SOME ASPECTS OF THE PHYSICAL LIMNOLOGY OF HAMILTON HARBOUR

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ABSTRACT

This report reviews previous work on the physical limnology of Hamilton Harbour and presents results and preliminary interpretations of an extensive measurement program undertaken in the harbour from May-September, 1988. The program was designed to treat the harbour-canal system as a combined entity and to provide a broad overview of canal flow regimes and the fate of Lake Ontario water in Hamilton Harbour. The dominant flow regime observed in the canal was a stratified exchange flow, although cases were observed in which either the inflow or outflow was blocked and flow was mainly in one direction. These latter cases tended to be associated with unsteady conditions presumably brought about by oscillating water levels in Lake Ontario. Results of current-metering across the canal indicate that the flow field is in general three-dimensional, precluding efforts to measure cross-sectionally averaged velocities with one or two current meters of fixed depths. The advection of oxygen to the hypolimnion by inflowing lake water is probably several times larger than the downward flux of oxygen through the thermocline by eddy diffusion.

MANAGEMENT PERSPECTIVE

This report is the final contract report of National Water Research Institute Contract No. 89-08 undertaken to resolve the nature of the complex bidirectional exchange flow between Hamilton Harbour and Lake Ontario and to extend knowledge of the physical limnology of the harbour. A thorough review of past work on the physics of Hamilton Harbour and its impact on Lake Ontario is followed by description of the field methods used to examine the flow and water property structure. Results of nearly weekly field experiments on the exchange flow, temperature, conductivity and dissolved oxygen transects over the stratified period are provided in five appendices. The description of the physics contained herein should provide a second basis for more detailed quantitative analysis with the goal of simulating the past and present exchange flow during the stratified period.

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I. INTRODUCTION

Hamilton Harbour is a medium-sized lake located at the western end of Lake Ontario between latitudes 43°16'N to 43°19'N and longitudes 79°47'W to 79°53'W. The harbour has a roughly triangular shape (Figure 1-1) with a length of 8 km along its main axis and a maximum width of 6 km along its eastern shore parallel to the shoreline of Lake Ontario. The eastern shoreline is formed by a narrow sand bar separating Hamilton Harbour from Lake Ontario. The Burlington Ship Canal (length 836 m, width 89 m, average depth 9.55 m*) passes through this sand bar and connects the harbour to Lake Ontario. The harbour has a maximum depth of 25 m, an average depth of 13 m, a surface area of 21.5 km^2, and a volume of 2.8 (10^8 m^3) (OME 1974). The harbour catchment of 494 km^2 contains the City of Hamilton and a large part of the City of Burlington with a total population close to one-half million people. Extensive filling of littoral areas on the southern shoreline of the harbour has provided space for one of Canada's major concentrations of heavy manuacturing industry, including two large steel mills and docking facilities for large Great Lakes freighters. Industry draws process and cooling water from the harbour and returns treated effluent. The cities of Burlington

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* Depth referred to chart datum, corresponding to a low water level at Kingston of 74.0 m above International Great Lakes Datum (IGLD 1955).

and Hamilton draw their water supplies from Lake Ontario but release all of their treated sewage into the harbour.

As a result of loadings from sewage treatment plants, industry, combined sewer overflows during storms and urban storm runoff, Hamilton Harbour suffers severe water quality problems. Aspects of these problems have been discussed by several authors, including Harris _et al_. (1980; general limnology), Polak and Haffner (1978; oxygen depletion), Nriagu _et al_. (1983; metal pollution), Poulton (1987; trace contaminants), by Gorrie (1987) in a popular aticle, and by OME in several reports (1974, 1975, 1977, 1978, 1985, 1986). Hamilton Harbour has been designated as one of 42 areas of concern in the Great Lakes basin by the International Joint Commission. and work is currently underway to develop a remedial action plan to improve water quality (RAP 1988).

This report describes the results of research undertaken on the physical limnology of Hamilton Harbour to support the formulation of a remedial action plan. Physical processes of particular importance to the harbour ecology include flushing rates due to inflowing rivers and the exchange with Lake Ontario through the ship canal; the fate of Lake Ontario water after it enters the harbour; circulation and mixing in the harbour; the impact of filling of littoral areas; and sources of transport of suspended particulate matter in the harbour. These processes are discussed in varying degrees of detail in this report. However, questions relating to transport of sediments and particulate matter are the subject of research by other workers and will not be considered in this report.

The patterns of thermal stratification, mixing, and circulation observed in a lake reflect the response of that lake to energy exchanges with the atmosphere and with inflowing and outflowing rivers. While this is a truism for any lake, Hamilton Harbour seems particularly sensitive to changes in meteorological conditions and to variations in inflows and outflows. A cursory examination of existing literature on Hamilton Harbour (cf. Harris _et al_. 1980) reveals that the harbour is frequently characterized as a dynamic water body, subject to constant changes in its physical, chemical, and biological properties. It is the coupling of flow in the canal with weather conditions and water temperatures that provides the key to the dynamism of the harbour. Unlike a lake with inflowing rivers whose discharges depend only on rainfall and runoff from the surrounding catchment, Hamilton Harbour receives its major inflow through the ship canal from Lake Ontario. The harbour's only natural outflow is also through the canal. Flow rates in the canal depend on small differences in water levels and water densities at either end of the canal, with wind-drift currents probably being of minor significance. The importance of the wind lies in its effect on relative water levels and temperatures (hence densities) at the ends of the canal. The wind excites basin-scale waves in both the lake and the harbour (Hamblin 1968, Freeman et al. 1974). These disturbances are in turn accompanied by upwelling or downwelling and the appearance of colder or warmer water along the lake or harbour shorelines. The role of westerly winds in depressing water levels and bringing cold water to the surface along the northern and western shores of Lake Ontario has been well documented (Simons and Schertzer 1987). Exactly the reverse occurs during easterly wind episodes. Moving pressure disturbances accompany the weather systems that bring changing winds; the pressure variations can act to amplify or dampen water surface displacements driven by the wind. Changing meteorological conditions on time scales of hours or days to a few weeks at most cause changes in conditions at the ends of the canal and therefore in the inflow and outflow rates. The temperature of the inflowing Lake Ontario water in turn largely determines the fate of the lake water in the harbour.

Previous investigators recognized the importance of the exchange flow for the limnology of Hamilton Harbour. The next section of this report includes a short review of previous work. The review is not exhaustive but rather emphasizes questions about physical limnology that require further clarification. These questions influenced the design of the sampling program. I felt that the sampling program should provide a broad overview of the physical processes occurring in the harbour-canal system, rather than focus in detail on a single process, location, or type of measurement. Previous research on the harbour has been fragmented and until now resources have never been available to study harbour processes in a comprehensive fashion. In this study, an effort was made to observe the major physical variables that drive mixing and circulation, and simultaneously to observe the harbour response. The Canada Centre for Inland Waters (CCIW) is ideally situated and has the necessary facilities and technical expertise to support such a program. The third section of this report presents the methods and results of the sampling program and discusses some of the implications of the results.

II. BACKGROUND AND REVIEW OF PREVIOUS WORK

This section contains a review of previous work that pertains to canal flows and harbour mixing and circulation. At the same time, an effort is made to clarify some concepts related to canal flow regimes, harbour water balance, and residence or flushing time. Part of this section is drawn from my earlier contribution to the RAP report (RAP 1988, pp. 62-68), but modified somewhat in light of the results from the 1988 summer sampling in the harbour.

II.1 Early Work on Exchange Flows and on the Effects of Landfilling

One of the earliest reports of current meter measurements in the canal was that of Matheson (1958), Director of the City of Hamilton's Municipal Laboratory. Matheson observed stratified exchange flow in the canal during summer, with warmer outflowing harbour water overflowing cooler, incoming Lake Ontario water.

Dick and Marsalek (1972, 1973) presented results of numerical modelling of both unstratified and stratified canal flows. Their paper (1972) and the second part of their report (1973, Chapter 3) presented results from 11 velocity profiles measured during the summer of 1971 concurrently with temperature profiles in the middle and at both ends of the canal. All of their velocity profiles indicated the occurrence of exchange flow, with warmer harbour water leaving the harbour, overflowing cooler, incoming lake water. Dick and Marsalek used the gradually varied two-layer flow equations of Schifj and Schönfeld (1953) to compute interface slopes in the canal for a range of friction factors. These equations are the two-layer analogues of the gradually varied flow equations for single-layer, uniform density flow used in hydraulic engineering to predict backwater curves or free surface water profiles in open channel flow (e.g., Henderson 1966). Just as the free surface must slope downward in the direction of flow for a uniform density open channel flow, the interface between the warm and cold layers in the canal must slope downward from the lake end to the harbour end of the canal in order to drive an inflow of colder, denser lake water through the canal against fiction of the canal sidewalls and bottom. At the same time, the water surface must slope downward in the opposite direction to drive the warmer overflow from the harbour to the lake. The slope of the free surface is much less than that of the interface, however. Dick and Marsalek did not use the theory to predict flow rates. Rather they used the flow rates computed from measured velocity profiles to predict interface slopes for a range of friction factors, and compared these slopes with those inferred from measured profiles. The inverse problem of computing exchange flow water from given temperature profiles and water levels at each end of the canal is a much more difficult one and as far as I am aware has not yet been attempted for Hamilton Harbour. Dick and Marsalek concluded that the two-layer theory gave a reasonable representation of the observed interface slopes for the range of bottom friction factors they considered: Manning's n = 0.015 to 0.020 with n = 0.02 producing the best fit.

The choice of an appropriate friction factor is an important problem for anyone seeking to model flow rates in open channels. The value n = 0.02 corresponds to a fairly flat bed of fine sand (e.g., Henderson 1966, p. 99). However, recent soundings by the Ontario Public Works Department (PWD 1988) reveal that the bed is far from flat, with irregularities of heights up to 0.5 m. Scour holes approximately 1 m deep mark both ends of the channel. The canal was last dredged in 1963-1964 when both the canal and approaches were deepened to their present depths and the canal face walls were reconstructed (J. Grossi, personal communication). The walls are of vertical steel sheet piling with sharp cornered corrugations of depth 260 mm projecting into the flow with a wavelength of 885 mm. Dredging is sometimes necessary to maintain the approach channel on the lake side at the required depth (8.2 m) but no dredging has been necessary to maintain the project depth of 8.8 m in the canal itself. Hence sediment transport probably occurs along the canal bed, and this will have a bearing on the existence of bed forms and hence roughness or friction factor. However, to date there have been no studies of sediment size, sediment motion, or bed forms in the canal. In the first part of their 1973 report (Chapter 2), Dick and Marsalek addressed the question of how decreasing the harbour's surface area by infilling of littoral zones had altered the volume of exchange flows. To carry out their calculations, Dick and Marsalek combined the open channel flow equation for the steady flow of water of uniform density with a simplified water balance for the harbour relating inflow and outflow to harbour volume and water surface elevation. The model was driven by a time series of water levels at the western end of Lake Ontario, and assumed values of friction factors for the canal flow were used. Their results, as well as those of Freeman _et al_. (1974), have clearly shown that the duration and magnitude of flows from Lake Ontario to the harbour depend on the surface area of the harbour. Decreasing harbour surface area decreases the total annual volume of inflow from the lake. This is essentially because decreasing the surface area decreases the volume inflow required to overcome a given water level deficit between the harbour and the lake. (Naturally there will be less total outflow from the harbour to the lake as well.) For detailed derivation of this result the reader is referred to the original papers. Dick and Marsalek stated that landfilling from 1926 to 1972 resulted in a decrease in harbour surface area of approximately 25%, from 2.8×10^7 m^2 to

2.1×10^7 m^2. They estimated that the total volume of the lake water entering the harbour annually decreased by approximately 3.2×10^8 m^3 over that period as a result. Their calculations included the effects of surface area changes on water levels as well as flows. Moreover, their results indicated that percentage decreases in surface area and annual inflows were roughly equal and therefore, the 25% decrease in surface area given above resulted in an estimated 24% decrease in inflow volume from 1.35×10^9 m^3/year to 1.03×10^9 m^3/year. (This latter figure is roughly equal to the 1.04×10^9 m^3/year for lake inflow deduced from Klapwijk and Snodgrass's figures cited earlier.) Dick and Marsalek concluded that further percentage decreases in harbour surface area would result in roughly equal percentage decreases in lake inflows.

The question arises, then, as to the effect of decreasing lake inflow on harbour water quality. Intuitively one would expect that a decrease of lake water inflow of 24% could not fail to have a deleterious effect on harbour water quality. While the impact of lake inflows on harbour water quality is beyond the scope of this report, it may be worthwhile to briefly examine the relationships between harbour volume, inflow rate, and residence or flushing time. In general, residence time, T, for any volume of water can be defined as the volume, V, divided by the throughflow, Q (assumed equal to the inflow and to the outflow):

$$T = V/Q. \tag{II-1}$$

One can use equation II-1 to derive an estimate for the change in residence time, dT, due to changes in volume, dV, and flow, dQ, as (to first order):

$$dT/T = dV/V - dQ/Q, \tag{II-2}$$

i.e., the relative change in T is equal to the relative change in V minus the relative change in Q. From Dick and Marsalek's work one can estimate, for the period 1926 to 1972, $dQ/Q = -0.24$ (as given earlier) while the relative change in volume $dV/V = -0.027$, or less than 3% (from 2.95×10^8 m^3 to 2.87×10^8 m^3; Dick and Marsalek, p. 1). The net effect is therefore to increase the residence time by 21%. The change in residence time is dominated by the change in flow rate, dQ/Q; the relative change in volume, dV/V, is very small because most of the landfilling was carried out in shallow littoral areas where large losses of surface area result in only small losses in volume. A corollary is that there has been no change in volume to the deeper regions of the harbour.

If one considers the residence time of the hypolimnion alone, rather than that of the entire harbour, it is clear that increases in residence time due to decreases in flushing flows are not offset at all by decreases in volume. As discussed later, because of the way in which flushing occurs - first via the hypolimnion by underflow - it may be argued that the residence time of the hypolimnion is a more meaningful index for water quality than the residence time of the entire harbour. Using Dick and Marsalek's estimate of the inflow of 1.03 x 10^9 m^3/year, assuming that all of this is used to flush the hypolimnion, and taking the volume of the hypolimnion as roughly one half the total lake volume (cf. Klapwijk and Snodgrass 1985) or 1.4 x 10^8 m^3, gives a residence time for the hypolimnion of approximately 50 days.

The significance of the residence time becomes clear if one compares it with the time for oxygen depletion in the hypolimnion during summer stratification, a time which is of the order of a month or less (OME 1985, Chapter 6). Decreasing the flushing time to less than that of the oxygen decay time would prevent the occurrence of anoxia. Increasing the flushing time would further prolong the period of anoxia.

A further consequence of infilling shallow littoral areas is to reduce the net heat capture from the atmosphere by the epilimnion in summer. This in turn reduces the temperature (and hence density) differential between harbour and lake waters during summer. The net effect is to decrease exchange flows that are driven by density differences alone, as opposed to those driven by water level differences. It should be noted that Dick and Marsalek's model accounted only for flows driven by water level differences. Density driven flows can be considerable and the exchange rate is proportional to the square root of the density difference between the water at either end of the canal (Armi and Farmer 1986). The temperature stratified flows observed in the canal by Dick and Marsalek, Kholi (1979), and others, are probably driven by a combination of density and water level differences.

II.2 Water Balance and Residence Times

Following Dick and Marsalek's work, an effort was made by other workers to better quantify the water balance of the harbour and compute harbour flushing times. Before reviewing the results of this work, however, it is worthwhile to set out the framework of the water balance with the terminology that will be used throughout this report. The water balance for the harbour is simply a statement that equates the rate of change of volume of water in the harbour to the sum of all inflow rates minus the sum of all outflow rates. The rate of change of harbour volume is positive if volume is increasing, negative if volume is decreasing. The various inflows and outflows are defined as follows (all discharges may be thought of as in units of m^3/s; see Figure II-1 taken from OME 1985, for locations).

$Q_{\cancel{de}}$ = discharge in the Desjardins canal (positive
DC for flow into the harbour);

Q_{SC} = discharge in Spencer Creek above Dundas Sewage Treatment Plant;

Q_{DSTP} = flow rate from Dundas Sewage Treatment Plant (into Spencer Creek);

Q_{RC} = discharge in Redhill Creek above Hamilton Sewage Treatment Plant;

Q_{HSTP} = discharge from Hamilton Sewage Treatment Plant (into Redhill Creek);

Q_{GC} = discharge in Grindstone Creek;

Q_{MC} = discharge from miscellaneous smaller creeks in the harbour catchment (other than Grindstone, Redhill, or Spencer Creeks) into the harbour;

Q_{BSTP} = discharge into the harbour from Burlington Sewage Treatment Plant;

Q_{IND} = industrial water use; the intake and return flow rates are assumed equal so that there is not net flow of volume to or from the harbour by industry;

Q_{SO} = flow into the harbour during storms from combined sewer overflows and other storm drainage channels;

Q_{GW} = net groundwater inflow to the harbour, equal to total groundwater inflows minus total groundwater outflows;

Q_{LO} = inflow to the harbour from Lake Ontario through the ship canal;

Q_{HH} = outflow from Hamilton Harbour to Lake Ontario through the ship canal;

Q_{CNET} = $Q_{LO} - Q_{HH}$ = the net discharge into harbour through the canal; positive for inflow into the harbour, negative for outflow from the harbour.

The remaining components of the water balance include rainfall and evaporation and rate of change of harbour volume. Normally, the units of rainfall and evaporation are mm/h, but in order to be consistent with the remaining terms in the water balance the must be expressed in terms of m/s when carrying out computations. Similarly, harbour volume must be in terms of m^3, harbour surface area in m^2, and time in seconds.

R = rainfall on the surface of the harbour;

E = evaporation from the surface of the harbour;

V = harbour volume;

A = harbour surface area;

H = harbour-wide average elevation of the water surface.

It is convenient to combine the discharges from all inflowing streams in the harbour watershed into a single term:

$$Q_W = Q_{SC} + Q_{GC} + Q_{RC} + Q_{MC} \qquad \text{(II-3)}$$

Similarly, for the flow from the STPs:

$$Q_{STP} = Q_{BSTP} + Q_{HSTP} + Q_{DSTP} \qquad \text{(II-4)}$$

I will also assume that to the order of accuracy attainable in the water balance terms that changes in harbour volume are related to changes in water surface elevation as:

$$dV/dt = AdH/dt \qquad \text{(II-5)}$$

where the value of A may be taken as 21.5 km^2.

The water balance for the harbour can then be written as:

$$AdH/dt = Q_W + Q_{STP} + Q_{GW} + Q_{SO} + Q_{LO} - Q_{HH} + (R - E)A. \qquad \text{(II-6)}$$

It should be noted that equation II-6 is not strictly correct unless one assumes either that Cootes Paradise is part of the harbour basin or that

$$Q_{DC} = Q_{SC} + Q_{DSTP}, \qquad \text{(II-7)}$$

i.e., flow through the Desjardins canal at the western end of the harbour is the same as the flow into Cootes Paradise from Spencer Creek and the Dundas Sewage Treatment Plant. Equations II-6 and II-7 effectively ignore storage effects in Cootes Paradise and the hydraulic effect of the constriction separating Cootes Paradise from Hamilton Harbour. While this may be quite misleading from the point of view of the dynamics of Cootes Paradise it will be assumed to be of little consequence for the water balance of Hamilton Harbour, especially when considering averages of equation II-6 over time intervals longer than one day.

The magnitudes of some of the terms in equation II-6 have been estimated on a average annual basis by OME (see 1974, p. 1; 1975, p. H-1; 1977, pp. 3, B-1; 1978, pp. 3, F-2; 1985, p. 5) as follow: combined streamflow from the watershed Q_W = 1.27 (10^8) m^3/year = 4.03 m^3/s; industrial use Q_{IND} = 8.52 (10^8) m^3/year = 27 m^3/s; municipal sewage effluent Q_{STP} = 1.01 (10^8) m^3/year = 3.2 m^3/s; combined sewer outflows Q_{SO} = 3.2 (10^6) m^3/year = 0.1 m^3/s. Estimates by Snodgrass (1980), Klapwijk and Snodgrass (1985), and Harris <u>et al</u>. (1980) for some of these terms are slightly different. Harris <u>et al</u>. give the total inflow of all streams as Q_W = 2.83 (10^8) m^3/year = 9.97 m^3/s; Klapwijk and Snodgrass (1985) give Q_W = 1.92 (10^8) m^3/year = 6.09 m^3/s;

~~Q_{STP} = 1.13 (10^8) m^3/year; and Q_{SO} = 6.94 (10^6) m^3/year =~~

Q_{STP} = 1.13 (10^8) m^3/year; and Q_{SO} = 6.94 (10^6) m^3/year = 0.22 m^3/s. These values are of the same order as the OME estimates, but I do not know what the reasons are for the discrepancies; perhaps different years were used in computing averages. Annual rainfall is in the range 950 to 1080 mm/year (RA = 0.443 to 0.736 m^3/s into the harbour). No estimates have been given for annual evaporation. Based on studies in Lake Ontario during IFYGL (Quinn and den Hartog 1981), however, an estimate of 700 mm/year (EA = 0.48 m^3/s out of the harbour) is probably of the correct order of magnitude.

Efforts to quantify the exchange flow in the canal were made by OME in a series of current metering measurements from instruments moored in the canal. Results of these measurements are documented in OME (1974, 1975) for installations of two recording currnt meters installed at two depths at a distance of approximately 2 m from the canal wall at the harbour end of the canal during 3 to 5 October, 1972, 26 September to 6 October, 1973, and 13 June to 22 July, 1974. A wide range of discharges were calculated by assuming that the flows measured were representative of those over the entire cross-section. These varied from 106 m^3/s for both Q_{LO} and Q_{HH} (but over different time intervals) for the 1973 data to average values of 35 m^3/s for Q_{HH} and 61 m^3/s for Q_{LO} for the 1974 data. Further installations from

14 August to 13 September, 1975 gave average values of Q_{HH} = 25 m^3/s and Q_{LO} = 9 m^3/s.

Calculations of turnover rates for the harbour have been made from the current metering results. Turnover rate is the inverse of residence or flushing time and is calculated as the flow through a given volume, divided by the volume (cf. equation II-1)

$$r = 1/t = Q/V. \qquad \text{(II-8)}$$

Considering the water balance for Hamilton Harbour (equation II-6) it is clear that the value that should be used for Q in equation II-8 is either Q_{HH} or the sum of all the remaining terms on the right-hand side of equation II-6 (i.e., the total inflows). This is because the concept of turnover rate or residence time applies to a steady state balance in which $dV/dt = 0$ and total inflows are equal to outflows. However, in OME (1975, p. D-5) the turnover rate is calculated from $(Q_{LO} - Q_{HH})/V = (61\ m^3/s - 35\ m^3/s)/2.8\ (10^8)\ m^3$, equal to 1% of the total harbour volume/day. The calculation in OME (1978, p. F-10), on the other hand, is based on $(Q_{LO} + Q_{HH})/V = (9 + 25)//(2.8\ (10^8))$, again 1% of the total volume/day. Neither calculation gives the correct turnover rate. yet the figure of 1% of the harbour volume/day has found its way into the literature as an accepted measure of the exchange rate due to canal flow, e.g., Polak and Haffner (1978).

More comprehensive current metering in the canal was undertaken by the Ontario Ministry of the Environment from May 1979 to April 1980. The results were summarized by Kholi (1984) who presented monthly estimates for all major harbour inflows and outflows, including the lake-harbour exchange for the entire study period. Hence Kholi was able to put current meter results into the broader context of a water balance for the entire harbour and to follow correct procedures for calculating replacement rates and flushing times. His results did incorporate some additional assumptions, however, being based on a method for analyzing current meter records in terms of the excursion length of water particles between flow reversals (Kohli 1979). Kholi's results indicated an average annual inflow to the harbour for all land-based sources of 6.46×10^5 m^3/day,* or a replacement of 0.23% of the total harbour volume of 2.8×10^8 m^3 every day, on average. The corresponding average retention time or flushing time (harbour volume divided by flow rate) is 430 days. However, the total annual flow out of the harbour (which includes land-based plus

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* Equal to 2.36 (10^8) m^3/yr or 7.48 m^3/s, which in turn is almost exactly the sum of $Q_W + Q_{SO} + Q_{STP}$ using values given earlier by OME (1974).

lake sources) was estimated by Kholi as 3.32×10^6 m^3/day; the corresponding daily replacement is 1.2% and the retention time is reduced to 84 days. Kholi's results showed higher flows from the lake to the harbour in winter (November to January) with lower flows in summer. Kholi's (1984) report also summarized water budget estimates calculated by Snodgrass (1981).

Klapwijk and Snodgrass (1985) discussed the difficulties inherent in measuring long-term lake-harbour exchanges directly with current meters and suggested that flushing rates could be estimated using a mass balance for conservative dissolved substances, as measured by conductivity. The conductivity (and hence the concentration of dissolved substances) of the harbour waters depends on the discharge and concentration of dissolved solids in the inputs to the harbour from runoff, industry, and sewage treatment plants, and on the amount of flushing of the harbour by Lake Ontario. Lake Ontario has a markedly lower dissolved substance content than some of the other harbour inflows. Hence it is possible, in principle, to solve a mass balance for the lake-harbour exchange, given all other inputs. However, as Klapwijk and Snodgrass pointed out, not all inputs are known with certainty, and they discussed the assumptions necessary to arrive at a mass balance. They estimated a mean annual flow from all land-based sources of 9.5×10^5 m^3/day for June 1977 to May 1978 corresponding to a replacement rate of 0.34% of the harbour volume/day or a retention time of 295 days. The total annual average flow out of the harbour was estimated as 3.8 x 10^6 m^3/day corresponding to a replacement rate of 1.4% of the harbour volume/day or a retention time of 74 days. Hence both Klapwijk and Snodgrass (1985) and Kholi (1984) give estimates for the annual average total discharge out of the harbour that are of the same order of magnitude, and both indicated that harbour-lake exchange is responsible for significantly reducing the flushing time of the harbour to 20 to 25% of its value in the absence of such an exchange. However, the monthly pattern of flows given by Klapwijk and Snodgrass have a distinct peak in the late summer and autumn months (July to October) in contrast to the pattern of flows given by Kholi.

II.3 Residence Time, Short-Circuiting, and Density Underflows

The rate at which the harbour is flushed by cleaner Lake Ontario water provides the simplest index for water quality considerations. However, the calculation of a flushing time or retention time is meaningful only if a water body mixes completely with the flows used in the flushing time calculation. If the flows are short-circuited from their point of inflow to the harbour outlet without completely mixing with the main body of the harbour, the flows will have less impact on concentrations within the harbour. Short-circuiting can occur in two ways.

Barica et al. (1987) have pointed out that under some circumstances flow from the Hamilton and Burlington Sewage Treatment Plants could follow a path along the eastern shoreline directly to the harbour outlet without first extensively mixing with the main body of the harbour. Obviously, this would be beneficial for the harbour, but would result in higher concentrations in the outflow plume from the harbour to Lake Ontario. The second short-circuiting mechanism involves the oscillation of the lake-harbour exchange, as exhibited by flow reversals in the Burlington Ship Canal. The measurement and explanation of the periodicities associated with these oscillations has been a subject of great interest and study (OME 1974, 1986, Freeman et al. 1974, Palmer and Poulton 1976). If the reversals occur more rapidly than mixing and circulation in the harbour or in the coastal region of Lake Ontario, then a water mass would retain its identity as it oscillated from lake to harbour and back again. Lake water may thus be short-circuited out of the harbour before effective exchange with harbour water can take place. It is for this reason that Kholi (1979, 1984) corrected his current meter results for an assumed mixing excursion length. However, it is possible that lake water entering the harbour is retained within the harbour because of density effects. This may occur if the lake water is colder, and hence heavier, than harbour water in the upper 10 m (the canal depth) of the water column. The flows that results in these conditions will be considered in more detail below.

From the above discussion it is clear that two separate questions must be answered to understand the role of lake-harbour exchange in flushing the harbour. The first question concerns how to quantify the flows into and out of the harbour through the canal itself. As noted above, agreement still does not exist on this very basic issue, even on a monthly time scale. The second question involves the fate of lake water once it enters the harbour: under what conditions is lake water retained within the harbour for a time long enough to have a beneficial effect on water quality? The answer to this second question depends on mixing and circulation in the harbour rather than on the hydraulics of flow in the canal.

Mixing of lake water within the harbour could occur by large scale harbour circulation advecting lake water away from the canal or less efficiently by smaller scale turbulent diffusive processes in the vicinity of the canal entrance. If lake and harbour waters are at different temperatures, density effects may determine the fate of incoming lake water (Fischer et al. 1979, pp. 209-212). It is often the case that lake water temperatures are colder than harbour water temperatures. If colder lake water flows into the harbour (whether or not the flow in the canal itself is temperature stratified) then the colder lake water will plunge below the harbour water and form an underflow along the harbour bottom, following the steepest path down the bathymetric contours. Such an underflow will continue along the bottom until it reaches a depth at which there is water of the same density. The lake water will then flow as an intrusion along a surface of constant density within the harbour. Evidence for the presence of such intrusions, such as oxygen-rich lenses of water between the harbour entrance and the middle of the harbour has been noted by several investigators (Harris _et_ _al_. 1980, OME 1975, 1977, 1985). Figure II-2 sketches flow regimes associated with some possible density conditions.

It is important to realize that once the flow reaches a depth below that of the bottom of the canal (approximately 10 m), the water in that underflow below that depth is trapped within the harbour. It cannot flow back uphill and out through the canal. The water will remain within the harbour until it is displaced upward by still colder inflows, or mixed vertically within the water column by atmospherically driven processes such as wind stirring or surface cooling.

The frequency with which lake water forms an underflow in the harbour is obviously a statistic of considerable importance for harbour water quality. No concurrent study of water temperature profiles at either end of the canal has been made but a glance at data from OME (1985) for temperatures in the harbour and from Dobson (1984, Figures 35, 38) for Lake Ontario, indicates that underflow may be frequent and may occur at any time of year. The dominant pattern of lake-harbour exchange may thus be one in which water from Lake Ontario enters the hypolimnion of the harbour displacing harbour water upward, with water from the epilimnion or thermocline of the harbour comprising the outflow from the harbour. Klapwijk and Snodgrass (1985) have included this pathway as one possible circulation in their model, although their model predicts a higher frequency of lake inflow to the epilimnion of the harbour. However, their model does not include any consideration of the dynamics of density stratified flow and is based only on approximate heat and salt balances.

II.4 Harbour Dynamics and Circulation

The Ontario Ministry of the Environment has installed recording current meters at various positions in Hamilton Harbour at different times over the period 1972 to 1980, in addition to the current metering carried out in the ship canal. The results are described in the OME report cited earlier. A map summarizing the location of moorings is given in OME (1985, p. 18), and a brief summary of the current measurements is given in the same report (pp. 7-8). Application of two-dimensional, depth-integrated, numerical hydrodynamic models of wind-driven currents in the harbour, using measured canal flows as a boundary condition, has accompanied the Ministry's current measuring program. Results of the modelling effort are described in OME (1974); see also the report by James and Eid (1978). Results of modelling do not yet appear to be conclusive and further applications are underway (Kholi 1988).

Modelling of the thermal structure of the harbour using the one-dimensional (in the vertical) reservoir simulation model DYRESM (Imberger and Patterson 1981) has been carried out by McCrimmon and Schertzer (1987). They give results for two simulations, one using the monthly average canal inflows from Kholi (1984), the other using the monthly average inflows from Klapwijk and Snodgrass (1985). Results are promising but more work needs to be done to build a dataset with more accurate inflow discharges, temperatures, and salinities for all the major inflows including sewage treatment plants and industry.

Because of its relatively small size compared to the Great Lakes and its ready accessibility to CCIW, Hamilton Harbour and the ship canal have, in the past, been used as testing sites for new measurement techniques developed at CCIW. In one such experiment, documented by Simons and Schertzer (1983), the pressure difference between the two ends of the canal was measured directly using two long tubes attached to pressure ports at either end of the canal. At their other ends the tubes were attached to a differential pressure transducer via stilling wells.

Simultaneously, measurments of currents in the canal were made by a pair of fixed current meters mounted at depths of 6 and 7 m: one current meter measured lakeward flow, while the other measured flow into the harbour. The system operated (with some breaks) from the end of January 1983 through early March 1983. Statistical comparison of the water level and current records showed a high correlation, but application of a one-dimensional, unsteady, linearized numerical model for unstratified open channel flow was not completely successful.

Finally, in another experimental deployment a remarkable dataset was collected by a vertical automated profiling system (VAPS) at a site (latitude 43°17'12"N, longitude 79°51'11"W) somewhat southwest of the deep central basin of the harbour. VAPS operated from 27 July, 1981 to 19 September, 1981 (with some gaps in the record), recording continuous profiles of temperature and velocity at roughly 20-minute intervals from the bottom to 2 m below the water surface. Deployment of VPAS in Lake Erie and the capabilities of the system has been described by Royer _et al._ (1987). The Hamilton Harbour data have been edited by I. Royer but await further analysis. Some of the initial plots reveal a high level of activity in and below the thermocline with velocities of 5 to 10 cm/s. The corresponding temperature profiles have noticeably step-like structures characteristic of the presence of intrusions. The dataset contains a great deal of information about the dynamics of the harbour but will require extensive analysis and interpretation in order to permit an assessment of the relative effects of wind and inflows.

III. SAMPLING PROGRAM

III.1 Methods

Field measurements for the 1988 season were comprised of four components: meteorological measurements from a moored buoy in the harbour and from the rooftop of Canada Centre for Inland Waters (CCIW); weekly surveys of temperature, conductivity and dissolved oxygen at 25 stations in the harbour and along a line extending through the canal and approximately 2 km eastward into Lake Ontario (Figure I-1); current meter profiling at four positions along the lift bridge in the canal to coincide with the weekly temperature-conductivity-oxygen surveys; and time series of water levels and temperature profiles at both ends of the canal. Conductivity time series were also recorded at two depths at the lake end of the canal.

The meteorological measurements included total downward radiation, solar radiation, longwave radiation, wind speed and direction, air temperature, relative humidity, and surface water temperature. All radiation measurements were made from the rooftop of CCIW and are recorded as hourly integrated totals with respect to local apparent time (LAT). Solar radiation was measured with an Eppley Model 2 pyranometer, total radiation with a Net Swissteco Model S-1 net pyrradiometer, and longwave radiation with an Eppley Model IR pyrgeometer. All three instruments were calibrated on 10 June, 1988 by the National Atmospheric

Radiation Centre of the Atmospheric Environment Service. Replacement instruments were available during calibration for solar and total radiation, but not for longwave radiation. Gaps in the radiation time series occurred for solar radiation from 0800 LAT, 13 July, 1988, through 1300 LAT, 14 July, 1988 during switchover of the replacement instrument following calibration, and for the days 19 August, 1988 through 1200 LAT on 19 September, 1988 due to failure of channel 3 of the integrator. Gaps occurred in the longwave radiation record from 1 June, 1988 through 1300 LAT on the 14 July, 1988 for calibration. Gaps occurred in the total downward radiation record from 0800 LAT 13th July, 1988 through 14 July, 1988, during switchover of the replacement instrument after calibration. Except for 13 to 14 July there are no gaps that overlap all three sensors so it is possible to construct almost complete records for solar and longwave radiation from the definition:

$$H_{SW} + H_{LW} = H_{TDT} \qquad \text{(III-1)}$$

where H_{SW} = incoming shortwave or global solar radiation, H_{LW} = downward longwave radiation, and H_{TDT} = total incoming radiation. In practice, there is rarely complete agreement of the measured radiation values with equation III-1, although the discrepancy in the difference between measured values of H_{LW} and the difference $H_{TDT} - H_{SW}$ can be expected to be of the of 20 w/m^2, but should not exceed 100 w/m^2 (D. Wardle, personal communication). In the dataset collected here, differences are usually within this range although some pre-calibration differences were slightly larger.

Wind speed and direction, air temperature and relative humidity were measured at a buoy moored in the central basin of the harbour at the position marked MET in Figure I-1. The meteorological buoy system is described by Elder and Brady (1972). Instantaneous values were recorded every 20 minutes, stored on tape, and later downloaded to Cyber computer files at CCIW with all times referenced to Greenwich mean time (GMT). A single meteorological data file containing hourly averages of all variables has also been established on the Cyber. The meteorological buoy was deployed on 30 May, 1988 at 1400 h, EDT.

Weekly temperature-conductivity-oxygen transects were measured in the harbour from RV Agile using the Water Quality Profiler system developed at CCIW (Ford and Charlton 1984, Ford 1988). The system includes a sonde containing transducers for measuring pressure, temperature, conductivity, dissolved oxygen, light transmission, and pH; built-in electronics scan the signal from each transducer at a frequency of 2 Hz. The digitized signals are transmitted serially up the support cable and through a specially designed winch to an on-board Toshiba 1100-plus laptop microcomputer that simultaneously stores the data from a drop as a single file on 3½" compact disk and displays plots of the profiles of all parameters on the screen as the sonde descends. Printouts are produced after each drop. A record of all files produced during the season is summarized in Table III-1. As a rule, the file names contain eight digits, two each for the month, day, hour, and minute when the drop was initiated. The individual files from a single day's cruise can be combined later into a single "day file" using a program (GDUMP) from the Water Quality Profiler software developed by J. Ford.

Calibration of the Water Quality Profiler sensors was carried out in a dockside calibration bath before and after every cruise. A summary of the calibration results is given in Table III-2. In general, the sensors remained stable and accurate throughout the season. Limitations on the ranges of the oxygen and temperature sensors did become apparent during a few of the cruises, however. During the 14 August cruise, an algal bloom raised dissolved oxygen concentrations in the surface waters to supersaturated levels, in excess of 14 mg/L and outside the range of the oxygen measuring system. Similarly, during three cruises in August (3, 10, 17 August) surface water temperatures exceeded the limit of 24.7°C of the temperature measuring system. Bucket samples measured with a mercury-in-glass thermometer indicated surface temperatures as high as 28.2°C on 10 August.

It should also be noted that while the Water Quality Profiler system provides a very reliable and convenient method for acquiring, displaying, and storing profile data for several important water quality parameters, it is not a fast response system. Drop speeds are therefore limited not only by the frequency of sampling but also by the respose time of the transducers. Of these the YSI membrane-based oxygen system is certainly the slowest, but caution must be exercised with conductivity as well (Ford 1984). During summer stratification, when sharp gradients of most water properties can exist, drop speeds should be restricted to 20% or less of the maximum. It is noted in Table III-1 that for the first three cruises only temperature and conductivity were measured. This was done to allow faster drop speeds in an attempt to reduce the total cruise survey time. It was later decided that savings in time were negligible, with most of the cruise time being spent moving between stations. Hence all parameters from the sonde were recorded for the remainder of the season.

Velocity profiles were measured from four positions on the lift bridge over the canal, approximately 460 m from the lake end of the canal, at depth intervals of 1 m through the water column (Figure III-1). The profiling coincided as closely as possible with the temperature-conductivity-oxygen transect by RV Agile through the canal so that the velocities would correspond to the measured longitudinal distributions of temperature, conductivity, and oxygen in the canal. Currents were measured with a Neil Brown acoustic current meter with direct digital readout for depth, temperature, and current speed and direction. Calibration of the current sensor was carried out in 1983 with the towing carriage of the National Calibration Facility at CCIW to an accuracy of several percent of the true towing speed. The calibration is documented in a report by Hamblin (1989) and shows that while the meter can detect currents less than 1 cm/s, in practice there occurs a zero-offset (i.e., the meter indicates a current in still water) that is of the order of 1 cm/s and can be variable in the field, so that accuracies below 2 cm/s are uncertain. Fortunately, almost all of the currents measured in the canal were well above 5 cm/s.

Initial results indicated the existence of significant transverse velocity components in the canal. Subsequent calibration of the current meter's flux-gate compass on 11 July, 1988 by the National Water Research Institute's (NWRI) Calibration Unit showed the compass to be accurate to within less than 1° except within the range 135° to 270°, where a maximum error of 5° occurred. This did not explain the observed magnitude of the transverse velocity components, however. Further investigation revealed that the magnetic compass of the ACM was influenced by the large mass of iron in the bridge and canal walls surrounding the current metering site. Tests carried out with the current meter mounted on a fixed bracket extended from RV Agile at several positions across the canal showed that the net result of the magnetic influence was to increase the local grid-magnetic angle by approximately 9° everywhere in the cross-section, except within a distance of 2 m from the steel sidewalls of the canal where the change was much larger. Since all current measurements were made at distances much greater than 2 m, a correction could be applied over the entire cross-section by adding 9° to the chart grid-magnetic angle of 9° (west of north), giving a total correction for an effective grid-magnetic angle of 18°. These adjustments are summarizd in Figure III-2 and have been incorporated together with the tow-tank calibration and the compass calibration, in the data reduction program for the ACM output. Data from ACM were recorded by hand in a field book, transferred to a computer file, and then processed by the data reduction program to produce an output file giving along- and across-canal velocity components, temperatures, densities, and summary statistics for the entire cross-section.

Time series data at both ends of the canal were recorded by different kinds of instruments, as dictated by availability. Only the two water level sensors, one at each end of the canal, were identical: Applied Microsystems tide gauges, recording once every 10 minutes on Aandara reel-to-reel tapes. At the lake end of the canal, the mooring consisted of four Richard Brancker Research (RBR) submersible data loggers in addition to the tide gauge. Top and bottom RBR loggers recorded conductivity and temperature once every 10 minues; the middle two loggers recorded only temperture. Times recorded by the RBR loggers are local standard time (i.e., Eastern daylight savings time). At the harbour end of the canal, the mooring consisted of eight Fenwall thermistors sending data once every 15 minutes to cassette tape or a Seadata Model 650 16-channel logger. All canal moorings were installed on 6 June, 1988 and retrieved on 27 July, 1988. Data from the RBR loggers were dumped directly to microcomputer and the four separate files from the individual loggers have been combined into a single file. Data from the Seadata logger and the tide gauges are referenced to GMT but present greater processing problems. Processing is still i~~m~~ncomplete and there appears to be gaps in both datasets. The tide gauge at the lake end flooded for an as yet unde~~r~~termined period of time, and the thermistor data may have overwritten part of its own record. These questions will be clarified with the next few months. The moorings were redeployed on the same day after data were downloaded. Records for the temperature and conductivity ended on 3 October; tide gauge recording continued until 16 October. Table III-3 summarizes the elevations of the sensors for the two moorings. The distance between the two moorings was 800 m.

III.2 Results

Weekly sampling cruises on RV Agile to measure temperature and conductivity transects in the canal and the harbour started on 11 May, 1988. Since 9 June, oxygen, transmission, and pH were recorded as well, although transmission and pH will not be considered here. With the exception of the week 24-30 July, when the boat and winch were under repair, and the weeks 4-10 September and 9-15 October, when staff were unavailable, there has been one cruise per week. Usually 25 stations were occupied during each cruise (Figure I-1; B7 is not normally occupied). Velocity profiles measured at four stations across the lift bridge (Figure III-1) were timed to coincide as closely as possible with the boat transect through the canal.

This section of the report focuses on the results of the transects and velocity profiles. A complete set of drawings of the temperature-conductivity-oxygen transects and velocity profiles is included in the report. Also included are weekly plots of time series data that were available at the time of writing. Of necessity, the comments in this section are preliminary interpretations of the results. The subsections below address specific points of interest brought out in the transects, using time series data where available to support the interpretations. The transect drawings are referred to by date rather than figure number. Temperature-conductivity transects are grouped together, as pairs, with all of the main east-west transects (stations prefixed by the letter A) first, followed by the two sets of north-south transects (B and C; refer to Figure I-1 for locations). Oxygen transects follow the temperature-conductivity pairs, again grouped according to A, B, and C transects. Weekly plots of current meter data follow the oxygen transects. Time series of meteorological data are next, followed by any temperature-conductivity-water level time series available at the time of writing. Time series are plotted week-by-week to facilitate comparison with the cruise data.

III.2.1 Flow regimes in the canal

The flow regimes sketched in Figure II-2 provide a guide to interpreting the transects. A brief glance of the temperature-conductivity transects shows that conductivity can be used to differentiate harbour and lake water and to identify the path taken by incoming lake water after it enters the harbour. The higher conductivity of harbour water is a result of its higher total dissolved solids content. For lack of a better rule, I have adopted the relation used by Klapwijk and Snodgrass (1985) relating total dissolved solids concentration S to conductivity C as:

$$S = 0.65C, \tag{III.1}$$

where S is in mg/L and C is in μS/cm. Using this relation with typically observed harbour and lake conductivities in an equation of state for lake water (Chen and Millero 1977) indicates that, with the exception of the very high conductivities observed in the inflows from Redhill Creek and Windermere Basin, total dissolved solids concentration has a minor influence on harbour water densities. Density variations depend mainly on temperature. Temperature and oxygen can be used as tracers of water masses in the canal, yielding the same picture that conductivity does of interface position and the degree of mixing between lake and harbour water (as indicated by the thickness of the interface between lake and harbour water). However, oxygen and temperature loose their utility as tracers within the harbour itself. This is because the harbour is temperature-stratified and inflows form intrusions along surfaces of constant temperature in the harbour that match the temperatures of the intrusions. Hence it is impossible to use temperature to differentiate between the two water masses. Also, the demand for oxygen is so high in the harbour water that oxygen in the incoming lake water is depleted very rapidly. Conductivity, however, measures a property that is for all practical purposes conservative, having very few sources or sinks in the water column.

A glance at the A transects confirms that the most common flow regime observed in the canal was a stratified exchange flow with colder lake water flowing into the harbour under warmer, outflowing harbour water. The flow ratio (inflow/outflow) is theoretically very sensitive to differences in water levels between the two ends of the canal (Armi and Farmer 1986), and indeed the flow ratio was observed to be quite variable. Flow ratios deduced from current meter measurements are summarized in Table III-4, which contains the integrated current meter statistics for the entire season. The last column in the table indicates the flow regime deduced from the temperature-conductivity-oxygen transects in the canal. From the table it can be seen that flow rates in either layer are typically of the order of 70 m^3/s, corresponding to a residence time for the entire harbour of 47 days due to lake inflow alone. Average velocities in either the incoming or outgoing layers are of the order of 15 cm/s, although peak velocities in excess of 70 cm/s have been observed. The layer depths, layer-average velocities, layer-average densities, and layer-flow rates for each day given in Table III-4 have been computed by partitioning the cross-sectional area of the canal, according to whether the direction of flow at a sampling point was into or out of the harbour. The calculations were carried out in the data reduction program described earlier, using areas for each sampling point from Figure III-1.

Instances were also observed when either the inflow was blocked (only harbour water flowing out, 17 August) or the outflow was blocked (only lake water flowing in; 11 May, 1 June). Inspection of the transects for these dates shows that the front separating lake and harbour water occurred inside the canal, as opposed to extending through both ends of the canal as for exchange flows. In most cases, the location of the front was clearly visible during the cruise because of the different colours of lake and harbour water. The front appears in transects of all three properties as a region of sharp gradient separating relatively homogeneous water masses. No cases were observed corresponding to Figure II-2b, unstratified flow in the canal. It would be of considerable interest to observe this case later in the season as cooling progresses and the density difference between lake and harbour water diminishes.

Some of the temperature-conductivity-oxygen transects in the canal lead one to question whether the classification scheme of Figure II-2, which depicts the stratification as two-layered, represents an oversimplification. There are two aspects to this question; one concerns the absence of a definite two-layered structure within the canal (e.g., 15 June, 6 July; see also the temperature transects accompanying the velocity profiles for these dates), and the other concerns the merging of stratification in the canal with thermoclines in either or both the lake and harbour (e.g., 20 July, 3 August). Both aspects have considerable bearing on how the canal flows are to be modelled mathematically. The question of whether the interface is diffuse or sharp is probably not of great importance in most cases. The essential difference between a two-layer and a continuous stratification is that a continuous stratification can support an infinity of internal wave modes, while a two-layer stratification can support only one internal mode. For a two-layer flow the internal mode is one with flow in opposite directions in the two layers. For a continuous stratification only the lowest or fundamental mode behaves in this way, with progressively higher modes giving rise to more flow reversals with depth. In the case of the canal flow, it appears, even when the canal stratification appears continuous and distinctly unlayered, that the lowest mode dominates the flow. Effectively, there are only two layers flowing, in opposite directions as in the two-layer case. Moreover, the wave propagation speed of the lowest continuous wave mode is very little different from the interfacial wave speed of an "equivalent" two-layer mode (Mortimer 1953). Theoretical considerations show that the dominant characteristics of the exchange flow can be explained in terms of the relative magnitudes of the internal wave speed and the speed of the flow itself (Armi and Farmer 1986, Denton, 1987, Holley and Waddell 1976). The importance of the lowest mode therefore provides a criterion for choosing an equivalent two-layer structure, i.e., that structure with the same internal wave speed as that of the lowest mode of the continuous stratification (cf. Patterson et al. 1984). Having given this explanation, it should nevertheless be pointed out that the transects have captured events in whch higher modes may have been present in the approaches to the canal although not in the canal itself (see the A transects for 6 July and 20 July).

The second aspect concerns the merging of stratification in the canal with thermoclines in either one or both receiving waters at the ends of the canal. The difference between this case and the simpler one depicted in Figure II-2, where any thermoclines are well below the elevation of the canal bottom, is sketched in Figure III-3. The theoretical implications of what might appear to be subtle differences in Figure III-3 are discussed by Armi and Farmer (1986). They show that for a given density difference between two basins the resulting exchange flow through a contraction is maximal for the case when each basin is completely mixed. When the flow through a contraction merges with an elevated interface, the exchange flow is in general reduced. Computational strategies for modelling the exchange flows must account for the differences pictured in Figure III-3.

III.2.2 Velocity structure in the canal

Some examples of what appear to be two-dimensional, steady flow-fields have been observed in the canal (see the velocity profiles for 15 June, 30 June, 14 July, 3 August) in which the velocity profiles did not vary greatly across the canal. Examination of the meteorological data shows that fairly steady weather conditions prevailed in most of these cases, and Table III-4 indicates that these periods of two-dimensional canal flow tended to coincide with conditions of strong density stratification, as measured by the value of the buoyancy.* However, in general, the flow field in the canal is three-dimensional and cannot be characterized by a single velocity profile (11 May, 27 May, 1 June, 9 June, 21 June, 6 July, 20 July, 10 August). In all cases, transverse (cross-canal) velocities tended to be an order of magnitude less than the along-canal components, of similar magnitude (1 to 2 cm/s) to the noise level of the current meter. Some, but definitely not all, of the spatial variability seen in the current meter profiles may be due to unsteady effects: the flow field can change before completion of the four profiles. On 17 August the flow was highly unsteady and was observed by the current metering crew to reverse itself completely within an hour, from a case in which the inflow was blocked to one in which the outflow was blocked with inflow velocities in excess of 70 cm/s

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* Defined as the acceleration of gravity ($g = 9.81\ m/s^2$) multiplied by the relative density difference between the inflowing and outflowing layers $\Delta\rho/\rho$, where $\Delta\rho = \rho_2 - \rho_1$, $\rho = (\rho_2 + \rho_1)/2$, ρ_1 = density of top layer, ρ_2 = density of bottom layer, and buoyancy = $g\Delta\rho/\rho$.

measured near the bed. This situation was atypical and coincided with the passage of a storm front, the weak signature of which can be seen in the wind data. In other cases, for which temporal or unsteady effects can be ruled out, the primary cause of spatial variability of the velocity field is probably the existence of secondary flows in the canal. As anyone who has worked in laboratory flumes is well aware, secondary flows arising from entrance effects or small variations in the cross-sectional shape are the rule rather than the exception even in straight channels. This is true especially in relatively short channels, in which the channel length is less than 20 to 30 times the breadth, and in which care is not taken to introduce the flow so that it is parallel to the channel walls at the entrance. The length/width ratio of the ship canal is less than 10, and as noted earlier its bottom is not flat. Moreover, cross-channel flows are probably a feature of the entrance conditions, especially in Lake Ontario. Other possible causes of the spatial variability are baroclinic instability of the layered flow and Coriolis effects. Intuitively, one would expect these latter two effects to be minor as the Rossby radius of deformation of the two-layer flow is of the order of 2 km, much greater than the width of the canal, and the travel time for a water particle through the canal is of the order of one to two hours, much less than the inertial period for the harbour of 17.5 hours. The Rossby radius is computed as c/f, where c is the internal wave speed corresponding to the two-layer stratification and f is the Coriolis parameter, $f = 2\Omega\sin\phi$ where Ω is the angular velocity of the earth's rotation (7.29 (10^{-5}) rad/s) and ϕ is the latitude of the harbour. The internal wave speed can be estimated from $c = (g'h_1h_2/H)^{\frac{1}{2}}$ where g' is the acceleration of gravity reduced by the relative density difference (values are given as "buoyancy" in Table III-4) and h_1, h_2 are the layer depths with $H = h_1 + h_2$ (also given in Table III-4). For Hamilton Harbour, c is of the order of 20 cm/s for the summer profiles measured in the canal and $f = 1.00\ (10^{-4})$ rad/s. The inertial period is calculated as $2\pi/f$ and is the time scale to be used in assessing the effects of the earth's rotation on a water particle's path. Since the time of travel of a water particle through the canal is short compared with the inertial period, one would not expect that the flow in the canal would have time to "feel" the effects of the earth's rotation. However, if the exchange flow were somehow set up at a large distance from the canal, then the expectation could be false.

Whatever the reason for the transverse variability of velocities in the canal, it is clear that accurate measurement of canal flow rates is not a simple task. It is highly unlikely that a reliable estimate of flow can be gained from one or two current meters placed at fixed depths; even a single vertical profile with 1 m resolution is not likely to be sufficient. In general at least four vertical profiles measured within a short time span are needed to give an accurate picture of the flow field at any time.

II.2.3 Fate of lake water in the harbour

In all of the transects inflows can be seen to form density underflows along the harbour bottom for some distance after leaving the confines of the canal. The distance that the inflowing water travels before lifting off from the bottom and moving as an intrusion into the main part of the harbour depends on the temperature of the underflowing water compared to that of the ambient harbour water. Lift-off and intrusion occur at the depth at which the density of the underflow matches that of the harbour water. Underflow temperatures, in turn, depend on conditions in the lake outside the canal and on the amount of mixing with harbour water that occurs in the canal and at the canal exit. Temperature conditions in the lake change in response to upwelling and downwelling events. One would therefore expect intrusion depths to be variable and indeed this was observed to be the case. During a period of westerly winds that caused upwelling of 5°C water in Lake Ontario on 15 June the lake water underflow could be observed in both the conductivity and oxygen transects at depths as great as 21 m (see A transect, 15 June). Generally, lake water intrusions were usually observed at shallower depths, as inferred from conductivity transects. At no time were intrusions observed to reach the very bottom of the harbour.

A striking feature of temperature and oxygen profiles in Hamilton Harbour is the absence of a sharp thermocline or oxycline overlying a quiescent hypolimnion containing weak vertical gradients. Rather, harbour temperature and oxygen profiles exhibit complex structures, often with uniform steps alternating with continuously stratified layers from the base of the epilimnion almost to the harbour bottom. This complex, layered density structure can be explained in large part as resulting from the variable but ever present inflow intrusions of lake water at many depths (e.g., A transect, 14 July).

Conductivity transects along the main axis of the harbour show that lake water penetrates the harbour for the full length of the central basin (see the series of A transects for conductivity). However, in the north-south transects from La Salle Marina to the Stelco Pier (C transects) low conductivity water is usually found at depth along the north shore. This is probably the results of veering of inflow intrusions to form shore-bound currents because of Coriolis forces. The travel time of intrusion water particles from the canal mouth to the yacht harbour (assuming an intrusion speed of approximately 5 cm/s) is of the same order as the inertial period of 17.5 hours. Hence there is time for an intrusion to be influenced by the earth's rotation. Moreover, the lateral extent of the low conductivity water is of the same size as the Rossby radius of deformation (~2 km), as would be the case for rotationally influenced flows. Finally, the conductivity transects show that harbour salinity decreased significantly over the time span of the sampling program, with conductivities greater than 600 µS/cm in late May declining to 450 µS/cm in September. This can only have occurred as the result of continuous replacement of harbour water by fresher lake water; these trends should be better quantified in the context of a total dissolved solids budget for the harbour.

III.2.4 The Windermere Basin arm

The narrow southern arm of the harbour extending from the Windermere Basin outflow to the corner of the Dofasco pier at a point just beyond station B5 (FigureI-1) consistently exhibits features that set it apart from the rest of the harour. Examination of the north-south B transects shows that elevated water surface temperatures and depressed oxygen levels often occur in the vicinity of station B5. These effects may be associated with industrial discharges. The most sriking feature of the B transects are the intrusions of high conductivity water flowing from Windermere Basin. Measurements on 25 August were made as close as possible to the exit channel from Windermere Basin. It was possible to secure the *Agile* in a position behind the front separating greyish, turbid Windermere Basin water from browner, more transparent harbour water. The front was clearly visible and marked the plunge line for water flowing from Windermere Basin. Conductivity and temperature of the water upstream of the front were 860 μS/cm and 23.8°C; corresponding values of the harbour water downstream of the front were 525 μS/cm and 22°C. In spite of the drop in temperature across the front the difference in total dissolved solids concentration was great enough to make Windermere Basin water heavier than harbour water and to plunge down the steep slope near the Windermere Basin exit. High conductivity intrusions are visible in virtually all the B transects; depths of the intrusions are variable, however. Presumably the water in Windermere Basin and Redhill Creek, being relatively shallow, experience greater amplitudes in both daily and seasonal temperature fluctuations than does harbour water. During the spring, when the harbour was very weakly stratified, both surface and subsurface intrusions were often observed in the same transect (see B transects for 27 May, 1 June, 9 June; see also 6 July). This probably arises as a result of diurnal temperature variations in the inflowing water: colder inflows occur at night or early in the morning, while warmer inflows occur during the day. Later in summer when stratification in the harbour became strong and diurnal fluctuations in air temperature weakened, most of the inflow intrusions appeared in the thermocline (B transects for 15

June, 21 June, 14 July, 20 July, 3 August, 10 August, 17 August). Evidence of the intrusions usually diminished beyond station B5 where the arm of the harbour widens to join the main body of the harbour. The expansion in cross-section allows an intrusion to spread laterally, becoming thinner and hence more readily mixed.

Also worthy of note in all of the B transects is the occurrence of low conductivity water north of station B3 where the B and A transects intersect. The low conductivity is a signature of colder inflowing lake water. The north-south gradient at depth in conductivity is invariably accompanied by a north-south gradient in oxygen of the opposite sense, with oxygen concentrations increasing to the north.

III.2.5 Wind mixing

Although the emphasis in this report has been on the importance of canal flows to harbour dynamics, the data clearly show that the main body of the harbour responds to wind and heat exchange with the atmosphere in the same way that most small to medium sized lakes do. Away from the canal entrance, to the west of stations A2 and A25, isotherms are predominantly horizontal (e.g., A transects for 20 July, 3 August, 10 August). Departures from the horizontal in and below the thermocline probably reflect internal wave activity (15 June, 21 June). Internal wave activity is a feature of the thermocline and hypolimnion of most lakes, often arising as a result of changes in wind stress on the water surface. In Hamilton Harbour an additional mechanism exists: changes in inflow intrusion depths and discharges almost certainly give rise to internal waves.

The plots of meteorological data show that the dominant wind direction in the harbour is from the west. Upwelling of colder, less oxygenated water at the western end of the harbour can be clearly seen in the A transects that coincided with strong easterly wind conditions (15 June, 14 July, 25 August).

III.2.6 Implications for the oxygen budget

One of the most interesting results visible in the oxygen transects is the relative stability of oxygen storage in the hypolimnion below 12 m. Oxygen concentrations did undergo fluctuations throughout the season, but in general the impression gained from the transects is that a quasi-equilibrium existed. Uptake was balanced by downward eddy-diffusion of oxygen through the thermocline and by horizontal advection of lake water. A simple calculation for the oxygen budget below 12 m can be made as follows. Assuming a demand for oxygen of 0.3 to 1 g/m^3-d (M. Charlton, unpublished data based on consumption in bottles) and taking the volume of the harbour below 12 m as 5 (10^7) m^3 (McCrimmon and Schertzer 1987) gives a demand of 1.5 (10^4) to 5 (10^4) kg/d for the hypolimnion below 12 m. Downward diffusive flux of oxygen through the thermocline F_D can be parameterized in terms of the oxygen gradient and an eddy diffusivity as:

$$F_D = -AK\partial c/\partial z \qquad \text{(III-2)}$$

where A is the area (at 12 m, A = 10 km^2; from McCrimmon and Schertzer), K is the eddy diffusivity, and $\partial c/\partial z$ is the concentration gradient of oxygen. Taking a value for K of 10^{-5} m^2/s from Quay _et_ _al_. (1980) (Figure 11) for lakes of similar size and stratification, and approximately $\partial c/\partial z$ from the oxygen transects as a decline in concentration of 6 g/m^3 over a depth interval of 8 m gives a diffusive flux downward of approximately 0.5 (10^4) kg/d at 12 m. The flux of oxygen advected by the underflow F_A can be estimated from:

$$F_A = Qc \qquad \text{(III-3)}$$

where Q is the discharge in the underflow and c is the concentration of oxygen. Taking Q = 70 m^3/s from the current meter summaries (Table III-4) and c = 7 g/m^3 at 12 m from the oxygen transects gives an advective flux of 4.1 (10^4) kg/d. Hence the oxygen demand is largely supplied by the advective flux in the inflowing lake water, roughly eight times the amount of oxygen supplied by vertical eddy diffusion. Crude though the calculation is, it does serve to emphasize the importance of the underflow as a source of oxygen for the hypolimnion. This conclusion would not be altered by reasonable changes in the figures used in the calculation.

IV. CONCLUSIONS

The results of this study confirm the conclusions of earlier workers regarding the importance of flow in the Burlington Canal for water quality in Hamilton Harbour. Canal flows comprise by far the largest single component in the water balance of the harbour. Because of the close coupling of canal flow rates with relative water levels and temperatures at both ends of the canal, and the sensitivity of these variables in turn to changes in meteorological conditions, inflow discharge and temperatures are highly variable. Hence, the depth at which lake water intrusions occur is also variable. Conductivity transects indicate that lake water penetrates the full length of the harbour below the thermocline. The presence of multiple intrusions continuously occurring at different depths explains the complex structure of density stratification below the thermocline. Evidence from oxygen transects indicates that oxygen is depleted rapidly in inflowing lake water. Yet, the quantities of oxygen advected into the harbour's hypolimnion are probably several times the amount transported vertically downward through the thermocline by eddy diffusion. While many of these conclusions are not entirely new, they are drawn from results of a sampling program that encompassed the harbour-canal system as a combined entity. Much previous work has focused on individual processes in either the canal or the harbour, and because of the dynamic way in which the harbour and canal interact it has often been difficult in the past to interpret measurements made in isolation.

While past studies have emphasized the unsteadiness in time of canal flow, this is the first study to document spatial variability as well. Velocity varied in the canal with both width and depth even under steady conditions. Highly unsteady events were observed in which flow reversals occurred or flow regimes changed within the time span of the current metering. However, it is unlikely that unsteadiness can explain all of the horizontal variability observed in the velocity profiles. Final interpretation will have to await reduction of water level data. Horizontal variations are to be expected even in straight channels with length/width ratios less than 20 or 30, especially if the entering flow is not aligned parallel with the sidewalls; in the Burlington Canal length/width is less than 10.

Because of the three-dimensional nature of the velocity field in the canal it is not possible to accurately measure cross-sectionally averaged velocities with one or two fixed current meters. Even current meters with the capability of averaging the flow over the depth or width of the canal would be of little use in quantifying flushing effects because such instruments would not be able to separate inflows from outflows. Hence accurate measurement of inflows and outflows remains a difficult and unsolved problem. Difficulties with current meter-based techniques makes salt-balance or dilution techniques appear attractive. However, much more work is necessary to identify, quantify, and monitor all dissolved-solids loadings to the harbour before confidence can be placed in salt balance results. In addition, efforts should probably be made to verify or update the relation between conductivity and TDS concentration used by Klapwijk and Snodgrass (1985). Considerable work on this problem seems to have been done (OME 1977), but the results are not easily accessible.

Salt balance techniques depend on the ability to accurately measure changes in salt storage in the entire harbour. The techniques therefore can only provide estimates of flow rates averaged over time spans of a week or longer. In order to provide finer resolution it may be possible to develop a mathematical model that captures the dominant processes that control canal hydraulics. The input for such a model would be density profiles and water levels at both ends of the canal. If such a model could be succesfully developed, it could be coupled with a model of harbour thermal structure (e.g., McCrimmon and Schertzer 1987) to simulate harbour response to different meteorological and inflow conditions. Providing the proper boundary conditions on water level and temperature at the Lake Ontario end of the canal so that the model could function in a predictive way is a further problem that requires some thought. Careful measurement of water level difference between the two ends of the canal is a difficult task, but this measurement is crucial initially for model development and subsequently for verification. Finally, entrance and exit effects could be significant sources of energy loss in the flow and need to be considered.

The dominant flow regime observed in the canal was a stratified exchange flow. Even when either the inflow or outflow was blocked, a front separating harbour and lake water was present in the canal. Unstratified flow was not observed. Previous work has emphasized modelling and measurement of unstratified flow, sometimes termed plug-flow (e.g., Dick and Marsalek 1972, OME 1974, Simons and Schertzer 1983). The concept of mixing excursion length, developed by Kholi (1979) for the canal flows, is a valid one for unstratified flows and necessary to account for the effect on harbour flushing of short-circuiting by flow oscillations in unstratified flow. It would be of interest to continue the sampling program through the cooling and turnover periods to document unstratified flow regimes. Different flow regimes could occur in winter and during spring thaw as water temperatures approach 4°C, especially if cooling rates differ for lake and harbour water. This, however, is a subject for another project.

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TABLE CAPTIONS

Table III-1	Hamilton Harbour 1988 water quality profiles - disk file names.
Table III-2	Water quality probe - calibration summary for Hamilton Harbour cruises 1988.
Table III-3	1988 canal moorings.
Table III-4	Summary of current metering, Burlington Ship Canal, 1988.

TABLE III-1

HAMILTON HARBOUR 1988 WATER QUALITY PROFILES - DISK FILE NAMES

	Cruise Number and Date			
Station	1* 11 May 1988	2* 27 May 1988	3* 1 June 1988	4* 9 June 1988**
AM4	05111005	05270907	06011313	06091154
AM3	05111018	05270912	06011308	06091205
AM2	05111045	05270922	06011256	06091212
AM1	05111051	05270930	06011248	06091223
A0	05111058	05270936	06011243	06091235
A1	05111130	05270997	06011232	06091241
A2	05111225	05271020	06011224	06091250
A25	-	-	06011210	-
A3	05111233	05271030	06011200	06091258
A4	05111242	05271137	06011134	06091307
A5	05111252	05271051	06011137	06091323
A6	05111302	05271105	06011058	06091335
A7	05111308	05271120	06011053	06091346
A8	05111317	05271130	06011040	06091352
C1	05111328	-	06011147	06091410
C2	05111340	-	06011140	06091418
B8	-	05271158	06011215	-
B6	-	05271212	06011352	06091436
B9	-	-	-	06091457
B10	-	-	-	06091503
B5	-	05271126	06011404	06091512
B4	05111150	05271236	06011425	06091523
B3	05111219	05271009	06011432	06091643
B2	05111405	-	06011443	06091553
B1	05111355	-	06011454	06091608
B7***	05111138	-	06011340	-
AM2B			06011320	
AM1B			06011333	
A1A		05270951		
A1C		05270003		
AM25	05111030			
A4		05271042		

* For cruises 1, 2, and 3 data were acquired using program SPIGEL with fast drop speed and oxygen and pH probes disabled. For all later crises data were acquired with program HHP and slower drop speed, including oxygen and pH.

** Data recorded with incorrect calibration coefficients. See data printouts for other dates for correct coefficients.

*** B7 seldom occupied.

Note: Calibration profiles usually appear on disks at the beginning and end of each day's data. They are not listed in this table.

TABLE III-1 (cont'd)

HAMILTON HARBOUR 1988 WATER QUALITY PROFILES - DISK FILE NAMES

	Cruise Number and Date			
Station	5 15 June 1988	6 21 June 1988	7 30 June 1988	8 6 July 1988
AM4	06150918	06210930	06301005	07060938
AM3	06150925	06210938	06301016	07060946
AM2	06150937	06210946	06301024	07060958
AM1	06150945	06211055	06301032	07061004
A0	06150955	06211002	06301040	07061012
A1	06151012	06211010	06301107	07061018
A2	06151027	06211018	06301115	07061040
A25	06151057	06211028	-	07061145
A3	06151104	06211038	06301140	07061057
A4	06151115	06211050	06301147	07061108
A5	06151134	06211110	06301205	07061118
A6	06151143	06211122	06301212	07061134
A7	06151155	06211129	06301225	07061139
A8	06151206	06211137	06301239	07061147
C1	06151220	06211207	06301302	07061214
C2	06151235	06211215	06301341	07061222
B8	06151250	06211225	-	07061234
B6	06151258	06211240	06301403	07061244
B9	06151309	06211256	06301410	07061258
B10	06151320	06211303	-	07061304
B5	06151327	06211312	06301417	07061308
B4	06151336	06211318	06301427	07061315
B3	06151350	06211328	06301437	07061324
B2	06151358	06211353	06301454	07061332
B1	06151410	06211401	06301503	07061342
B7			06301447	

TABLE III-1 (cont'd)

HAMILTON HARBOUR 1988 WATER QUALITY PROFILES - DISK FILE NAMES

	Cruise Number and Date			
Station	9 14 July 1988	10 20 July 1988	11 3 Aug 1988	12 10 Aug 1988
AM4	07141007	07200932	08030910	08100924
AM3	07141023	07200947	08030927	08100940
AM2	07141032	07200953	08030939	08100953
AM1	07141043	07201005	08030946	08101000
A0	07141050	07201012	08030955	08101009
A1	07141100	07201020	08031008	08101020
A2	07141107	07201032	08031016	08101028
A25	07141118	07201042	08031027	08101035
A3	07141132	07201048	08031035	08101043
A4	07141140	07201056	08031044	08101052
A5	07141158	07201107	08031100	08101114
A6	07141205	07201117	08031109	08101129
A7	07141220	07201132	08031122	08101138
A8	07141228	07201126	08031129	08101145
C1	07141240	07201213	08031125	08101200
C2	07141258	07201220	08031157	08101223
B8	07141310	07201233	08031212	08101243
B6	07141322	07201243	08031223	08101247
B9	07141335	07201259	08031238	08101304
B10	07141342	07201312	08031245	08101310
B5	071447	0720	08031257	08101316
B4	07141352	07201318	08031300	08101326
B3	07141403	07201328	08031310	08101327
B2	07141410	07201327	08031317	08101350
B1	07141420	07201345	080318-2	08101356

TABLE III-1 (cont'd)

HAMILTON HARBOUR 1988 WATER QUALITY PROFILES - DISK FILE NAMES

Station	Cruise Number and Date 13 17 Aug 1988	14 25 Aug 1988	15 31 Aug 1988	16 15 Sept 1988
AM4	08170936	08250950	08310912	09150912
AM3	08170944	08251010	08310925	09150928
AM2	08170954	08251018	08310934	09150935
AM1	08171000	08251026	08310940	09150942
A0	08171010	08251035	08310948	09150950
A1	08171021	08251052	08310957	09151000
A2	08171028	08251100	08311003	09151005
A25	08171035	08251107	08311010	09151015
A3	08171042	08251115	08311017	09151022
A4	08171047	08251123	08311024	09151034
A5	08171058	08251137	08311036	09151045
A6	08171106	08251145	08311043	09151054
A7	08171115	08251152	08311053	09151103
A8	08171125	08251203	08311058	09151112
C1	08171141	08251223	08311120	09151130
C2	08171150	08251235	08311132	09151144
B8	08171205	08251252	08311141	09151202
B6	08171212	08251303	08311154	09151213
B9	08171226	08251320	08311205	09151225
B10	08171223	08251327	08311222	09151234
B5	08171240	08251333	08311227	09151240
B4	08171247	08251340	08311233	09151252
B3	08171255	08251350	08311240	09151305
B2	08171305	08251400	08311248	09151314
B1	08171310	-	08311256	09151323
BW		08251315*		
BT			08311215**	

* Near entrance to Windermere Basin.

** Tow.

TABLE III-1 (cont'd)

HAMILTON HARBOUR 1988 WATER QUALITY PROFILES - DISK FILE NAMES

	Cruise Number and Date			
	17	18	19	20
Station	21 Sept 1988	 1988	 1988	 1988
AM4	09210938	....	....	....
AM3	09210947			
AM2	09210955			
AM1	09211007			
A0	09211016			
A1	09211025			
A2	09211034			
A25	09211042			
A3	09211050			
A4	09211100			
A5	09211110			
A6	09211118			
A7	09211130			
A8	09211137			
C1	09211203			
C2	09211212			
B8	09211224			
B6	09211240			
B9	09211249			
B10	09211255			
B5	09211302			
B4	09211311			
B3	09211320			
B2	09211330			
B1	09211340			

TABLE III-2

WATER QUALITY PROBE - CALIBRATION SUMMARY FOR HAMILTON HARBOUR CRUISES 1988

Cruise Number	Date	pH		Temperature °C			Conductivity µS/cm	
		Meter	Sonde	pH	Hg	Sonde	Meter	Sonde
1	11 May 88		6.82		12.5	12.6	277	253
2	27 May 88							
		8.04	8.22		14.0	13.40	348	262
3	1 Jun 88				12.5	12.45	334	255
					12.1	12.2	341	245
4	9 Jun 88	8.09	7.94	15.7	15.3	15.6	377	273
		8.05	8.02	13.6	13.1	13.4	385	260
5	15 Jun 88	8.30	8.44	13.5	13.5	13.5	387	267
		7.95	8.16	9.1		9.05	355	212
6	*21 Jun 88	8.22	8.51	12.6	12.7	12.10	260	256
		8.33	8.33	11.4	11.8	11.6	230	241
7**	30 Jun 88							
8	6 Jul 88		8.04		12.4	12.5	270	***
			8.11		11.5	11.4		
9	14 Jul 88	8.39	8.41	9.8	9.9	9.9	248	249
		8.29	8.25	10.3	10.5	10.4	259	257
10	20 Jul 88	8.39	8.40	12.1	12.2	12.15	248	264
		8.34	8.36	12.9	12.9	12.85	255	265
11	3 Aug 88	8.04	8.40	10.4	10.8	10.7	215	211
		7.93	8.06	9.1	9.5	9.5	216	204
12	10 Aug 88	8.73	7.88	12.2	12.3	12.3	218	208
		8.8-9.0	8.11	11.6	11.7	11.6	215	216
13	17 Aug 88	7.90	7.72	10.8		10.9	195	188
		8.12	8.13	10.7		13.4	200	184

* Conductivity meter calibrated between cruise numbers 5 and 6.

** Combined cruise: M. Charlton DO survey.

*** Sensor not submerged in both.

TABLE III-2 (cont'd)

WATER QUALITY PROBE - CALIBRATION SUMMARY FOR HAMILTON HARBOUR CRUISES 1988

Cruise Number	Date	pH		Temperature °C			Conductivity µS/cm	
		Meter	Sonde	pH	Hg	Sonde	Meter	Sonde
15	31 Aug 88	8.12 8.22	8.33 8.26	13.2 13.0	13.3	13.2 13.1	205 207	195 190
16	15 Sep 88	7.84 7.94	8.34 8.30	14.9 14.0		14.9 14.0	202 181	192 178
17	21 Sep 88	8.14	8.38	12.0		12.0	186	190

TABLE III-3

1988 CANAL MOORINGS

	Water Depth	Elevation
Harbour side:		
Total water depth: 11.3 m		
Installation: June 6, 1220 EDT		
Mooring consists of 8 thermistors and 1 tide guage		
T1	10.131	64.148
Tide Guage	9.776	64.503
T2	9.167	65.112
T3	8.091	66.188
T4	7.111	67.168
T5	5.630	68.649
T6	4.202	70.077
T7	3.141	71.138
T8	2.146	72.133
Water Level		74.279
Lakeside:		
Total water depth: 12.5 m		
Installation: June 3, 1445 EDT		
Mooring consists of 2 temperature loggers, 2 temperature/conductivity loggers and 1 tide guage		
T1/conductivity	11.720	62.845
Tide Guage	11.263	63.302
T2	8.466	66.099
T3	5.298	69.267
T4/conductivity	2.006	72.559

TABLE III-4

SUMMARY OF CURRENT METERING, BURLINGTON SHIP CANAL, 1988

Cruise		Depth (m)		Velocities (cm/s)				Buoyancy (10^{-3} m/s^2)		Flow (m^3/s)		Flow Ratio In/Out	Flow Regime*
				Maximum		Average							
No.	Date Time (EST)	In	Out	In	Out	In	Out	Max	Avg	In	Out		
1	11 May 88 0925-												Outflow blocked
2	27 May 88 0730-0925	4.61	4.89	44.6	30.9	22.5	15.7	9.07	1.56	92.6	68.3	1.36	Exchange
3	1 Jun 88 0930-1130	4.34	5.16	43.6	48.2	19.0	21.0	15.6	2.95	73.9	96.9	0.762	Outflow blocked**
4	9 Jun 88 1045-1530	5.07	4.43	28.2	22.2	12.5	11.5	8.80	1.58	56.4	45.6	1.24	Exchange
5	15 Jun 88 0820-1010	5.70	3.80	22.5	31.0	12.6	17.9	18.1	10.9	64.0	60.0	1.06	Exchange
6	21 Jun 88 0830-0940	3.98	5.52	28.0	33.5	14.5	17.3	18.4	9.18	51.7	85.2	0.607	Exchange
7	30 Jun 88 0855-0955	8.01	1.49	22.6	10.1	14.4	5.0	11.8	6.01	103.1	6.6	15.5	Exchange
8	6 Jul 88 0815-0915	5.72	3.78	27.0	22.2	8.7	8.5	18.3	3.51	44.4	28.6	1.55	Exchange
9	14 Jul 88 0905-1054	5.63	3.87	26.7	19.9	18.7	11.4	21.7	14.3	93.9	39.4	2.38	Exchange

* Flow regime deduced from temperature/conductivity transects.

** Temperature/conductivity transect and current metering did not coincide.

TABLE III-4 (cont'd)

SUMMARY OF CURRENT METERING, BURLINGTON SHIP CANAL, 1988

Cruise		Depth (m)		Velocities (cm/s)				Buoyancy (10^{-3} m/s^2)		Flow (m^3/s)		Flow Ratio In/Out	Flow Regime*
				Maximum		Average							
No.	Date Time (EST)	In	Out	In	Out	In	Out	Max	Avg	In	Out		
10	20 Jul 88 0810-0945	6.32	3.18	27.9	13.3	12.7	6.7	18.2	6.28	71.8	18.9	3.80	Exchange
11	3 Aug 88 0750-0945	5.92	3.58	32.1	15.6	17.5	8.1	24.9	13.8	92.6	25.8	3.59	Exchange
12	10 Aug 88 0902-1105	5.25	4.25	56.0	55.3	39.0	28.0	24.8	7.88	182.7	106.3	1.72	Exchange
13	17 Aug 88 0930-1030	3.98	5.52	77.7	56.4	52.3	34.6	20.3	2.32	185.6	170.8	1.09	Inflow blocked, reversing to outflow blocked
14	25 Aug 88 0825-0915	8.50	0.21	39.4	8.9	27.2	8.9	10.1	4.46	206.8	1.7	121.7	Outflow blocked
15	31 Aug 88 0800-0900	1.99	7.51	16.3	22.5	7.4	12.6	6.71	3.65	13.2	84.3	0.157	Inflow almost blocked
16	15 Sep 88 0825-0900	4.21	5.29	9.4	24.7	6.5	16.7	12.4	9.01	24.3	79.1	0.307	Exchange
17	21 Sep 88 0839-0929	2.77	6.73	25.1	38.1	14.7	15.2	13.6	5.43	36.4	91.4	0.398	Exchange
18	28 Sep 88 0828-0950									76	54.6		

* Flow regime deduced from temperature/conductivity transects.

FIGURE CAPTIONS

Fig. I-1	Location map for Hamilton Harbour showing bathymetry, sampling sites, and position of the meteorological buoy (MET).
Fig. II-1	Hamilton Harbour catchment, showing all inflows; taken from OME (1985).
Fig. II-2	Classification of flow regimes depending upon whether the flow in the canal is (a) stratified, or (b) unstratified. Note that in cases (a-2) and (a-3) stratified flow occurs even though there is flow in only one layer. Depending upon the location of the front separating lake and harbour water the flow may appear to be unstratified to an observer upstream of the front. Note that in winter if harbour temperatures approach 4°C before lake temperatures the relative densities of harbour and lake water will be reversed and so will the pictures of flow. In the case in which densities of harbour and lake water are equal the pictures would be as in (b) except that no plunge would occur as in (b-1), and no overflow would occur as in (b-2); the flow would simply mix as a jet with the receiving waters.

Fig. III-1 Canal cross-section showing velocity measuring stations 3, 9, 15, 21 and positions where velocities were measured (solid circles). The bottom is drawn as flat but is actually slightly uneven. When water levels dropped in autumn it was not possible to measure at 9 m, so measurements were made at 8.5 m. The dashed lines illustrate the partitioning of the cross-section for the purposes of computing discharges.

Fig. III-2 Definition sketch or reduction of acoustic current meter directions. B = direction from readout of current meter; E = angle used to compute along/across-canal components. The sketch illustrates how E is computed in the data reduction program after B has been corrected according to the compass calibration (see text for details).

Fig. III-3 Subclassification of flow regimes for stratified exchange flow, according to wehther or not the interface in the canal merges with an interface in either receiving water body without passing through an hydraulic control at the ends of the ends of the canal.

a) Different densities in harbour and lake, but no stratification in either. The flow passes from internally subcritical in the canal to internally supercritical flow in both the lake and the harbour.

b) Interface in harbour; inflow remains internally subcritical throughout.

c) Interface in both harbour and lake. Inflow and outflow are internally subcritical throughout.

d) Interface in lake; outflow is internally subcritical throughout.

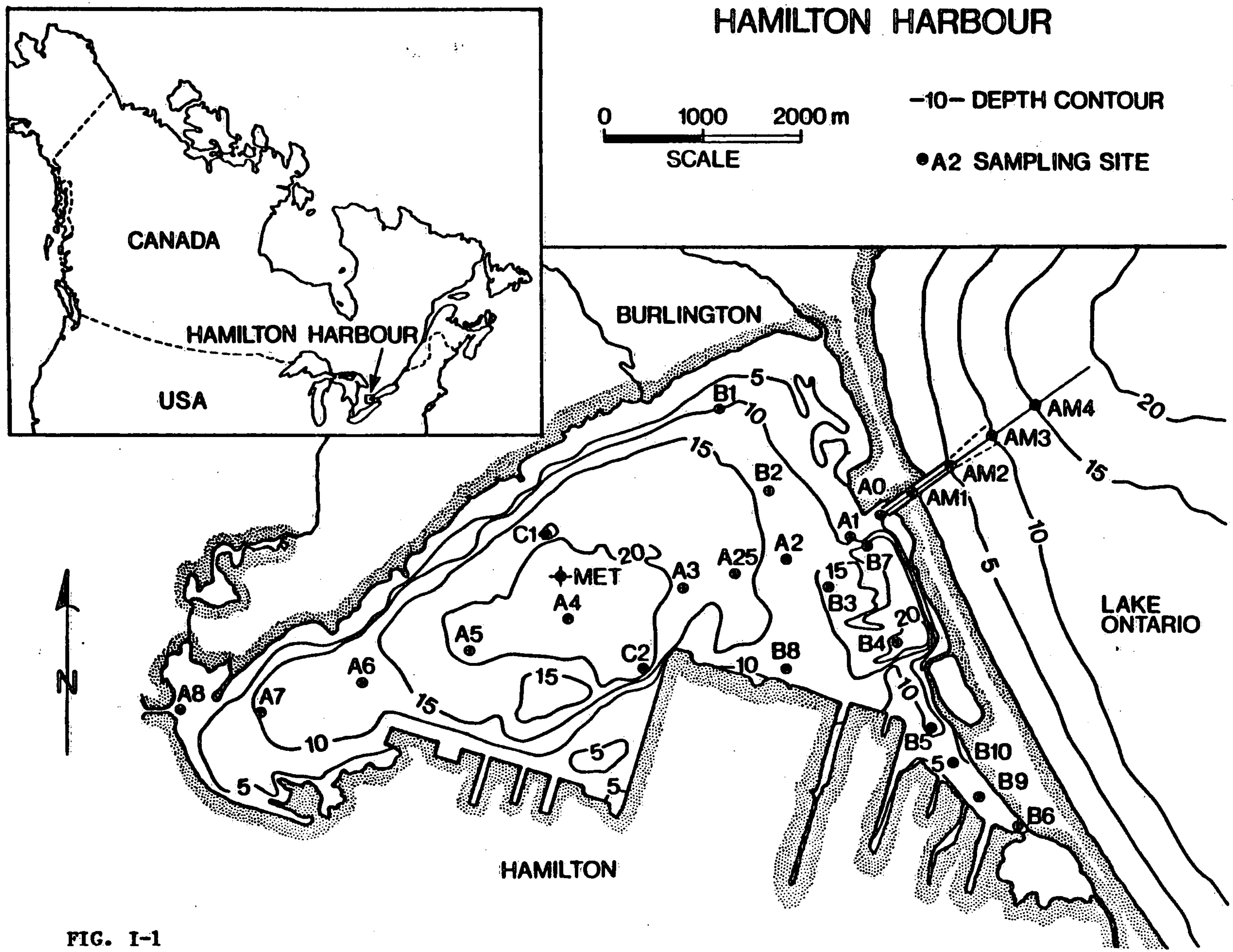

HAMILTON HARBOUR
0 1000 2000 m
SCALE
-10- DEPTH CONTOUR
●A2 SAMPLING SITE
CANADA
USA
HAMILTON HARBOUR
BURLINGTON
HAMILTON
LAKE ONTARIO
N
AM4
AM3
AM2
AM1
A0
A1
A2
A25
A3
A4
A5
A6
A7
A8
B1
B2
B3
B4
B5
B6
B7
B8
B9
B10
C1
C2
MET
5
10
15
20

FIG. I-1

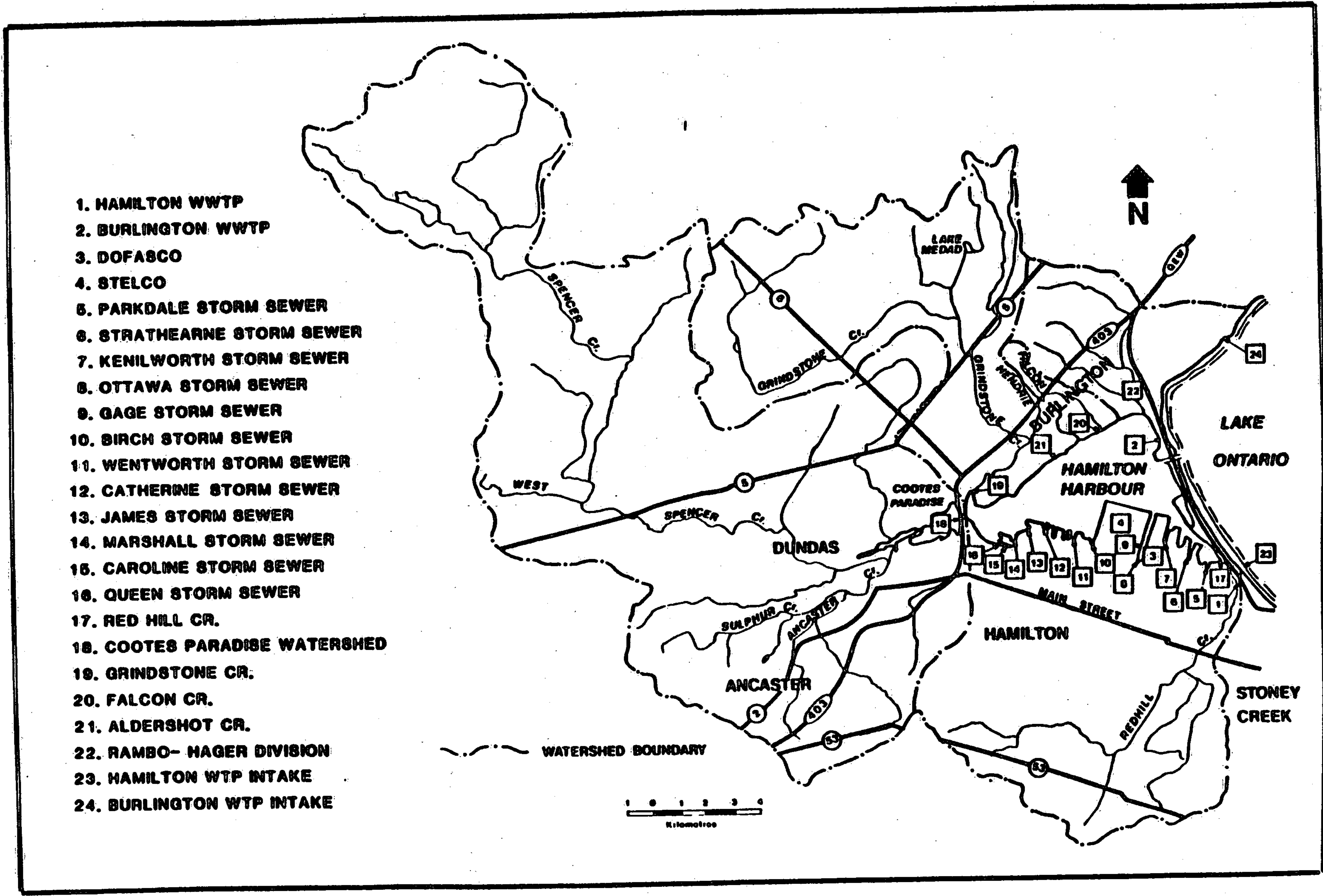

1. HAMILTON WWTP
2. BURLINGTON WWTP
3. DOFASCO
4. STELCO
5. PARKDALE STORM SEWER
6. STRATHEARNE STORM SEWER
7. KENILWORTH STORM SEWER
8. OTTAWA STORM SEWER
9. GAGE STORM SEWER
10. BIRCH STORM SEWER
11. WENTWORTH STORM SEWER
12. CATHERINE STORM SEWER
13. JAMES STORM SEWER
14. MARSHALL STORM SEWER
15. CAROLINE STORM SEWER
16. QUEEN STORM SEWER
17. RED HILL CR.
18. COOTES PARADISE WATERSHED
19. GRINDSTONE CR.
20. FALCON CR.
21. ALDERSHOT CR.
22. RAMBO- HAGER DIVISION
23. HAMILTON WTP INTAKE
24. BURLINGTON WTP INTAKE
WATERSHED BOUNDARY
1 0 1 2 3 4
Kilometres
N
LAKE ONTARIO
HAMILTON HARBOUR
BURLINGTON
HAMILTON
DUNDAS
ANCASTER
STONEY CREEK
LAKE MEDAD
COOTES PARADISE
SPENCER CR.
WEST
GRINDSTONE CR.
GRINDSTONE CR.
FALCON
MEADOWS
SULPHUR CR.
ANCASTER CR.
REDHILL
MAIN STREET
CR.
QEW
403
403
6
6
5
2
53
53

FIG. II-1

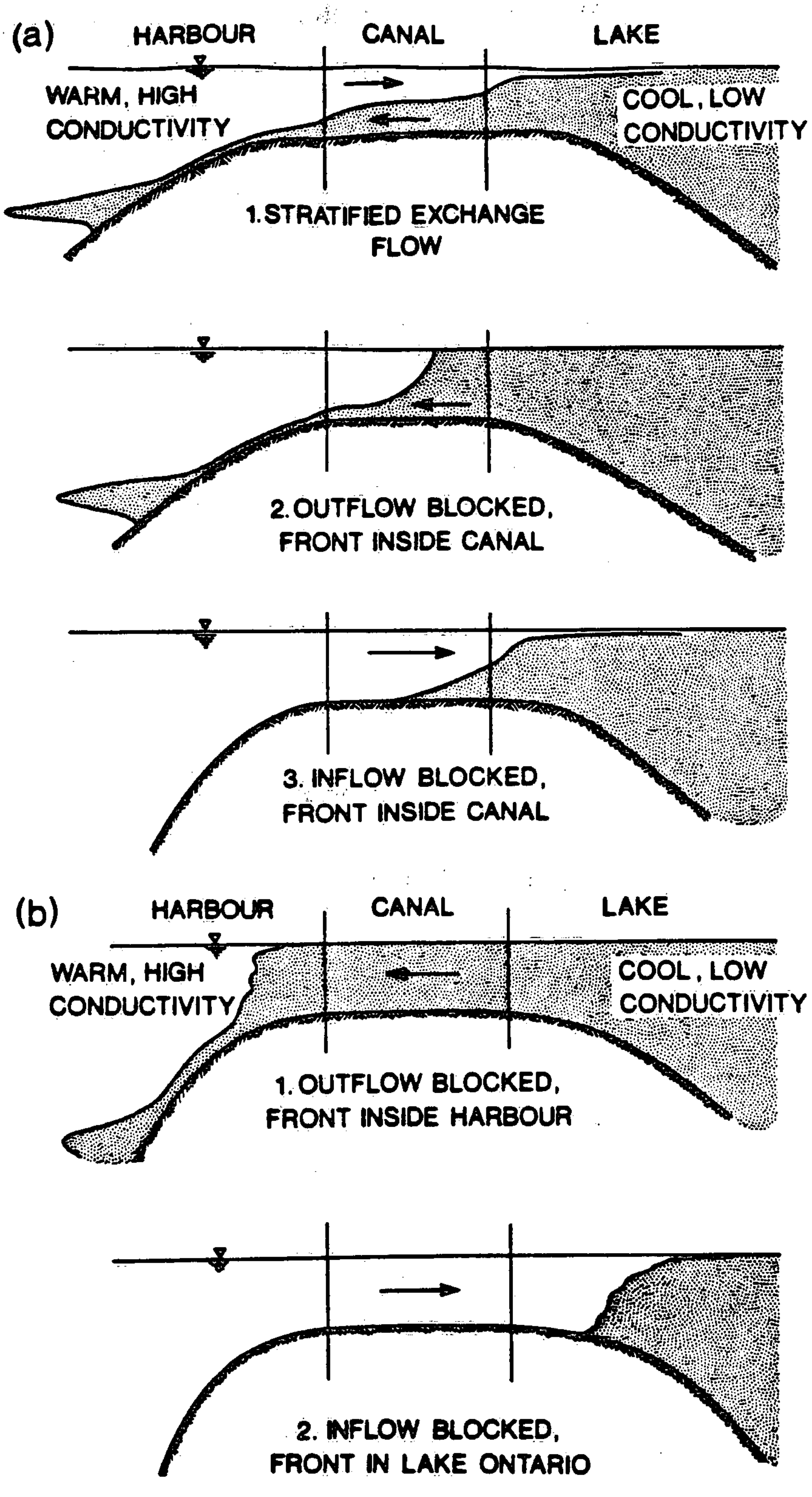

(a)
HARBOUR
CANAL
LAKE
WARM, HIGH CONDUCTIVITY
COOL, LOW CONDUCTIVITY
1. STRATIFIED EXCHANGE FLOW
2. OUTFLOW BLOCKED, FRONT INSIDE CANAL
3. INFLOW BLOCKED, FRONT INSIDE CANAL
(b)
HARBOUR
CANAL
LAKE
WARM, HIGH CONDUCTIVITY
COOL, LOW CONDUCTIVITY
1. OUTFLOW BLOCKED, FRONT INSIDE HARBOUR
2. INFLOW BLOCKED, FRONT IN LAKE ONTARIO

FIG. II-2

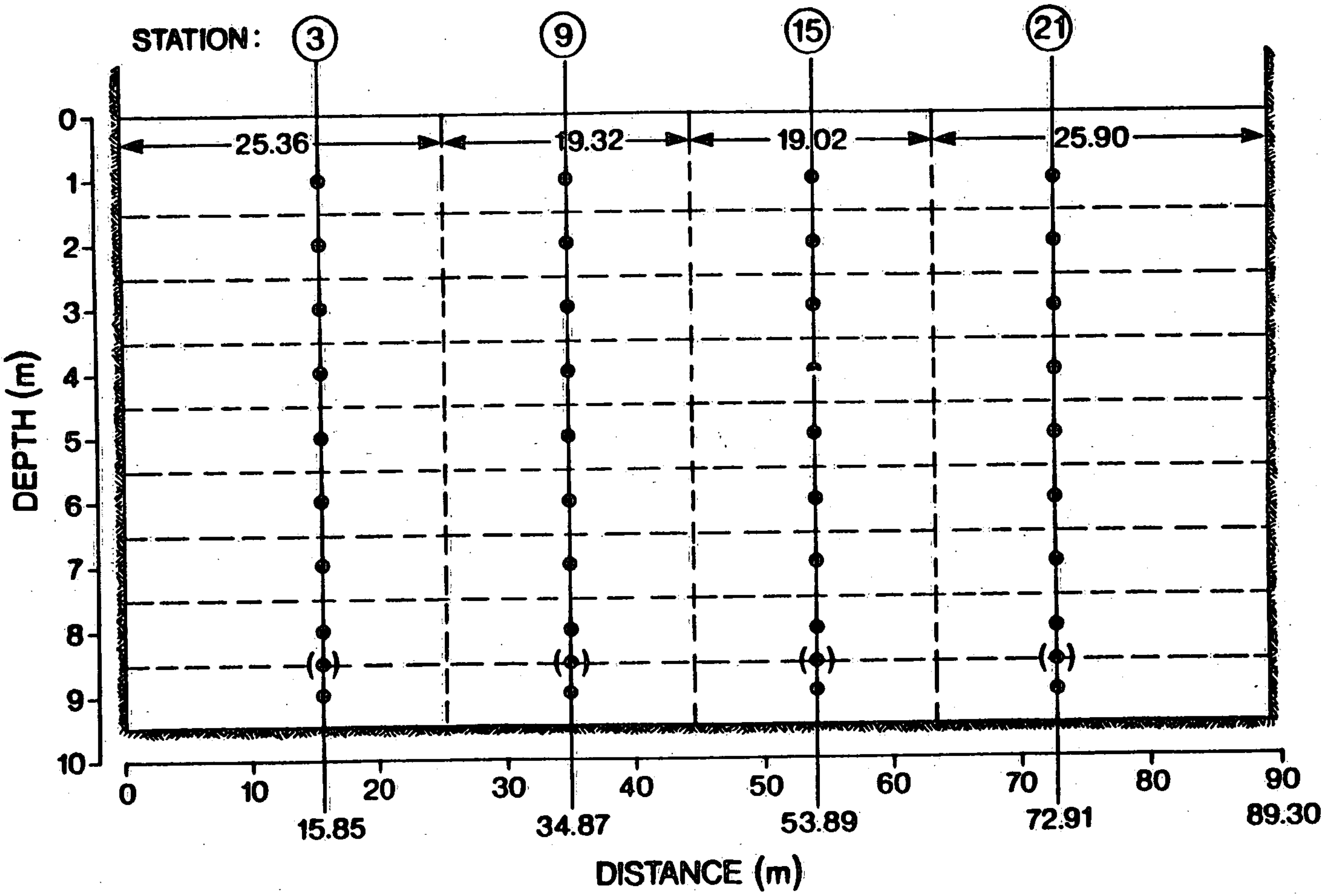

STATION:
3
9
15
21
25.36
19.32
19.02
25.90
DEPTH (m)
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
15.85
34.87
53.89
72.91
89.30
DISTANCE (m)

FIG. III-1

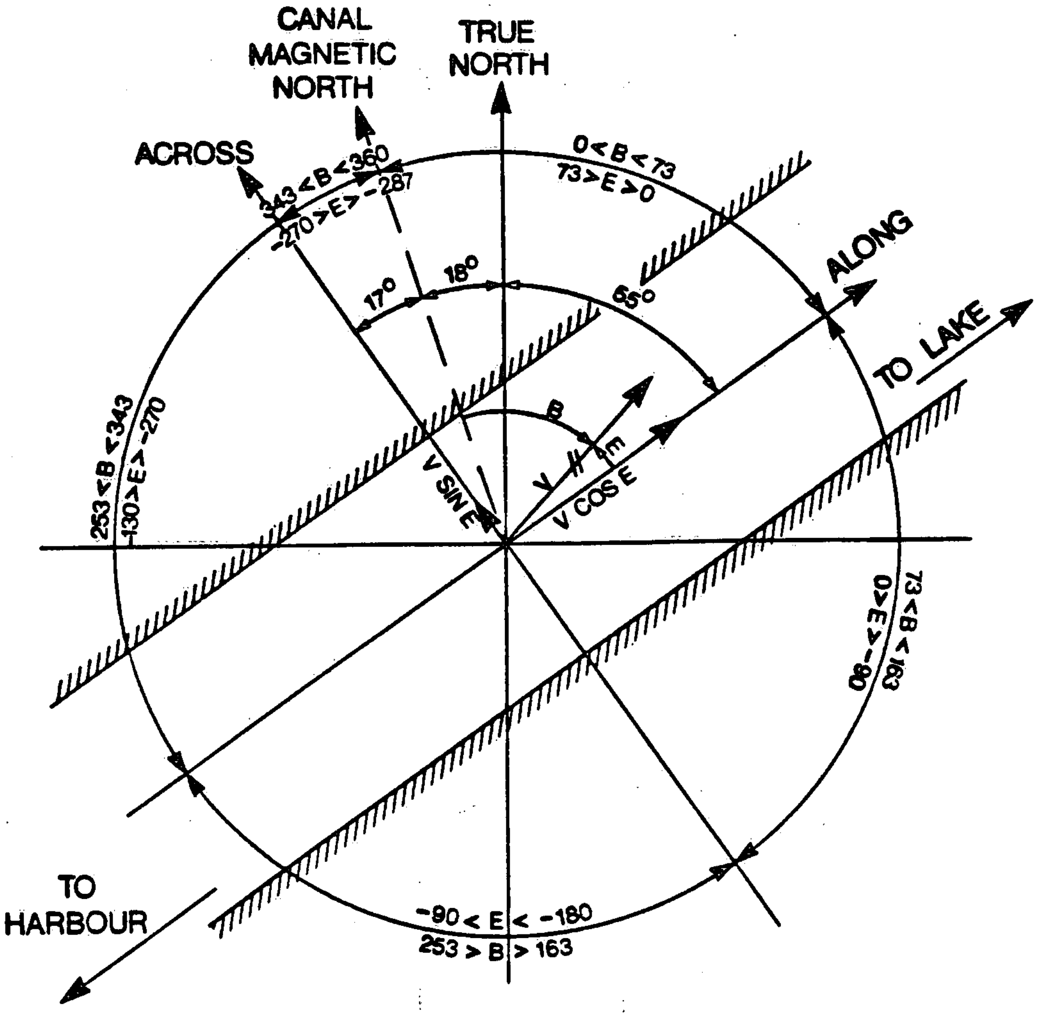

CANAL MAGNETIC NORTH
TRUE NORTH
ACROSS
343<B<360
-270>E>-287
0<B<73
73>E>0
17°
18°
65°
ALONG
TO LAKE
B
E
V
V SINE
V COS E
253<B<343
-130>E>-270
73<B<163
0>E>-90
-90<E<-180
253>B>163
TO HARBOUR

FIG. III-2

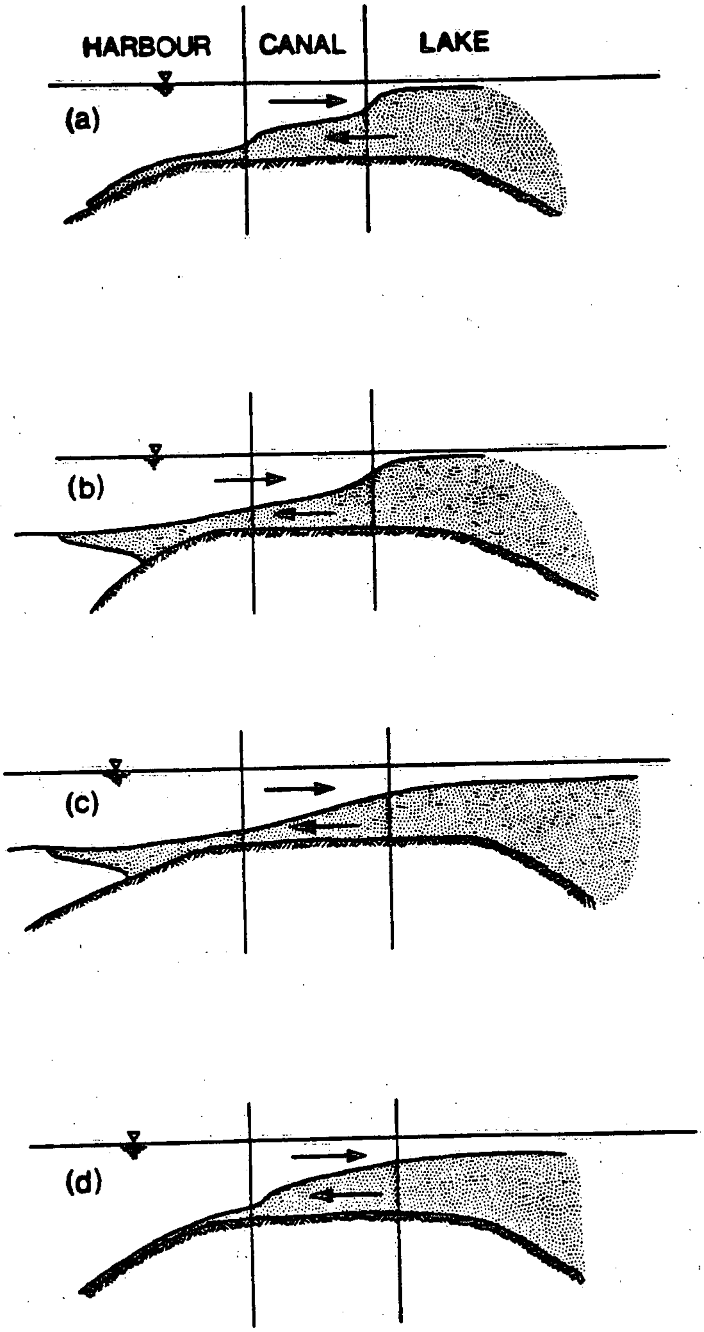
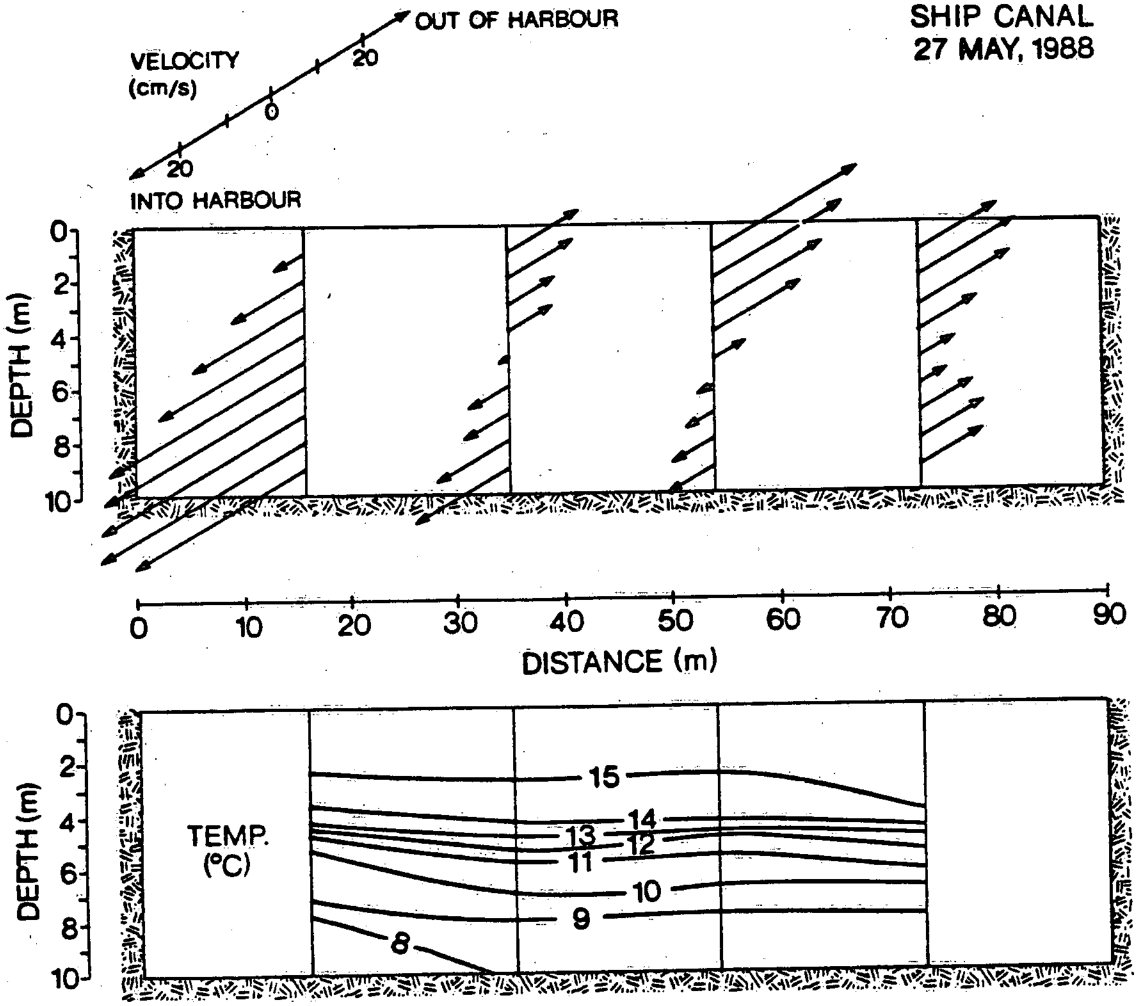


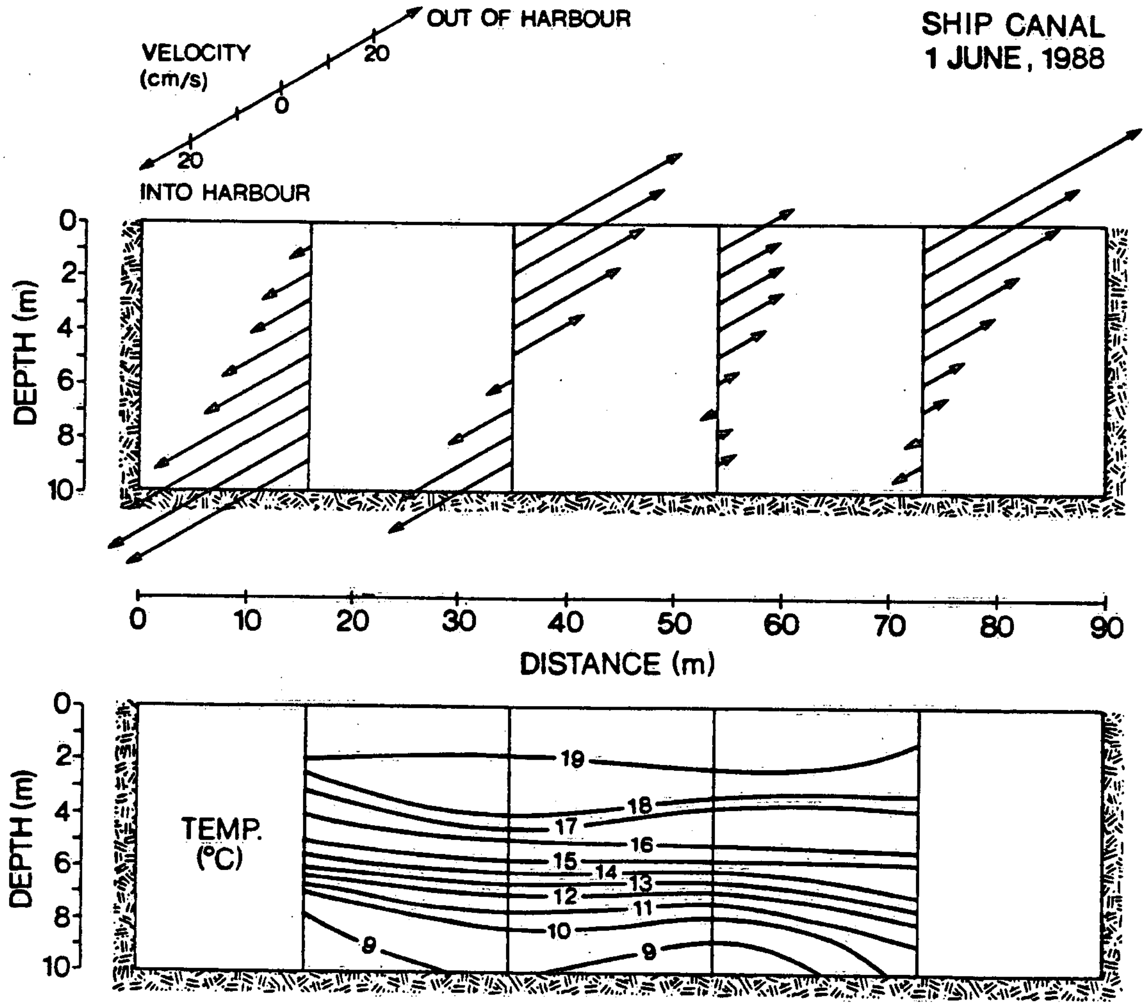
FIG. III-3

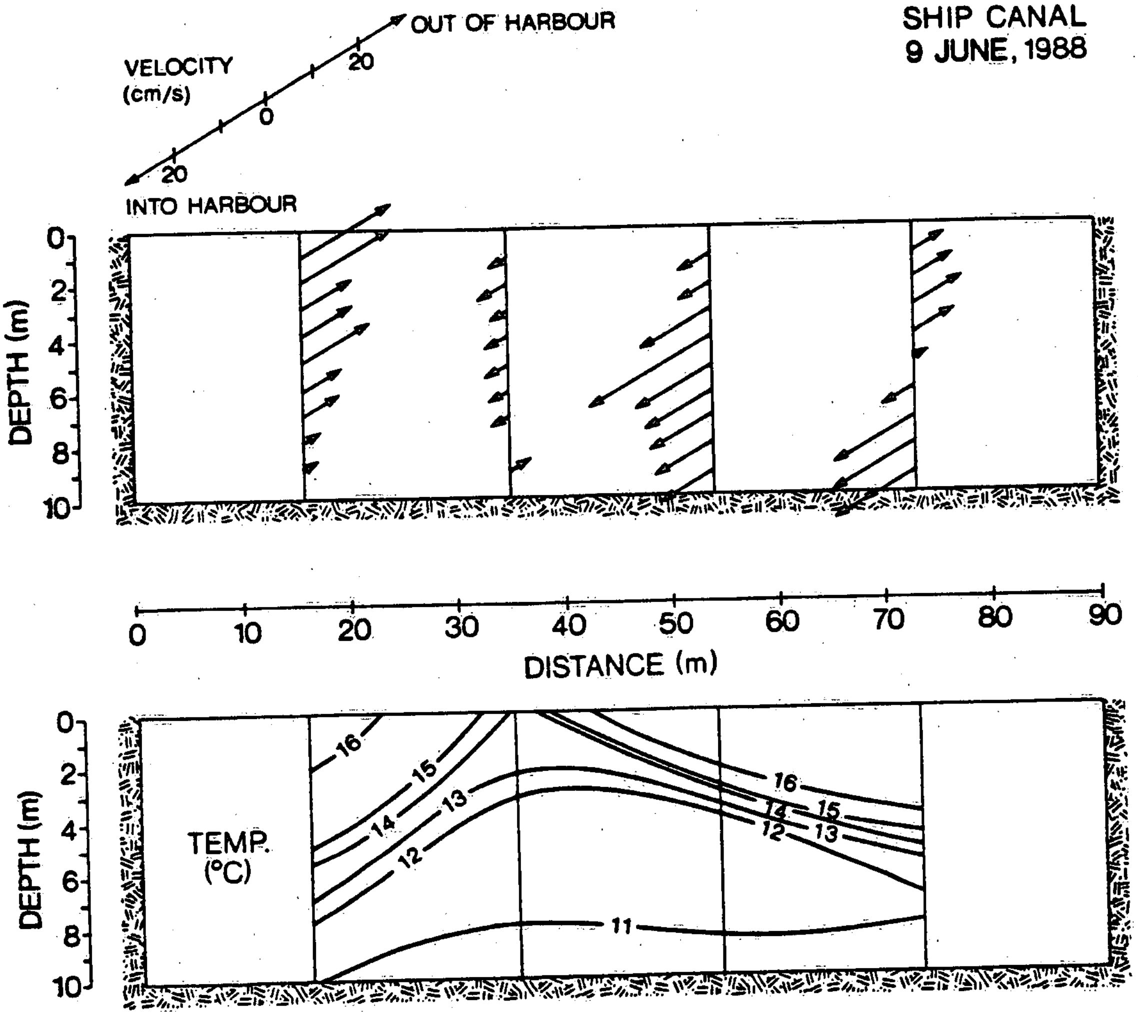
APPENDIX I

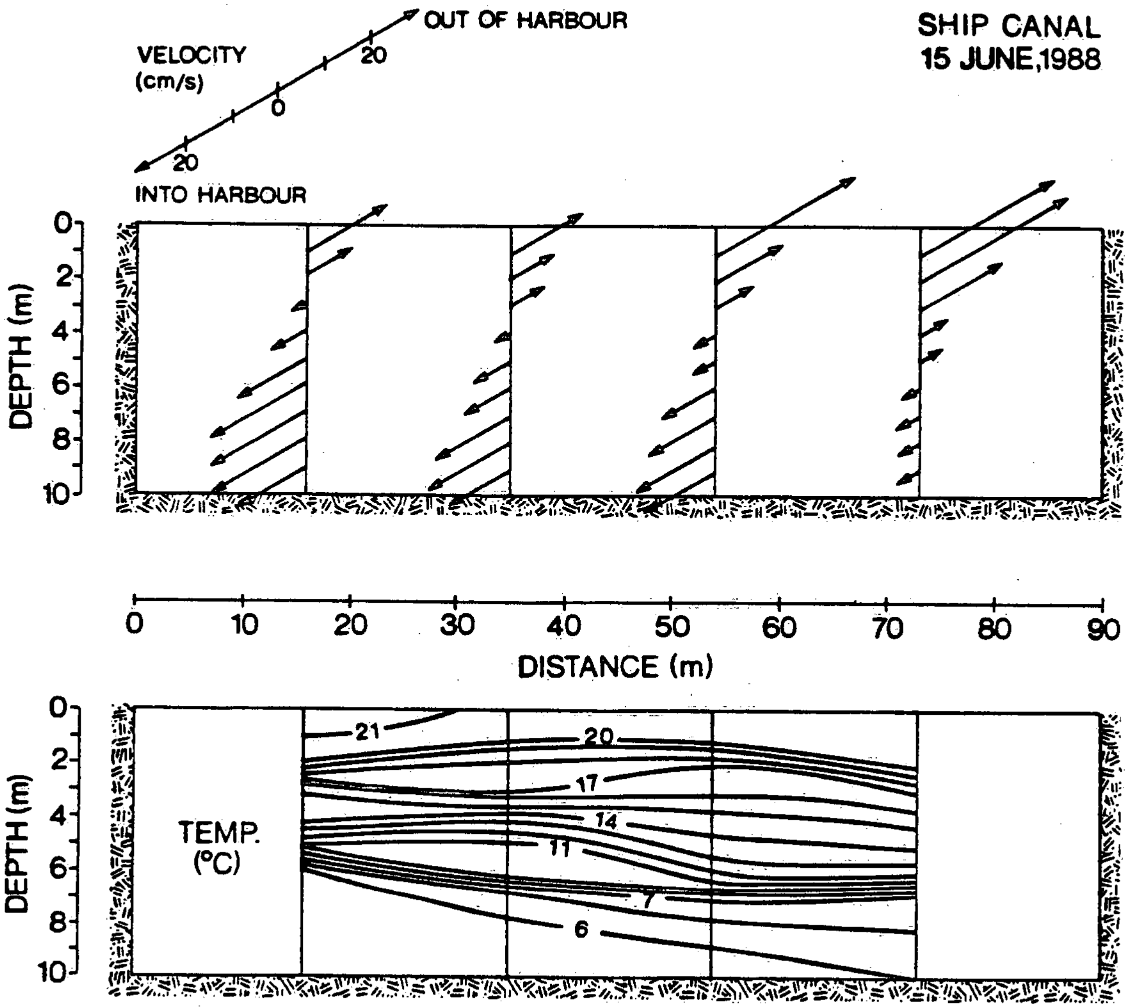
CURRENT PROFILE MEASUREMENTS
BURLINGTON SHIP CANAL

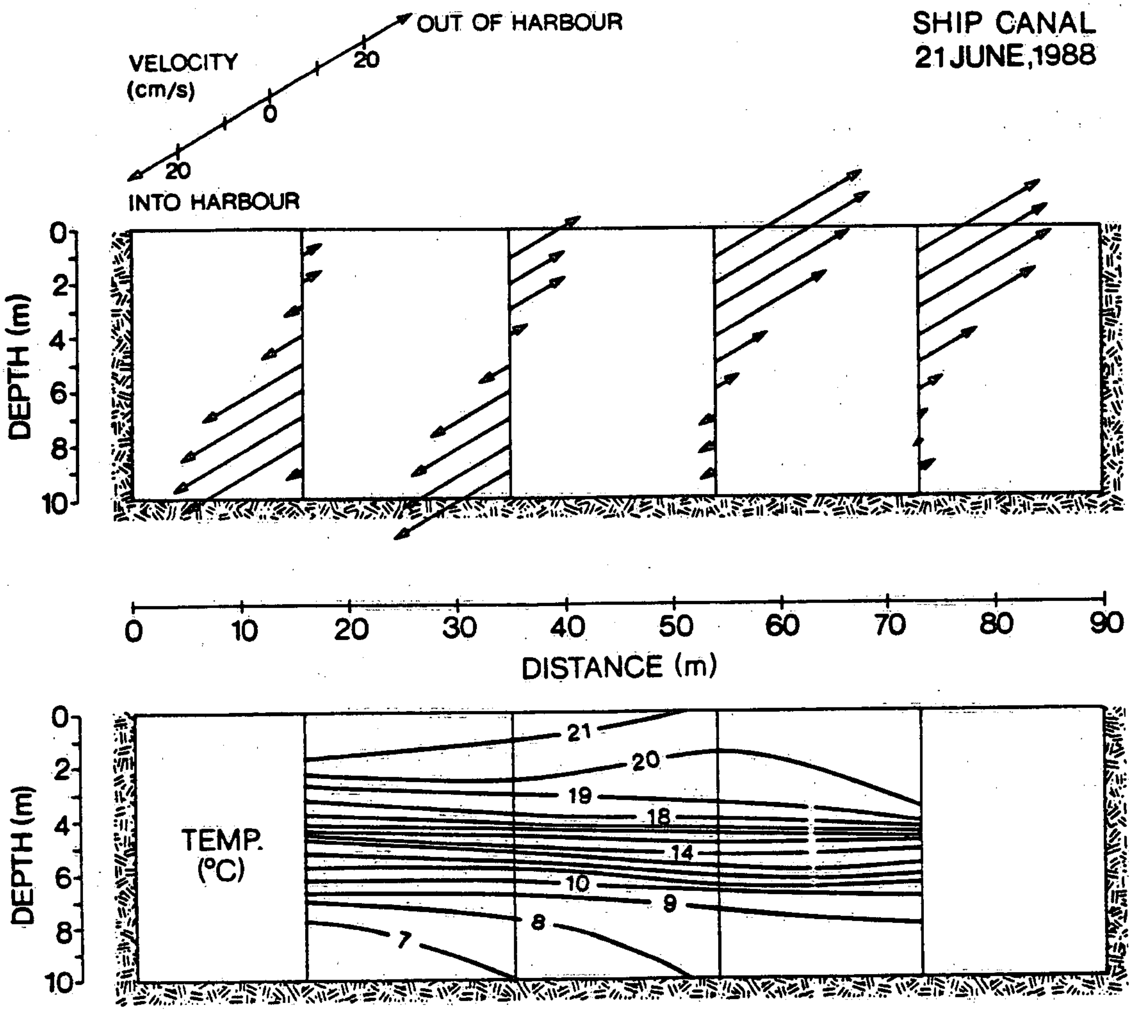


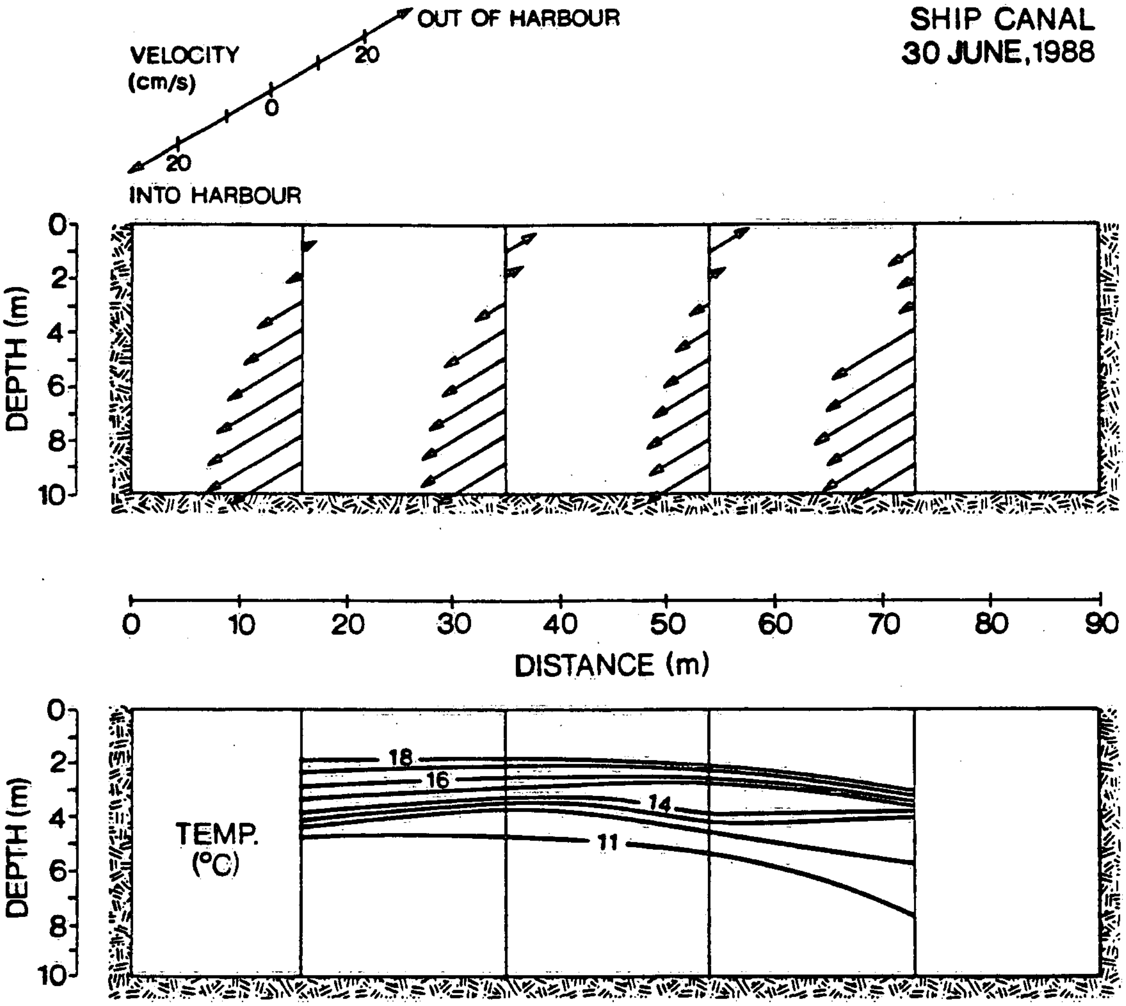
SHIP CANAL
27 MAY, 1988


SHIP CANAL
1 JUNE, 1988

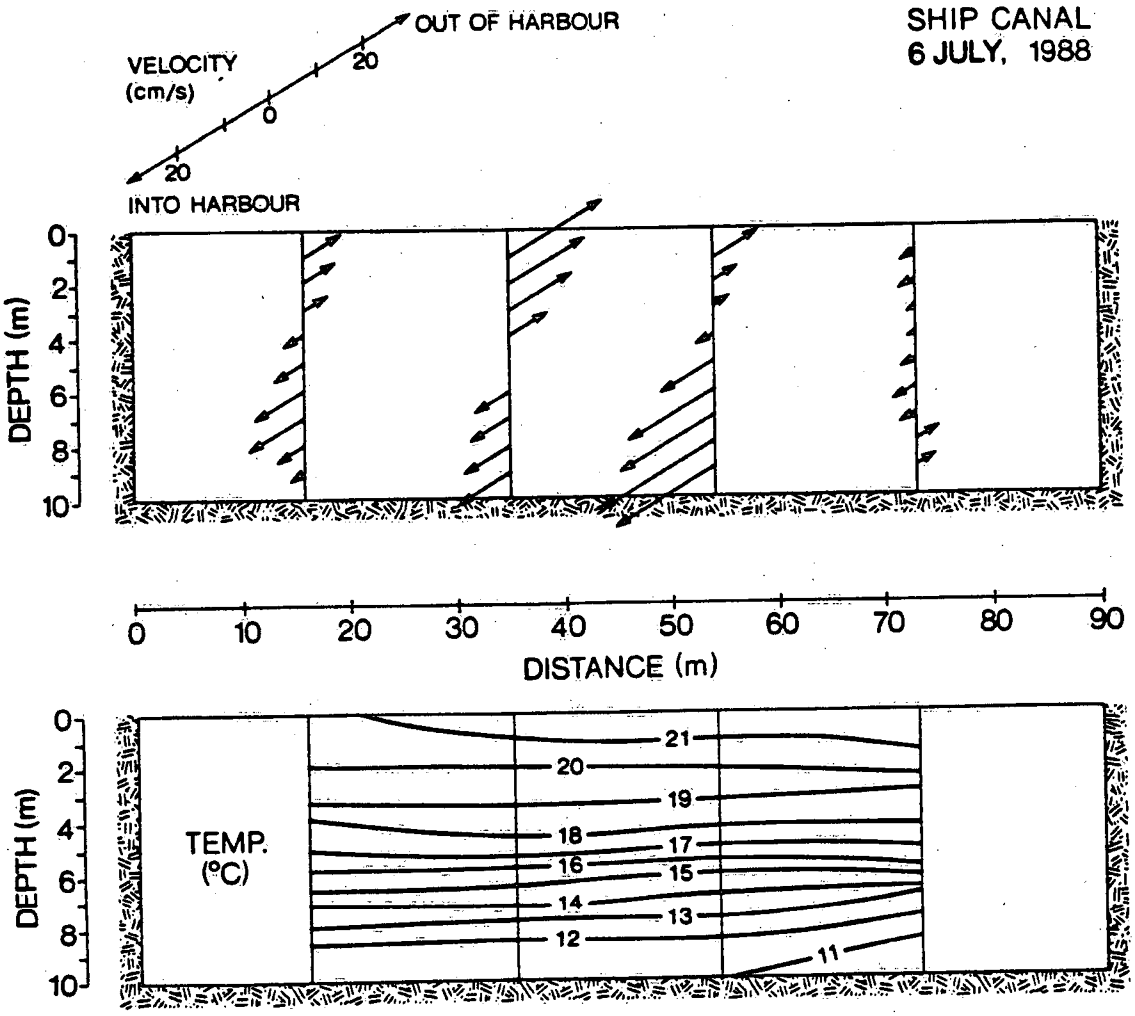

SHIP CANAL
9 JUNE, 1988
VELOCITY
(cm/s)
OUT OF HARBOUR
INTO HARBOUR
20
0
20
DEPTH (m)
0
2
4
6
8
10
DISTANCE (m)
0
10
20
30
40
50
60
70
80
90
TEMP.
(°C)
16
15
14
13
12
11

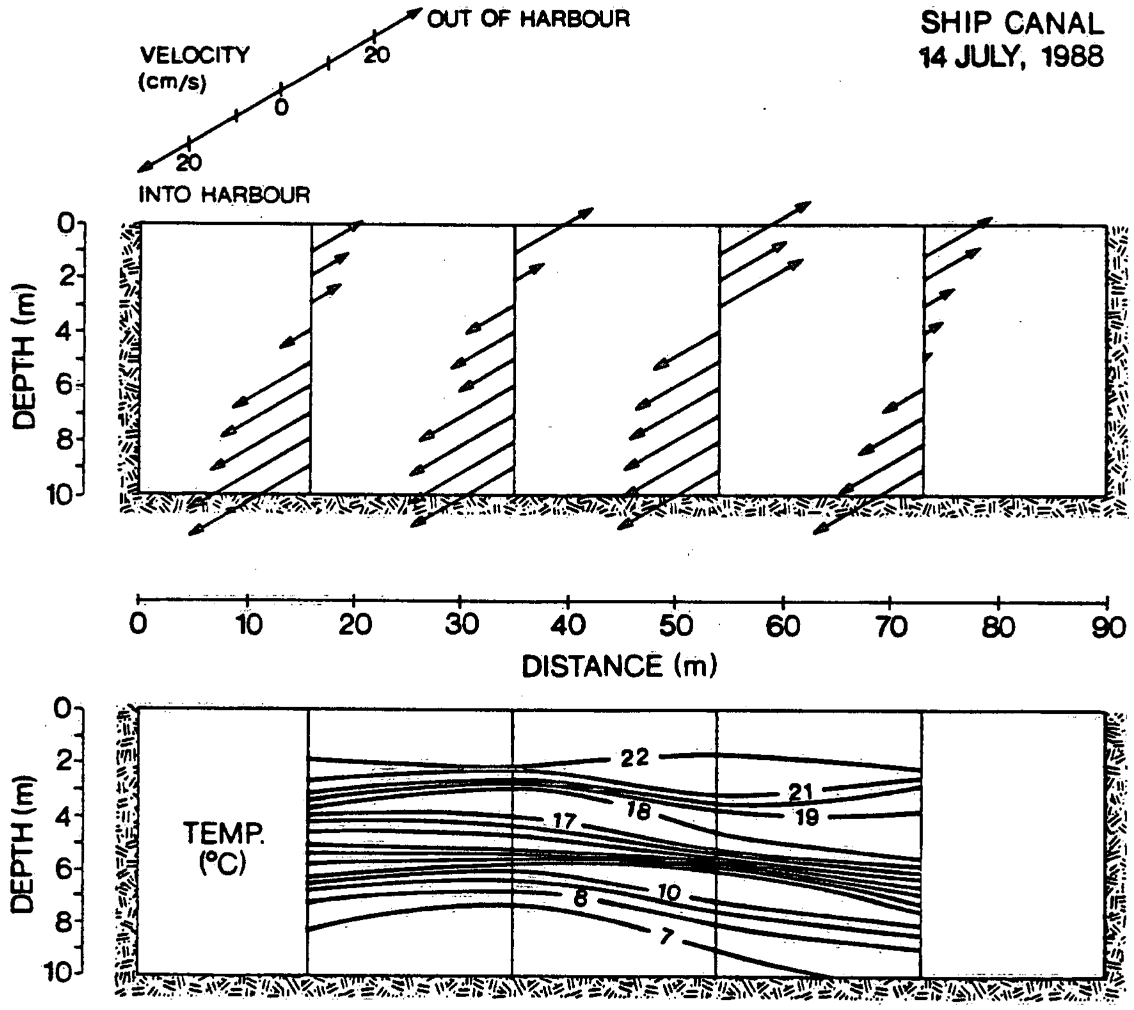

SHIP CANAL
15 JUNE,1988

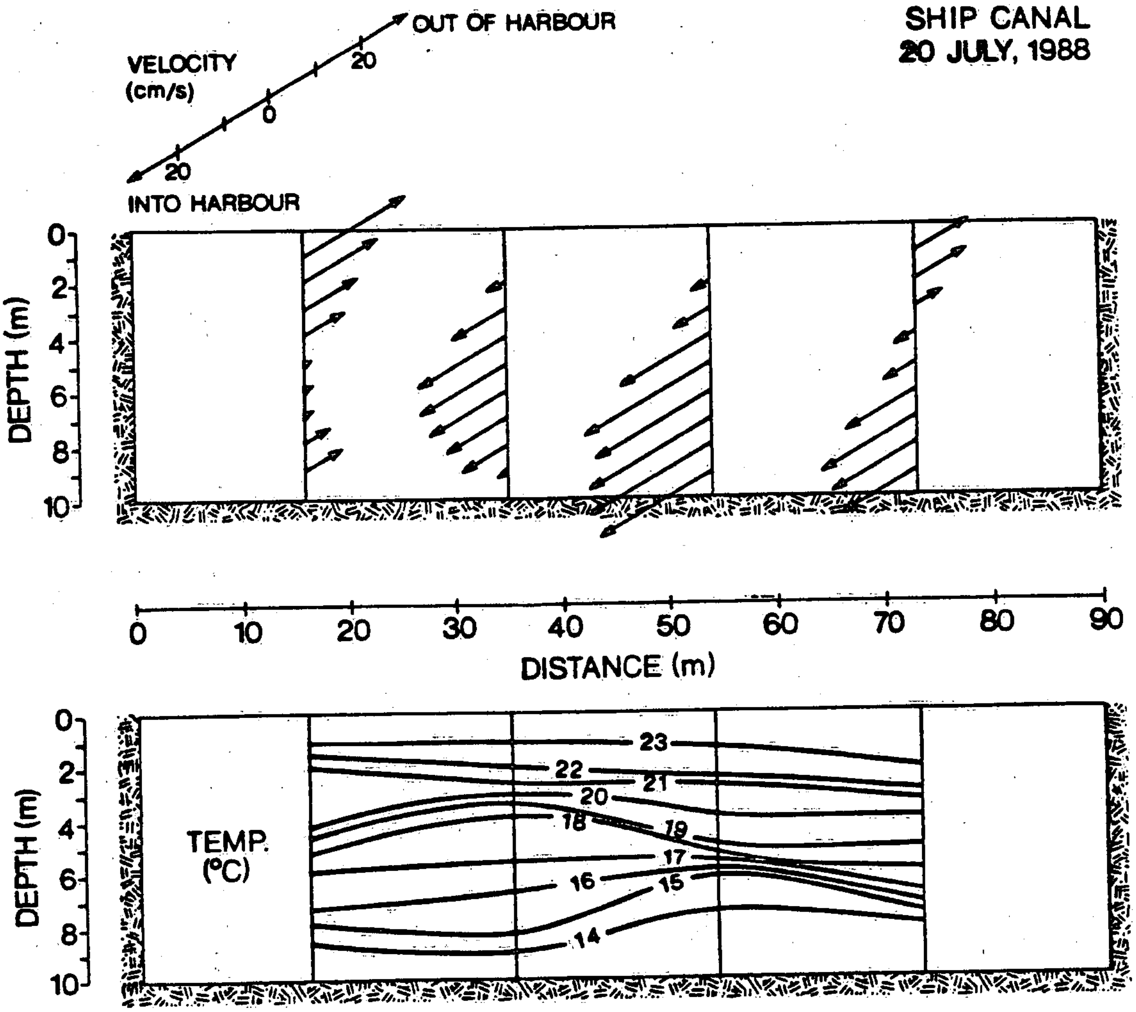

SHIP CANAL
21 JUNE, 1988
VELOCITY (cm/s)
OUT OF HARBOUR
INTO HARBOUR
20
0
20
DEPTH (m)
0
2
4
6
8
10
DISTANCE (m)
0
10
20
30
40
50
60
70
80
90
TEMP. (°C)
21
20
19
18
14
10
9
8
7

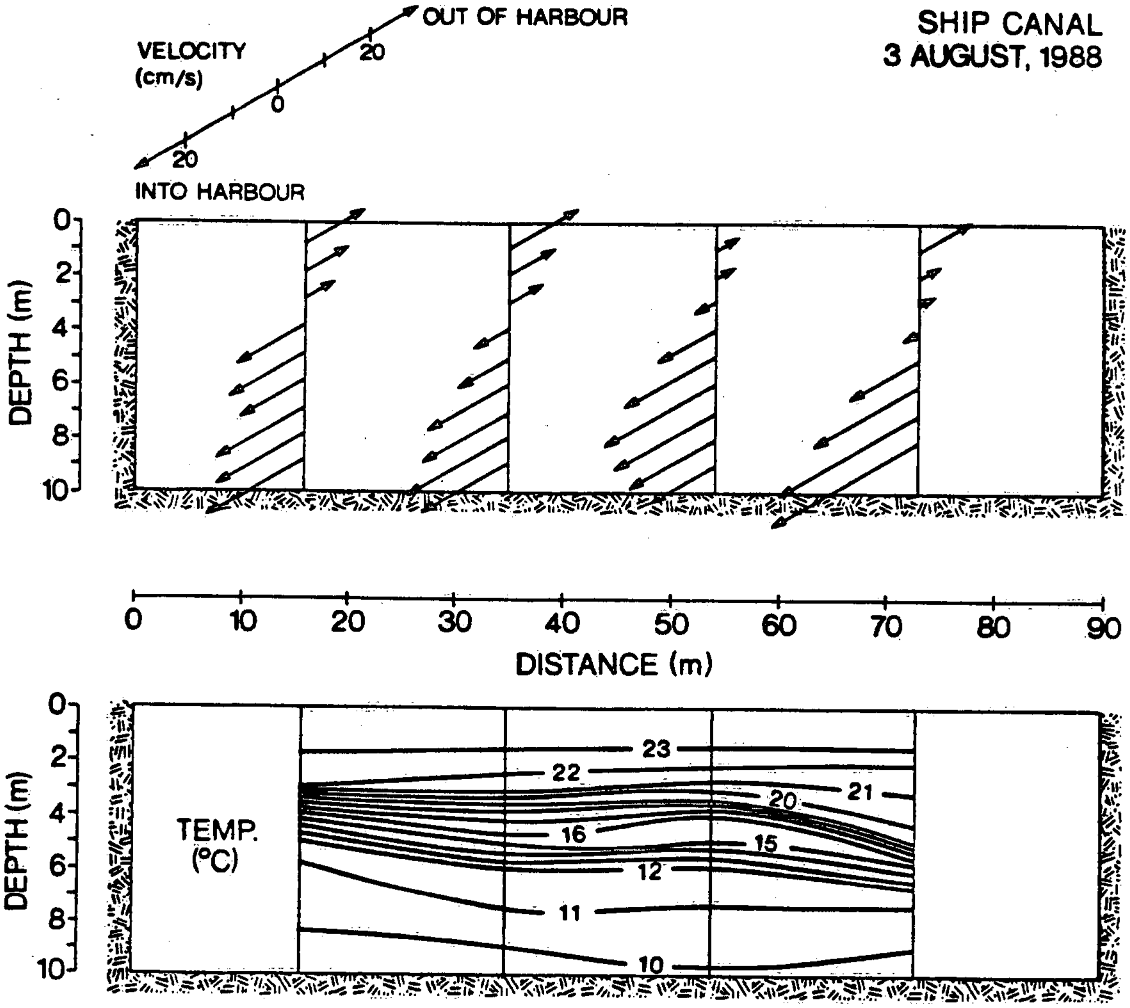


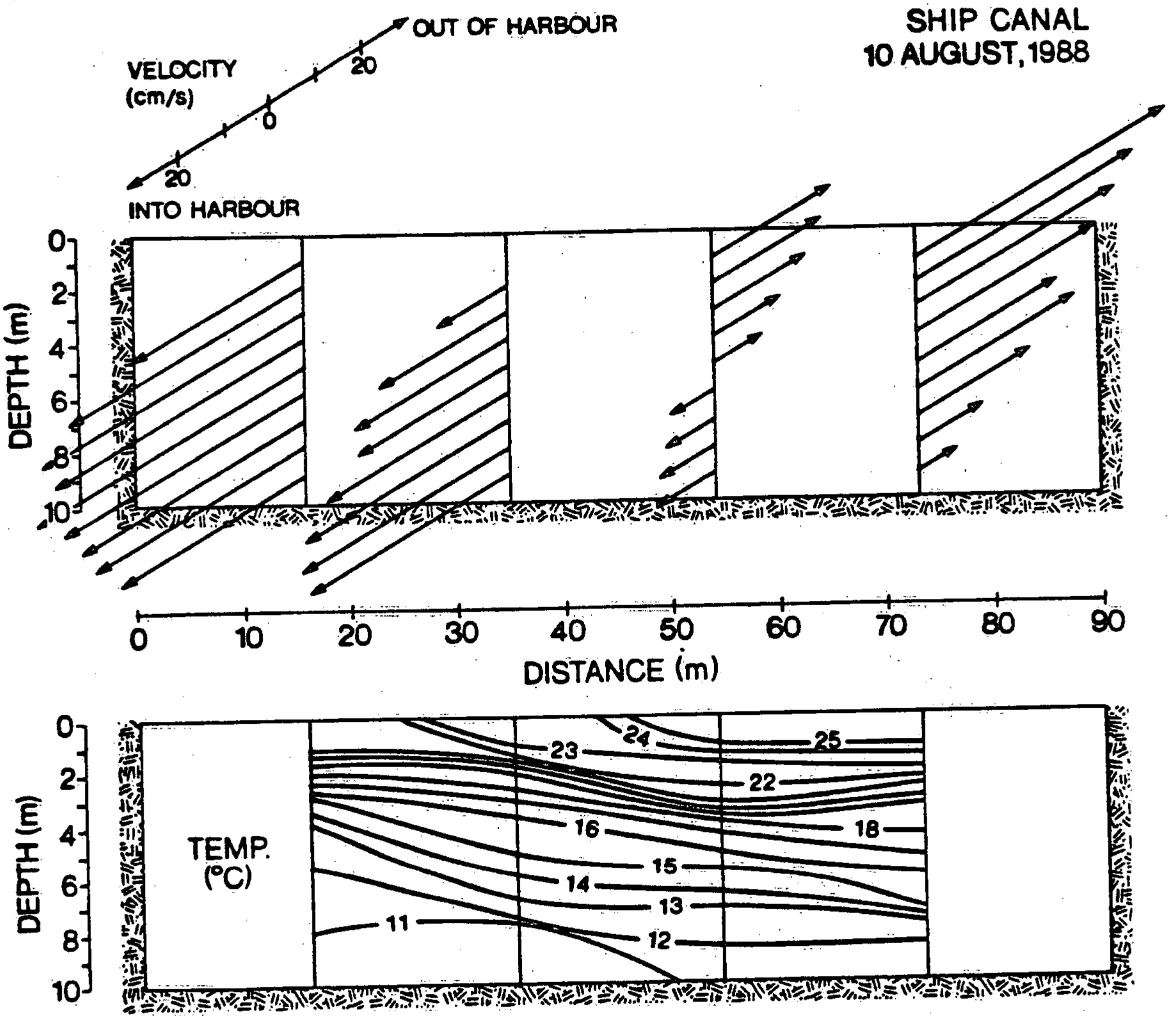
SHIP CANAL
30 JUNE, 1988
VELOCITY
(cm/s)
OUT OF HARBOUR
INTO HARBOUR
20
0
20
DEPTH (m)
0
2
4
6
8
10
DISTANCE (m)
0
10
20
30
40
50
60
70
80
90
TEMP.
(°C)
18
16
14
11

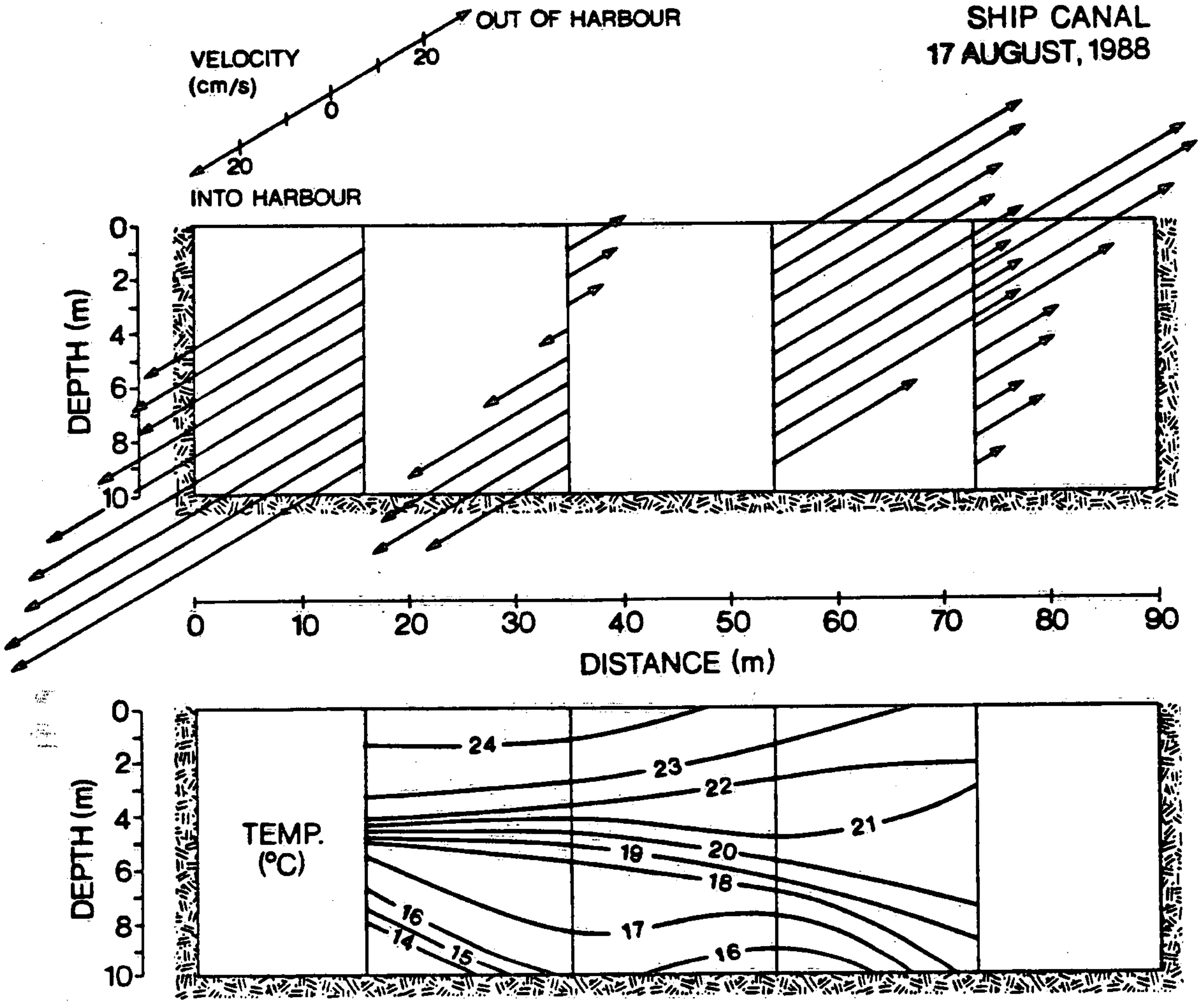

SHIP CANAL
6 JULY, 1988
VELOCITY
(cm/s)
OUT OF HARBOUR
20
0
20
INTO HARBOUR
DEPTH (m)
0
2
4
6
8
10
0
10
20
30
40
50
60
70
80
90
DISTANCE (m)
DEPTH (m)
0
2
4
6
8
10
TEMP.
(°C)
21
20
19
18
17
16
15
14
13
12
11


SHIP CANAL
14 JULY, 1988
VELOCITY
(cm/s)
OUT OF HARBOUR
INTO HARBOUR
20
0
20
DEPTH (m)
0
2
4
6
8
10
0
10
20
30
40
50
60
70
80
90
DISTANCE (m)
DEPTH (m)
0
2
4
6
8
10
TEMP.
(°C)
22
21
18
19
17
10
8
7

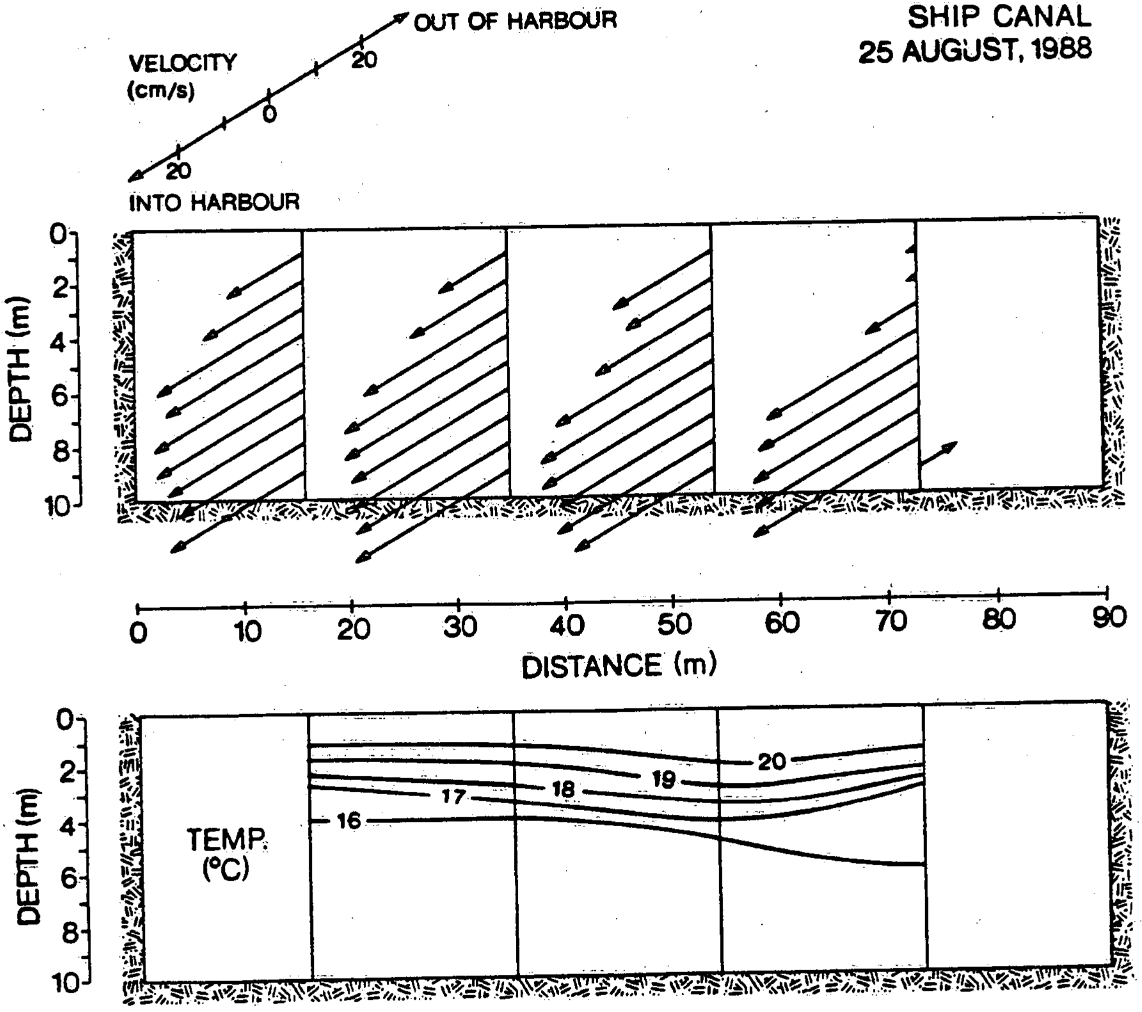

SHIP CANAL
20 JULY, 1988
VELOCITY
(cm/s)
OUT OF HARBOUR
20
0
20
INTO HARBOUR
DEPTH (m)
0
2
4
6
8
10
0
10
20
30
40
50
60
70
80
90
DISTANCE (m)
DEPTH (m)
0
2
4
6
8
10
TEMP.
(°C)
23
22
21
20
18
19
17
16
15
14

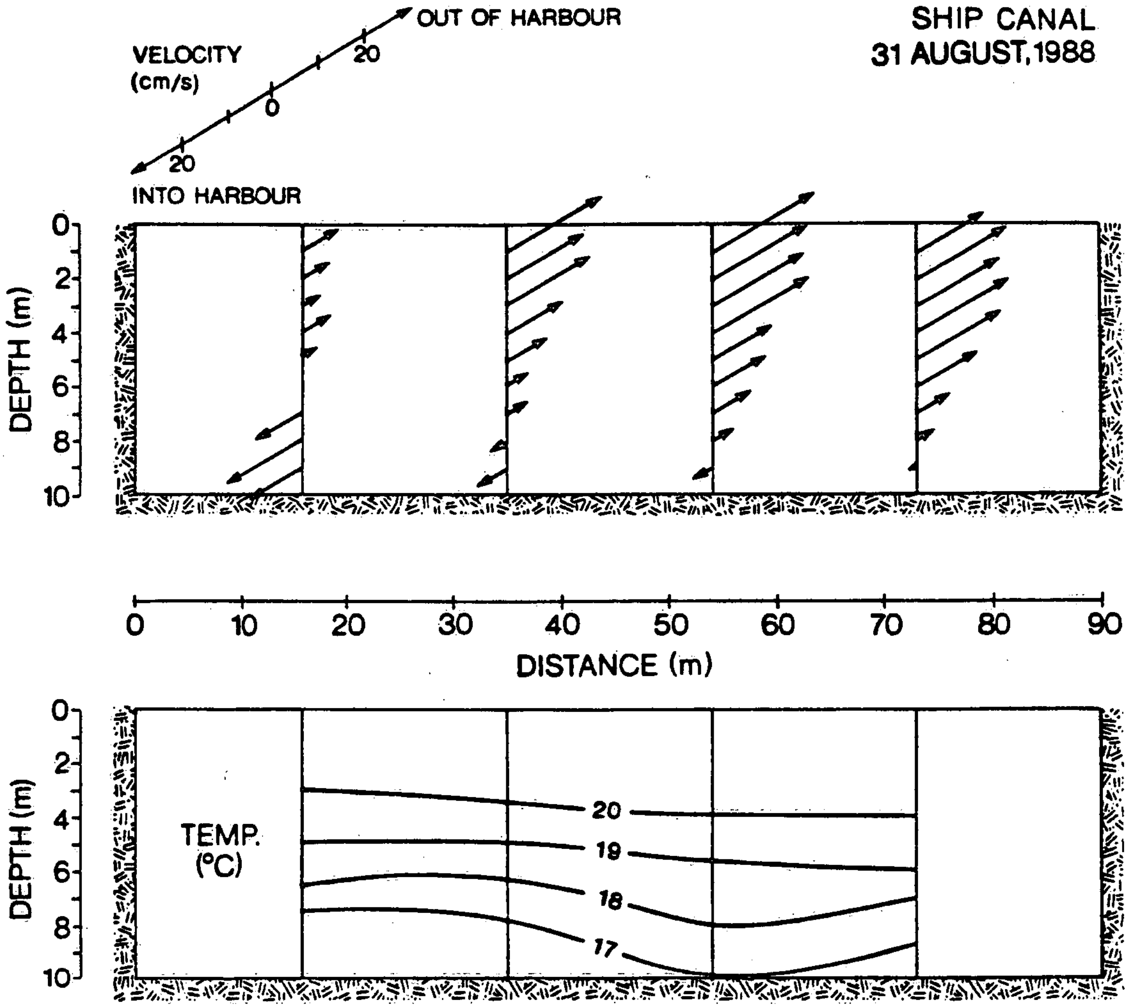

SHIP CANAL
3 AUGUST, 1988

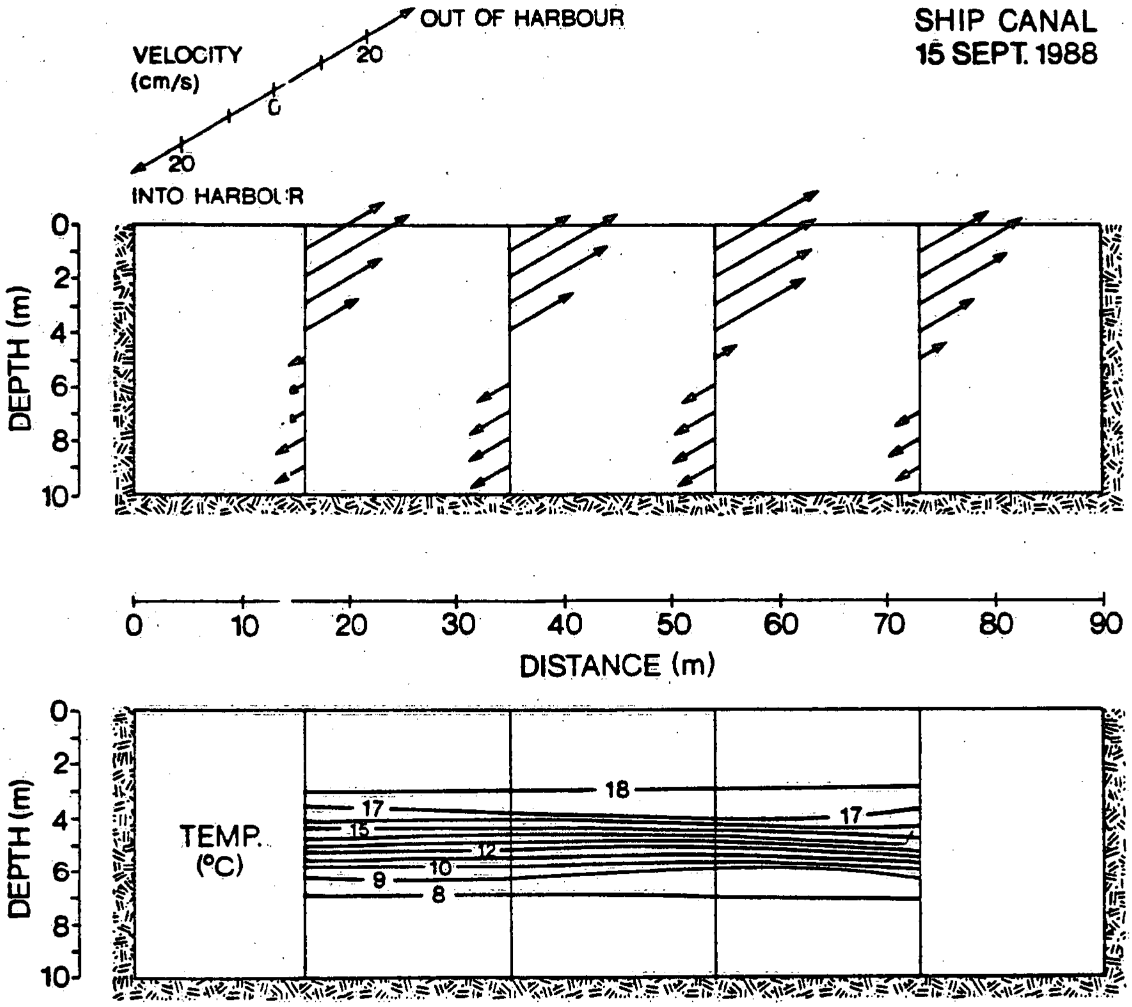

SHIP CANAL
10 AUGUST, 1988

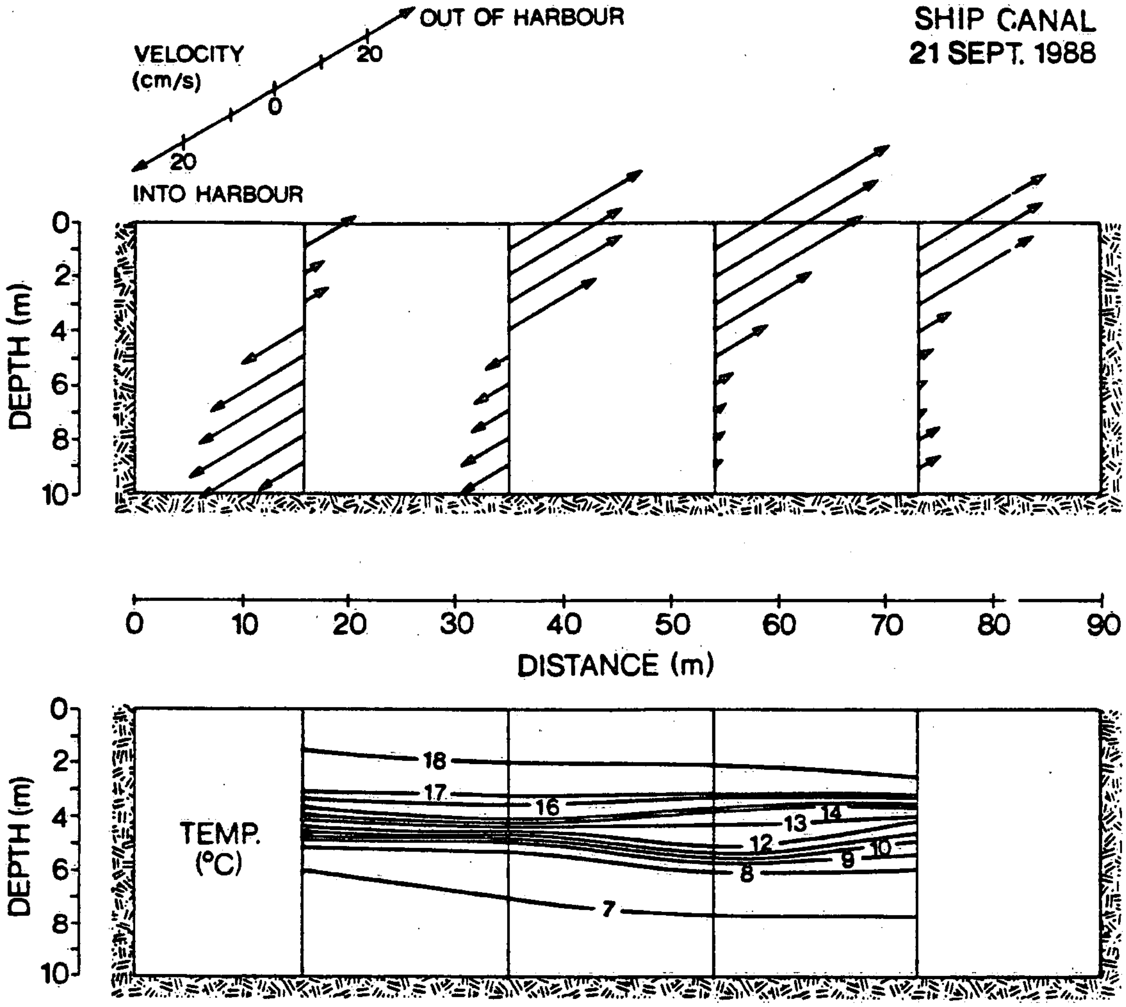

SHIP CANAL
17 AUGUST, 1988
VELOCITY
(cm/s)
OUT OF HARBOUR
20
0
20
INTO HARBOUR
DEPTH (m)
0
2
4
6
8
10
0
10
20
30
40
50
60
70
80
90
DISTANCE (m)
DEPTH (m)
0
2
4
6
8
10
TEMP.
(°C)
24
23
22
21
20
19
18
17
16
16
14
15

SHIP CANAL
25 AUGUST, 1988

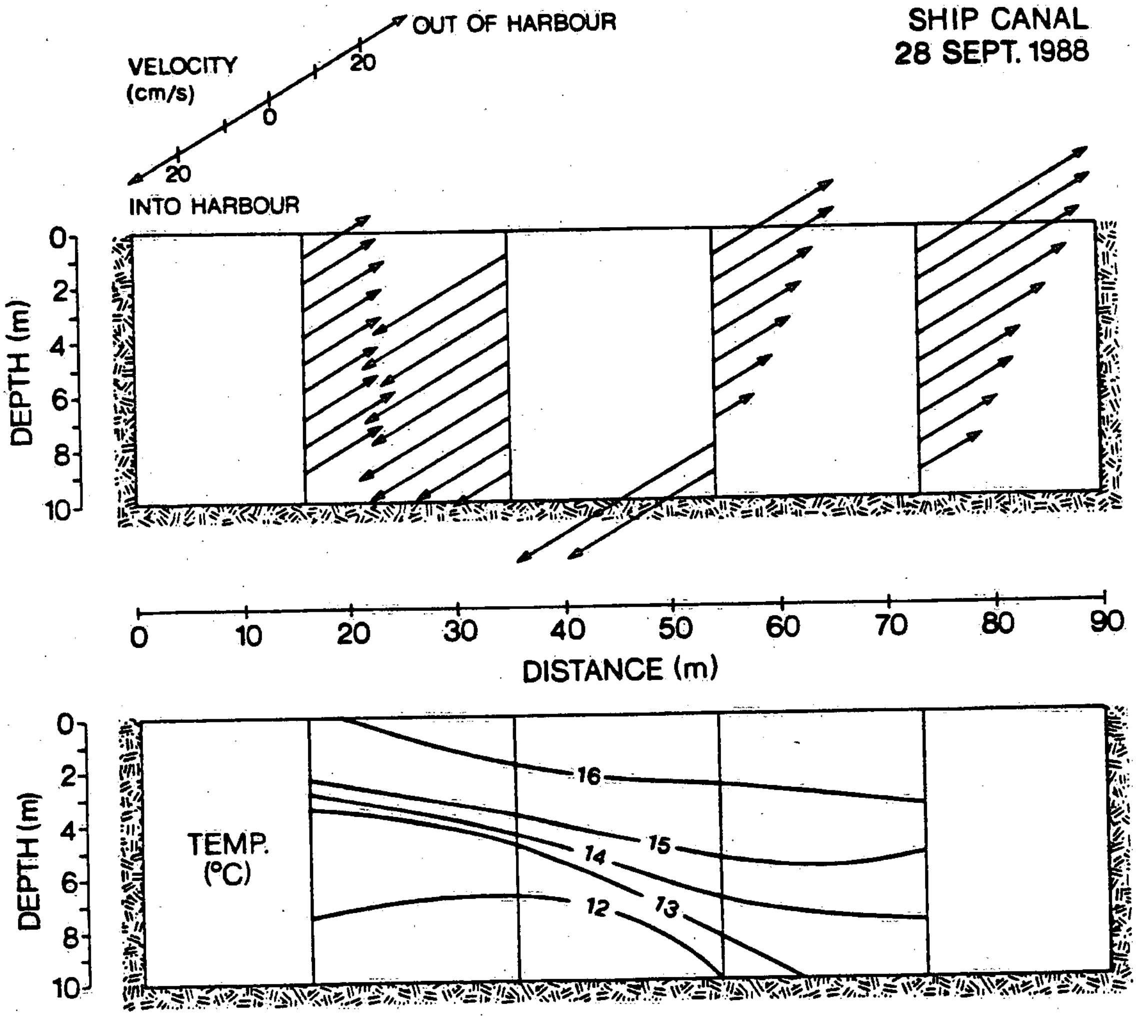



SHIP CANAL
31 AUGUST, 1988
VELOCITY
(cm/s)
OUT OF HARBOUR
INTO HARBOUR
20
0
20
DEPTH (m)
0
2
4
6
8
10
0
10
20
30
40
50
60
70
80
90
DISTANCE (m)
DEPTH (m)
0
2
4
6
8
10
TEMP.
(°C)
20
19
18
17

SHIP CANAL
15 SEPT. 1988
VELOCITY
(cm/s)
OUT OF HARBOUR
INTO HARBOUR
20
0
20
DEPTH (m)
0
2
4
6
8
10
0
10
20
30
40
50
60
70
80
90
DISTANCE (m)
DEPTH (m)
0
2
4
6
8
10
TEMP.
(°C)
18
17
17
15
12
10
9
8



SHIP CANAL
21 SEPT. 1988

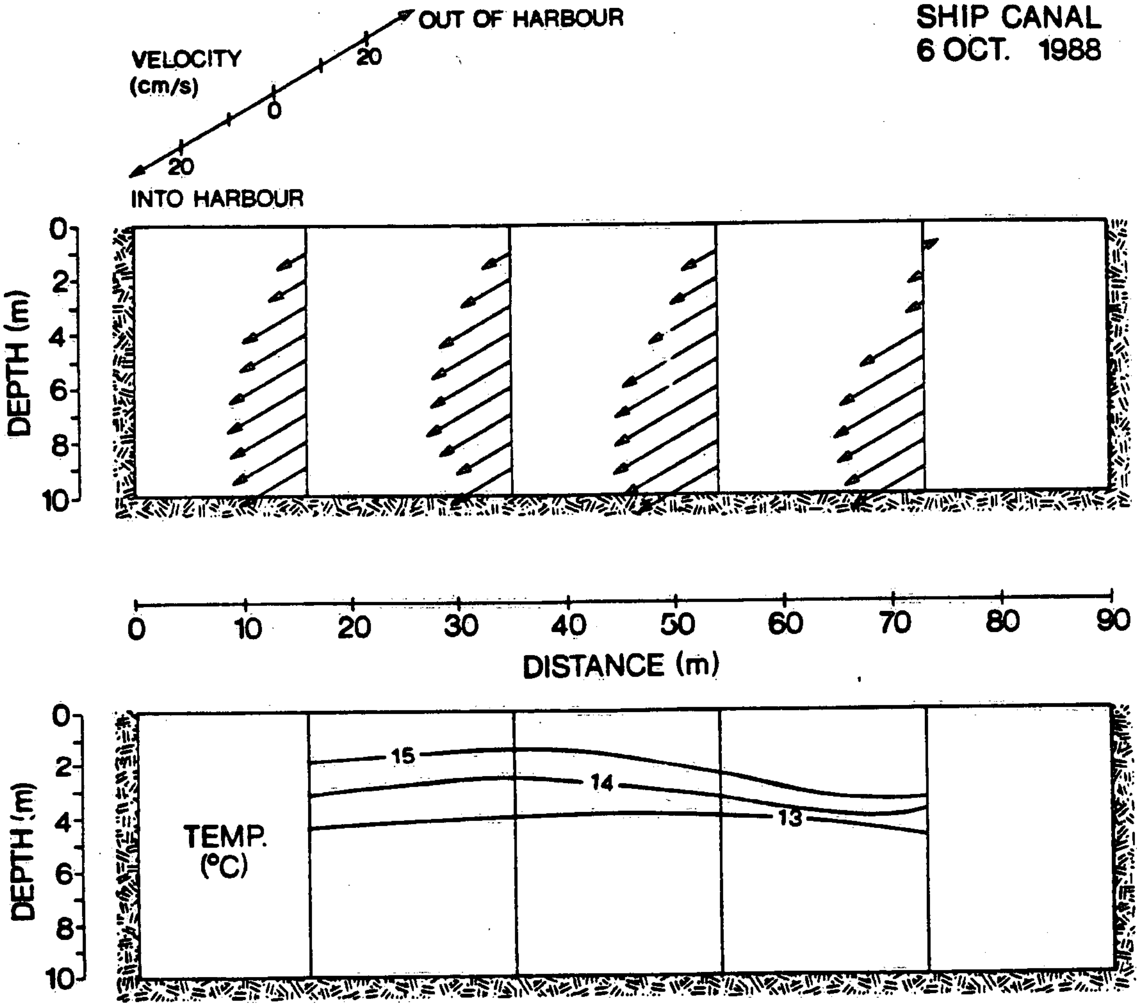

SHIP CANAL
28 SEPT. 1988
VELOCITY
(cm/s)
OUT OF HARBOUR
20
0
20
INTO HARBOUR
DEPTH (m)
0
2
4
6
8
10
DISTANCE (m)
0
10
20
30
40
50
60
70
80
90
DEPTH (m)
0
2
4
6
8
10
TEMP.
(°C)
16
15
14
13
12

APPENDIX II

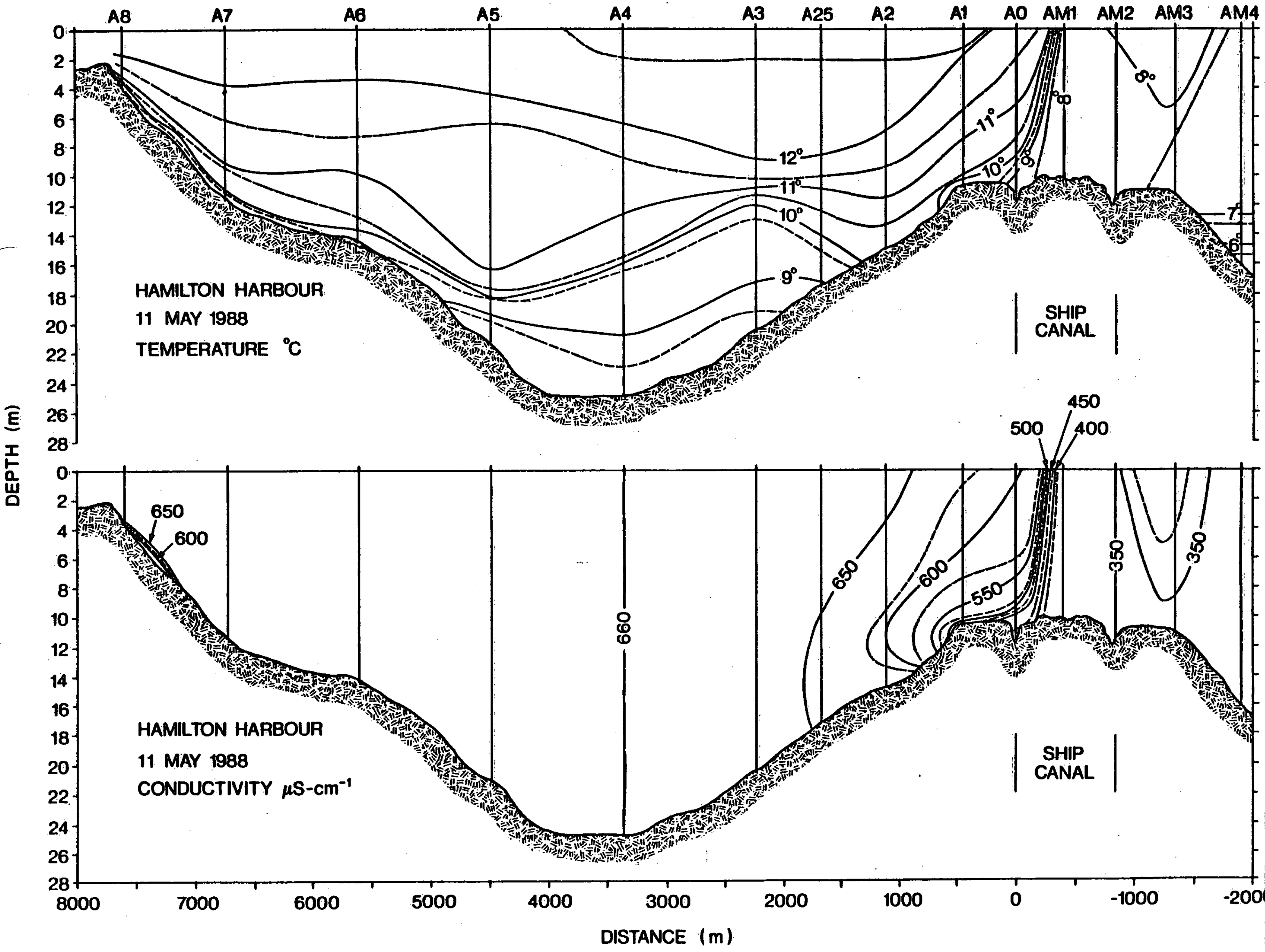
TEMPERATURE AND CONDUCTIVITY TRANSECTS

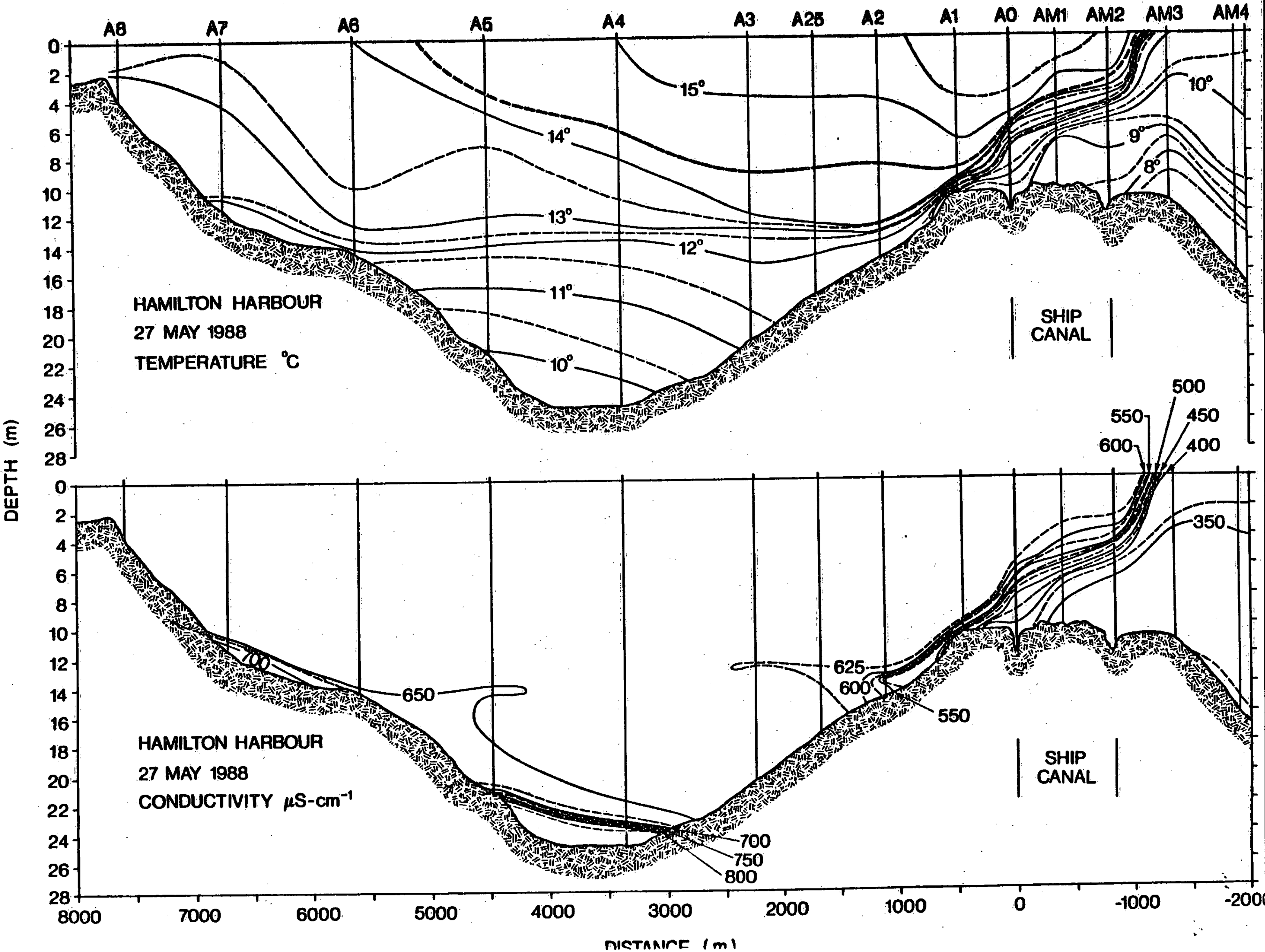
LINE A8 to AM4

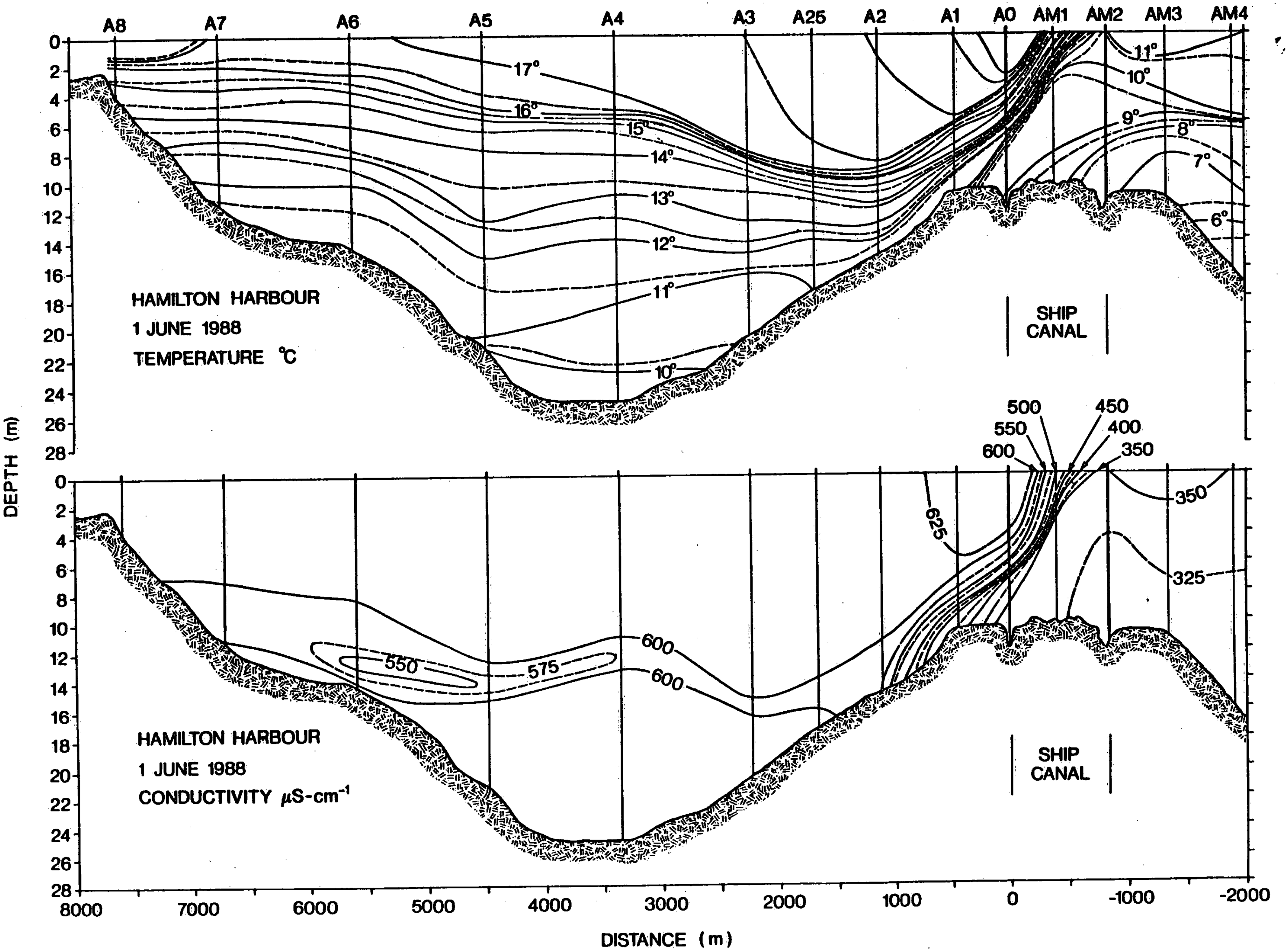
May 11 to September 21, 1988

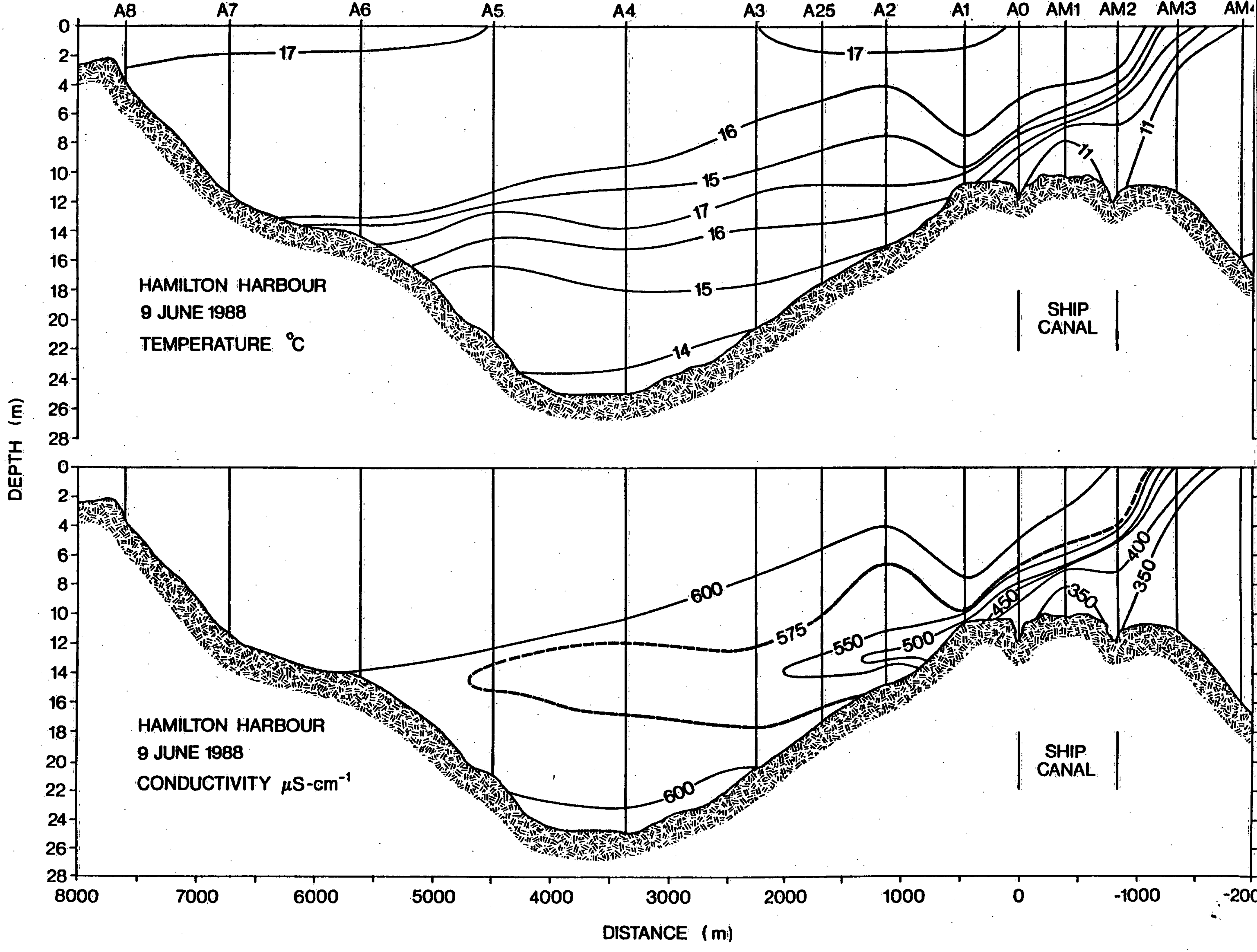


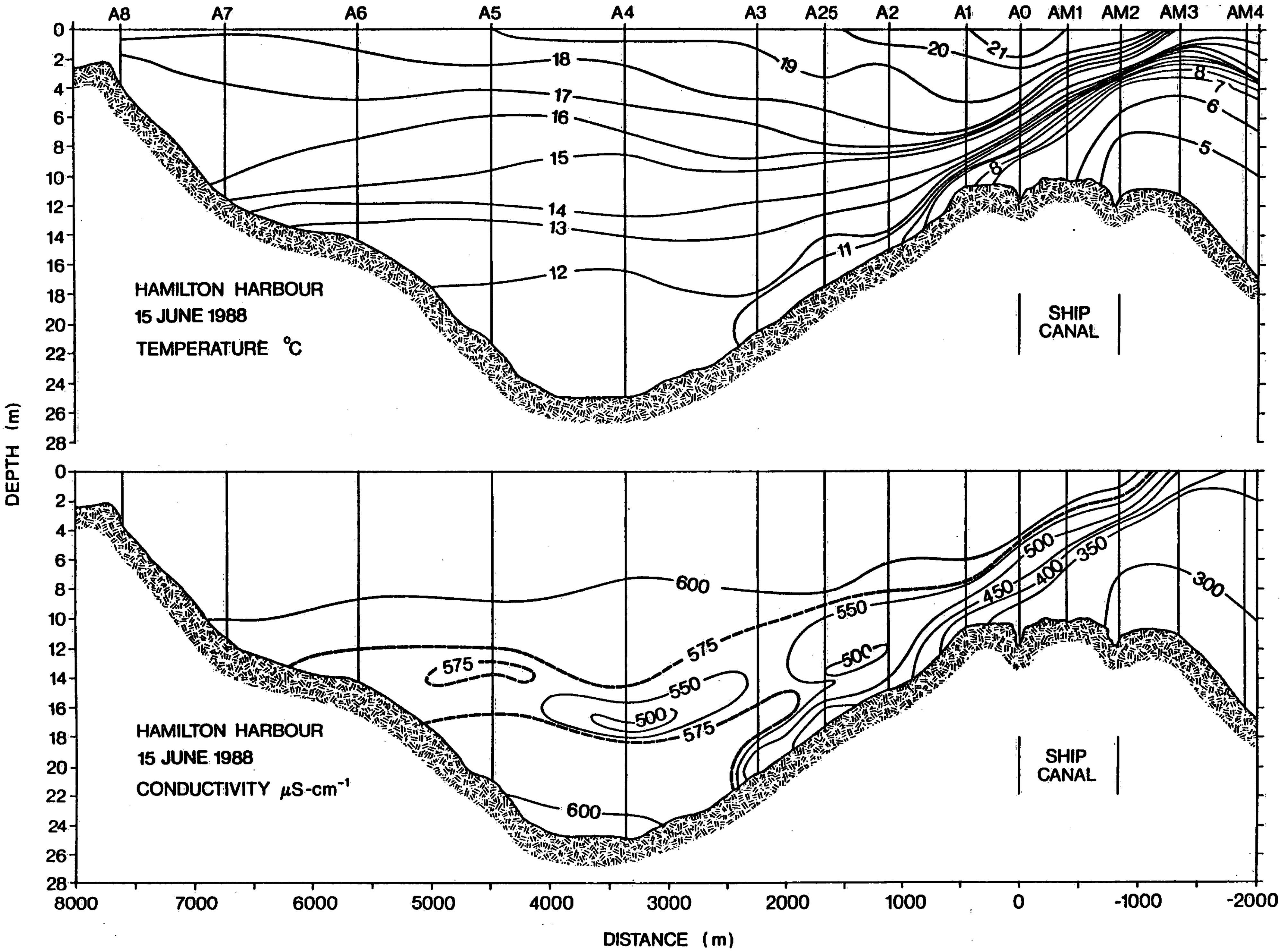
SHIP CANAL
6 OCT. 1988


A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
12°
11°
10°
9°
8°
7°
6°
HAMILTON HARBOUR
11 MAY 1988
TEMPERATURE °C
SHIP CANAL
650
600
660
550
500
450
400
350
HAMILTON HARBOUR
11 MAY 1988
CONDUCTIVITY μS-cm^{-1}
SHIP CANAL
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-200
DISTANCE (m)

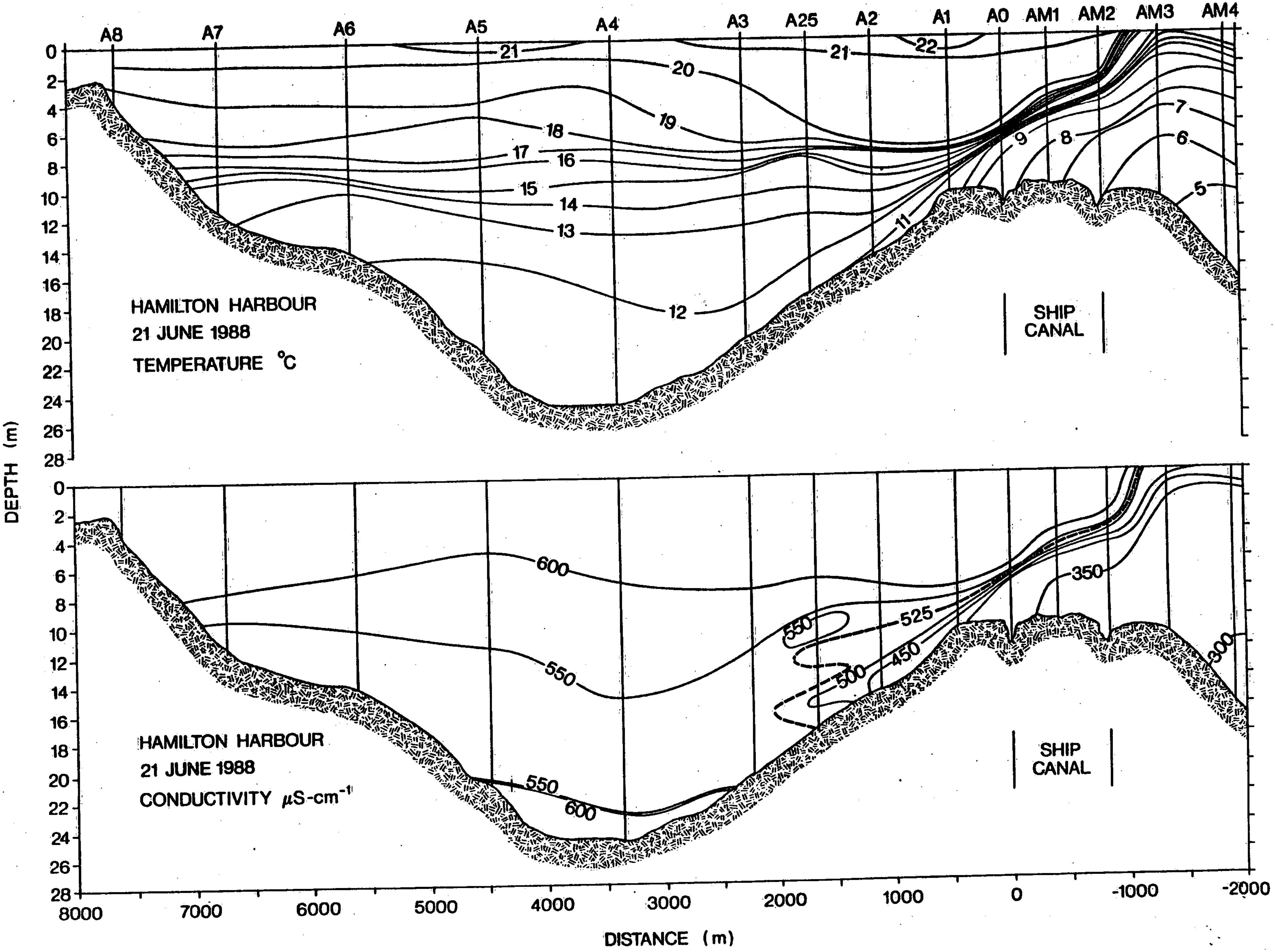

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
15°
14°
13°
12°
11°
10°
10°
9°
8°
HAMILTON HARBOUR
27 MAY 1988
TEMPERATURE °C
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
600
550
500
450
400
350
700
650
625
600
550
700
750
800
HAMILTON HARBOUR
27 MAY 1988
CONDUCTIVITY µS-cm⁻¹
SHIP CANAL
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000

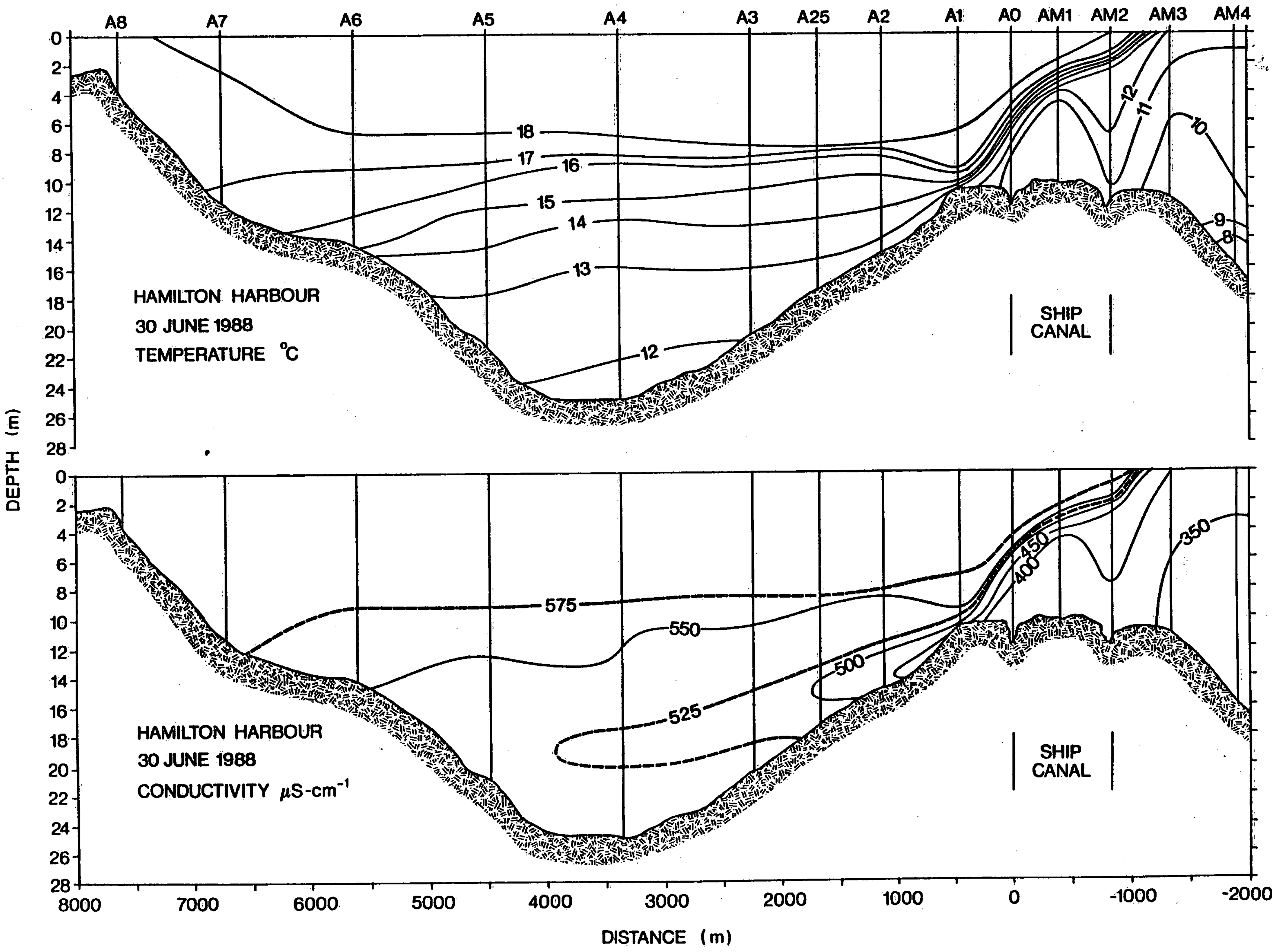

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
17°
16°
15°
14°
13°
12°
11°
10°
9°
8°
7°
6°
HAMILTON HARBOUR
1 JUNE 1988
TEMPERATURE °C
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
500
550
600
450
400
350
625
325
550
575
600
HAMILTON HARBOUR
1 JUNE 1988
CONDUCTIVITY μS-cm-1
SHIP CANAL
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
DISTANCE (m)

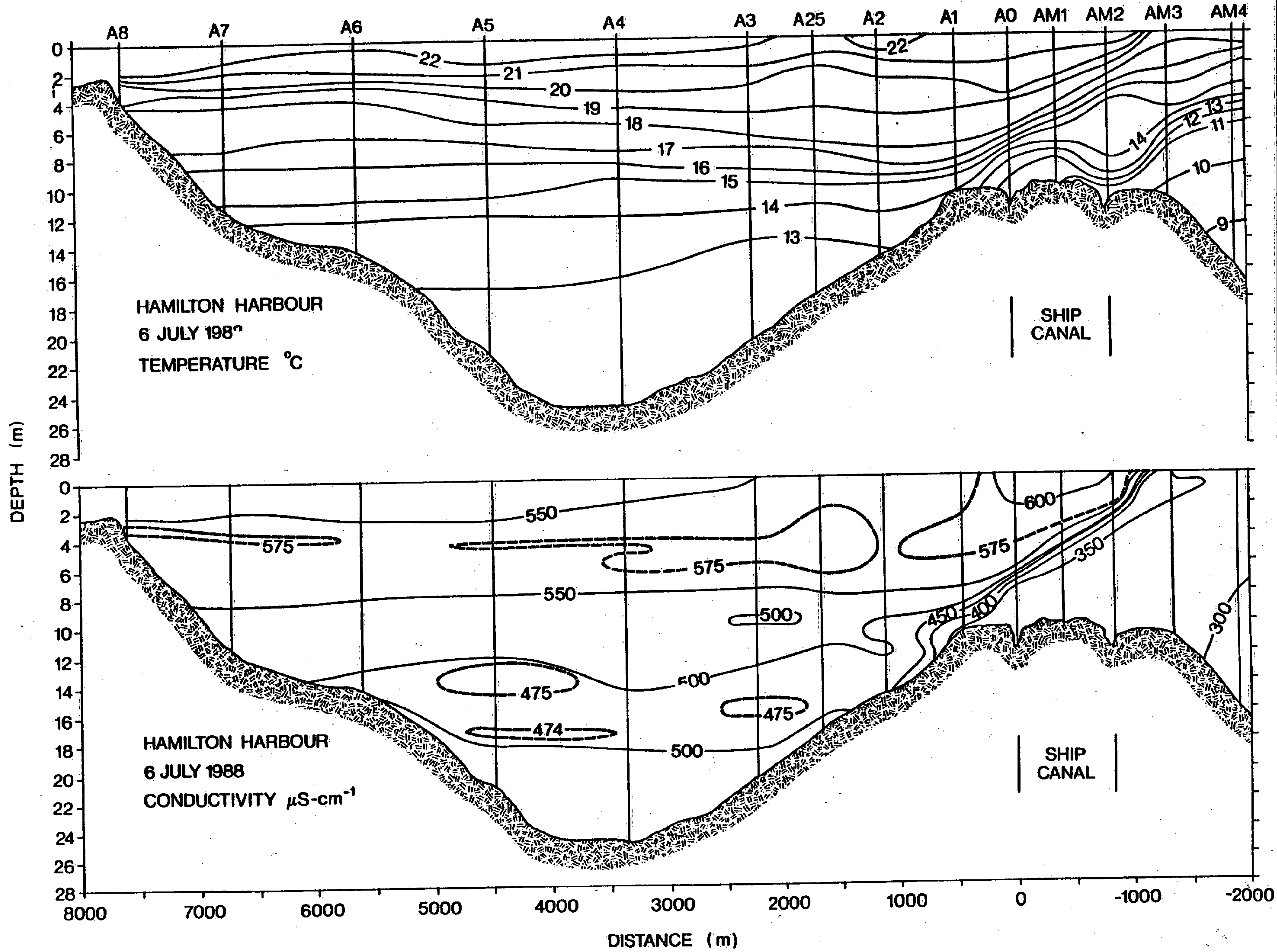

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
HAMILTON HARBOUR
9 JUNE 1988
TEMPERATURE °C
17
16
15
14
11
SHIP CANAL
HAMILTON HARBOUR
9 JUNE 1988
CONDUCTIVITY µS-cm⁻¹
600
575
550
500
450
400
350
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000

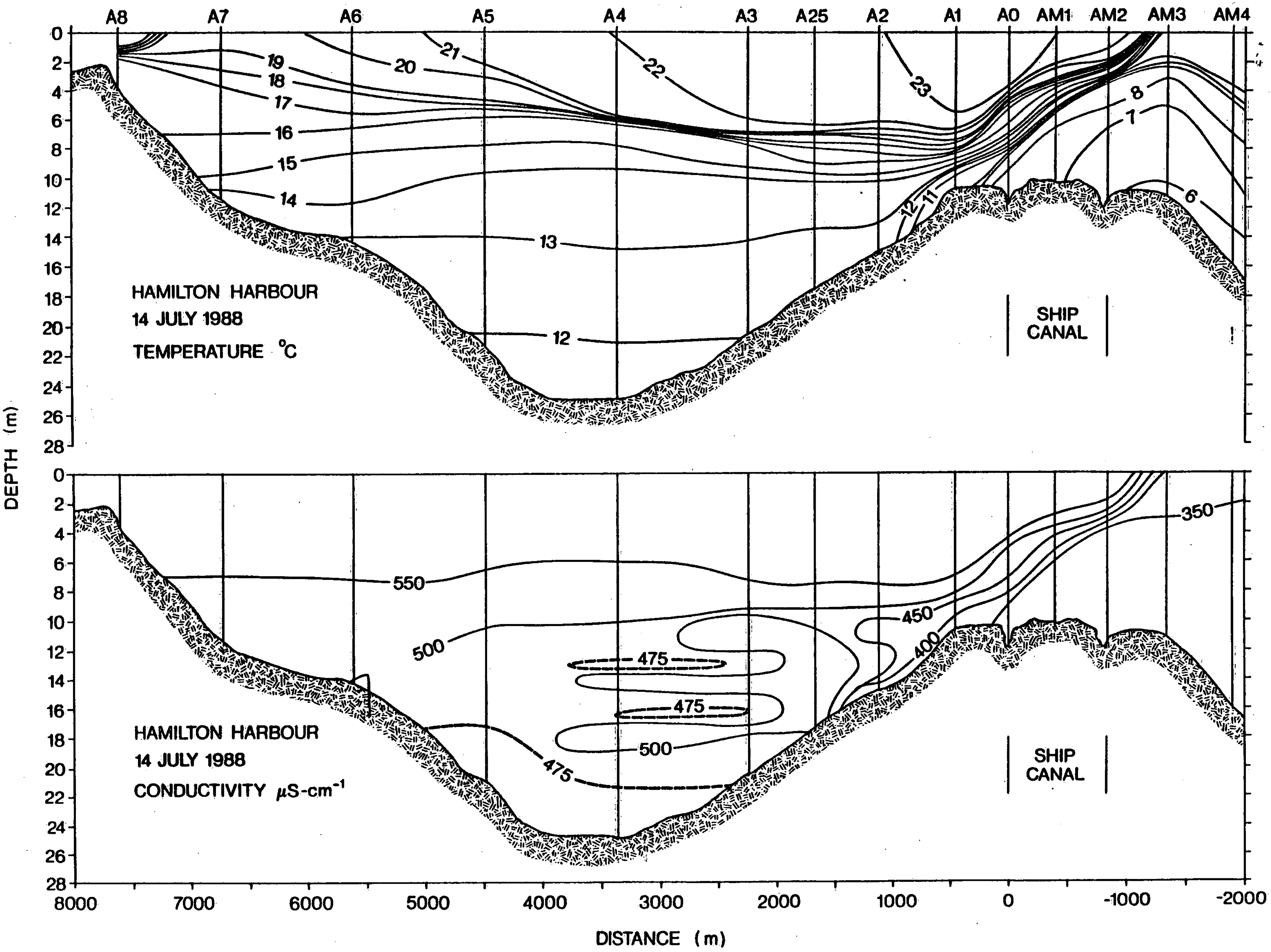


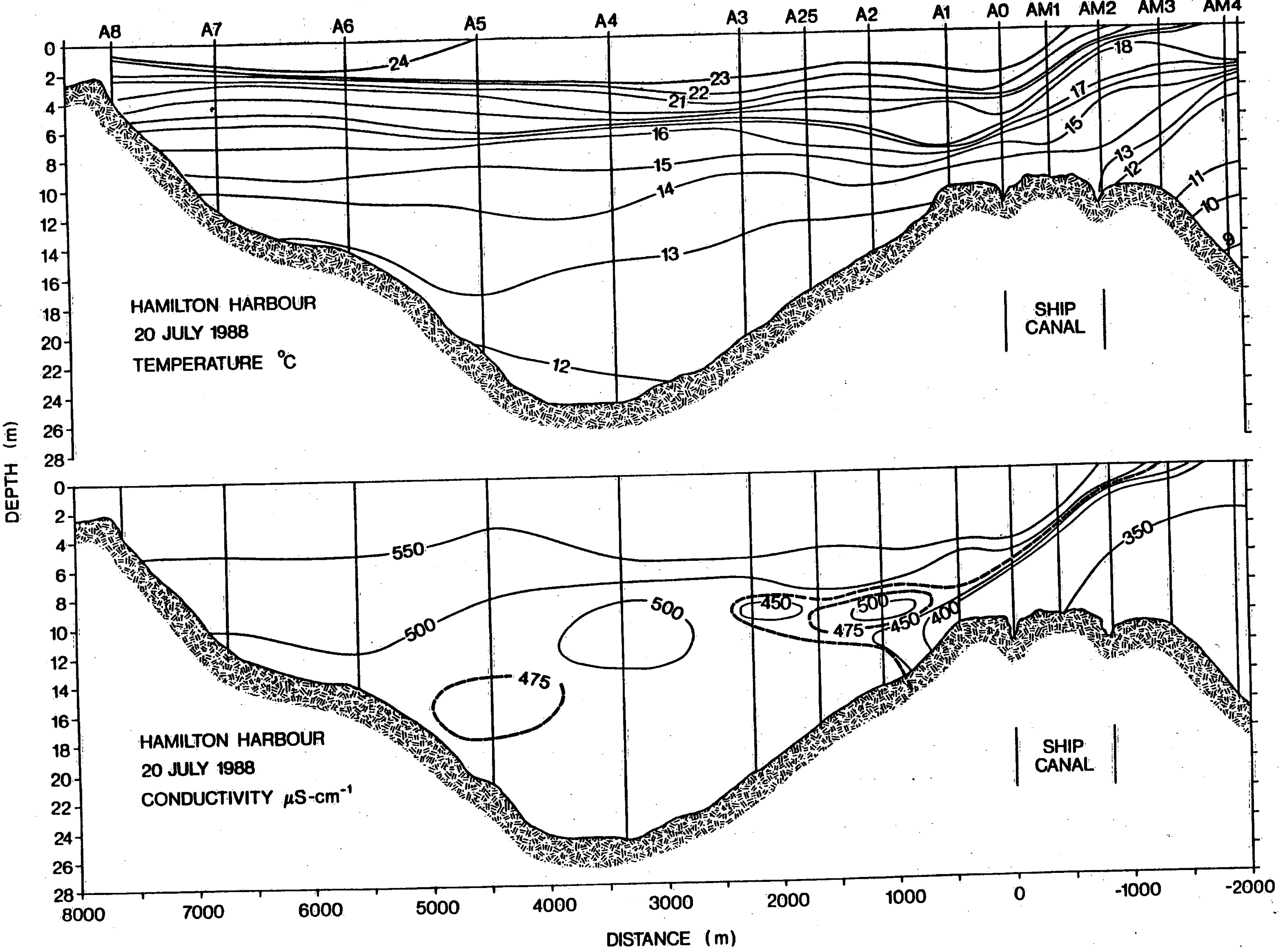
A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
HAMILTON HARBOUR
15 JUNE 1988
TEMPERATURE °C
18
19
20
21
17
16
15
14
13
12
11
8
7
6
5
SHIP CANAL
HAMILTON HARBOUR
15 JUNE 1988
CONDUCTIVITY µS-cm-1
600
575
550
500
450
400
350
300
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000

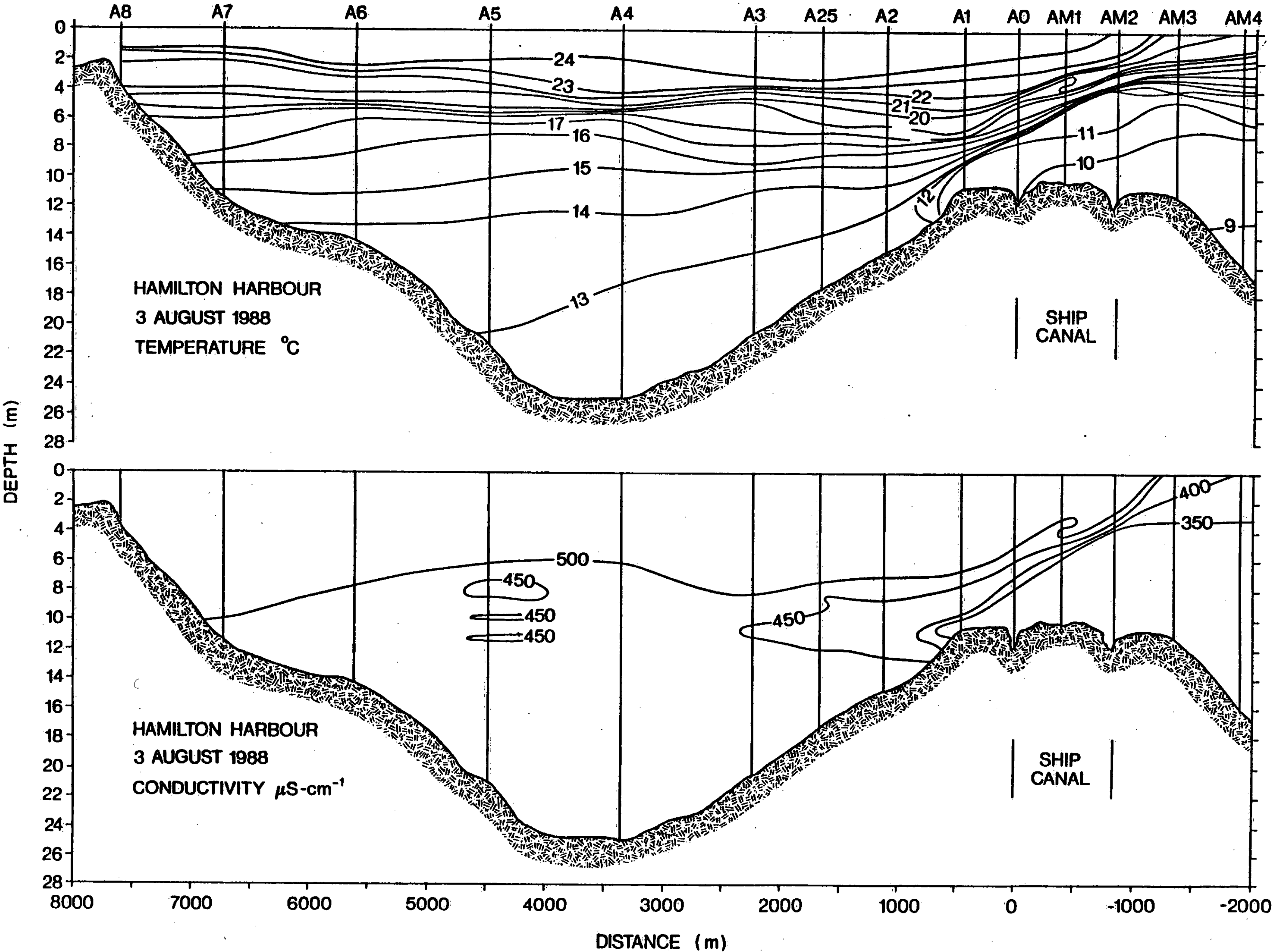

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
21
21
22
20
19
18
17
16
15
14
13
12
11
9
8
7
6
5
SHIP CANAL
HAMILTON HARBOUR
21 JUNE 1988
TEMPERATURE °C
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
600
550
525
500
450
350
300
550
600
SHIP CANAL
HAMILTON HARBOUR
21 JUNE 1988
CONDUCTIVITY µS-cm⁻¹
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
DISTANCE (m)

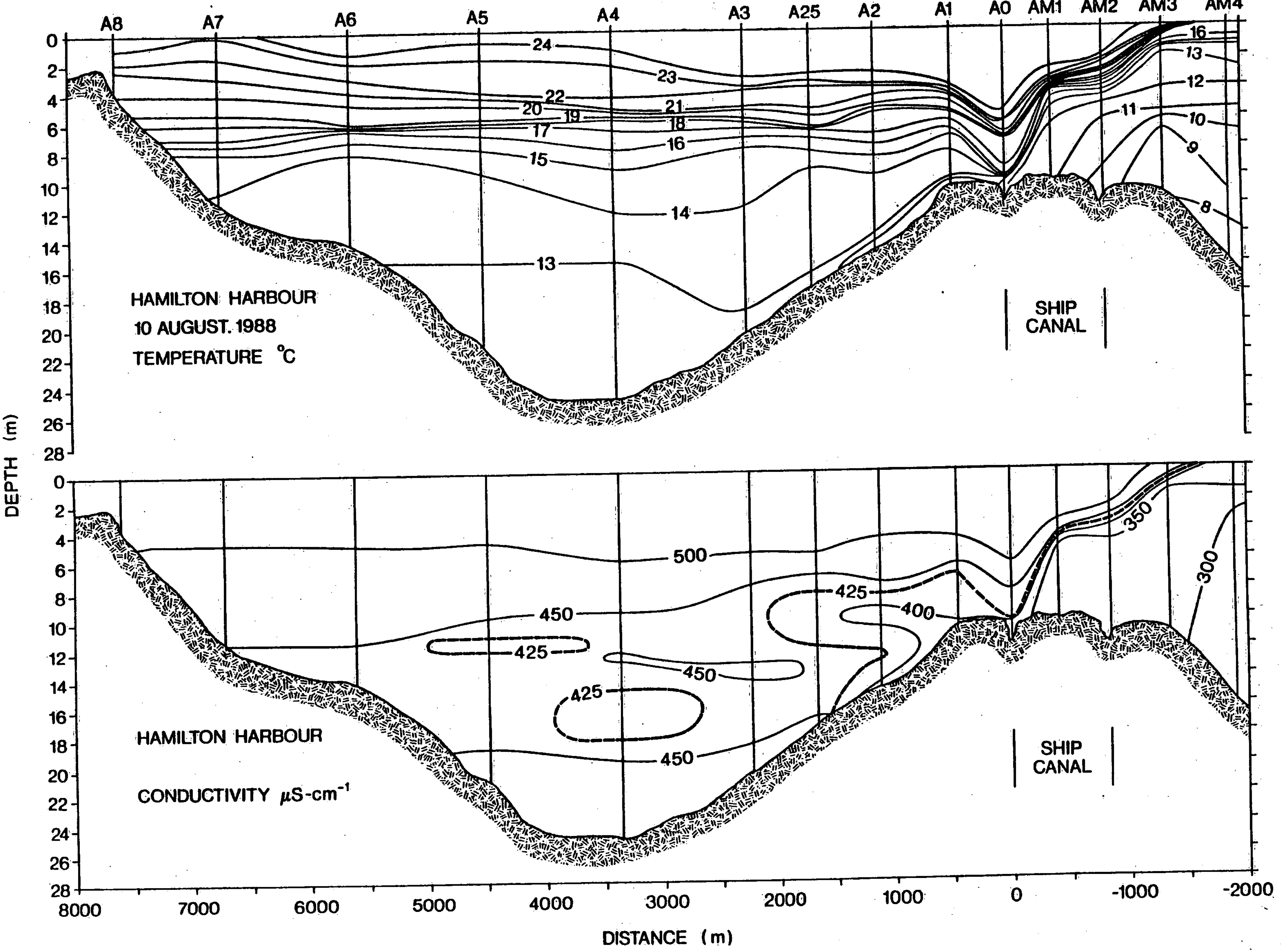

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
HAMILTON HARBOUR
30 JUNE 1988
TEMPERATURE °C
18
17
16
15
14
13
12
11
10
9
8
SHIP CANAL
HAMILTON HARBOUR
30 JUNE 1988
CONDUCTIVITY µS-cm⁻¹
575
550
525
500
450
400
350
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000

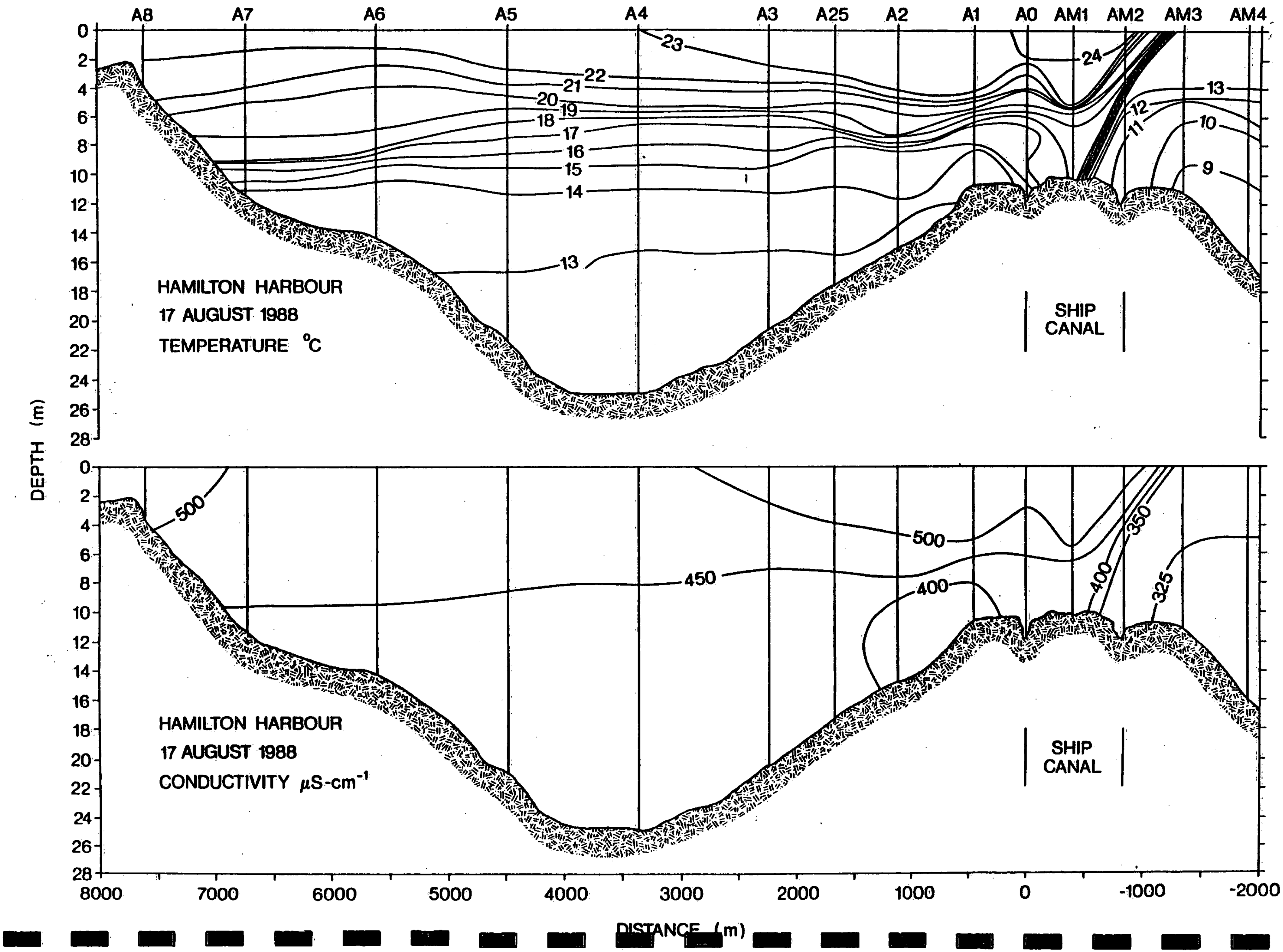

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
22
21
20
19
18
17
16
15
14
13
22
14
13
12
11
10
9
HAMILTON HARBOUR
6 JULY 198°
TEMPERATURE °C
SHIP CANAL
550
575
575
575
600
575
350
550
500
450
400
300
500
475
475
474
500
HAMILTON HARBOUR
6 JULY 1988
CONDUCTIVITY μS-cm⁻¹
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000

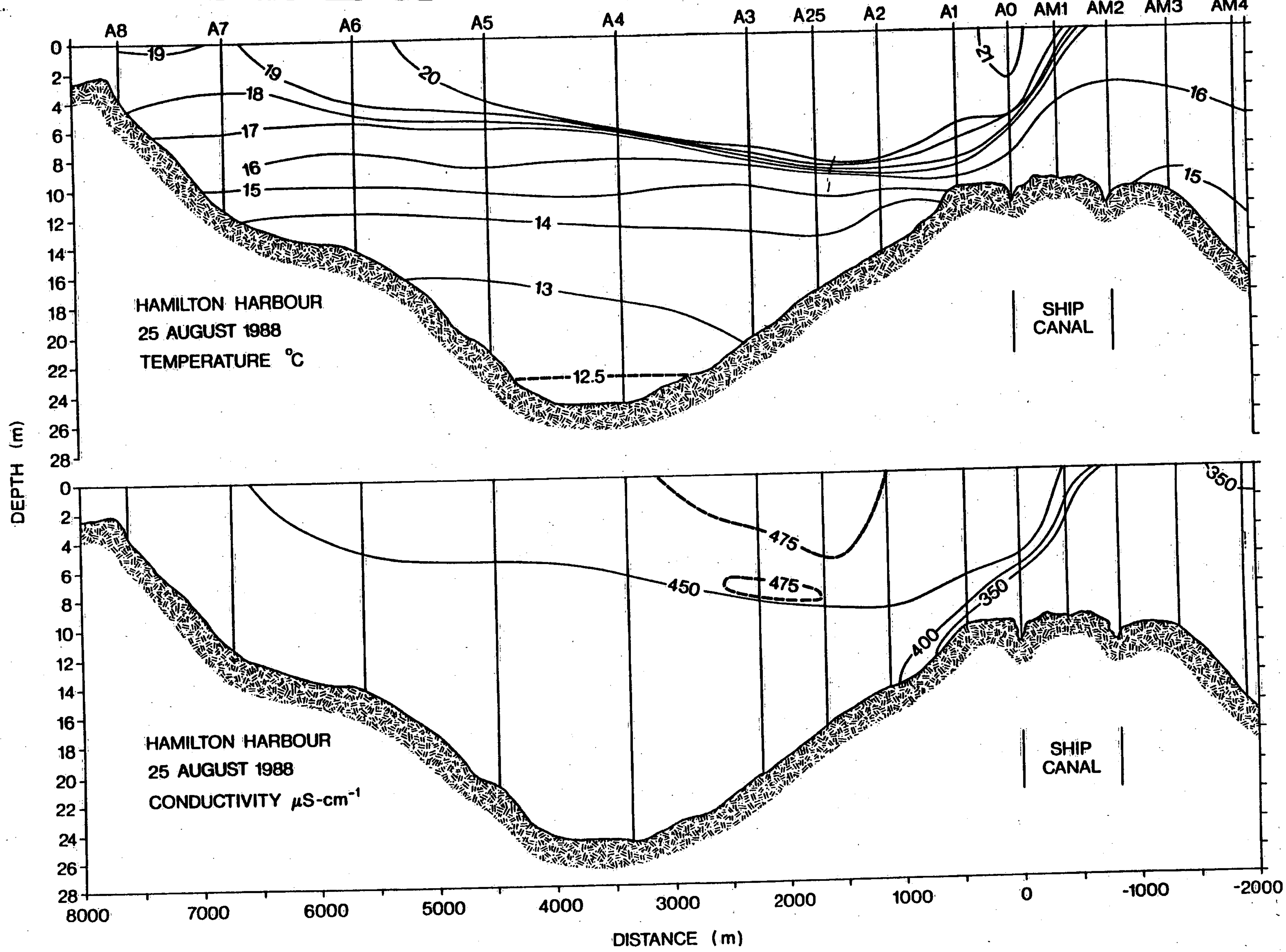

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
HAMILTON HARBOUR
14 JULY 1988
TEMPERATURE °C
19
18
17
16
15
14
13
12
20
21
22
23
12
11
8
7
6
SHIP CANAL
HAMILTON HARBOUR
14 JULY 1988
CONDUCTIVITY µS-cm⁻¹
550
500
475
475
500
475
450
400
350
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000

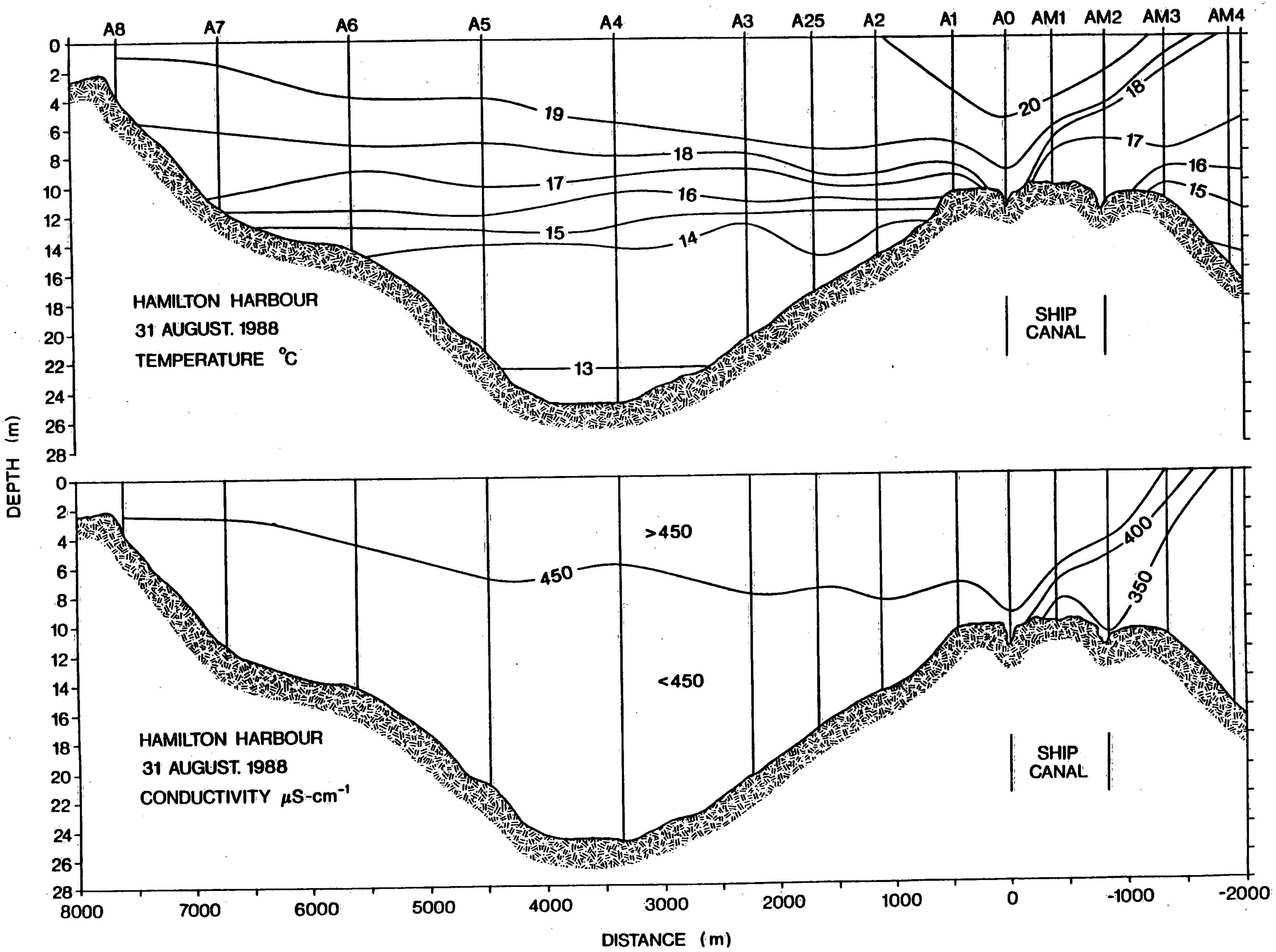

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
24
23
22
21
16
15
14
13
12
18
17
15
13
12
11
10
9
HAMILTON HARBOUR
20 JULY 1988
TEMPERATURE °C
SHIP CANAL
550
500
500
475
450
500
475
450
400
350
HAMILTON HARBOUR
20 JULY 1988
CONDUCTIVITY µS-cm⁻¹
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000

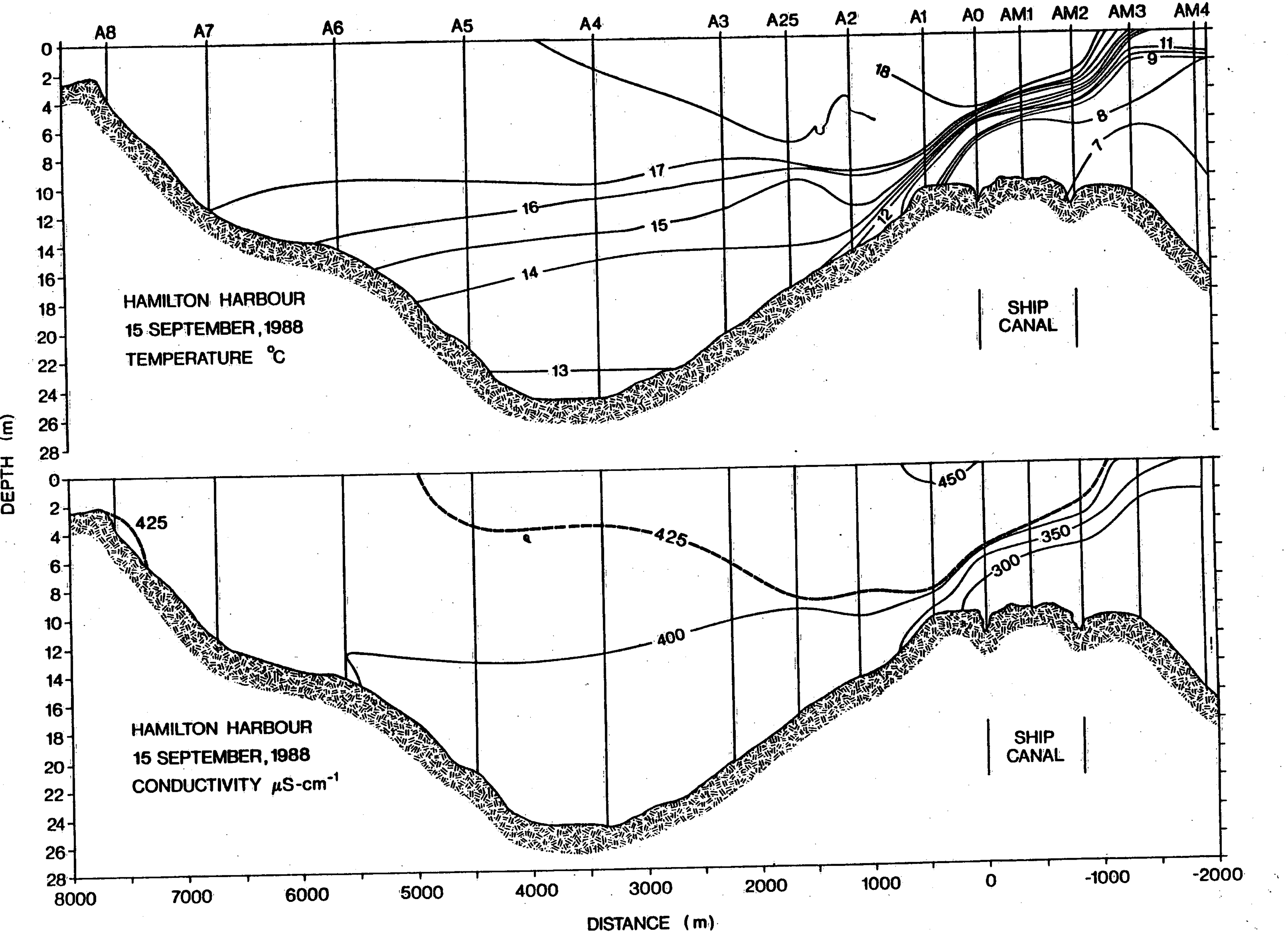

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
24
23
22
21
20
17
16
15
14
13
12
11
10
9
HAMILTON HARBOUR
3 AUGUST 1988
TEMPERATURE °C
SHIP CANAL
500
450
450
450
450
400
350
HAMILTON HARBOUR
3 AUGUST 1988
CONDUCTIVITY µS-cm-1
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000

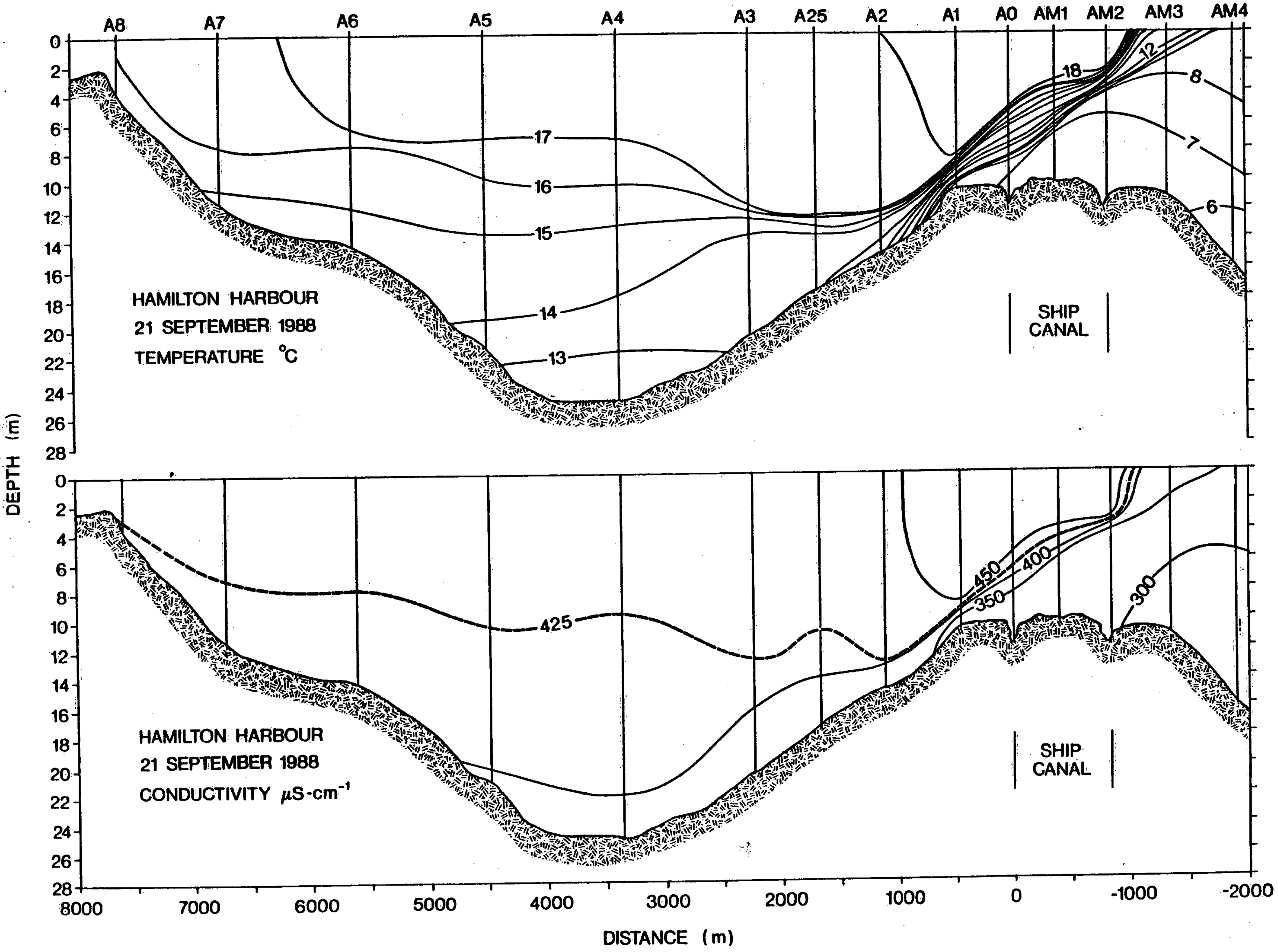

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
HAMILTON HARBOUR
10 AUGUST. 1988
TEMPERATURE °C
SHIP CANAL
500
450
425
400
350
300
HAMILTON HARBOUR
CONDUCTIVITY µS-cm-1
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000


A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
23
24
22
21
20
19
18
17
16
15
14
13
13
12
11
10
9
HAMILTON HARBOUR
17 AUGUST 1988
TEMPERATURE °C
SHIP CANAL
500
500
450
400
400
350
325
HAMILTON HARBOUR
17 AUGUST 1988
CONDUCTIVITY µS-cm-1
SHIP CANAL
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
DISTANCE (m)


A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
19
19
20
21
18
17
16
15
14
13
12.5
16
15
HAMILTON HARBOUR
25 AUGUST 1988
TEMPERATURE °C
SHIP CANAL
475
475
450
400
350
350
HAMILTON HARBOUR
25 AUGUST 1988
CONDUCTIVITY μS-cm⁻¹
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000


A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
19
18
17
16
15
14
13
20
18
17
16
15
HAMILTON HARBOUR
31 AUGUST. 1988
TEMPERATURE °C
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
>450
450
<450
400
350
HAMILTON HARBOUR
31 AUGUST. 1988
CONDUCTIVITY μS-cm^{-1}
SHIP CANAL
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
DISTANCE (m)


A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
18
17
16
15
14
13
12
11
9
8
7
HAMILTON HARBOUR
15 SEPTEMBER, 1988
TEMPERATURE °C
SHIP CANAL
425
450
425
400
350
300
HAMILTON HARBOUR
15 SEPTEMBER, 1988
CONDUCTIVITY µS-cm⁻¹
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000


A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
HAMILTON HARBOUR
21 SEPTEMBER 1988
TEMPERATURE °C
17
16
15
14
13
18
12
8
7
6
SHIP CANAL
HAMILTON HARBOUR
21 SEPTEMBER 1988
CONDUCTIVITY µS-cm⁻¹
425
450
400
350
300
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000

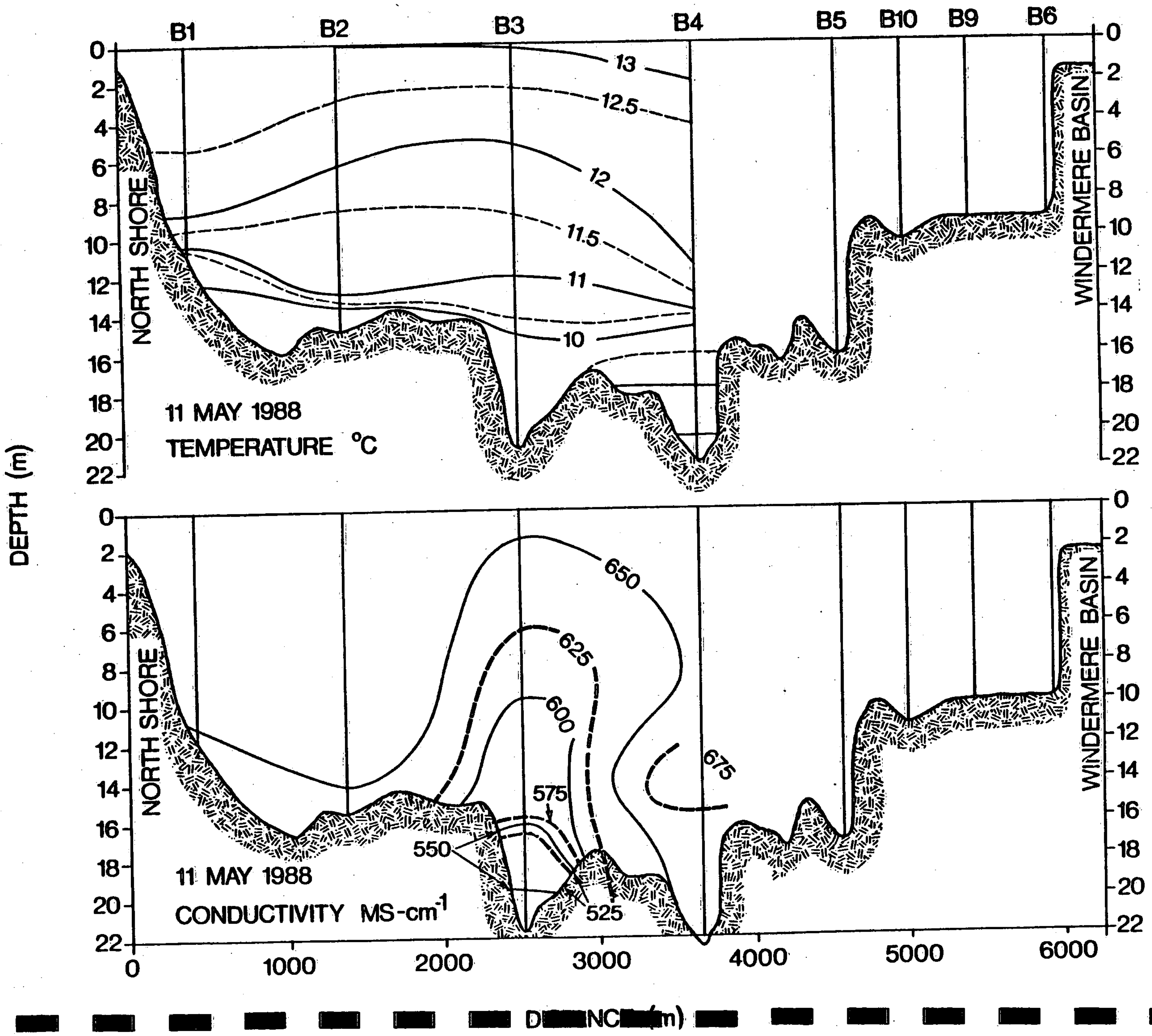
APPENDIX III

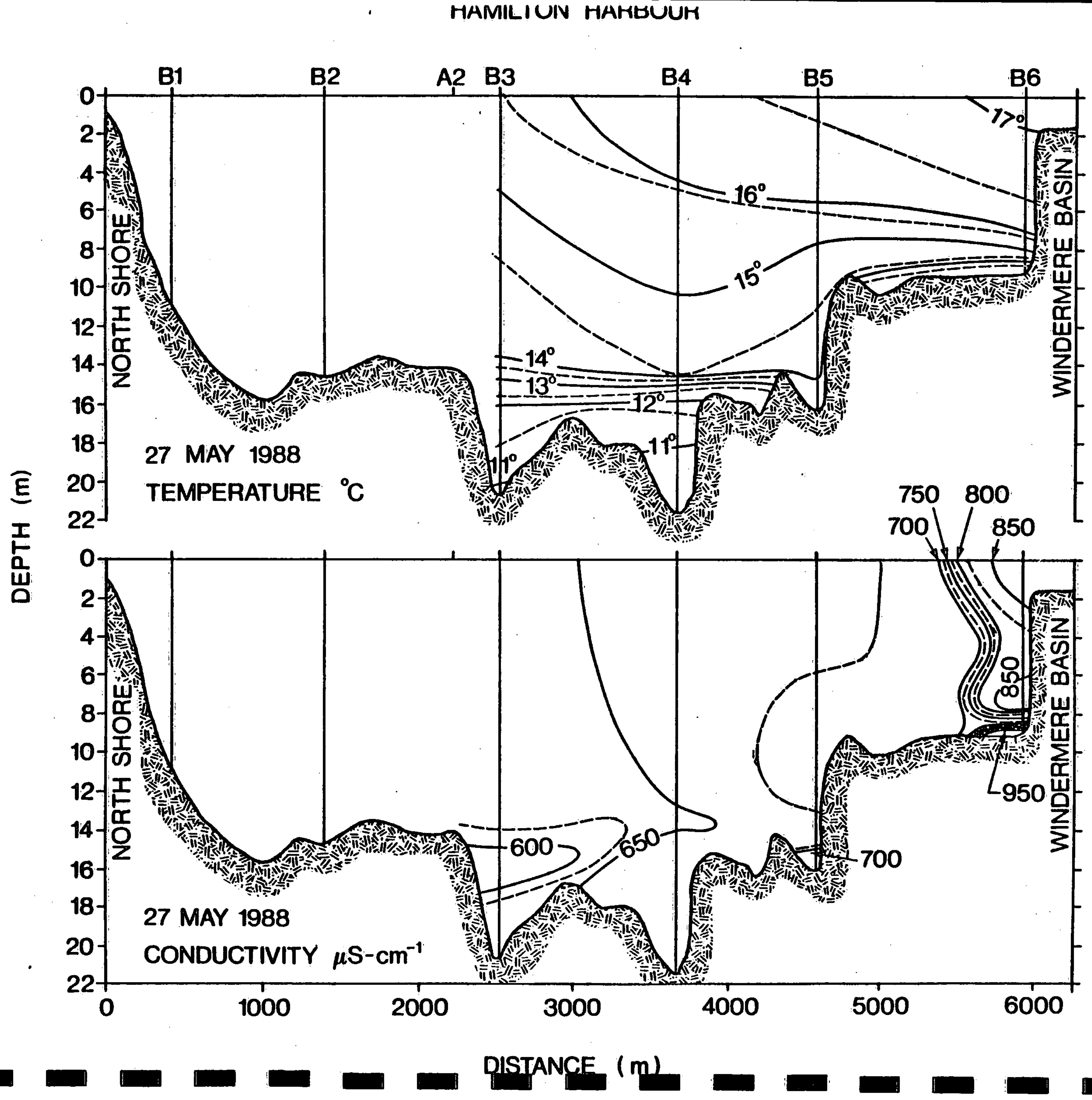
TEMPERATURE AND CONDUCTIVITY TRANSECTS

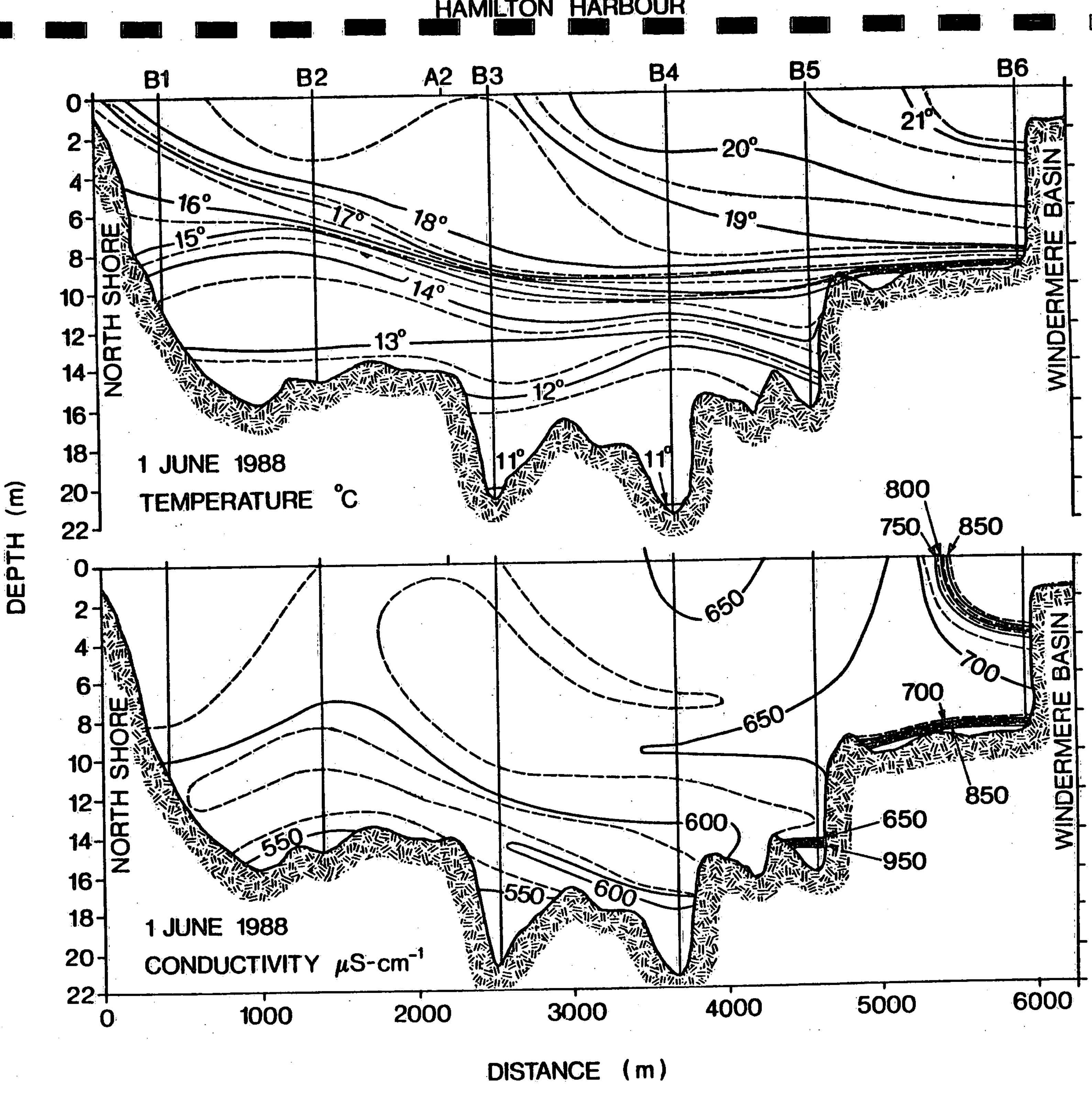
LINE B2 to B6

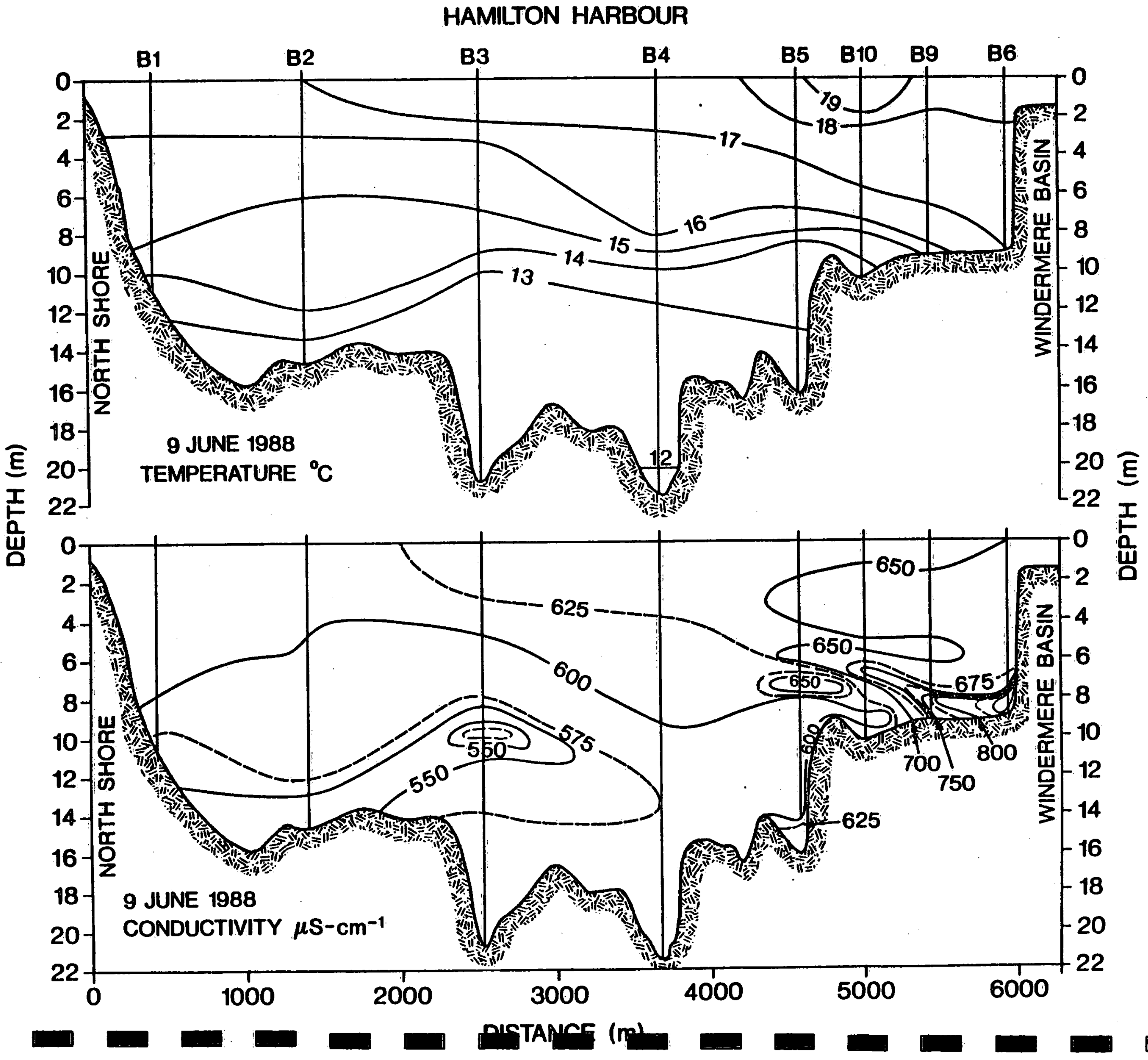
May 11 to September 21, 1988

HAMILTON HARBOUR

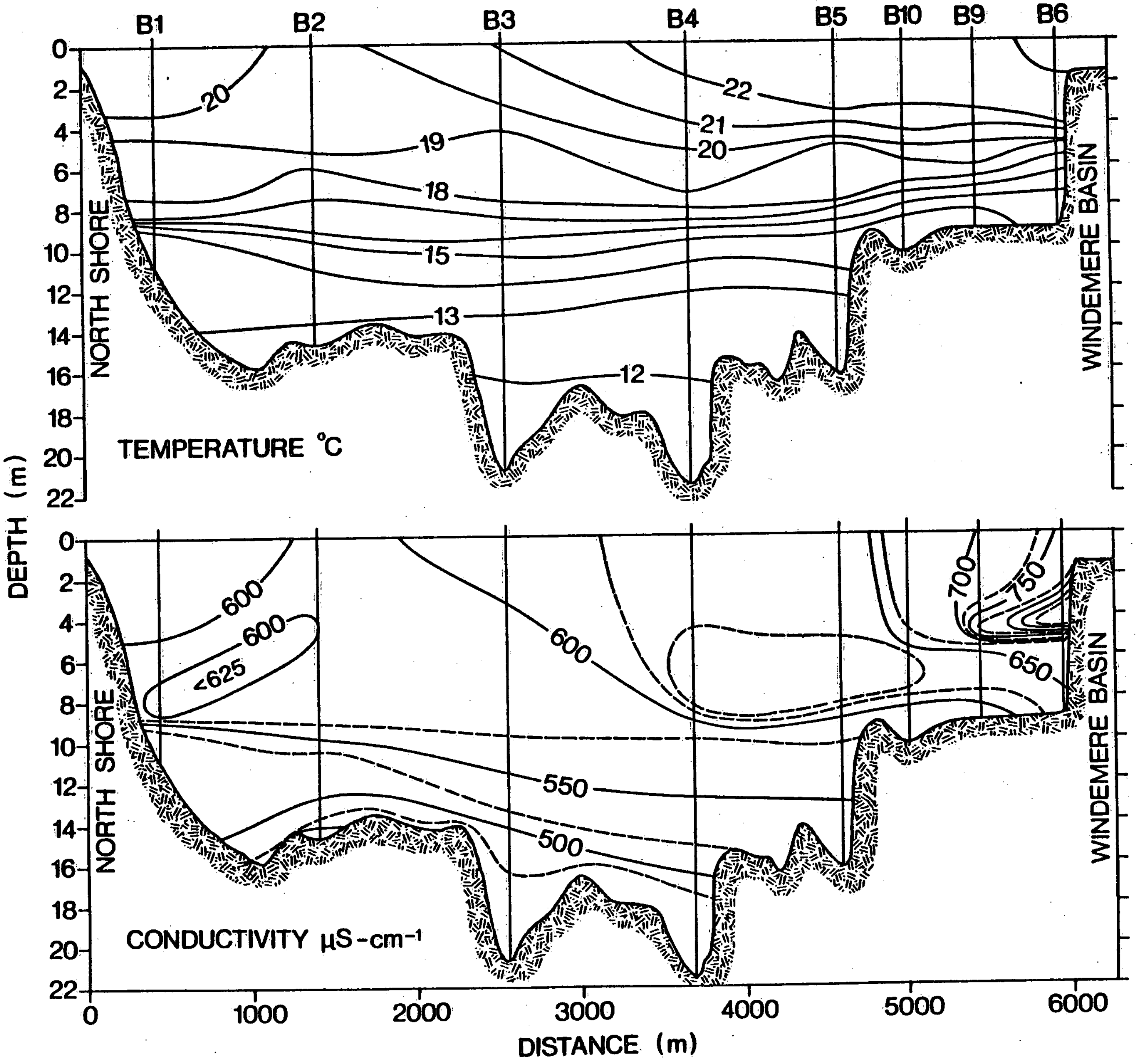


HAMILTON HARBOUR
B1
B2
A2
B3
B4
B5
B6
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
NORTH SHORE
WINDERMERE BASIN
27 MAY 1988
TEMPERATURE °C
17°
16°
15°
14°
13°
12°
11°
11°
27 MAY 1988
CONDUCTIVITY µS-cm⁻¹
600
650
700
700
750
800
850
850
950
0
1000
2000
3000
4000
5000
6000
DISTANCE (m)

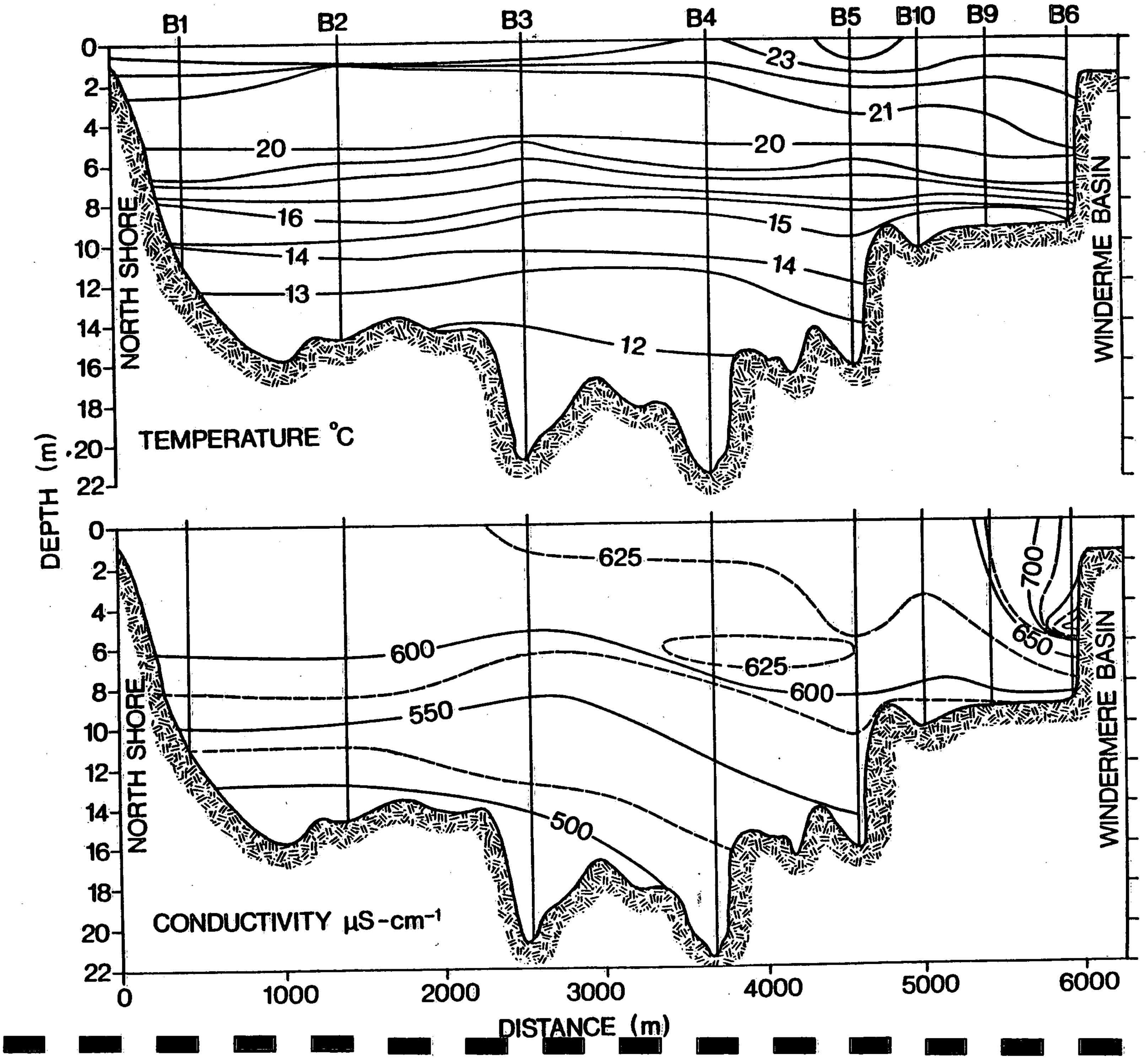

HAMILTON HARBOUR
B1
B2
A2
B3
B4
B5
B6
NORTH SHORE
WINDERMERE BASIN
16°
17°
18°
15°
14°
13°
12°
11°
11°
20°
19°
21°
1 JUNE 1988
TEMPERATURE °C
650
650
700
700
800
750
850
850
650
950
600
550
550
600
1 JUNE 1988
CONDUCTIVITY µS-cm⁻¹
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
DISTANCE (m)
0
1000
2000
3000
4000
5000
6000


HAMILTON HARBOUR
B1
B2
B3
B4
B5
B10
B9
B6
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
NORTH SHORE
WINDERMERE BASIN
9 JUNE 1988
TEMPERATURE °C
19
18
17
16
15
14
13
12
9 JUNE 1988
CONDUCTIVITY μS-cm⁻¹
650
625
600
575
550
550
650
650
675
600
625
700
750
800
0
1000
2000
3000
4000
5000
6000
DISTANCE (m)

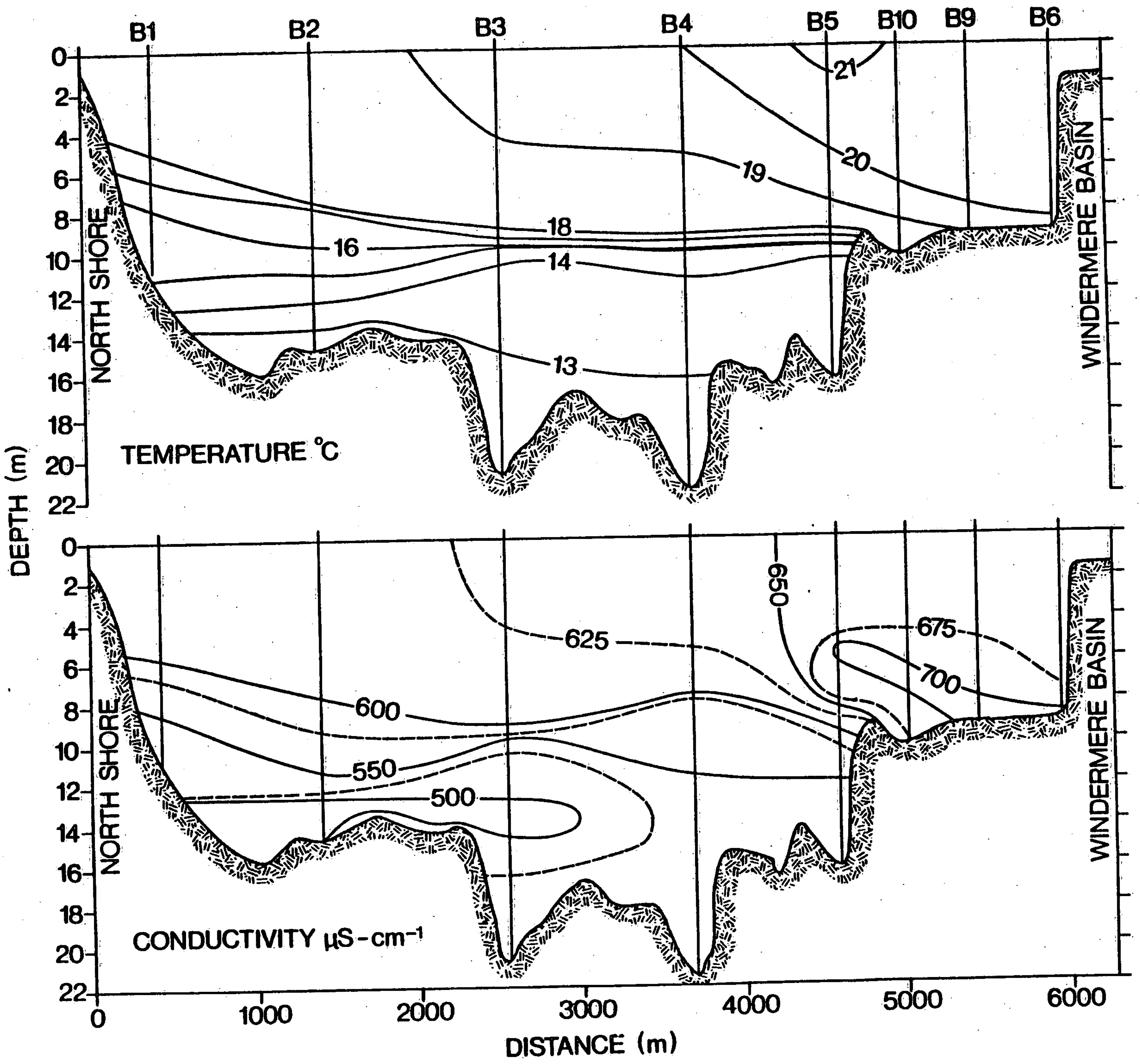
HAMILTON HARBOUR 15 JUNE 1988

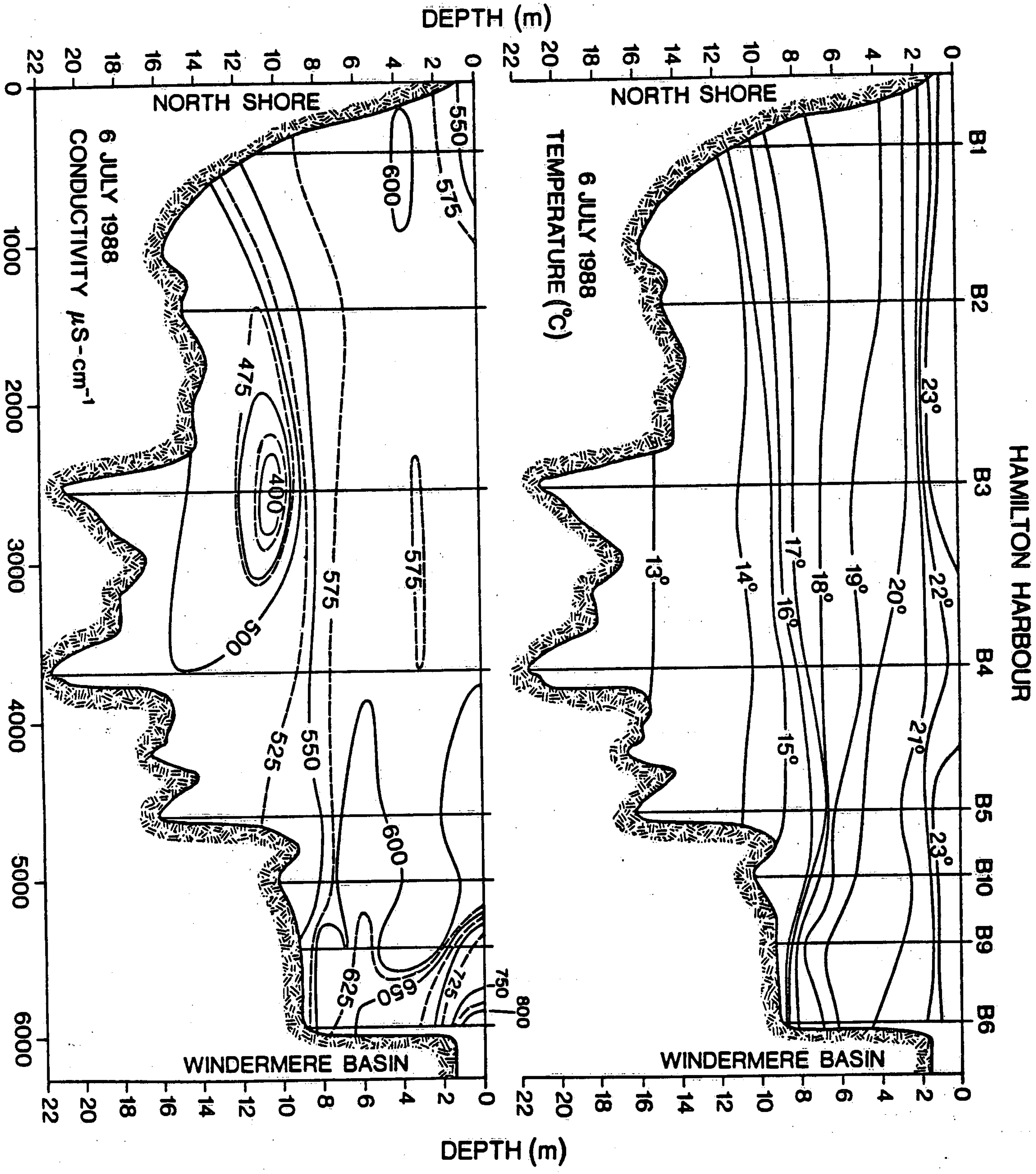


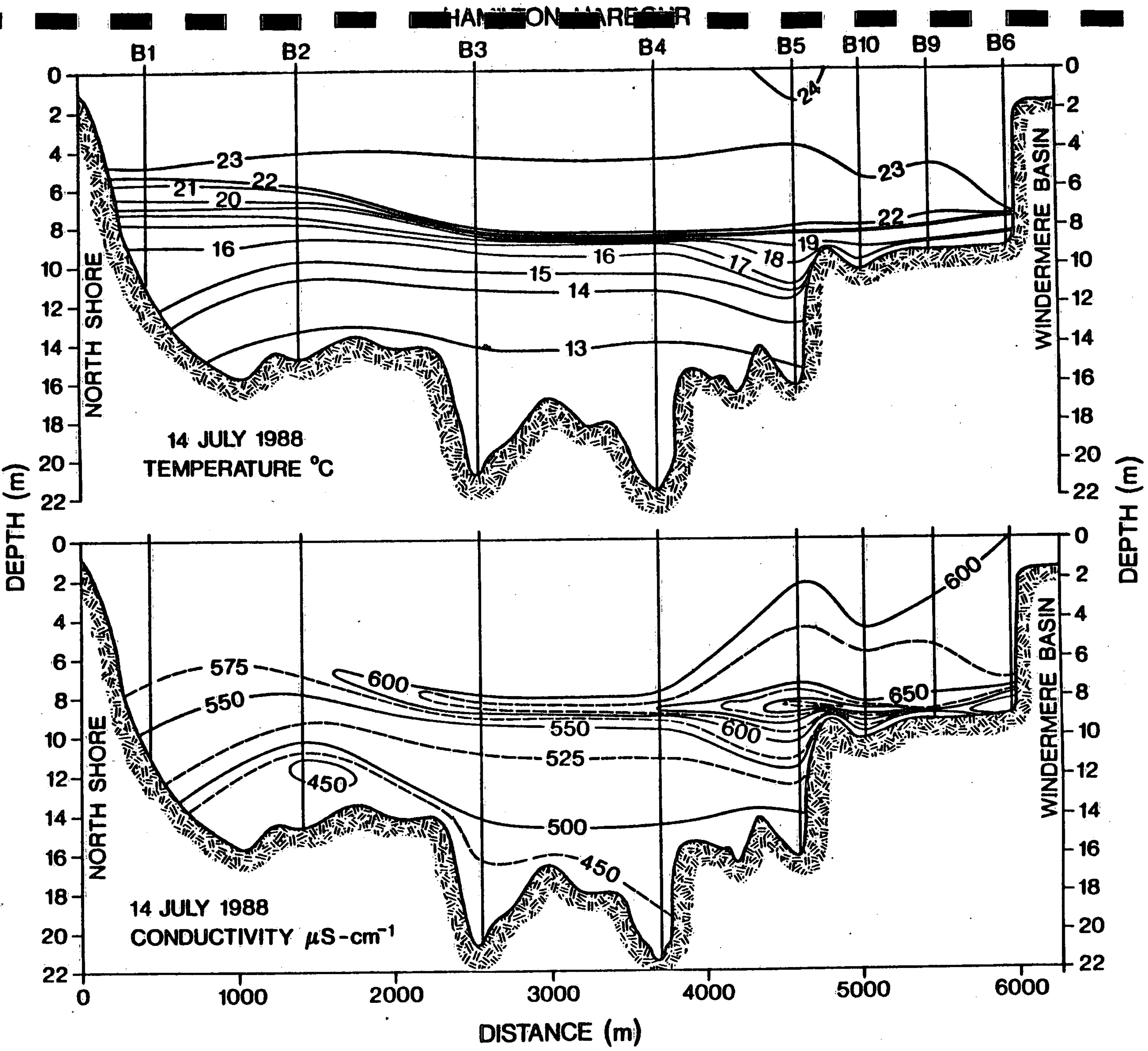
HAMILTON HARBOUR 21 JUNE 1988



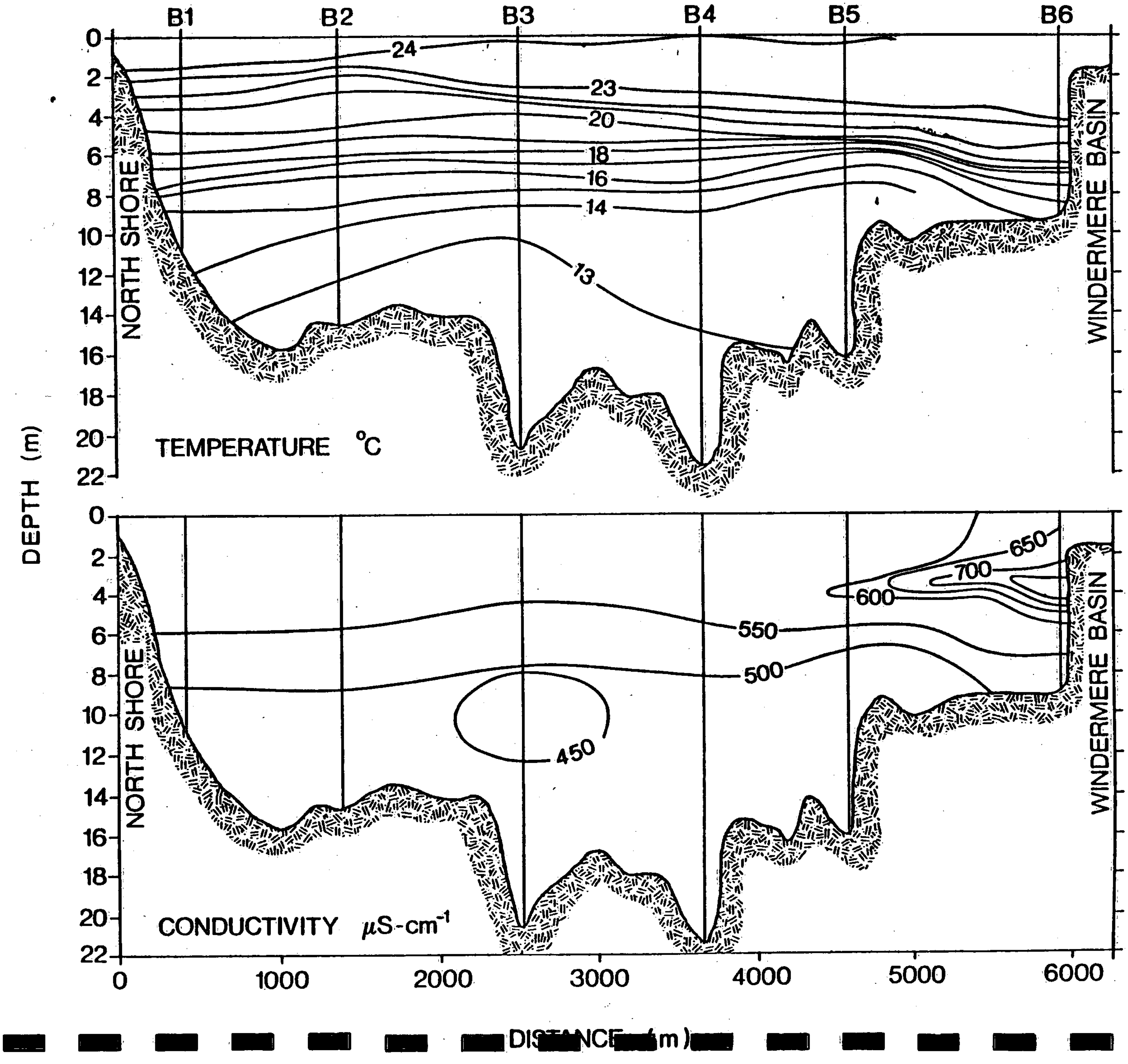
HAMILTON HARBOUR 30 JUNE 1988



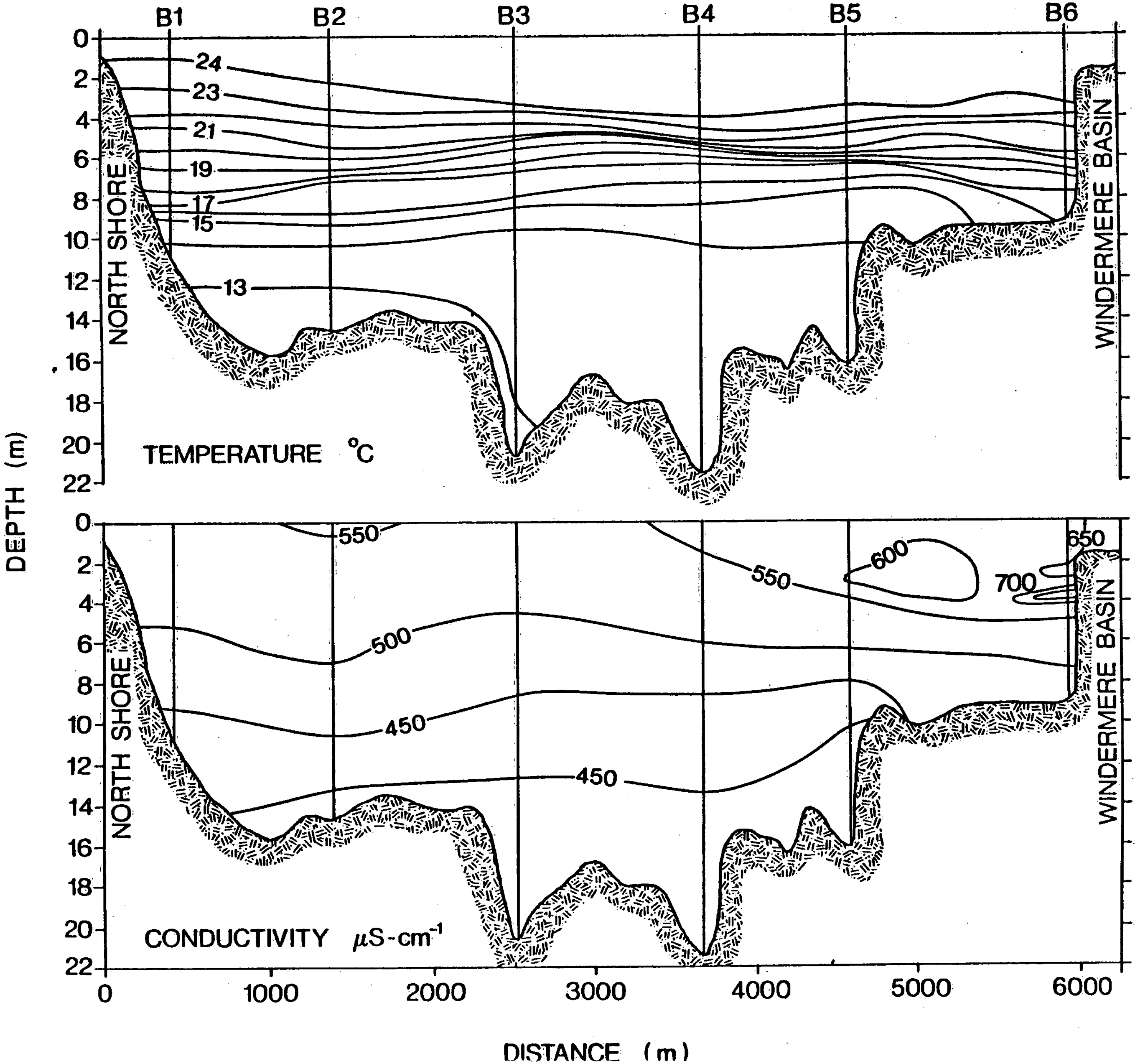

HAMILTON HARBOUR
B1
B2
B3
B4
B5
B10
B9
B6
NORTH SHORE
WINDERMERE BASIN
6 JULY 1988
TEMPERATURE (°C)
23°
22°
21°
20°
19°
18°
17°
16°
15°
14°
13°
NORTH SHORE
WINDERMERE BASIN
6 JULY 1988
CONDUCTIVITY µS-cm⁻¹
550
575
600
475
400
500
525
625
650
725
750
800
DEPTH (m)
DEPTH (m)
DISTANCE (m)
0
1000
2000
3000
4000
5000
6000
0
2
4
6
8
10
12
14
16
18
20
22


HAMILTON HARBOUR
B1
B2
B3
B4
B5
B10
B9
B6
NORTH SHORE
WINDERMERE BASIN
14 JULY 1988
TEMPERATURE °C
24
23
22
21
20
16
16
15
14
17
18
19
13
23
22
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
NORTH SHORE
WINDERMERE BASIN
14 JULY 1988
CONDUCTIVITY µS-cm⁻¹
575
550
600
450
550
525
500
450
600
650
600
0
1000
2000
3000
4000
5000
6000
DISTANCE (m)

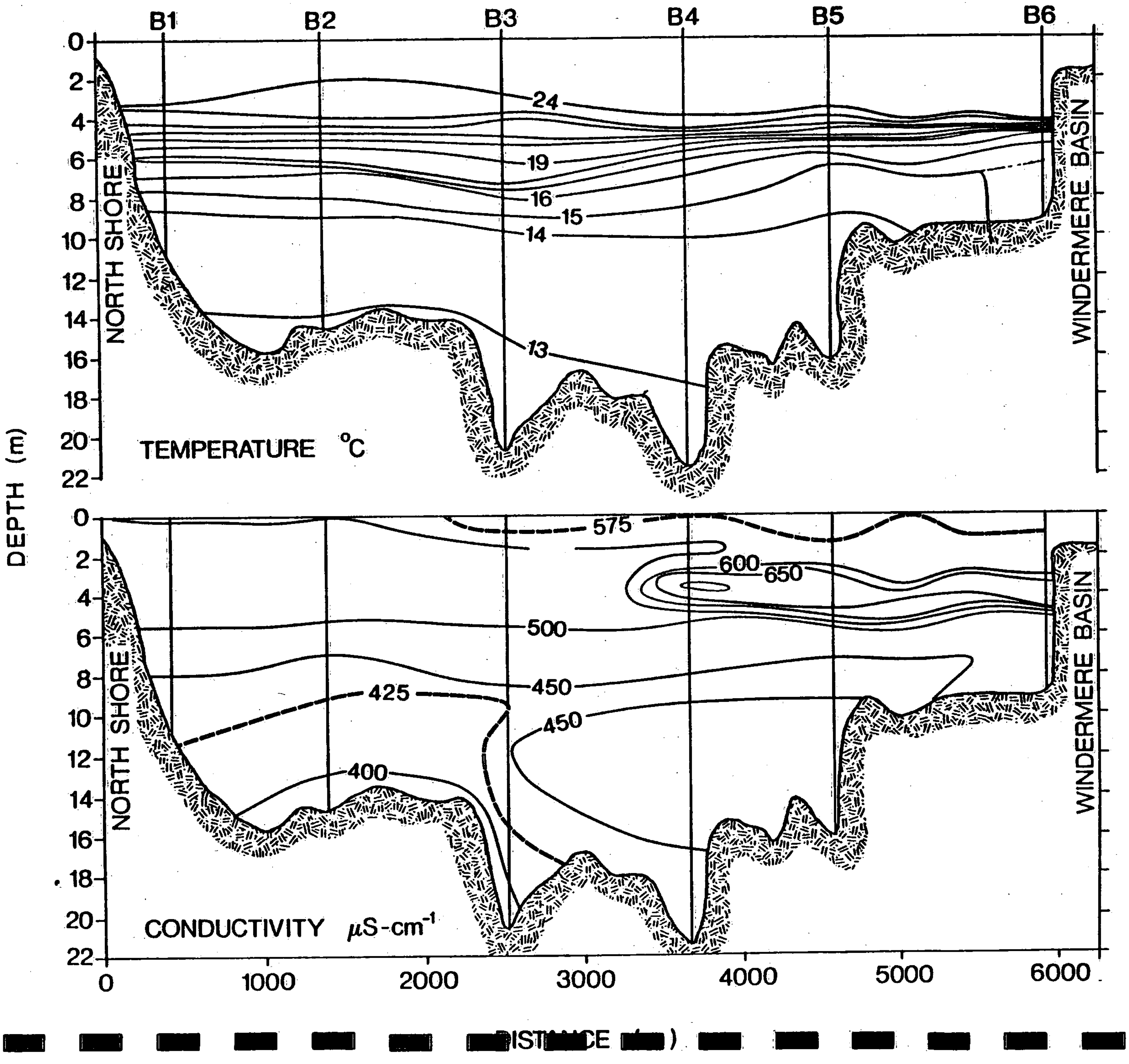
HAMILTON HARBOUR
20 JULY 1988

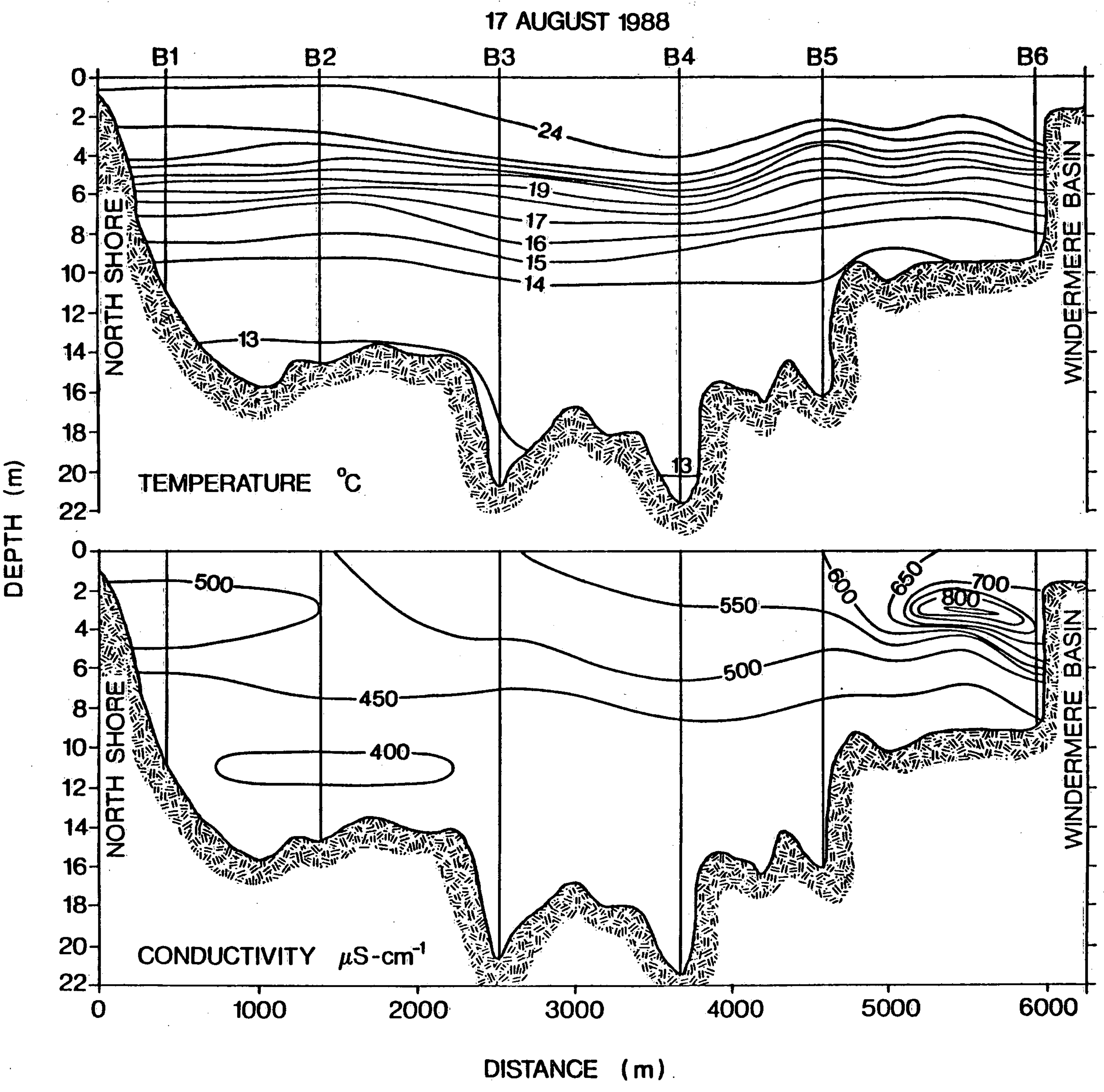


HAMILTON HARBOUR
3 AUGUST 1988

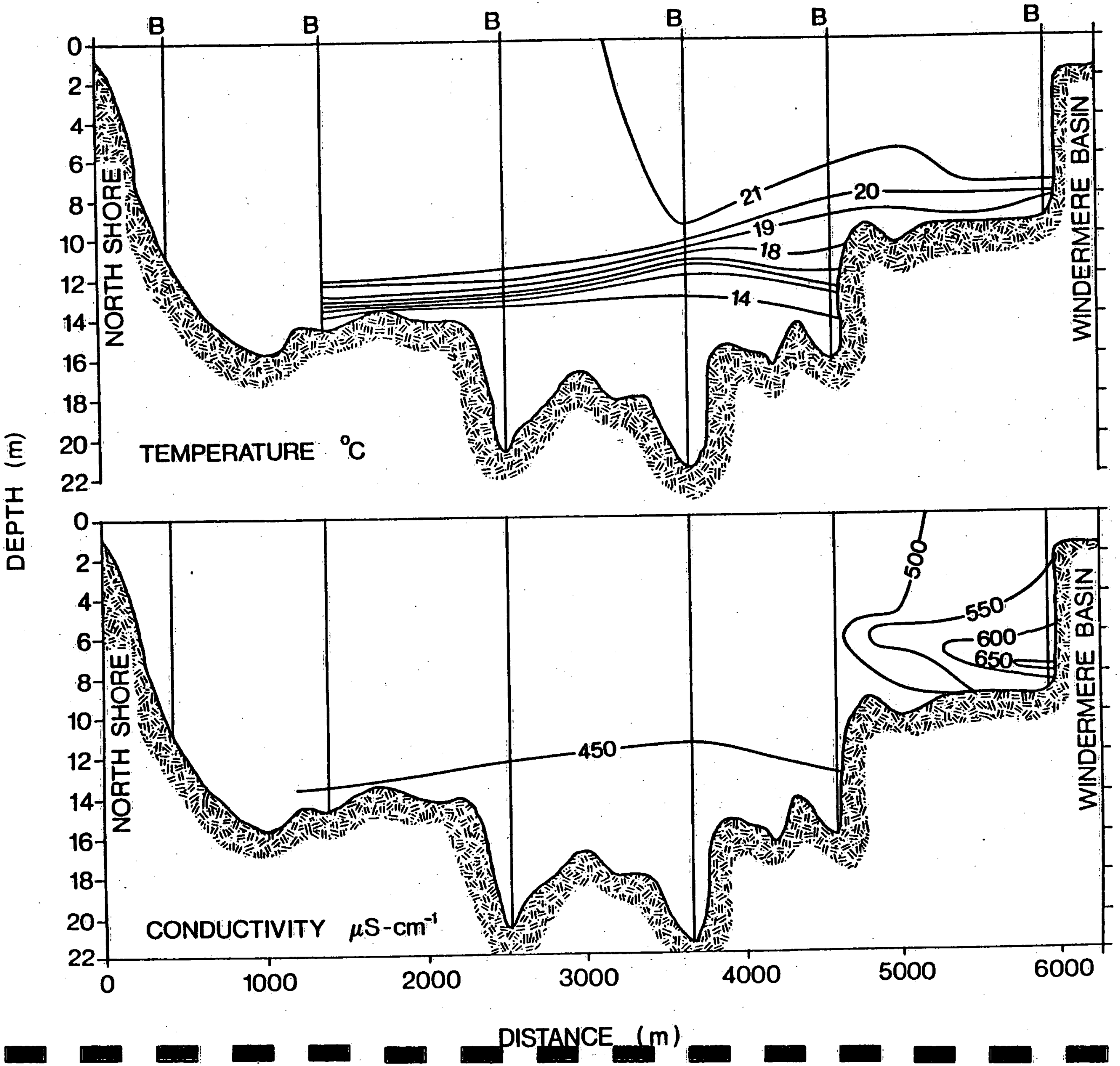


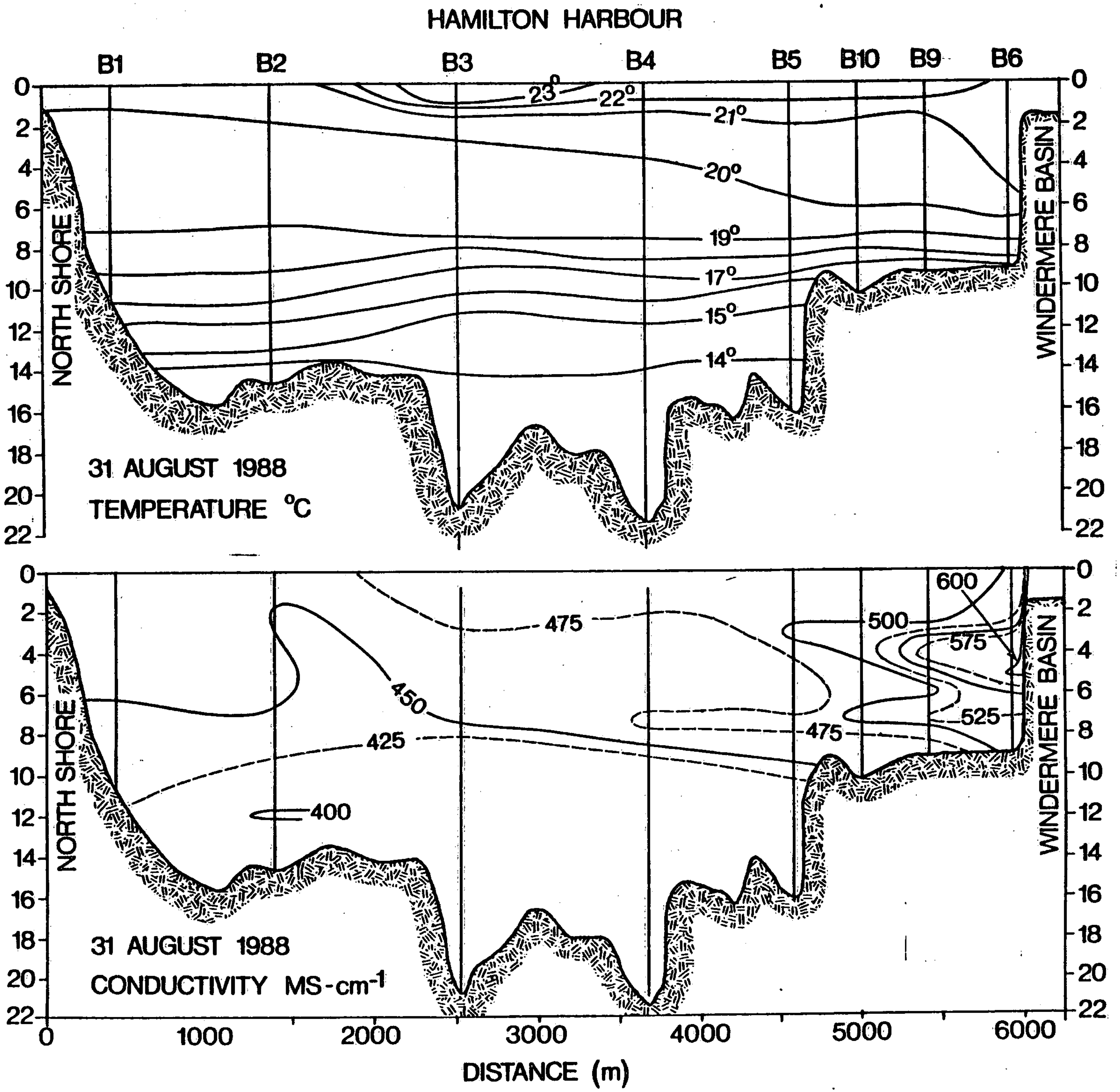
HAMILTON HARBOUR
10 AUGUST 1988

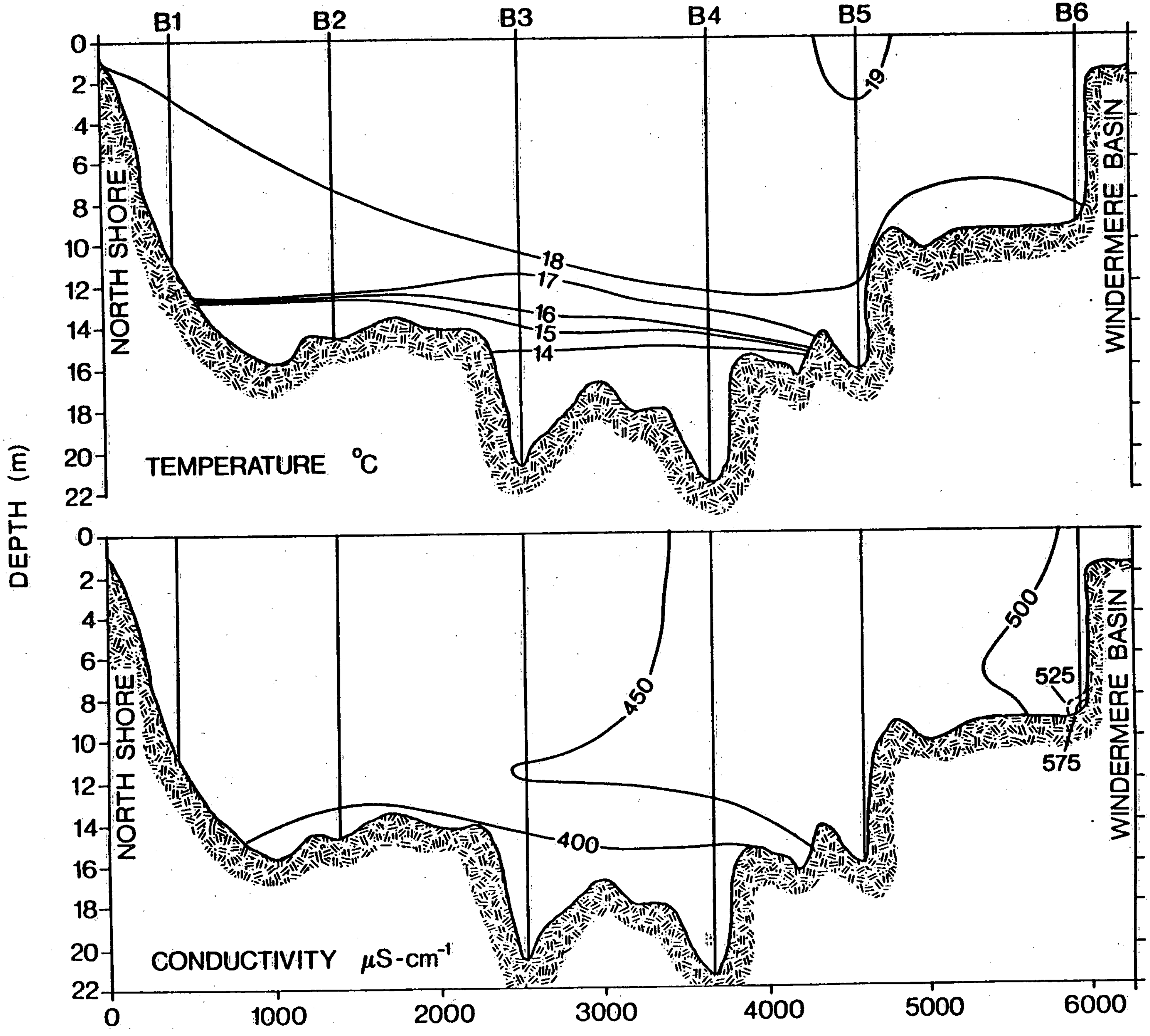



HAMILTON HARBOUR
17 AUGUST 1988
B1
B2
B3
B4
B5
B6
NORTH SHORE
WINDERMERE BASIN
24
19
17
16
15
14
13
13
TEMPERATURE °C
500
400
450
550
500
600
650
700
800
CONDUCTIVITY µS-cm-1
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
0
1000
2000
3000
4000
5000
6000
DISTANCE (m)

HAMILTON HARBOUR
25 AUGUST 1988

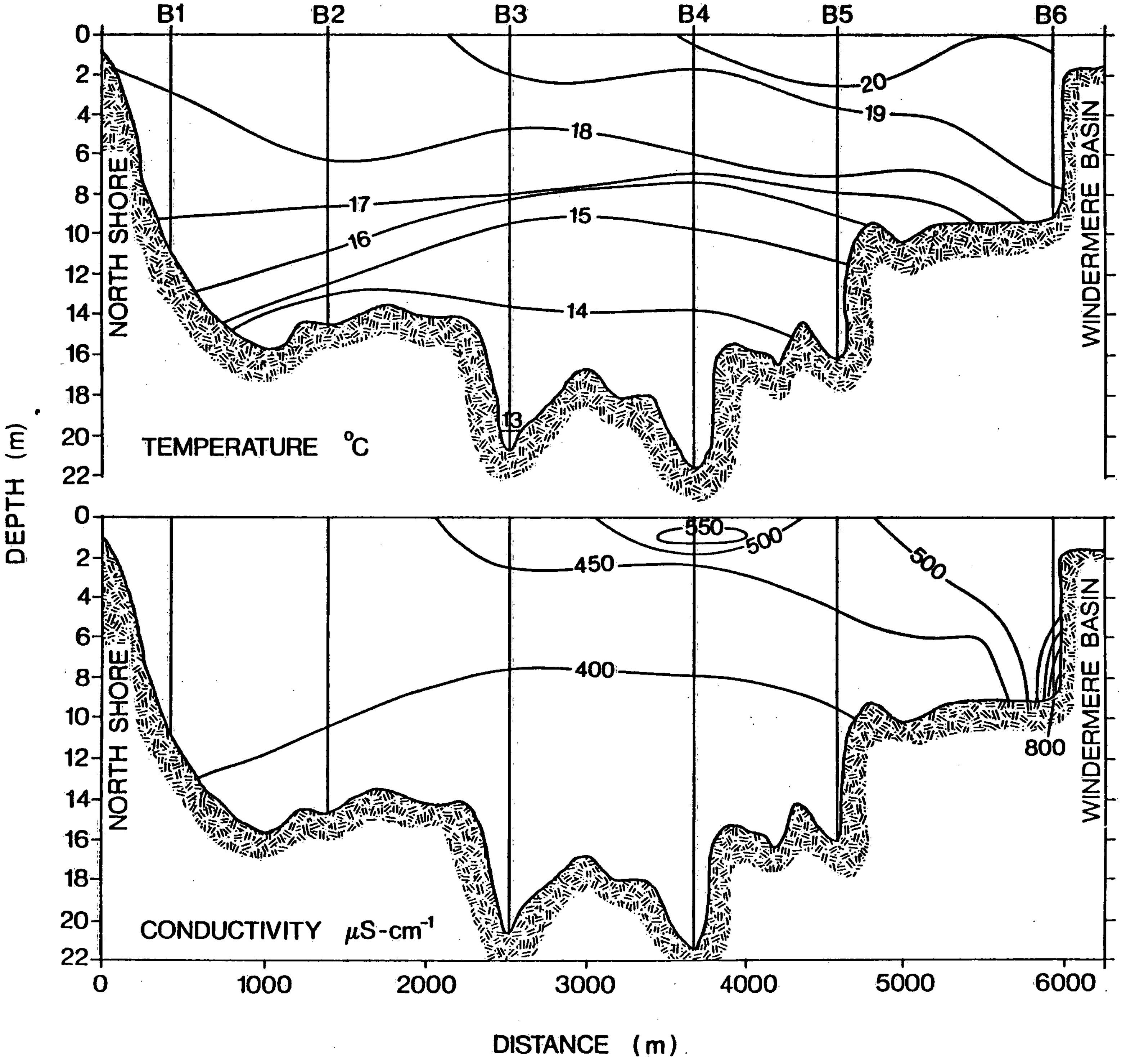



HAMILTON HARBOUR
B1
B2
B3
B4
B5
B10
B9
B6
NORTH SHORE
WINDERMERE BASIN
23°
22°
21°
20°
19°
17°
15°
14°
31 AUGUST 1988
TEMPERATURE °C
0
2
4
6
8
10
12
14
16
18
20
22
475
450
425
400
500
575
600
525
475
31 AUGUST 1988
CONDUCTIVITY MS-cm-1
0
1000
2000
3000
4000
5000
6000
DISTANCE (m)



HAMILTON HARBOUR
21 SEPTEMBER 1988

HAMILTON HARBOUR
15 SEPTEMBER 1988



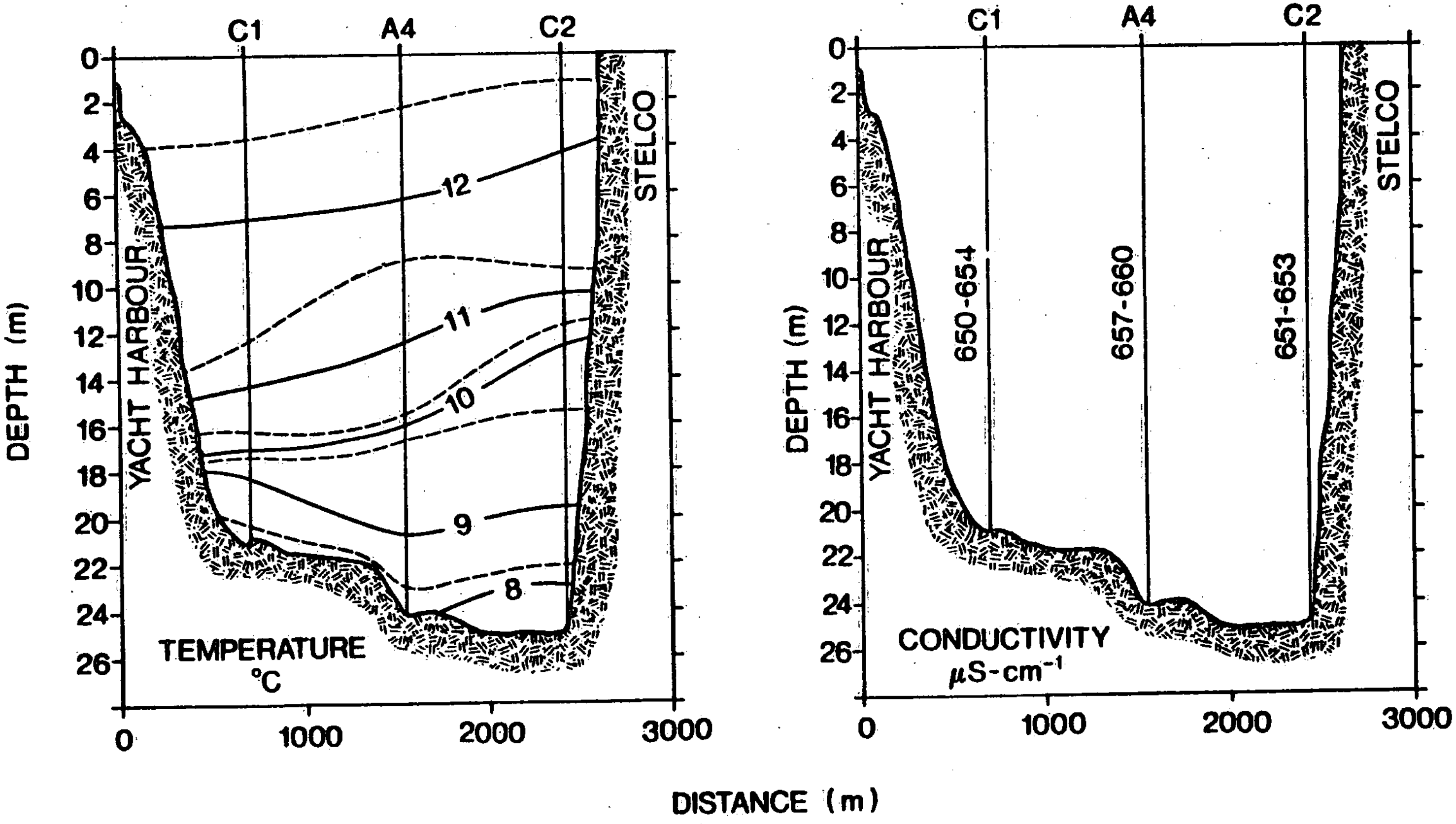
APPENDIX IV

TEMPERATURE AND CONDUCTIVITY TRANSECTS

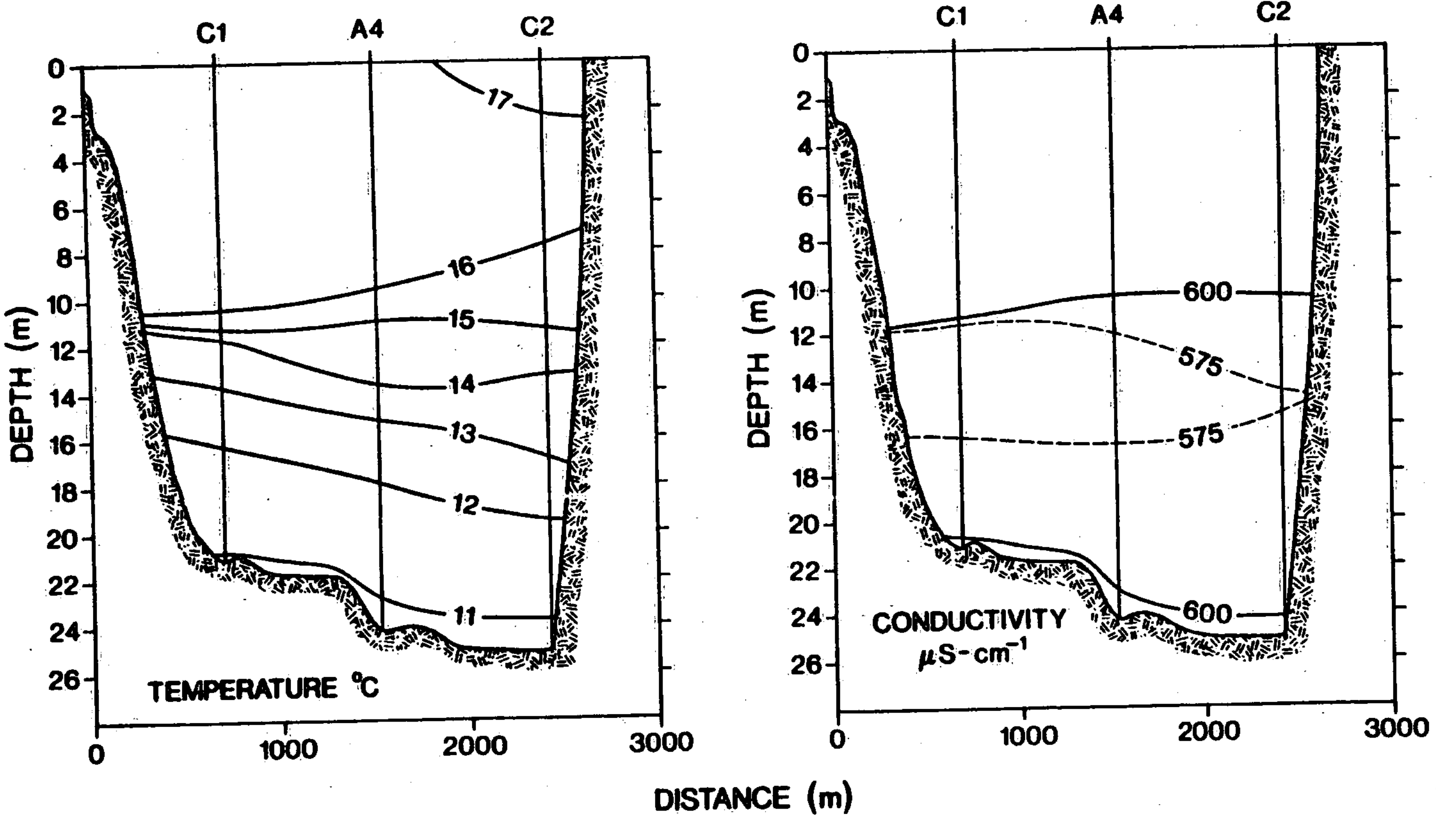
LINE C1 to C2

May 11 to September 21, 1988

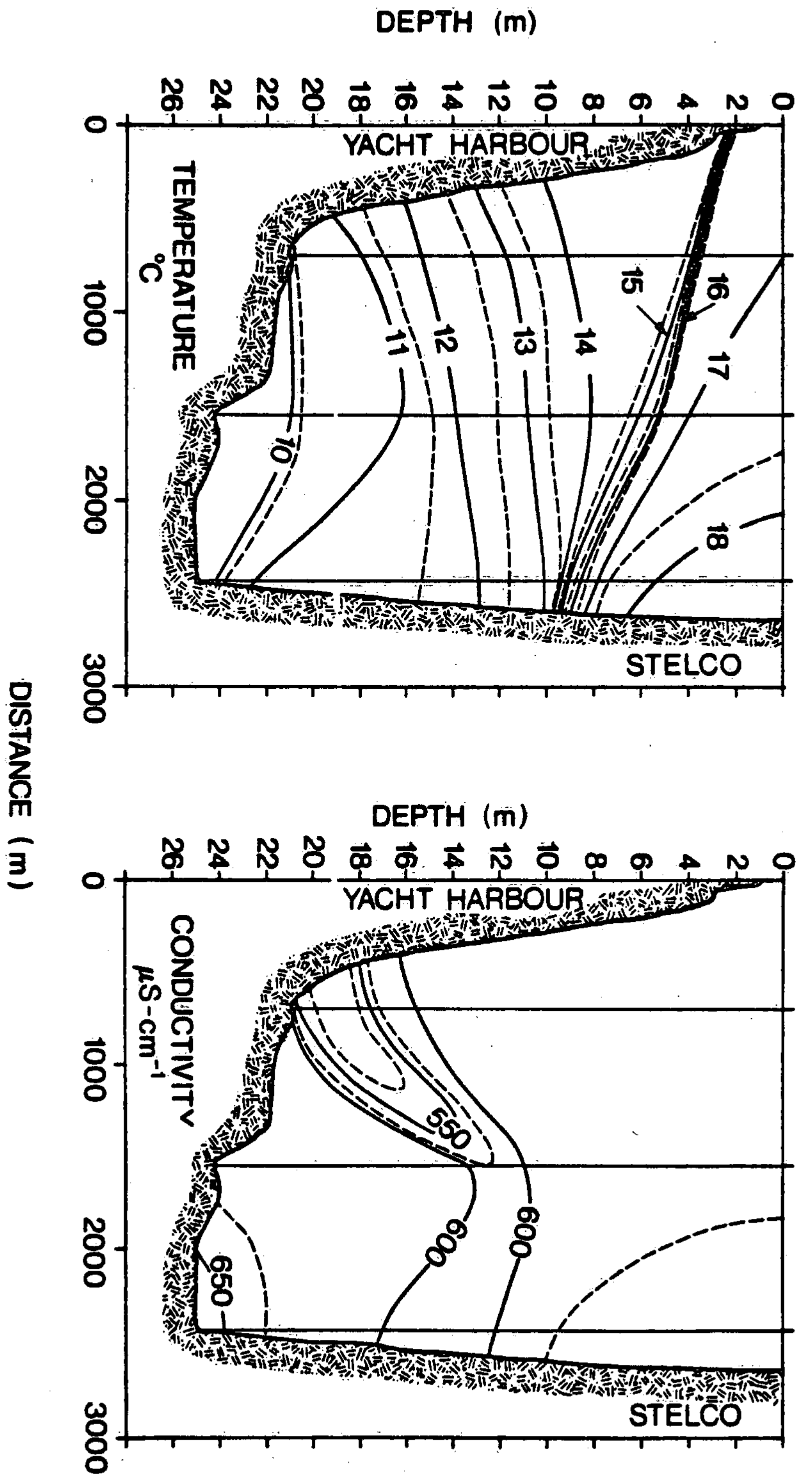
HAMILTON HARBOUR
11 MAY 1988



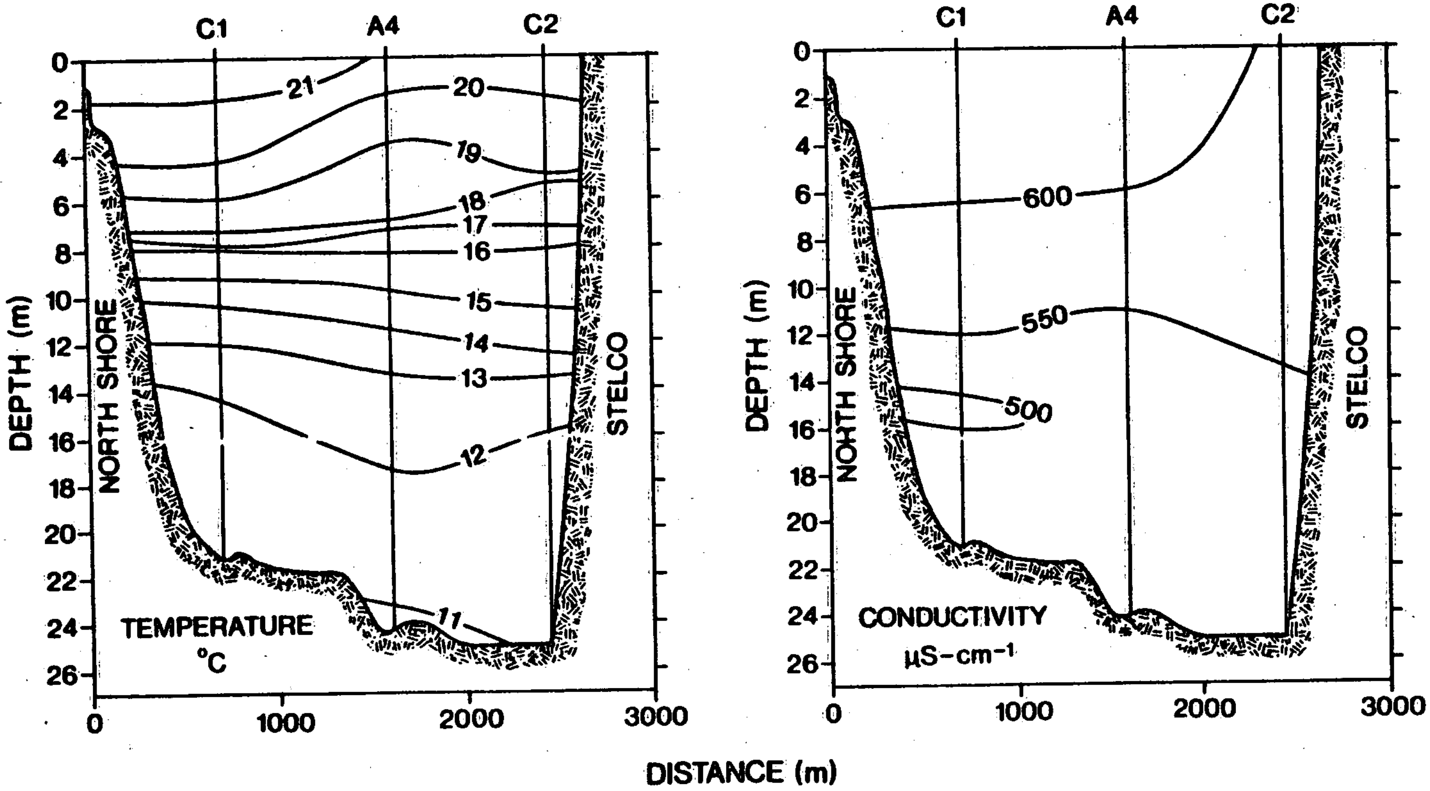
HAMILTON HARBOUR - 9 JUNE 1988



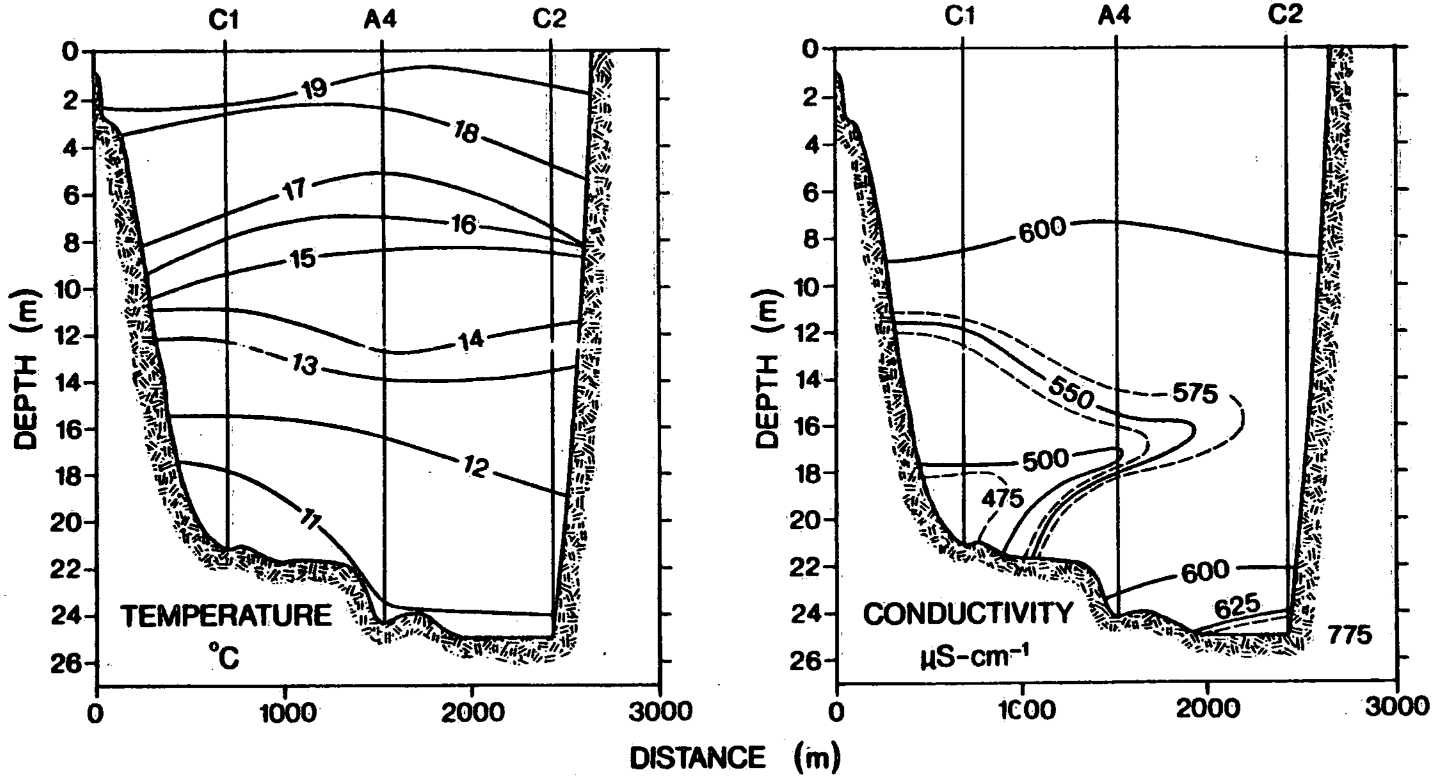
HAMILTON HARBOUR
1 JUNE 1988



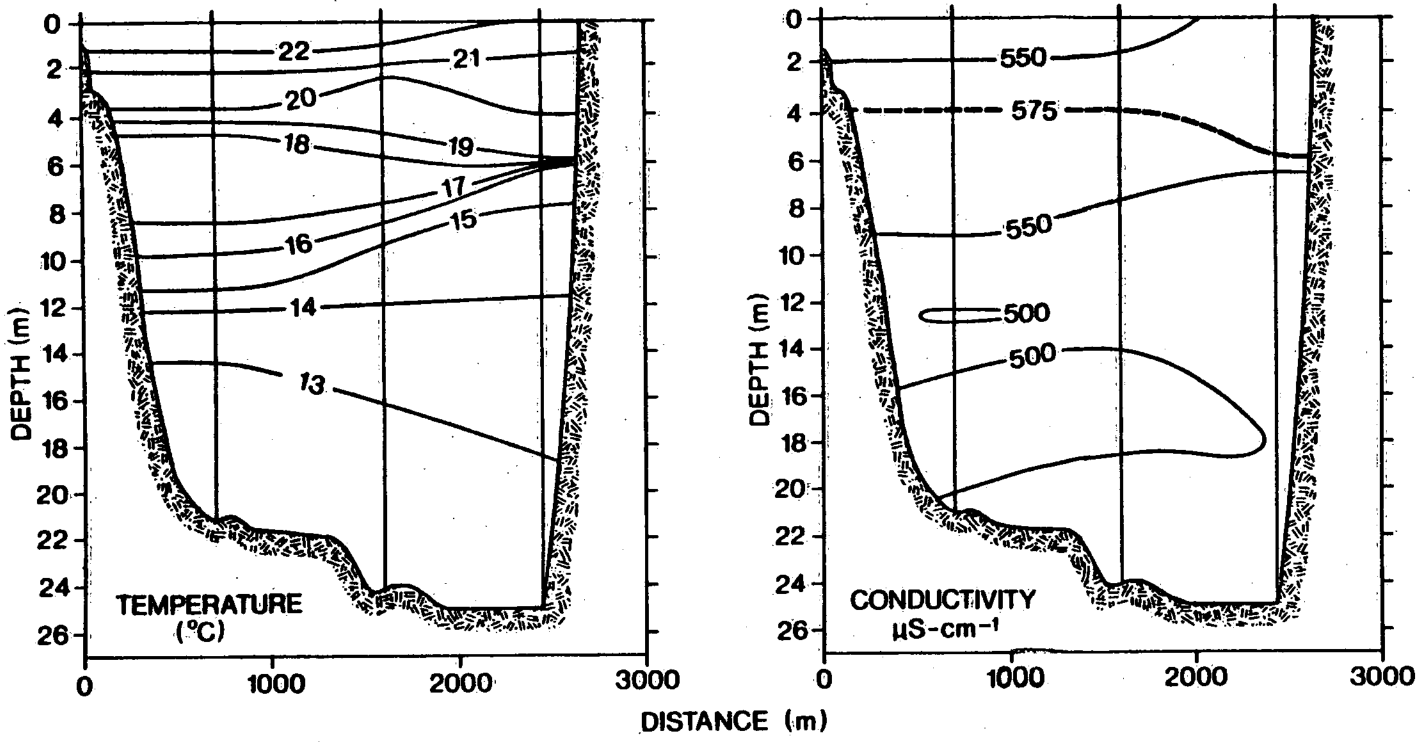
HAMILTON HARBOUR–21 JUNE 88



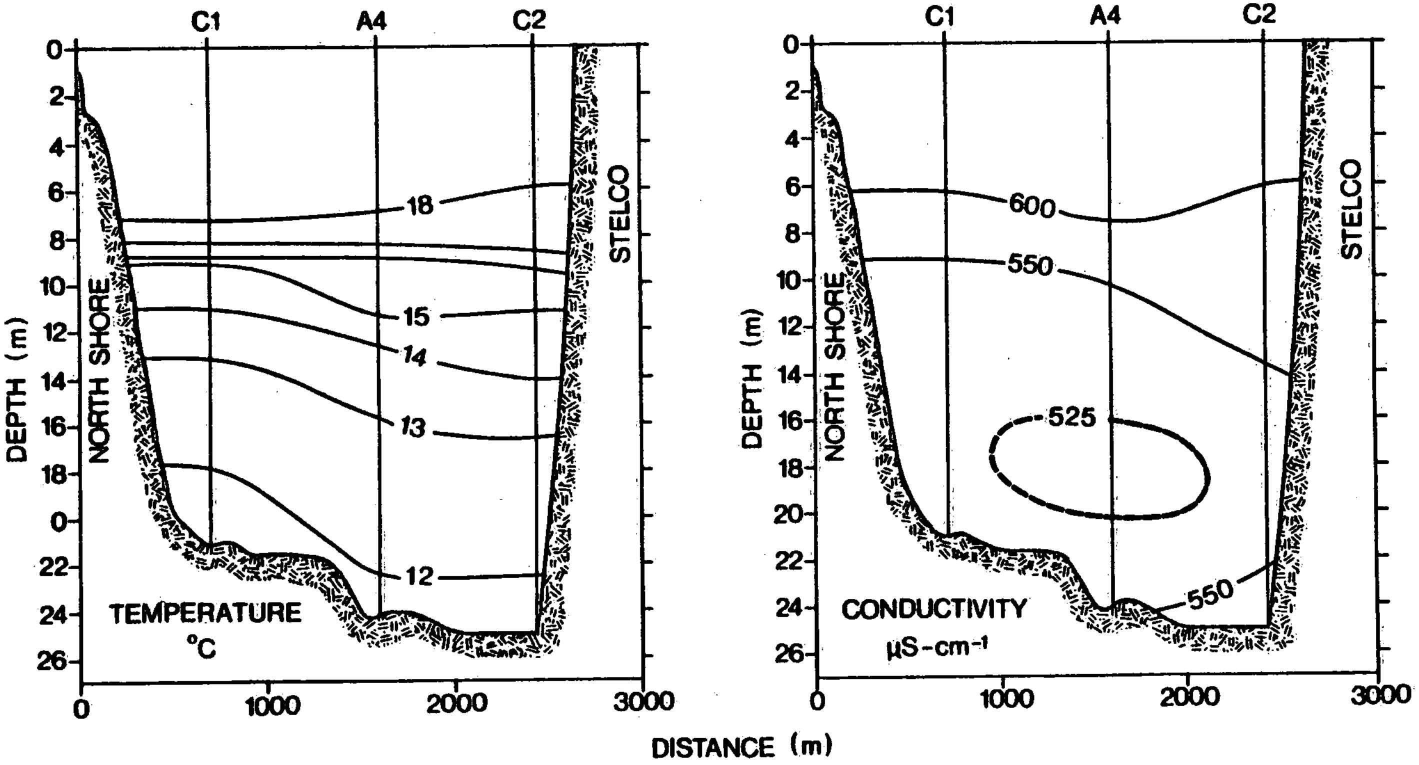
HAMILTON HARBOUR - 15 JUNE 1988



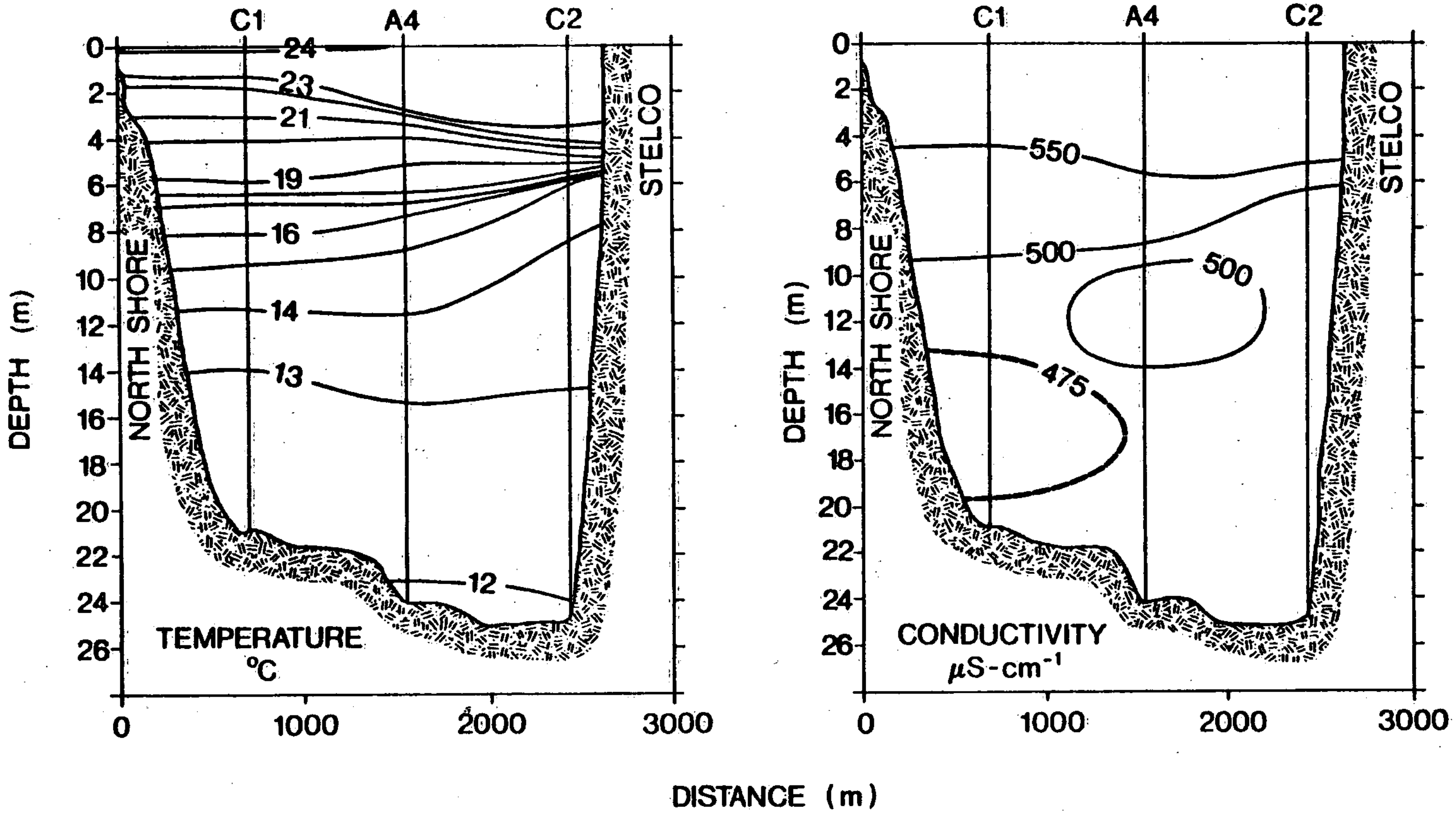
HAMILTON HARBOUR
6 JULY 1988



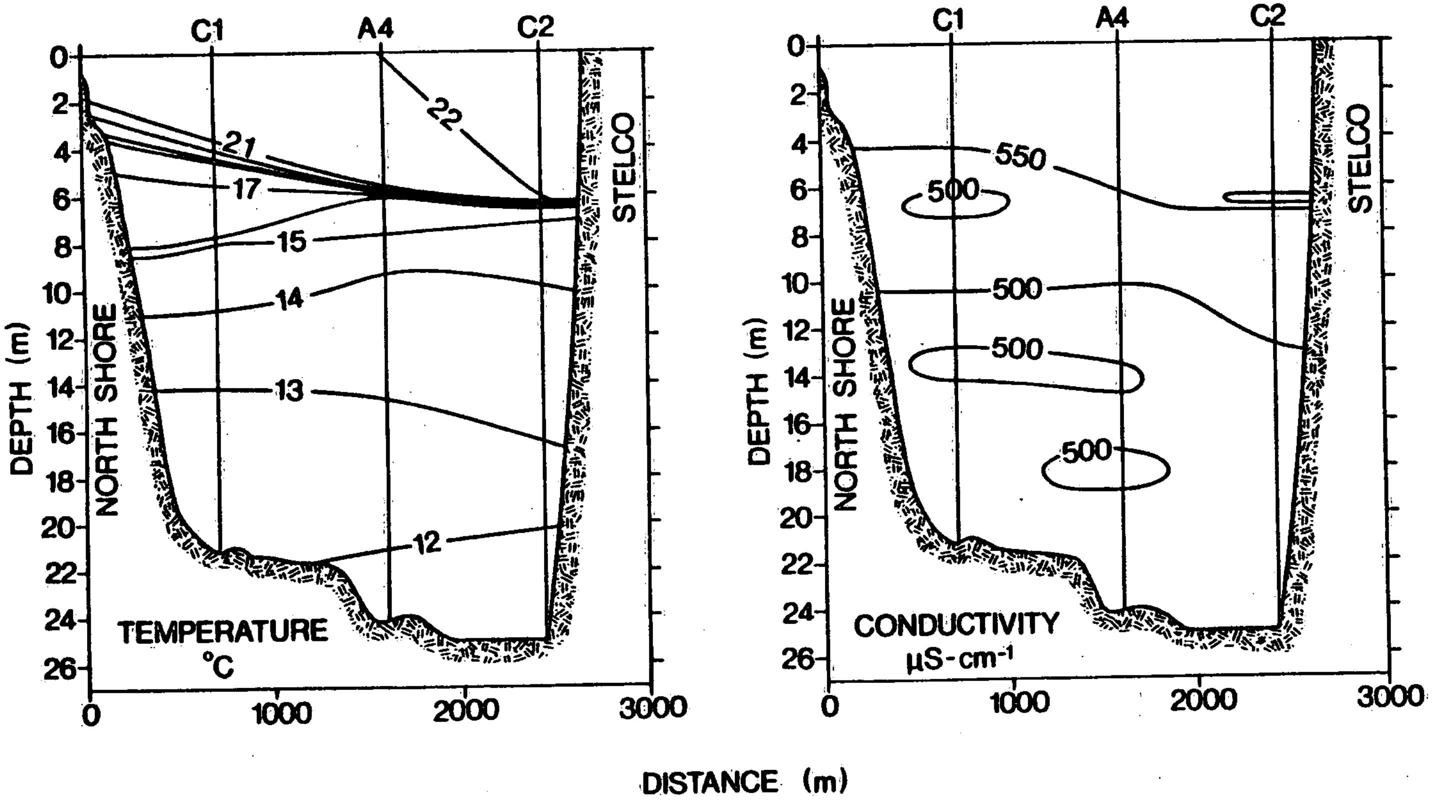
HAMILTON HARBOUR 30 JUNE 1988



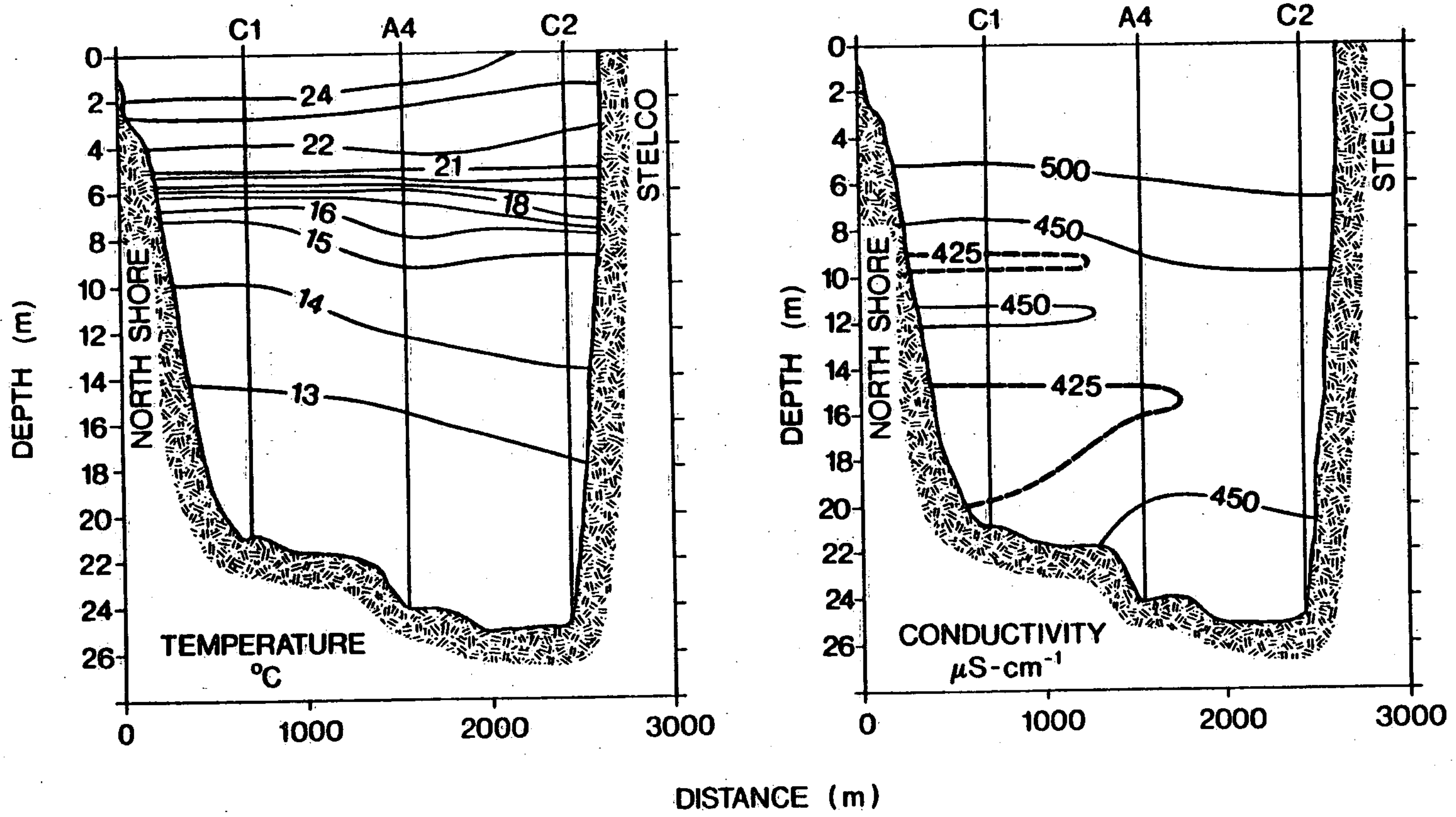
HAMILTON HARBOUR
20 JULY 1988



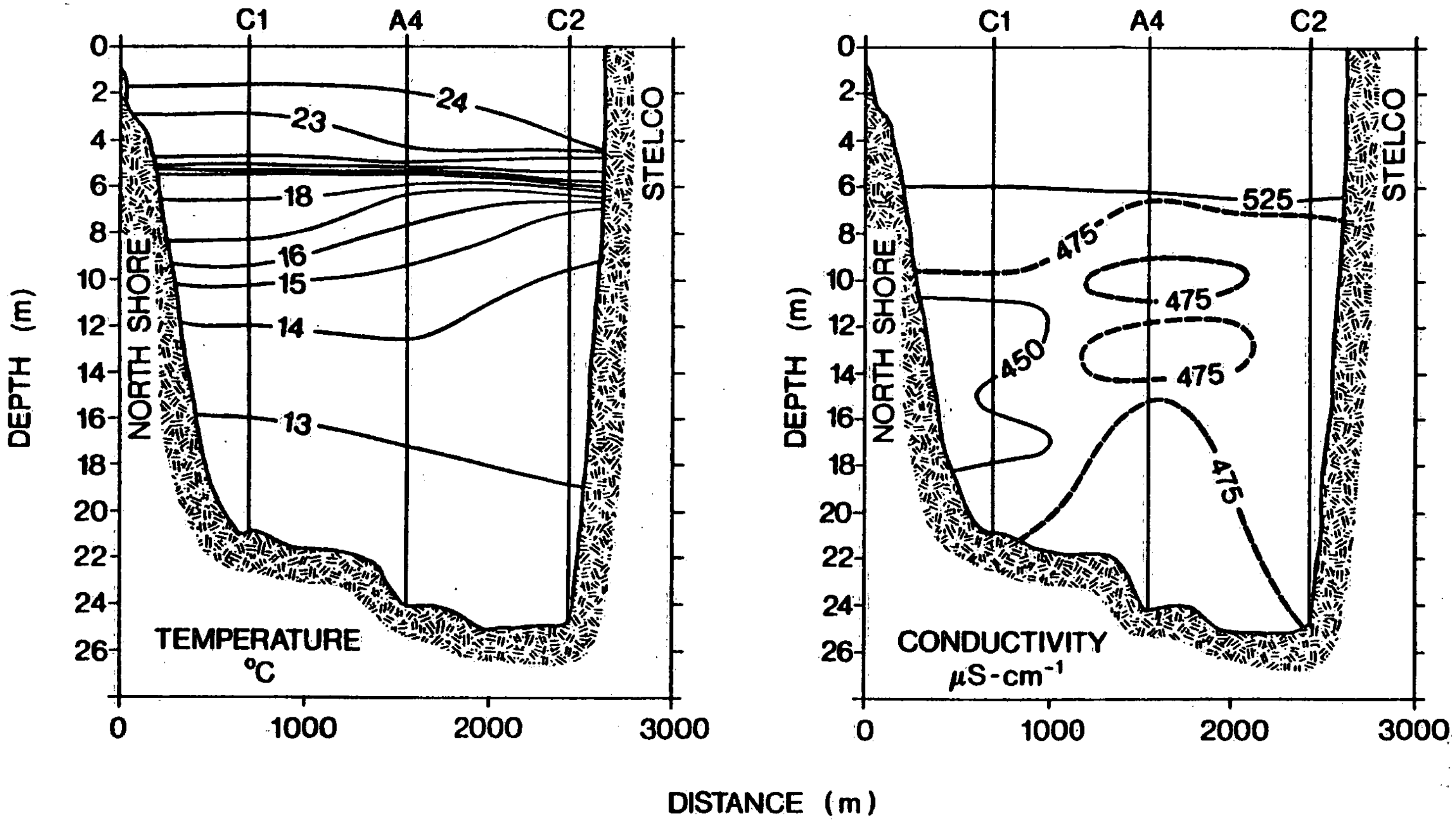
HAMILTON HARBOUR
14 JULY 1988



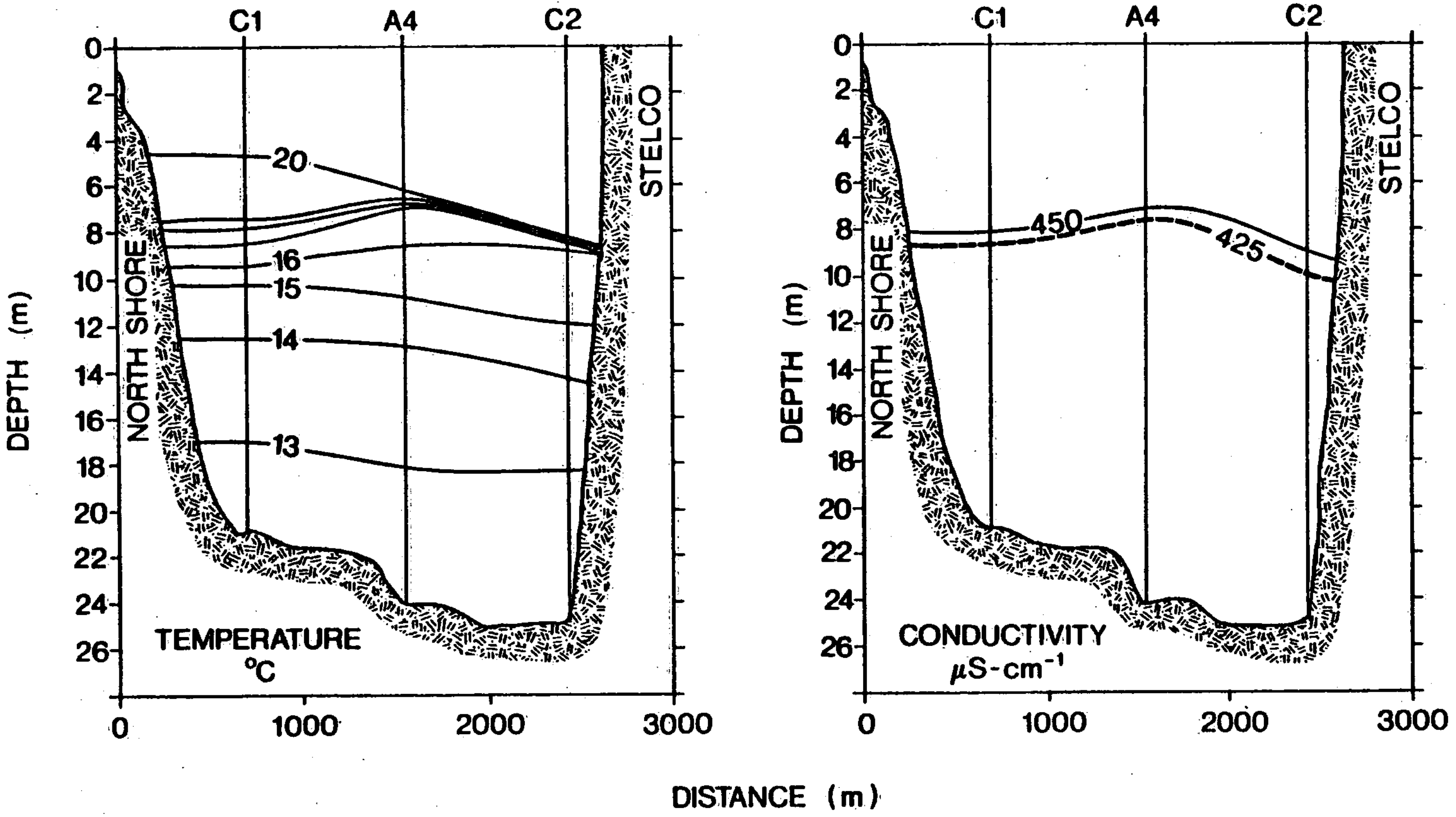
HAMILTON HARBOUR
10 AUGUST 1988



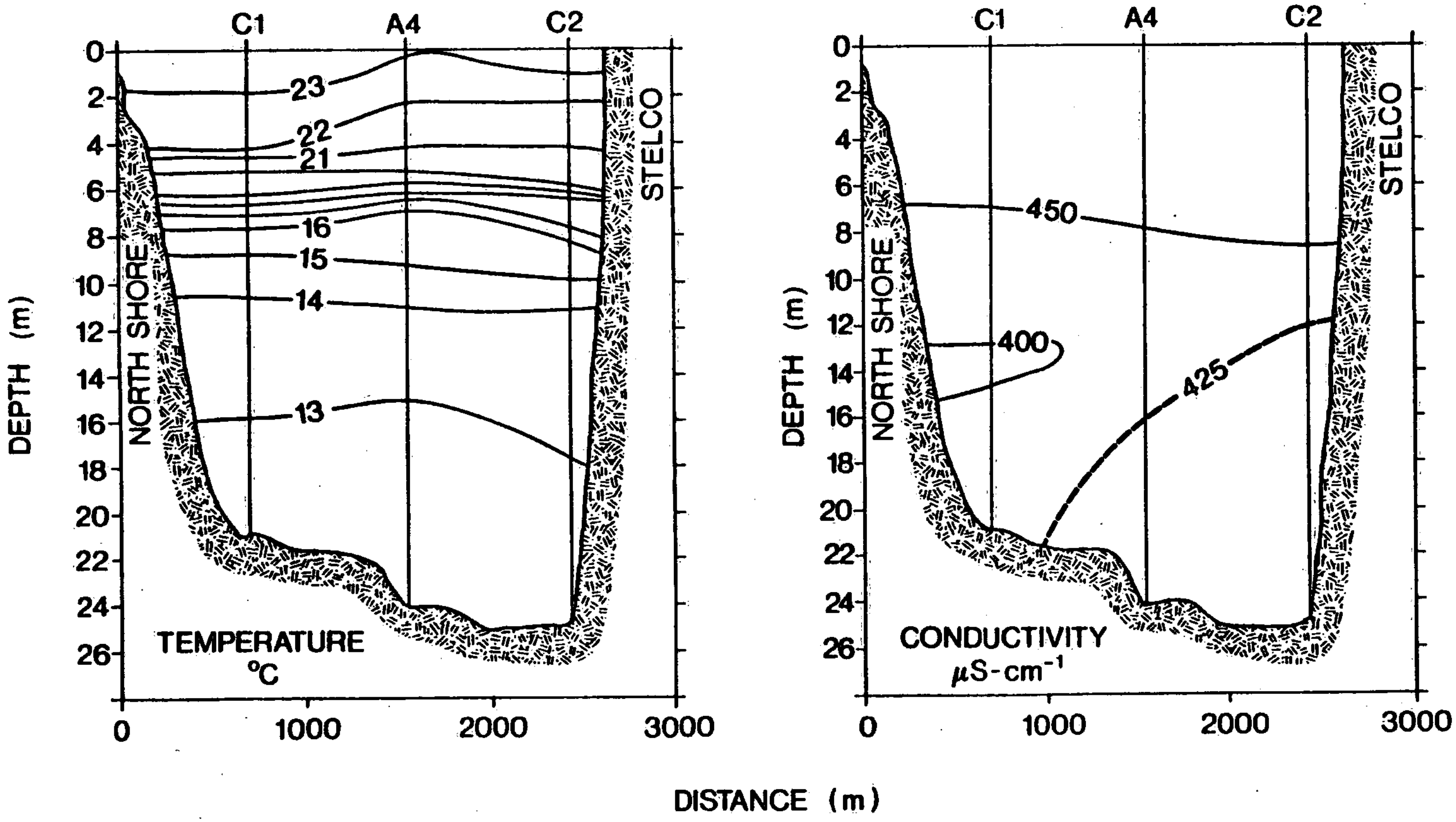
HAMILTON HARBOUR
3 AUGUST 1988



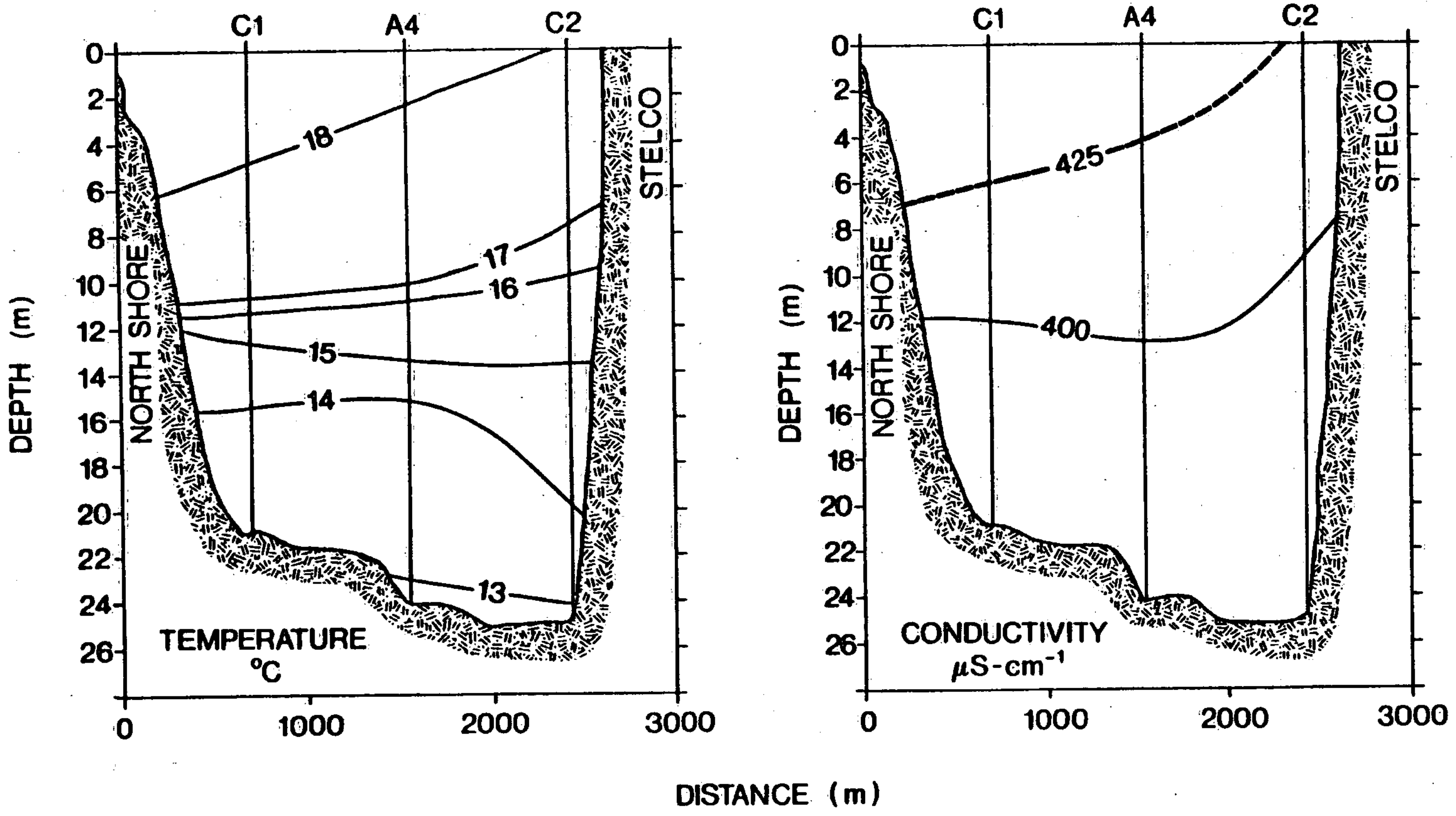
HAMILTON HARBOUR
25 AUGUST 1988



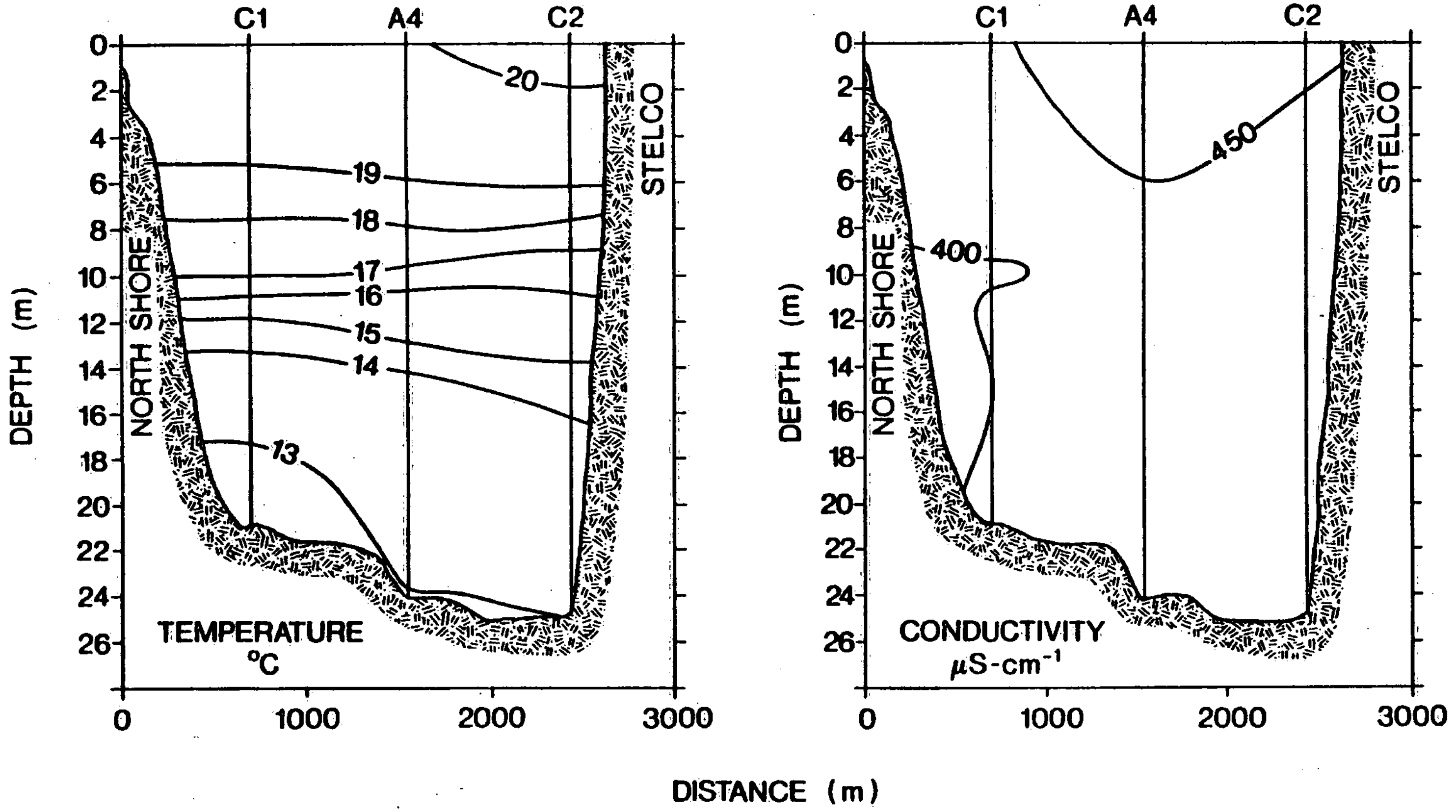
HAMILTON HARBOUR
17 AUGUST 1988



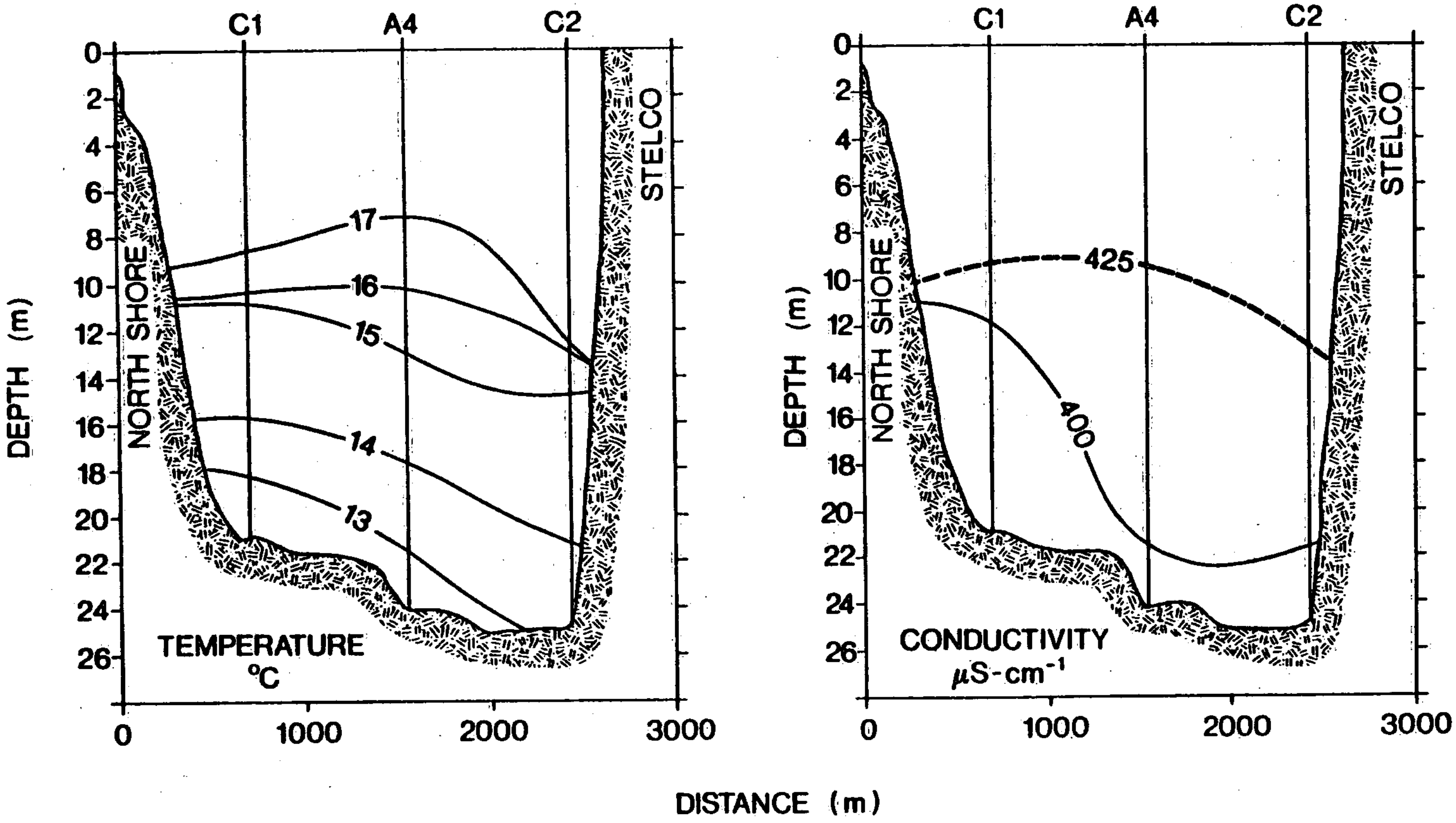
HAMILTON HARBOUR
15 SEPTEMBER 1988



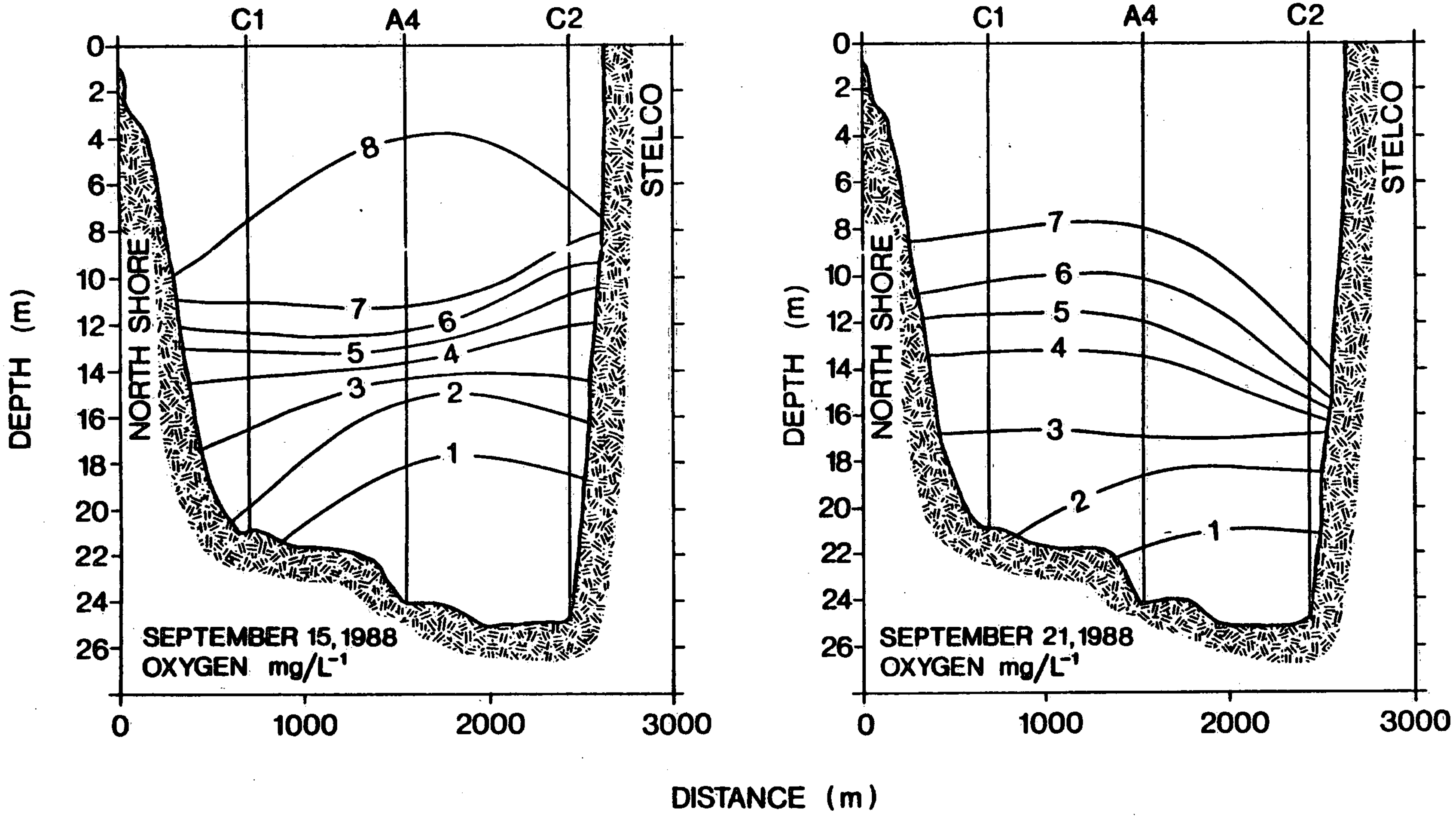
HAMILTON HARBOUR
31 AUGUST 1988



HAMILTON HARBOUR
21 SEPTEMBER 1988



HAMILTON HARBOUR

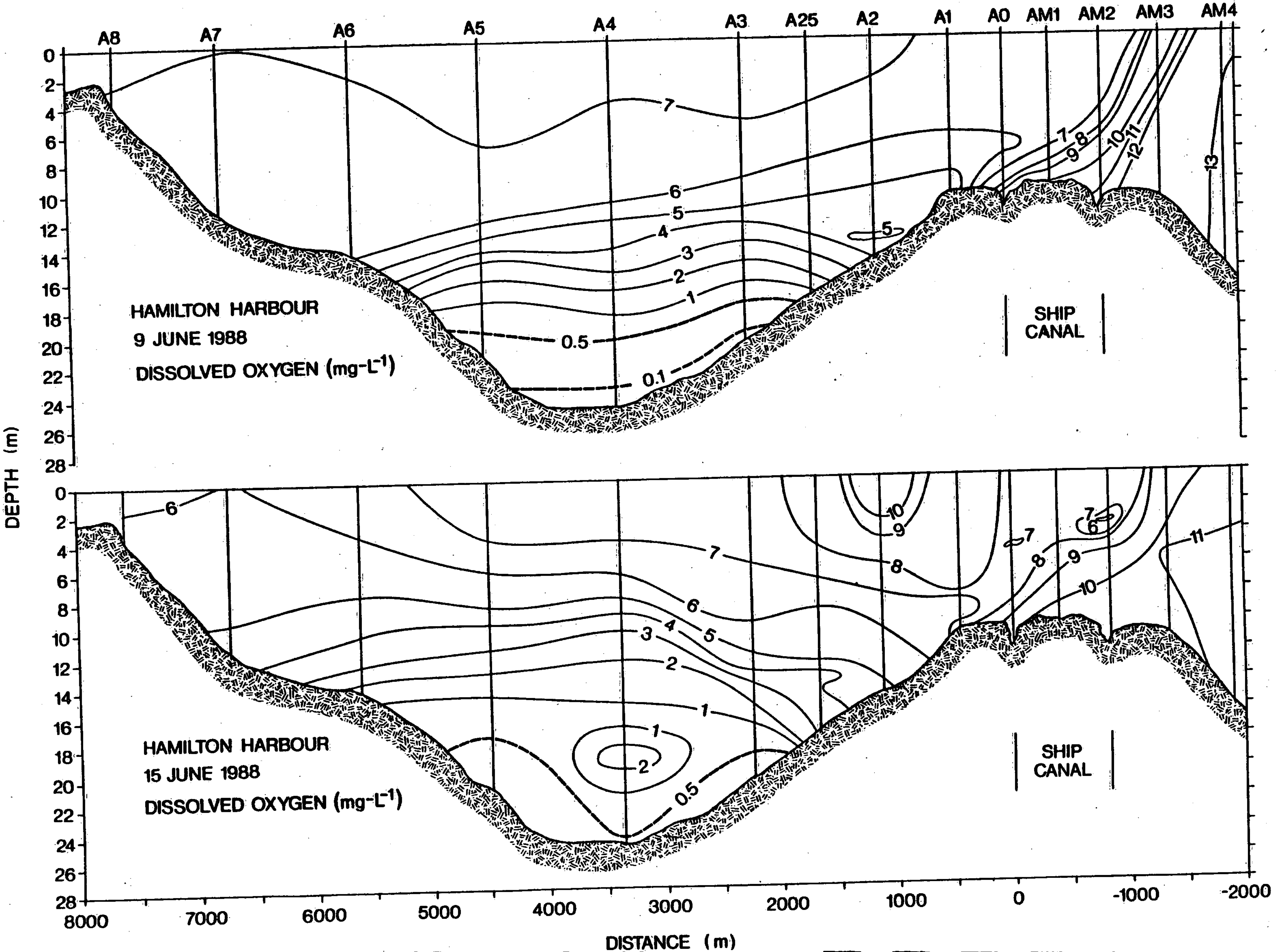


APPENDIX V

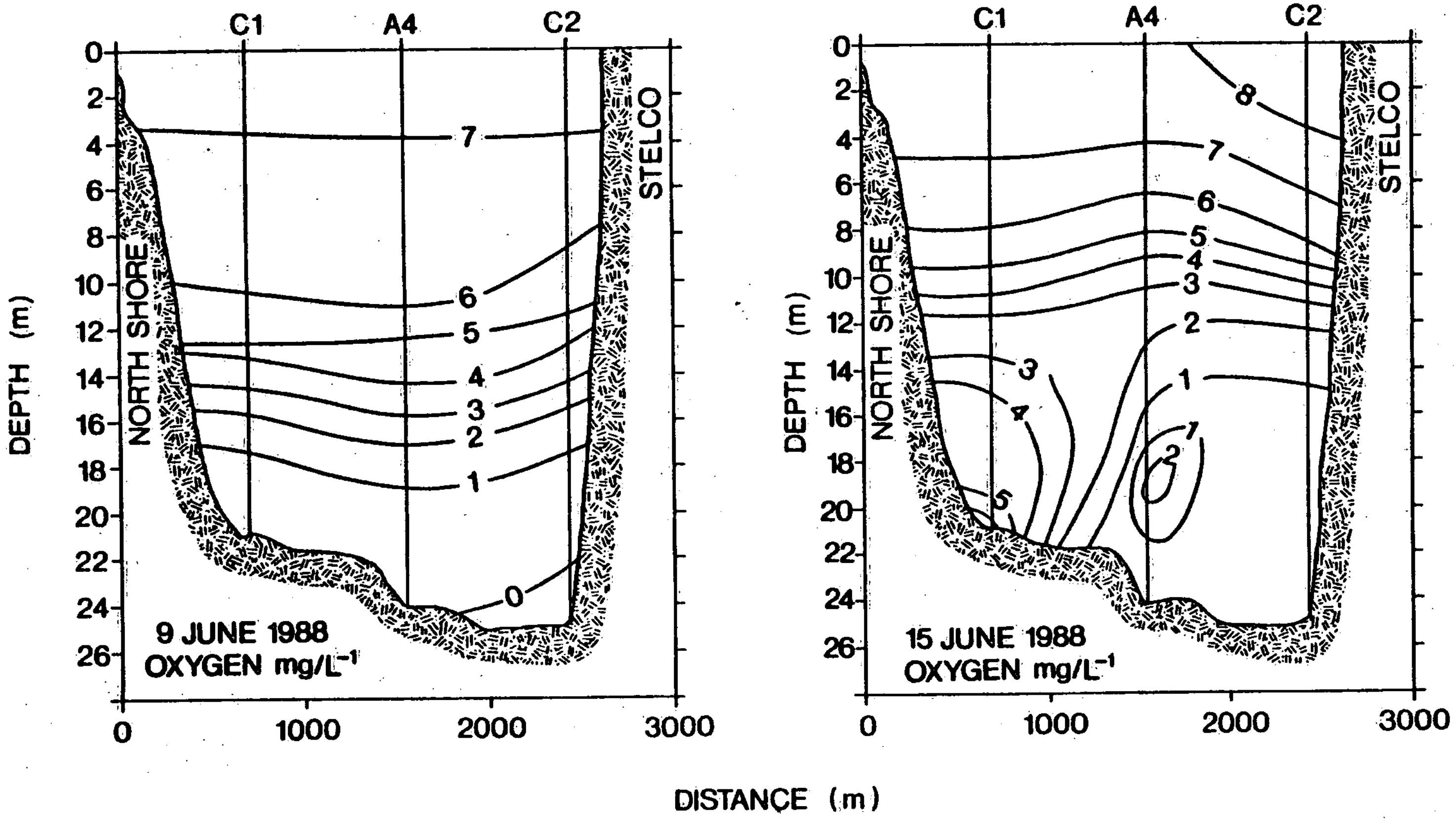
DISSOLVED OXYGEN TRANSECTS

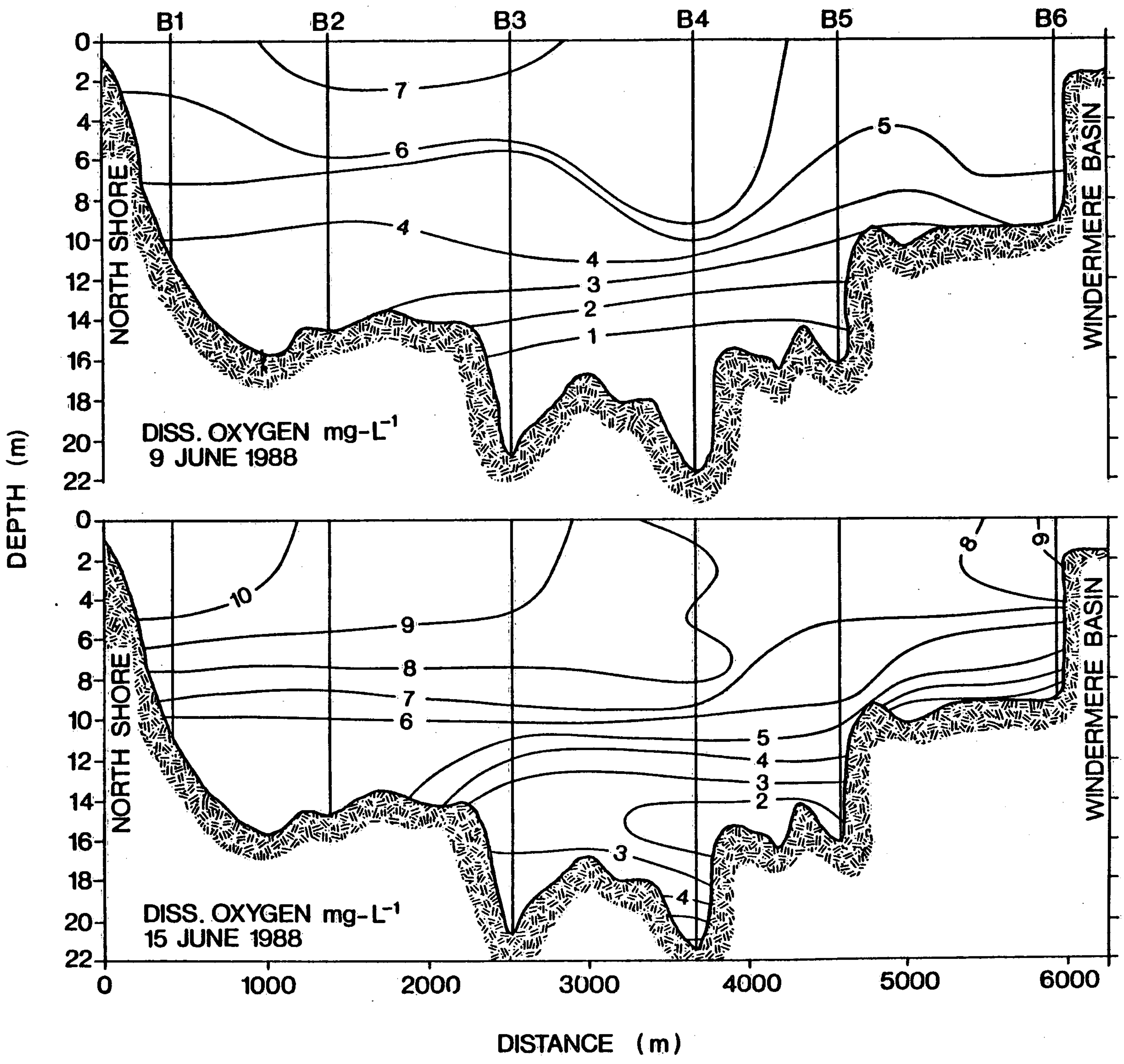
Lines A8 to AM4, B2 to B6 and C1 to C2

June 9 to September 21, 1988

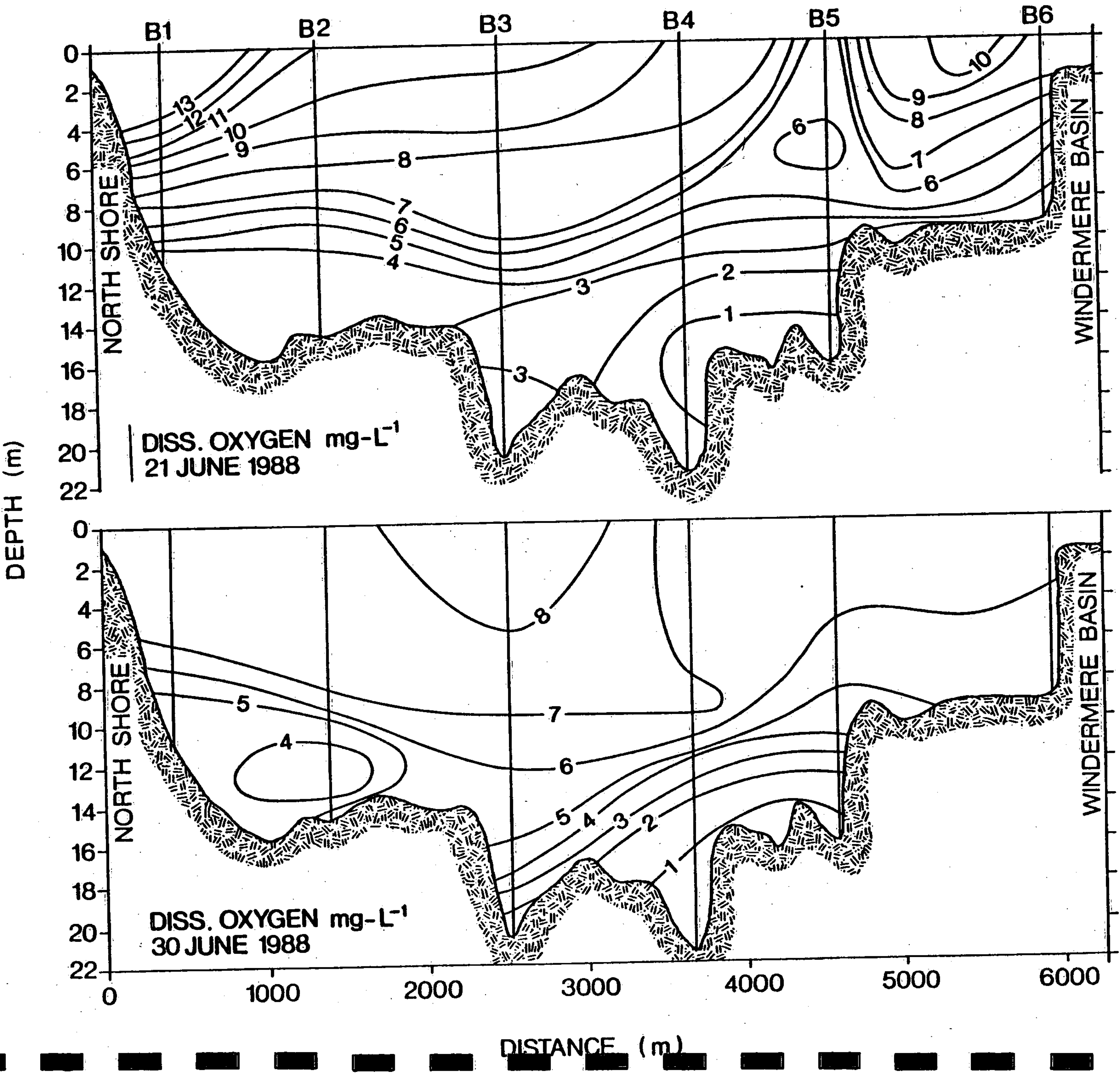

HAMILTON HARBOUR
9 JUNE 1988
DISSOLVED OXYGEN (mg-L-1)
HAMILTON HARBOUR
15 JUNE 1988
DISSOLVED OXYGEN (mg-L-1)
A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
SHIP CANAL
SHIP CANAL
DEPTH (m)
DISTANCE (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
7
6
5
4
3
2
1
0.5
0.1
8
9
10
11
12
13
6
7
8
9
10
11
6
5
4
3
2
1
2
1
0.5

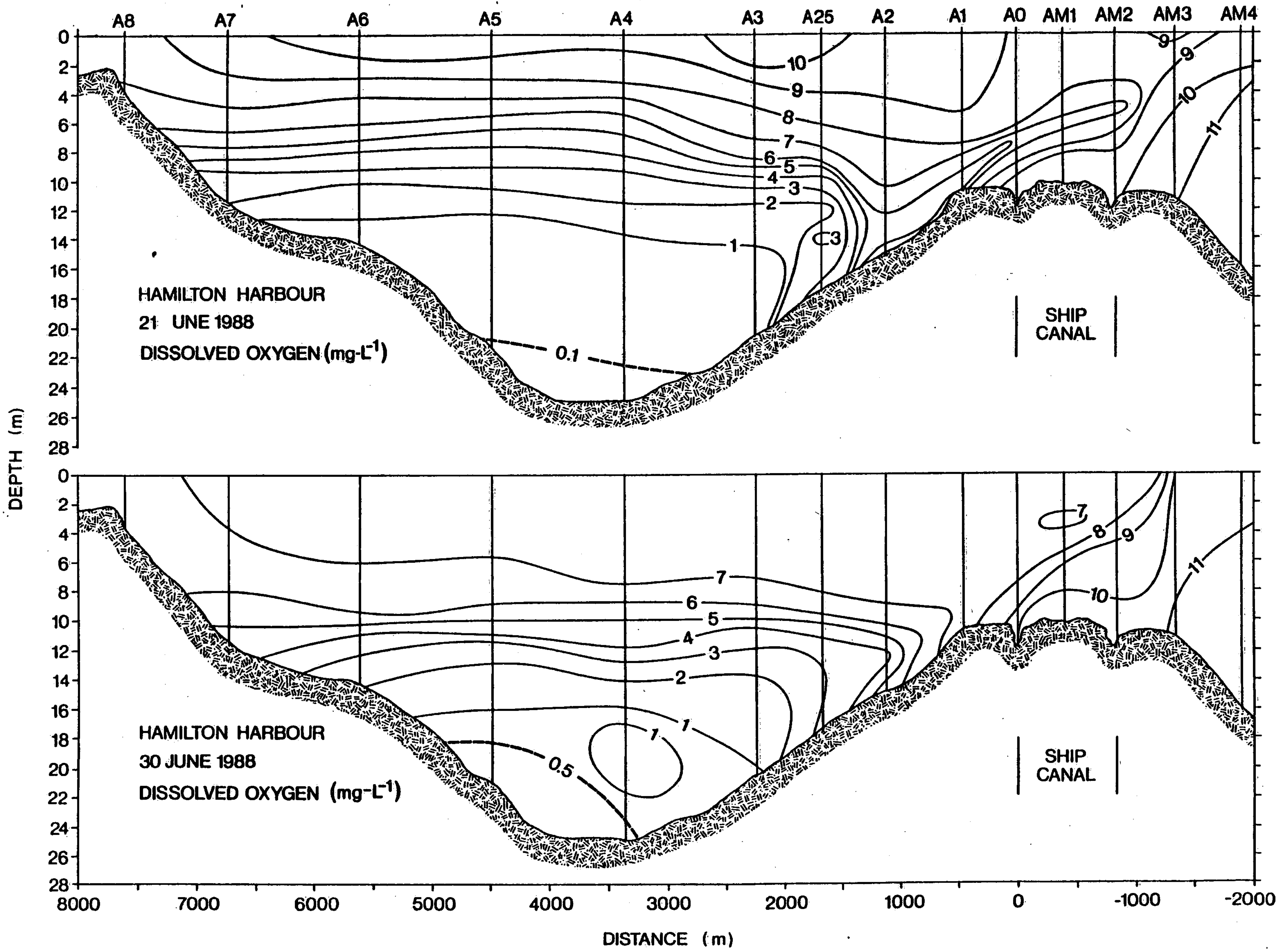
HAMILTON HARBOUR

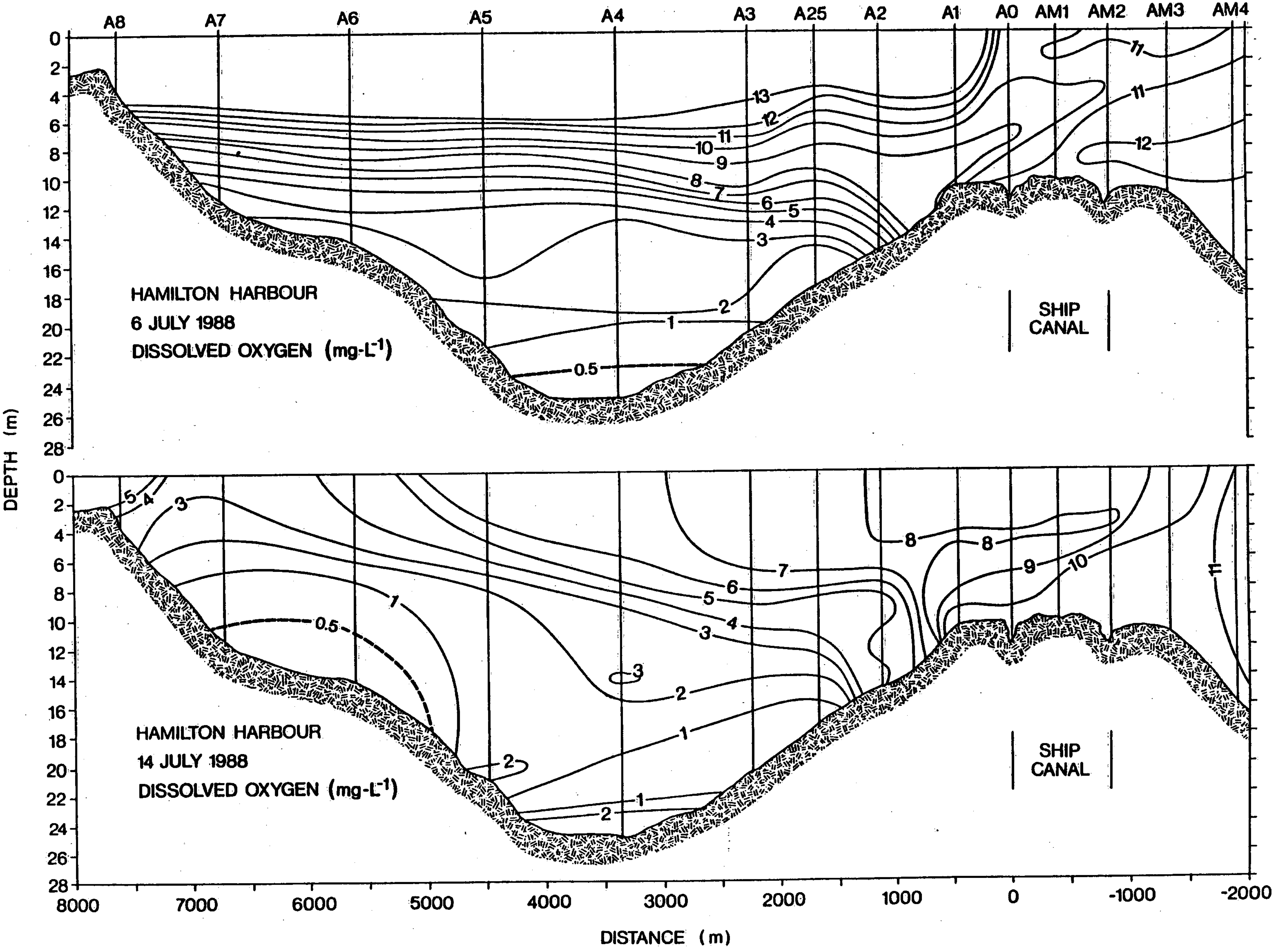



B1
B2
B3
B4
B5
B6
7
6
5
4
4
3
2
1
NORTH SHORE
WINDERMERE BASIN
DISS. OXYGEN mg-L^{-1}
9 JUNE 1988
10
9
8
7
6
5
4
3
2
3
4
8
9
NORTH SHORE
WINDERMERE BASIN
DISS. OXYGEN mg-L^{-1}
15 JUNE 1988
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
DISTANCE (m)
0
1000
2000
3000
4000
5000
6000

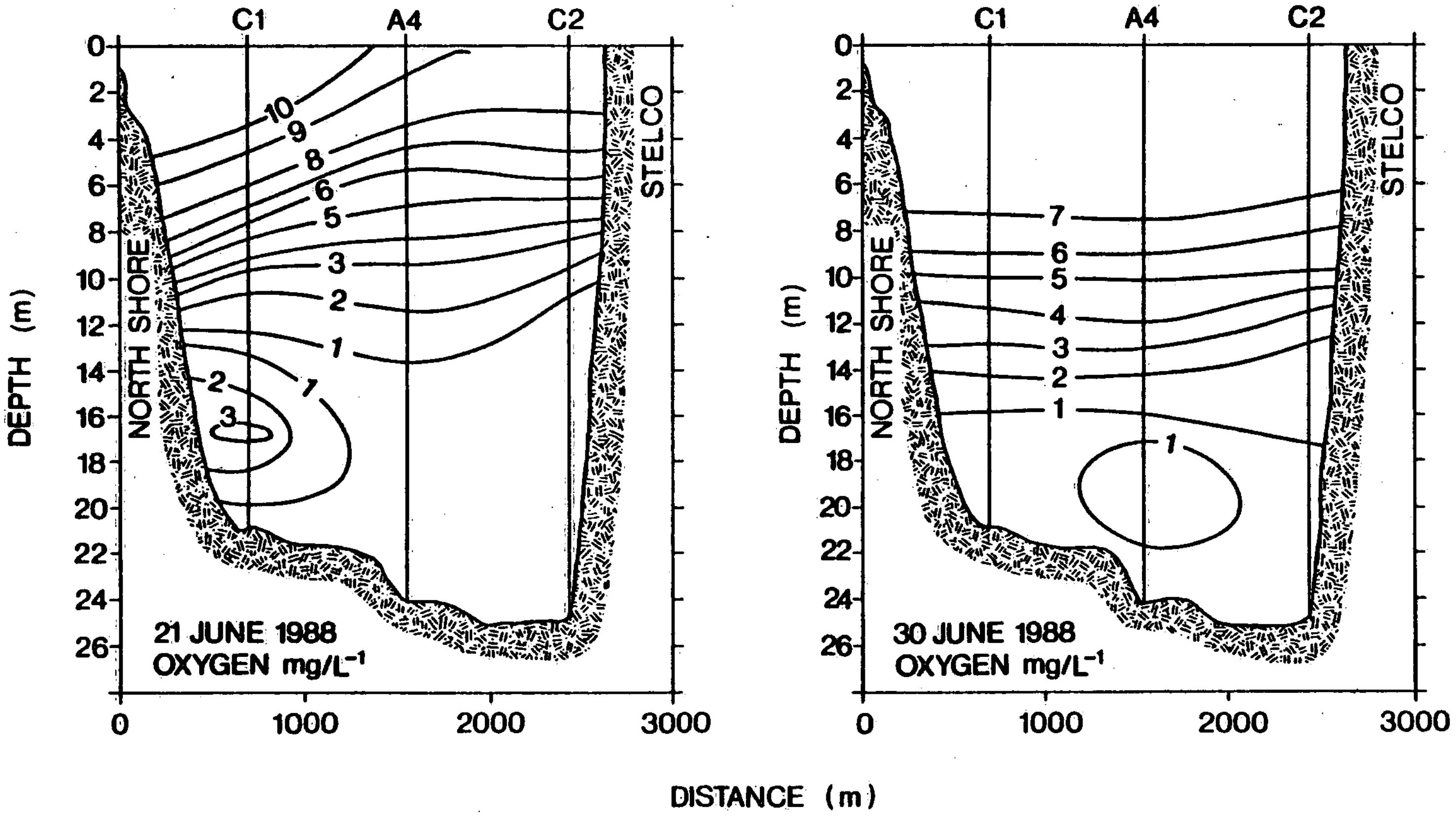
HAMILTON HARBOUR



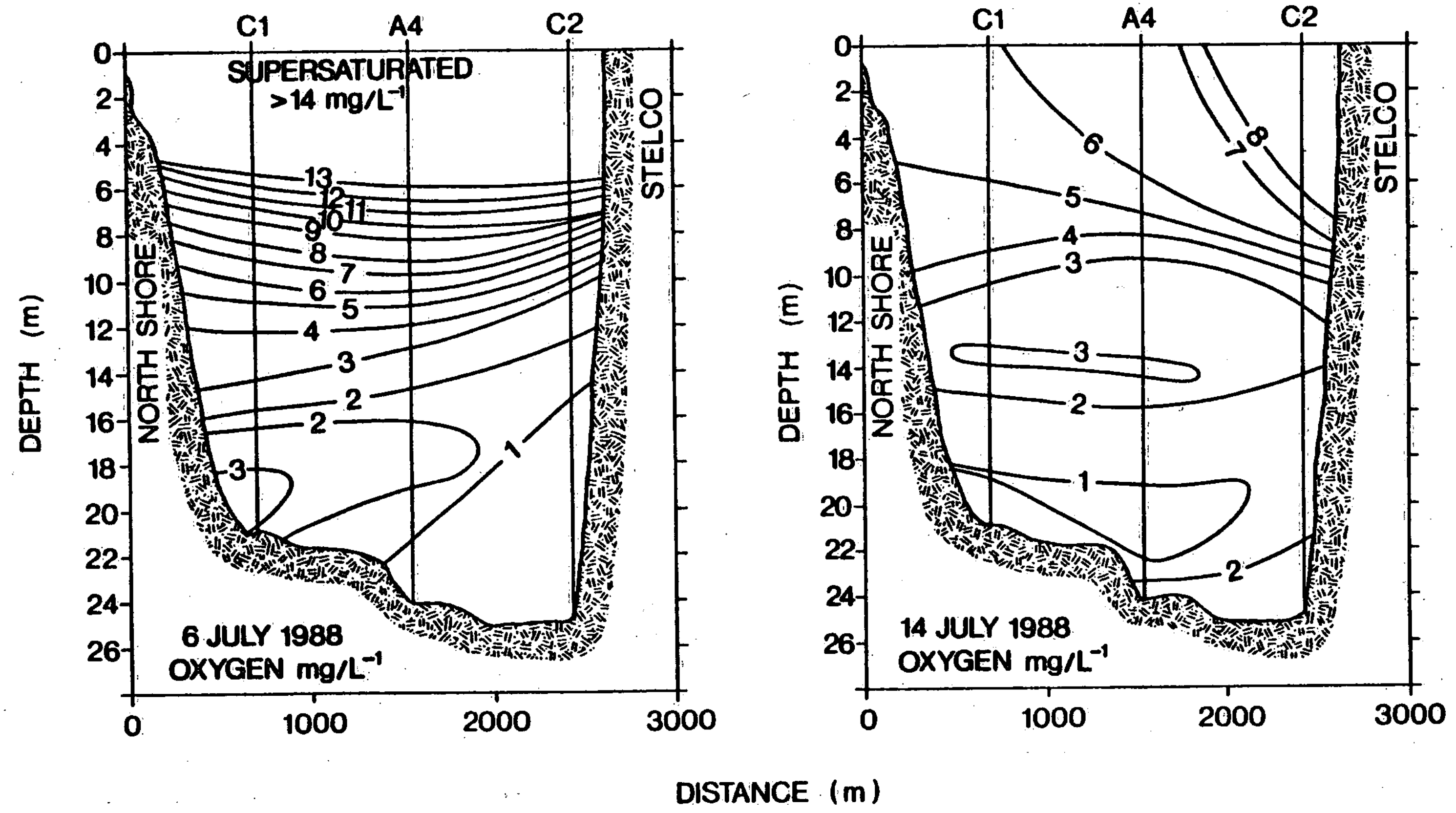

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
HAMILTON HARBOUR
21 UNE 1988
DISSOLVED OXYGEN (mg-L^{-1})
SHIP CANAL
0.1
1
2
3
4
5
6
7
8
9
10
11
HAMILTON HARBOUR
30 JUNE 1988
DISSOLVED OXYGEN (mg-L^{-1})
SHIP CANAL
0.5
1
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000

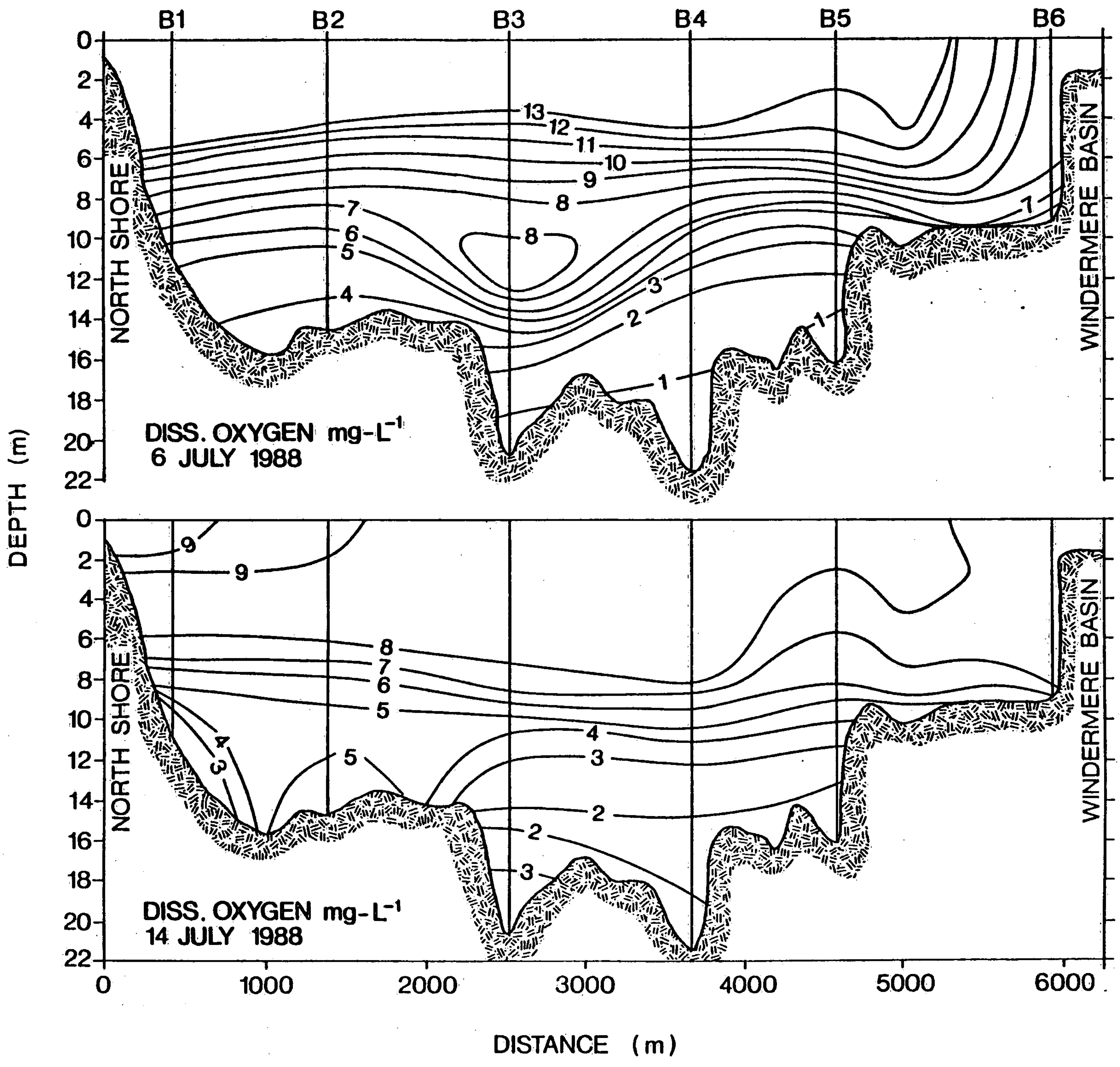

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
HAMILTON HARBOUR
6 JULY 1988
DISSOLVED OXYGEN (mg-L-1)
SHIP CANAL
13
12
11
10
9
8
7
6
5
4
3
2
1
0.5
HAMILTON HARBOUR
14 JULY 1988
DISSOLVED OXYGEN (mg-L-1)
SHIP CANAL
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000

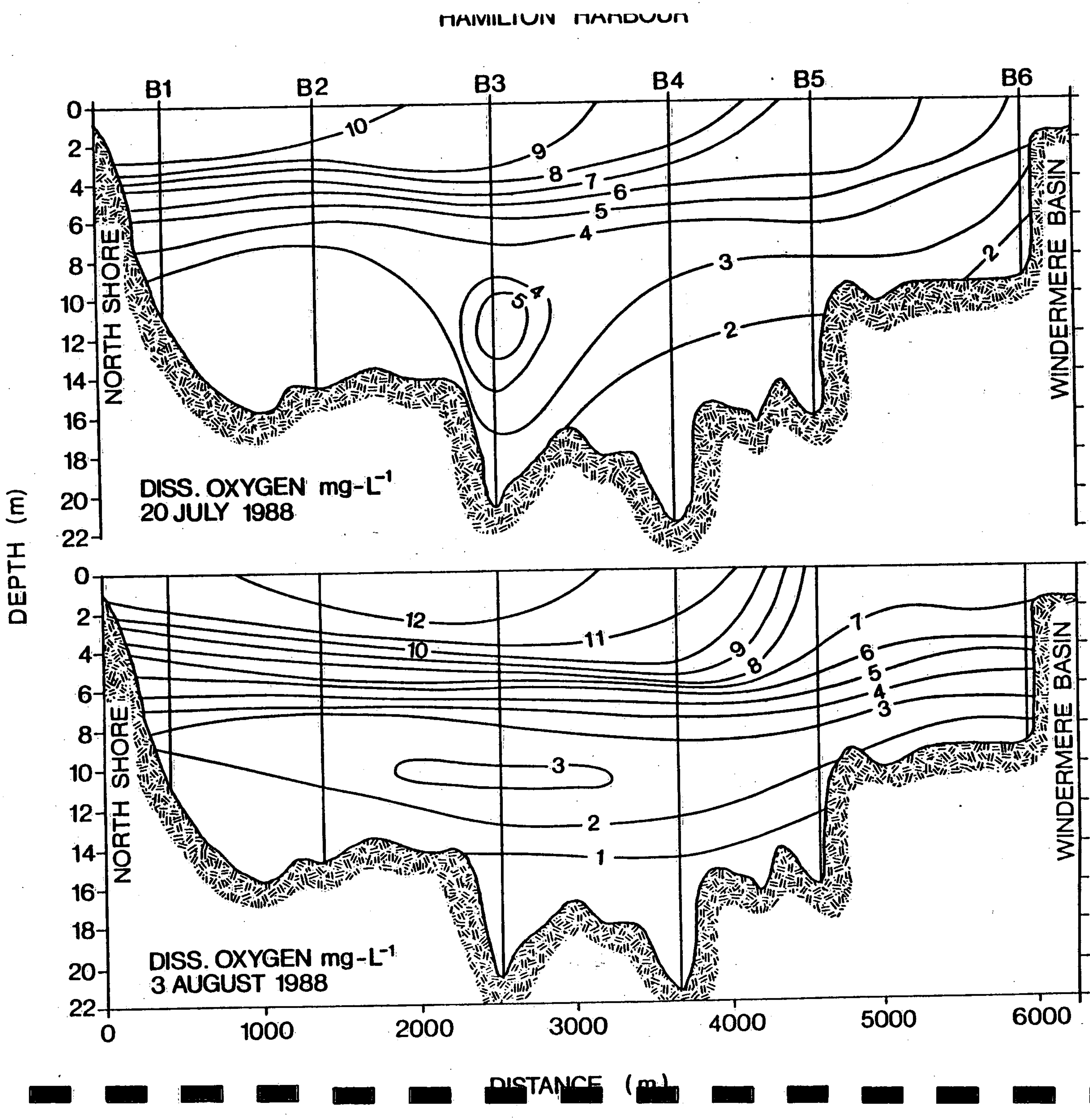
HAMILTON HARBOUR



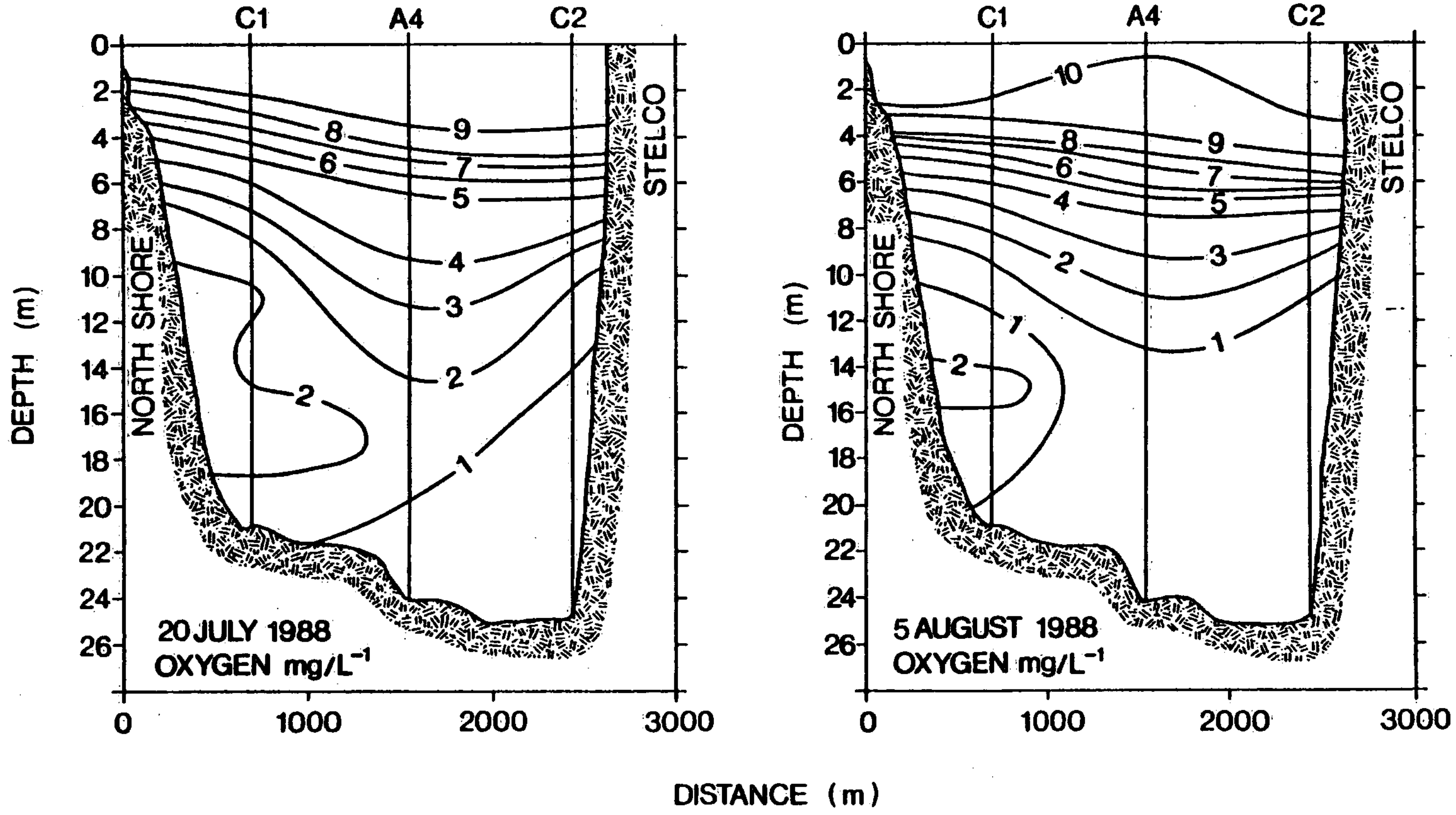
HAMILTON HARBOUR

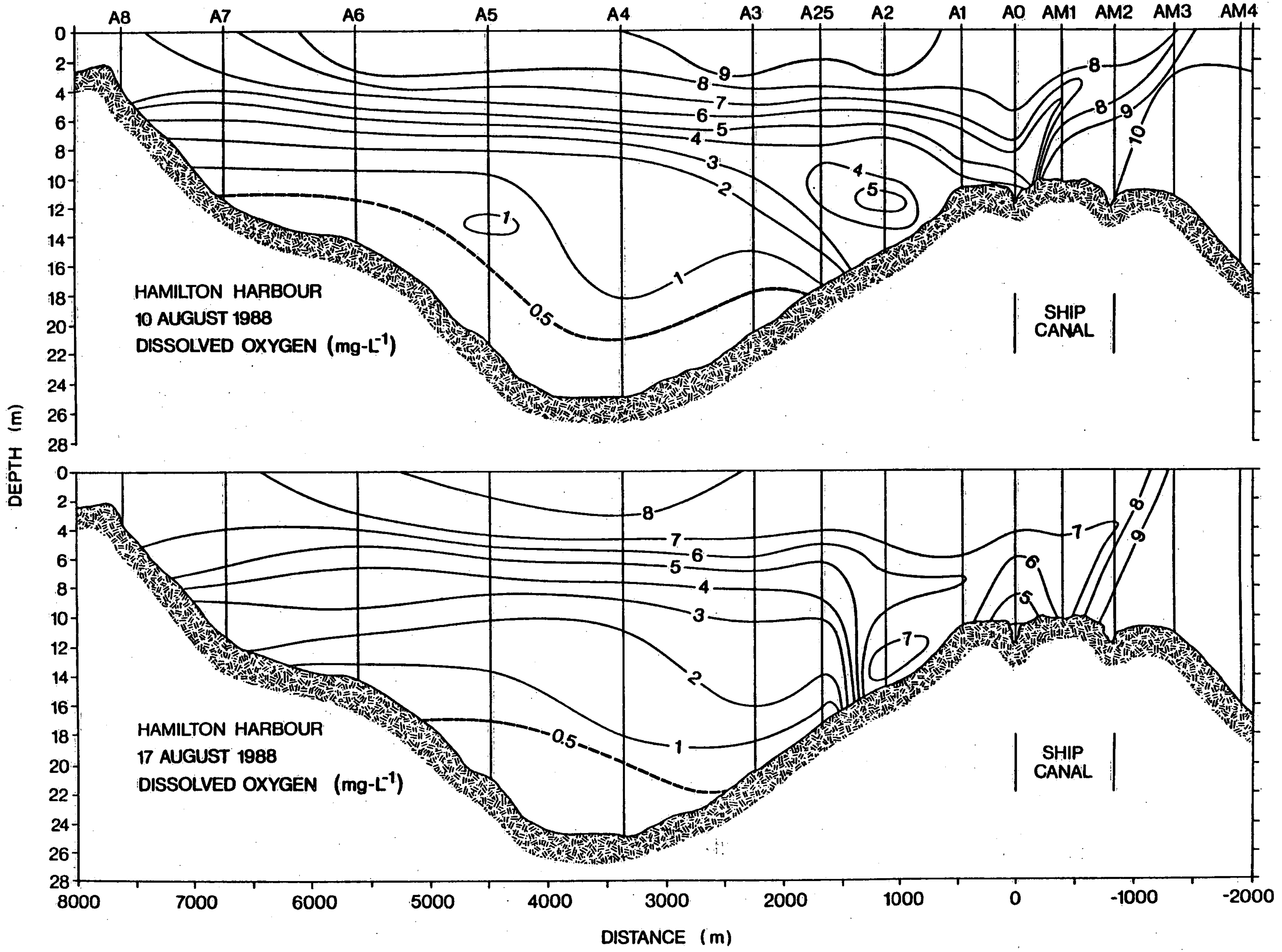


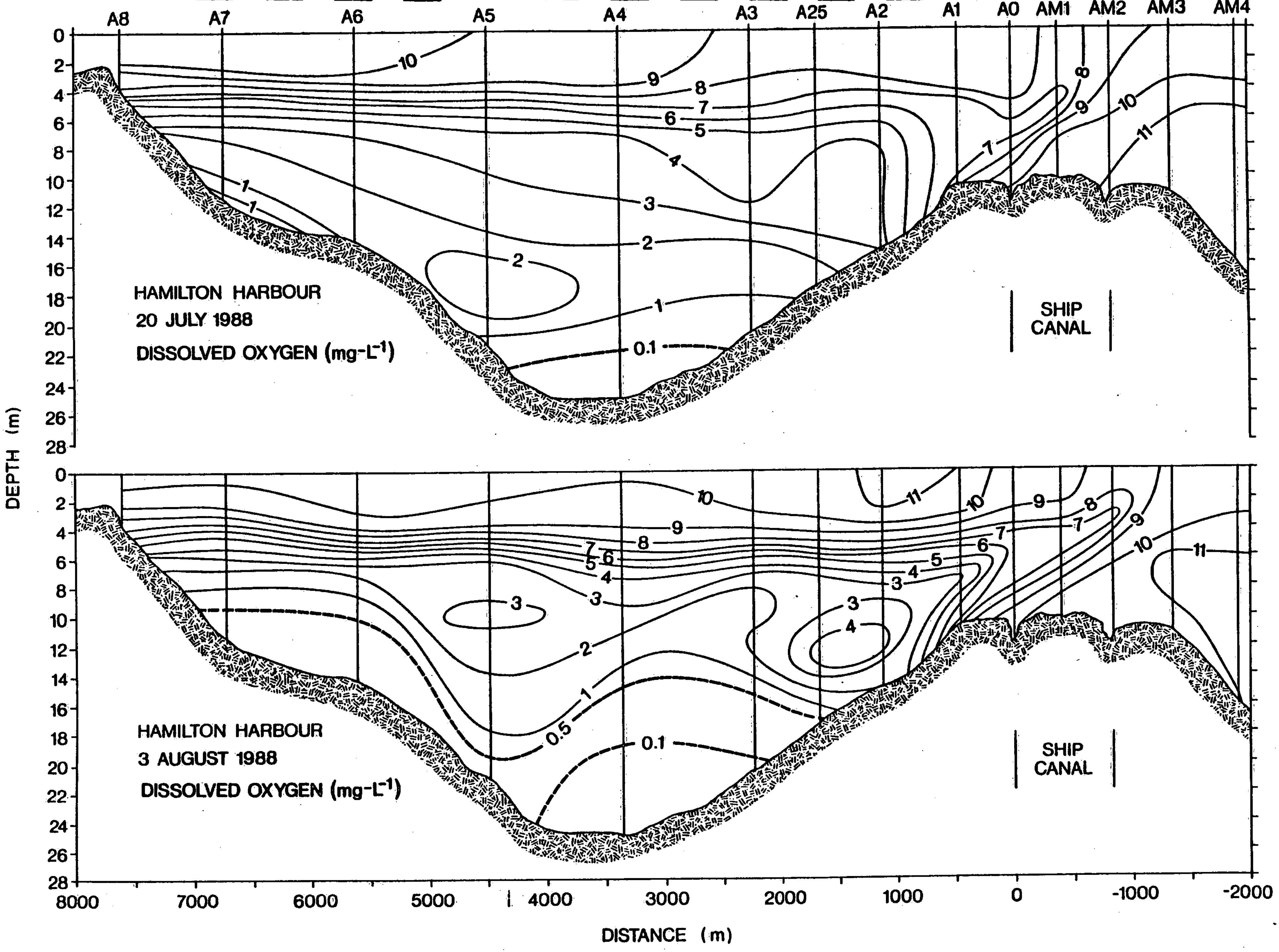

B1
B2
B3
B4
B5
B6
NORTH SHORE
WINDERMERE BASIN
13
12
11
10
9
8
7
6
5
4
3
2
1
DISS. OXYGEN mg-L^{-1}
6 JULY 1988
DISS. OXYGEN mg-L^{-1}
14 JULY 1988
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
DISTANCE (m)
0
1000
2000
3000
4000
5000
6000


HAMILTON HARBOUR
B1
B2
B3
B4
B5
B6
NORTH SHORE
WINDERMERE BASIN
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
10
9
8
7
6
5
4
3
2
5
4
2
DISS. OXYGEN mg-L-1
20 JULY 1988
12
11
10
9
8
7
6
5
4
3
3
2
1
DISS. OXYGEN mg-L-1
3 AUGUST 1988
0
1000
2000
3000
4000
5000
6000
DISTANCE (m)

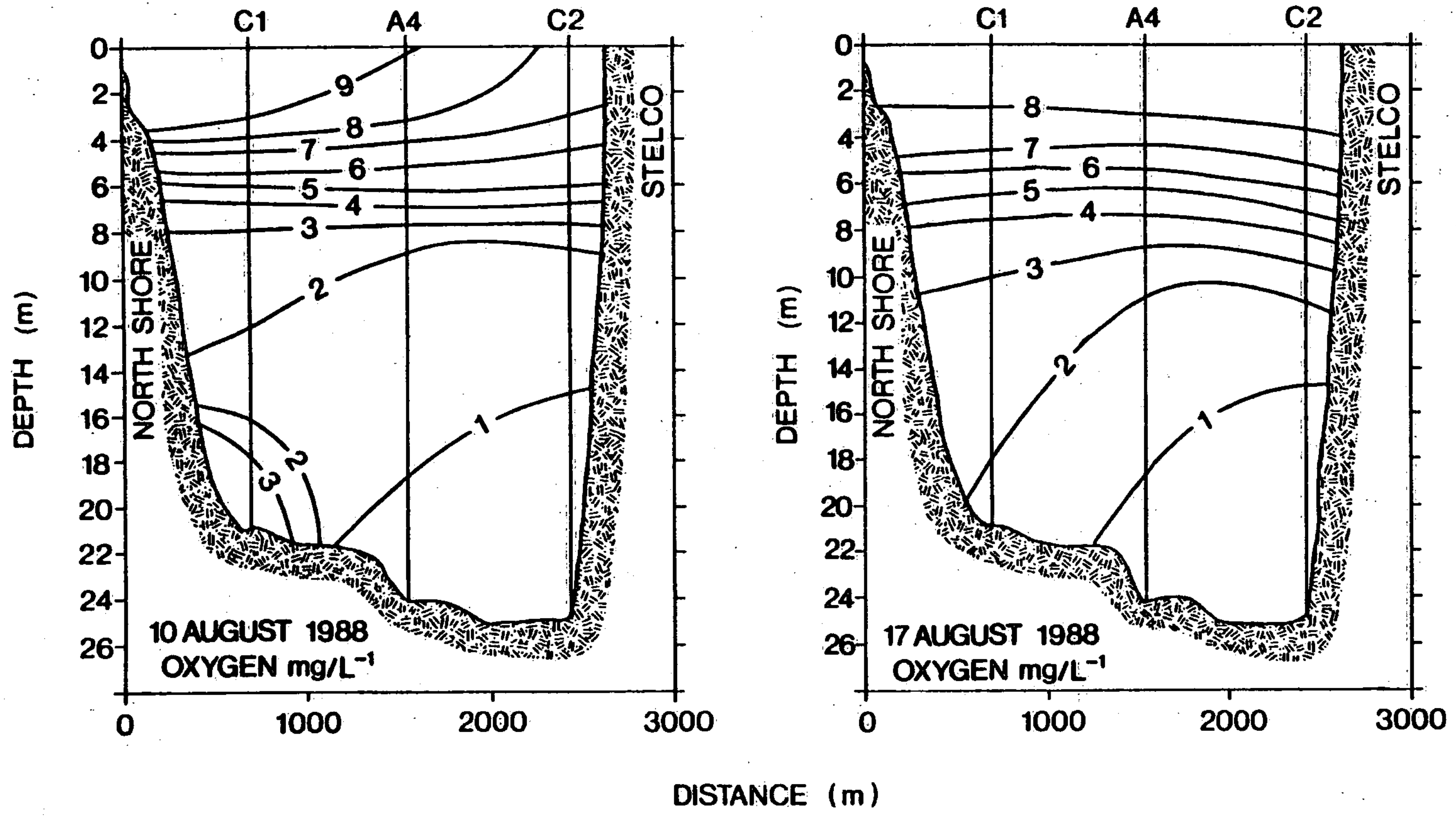
HAMILTON HARBOUR



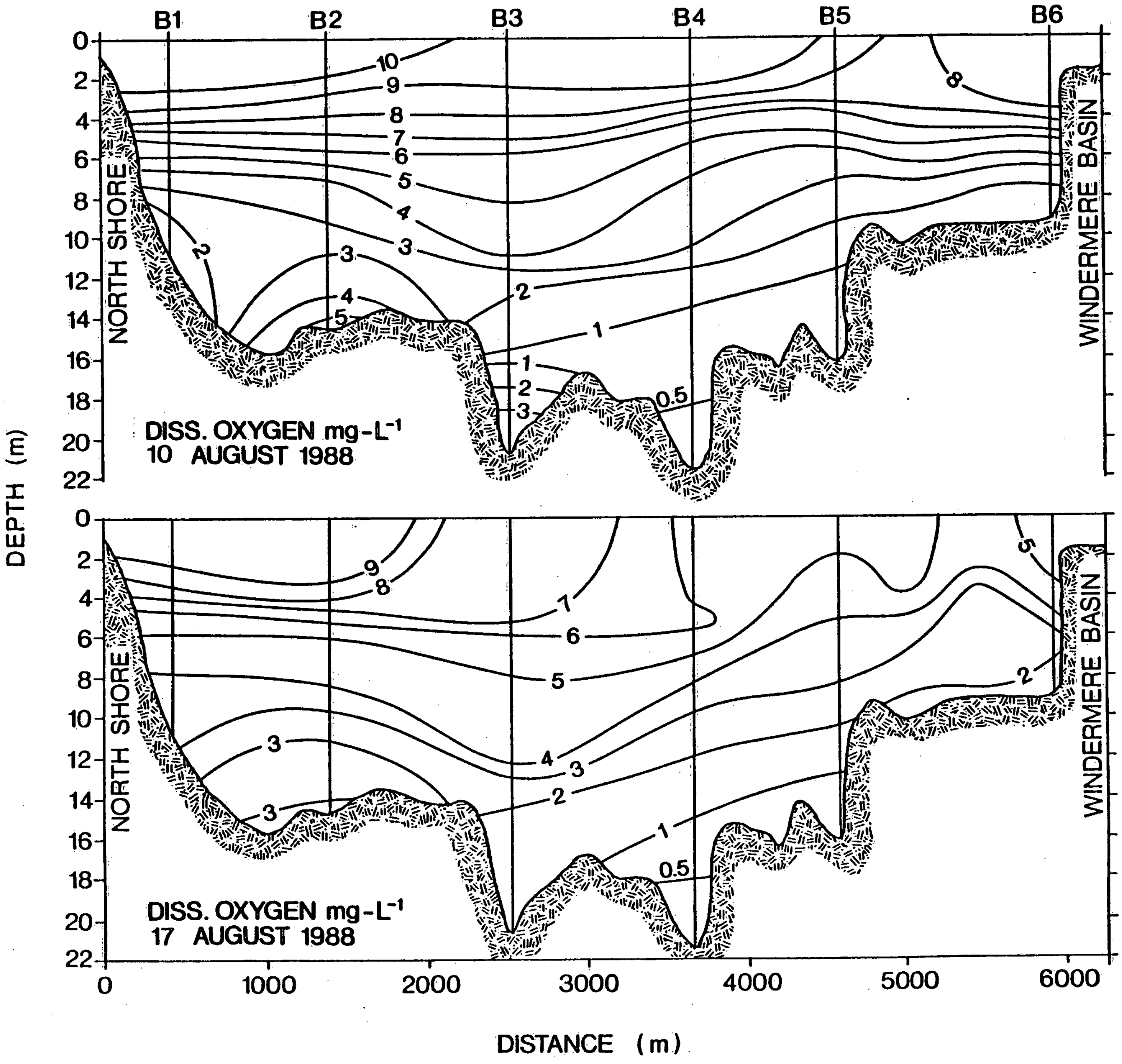

A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
HAMILTON HARBOUR
10 AUGUST 1988
DISSOLVED OXYGEN (mg-L^{-1})
HAMILTON HARBOUR
17 AUGUST 1988
DISSOLVED OXYGEN (mg-L^{-1})
SHIP CANAL
SHIP CANAL
0.5
1
2
3
4
5
6
7
8
9
10
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000


A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
HAMILTON HARBOUR
20 JULY 1988
DISSOLVED OXYGEN (mg-L-1)
SHIP CANAL
HAMILTON HARBOUR
3 AUGUST 1988
DISSOLVED OXYGEN (mg-L-1)
SHIP CANAL
DEPTH (m)
DISTANCE (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
0.1
0.5
1
2
3
4
5
6
7
8
9
10
11

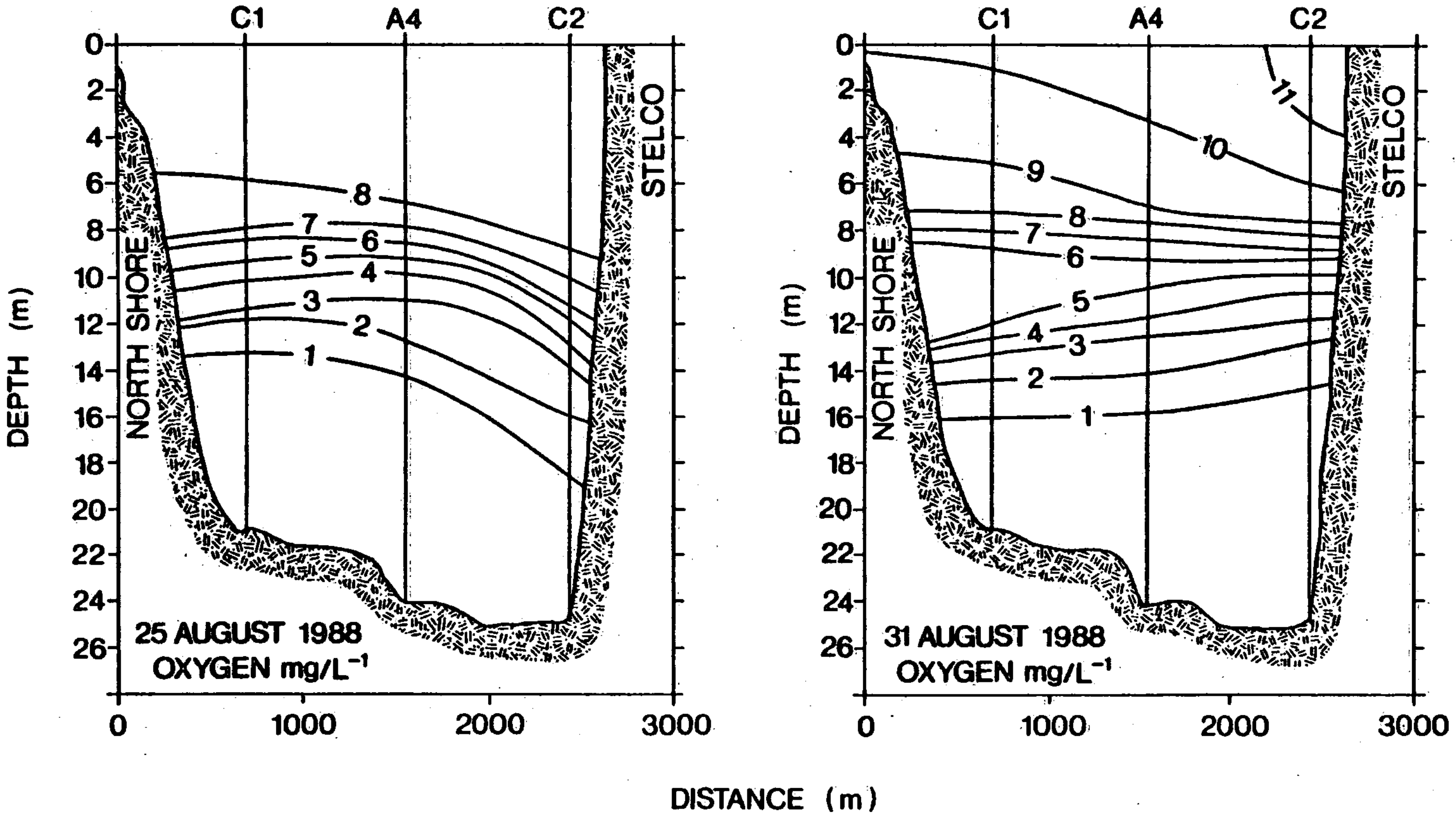
HAMILTON HARBOUR

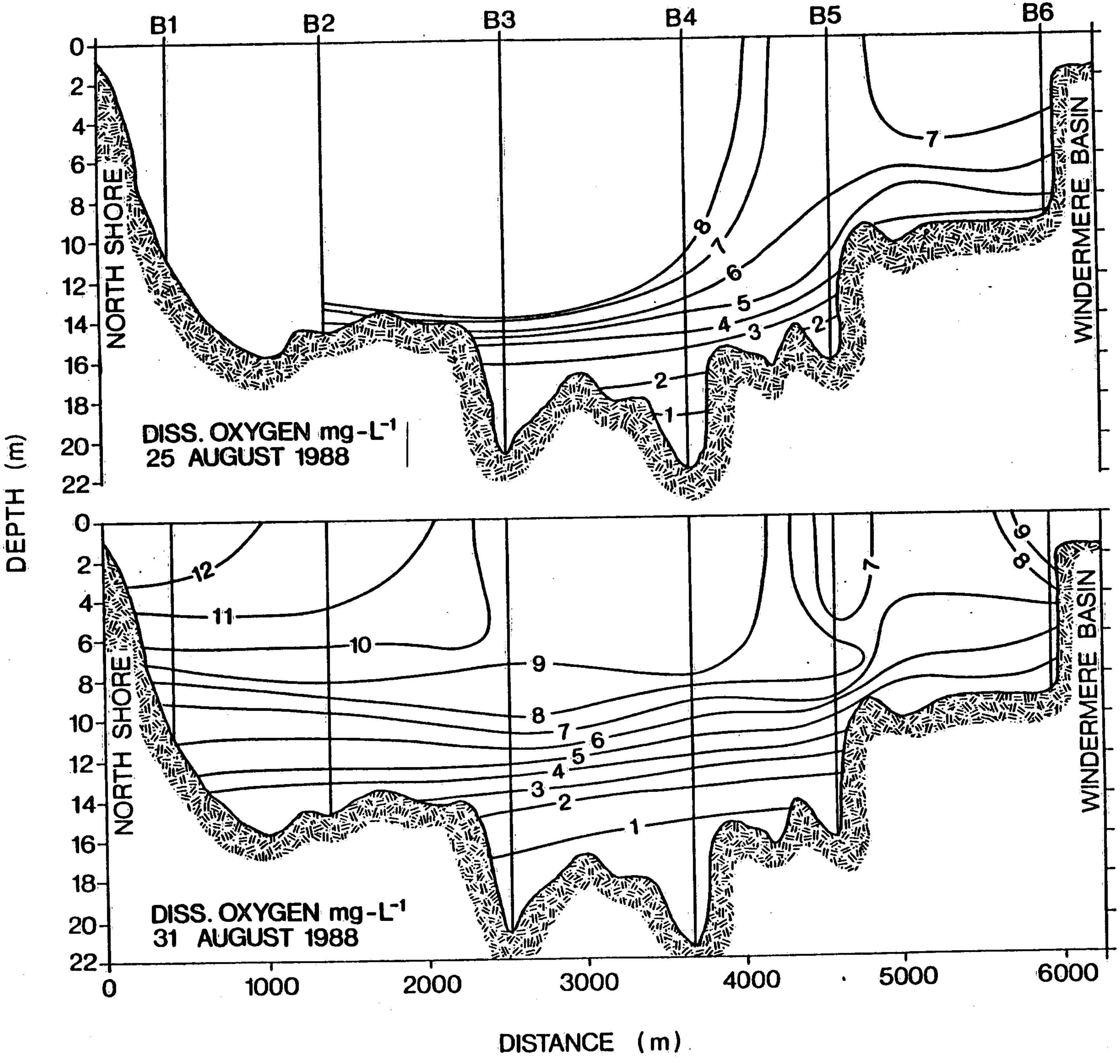


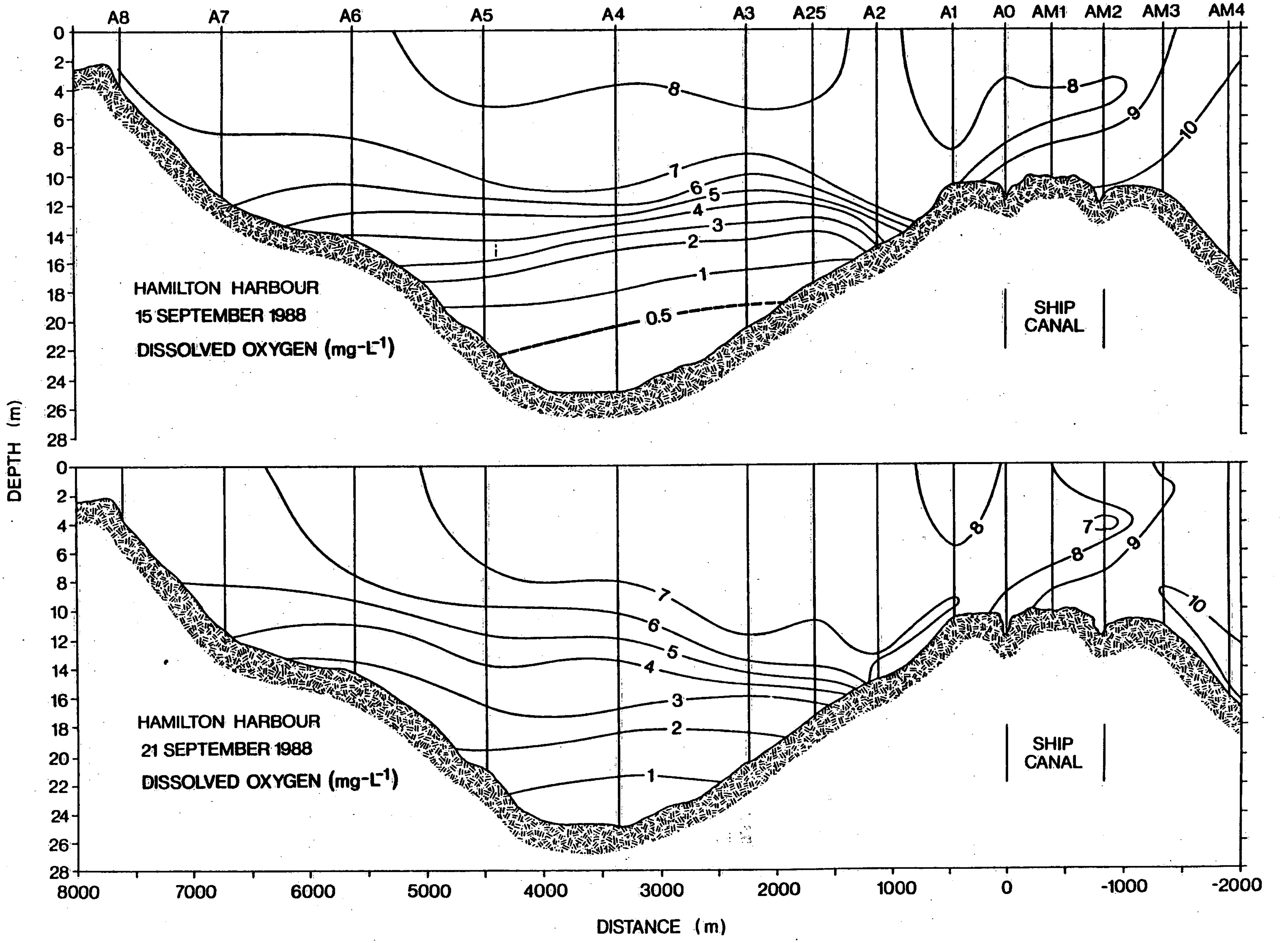
HAMILTON HARBOUR



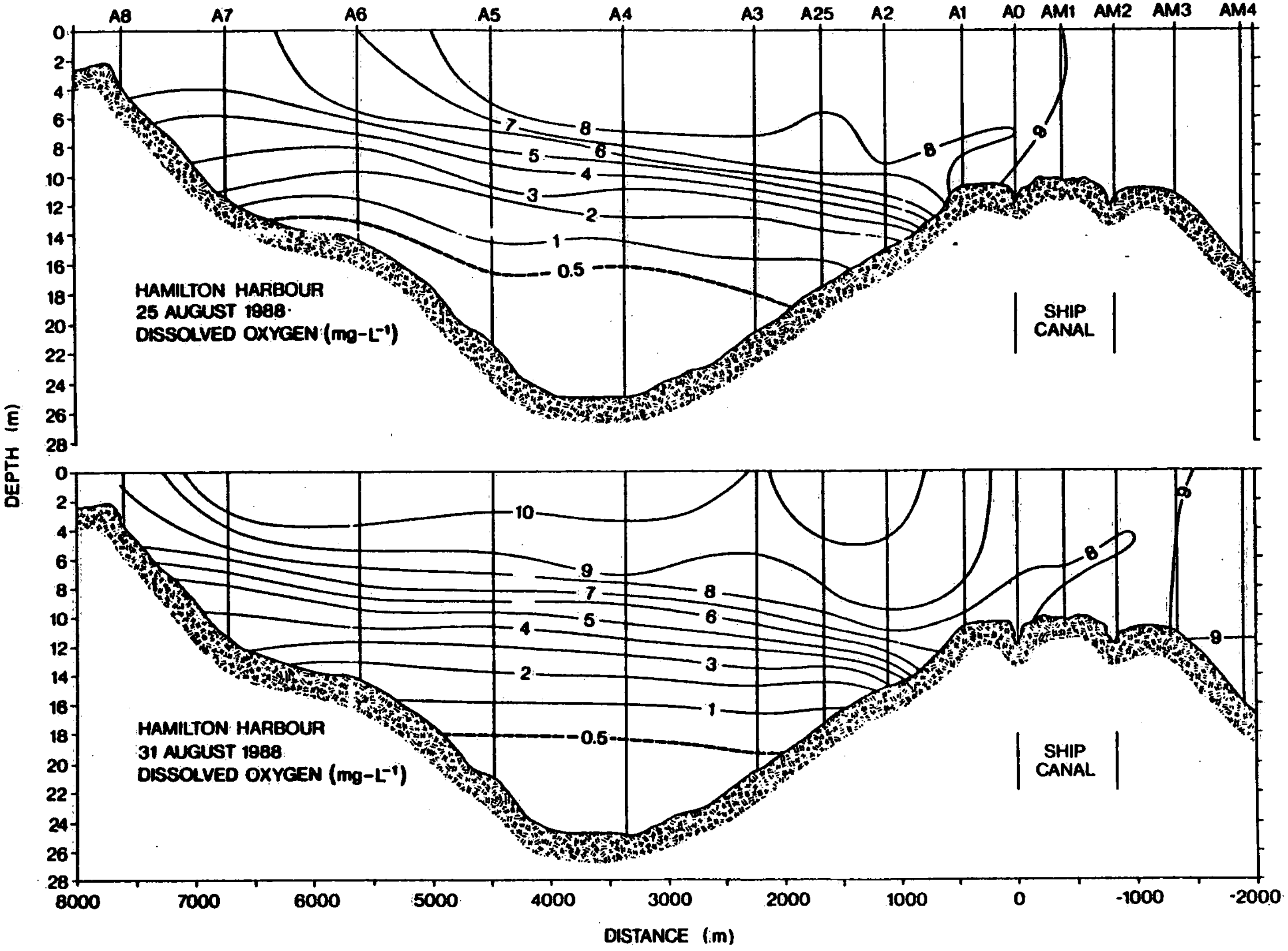
HAMILTON HARBOUR

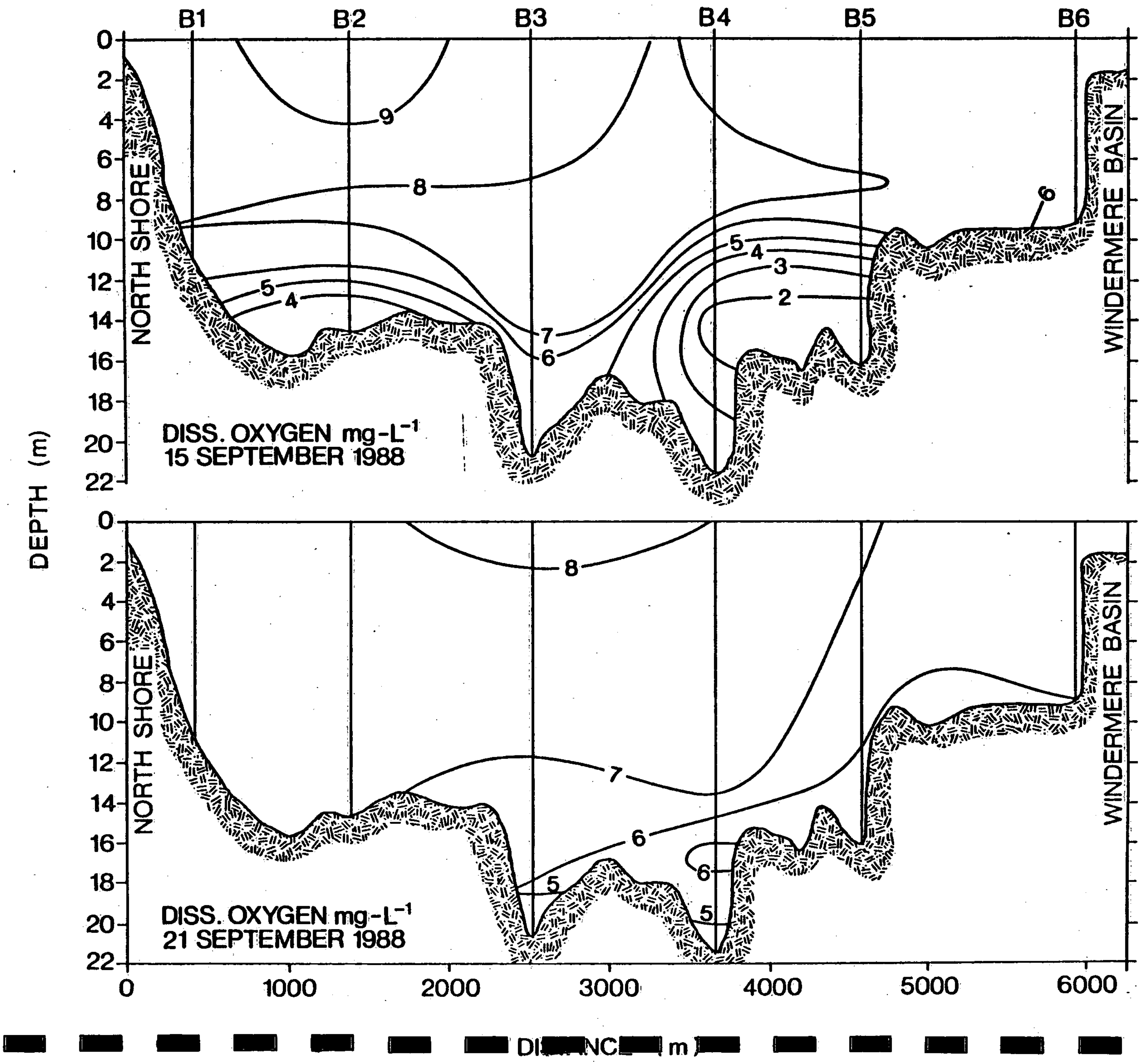



B1
B2
B3
B4
B5
B6
NORTH SHORE
WINDERMERE BASIN
DISS. OXYGEN mg-L-1
25 AUGUST 1988
DISS. OXYGEN mg-L-1
31 AUGUST 1988
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
DISTANCE (m)
0
1000
2000
3000
4000
5000
6000
1
2
3
4
5
6
7
8
9
10
11
12


HAMILTON HARBOUR
15 SEPTEMBER 1988
DISSOLVED OXYGEN ($mg\text{-}L^{-1}$)

HAMILTON HARBOUR
21 SEPTEMBER 1988
DISSOLVED OXYGEN ($mg\text{-}L^{-1}$)


A8
A7
A6
A5
A4
A3
A25
A2
A1
A0
AM1
AM2
AM3
AM4
HAMILTON HARBOUR
25 AUGUST 1988
DISSOLVED OXYGEN (mg-L⁻¹)
SHIP CANAL
HAMILTON HARBOUR
31 AUGUST 1988
DISSOLVED OXYGEN (mg-L⁻¹)
SHIP CANAL
10
9
8
7
6
5
4
3
2
1
0.5
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
DISTANCE (m)
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000


B1
B2
B3
B4
B5
B6
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
22
NORTH SHORE
WINDERMERE BASIN
9
8
7
6
5
4
3
2
DISS. OXYGEN $mg\text{-}L^{-1}$
15 SEPTEMBER 1988
8
7
6
5
6
5
DISS. OXYGEN $mg\text{-}L^{-1}$
21 SEPTEMBER 1988
0
1000
2000
3000
4000
5000
6000
DISTANCE (m)