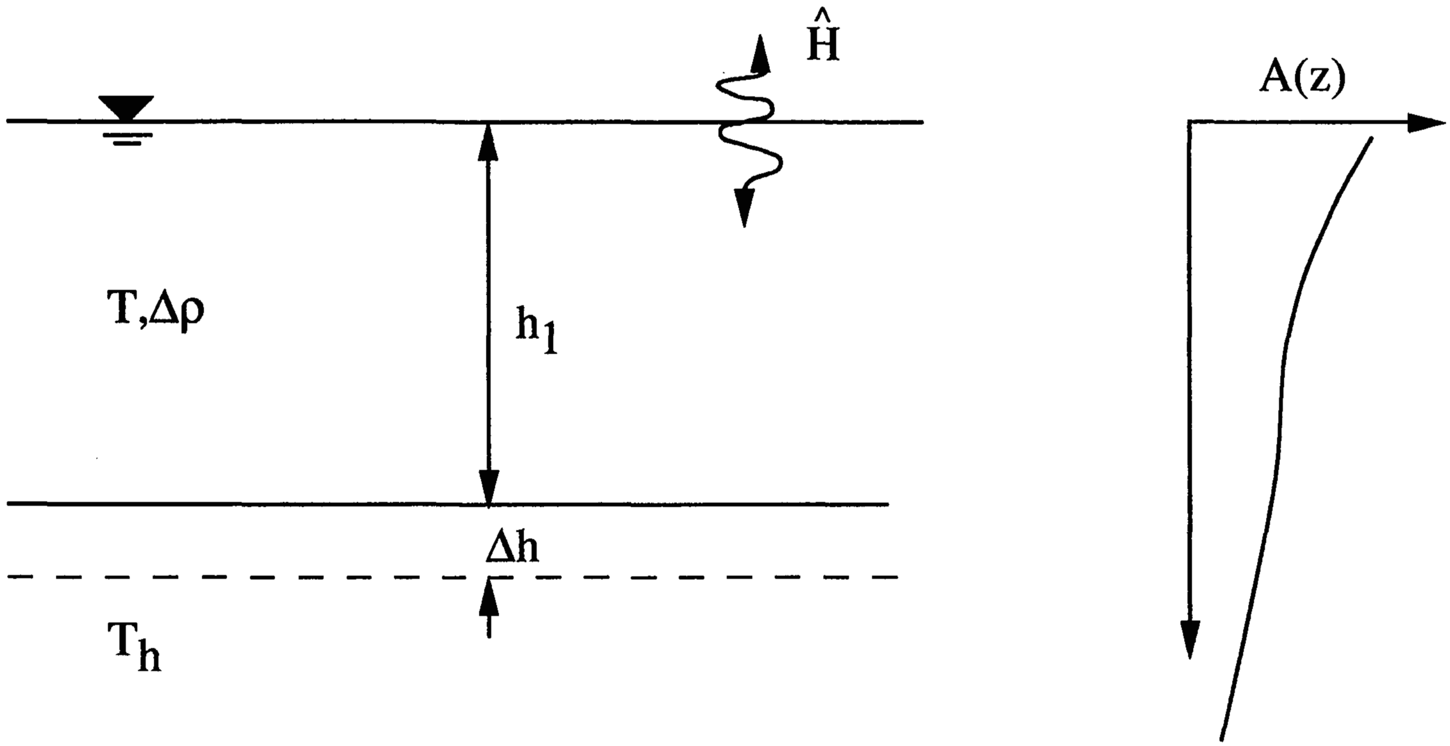


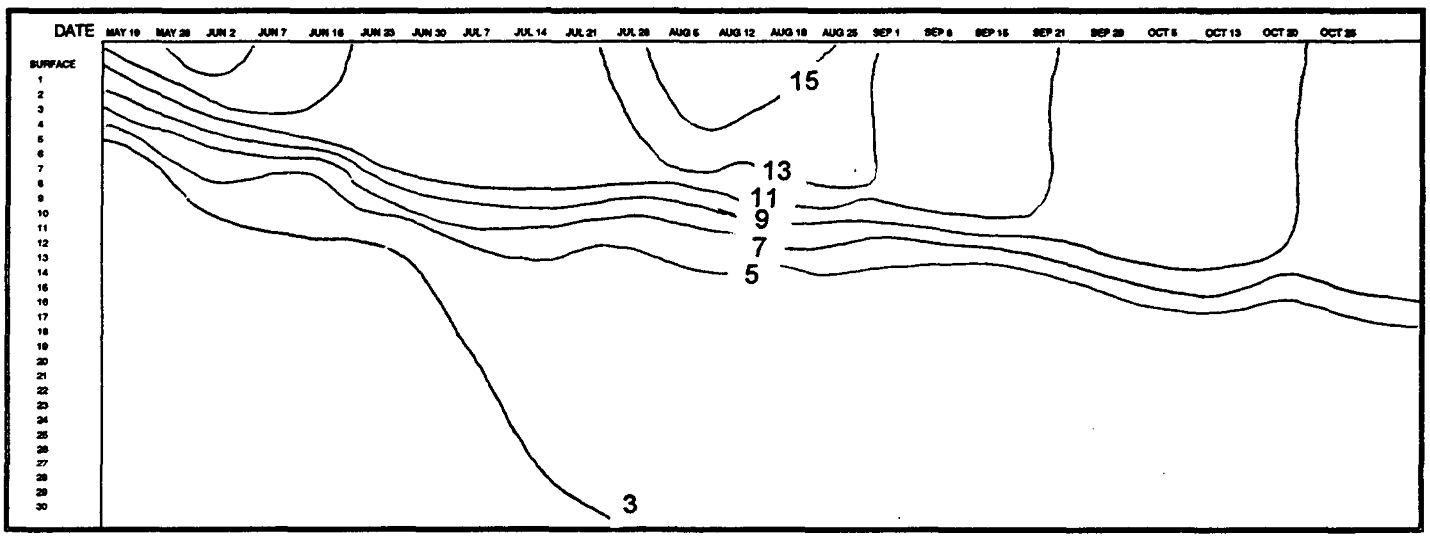
figure 5: model sketch

FIGURE 6 : Temperature and Dissolved Oxygen Profiles in the Pit Lake, 1993.

BRENDA MINES

PIT LAKE - 30 M TEMPERATURE PROFILE - 1993

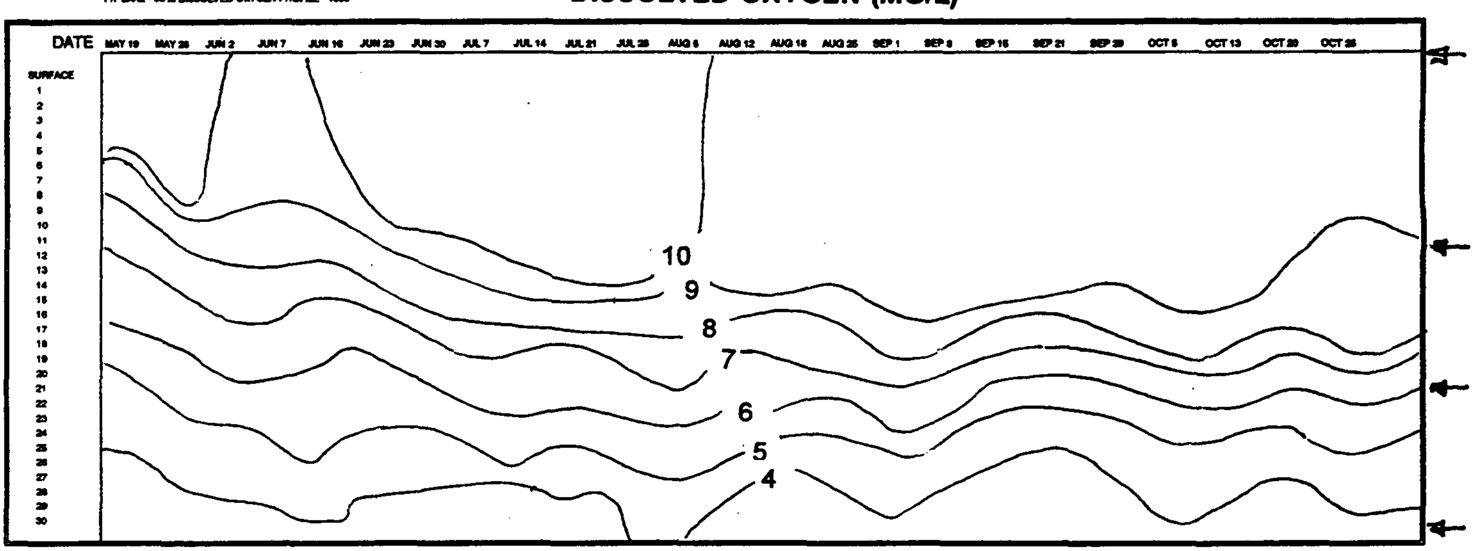
TEMPERATURE (° C)



BRENDA MINES

PIT LAKE - 30 M DISSOLVED OXYGEN PROFILE - 1993

DISSOLVED OXYGEN (MG/L)



from H. Larratt Data Report 1994.

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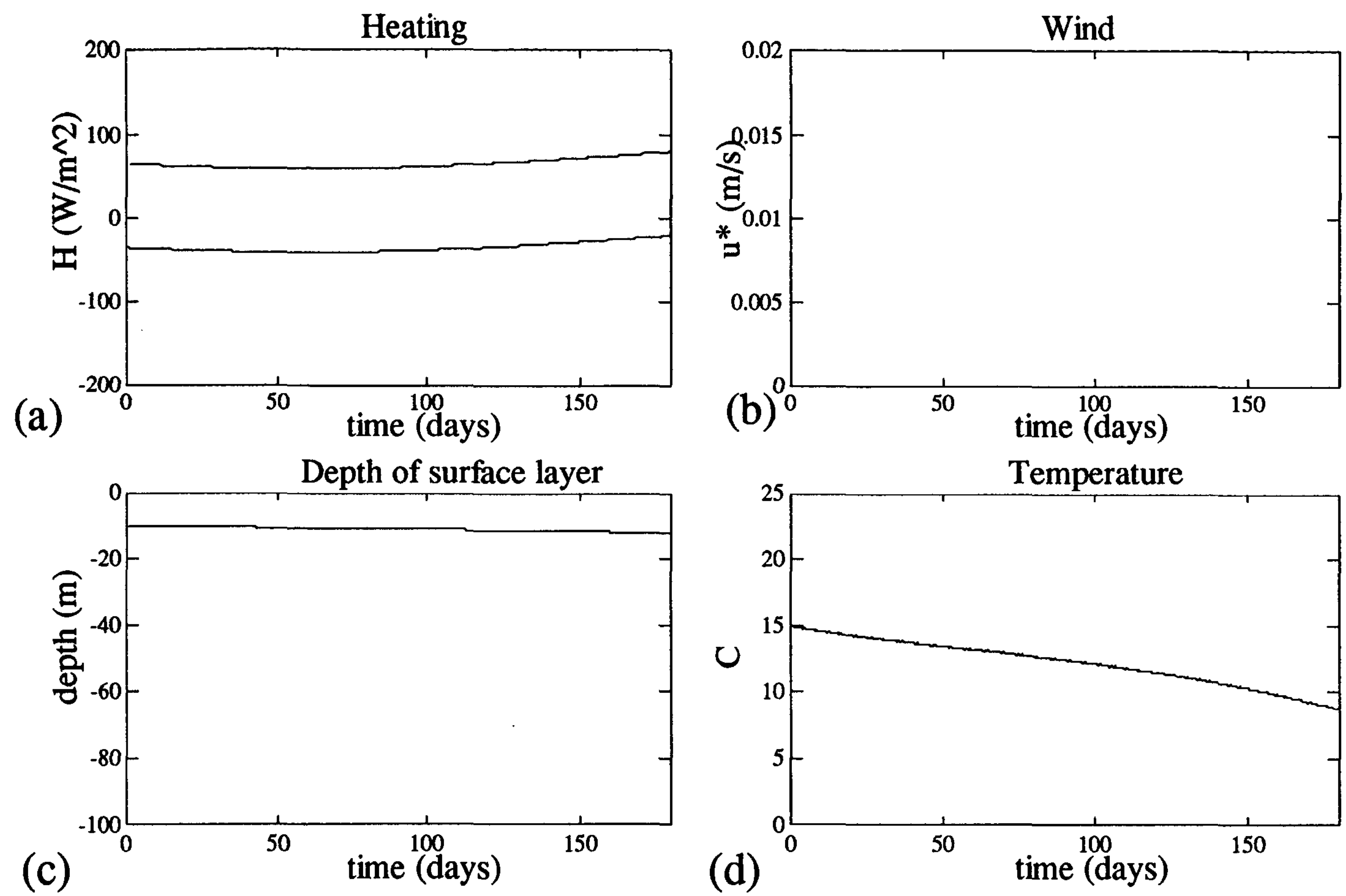
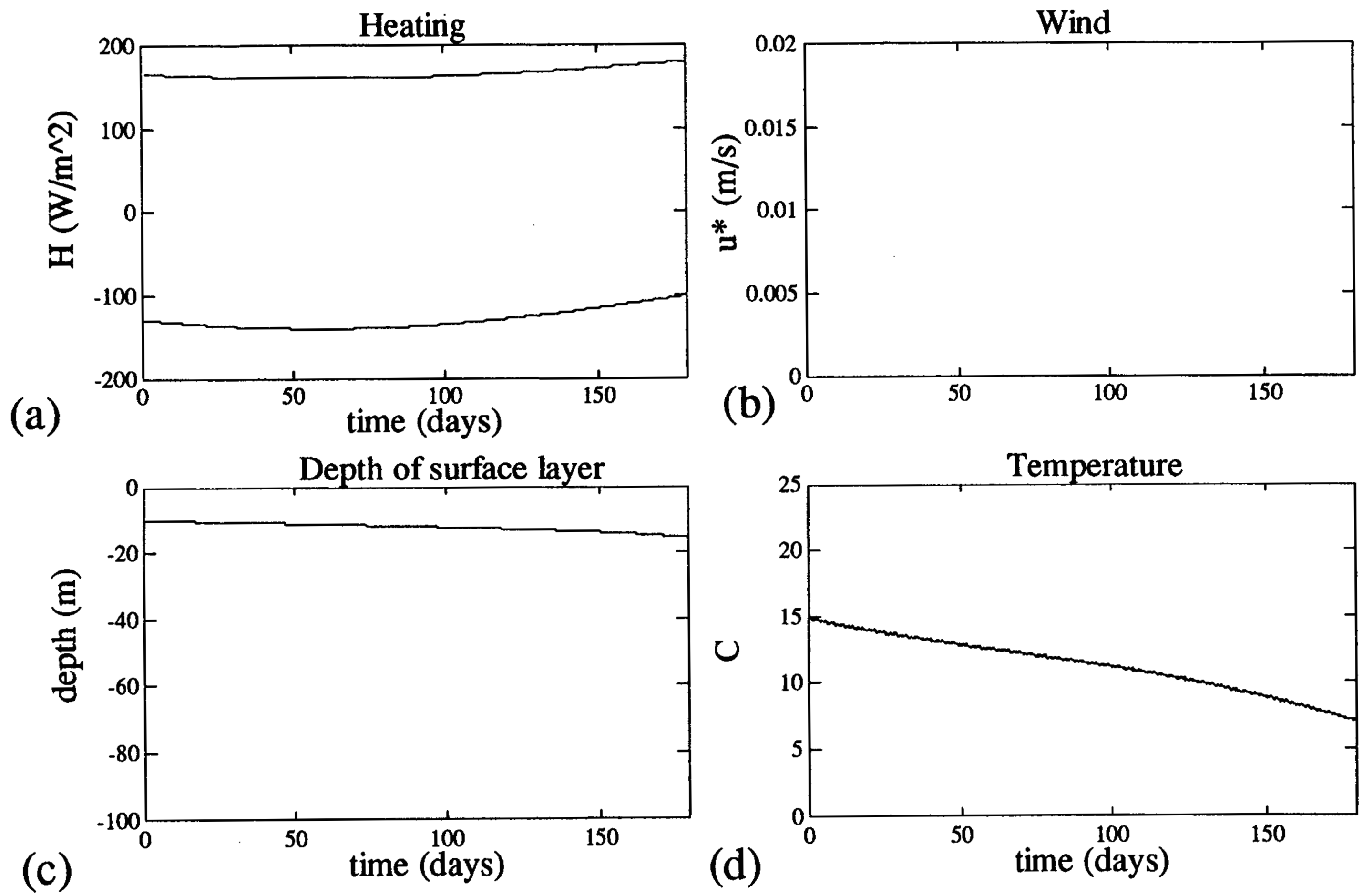

Heating
H (W/m^2)
200
100
0
-100
-200
0
50
100
150
time (days)
(a)
Wind
u* (m/s)
0.02
0.015
0.01
0.005
0
time (days)
(b)
Depth of surface layer
depth (m)
-20
-40
-60
-80
-100
time (days)
(c)
Temperature
C
25
20
15
10
5
time (days)
(d)

Run 2.1

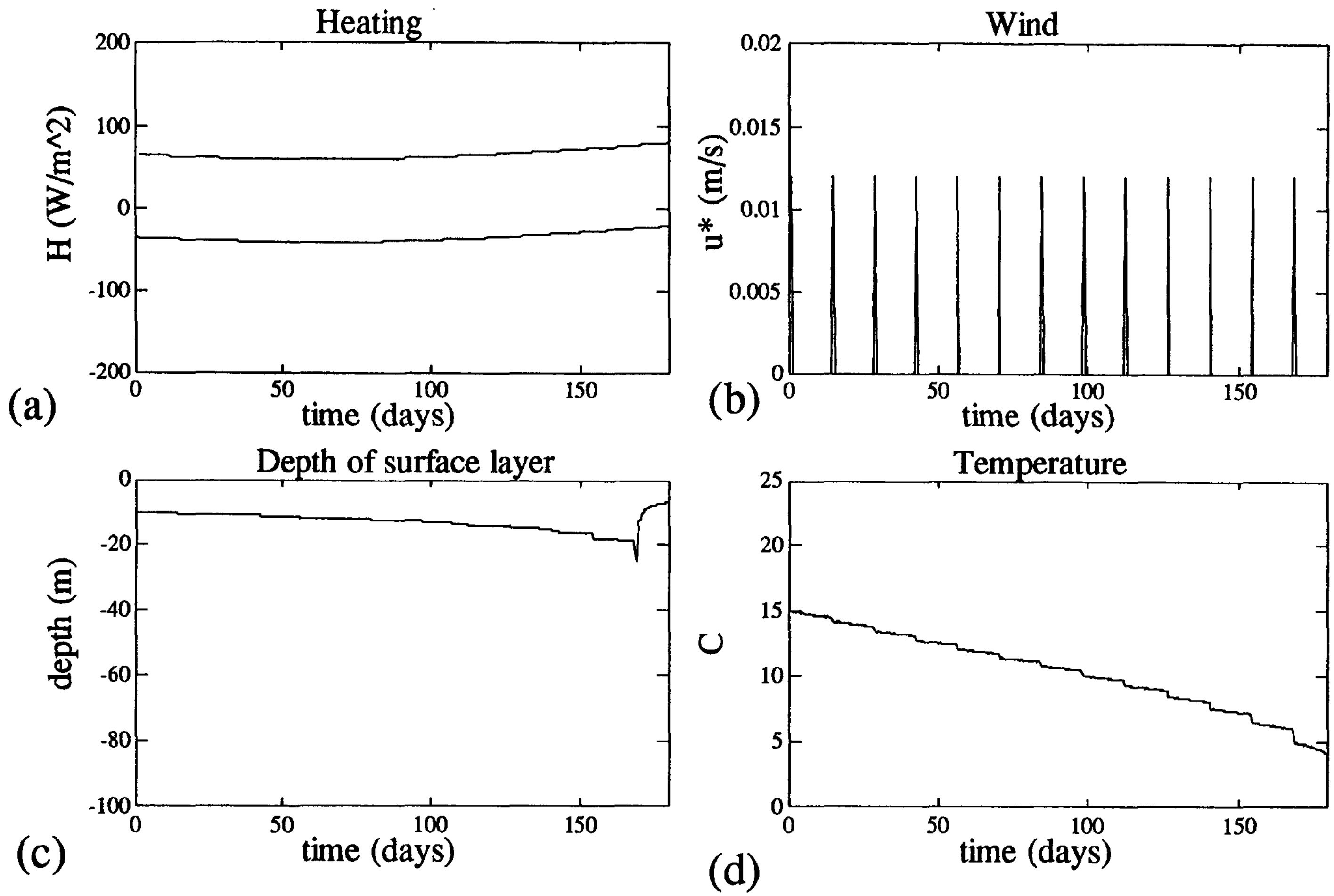
Fig. 7



Heating
H (W/m^2)
200
100
0
-100
-200
0
50
100
150
time (days)
(a)
Wind
u* (m/s)
0.02
0.015
0.01
0.005
0
0
50
100
150
(b)
Depth of surface layer
depth (m)
0
-20
-40
-60
-80
-100
0
50
100
150
time (days)
(c)
Temperature
C
25
20
15
10
5
0
0
50
100
150
time (days)
(d)

Run 2.2

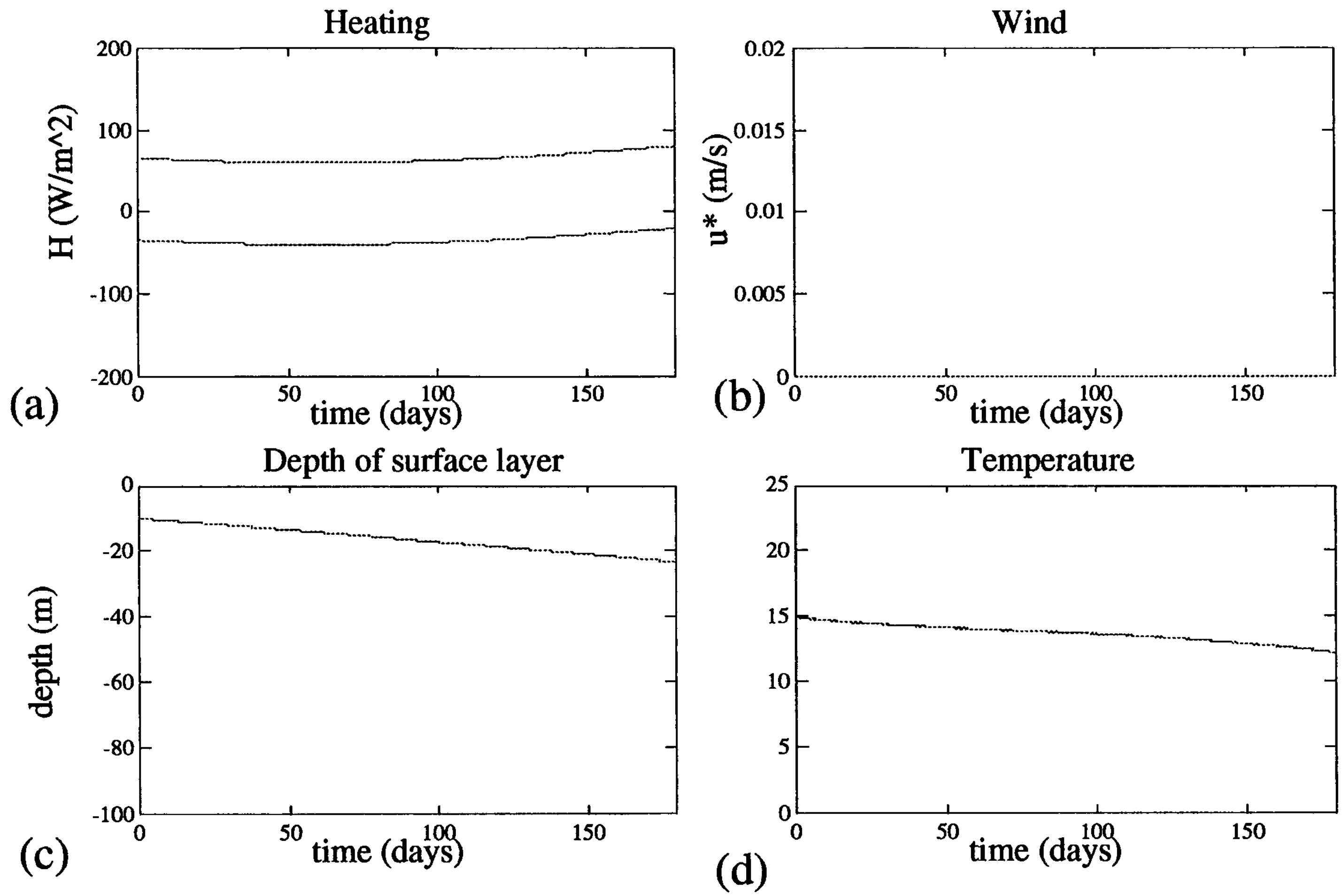
Fig. 8



Heating
H (W/m^2)
200
100
0
-100
-200
0
50
100
150
time (days)
(a)
Wind
u* (m/s)
0.02
0.015
0.01
0.005
0
0
50
100
150
time (days)
(b)
Depth of surface layer
depth (m)
0
-20
-40
-60
-80
-100
0
50
100
150
time (days)
(c)
Temperature
C
25
20
15
10
5
0
0
50
100
150
time (days)
(d)

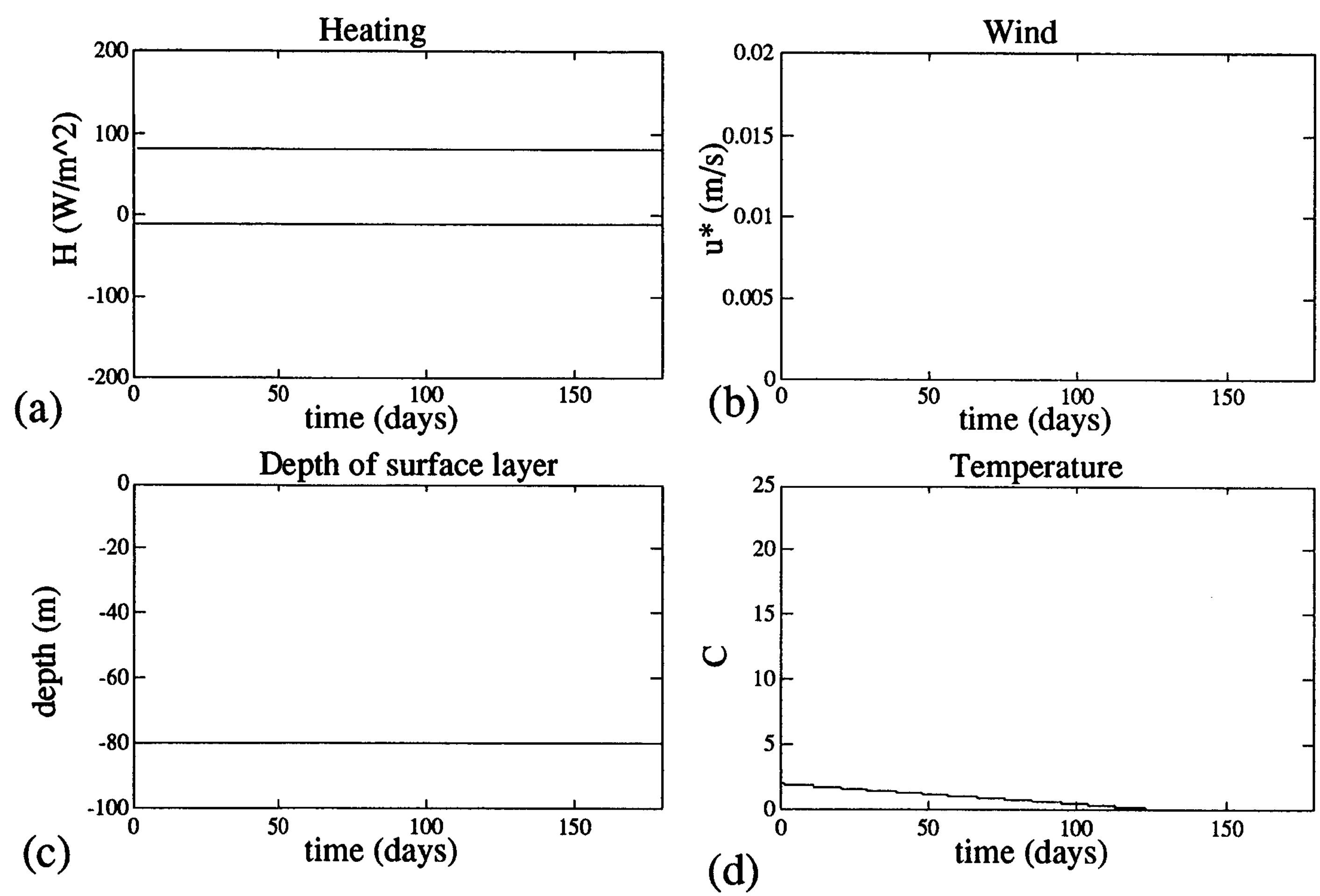
Run 2.3.2

Fig. 9



Run 2.4.2

fig 10



Run 2.5.1

Fig. 11

APPENDIX I: NOTATION

u_e =vertical entrainment velocity (ms^{-1}),
u_i =velocity of Tailings inflow (ms^{-1}),
u_* =friction velocity (ms^{-1}),
u_f =velocity of falling plume (ms^{-1}),
U =wind velocity (ms^{-1}),
L =Pit-Lake length (m),
$h_1,\ \Delta h$ =absolute and change in surface layer depth (m),
H_w =Height of pit walls *above* water surface (m),
circum =1/4 of cicumference at surface (m),
δ =tailing inflow layer thickness (m),
Q =inflow ($m^3 s^{-1}$),
ΔE_p =change in Potential Energy (J),
$\hat{H}$ =Heat flux (W/m^2),
C_1 =entrainment coefficient ,
C_k =plume energy conversion coefficient,
C_D =air-water drag coefficient,
A =surface layer aspect ratio,
R_i =Richardsons Number of surface layer,
Ri_i =Richardsons Number of inflow,
Re =Reynolds Number,
W =Wedderburn Number,
α =coefficient of thermal expansion ($^\circ C^{-1}$),
c_p =specific heat of water ($Jkg^{-1}{}^\circ C^{-1}$),
ν_a =viscosity of air ($m^2 s^{-1}$),
g' =modified gravity (ms^{-2}),
g =gravitational acceleration (ms^{-2}),
$\Delta\rho$ =density difference at thermocline (kgm^{-3}),
$\Delta\rho_i$ =density difference between surface and inflow (kgm^{-3}),
$\Delta\rho'$ =change in density difference (kgm^{-3}),
ρ_0 =average density (kgm^{-3}),
ρ_a =air density (kgm^{-3}),

APPENDIX II: CODE

```
function output=brenda2(watts,wind,Q,dt);
% routine to look at surface layer penetration
% thru penetrative convection
% clsmar94..based on Fischer etal & Ward etal

% INPUTS......................................
% watts is rate of cooling....
% wind is ustar (m/s)....
% dt is time step in decimal days.....
% nt is number of timesteps....
% Q is  inflow in m^3/s.....
nt=length(watts);

% convert time to seconds...
dts=dt*3600*24;

% CONSTANTS........................
grav        =      9.81;       %gravity obviously
alpha       =    1.8e-4;  % coeff thermal expan...use poly below
rho0        =      1000;  % density average
ceepee      =      4882;  % specific heat
visc        =    1.0e-6;  % kinem. visc
t_poly      =    [6.536332e-9,-1.120083e-6,1.001685e-4...
      ,-9.095290e-3,6.793952e-2,999.842594]; %polynomial to
                                               % calc tho from T
alpha_poly = [2.6667e-12,-2.3030e-10,9.4848e-09 ...
     ,-3.4818e-07,1.8334e-05,-6.8002e-05]; %poly to calc
                                             % coeff therm exsp
% COEFFICIENTS................................
ceekay      =      0.13;  % Imberger....
ceetee      =      0.5 ;  %  "   "
cstar       =      0.23;  % Kranenburg

% INITIAL CONDITIONS..........................
h           =        80;  % depth of initial layer (m) [10]
temp        =        2;  % initial temp of top layer (C) [15]
temphyp     =         4;  % temp of hypolimnion layer in C [5]
surfA       = pi*350^2;  % surface area.... (m^2)
deetemp     =         2;  % deg. C of inflow over pit...
% storage vectors....
output=zeros(nt,3); % [h,rho ,time]

output(1,1)=h;
output(1,2)=temp;
output(1,3)=polyval(t_poly,temphyp)-polyval(t_poly,temp);
for i=2:nt % start time loop...............

% get appropriate alpha
alpha=polyval(alpha_poly,temp);

% calculate plume speed uplume...(Ward et al)
uplume=(watts(i)*alpha*grav*h/(rho0*ceepee))^0.333;
```

```
% keep coeff as Ck..possibly change?
coeff = ceekay ;

% area at depth h....
Area = pi * (350 - (460/120)*h)^2;

% calculate change in potential energy
% in time step dt..due to pluming...
% only if heat loss.........

if watts(i) > 0   % COOLING.....~~~~~~~~~~~~~~~~~~

% total energy reqd per unit rate of deepening..
delEpdz=Area*ceetee*uplume^2 ...
                   + 0.5*(surfA+Area)*alpha*(temp-temphyp)*grav*h;

% work done by penetrative convect
workdone=Area*dts*coeff*uplume^3;

% calculate required change in surface layer....
delh=workdone/delEpdz;

% check for +ve...
%if delh < 0
%delh=0;
%end

% calulate entrainment loss of heat....
deltemp1=(temp-temphyp)*delh/(h+delh); %

% calulate thermal component of heat change....
desratio=2.*surfA/(surfA+Area);
deltemp2=arearatio*watts(i)*dts...
    /(ceepee*rho0*h); %

else   % HEATING........

      deltemp1=0;  % no entrainment with heating....
      arearatio=2.*surfA/(surfA+Area);
      deltemp2=arearatio*watts(i)*dts...
    /(ceepee*rho0*h); %

      delh=0.; % nochange in layer depth.....

end %~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

% a +ve watts (cooling) => decrease in density difference...
% and a -ve leads to the opposite......
```

```
%new temperature ...
temp = temp - deltemp1 -deltemp2 ;

if temp < 0.
temp=0. ;
end

h=h+delh;  %......new layer thickness.....
% check for +ve...
if h < 0
h=0;
end


% wind mixing.........
if wind(i) > 0
delrho=polyval(t_poly,temphyp)-polyval(t_poly,temp);
  Ri      = (delrho/rho0)*grav*h/wind(i)^2 ; % Richardson Number....
 winddelh  = cstar * Ri^(-1) * wind(i) * dts;
   temp=temp*(h/(h+winddelh));
  h=h+winddelh;
end

% inflow..............................
if Q(i) >0
avgarea=(surfA+Area)/2;
flowdelh=Q(i)*dts/avgarea;
newtemp=(temp*h + flowdelh*(temp+deetemp))/(h+flowdelh);

h=h+flowdelh;
temp=newtemp;
end  %..............................


%evaluate density difference
delrho=polyval(t_poly,temphyp)-polyval(t_poly,temp);

output(i,1)=h;
output(i,2)=temp;
output(i,3)=delrho;



end % endloop.....

out=real(out); % just in case.......

end
```

Appendix III

AVAILABLE DATA FOR OTHER FILLED PITS

In 1982, 1992 and 1993, Environment Canada (DOE) personnel collected water samples and profiles at seven filled pits in British Columbia, the Yukon Territory, and Washington. Sample collection and handling followed DOE protocols, with DOE's West Vancouver lab performing the analyses. A Hydrolab Surveyor II instrument provided dissolved O_2, pH, conductivity and temperature.

Table 1A-1G, Brenda Mines Ltd: This 33,000 tpd copper-molybdenum mine opened in 1970 and closed in 1990 with a two-year temporary closure 1983-1985. It has filled to its present depth from runoff and waters pumped in from the tailings pond. Water quality data reported here confirms and supplements the very large data set collected by Brenda Mines Ltd and reported elsewhere.

Table 2A-2C, Nickel Plate South: Homestake Canada Inc now owns this 3400 TPD gold mine near Hedley, BC, first opened in 1987. The small south pit was mined in 1988 and 1989 and allowed to fill. Since DOE sampling in 1991, the pit has been backfilled with waste rock.

Table 3A-3C, Gibraltar West pit: The large Gibraltar copper mine, 38,000 TPD at full capacity, first opened in 1972 and mined several pits on the property before closing temporarily in the fall of 1993. Waters in the small west pit shows no evidence of the oxidation and increased metals content shown by waste rock and waters elsewhere on the property, from which the company obtains anode copper by leaching and solvent extraction (SX/EW).

Table 4A-4D, War Eagle pit: New Imperial Mines (Whitehorse Copper Mines Ltd) mined the small War Eagle pit near Whitehorse, Yukon, between 1969 and 1971. Until the early 1980's the city then used the pit area and ramp for disposal of municipal waste. Pit waters reflect this runoff contamination in elevated chloride and ammonia. The limited data set shows the absence of oxygen, the decrease in nitrate, and the increase in ammonia at depth, which suggests meromixis.

Table 5A-5C, Wellpinit, Wa: The Midnite uranium mine on the Wellpinit Reservation in north central Washington has two small pits. DOE sampled only the lower or southern pit. Seepage from this pit is collected downslope and pumped back. This 'recycling' of waters and high evaporation in this drybelt area concentrates pit waters, which in turn precipitate a gelatinous aluminum hydroxide. Note that mixing seems independent of high salt concentrations.

Table 6A-6C, Highland Valley Copper: This mine, Canada's largest metal mine, has assembled three adjacent mining properties which have produced copper-molybdenum ore since 1963. The large pit sampled, Highmont West, was mined between 1980 and 1983 and has filled from runoff since that date. Water quality resembles that at Brenda and Similco, except for elevated molybdenum.

Table 7A-7C, Similco-Ingerbelle: Similco Mines Ltd mined the Ingerbelle pit beginning in 1972, and has allowed it to fill from runoff since 1984. Pit size and water quality resemble those found at Brenda and Highland Valley Copper.

TABLE 1A

SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, SEPT 24, 1991

Time	Diss Depth m.	O2 (mg/l)	Temp (oC)	pH	CondRedox (mmhos/cm)(mv)
-	1	7.40	13.67	7.74	1.590.207
-	5	7.65	12.84	7.73	1.620.205
-	10	7.55	12.79	7.73	1.610.203
-	15	7.47	12.76	7.73	1.600.202
-	20	3.89	8.87	7.36	1.700.218
-	25	4.12	4.89	7.29	1.860.217
-	30	4.11	4.24	7.28	1.870.216
-	35	4.08	4.11	7.27	1.870.215
-	40	4.04	4.11	7.26	1.890.214
-	45	4.00	4.01	7.26	1.850.214
-	50	3.90	4.01	7.25	1.860.212
-	55	3.85	3.99	7.25	1.850.212
-	60	3.81	3.96	7.25	1.850.212
-	65	3.71	3.96	7.25	1.860.211
-	70	3.61	3.94	7.25	1.830.210
-	75	3.56	3.92	7.25	1.850.209
-	80	3.36	3.91	7.25	1.850.208
-	85	3.16	3.88	7.25	1.850.208
-	89.7	2.85	3.85	7.25	1.850.202

TABLE 1A

SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, SEPT 24, 1991

Time	Diss Depth m.	O2 (mg/l)	Temp (oC)	pH	Cond (mmhos/cm)	Redox (mv)
-	1	7.40	13.67	7.74	1.59	0.207
-	5	7.65	12.84	7.73	1.62	0.205
-	10	7.55	12.79	7.73	1.61	0.203
-	15	7.47	12.76	7.73	1.60	0.202
-	20	3.89	8.87	7.36	1.70	0.218
-	25	4.12	4.89	7.29	1.86	0.217
-	30	4.11	4.24	7.28	1.87	0.216
-	35	4.08	4.11	7.27	1.87	0.215
-	40	4.04	4.11	7.26	1.89	0.214
-	45	4.00	4.01	7.26	1.85	0.214
-	50	3.90	4.01	7.25	1.86	0.212
-	55	3.85	3.99	7.25	1.85	0.212
-	60	3.81	3.96	7.25	1.85	0.212
-	65	3.71	3.96	7.25	1.86	0.211
-	70	3.61	3.94	7.25	1.83	0.210
-	75	3.56	3.92	7.25	1.85	0.209
-	80	3.36	3.91	7.25	1.85	0.208
-	85	3.16	3.88	7.25	1.85	0.208
-	89.7	2.85	3.85	7.25	1.85	0.202

TABLE 1B

SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, SEPT 24, 1991

Depth* (m)	Diss. O2** (mg/L)	Temp** (C)	Lab pH	Lab Cond. (umhos/cm)	Alkalinity (mg/L)	Total Hardness (mg/L)	Hardness [as CaCO3] (mg/L)	Sulfate (mg/L)	Nitrite & Nitrate (mg/L)	Ammonia (mg/L)	Total P (mg/L)
1	7.40	13.67	8.0	1550	--	375	371	330	3.33	0.075	0.009
15	7.47	12.76	8.0	1550	--	403	399	370	3.14	0.063	0.024
30	4.11	4.24	7.8	1790	--	492	487	420	5.79	0.014	0.007
45	4.00	4.01	7.8	1790	--	509	503	450	6.04	0.006	0.014

* = By calibrated pulley. ** From Table 1A. -- = not performed. < = equal to, or less than concentration detection limit. Analyses for **sulphide** gave concentrations equal to or below detection limits.

TABLE 1C

SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, Sept 24, 1991

Depth* m	B (mg/l)	Ba (mg/l)	Ca (mg/l)	Co (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	K (mg/l)	Mg (mg/l)	Mn (mg/l)	Mo (mg/l)	Na (mg/l)	Si (mg/l)	Ti (mg/l)	V (mg/l)	Zn (mg/l)
1	.11	.052	134	<	<	.012	.016	25	24.1	.006	1.46	140	3.21	.005	.02	.007
15	.1	.052	134	<	<	.009	.024	24	24	.005	1.45	141	3.21	.004	<	.005
30	.13	.058	172	.006	.007	.01	.048	23	29.8	.263	1.7	162	4.38	.007	.02	.1
45	.1	.057	167	.008	.01	.019	.044	23	29.3	.258	1.65	161	4.32	.006	.02	.094

* = By calibrated pulley.< = equal to, or less than concentration detection limit. Concentrations are for total metals. Analyses for **Al, Ag, As, Be, Cd, Ni, P, Pb, Sb, Se, Si, Sn** showed concentrations equal to or below detection limits.

TABLE 1D

SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, June 23, 1992

Time	Depth m.	Diss O2 (mg/l)	Temp (oC)	pH	Cond (mmhos/cm)	Redox (mv)
1330	1	10.57	19.56	8.74	1.72	0.337
1340	10	7.88	8.28	8.05	1.79	0.360
1344	20	5.57	4.19	7.75	2.00	0.371
1347	30	3.83	4.26	7.66	2.09	0.373
1349	40	2.71	4.33	7.64	2.12	0.373
1350	50	2.55	4.28	7.64	2.10	0.373
1352	60	2.46	4.24	7.63	2.14	0.372
1354	70	2.39	4.20	7.63	2.12	0.372
1357	80	2.33	4.13	7.65	2.18	0.371

TABLE 1E

SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, JUNE 23, 1992

Depth* (m)	Diss. O2** (mg/L)	Temp** (C)	Lab pH	Lab Cond. (umhos/cm)	Alkalinity (mg/L)	Total Hardness (mg/L)	Hardness [as CaCO3] (mg/L)	Sulfate (mg/L)	Nitrite & Nitrate (mg/L)	Ammonia (mg/L)	Filterable Residue (mg/L)
1	10.57	19.56	8.4	1390	47	363	366	340	1.6	0.097	990
22	5.43	4.21	7.9	1660	76	484	489	410	4.43	0.012	1230
44	2.65	4.30	7.9	1720	83	513	519	410	4.28	0.012	1270
66	2.42	4.22	7.8	1720	83	510	516	410	4.65	0.018	1270
88	2.33	4.13	7.8	1740	85	518	524	360	4.81	0.05	1280

* = By calibrated pulley. ** From Table 1D. All analyses for **sulphide** and **total phosphorous** gave concentrations equal to or below detection limits.

TABLE 1F

SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, JUNE 23, 1992

Depth* m	Al (mg/l)	B (mg/l)	Ba (mg/l)	Ca (mg/l)	Cu (mg/l)	Fe (mg/l)	K (mg/l)	Mg (mg/l)	Mn (mg/l)	Mo (mg/l)	Na (mg/l)	Si (mg/l)	Sr (mg/l)	Zn (mg/l)
1	<	.09	.045	108	<	.029	21	22.7	.041	1.93	123	1.73	2.72	.003
22	.05	.11	.063	148	.013	.044	22	27.6	.14	2.03	144	1.66	3.92	.05
44	.07	.1	.063	157	.015	.065	21	29.5	.241	1.95	152	1.93	4.3	.07
66	.06	.11	.058	156	.018	.045	21	29.5	.239	1.98	151	1.93	4.29	.081
88	.08	.11	.058	158	.021	.087	21	30.1	.258	1.97	154	2.02	4.44	.081

* = By calibrated pulley. Concentrations are for extractable metals. < = equal to, or less than concentration detection limit. All analyses for **Ag, As, Be, Cd, Co, Cr, Ni, P, Pb, Sb, Se, Sn, Tl, V** showed concentrations equal to or below detection limits.

TABLE 1G

SUB-SURFACE WATER QUALITY, BRENDA PIT, MARCH 10, 1994

Depth m.	Diss O2 (mg/l)	Temp (oC)	pH	Cond (mmhos/cm)	Redox (mv)
0.5	10.68	1.02	1.218	8.23	0.309
10.0	10.82	2.70	1.215	8.05	0.318
15.0*	9.64	3.43	1.240	8.00	0.314
17.5*	8.90	3.81	1.290	7.91	0.317
18.0*	7.87	4.08	1.400	7.79	0.321
20.0	6.24	4.28	1.490	7.64	0.327
20.0*	5.20	4.41	1.510	7.56	0.325
30.0	3.06	4.25	1.580	7.49	0.331
30.0*	2.59	4.28	1.540	7.48	0.327
40.0	2.42	4.26	1.580	7.49	0.330
50.0	2.22	4.26	1.600	7.47	0.330
60.0	2.01	4.26	1.600	7.49	0.328
70.0	1.46	4.28	1.600	7.47	0.329
80.7	0.98	4.32	1.600	7.47	0.328
91.0	0.67	4.35	1.620	7.46	0.329
99.0	0.35	4.42	1.600	7.45	0.328

*Readings on return of sensor to surface

TABLE 2A

SUB-SURFACE WATER QUALITY, NICKEL PLATE SOUTH PIT, SEPT. 23, 1991

Depth m.	Diss O2 (mg/l)	Temp (oC)	pH	Cond (mmhos/cm)	Redox (mv)
1	8.50	10.91	7.60	1.205	0.206
2	8.48	10.63	7.67	1.223	0.202
5	8.62	10.64	7.69	1.236	0.202
6	5.50	9.91	7.39	1.361	0.208
7	2.87	7.89	7.39	1.49	0.218
10	1.63	6.25	7.48	1.52	0.220
15	0.99	5.29	7.42	1.54	0.220
18.5	0.62	5.11	7.41	1.54	0.218

TABLE 2B

SUB-SURFACE WATER QUALITY, NICKEL PLATE SOUTH PIT, SEPT. 23, 1991

Depth* (m)	Diss. O2** (mg/L)	Temp** (C)	Lab pH	Lab Cond. (umhos/cm)	Total Phosphorous (mg/L)	Total Hardness (mg/L)	Hardness [as CaCO3] (mg/L)	Sulfate (mg/L)	Nitrite & Nitrate (mg/L)	Ammonia (mg/L)
1	8.50	10.91	8.0	1160	0.009	573	575	370	42.4	.499
10	1.63	6.25	7.8	1460	0.011	701	704	500	58.1	2.42
19	0.62	5.11	7.8	1490	0.01	704	708	524	60.5	2.82

* = By calibrated pulley. ** From Table 2A.

TABLE 2C

SUB-SURFACE WATER QUALITY, NICKEL PLATE SOUTH PIT, SEPT. 23, 1991

Depth* m	As (mg/l)	B (mg/l)	Ba (mg/l)	Ca (mg/l)	Cu (mg/l)	Fe (mg/l)	Mg (mg/l)	Mn (mg/l)	Na (mg/l)	Se (mg/l)	Sr (mg/l)	Ti (mg/l)	Zn (mg/l)
1	.07	.13	.009	223	.015	.031	19.4	.11	6.5	0.1	1.7	.007	.015
10	.07	.15	.009	289	<	.023	20.5	.492	11	.18	2.65	.009	.006
19	.06	.15	.008	294	<	.024	21.4	.537	11	.15	2.72	.008	.003

* = By calibrated pulley. Concentrations are for total metals. < = equal to, or less than concentration detection limit. All analyses for **Ag, Al, Be, Cd, Co, Cr, K, Mo, Ni, P, Pb, Sb, Si, Sn, Ti,** and **V** showed concentrations equal to or below detection limits.

TABLE 3A

SUB-SURFACE WATER QUALITY, GIBRALTAR WEST PIT, JUNE 25, 1992

Time	Depth m.	Diss O2 (mg/l)	Temp (oC)	pH	Cond (mmhos/cm)	Redox (mv)
1015	1	7.13	20.65	8.16	1.56	.328
1029	5	9.58	10.81	8.06	1.51	.343
1040	10	8.86	5.52	7.91	1.52	.355
1044	15	8.60	4.35	7.91	1.51	.357
1048	20	7.60	4.01	7.78	1.57	.362
1053	25	5.37	4.19	7.62	1.55	.367
1056	30	2.53	4.44	7.48	1.57	.371
1100	1	7.28	20.20	8.22	1.57	.332

TABLE 3B

SUB-SURFACE WATER QUALITY, GIBRALTAR WEST PIT, JUNE 25, 1992

Depth* (m)	Diss. O2** (mg/L)	Temp** (C)	Lab pH	Lab Cond. (umhos/cm)	Alkalinity (mg/L)	Total Hardness (mg/L)	Hardness [as CaCO3] (mg/L)	Sulfate (mg/L)	Nitrite & Nitrate (mg/L)	Ammonia (mg/L)	Filterable Residue (mg/L)
1	7.13	20.65	8.2	1220	106	730	729	536	3.56	<	1050
8	9	7	8.2	1200	112	687	685	539	3.53	.013	1060
16	8.60	4.35	8.0	1230	113	690	688	500	3.81	.007	1080
24	5.37	4.19	7.9	1240	114	702	701	550	3.82	<	1090
32	2.53	4.44	7.7	1260	116	716	714	559	3.64	.003	1120

* = By calibrated pulley. ** From Table 3A. All analyses for **sulphide** gave concentrations equal to or below detection limits.

TABLE 3C

SUB-SURFACE WATER QUALITY, GIBRALTAR WEST PIT, JUNE 25, 1992

Depth* m	Ba (mg/l)	Ca (mg/l)	Cu (mg/l)	Fe (mg/l)	K (mg/l)	Mg (mg/l)	Mn (mg/l)	Mo (mg/l)	Na (mg/l)	Si (mg/l)	Sr (mg/l)	Ti (mg/l)	Zn (mg/l)
1	.012	241	.007	<	3	30.7	.022	.16	22	6.48	.707	.003	.051
8	.012	227	.052	.025	3	28.6	.132	.15	20.5	6.29	.672	.004	.275
16	.012	228	.072	.039	4	28.6	.156	.14	20.5	6.32	.681	.004	.275
24	.011	233	.079	.037	3	28.9	.13	.15	20.5	6.41	.695	.004	.305
32	.009	238	.091	.023	2	29.3	.078	.15	20.6	6.27	.729	.004	.349

* = By calibrated pulley. Concentrations are for extractable metals. < = equal to, or less than concentration detection limit. All analyses for **Ag, Al, As, B, Be, Ca, Cd, Co, Cr, Ni, P, Pb, Sb, Se, Sn,** and **V** showed concentrations equal to or below detection limits.

TABLE 4A

SURFACE WATER QUALITY, WAR EAGLE PIT, YUKON TERRITORY: 1982 TO 1992

YEAR	Temp (C)	pH lab	Lab Cond. (umhos/cm)	Hardness (asCaCO3) (mg/L)	Total Hardness (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Inorg Carbon (mg/L)	Organic Carbon (mg/L)	Total P (mg/L)	Nitrite (mg/L)	Nitrite & Nitrate (mg/L)	Ammonia (mg/L)	FR (mg/L)
1981	6.5	7.8	825	---	---	265	8.38	---	---	<	0.128	19.5	0.02	610
1982*	3.9	7.7	900	418	420	300	9.77	---	---	0.017	0.15	22.8	0.33	---
	3.9	7.7	910	418	419	200	9.49	---	---	0.015	0.14	23.8	0.323	---
	3.9	7.8	900	416	417	310	9.72	---	---	0.014	0.13	6.52	0.419	---
	---	7.8	900	419	421	300	9.6	---	---	0.012	0.12	23.1	0.401	---
	---	7.8	900	422	424	300	9.4	---	---	0.012	0.12	23.1	0.412	---
1983	13.2	8.2	796	405	407	283	---	22	4	0.014	0.068	16.6	0.027	700
1984	9	7.9	738	364	365	210	---	22	7	0.015	0.042	15.8	0.02	610
1985	11	8.2	---	419	421	220	8.5	23.3	7.5	0.055	0.5	15	0.136	592
1986	10.5	8.2	750	393	394	210	<	21	6	0.044	0.033	13	0.024	628
1991	11.3	8.2	---	391	393	252	31	---	---	0.007	0.036	9.73	0.016	760
1992	1.8	7.9	1020	515	517	300	44.4	---	---	0.013	0.033	10.6	0.314	920

* Surface waters sampled through the ice at five different stations.
--- = not sampled < = equal to, or less than concentration detection limit.

TABLE 4B

SUB-SURFACE WATER QUALITY, WAR EAGLE PIT, YUKON TERRITORY: 1982 TO 1992

YEAR	Depth (m)	Diss. O_2 (mg/L)	Temp (C)	pH	Cond. (umhos/cm)	Hardness (asCaCO3) (mg/L)	Total Hardness (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Inorg Carbon (mg/L)	Organic Carbon (mg/L)	Total P (mg/L)	Nitrite (mg/L)	Nitrite & Nitrate (mg/L)	Ammonia (mg/L)	FR (mg/L)
1982*	1	6.0	1.7	7.8	900	418	420	300	9.7	---	---	0.015	0.13	23.1	0.40	---
	25	nil	3.9	7.9	1200	468	470	300	9.4	---	---	0.012	0.12	23.1	4.64	---
1991	1	10.0	11.3	8.2	---	391	393	252	31	---	---	0.007	0.036	9.73	0.026	760
	6	10.9	5.7	8.1	---	412	414	280	30	---	---	0.006	0.029	9.86	0.002	750
	12	0.9	4.3	7.9	---	507	509	300	61	---	---	0.01	0.111	7.4	1.93	970
	18	nil	3.8	7.8	---	572	575	250	123	---	---	0.049	0.058	3.28	7.59	1210
	22	nil	3.6	7.8	---	579	581	300	140	---	---	0.055	0.069	1.8	7.99	1230
1992	1	---	1.8	7.8	1020	515	517	300	44.4	---	---	0.013	0.033	10.6	0.314	920
	12	---	3.0	7.8	1010	521	522	310	45	---	---	0.008	0.034	10.5	0.051	910
	23	---	3.8	7.4	1490	709	711	320	147	---	---	0.046	0.04	1.84	7.86	1260

* Average of five surface samples collected through ice. The 25 m. sample is a composite of five samples taken at that depth.
--- = not sampled < = equal to, or less than concentration detection limit.

TABLE 4C

SURFACE WATER QUALITY, WAR EAGLE PIT, YUKON TERRITORY: 1982 TO 1992

YEAR	B (mg/L)	Ba (mg/L)	Ca (mg/L)	Cd (mg/L)	Cu (mg/L)	Fe (mg/L)	K (mg/L)	Mg (mg/L)	Mn (mg/L)	Mo (mg/L)	Na (mg/L)	Si (mg/L)	Sr (mg/L)	Zn (mg/L)
1981	<	0.0289	136	<	0.091	0.107	---	9.86	0.029	0.27	11.8	17	1.18	0.0354
1982*	<	0.035	149	<	0.119	0.015	---	11.2	0.034	0.322	13.4	18.7	1.31	0.046
	<	0.035	149	<	0.119	0.009	---	11.4	0.032	0.328	13.4	18.7	1.31	0.038
	<	0.035	148	<	0.117	0.008	---	11.3	0.032	---	13.4	18.5	1.31	0.038
	<	0.035	149	<	0.121	0.009	---	11.4	0.033	0.319	13.4	18.7	1.31	0.037
	---	0.04	150	<	0.122	0.009	---	11.5	0.033	0.319	13.4	18.8	1.31	0.04
1983	0.01	0.032	145	<	0.099	0.068	---	10.4	0.022	0.262	12	17.1	1.16	0.026
1984	0.046	0.028	130	<	0.097	0.019	---	9.3	0.018	0.249	11.2	16.3	1.05	0.024
1985	0.017	0.032	151	0.002	0.113	0.083	---	10.3	0.019	0.263	11.9	11.6	1.14	0.071
1986	0.002	0.03	140	<	0.107	0.015	---	10.3	0.019	0.278	11.9	17.8	1.15	0.024
1991	0.03	0.025	155	<	0.065	0.041	4	11	0.019	0.26	14.3	18.5	1.12	0.016
1992	0.03	0.026	194	<	0.061	0.088	6	13.8	0.027	0.28	20	20.5	1.32	0.031

* Surface waters sampled through the ice at five different stations
Analyses are extractable or total metal concentrations
Analyses for Ag, Al, As, Be, Cd, Co, Cr, Ni, P, Pb, Sb, Se, Sn, Ti, V gave results equal to or below detection limits.
--- = not sampled   < = equal to, or less than concentration detection limit.

TABLE 4D

SUB-SURFACE WATER QUALITY, WAR EAGLE PIT, YUKON TERRITORY: 1982 TO 1992

YEAR	(mg/L)	B (mg/L)	Ba (mg/L)	Ca (mg/L)	Cd (mg/L)	Cu (mg/L)	Fe (mg/L)	K (mg/L)	Mg (mg/L)	Mn (mg/L)	Mo (mg/L)	Na (mg/L)	Si (mg/L)	Sr (mg/L)	Zn (mg/L)
1982*	1	<	0.03	149	<	0.119	0.009	---	11.4	0.033	0.322	13.4	18.7	1.31	0.04
	25	<	<	167	<	0.118	0.034	---	12.4	0.117	0.371	16.8	22.6	1.6	0.044
1991	1	0.03	0.025	155	<	0.065	0.041	4	11	0.019	0.26	14.3	18.5	1.12	0.016
	6	0.03	0.025	156	<	0.063	0.047	4	11	0.019	0.27	14.5	18.5	1.13	0.014
	12	0.05	0.033	196	<	0.069	0.056	5	14.1	0.115	0.29	23.8	23.6	1.48	0.018
	18	0.12	0.04	228	<	0.11	0.132	7	16.8	0.205	0.3	36.7	26.4	1.81	0.035
	22	0.14	0.041	236	<	0.164	0.13	8	17.8	0.223	0.28	40	27.4	1.88	0.043
1992	1	0.03	0.026	194	<	0.061	0.088	6	13.8	0.027	0.28	20	20.5	1.32	0.031
	12	0.04	0.025	194	0.006	0.055	0.031	4	13.2	0.027	0.26	19.8	20	1.32	0.025
	23	0.14	0.041	265	0.008	0.11	0.226	9	19.7	0.25	0.27	48.4	25	2.01	0.046

* Average of five surface samples collected through ice; the 25 m. sample was a composite of five samples taken at that depth.
Analyses are extractable or total metal concentrations
Metals Ag, Al, As, Be, Cd, Co, Cr, Ni, P, Pb, Sb, Se, Sn, Ti, V not reported: all concentrations were equal to or below detection limits.
--- = not sampled   < = equal to, or less than concentration detection limit.

TABLE 5A

SUB-SURFACE WATER QUALITY, WELLPINIT, WA, 1992

Depth* m.	Diss O2 (mg/l)	Temp (oC)	pH	Cond (mmhos/cm)	Redox (mv)
1	8.96	16.55	3.92	3.52	0.411
5	10.71	11.02	3.89	3.59	0.431
10	11.07	7.50	3.91	3.55	0.438
15	11.31	6.06	3.91	3.55	0.443
20	11.36	5.48	3.92	3.54	0.447
25	11.33	5.26	3.93	3.56	0.454
30	11.33	5.17	3.94	3.57	0.457
35	11.38	5.08	3.95	3.55	0.460
1	9.20	16.28	3.85	3.59	0.431

*Depths by calibrated pulley: sonde sensor inoperative.

TABLE 5B

SUB-SURFACE WATER QUALITY, WELLPINIT, WA, MAY 6, 1992

Depth (m)	Diss. O2* (mg/L)	Temp* (C)	Lab pH (mg/L)	T. Org Carbon (mg/L)	Hardness as CACO3 (mg/L)	Total Hardness (mg/L)	Sulfate (mg/L)	Total P (mg/L)	Nitrite & Nitrate (mg/L)	Chloride (mg/L)	Filterable Residue (mg/L)
1	8.96	16.55	4.3	5.1	2080	2490	2570	<	4.86	2.8	4410
10	11.07	7.50	4.2	1.5	2080	2490	2580	<	4.82	3	4350
20	11.36	5.48	4.2	4.2	2130	2570	2570	.002	4.85	2.8	4520
30	11.33	5.17	4.2	2.0	2120	2550	2520	.003	4.8	2.8	4610
37	11.38	5.08	4.2	2.1	2170	2610	2300	.002	4.82	2.8	4600

*Field readings < = equal to, or less than detection limit
Analyses for **Alkalinity, Total Inorganic Carbon, Nitrite, Total Phosporous, Non-filterable Residue**, and **Sulphide** gave concentrations less than or equal to detection limits.

TABLE 5C

SUB-SURFACE WATER QUALITY, WELLPINIT, WA, MAY 6, 1992

Depth m	Al (mg/l)	As (mg/l)	Be (mg/l)	Ca (mg/l)	Cd (mg/l)	Co (mg/l)	Cu (mg/l)	Fe (mg/l)	Mg (mg/l)	Mn (mg/l)	Na (mg/l)	Ni (mg/l)	Si (mg/l)	SR (mg/l)	ZN (mg/l)
1	47.7	.31	.031	426	.064	.94	.244	.201	246	122	57.7	1.48	10.1	1.5	3.53
10	55.1	.34	.035	463	.069	1.04	.267	.204	224	113	65.4	1.65	10.5	1.67	3.93
20	54	.3	.034	449	.066	1.02	.269	.178	246	124	63.2	1.62	10.4	1.62	3.85
30	56.4	.34	.036	472	.073	1.07	.281	.333	229	115	65.2	1.72	10.7	1.68	4.04
37	58.6	.34	.037	484	.071	1.09	.284	.269	234	117	68.3	1.73	10.7	1.76	4.11

Concentrations are for **extractable** metals. Analyses for **Ag, B, Ba, Cr, K, Mo, P, Pb, Sb, Se, Sn, Tl, V** gave concentrations equal to or below detection limits.

I.C.P. Metal analyses of a light-coloured, gelatinous precipitate at the pit bottom totalled 0.11/g/g, with A1-67%, Fe-20%, Mg-3.6%, Ca-3% K-1.6%, with other constituents 1% or less.

TABLE 6A

SUB-SURFACE WATER QUALITY, HIGHLAND VALLEY COPPER, SEPT. 23 1992

Time	Diss Depth m.	O2 (mg/l)	Temp (oC)	pH	CondRedox (mmhos/cm)(mv)
1425	1	9.52	10.55	8.24	0.476336
1430	5	8.68	10.27	8.29	0.478335
1432	10	8.74	6.53	8.14	0.509342
1434	15	7.55	5.52	8.00	0.530356
1445	54	5.63	4.83	7.82	0.544356
1455	1	8.39	10.37	8.27	0.481341

*Depths by calibrated pulley: sonde sensor inoperative.

TABLE 6B

SUB-SURFACE WATER QUALITY, HIGHLAND VALLEY COPPER, SEPT. 23, 1992

Depth* (m)	Diss. O2** (mg/L)	Temp** (C)	Lab pH	Lab Cond. (umhos/cm)	Alkal. (mg/L)	Hardness as CaCO3 (mg/L)	Total Hardness (mg/L)	Sulfate (mg/L)	Total P (mg/L)	Nitrite & Nitrate
1	9.52	10.5	8.33	433	100	171	176	102	<	3.06
14	7.55	5.52	8.23	466	103	180	186	93	<	3.88
27	---	---	8.07	492	109	189	196	111	<	4.92
38	---	---	8.03	497	110	190	196	101	<	4.61
46	---	---	7.96	508	114	191	198	100	<	4.7
54	5.63	4.83	7.99	507	114	191	198	103	0.02	4.6

* From Table 6A. --- = not sampled < = equal to, or less than concentration detection limit.

TABLE 6C

SUB-SURFACE WATER QUALITY, HIGHLAND VALLEY COPPER, SEPT. 23, 1992

Depth m	Al (mg/l)	B (mg/l)	Ba (mg/l)	Ca (mg/l)	Cu (mg/l)	Mg (mg/l)	Mn (mg/l)	Mo (mg/l)	Na (mg/l)	Si (mg/l)	Sr (mg/l)	Zn (mg/l)
1	<	<	0.049	40.4	0.045	12.2	0.009	5.87	21.8	3.21	4.51	<
14	<	0.02	0.048	51.2	0.054	12.8	0.012	6.3	24.9	3.21	4.95	<
27	<	0.02	0.046	53.6	0.074	13.4	0.013	6.99	28	3.12	5.48	<
38	0.06	0.02	0.045	53.8	0.086	13.4	0.016	7.04	27.4	3.09	5.49	0.004
46	<	<	0.044	54.3	0.098	13.5	0.017	7.2	27.9	3.04	5.71	0.004
54	0.06	0.02	0.044	54.2	0.098	13.5	0.019	7.15	27.6	3.04	5.68	0.005

Concentrations are for **extractable** metals. < equal to, or less than concentration detection limit.
Analyses for **Ag, As, Be, Cd, Co, Cr, Fe, K, Ni, P, Pb, Sb, Se, Sn, Tl, V** gave concentrations equal to or below detection limits.

TABLE 7A

SUB-SURFACE WATER QUALITY, SIMILCO-INGERBELLE, MAY 5, 1992

Depth m.	Diss O2 (mg/l)	Temp (oC)	pH	Cond (mmhos/cm)	Redox (mv)
1.0	9.94	11.96	7.76	1.83	0.164
10	8.63	7.39	7.54	2.22	0.172
20	5.97	6.16	7.40	2.26	0.181
30	4.59	5.61	7.32	2.24	0.183
40	3.88	5.37	7.27	2.27	0.185
50	2.85	5.28	7.24	2.18	0.186
60	2.32	5.21	7.22	2.27	0.186
69	2.14	5.17	7.21	2.20	-
1	10.30	11.21	7.79	1.83	0.156

TABLE 7B

SUB-SURFACE QUALITY, SIMILCO-INGERBELLE, MAY 5, 1992

Depth (m)	Diss. O_2* (mg/L)	Temp (ºC)	Lab pH (mg/L)	Alkalinity (mg/L)	Sulphate (mg/L)	P Total Nitrite (mg/L)	Nitrite & Chloride (mg/L)	Inorg (mg/L)	Total org (mg/L)	Carbon Filt. (mg/L)	Residue
1	9.94	11.96	8.2	121	804	.004	3.03	16.7	29.8	6.5	1560
15	-	-	8.0	99	1020	.004	6.67	17.9	25.0	3.2	1900
30	4.59	5.61	7.9	99	1060	.004	6.82	18.1	25.6	3.1	1970
45	-	-	7.9	98	1030	.007	6.84	18.	25.3	2.9	1950
60	2.32	5.21	7.8	102	1060	.036	6.52	18.1	25.3	3.4	1960

*From Hydrolab readings Analyses for **Sulphide** gave results less than detection limit.

TABLE 7C

SUB-SURFACE QUALITY, SIMILCO-INGERBELLE, MAY 5, 1992

Depth m	Al (mg/l)	B (mg/l)	Ba (mg/l)	Ca (mg/l)	Cu* (mg/l)	Fe (mg/l)	Mg (mg/l)	Mn (mg/l)	Mo (mg/l)	Na (mg/l)	Si (mg/l)	Sr (mg/l)	Zn (mg/l)
1	.15	.08	.017	201	.0235*	.244	64.3	.006	.21	89.5	6.26	3.79	.026
15	<	.14	.016	220	.0183*	.029	72.5	<	.43	151	6.04	4.84	.024
30	<	.14	.015	234	.0156*	.049	76.7	.008	.45	159	6.09	5.17	.005
45	.09	.15	.017	237	.0158*	.054	78	.006	.47	162	6.35	5.27	.013
60	1.21	.16	.019	233	.036	.782	76.7	.017	.45	160	8.92	5.24	.018

*By graphite furnace; all other analyses by I CP. < = less than detection limit. Analyses for **Ag, As, Be, Cd, Co, Cr, K, Ni, P, Pb, Sb, Se, Sn, Tl, V** gave results at or below detection limits.

APPENDIX IV: CTD DATA: MARCH 10 1994

Figure iv-1 (a) pressure transducer check, (b) conductivity -vs- temperature for three profiles, (c) drop speed of profile # 2 and (d) profile # 3.

Figure iv-2 (a) temperature and (b) conductivity profiles from profile # 3.

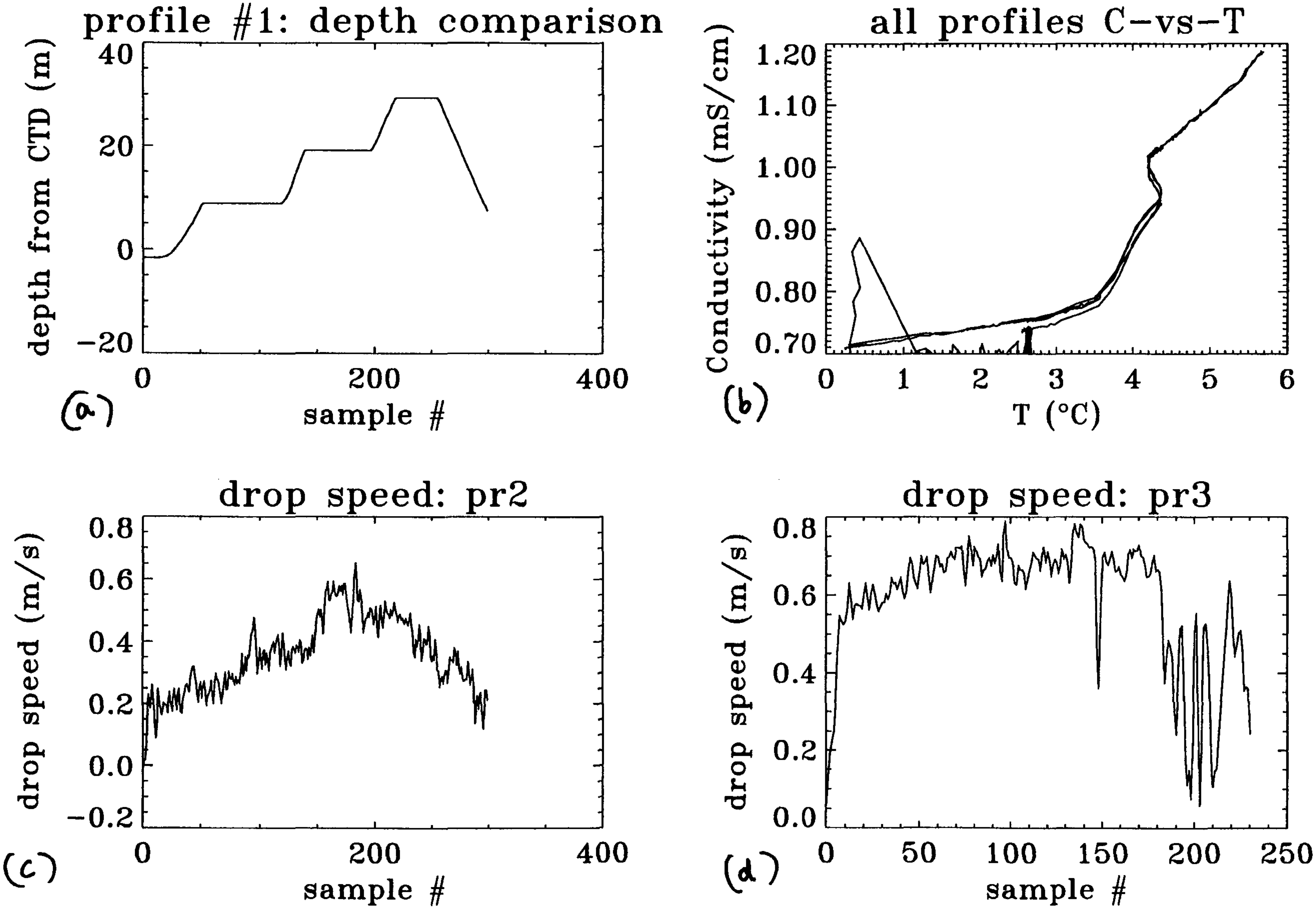
Figure iv-3 (a) temperature and (b) conductivity profiles from profile # 3, the top 30 metres of Figure iv-2.

Figure iv-4 (a) temperature and (b) conductivity profiles from profile # 3, the top 3 metres of Figure iv-2.

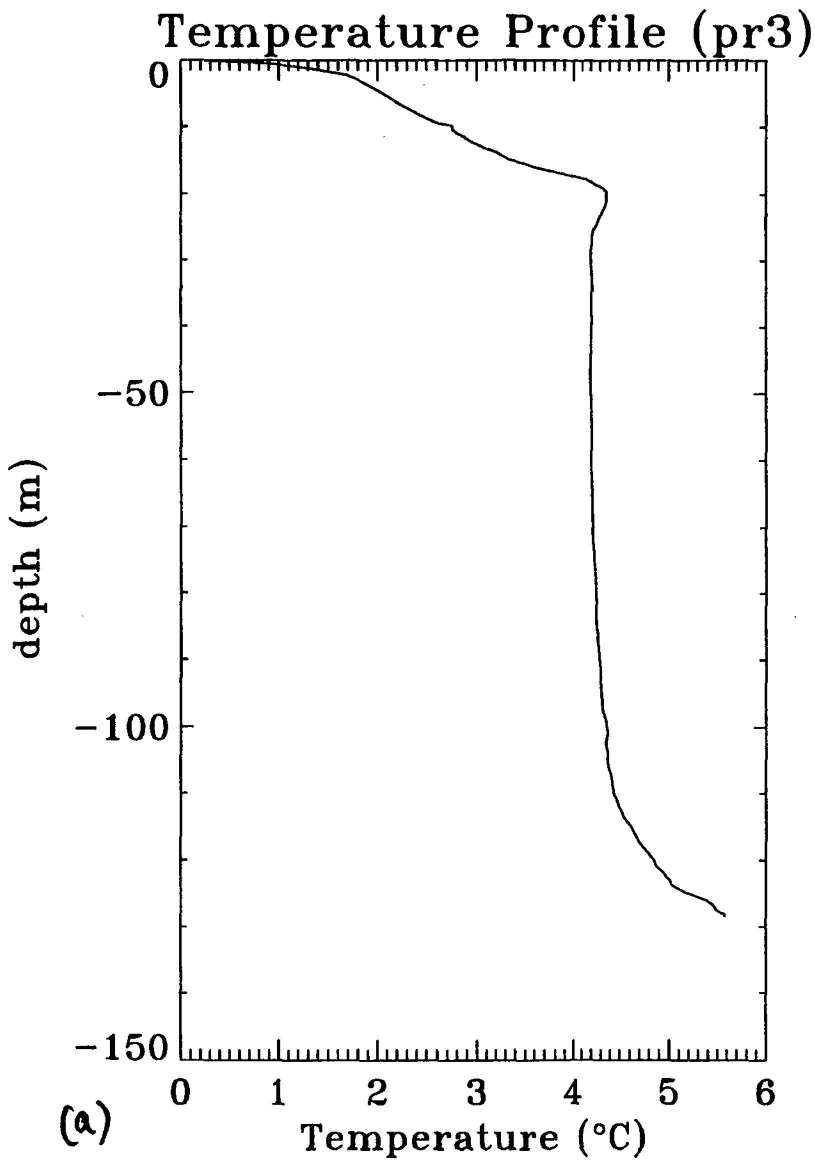
Figure iv-5 (a) the calculated density assuming seawater properties from conductivity and ignoring pressure component and (b) corresponding buoyancy frequency squared profile.

Figure iv-6 contributions to density due to (a) temperature, (b) pressure (n.b. this is static and ignored) and (c) conductivity.

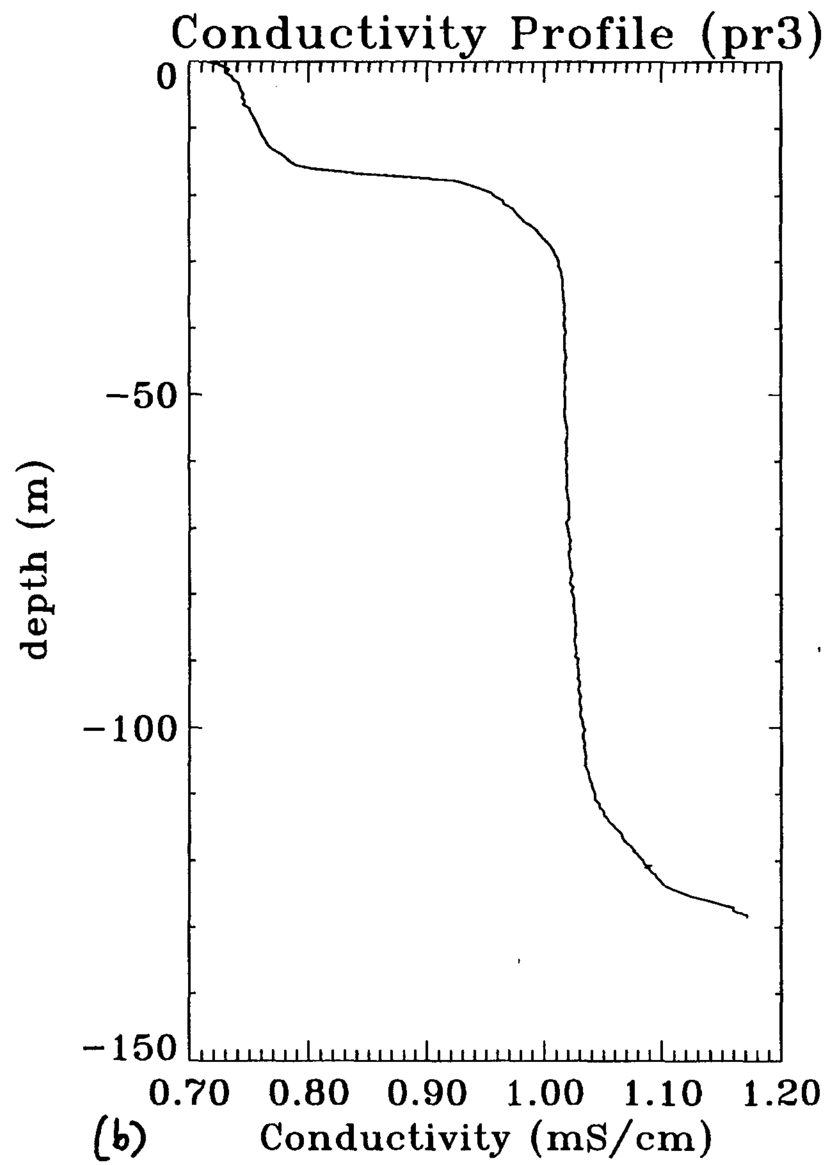
Figure iv-7 (a) temperature and (b) corresponding heat flux based on a constant thermal conductivity.



data recorded Mar 10 1994 Brenda Mines: processed 08apr94: cls

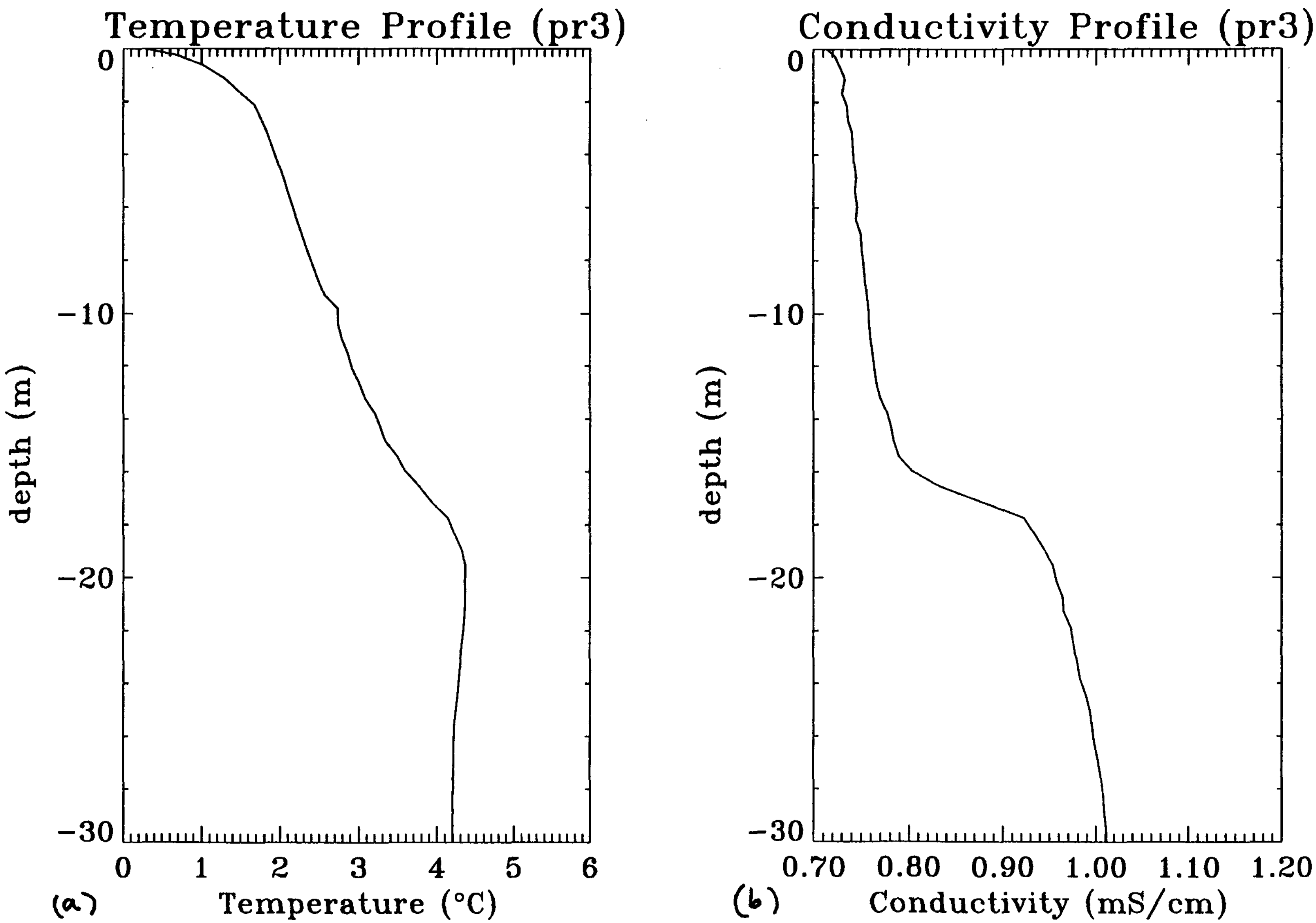


(a)



(b)

data recorded Mar 10 1994 Brenda Mines: processed 08apr94: cls



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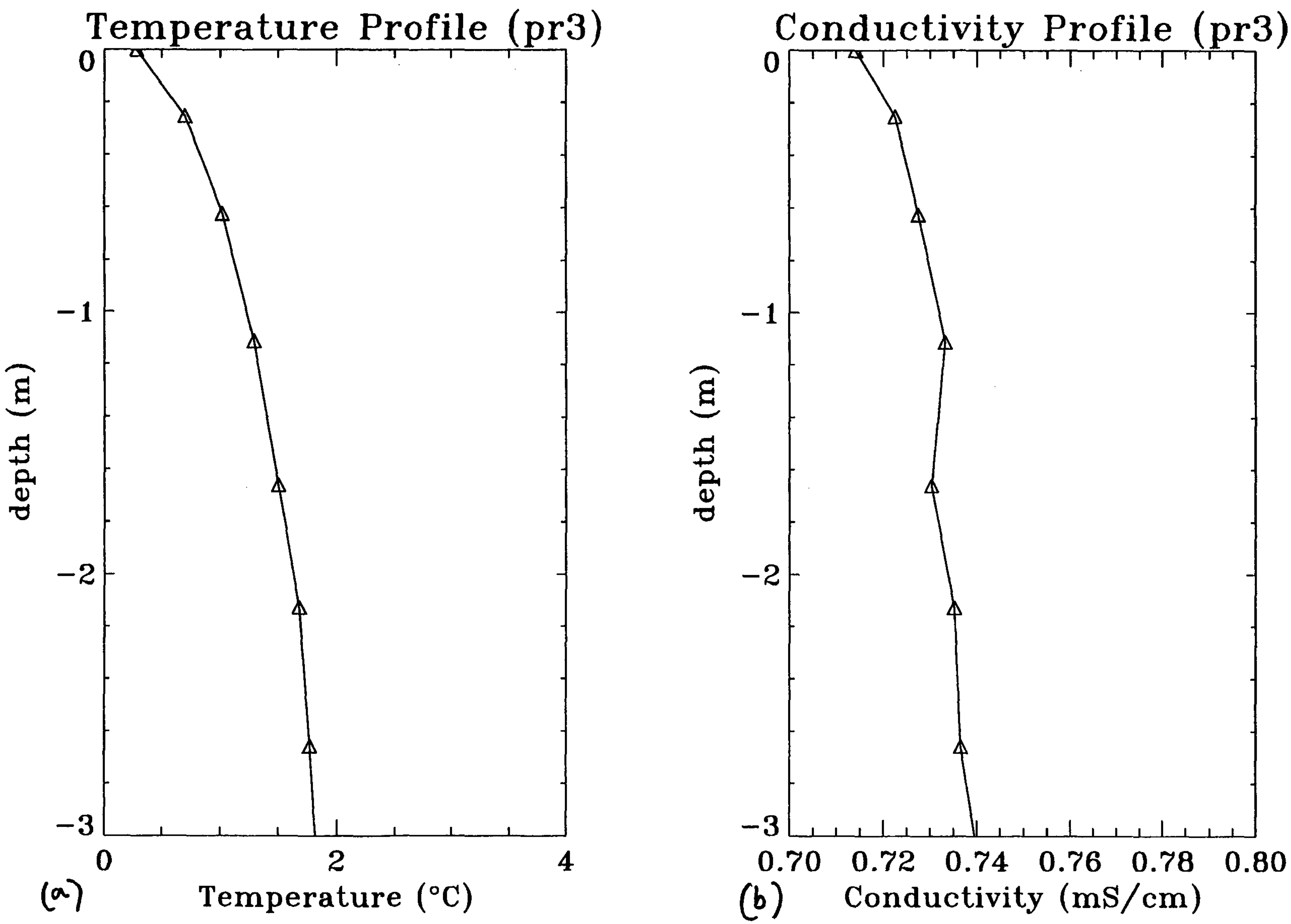

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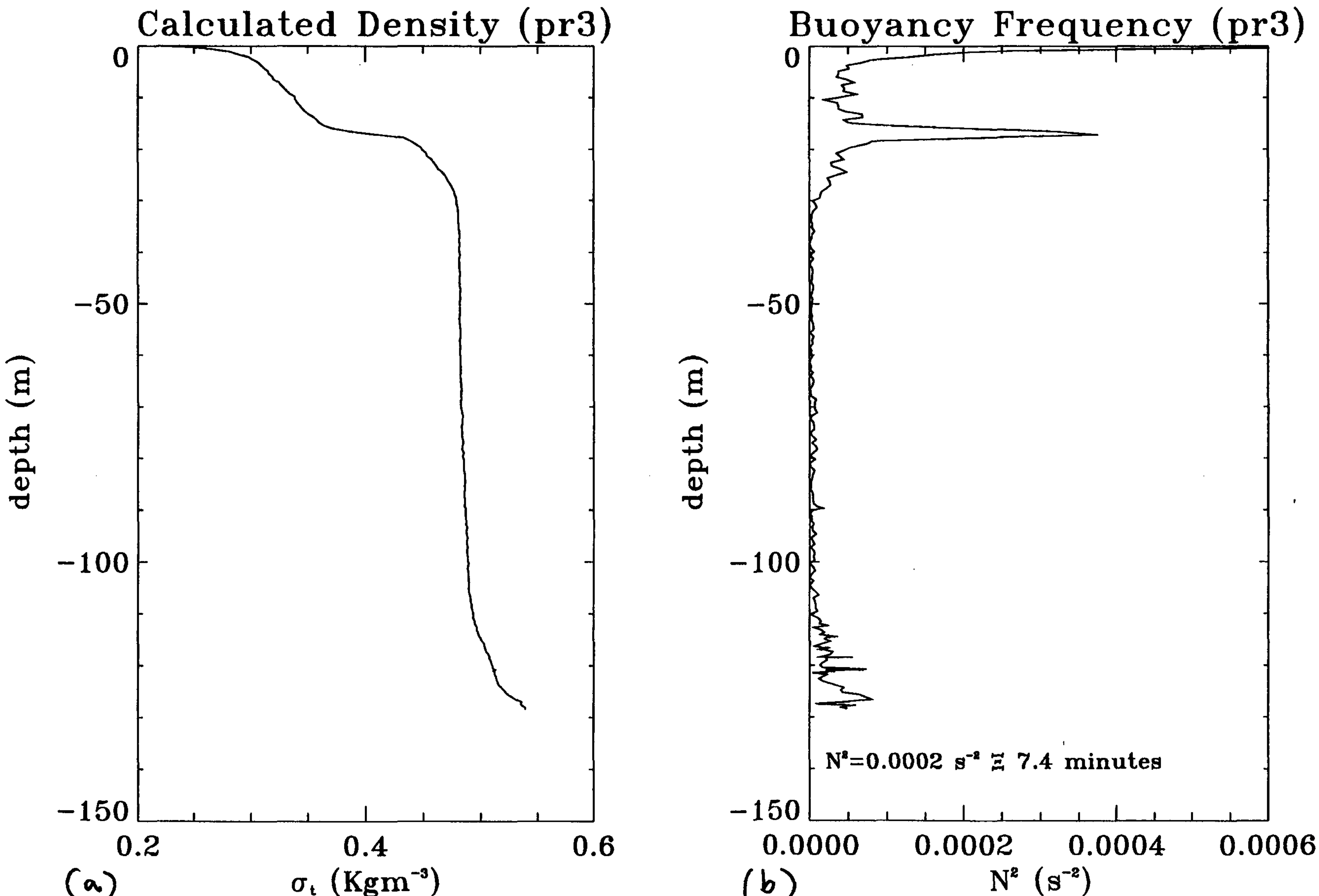

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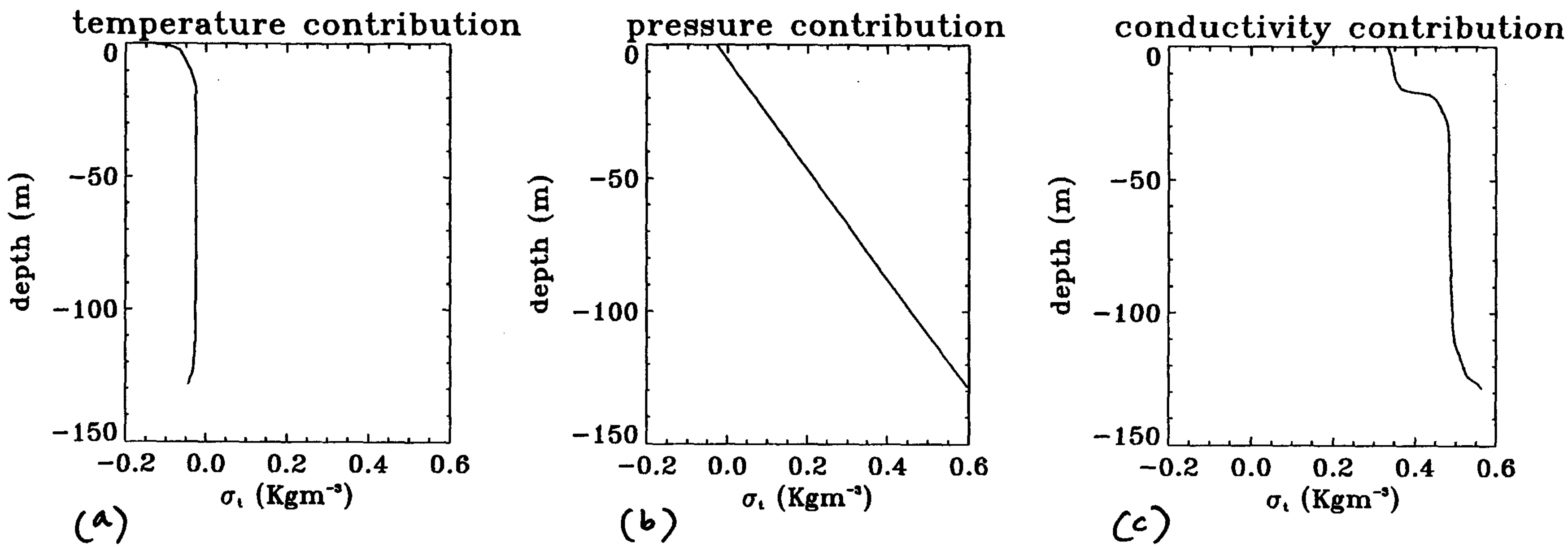
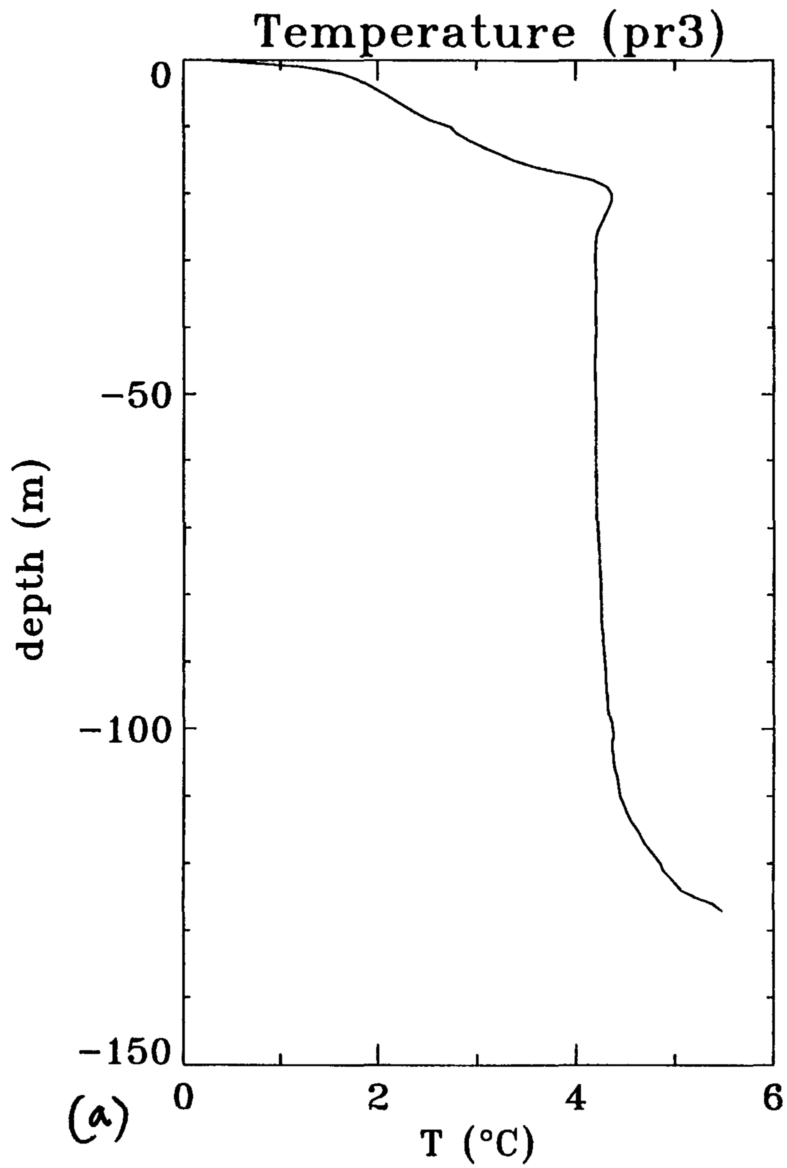
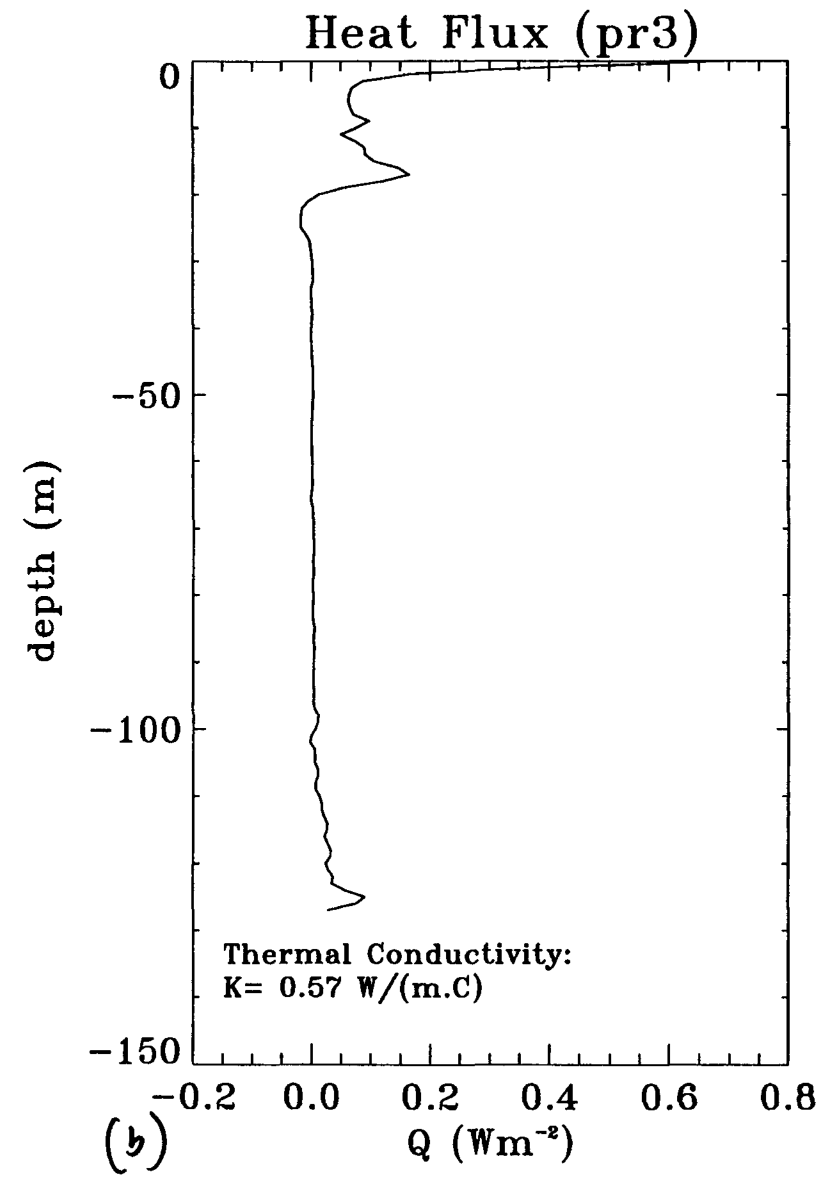


data calc by setting T=4, z=0 and Salinity=0 alternately

data recorded Mar 10 1994 Brenda Mines: processed 08apr94: cls





data recorded Mar 10 1994 Brenda Mines: processed Mar 11: cls

Appendix v: CTD Data: May 11 1994

Figure v-1 (a) salinity -vs- temperature and (b) drop speed of profile.

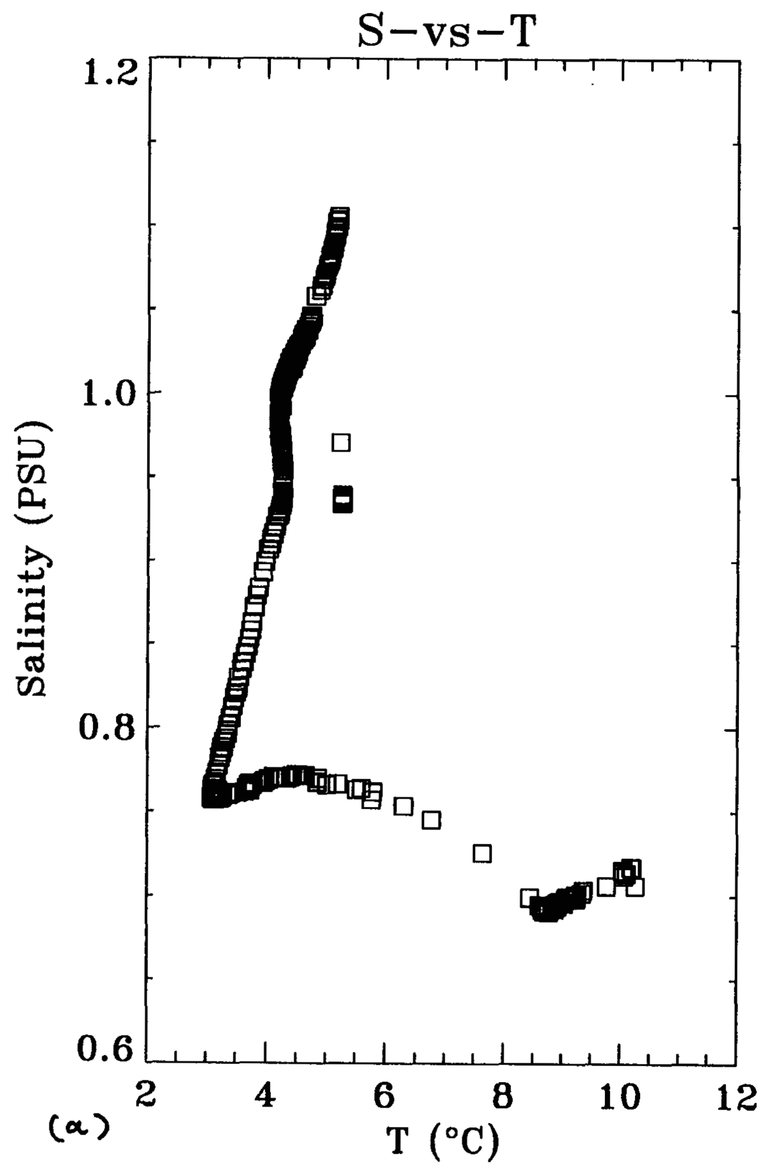
Figure v-2 (a) temperature and (b) conductivity profiles.

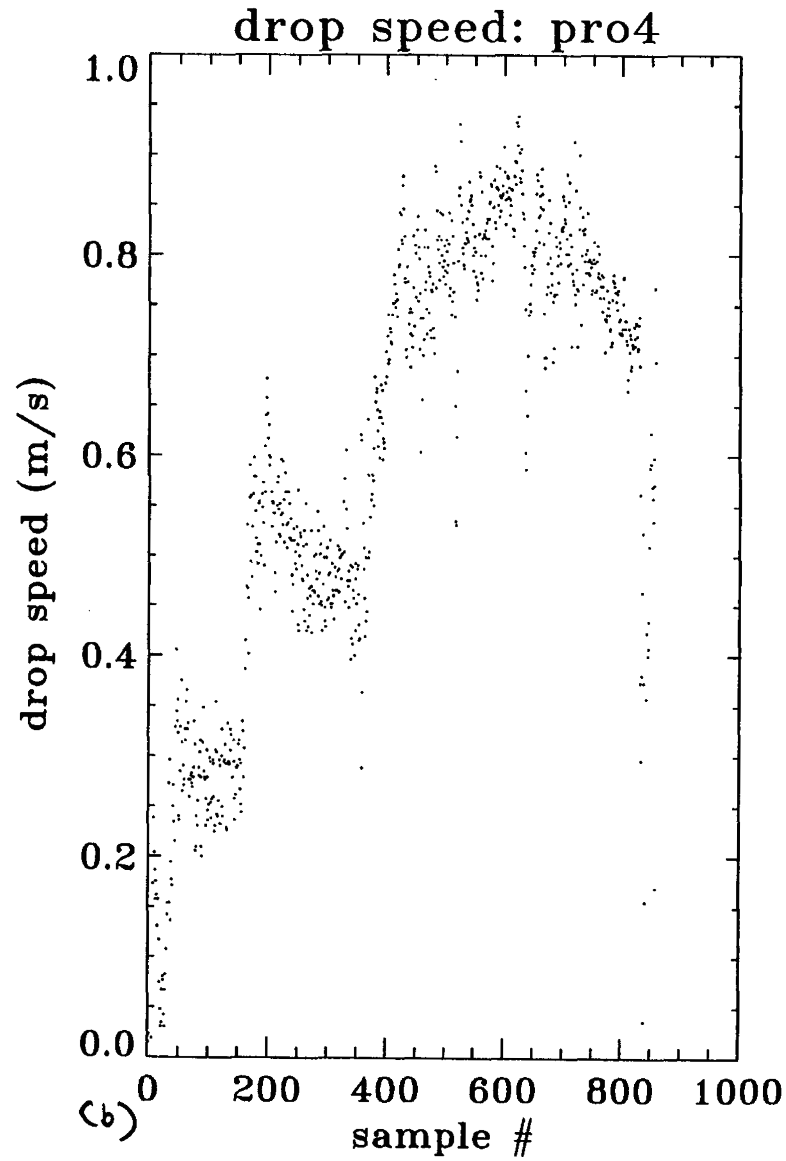
Figure v-3 (a) temperature and (b) conductivity profiles; the top 30 metres of Figure v-2.

Figure v-4 (a) the calculated density assuming seawater properties from conductivity and ignoring pressure component and (b) corresponding buoyancy frequency profile.

Figure v-5 contributions to density due to (a) temperature, (b) pressure (n.b. this is static and ignored) and (c) salinity.

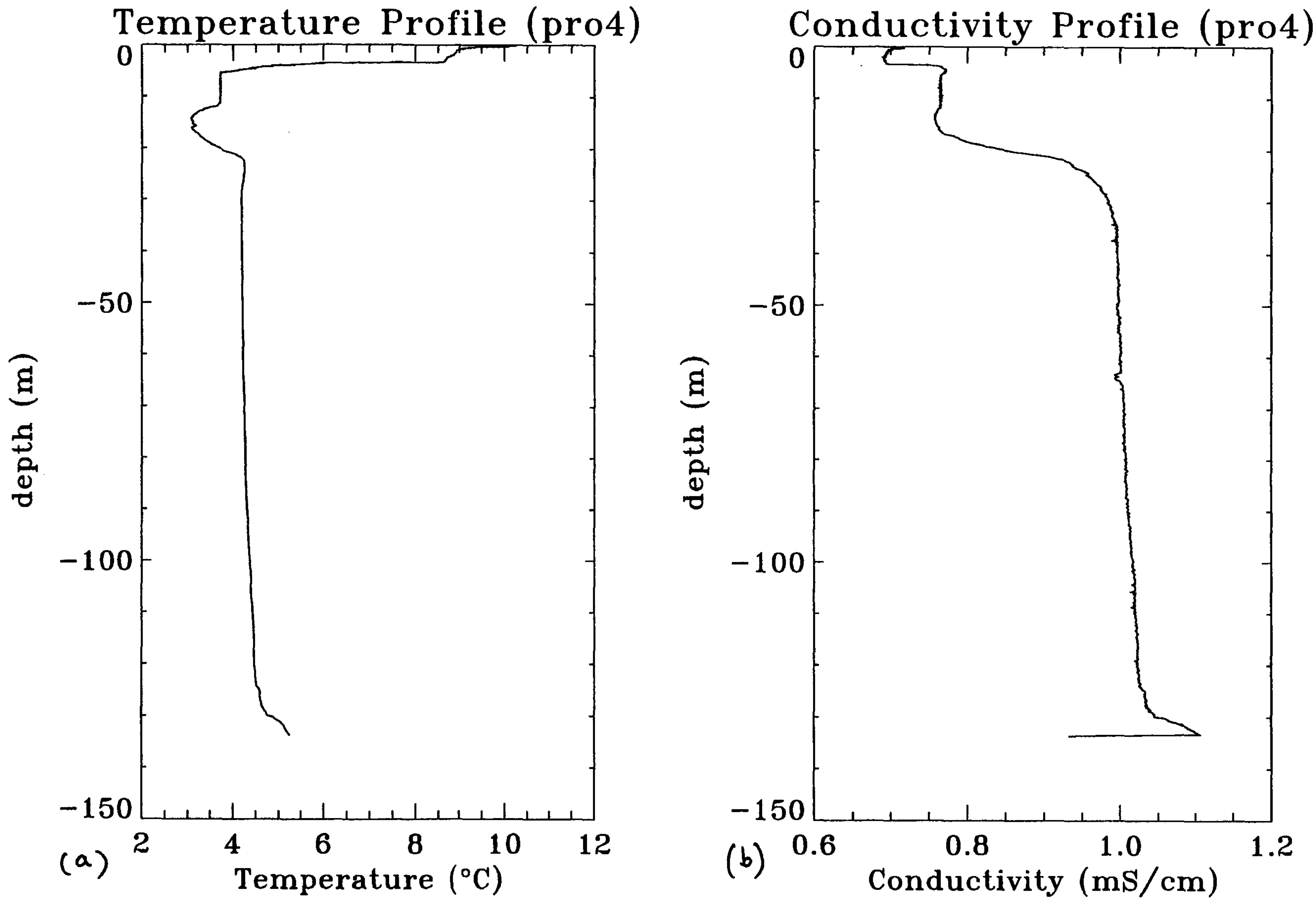
Figure v-6 (a) a comparison of the May 11 and March 10 temperature profiles and (b) their difference.





data recorded May 11 1994 Brenda Mines: processed 11may94: cls

V-i



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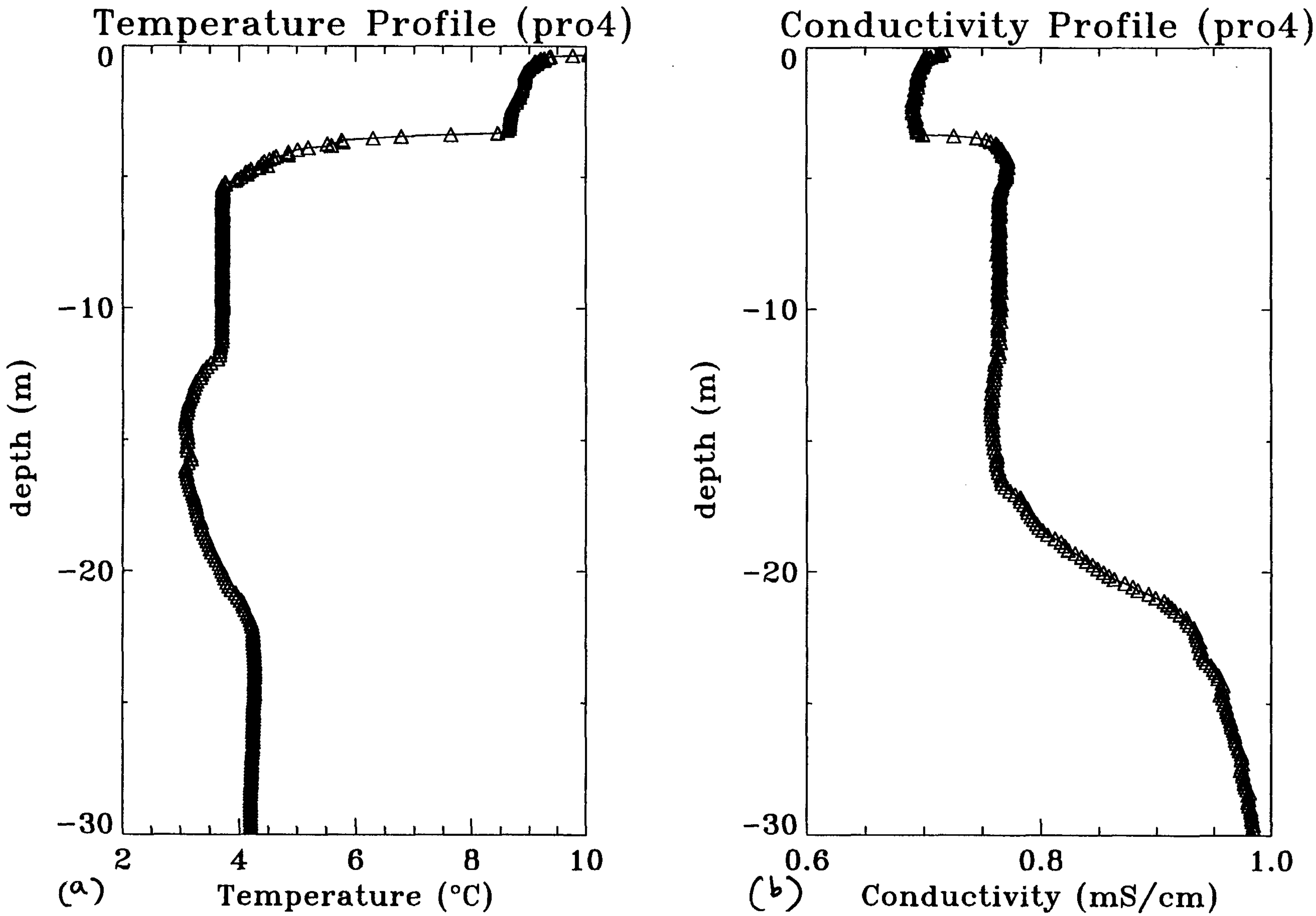

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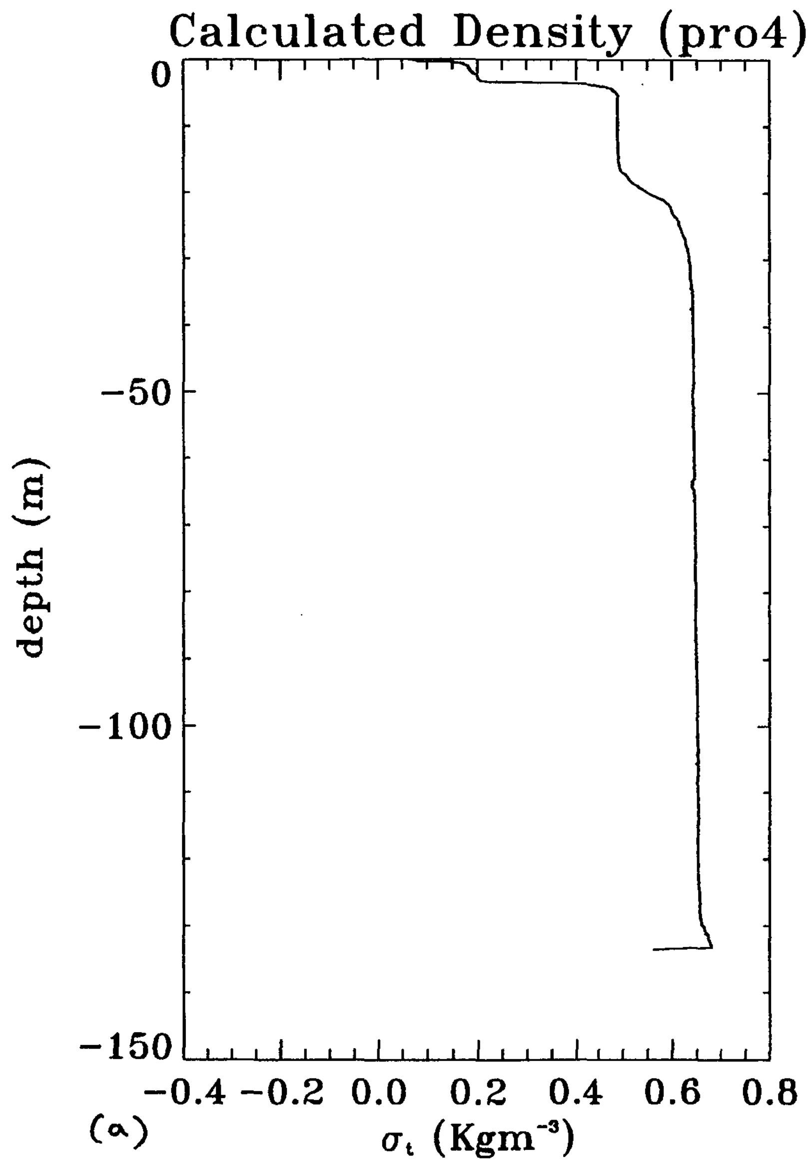
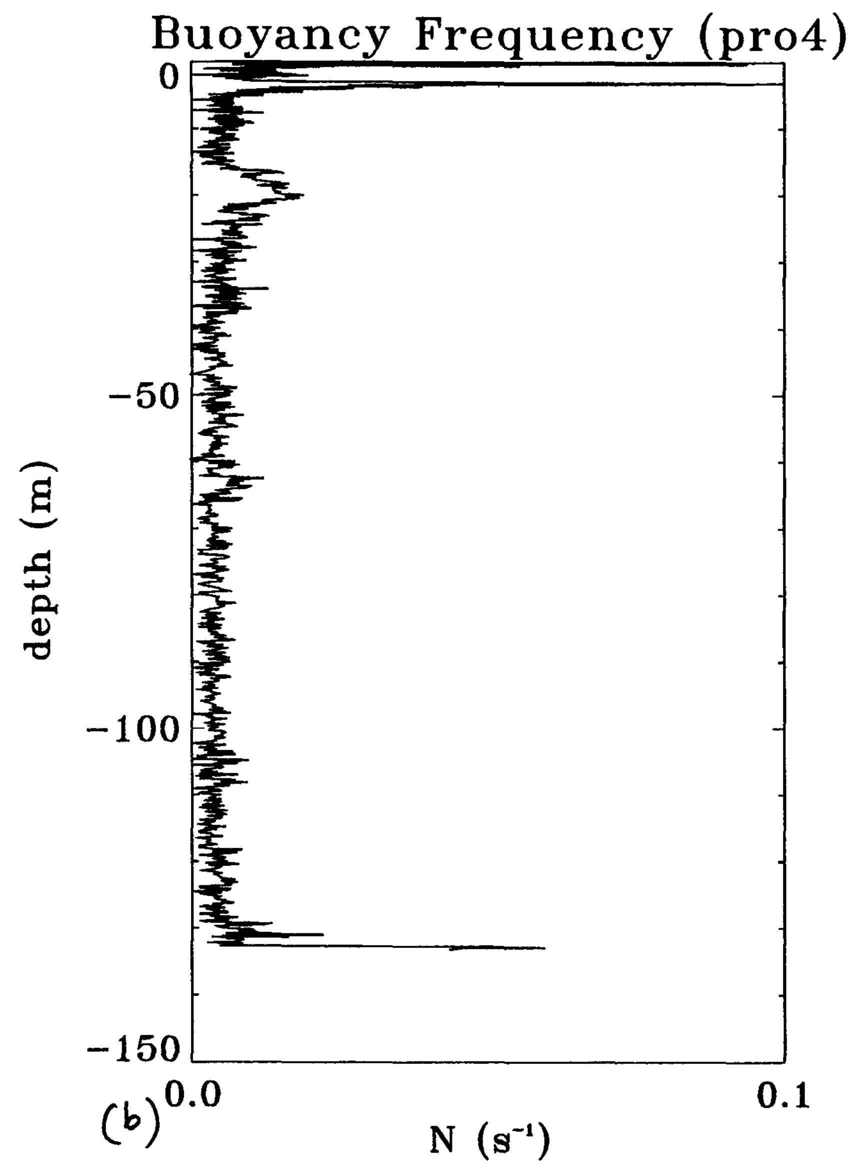
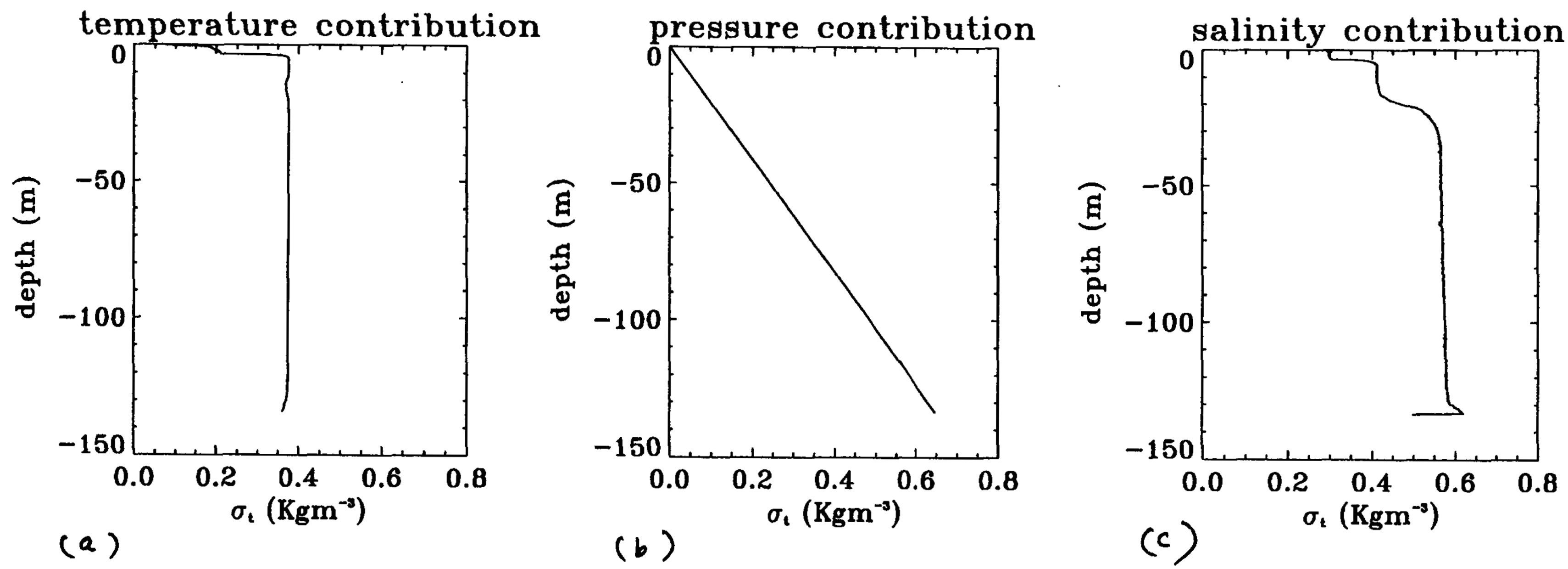




data recorded May 11 1994 Brenda Mines: processed 11may94: cls

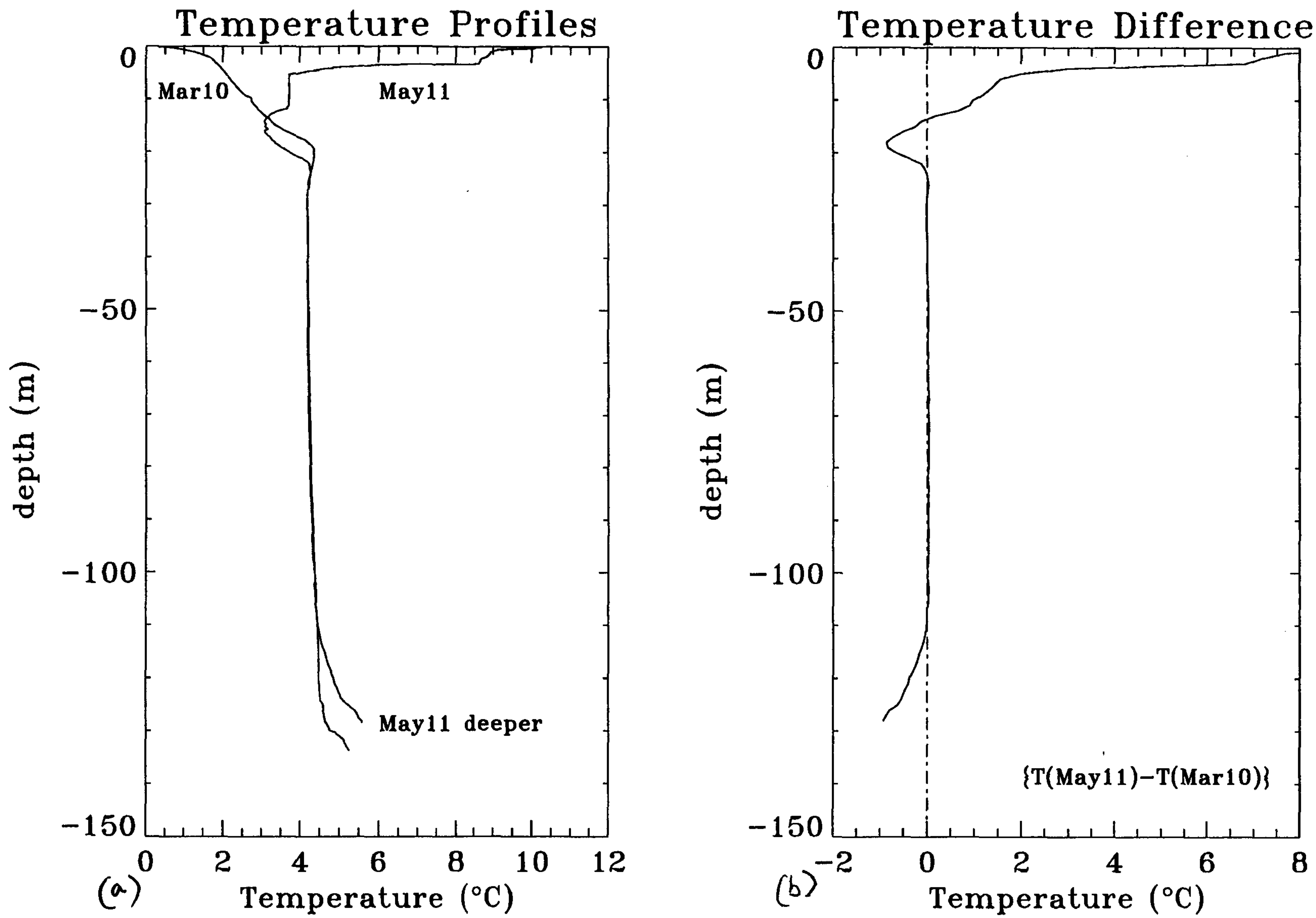


data calc by setting T=4, z=0 and Salinity=0 alternately

pressure ignored in total density calculations

data recorded May 11 1994 Brenda Mines: processed 11may94: cls

(v-5)



V-6

data recorded Mar 10 & May11 1994 Brenda Mines: processed 12may94: cls

APPENDIX VI:

Report Submitted to Brenda Process Technology, May 1994

Conductivity-Temperature-Depth Profiles from the Brenda Mines Pit-Lake

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A Report submitted to Brenda Process Technology.

May 1994

Brenda Process Technology requested that an additional conductivity temperature depth (CTD) profile be recorded in the pit-lake at the Brenda Mines Site West of Kelowna. These data were recorded on May 11 1994. It was required to complement an earlier profile recorded on March 10 1994. Both profiles were taken in the deepest known part of the pit-lake, marked with a buoy by Heather and Bruce Larratt. At the time of the March profile there was still at least 45 cm's of ice/snow-ice over the pit-lake, this broke away from the pit walls around mid-April and finally broke up approximately one week before the May 11 profile.

Figures 1*a* and *b* show the two temperature and conductivity profiles plotted on the same figure, respectively. Figure 1*c* shows the difference between the two temperature profiles. The May 10 profile proved to be slightly longer. This can be attributed to filling of the pit-lake, melt water from the ice cover, finding a deeper part of the lake or a pressure transducer calibration drift. It is most likely a combination of the first three as the pumping from the tailings pond had commenced prior to the second profile.

The point of the exercise was to quantify any change in the warm pool of water found at the base of the March profile. This region roughly between 110 and 130 metres deep apparently was almost 1.5 degrees Celsius warmer that that above. In the absence of dissolved salts and other solids this would rise and mix with water above it but the dissolved species maintain stability. We were concerned that it represents some as yet determined mechanism for deep mixing.

The upper part of the March 10 profile was largely as expected with a profile increasing from zero at the surface and reaching a temperature of maximum density at around 4 degrees; the water column maintains this for the majority of the profile. After ice-off the cold surface waters heat up, passing through the temperature of maximum density at which point the temperature distribution should be pretty much homogeneous. Once the temperature has increased above this level the surface layer then begins the diurnal heating/cooling cycle with the addition of wind mixing. This is complicated somewhat by the inflow. The newly formed surface layer is very clearly delineated in figure 1*a*, it is around 3 metres deep, representing (based on a radius of 350 metres) an approximate volume of 1.2×10^6 m^3. This is around half the total volume of the pit lake injected in 1993 so it is not possible that this warm surface layer is entirely attributed to the inflow. The March profile has been offset by 3 metres to account for this new surface layer region.

The effects of the onset of spring spring stratification is not felt below 18 metres by the May profile. Above this from -18 to-12 metres there is a transition region where slightly less saline fluid is maintaining stratification so that warmer (but still less than 4 degrees) water can sit over cooler water beneath. There is a well mixed region from -12 to -5 metres where it is apparent that the effects of temperature and dissolved substances are matched and the layer is homogenous in density. Above this we have the relatively warm surface layer.

All this varied structure behaves as expected and in the absence of unusual buoyancy fluxes (geothermal, bio-generated) the rest of the water column beneath 30 metres could reasonably be assumed quiescent and isothermal as any heat gradients would have been long ago smoothed out by diffusion. However, as stated, what we found was a warm salty pool of water which persisted in the second profile but in a diffused form. With an average radius of 100 metres and a thickness of $h = 20$ metres this can be assumed to represent 6×10^5 m^3 which is roughly 2% of the entire volume. With an average temperature perturbation in the "layer" of -0.24 degrees between March and May, we can estimate the energy lost from the deep pool over the month using the relationship

$$\text{Thermal Energy per unit area } = \rho_0 c_p h \Delta T$$

where ρ_0 is an average water density ($\approx 998\text{kgm}^{-3}$), c_p is the specific heat (here $\approx$ 4882 $\text{Jkg}^{-1}{}^{\circ}C$) and ΔT is the temperature difference. This numerically evaluates to around 3×10^7 J, and given that this occurs over one month this is a heat loss of around 9 W.m^{-2}.

If we compare this with the expected transport through molecular diffusion using the steady-state flux model

$$J = \kappa_c \frac{\partial C}{\partial z}$$

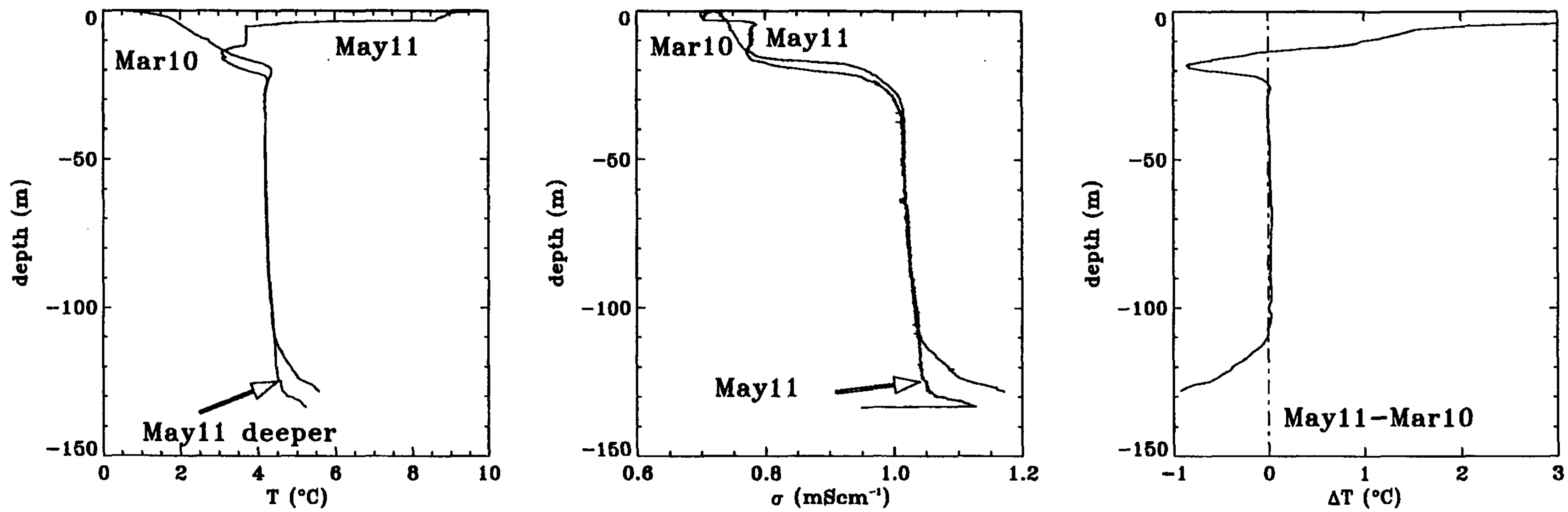
where J is the energy flux due to heat in W.m^{-2}, κ is the coefficient of thermal conduction (here taken as 0.57 $\text{W.m}^{-1}{}^{\circ}C^{-1}$) and $\partial C/\partial z$ is the local vertical temperature gradient. The depth and time averaged $\partial C/\partial z$ is estimated to be around 0.026 $^{\circ}Cm^{-1}$ so that the heat flux is then around $J = 0.015$ W.m^{-2} (see Fig. 2 for the depth distribution). There is almost 3 orders of magnitude difference here indicating that there must be some enhanced vertical transport.

It remains to be shown how this warm fluid arrived at the base of the water column. It is my opinion that a storm event observed late last year (H. Larratt, pers. comm.) generated significant entrainment of shoreline silts creating a heavy warm fluid that sank to the base of the water column. This would then create a double-diffusion type situation whereby the different "diffusion" rates of temperature and the silts leads to turbulent transport and possible fingering. Other possibilities such as biological production of heat or geothermal heating imply steady state behaviour which is not what these two profiles indicate. This is one of the questions we intend to answer with the proposed field study.

Figures:

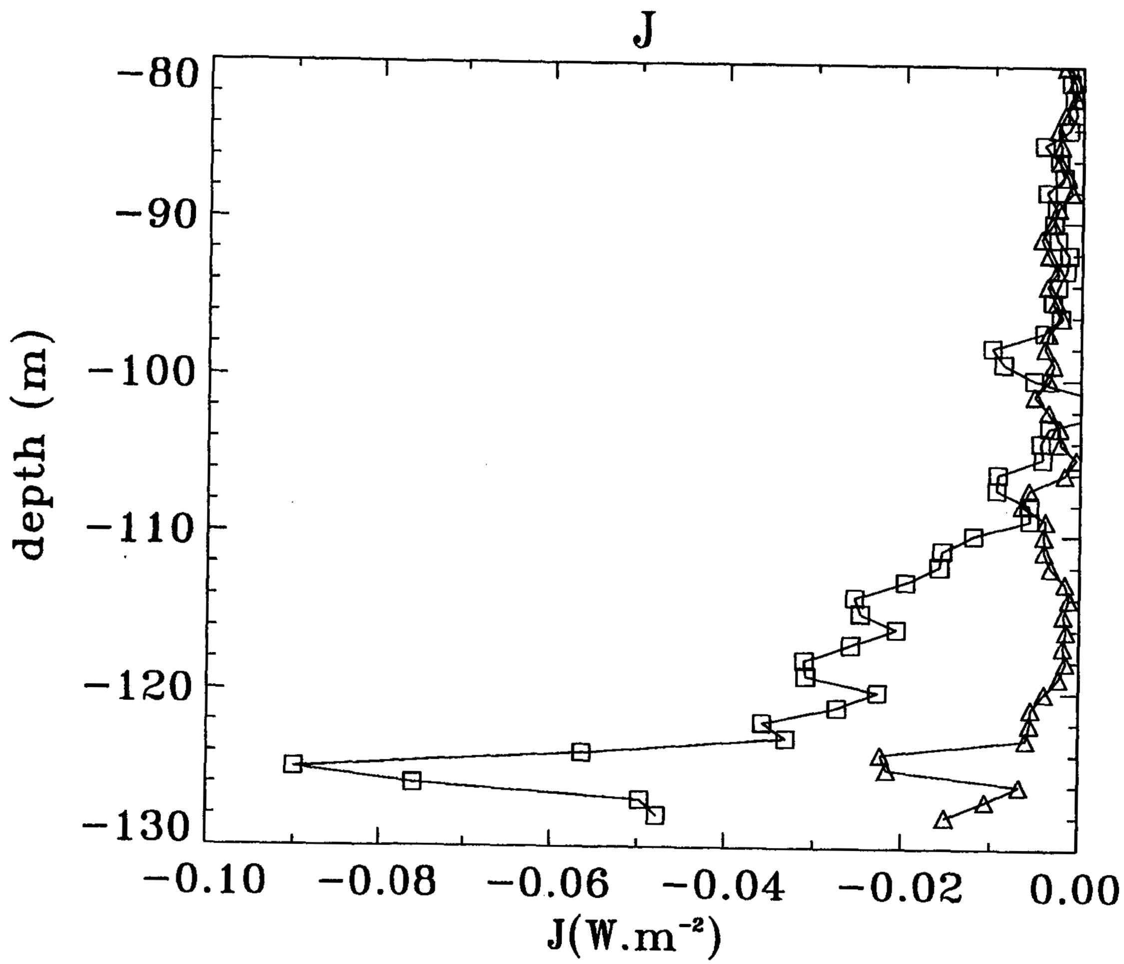
Figure 1 Profiles from March 10 and May 11 of (a) temperature, (b) conductivity and (c) the temperature difference.

Figure 2 The heat flux J is the lower 50 metres of the water column, the square symbols are for the March data and the triangles, for the May data.



(a) (b) (c)

data recorded Mar 10 & May11 1994 Brenda Mines: processed 23may94: cls


J
depth (m)
-80
-90
-100
-110
-120
-130
-0.10
-0.08
-0.06
-0.04
-0.02
0.00
J(W.m^-2)