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Simulation of Vertical Transport In a mining Pit Lake.

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SIMULATION OF VERTICAL TRANSPORT IN A MINING PIT LAKE

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Current Status:	The paper describes the results of .a field and modelling investigation of the Brenda Pit Lake in British Columbia. Sub–aqueous disposal of mine tailings is a technique whereby a mixture of water and finely ground rock is pumped to the bottom of a water body. Material from the slurry settles and consolidates forming a new lake bed with an overlying layer of water with high levels of dissolved material. The premise is that the water forms an inert cap, effectively containing the injected material. Environmental considerations require that the effectiveness of this storage method be explored.. Both the field data and the model confirm the capping effect of the relatively salty water in the pit.
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ABSTRACT

Sub-aqueous disposal is a technique that can, under suitable circumstances, delay or mitigate release into the surrounding environment of material containing high levels of dissolved compounds, for example, acid rock drainage. The technique places the material in question under a relatively inert cap of lighter fluid in a deep basin such as that left after mining. In many situations, because of low diffusion rates, the material may be considered as isolated from the environment. However, there are a number of naturally occurring physical mechanisms that can quite efficiently bring this material to the surface and hence to the surrounding environment. Here we describe a modelling application to a deep and steep-sided chemically stratified lake using an extended version of the lake and reservoir water quality model, DYRESM, incorporating algorithms for detailed ice cover, heat fluxes and also internal wave–driven boundary mixing. Sheltering and shading of the meteorological forcing is taken into account in the model. Both the field data and the model confirm the capping effects of the fresh water cap ($S<0.7g/l$) overlying the relatively salty water ($S>0.85g/l$)) in the pit. Examination of the mechanistically determined vertical eddy diffusivities suggests that at depths below the surface mixed layer, double diffusion dominates over vertical mixing due to bottom-generated turbulence stemming from basin-scale internal waves.

INTRODUCTION

The water quality of decommissioned mining open-pits presents two issues. First, as they fill with water from rain, surface runoff and groundwater they may eventually overflow and introduce contaminated water in excess of water quality guidelines into the surrounding watershed. Second, they offer convenient sites for the disposal of noxious mine tailings including acid rock drainage whereby the deleterious material is initially placed at the bottom and subsequently migrates upwards to the outflow. In order to assess the potential of decommissioned mining pits for releasing hazardous materials into the environment we initiated a field program to better understand the mechanics of mining pits. In addition, these field data were suitable for running and evaluating the simulations of a water quality model. In this paper we summarise the main findings of the observational program relevant to modelling and present an application of the water quality model to the Brenda Mines pit lake. This pit lake is one of number in Western Canada and the USA that are relevant to the present study (see Figure 1).

Pit Lakes

Pit lakes are most unusual in that they have very high ratios of depth to length (order unity) when compared to most natural lakes of order 10^{-3} to 10^{-6} with the possible exception of crater lakes. The water quality data on the seven pit lakes shown in Figure 1 are tabulated in Stevens et al. (1994). While the geochemistry of pit lakes has been studied (e.g., Klapper and Schultz, 1995), the physical transport mechanisms are poorly known. In Figure 2 thermal profiles are compared at the three nearby pits shown in Figure 1 illustrating the great diversity of structure. In one of the few reported studies Davis and Ashenburg (1989) describe the Berkeley Pit in Montana which had been filling for 13 years before the study. They found substantial wall slumpage and uniform thermal conditions which may be an indication of inflows of warm ground water. In another study of a flooded mine pit in Saskatchewan, Canada, Tones (1982) indicated that the autumnal overturn is arrested by the presence of a sharp gradient in dissolved salts (chemocline). This pit has a history of tailings dumping which may explain the chemocline. There is no evidence of groundwater inflow to the Saskatchewan pit. In the present study the depth of the pit is considered to be sufficient that wind-wave resuspension of tailings does not play a major role as in the case studied by Lawrence et al.(1991). It is noteworthy that the pit lakes in the region covered in Figure 1 will be covered by ice for long periods with the exception of Island Copper, necessitating the consideration of mixing regimes without direct wind forcing.

The limited literature and our limited observations indicate that water–filled pits have a wide range of physical and chemical properties and that analogous natural water bodies may offer some clues to their behaviour. A cross section of a crater lake, Pavin Lake (Martin, 1985) is compared to that of the Brenda Pit in Figure 3. The step-like morphology of the mine pit is shown schematically along with its smoothed equivalent. While the morphology is remarkably similar, the literature on the mechanics of this type of lake is nearly as scant as that of pit lakes. The only study of mixing in a crater lake that we are aware of is for Crater Lake (Crawford and Collier, 1997) which has a depth to width ratio about a tenth of the Brenda Pit.

Figure 3 also illustrates the limnological terms used in this paper. The monimolimnion is a zone of stable fluid at the bottom which remains poorly mixed and is maintained by an inflow of salt laden water. Note that a hyperadiabatic temperature profile is indicated in the monimolimnion in Figure 3. As will be subsequently shown, this seemingly unstable thermal profile is stabilized by the presence of salt. The energy required for mixing of the water column originates from the atmosphere. However, because the surface of a pit lake is seldom level with the surrounding terrain the microclimate created by the sidewalls of the cavity must be considered.

Sheltering and Shading Effects

Brenda Pit has at present steeply sloping and very steppy topography extending from the water surface to 60 to 120m above the water surface of the lake, see Figure 3. The standard formula for wind speed reduction due to obstacles on the shoreline (USACE, 1986) yields a boundary-layer adjustment length scale of eight times the obstacle height which in the case of Brenda Pit Lake exceeds its fetch length. A more realistic estimate of the speed reduction factor is obtained by reference to the boundary-layer meteorology literature. Taylor and Lee (1984) provide relatively simple formulae based on the slope of the basin for an axisymmetric depression in an otherwise flat plane and for a topography composed of undulating hills and valleys. Both approaches for a half–slope of 0.3 yield reduction factors from 0.52 to 0.6 for unstable or neutral stability conditions. The situation in depressions for stable atmospheric conditions which is likely to occur frequently has been recently treated by Weng et al. (1997). Taylor and Lee (1984) point out that the speed reduction factors can be decreased by up to 20% by the change of roughness from the order of 0.1m over the rocky sidewall to as small as 10^{-5}m over the much smoother water or ice surface. In the schematic of Figure 3 possible separation of the air flow into the pit is indicated which is likely to occur when the slope exceeds 0.25 as is the case here. In summary, there is some theoretical and empirical support for the specification of varying wind sheltering coefficients in a pit lake as it fills up. As will be evident subsequently there is a requirement to specify other meteorological inputs, namely solar radiation, air temperature, cloudiness and relative humidity. Solar radiation may be corrected with published tables (TVA, 1972) of solar elevation and length of the day provided the geometry of the shading sidewalls is sufficiently well known.

In this study two meteorological stations were mounted, one on the rim of the pit at a height of 60m above the water surface and the other at the centre of the lake as depicted in Figure 3. To establish transfer functions for the major forcing variables, concurrently observed wind speed, solar radiation and air temperature at the two stations are compared in Figure 4. First, there is some support for the wind speed reduction factors based on the boundary-layer literature, especially at higher wind speeds where the errors in the individual measurements are apt to be a smaller portion of the actual wind speed. A best-fit regression line through the data points of Figure 4 yields the relation for the wind speed reduction factor, α, in the pit, of $\alpha=1.148 + Uo(0.001Uo^2-0.003Uo-0.094)$ where Uo is the wind speed in m/s at the rim station. In the case of the daily total of short-wave radiation there is a shading reduction of 0.74 as might be expected during the shortest days of the year when the comparison was made. This reduction is assumed to be representative of the whole lake surface. At other times we have assumed for the purpose of modelling that the reduction in solar radiation would vary from this limit to unity for the longest day of the year. While the field data suggest a 2^{o}C rise in air temperature over the lake on average, unfortunately there is no theory to suggest how this might apply to other pit lakes or to Brenda Pit Lake as it fills up. Relative humidity is essential not only for the determination of the heat budget of the pit lake (i.e., latent heat fluxes) but also for its mass balance (i.e., evaporation). Due to equipment failure there were no overlapping relative humidity data sequences so it was not possible to make a comparison. The relative humidity over the ice covered surface of the pit was slightly greater over a nineteen-day period than the nearby values at Peachland (see location,Figure 1). Thus, the relative humidity ought to be higher at the water surface than in the vicinity of the pit. Measured shading and sheltering factors were incorporated in the mathematical model of the pit lake water quality model described in the following section. It is possible that the microclimate associated with the pit may not appreciably influence the heat budget of the pit due to such compensating effects as increased air temperature balancing reduced solar radiation .

MATHEMATICAL WATER QUALITY MODEL

Model Selection

A modelling approach based on the underlying physical processes with a minimum of site specific parameterization should offer more reliable predictions and be applicable to a wider range of physical conditions than an empirically based one. As a preliminary step, Stevens and Lawrence (1997a) applied a simplified vertical transport model to the general problem of sub-aqueous disposal of mining wastes in idealized basins. For the purpose of modelling the water quality of pit lakes the model, DYRESM, was chosen. It was originally developed for reservoirs (Fischer et al., 1979, Fischer, 1981) and extended to lakes by Patterson et al. (1984). Later, Patterson and Hamblin (1988) added to the model the ability to simulate ice cover and snow cover. Rogers et al.(1995) modified the ice formation routine to better model temperate zone ice formation which has been implemented by McCord (1996). The model DYRESM, despite being restricted to variation in the vertical direction, has received a wide application to lakes and reservoirs throughout the world; for an example of a recent application, see Boyce et al. (1993). The restriction to vertical variation is least problematic in pit lakes of all water bodies due to their extreme depth relative to horizontal dimensions. An important consideration for pit lakes is a model's ability to realistically treat inflows and outflows at any level and, in particular, at the surface should the pit eventually overflow. Further, the model ought to be able to accurately simulate such terms in the mass balance as evaporation which change as the surface area increases, so that the time of overflow can be predicted. Since simulation periods of many decades or even centuries may be called for to assess the potential for water quality exceedences accurate specification of eddy diffusion coefficients is vital.

Model Modifications and Extensions for Pit Lakes

On account of the extreme ratio of the area of the rock-water interface to the lake volume, bottom mixing processes are expected to play a significant role. Herein, we describe a new algorithm for handling bottom mixing caused by the stirring of bottom currents due to internal waves with particular focus on mixing in the hypolimnion and the monimolimnion. Little is known on the mixing in the monimolimnion. It is hypothesised that the direct wind-forced contribution to mixing does not apply in the monimolimnion and that mixing is controlled by bottom mixing and double diffusive convection. Double diffusive mixing (McDougall, 1983) arises from opposing vertical density gradients associated with dissolved salts and temperature. These gradients are thought to be maintained by either natural ground water inflows or the disposal of mine wastes in the pit (Stevens and Lawrence, 1997b).

Briefly, in the standard DYRESM model mixing processes are treated somewhat differently in the epilimnion and the hypolimnion. In the upper layer mixing is simulated by an integral approach based on the relevant terms in the turbulent kinetic equation (Fischer et al.,1979) and Fischer (1981) which accounts for the stirring action of wind and current shear, convective surface cooling (usually at night) and heating (usually during the day) including that due to the absorption of solar radiation. Parenthetically, it is mentioned that the absorption of short wave radiation varies widely from one water body to another and must be specified by field measurement. In this study we have estimated it from a single representative Secchi disc reading. Below the thermocline, the integral method is not applicable but instead, mixing is based on a semi-empirical formulation in which a fraction (approximately 5%) of the turbulent mixing energy goes to increase the potential energy of the water column. Thus, mixing in the hypolimnion depends on the stirring by the wind, by inflows and on the overall stratification of the water column. Hypolimnetic mixing in the model varies with the meteorological forcing on a daily basis. Unlike the version described in Fischer et al.(1979) and Fischer (1981) the mixing coefficient used is vertically uniform in the hypolimnion but varies in time. The wind stirring component is assumed to cease once full icecover is established.

As the vertical mixing depends on the stratification it is essential to accurately estimate the dependence of density on dissolved salts and temperature. In this study we have employed a generalized equation of state, (Chen and Millero, 1977) for lakes. However, the salts present in mining lakes are apt to be very different from those in natural lakes so that an individual determination of density dependence on dissolved constituents is recommended.

Internal Seiches

Although wind-driven internal seiches are modelled in the standard version of DYRESM for the purposes of establishing the shear responsible for the deepening of the upper mixed layer, no seiche currents are calculated other than at the base of the mixed layer. Seiche currents over the full extent of the water column are useful in that they provide a basis for the estimation of mixing through bottom mixing energetics which depend on the flow over the lake-bed. In order to establish a daily profile of bottom flows we developed a method of calculating the velocity distribution based on the modelled density structure, the input wind speed and an idealised two-layer model. This approach is supported by the findings of Lemmin and Imboden (1987) who demonstrated that currents at a height of 0.8m above the bed are closely related to the first mode internal seiche which is driven by the wind in a small deep lake. They successfully employed a two-layer model to simulate the observed flow over the bed.

First, the horizontal speed of propagation of the vertically standing internal wave and the associated vertical profile of horizontal velocity are calculated from the modelled density distribution in the vertical as a vertical eigenvalue problem. This characteristic equation is solved by an iterative shooting method. The equivalent thicknesses of the two layers giving the same horizontal speed of propagation are also determined from the solution of the characteristic equation for consistency. Then, for any given wind speed, the equilibrium thermocline tilt for a two-layer model is determined using the Wedderburn parameterization (Monismith, 1986). The non-dimensional continuous velocity profile from the eigen-solution is then scaled so that the mass transport matched that implied by the Wedderburn number. This provides an estimate of the vertical distribution of horizontal currents at steady-state due to the wind forcing while ignoring the development time scales and any residual oscillations. These effects should be opposing and tied to the internal seiche time scale so that by ignoring both the final outcome is an acceptable estimate.

As we have access to ten-minute wind readings the wind stress is calculated from the north and east components of wind every ten minutes as well as the associated velocity profiles. This favours the approximation made above whereby in the present application the wind input time step (10min) is less than one quarter of the fundamental seiche period (about 20min). This is the relative period identified by Stevens and Lawrence (1997c) as appropriate for the capture of internal wave effects. From the 10-min estimates of bottom velocity a daily average current speed profile is constructed. Winds less than 0.2m/s are ignored and no internal waves are allowed during full ice cover. Thus, during each daily time step a time series of vertical velocity profiles as well as bottom velocities are generated. The former could be used by some future incorporation of vertical shear into hypolimnetic eddy diffusion while the latter is used in the next section.

Bottom Mixing

In contrast to the empirical approach of Romero and Melack (1996) for modelling mixing in the monimolimnion, a mixing scheme based on the underlying physical processes is proposed. In a natural, deep, monomictic lake Wüest and Gloor (1995) used measured bottom currents to show that bottom-induced mixing can be a significant addition to the more standard vertical mixing schemes. Similarly, in the Central Basin of Lake Erie, Ivey and Patterson (1984) employed measured currents to specify the contribution to mixing by bottom currents. They developed a bottom mixing scheme based on energy conservation principles which is consistent with that of used by DYRESM for the epilimnion as described above. We extend their scheme to include the storage of turbulent kinetic energy.

The vertical distribution of volume is descretized into a number of layers, three of which are illustrated schematically in Figure 5. The descretization is not intended to coincide with the mining benches shown in Figure 3. As each successive layer increases in area upwards there is a portion of area of layer i, A_i, that impinges on the bottom, A_i-A_{i+1}. If the current of layer i is designated as u_i, then the bottom stress is according to standard practice, $C_D u_i^2$, where C_D is the bottom drag coefficient, $3x10^{-3}$. Taking the square root of the bottom stress, u_{b*}, as the characteristic scale for the bottom turbulent kinetic energy we have equation (1) for the energy balance integrated across the bottom mixed layer,

$$\left(C_T u_{b*}^{\,2} + g'h\right)\frac{\Delta h}{\Delta t} = C_{K_b} u_{b*}^{\,3} \qquad (1)$$

where Δ h is the incremental increase in the layer thickness over the bed in the elapsed time, Δt, g' is the so-called reduced acceleration of gravity reduced by the density difference between layer i and i-1 divided by the average density (ρ) of the two layers, and the coefficient, C_T, of 0.51 is based on standard mixed layer theory (Fischer et al., 1979) and C_{Kb} of 1.9 is the efficiency of stirring at the bottom (Hebbert et al., 1978). If the stirring energy is sufficient to entrain all the fluid of the layer above it or more in the allotted time, Δt, then the time step is reduced by a factor of two and the calculation repeated for the two sub-steps. At the end of each sub-step new volumes and properties are defined for each layer on the basis of the added volumes and conservation. At this point each new layer is checked to see if its volume lies within predefined limits. If not, then layers are either split or amalgamated as required.

The entrainment of less dense fluid from the layer above results in the water at the boundaries being less dense than that in the interior of the layer. This density difference drives a horizontal intrusion from the boundary to the interior and a consequent return flow. The time scale for this adjustment process has been shown by Stevens and Lawrence (1997b) to be much less than a day for similar sized water bodies. The net result is that the horizontal density contrasts are eliminated over the daily time step.

As the boundary mixing scheme does not explicitly generate an eddy diffusivity estimate, it is of interest to calculate an effective eddy coefficient for the sake of comparison with the standard mixing scheme. The vertical eddy diffusivity, K_v, may estimated from the laterally averaged heat diffusion equation according to (2).

$$K_v = \int_0^z A(z') \frac{\partial \rho}{\partial t} dz' / A \frac{\partial \rho}{\partial z} \qquad (2)$$

Double Diffusion

Since heat conducts molecularly at approximately 100 times the rate of salt, the heat flowing from the monimolimnion will destabilize the fluid at the base of the hypolimnion resulting in convective mixing due to double diffusion. By means of laboratory studies double diffusion has been characterized by the density ratio, R_ρ,

$R_\rho = \dfrac{\frac{\partial \rho_s}{\partial z}}{\frac{\partial \rho_T}{\partial z}}$, where ρ_s and ρ_T are the relative contributions to density through salinity and temperature variations only .

All modelled density profiles were examined for the occurrence of opposing contributions to the vertical density gradient from salt and temperature. Figure 6 shows concurrent modelled (a) and observed profiles of the density ratio. There is a general correspondence, especially in consideration of the observed variability of this quantity in this study and others. Empirically based formulae for the vertical eddy conductivity and diffusivity for a dissolved substance are parameterized in terms of R_ρ and molecular viscosity (McDougall, 1983). In the present work both the field and numerically derived R_ρ indicated that double diffusion took place at depths deeper than 90m, the position of the interface between the monimolimnion and hypolimnion. At these depths the vertical eddy conductivity and diffusivity for a dissolved substance was specified according to the Federov formulae summarized by Large et al. (1994) to account for double diffusion. Some evidence that double diffusion is occurring in the monimolinion is seen in Figure 7 where several overturning events, occurring well after the onset of full ice cover, are suggestive of vertical mixing. While these features are not as regular as the step structure found in Lake Kivu by Newman (1976), they are nonetheless indicative of mixing rates elevated beyond molecular.

Other Modelling Details

Lake geometry is represented in the model from known bathymetric data by means of vertical distributions of area and volume shown in Figure 8. These data are used in the model to establish the layer areas and volumes. A bottom inflow of 700 m^3/d and of a salinity of 950 mg/l and temperature of 5.7 ^oC was inferred from the six temperature and conductivity profiles taken during the 220-day study period and the more extensive observations reported by Stevens and Lawrence (1997b). No outflows were assumed.

The relative humidity sensor failed at the rim station after only a few weeks of operation. Data were obtained from the nearby Peachland station on a daily basis and substituted for the missing data. Unfortunately long-wave incoming radiation was not measured either. This essential term in the surface heat balance was derived from an empirically based formula (Fischer et al., 1979) based on air temperature and cloud cover. Cloudiness was not measured but was estimated from the measured and theoretical clear sky radiation for a given day and a formula from TVA (1972). The model requires daily light attenuation coefficients. No optical profiles were taken during the modelled period so that light extinction had to be estimated from the empirical expression, 1.6/Secchi depth, which gave an extinction coefficient of 0.11 m^{-1}.

In order to estimate snow cover, daily precipitation data from the Peachland station were used in the model. When the daily air temperature exceeded the melting point the snow melt from an area of 3.7 times the surface area was input to the surface layer at zero salinity and temperature.

The model was initialised with the temperature and dissolved solids profiles of October, 21, 1994 and run without adjustment for 220 days until May 26, 1995 when the rim observation station was decommissioned. The basic time step is one day although in our modified version sub-daily time steps as short as ten minutes are permitted.

RESULTS AND DISCUSSION

Modelled distributions of temperature and salinity are compared to the observations in Figures 9 and 10. It is evident that while the main features are modelled realistically there are some differences in detail. The hypolimnetic mixing in the model is similar to the prototype except at the end of May when the field mixing is more vigorous. It is postulated that this mixing is due to processes not included in the model such as sidewall slumping and disposal of mine tailings. Sidewall collapse is supported by the fact that a moored thermistor chain could not be retrieved due to ballast-connection burial, as well as the sudden occurrence of relatively large oscillations of thermal structure at a depth of 130m after the pit had been isolated from wind forcing by solid ice cover for at least 80 days, as shown in Figure 11. Possible errors in the specification of the meteorology over the lake surface may be responsible for the small lag in the modelled dates of ice formation and thaw. The salinity is seen to freshen in the field observations close to breakup whereas the modelled freshening from the melting of the snow cover in the pit was much weaker. Again, this indicates either the addition of unmonitored inflows likely arising from the disposal of water from the tailings pond or errors in runoff estimation.

The period of the internal seiche is a byproduct of the calculation of the bottom velocity profile. The minimum period was 1.4hr over the simulation period but during the summer when stratification is strongest this is likely to decrease to approximately one hour. Since a minimum of at least four wind values should be specified over the period of oscillation (Stevens et al, 1994b), hourly winds should not be used in the bottom velocity routine but rather at least 15 minute samples.

The profound effects of ice cover and relatively high salinity on vertical mixing in Brenda Pit-Lake are illustrated by reference to Crater Lake (Crawford and Collier, 1996). They found that the salinity was only 10% of the pit lake and that Crater Lake remained free of ice. Thus, strong convective overturns occurred which resulted in the mixing of as much as one-quarter of the volume of the hypolimnion in a single episode. Both the model and the observations are in agreement whereby deep penetrative convection does not take place in Brenda Pit. As well, neither display any indication of thermobaric mixing (Walker and Watts, 1995) that might be expected in deep temperate lakes in winter. Again, it is likely that the concentration of dissolved salts below the epilimnion is too elevated to permit this process.

The absence of deep penetrative convection in the pit lake is further confirmed in Figure 12 where the behavior of the upper mixed layer as deduced from the model is shown along with predicted eddy mixing coefficients. Although the simulation period is less than a year it is highly unlikely that the mixed layer depth would at any time exceed 19m which occurred just before freeze-up. In general, the eddy conductivity is higher in the monimolimnion than in the hypolimnion particularly during ice cover. It is interesting that the effect of bottom induced mixing as deduced from equation (2) is less than the specifications shown in Figure 13. However, it remains substantially higher than molecular levels ($10^{-9}m^2/s$) for salts so that it could be important for the mixing in the monimolimion in the absence of double diffusion (i.e., no groundwater input).

As is evident from Figure 8b the pit is rapidly filling up from the disposal of tailings pond water and will likely overflow between 2005 and 2010. An illustration of how the model results could be employed to predict the water quality of the outflow follows. Based on a conservative eddy coefficient from Figure 13 of $10^{-6}m^2/s$ and a characteristic time scale of the square of the depth divided by the diffusivity, a time scale required for a material introduced at the bottom in solution to diffuse over the 130m distance from the bottom to the base of the mixed layer is of the order of magnitude of 500 years provided conditions do not change. For material below the freshwater cap of about 20m in thickness, dissolved material would be incorporated into the outflow on a much smaller time scale of the order of a season. In this case use of the model is recommended to estimate the outflow water quality.

CONCLUSIONS

Our field investigation was aimed at obtaining a base-line understanding of a hitherto unknown type water body and was successful in discovering some new processes in limnology. The principal findings are that unlike most temperate zone lakes the overturn is restricted to near surface depths due to ice cover and relatively high salt content and that double diffusion dominates the mixing in the monimolimnion. Any further field programmes should employ a stable tracer such as sulphur hexafluoride introduced at the bottom of the pit and sampled at least monthly over the study period to validate the mixing scheme employed in the model. Attempts should be made to better quantify the effects of double diffusion and determine an equation of state for the pit water.

The result of such a future programme of study would be a water quality model that with a minimum of "tuning" could supply the linkage between the loading of acid rock drainage from sub-aqueous deposits of mine tailings and the water quality of surface outflows. Such a calibrated model could provide assistance for monitoring programmes and input to management decisions on the release of contaminant laden water from decommissioned mining pits. In model applications to mining pits where there is no prior environmental experience it is strongly advocated that a field and modelling investigation of the kind described in this study be undertaken.

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REFERENCES

Boyce, F.M., P.F.Hamblin, L.D.D.Harvey, W.M.Schertzer and R.C.McCrimmon. 1993. Response of the thermal structure of Lake Ontario to deep cooling water withdrawals and to global warming. J.Great Lakes Res. 19(3) 603-616.

Chen, C.T and F.J. Millero, 1977 The use and misuse of pure water PVT properties for lake water. Nature, 266: 707–708.

Crawford, G.B. and R.W.Collier. 1997. Observations of a deep mixing event in Crater Lake, Oregon. Manuscript submitted for publication.

Davis, A. and D. Ashenberg, 1989. The aqueous geochemistry of the Berkeley Pit, Butte Montana, U.S.A. Geochem., 4: 23–36.

Fischer, H.B, E. J. List, T.Y.C Koh, J Imberger,. and N.H. Brooks, 1979. Mixing in inland and coastal waters. Academic Press, 483p.

Fischer, H.B, 1981 Transport models in inland and coastal waters: proceedings of a symposium on predictive ability. Edited by H.B.Fischer, Academic Press, 542p.

Hebbert, R., J.Imberger, I.Loh, and J.Patterson 1979. Collie River underflow in the Wellington Reservoir. J. Hydraul. Div. Am. Soc. Civ. Eng. 105:553-546.

Ivey G.N. and J.C.Patterson, 1984. Vertical mixing in Lake Erie in summer. Limnol. Oceanogr. 29(3): 553-563.

Klapper, H. and M. Schultz, 1995. Geogenically acidified mining lakes- living conditions and possibilities for restoration. Int. Revue ges. Hydrobiol. 80(4), 639-653.

Large, W.G., J.C. McWilliams and S.C. Doney. 1994 Oceanic vertical mixing: a review and model with a nonlocal boundary layer parameterization. Rev. Geophys. 32:363-403.

Lawrence, G.A., P.R.B.Ward, and M.D.MacKinnon. 1991. Wind-wave induced suspension of mine tailings in disposal ponds-a case study. Can. J. Civ. Eng. 18(6): 1047-1053.

Lemmin, U. and D.M. Imboden. 1987. Dynamics of bottom currents in a small lake. Limnol. Oceangr. 32: 62-75.

Martin, J.M, 1985. The Pavin crater lake. In: Chemical Processes in Lakes, Stumm, W.(ed), 169–188.

McCord, S.A. 1996. Artificial reaeration of lakes. Abstract in North American Lake Management Society Conf., Minneapolis, MN Nov. 1996.

McDougall, T.J. 1983. Double diffusive plumes in unconfined and confined environments. J. Fluid Mech. 133:321-343.

Monismith,S. 1986. An experimental study of the upwelling response of stratified reservoirs to surface shear stress. J.Fluid Mech. 171:407-439.

Newman, F.C. 1976. Temperature steps in Lake Kivu: a bottom heated saline lake. J. Phys. Oceangr., 6:157-163.

Patterson, J.C., P. F. Hamblin and J. Imberger, 1984. Classification and dynamic simulation of the vertical density structure of lakes. Limnol. Oceanogr., 29(4), 845–861.

Patterson, J.C. and P.F. Hamblin, 1988. Thermal simulation of a lake with winter ice cover. Limnol. Oceanogr., 33(3), 323–338.

Rogers, C.K., G.A. Lawrence, and P.F. Hamblin, 1995 Observation and numerical simulation of a shallow ice–covered mid–latitude lake. Limnol. Oceanogr., 32 pp.

Romero, J. R. and J.M. Melack, 1996. Sensitivity of vertical mixing in a large saline lake to variations in runoff. Limnol. Oceangr., 41(5) 955-965.

Stevens, C.L.and G.A.Lawrence, 1997a The effect of sub-aqueous disposal of mine tailings in standing waters. IAHR J. Hydr. Res., 32(2):1-13.

Stevens, C.L.and G.A.Lawrence, 1997b. Stability and meromixis in a water filled mine pit. Manuscript submitted for publication to Limnology and Oceanography.

Stevens, C.; Lawrence, G.A; 1997c Estimation of wind-forced internal seiche amplitudes in lakes and reservoirs, with data from British Columbia, Canada Aquatic Sciences 59, 115-134.

Stevens C.L, G.A.Lawrence, C.K.Rogers and P.F.Hamblin. 1994a. Modelling the thermal stratification of water–filled mine pits. Regional Manuscript Report MS 94–01 Environment Canada, Pacific & Yukon Region.

Stevens C.L, G.A.Lawrence, P.F.Hamblin.and E. Carmack. 1994b. Wind forcing of internal waves in long narrow lakes. Dyn. Oceans and Atmos. 25:41-50.

Taylor, P.A. and R.J. Lee. 1984. Simple guidelines for estimating wind speed variations due to small scale topographic features. Climatological Bulletin 18:3-31.

TVA (Tennessee Valley Authority), 1972. Heat and mass transfer between a water surface and the atmosphere T.V.A. Rep. No. 0-6803.

Tones, P.I., 1982. Limnological and fisheries investigation of the flooded open pit at the Gunnar uranium mine. Saskatchewan Research Council, SRC Rep. C–803–10–E–82, 64pp.

USACE (United States Army Corps of Engineers), 1986. CE–QUAL–R1; A numerical one–dimensional model of reservoir water quality. Instructional Report, Environmental Lab., Vicsburg, Mississippi.

Walker, S.J. and R.G.Watts. 1995. A three-dimensional numerical model of deep ventilation in temperate lakes. J.Geophys. Res. 100:22,711-22,731.

Weng,W., L.Chan, P.A.Taylor and D.Xu. 1997. Modelling stably stratified boundary-layer flow over low hills. Quart. J. Roy. Meteorol. Soc., in Press.

Wüest, A. and M.Gloor, 1995. Bottom boundary mixing in lakes: the role of near sediment density stratification. Proceedings IUTAM Symposium on Physical Limnology, Broome, Australia 385–398.

List of Figure Captions

Figure 1. Location of mining pit lakes in British Columbia, Yukon Territory and Washington State, USA. The inset shows the location of the Brenda study site as well as Peachland, the site of .the supplementary meteorological station.

Figure 2. Vertical distribution of temperature for three neighbouring pit lakes shown in the Figure 1 insert. Brenda (jan,26, 1995), Simlico (Jan24,1995), Highland Valley Copper (HVC) (Feb.27,1995). Salinity levels in Similco and Highland Valley Copper were below the level of detection of 100 PPM so are not shown.

Figure 3. Cross-sectional views of Brenda Pit Lake and the Pavin Crater Lake. Key limnological terms and physical processes are shown schematically. The dashed curve is the hyperadiabatic temperature profile.

Figure 4. Comparison between a total of thirty days of meteorological data over the period from December 22, 1994 to February 14, 1995 for the central lake (subscript, L) and the rim observation (subscript, o) stations. Three meteorological variables are: (a) 10-min wind speeds with diamond symbols denoting wind directions from 0-90^0, triangles 90^0 to 180^0, squares from 180^0 to 270^0 and Xs from 270^0 to 360^0; (b) daily solar radiation and (c) 10-min air temperature with the rim station a black curve and the lake surface station overlain in grey .

Figure 5. Schematic of the layer structure for layers, i-1,i,i+1. The thickness of the layer of fluid entrained into layer i is Δh_{ib}.

Figure 6. Simulated (a) and observed (b) profiles of the density ratio, R_ρ on December 21, 1994 .

Figure 7.A segment of a fine-scale temperature profile in the monimolimnion recorded on December 20, 1994.

Figure 8 Hypsometric curves for Brenda Pit Lake, (a) area, (b) volume. Past water levels are indicated by the arrows in (b).

Figure 9. (a) Observed isotherms (°C) over the study period in compared to the modelled distribution in (b). Occurrence of observed and modelled fast ice is indicated at the surface of each panel. Observation days are indicated by vertical arrows.

Figure 10. Same as Figure 9 but for salinity in units of PPM or mg/l.

Figure 11 Temperature at a depth of 130m from a mooring located at the deepest point of Brenda Pit Lake.

Figure 12. Isopleths of the logarithm of 10-day averages of total eddy conductivity in m^2/s over the simulation period in the hypolimnion and monimolimnion employed in the model. The epilimnion position is indicated by the hatched region and observation days by vertical arrows.

Figure 13. Same as Figure 12 but for eddy diffusivity for a dissolved substance.

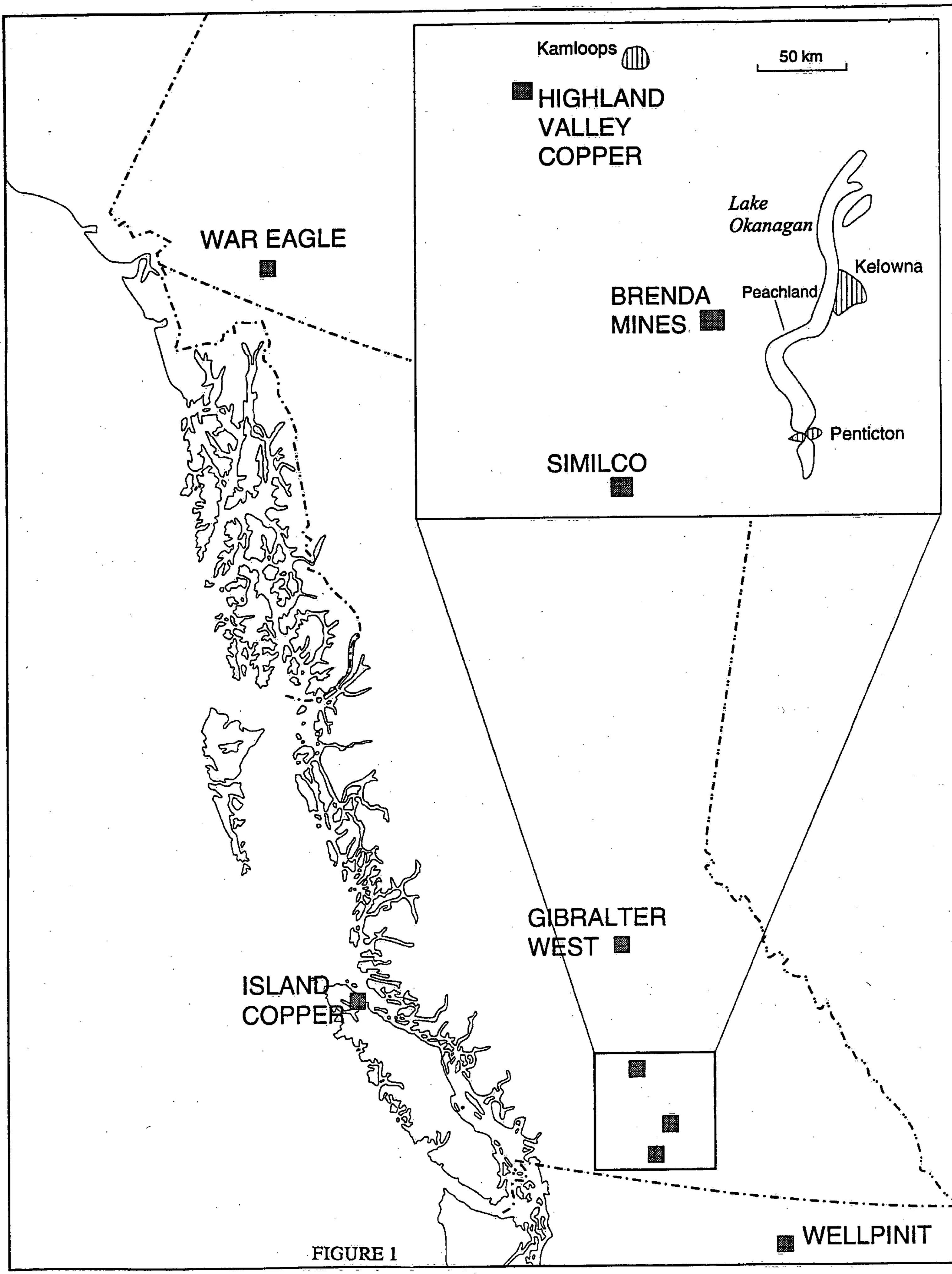

Kamloops
50 km
HIGHLAND VALLEY COPPER
Lake Okanagan
Kelowna
Peachland
BRENDA MINES
Penticton
SIMILCO
WAR EAGLE
GIBRALTER WEST
ISLAND COPPER
WELLPINIT

FIGURE 1

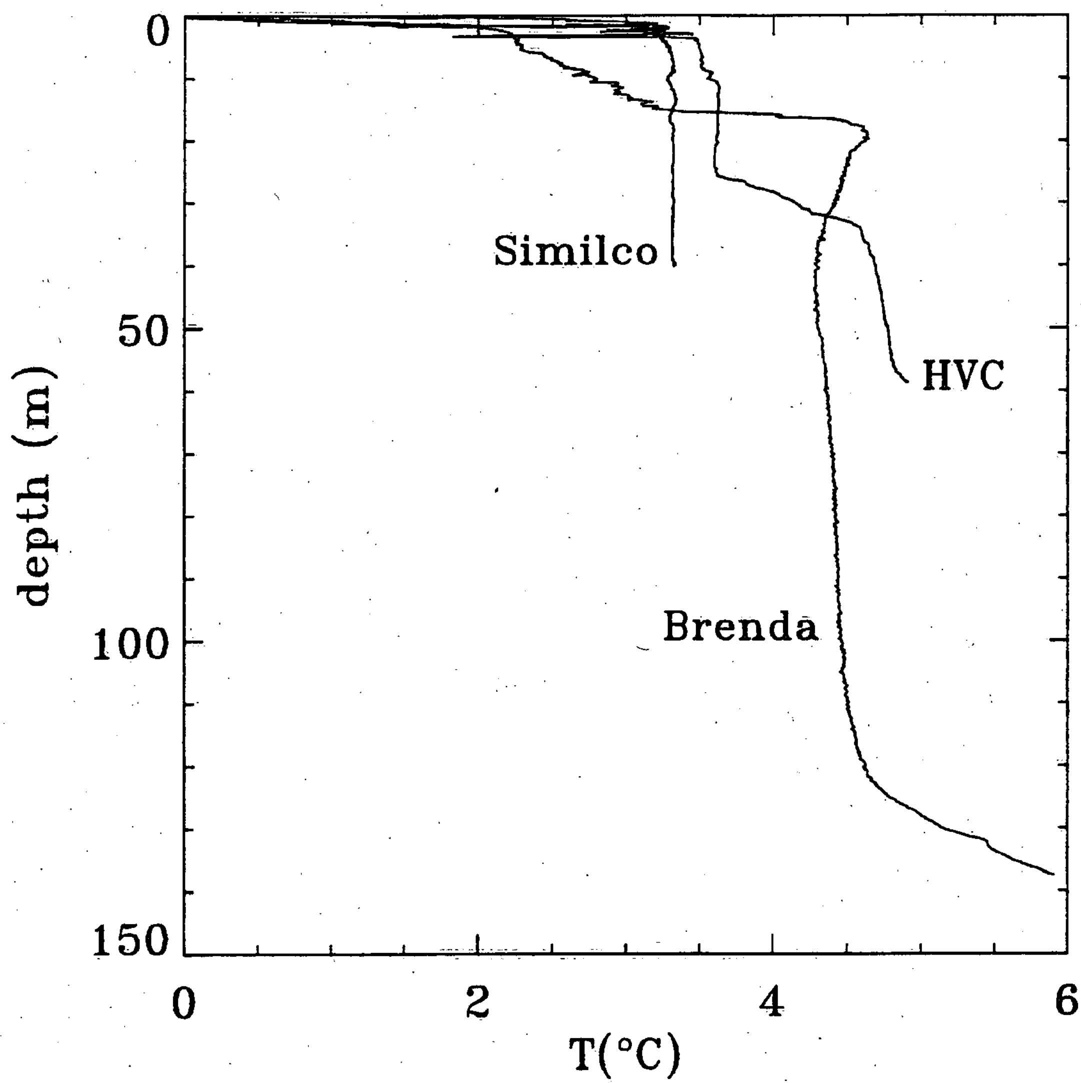


FIGURE 2

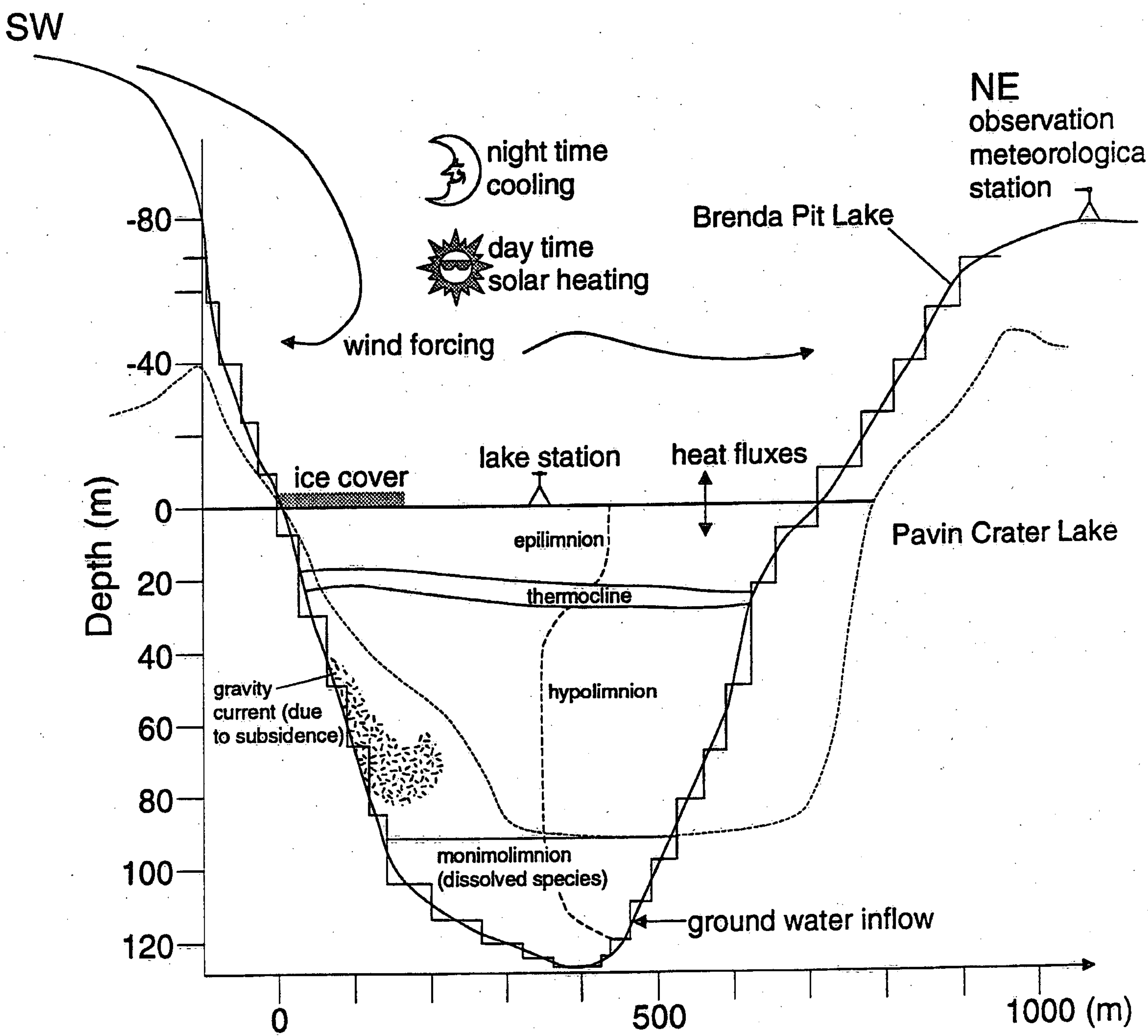

SW
NE
observation
meteorological
station
night time
cooling
day time
solar heating
Brenda Pit Lake
wind forcing
lake station
heat fluxes
ice cover
Pavin Crater Lake
epilimnion
thermocline
hypolimnion
gravity
current (due
to subsidence)
monimolimnion
(dissolved species)
ground water inflow
Depth (m)
-80
-40
0
20
40
60
80
100
120
0
500
1000 (m)

FIGURE 3

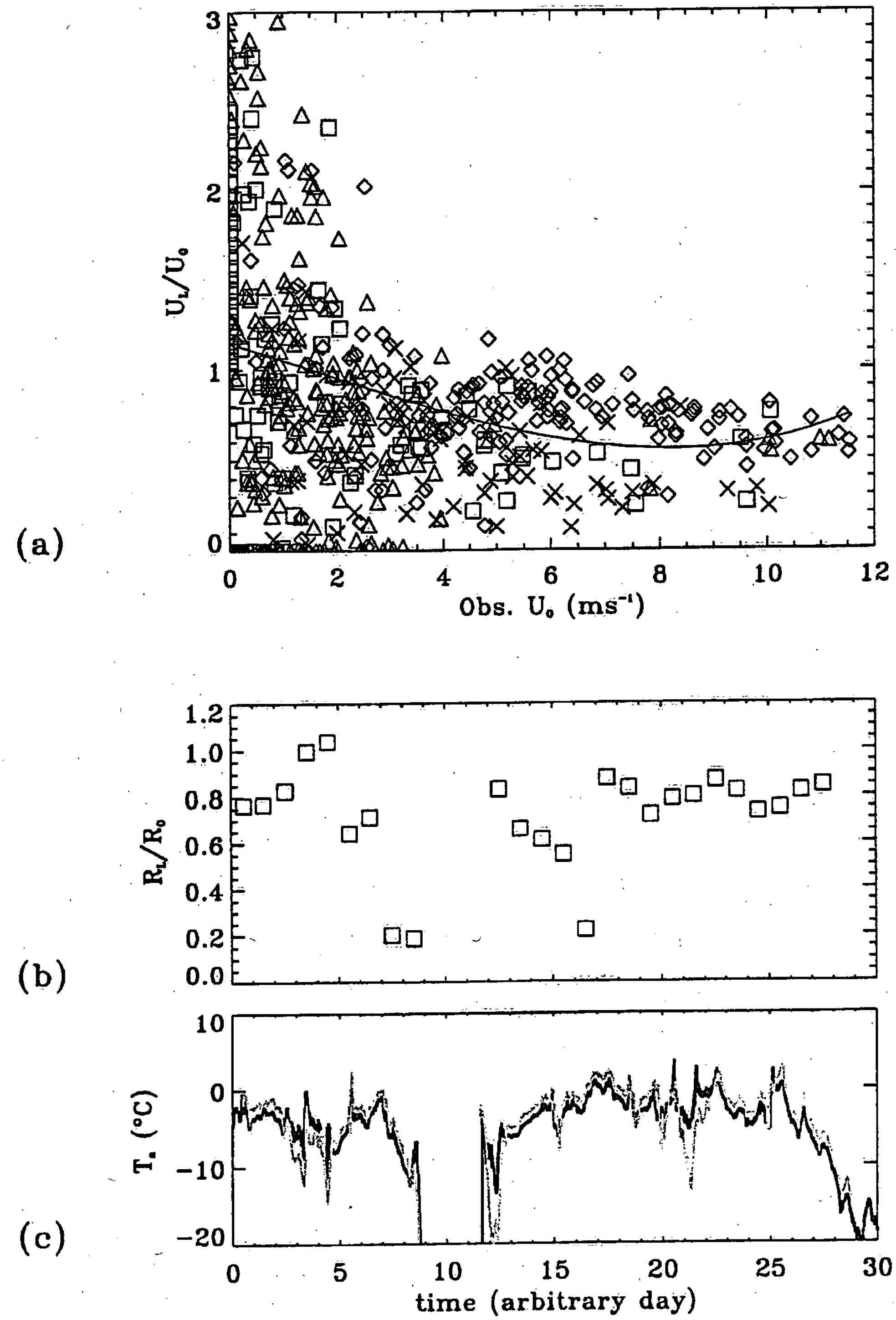

(a)
U_L/U_o
Obs. U_o (ms^{-1})
0
1
2
3
4
6
8
10
12
(b)
R_L/R_o
0.0
0.2
0.4
0.6
0.8
1.0
1.2
(c)
T_a (°C)
10
0
−10
−20
5
15
20
25
30
time (arbitrary day)

FIGURE 4

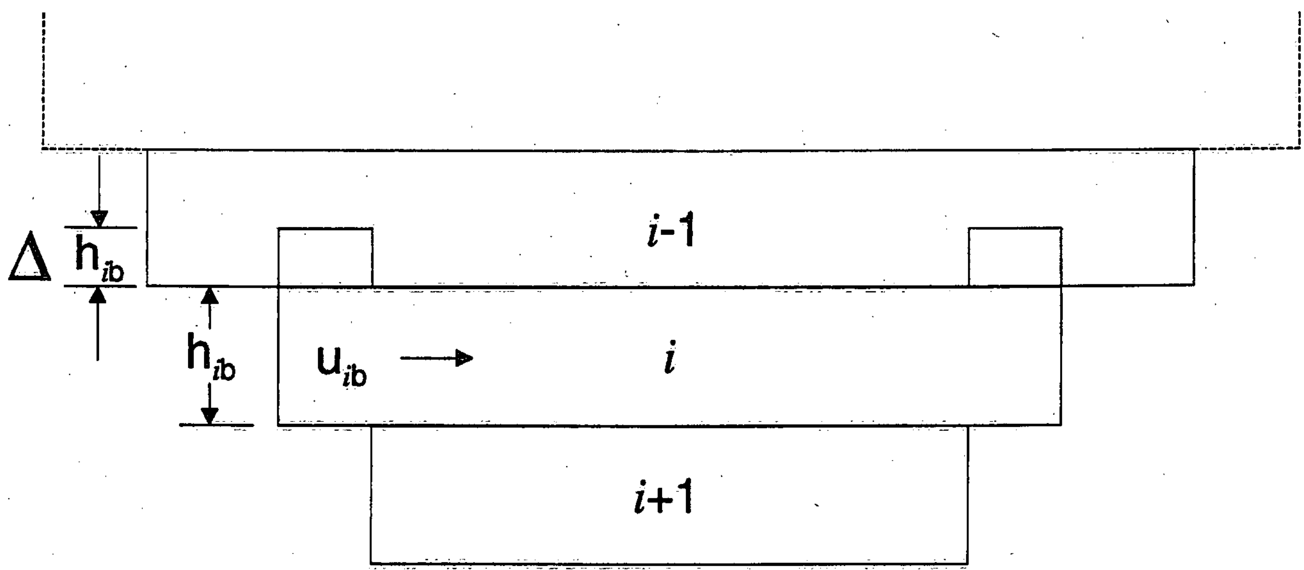


FIGURE 5

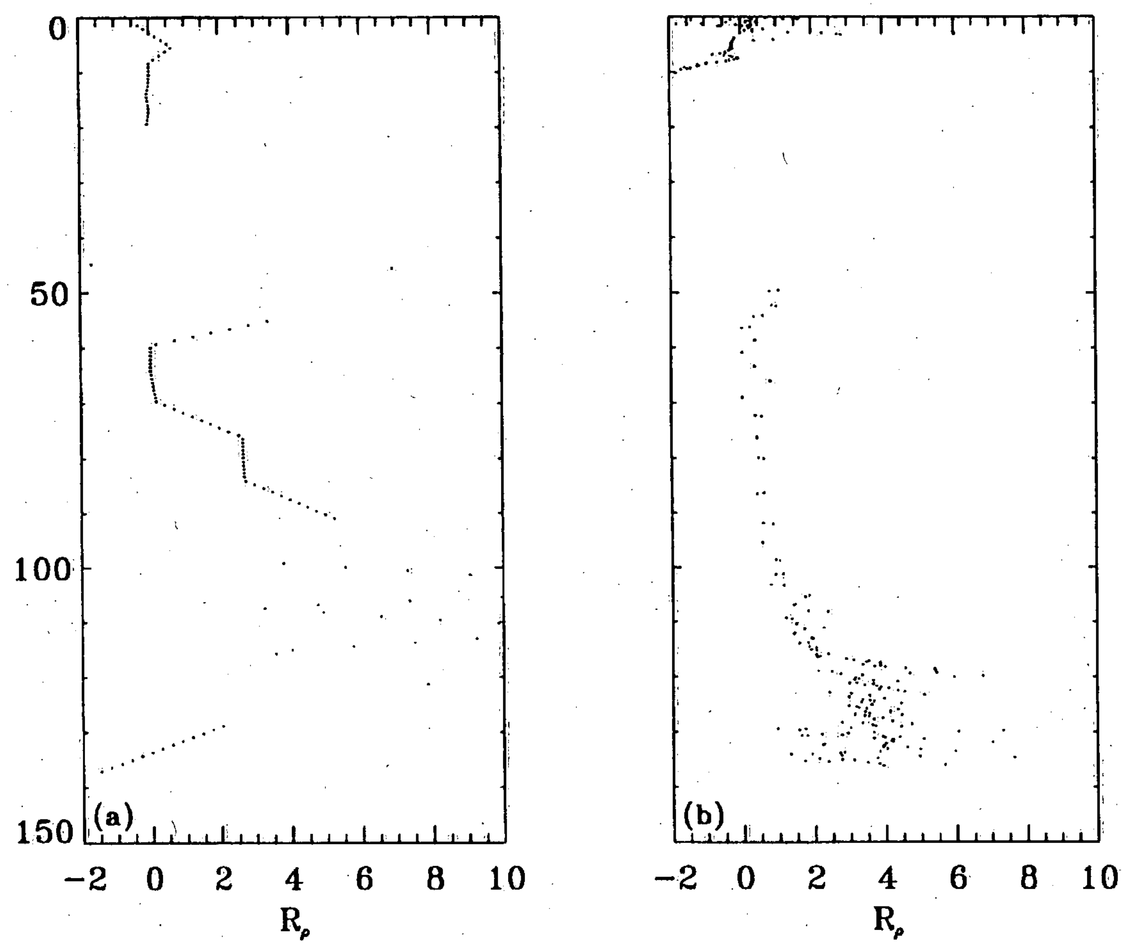


FIGURE 6

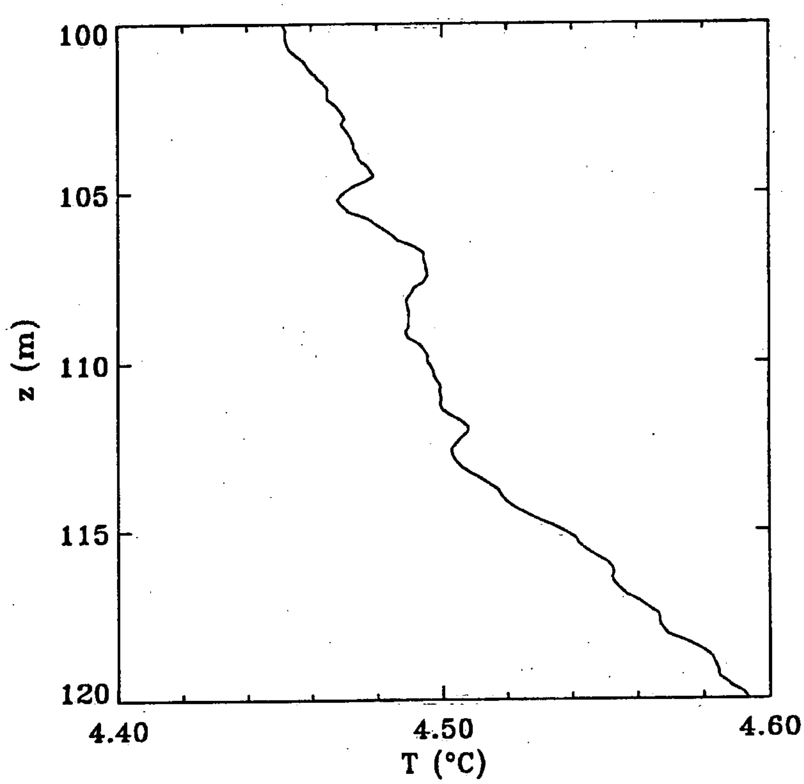
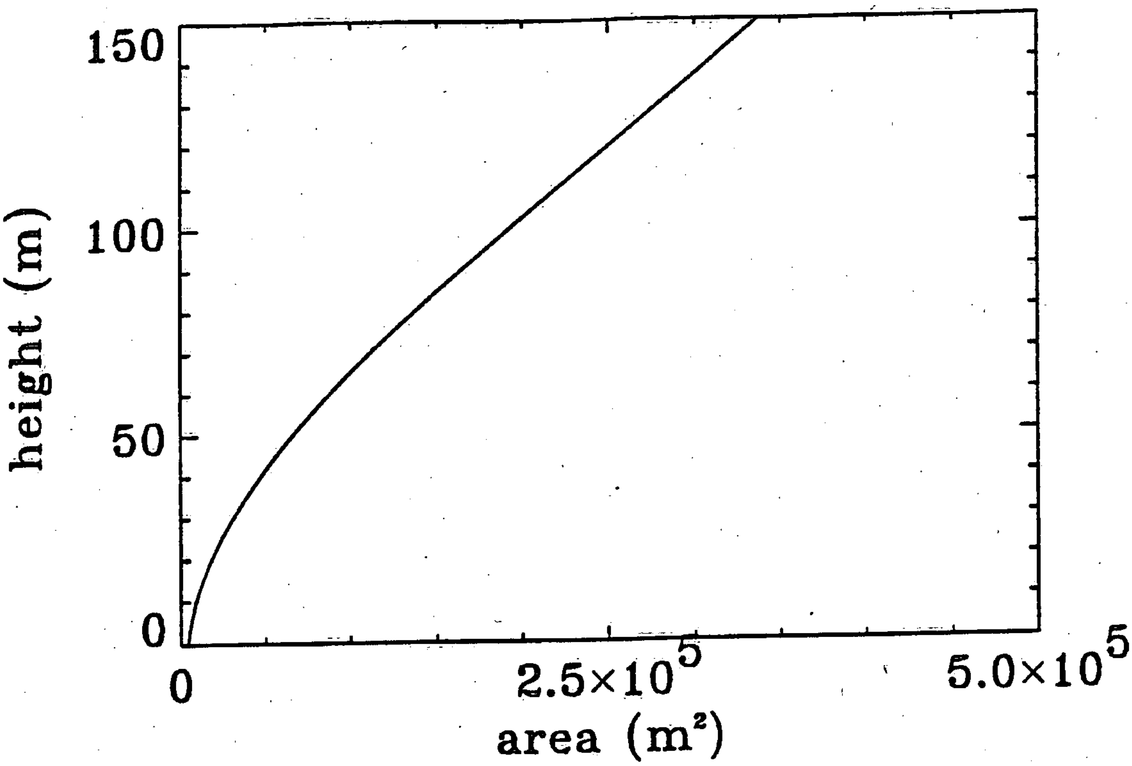
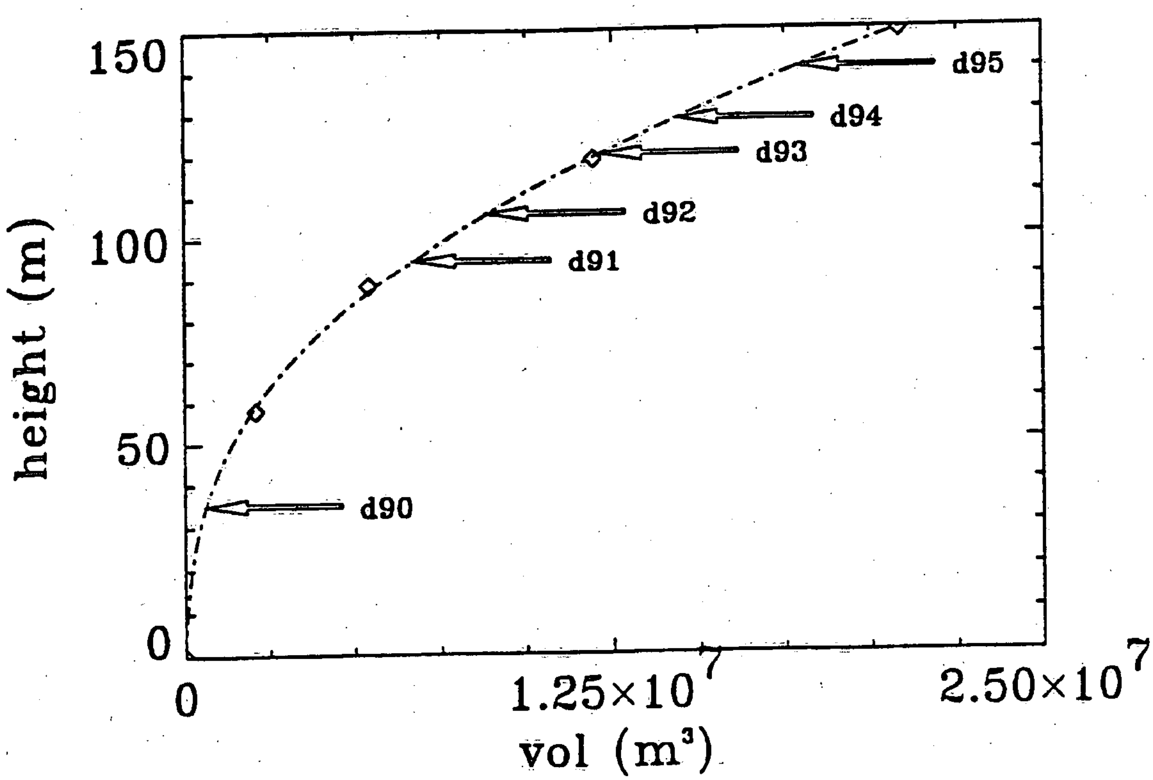


FIGURE 7

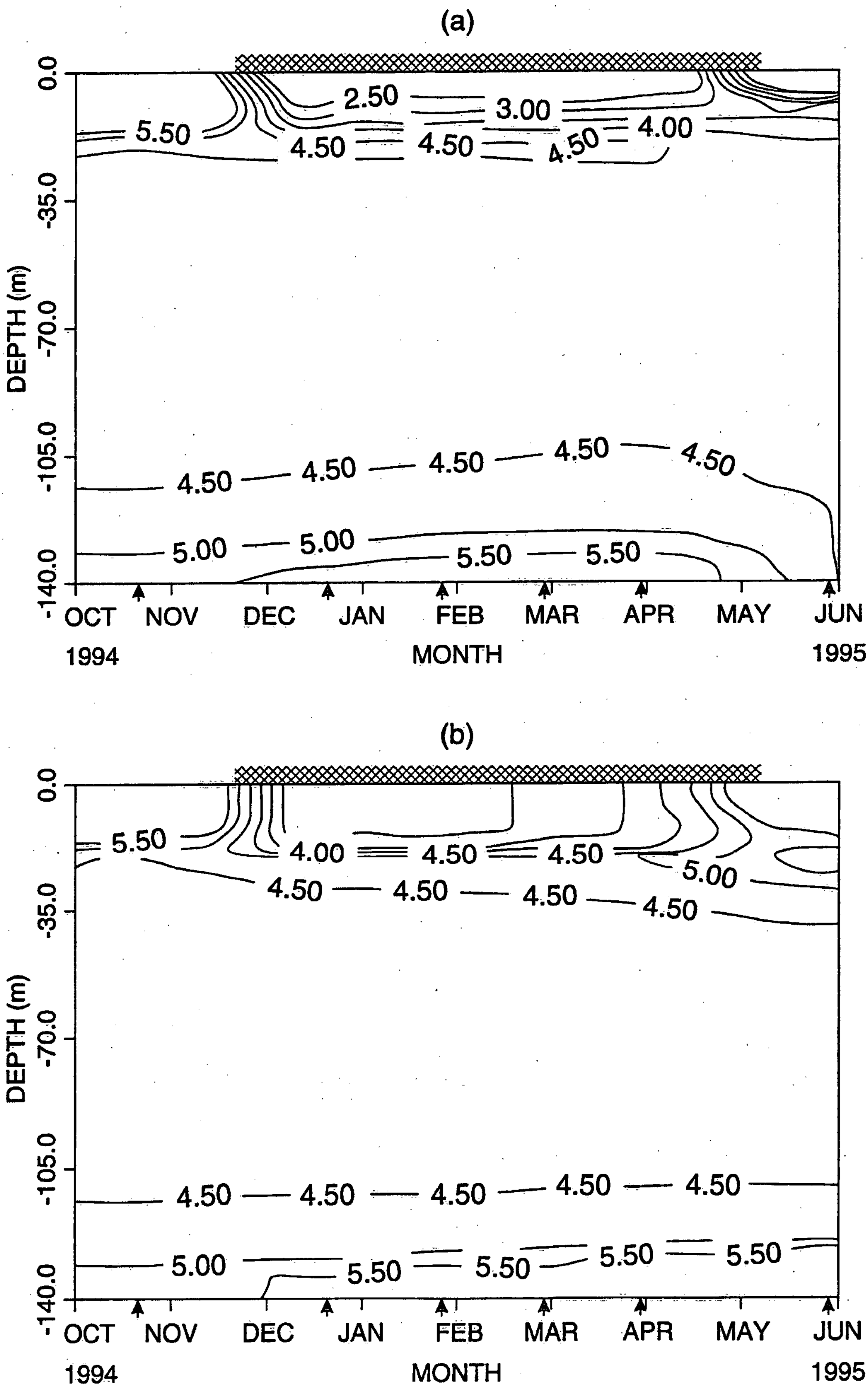


150
100
50
0
height (m)
0
2.5×10^5
5.0×10^5
area (m²)



150
100
50
0
height (m)
d95
d94
d93
d92
d91
d90
0
1.25×10^7
2.50×10^7
vol (m³)

FIGURE 8



(a)
2.50
3.00
5.50
4.50
4.50
4.50
4.00
4.50
4.50
4.50
4.50
4.50
5.00
5.00
5.50
5.50
0.0
-35.0
-70.0
-105.0
-140.0
DEPTH (m)
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1994
MONTH
1995
(b)
5.50
4.00
4.50
4.50
5.00
4.50
4.50
4.50
4.50
4.50
4.50
4.50
4.50
4.50
5.00
5.50
5.50
5.50
5.50
0.0
-35.0
-70.0
-105.0
-140.0
DEPTH (m)
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1994
MONTH
1995

FIGURE 9

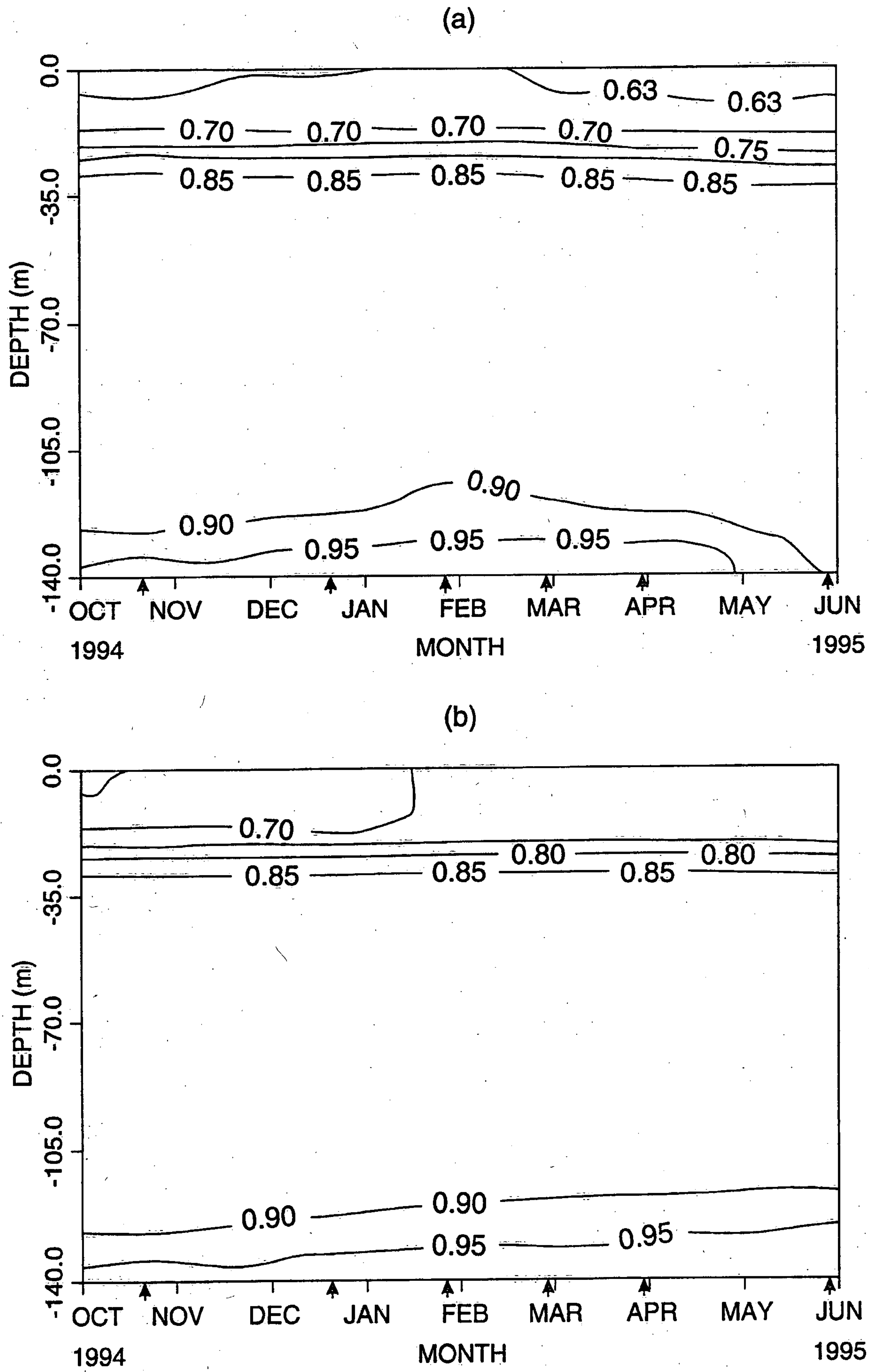

(a)
0.0
-35.0
-70.0
-105.0
-140.0
DEPTH (m)
0.63
0.63
0.70
0.70
0.70
0.70
0.75
0.85
0.85
0.85
0.85
0.85
0.90
0.90
0.95
0.95
0.95
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1994
MONTH
1995
(b)
0.0
-35.0
-70.0
-105.0
-140.0
DEPTH (m)
0.70
0.80
0.80
0.85
0.85
0.85
0.90
0.90
0.95
0.95
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1994
MONTH
1995

FIGURE 10

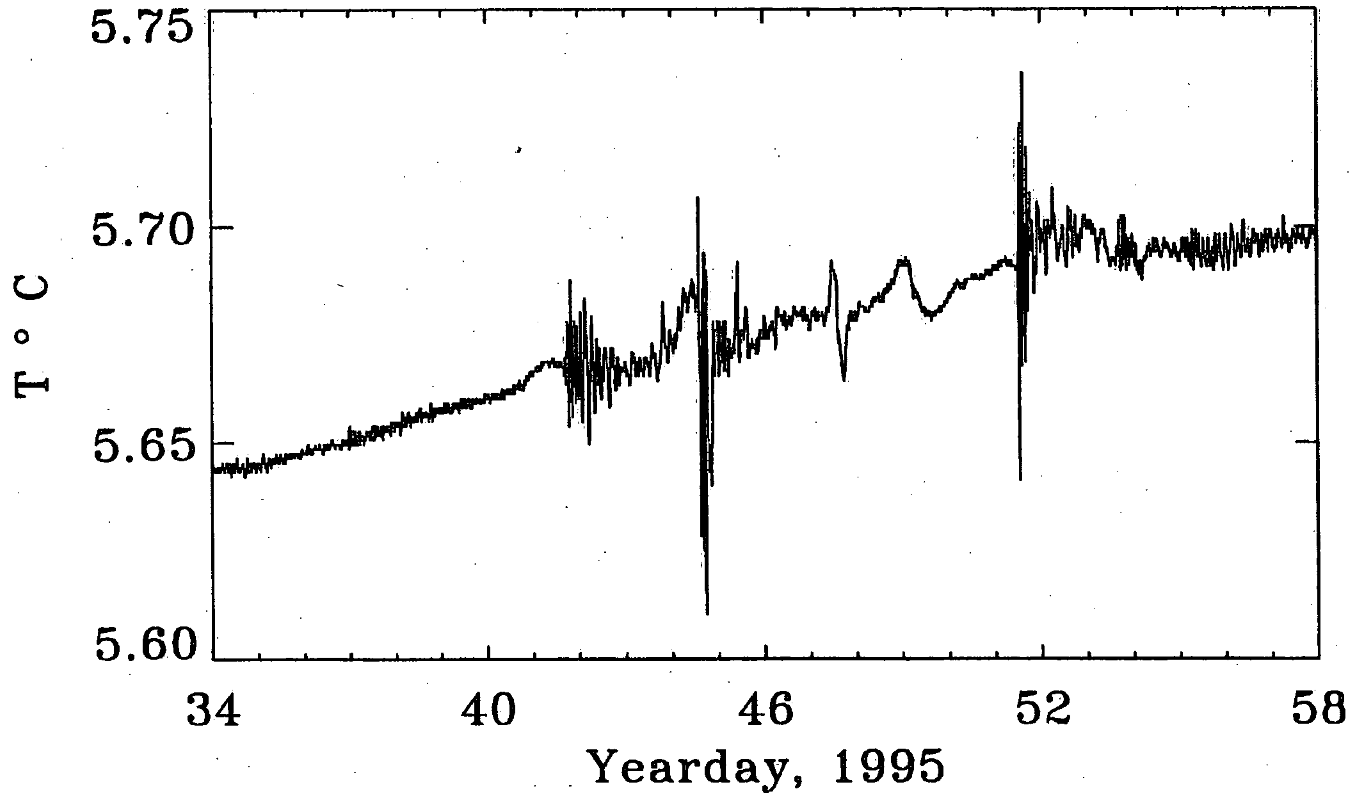


FIGURE 11

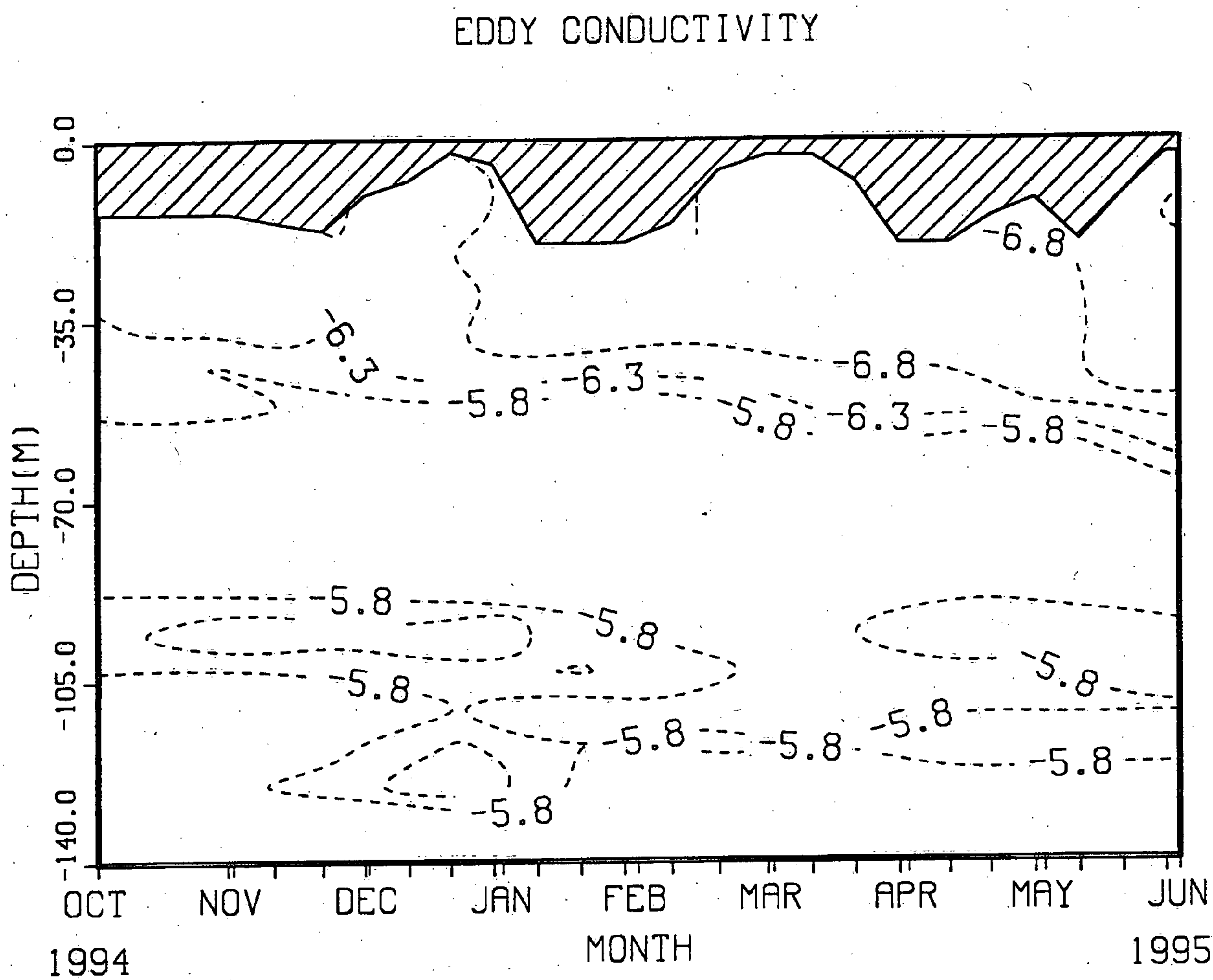
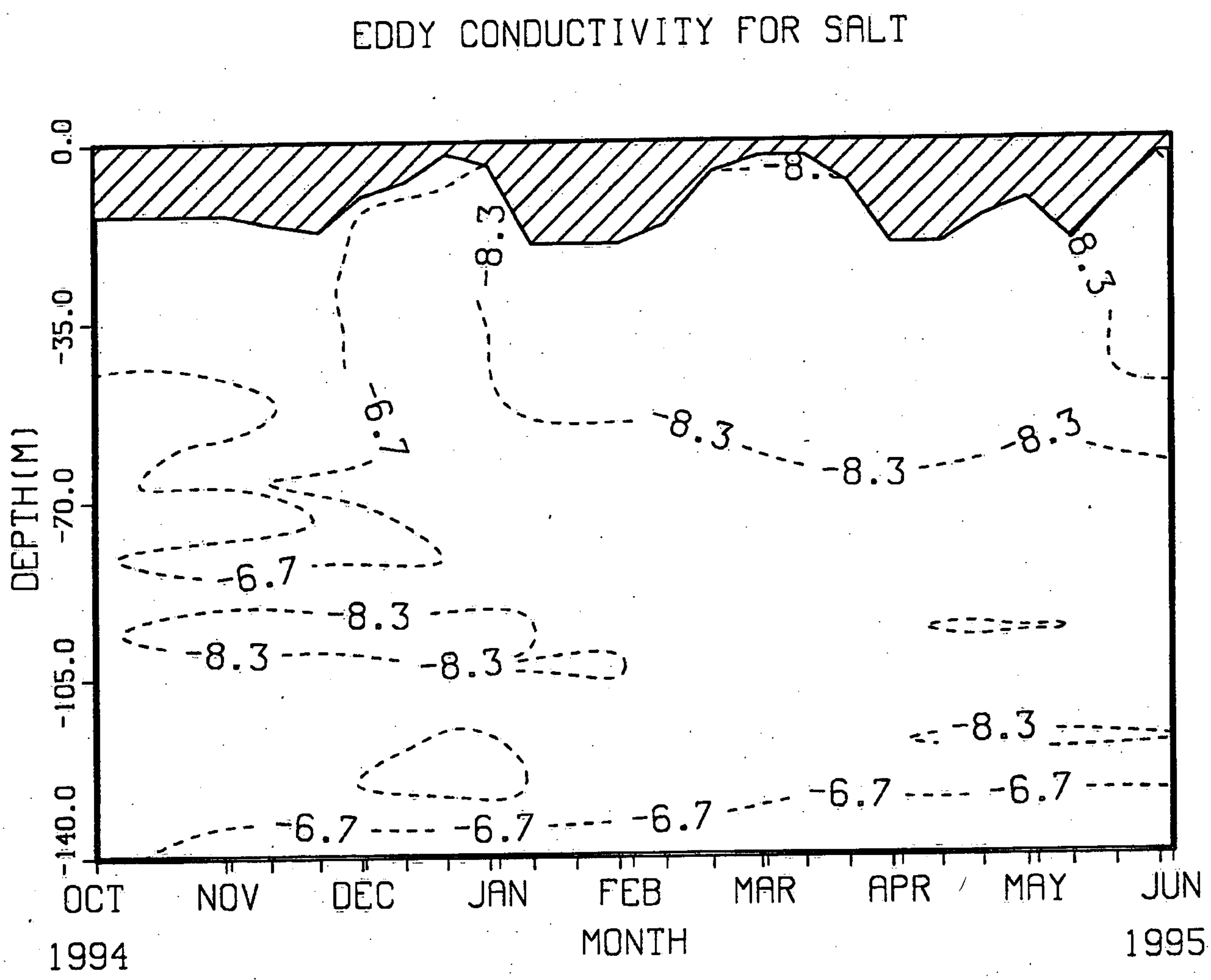

EDDY CONDUCTIVITY
0.0
-35.0
-70.0
-105.0
-140.0
DEPTH(M)
-6.8
-6.3
-5.8
-6.3
-6.8
-5.8
-6.3
-5.8
-5.8
-5.8
-5.8
-5.8
-5.8
-5.8
-5.8
-5.8
-5.8
-5.8
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1994
MONTH
1995

FIGURE 12



EDDY CONDUCTIVITY FOR SALT
DEPTH(M)
0.0
-35.0
-70.0
-105.0
-140.0
-8.3
-6.7
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
MONTH
1994
1995

FIGURE 13

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