Contractor Report Series 81-4

DEEP WATER FLOW AND EXCHANGE PROCESSES IN ALICE ARM, B.C.

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D.P. Krauel,

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This report was prepared by D.P. Krauel of Woodward-Clyde Consultants, Victoria, B.C. for the Environmental Protection Service, West Vancouver, B.C. The contents of this report are the responsibility of the Contractor.

Deep Water Flow and Exchange Processes in Alice Arm, B.C.

Prepared for

Environmental Protection Service,
Environment Canada
West Vancouver, B.C.

by

D.P. Krauel Ph.D.

March 1981

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Woodward-Clyde Consultants
16 Bastion Square, Victoria, British Columbia V8W 1H9

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1.0 INTRODUCTION

Amax Canada Limited (formerly Climax Molybdenum Corporation of British Columbia) is preparing to re-open the Kitsault mine located on Alice Arm, approximately 144 km north of Prince Rupert, British Columbia (Fig. 1.1). The Kitsault mine was originally operated by British Columbia Molybdenum Limited between October 1967 and April 1972 with a mill capacity of approximately 6,000 tons per day. The tailings effluent, which consists of a slurry of fine sand-like material after extraction of the molybdenum, was discharged directly into Lime Creek which flows into Alice Arm near its head. Approximately 12.6 million tons of tailings were discharged into Alice Arm during the period of operation.

Amax Canada Limited is proposing to start operations in April 1981 and will double the throughput rate to 12,000 tons per day. At the proposed production rate, the ore reserves are expected to last about 26 years which represents a total of approximately 100 million tons of tailings. The operations carried on at the Kitsault site include open-pit mining and milling of the ore to produce a molybdenum concentrate. The milling operation involves crushing and grinding the ore, and removing the molybdenum minerals. About 20 tons of molybdenum concentrate will be produced each day from the 12,000 tons of ore. The tailings will be introduced into Alice Arm via a pipeline from the mill that will terminate on the bottom of the Arm between the mouths of Lime Creek and Roundy Creek at a depth of 50 m below the surface (Fig.1.2)

The Alice Arm Tailings Deposit Regulations, passed in April 1979, authorize the deposit of the tailings from the Kitsault mine into Alice Arm. The Regulations contain several conditions, including the requirement that the tailings remain below the 100-m level and not pass west of a N-S line at 120° 39' 45" which runs through the vicinity of Hans Point.

The present review of the physical oceanography of Alice Arm was completed at the request of the Environmental Protection Service of Environment Canada. Emphasis has been placed on a comparison of the dynamics of Alice Arm

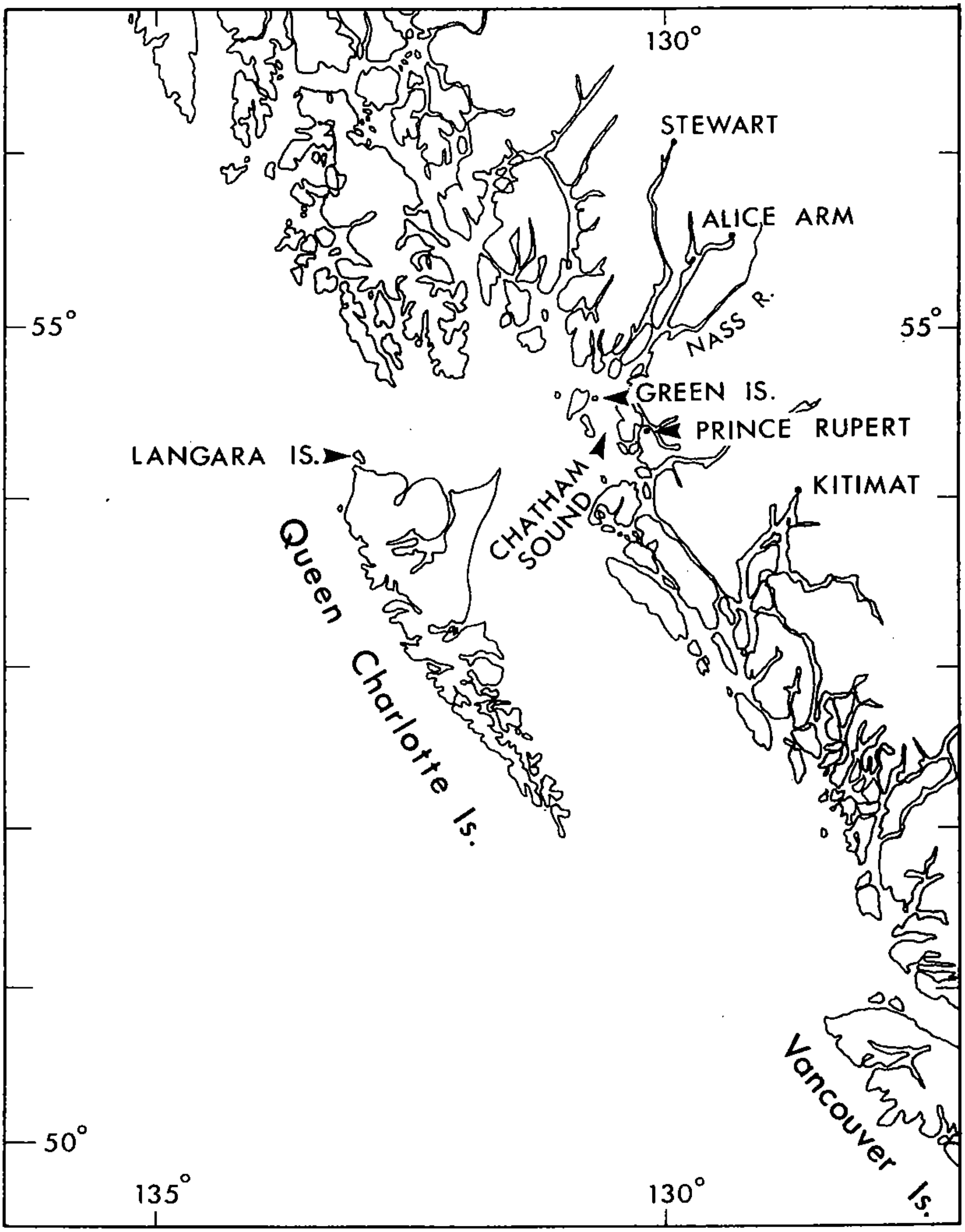


Figure 1.1 General location map.

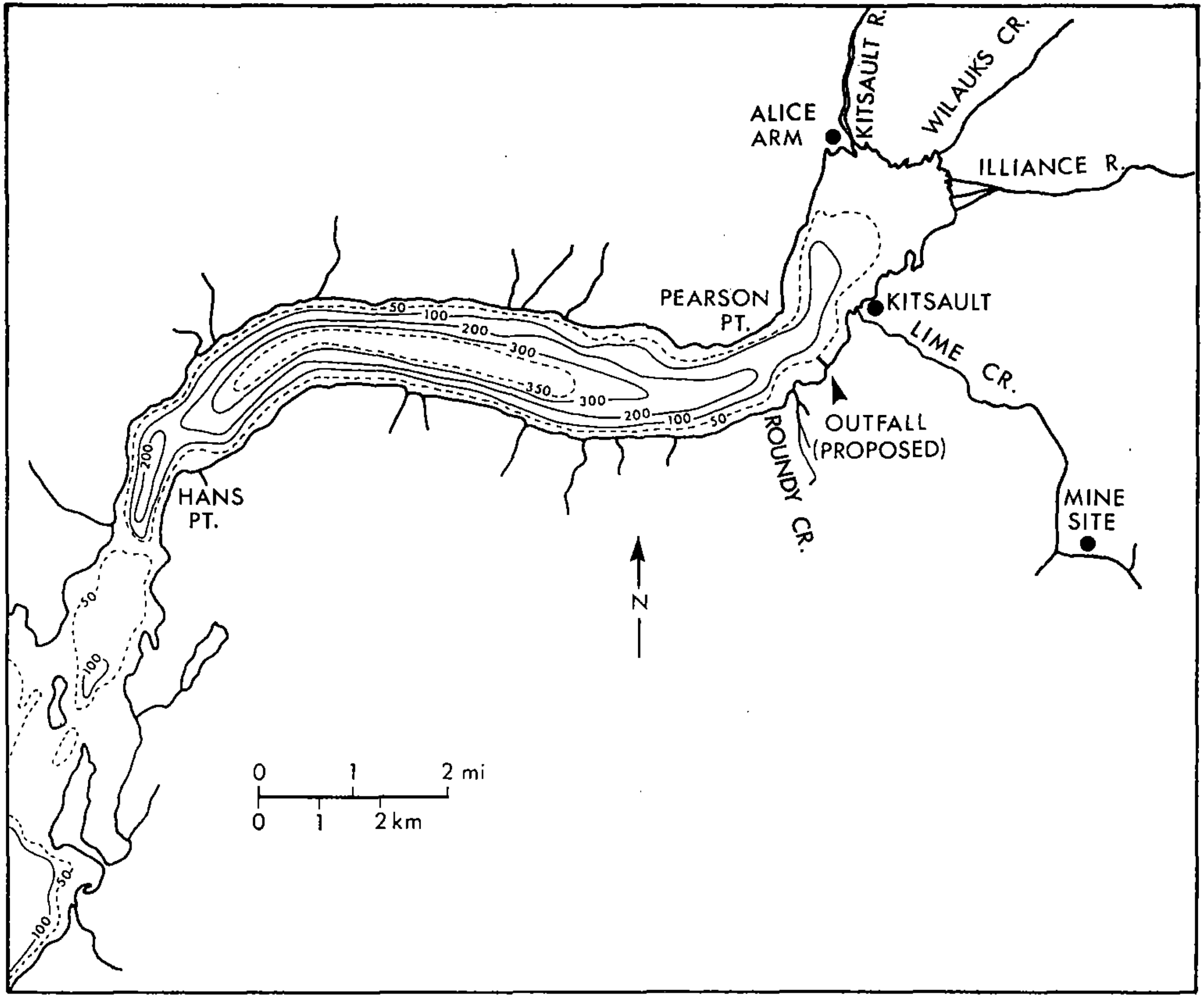


Figure 1.2 Plan view of Alice Arm, showing bathymetry and fresh water sources.

with that of similar fjords, which have been studied in more detail. In particular the circulation and the dynamics of deep water renewal in Alice Arm have been examined and an assessment of the probability of the advection or resuspension-and-advection of the tailings out of Alice Arm has been made.

This study does not address the impact of the tailings on the marine life within Alice Arm or the surrounding waters. It was not within the terms of reference of the present study to examine the toxicity of the dissolved metal content of the tailings, or the geochemistry of the tailings, which may leach further concentrations of metals while suspended in the water column or after deposit on the bottom. The maximum dissolved concentrations of arsenic, copper, lead, nickel, zinc, radium 226, and cadmium in the liquid portion of the mill effluent are set in the Regulations. An examination of the effect of increased sediment rates on the benthos of Alice Arm was also not within the terms of reference of the present study.

The present study reviewed all pertinent oceanographic and related data to determine:

(1) the circulation and dynamics of Alice Arm including the frequency and magnitude of deepwater exchange processes, and the water movements near the sill and near the proposed discharge point for the tailings,

(2) the dispersal of the tailings and the probability of resuspension as a result of bottom currents associated with the tides or exchange processes, or turbidity currents associated with submarine slides, and

(3) the type of additional data required to better understand the dynamics of Alice Arm.

The study did not undertake any further data collection but relied upon the existing data base. The majority of the physical oceanographic data were collected by Dobrocky Seatech under the direction of Dr. J.L. Littlepage for Climax Molybdenum Corporation of British Columbia and published in a series of reports listed in Appendix A. Additional oceanographic data were made available by the University of British Columbia, Pacific Geoscience Centre, and Environmental Protection Service.

2.0 PHYSICAL SETTING

2.1 Physiography

Alice Arm is a fjord inlet at the head of Observatory Inlet in the Coast Mountains of northwestern British Columbia near the Alaskan border (Figs. 1.1; 2.1). The Arm is approximately 19 km long and 1.4 km wide with a mean sea level surface area of 27 km^2. The Arm has a maximum depth of 386 m (below chart datum) and is separated from Observatory Inlet by two sills of 42 and 20 m depths (below chart datum) at distances of 16 and 19 km respectively from the head of the Arm (Figs. 1.2; 2.1).

At the junction of Alice Arm with Observatory Inlet, Hastings Arm branches off to the north with a sill depth of 51 m and extends a distance of 25 km, with a maximum depth of approximately 310 m and a mean width of 1.4 km. Observatory Inlet, with a maximum depth of 540 m, extends to the southwest a distance of 40 km where it shallows to a sill depth of 50 m before joining Portland Inlet. Portland Inlet continues to the southwest a distance of approximately 45 km with depths increasing to a maximum of approximately 600 m when it enters Chatham Sound.

Glacial activity during the Pleistocene steepened the valley walls to produce the typical U-shaped cross sections of deep fjords in the granitic Coastal Mountains, and deposited the shallow sills, which are composed of glacially transported debris or rock. The Alice Arm area was heavily glaciated during the Pleistocene and remnant glaciers still exist on the upper slopes of the headwaters of the region. Isostatic rebound has raised the land since the Pleistocene and marine clays, deltas, and beaches indicate that the maximum submergence was 148 m below the present sea level of Alice Arm (Holland, 1964).

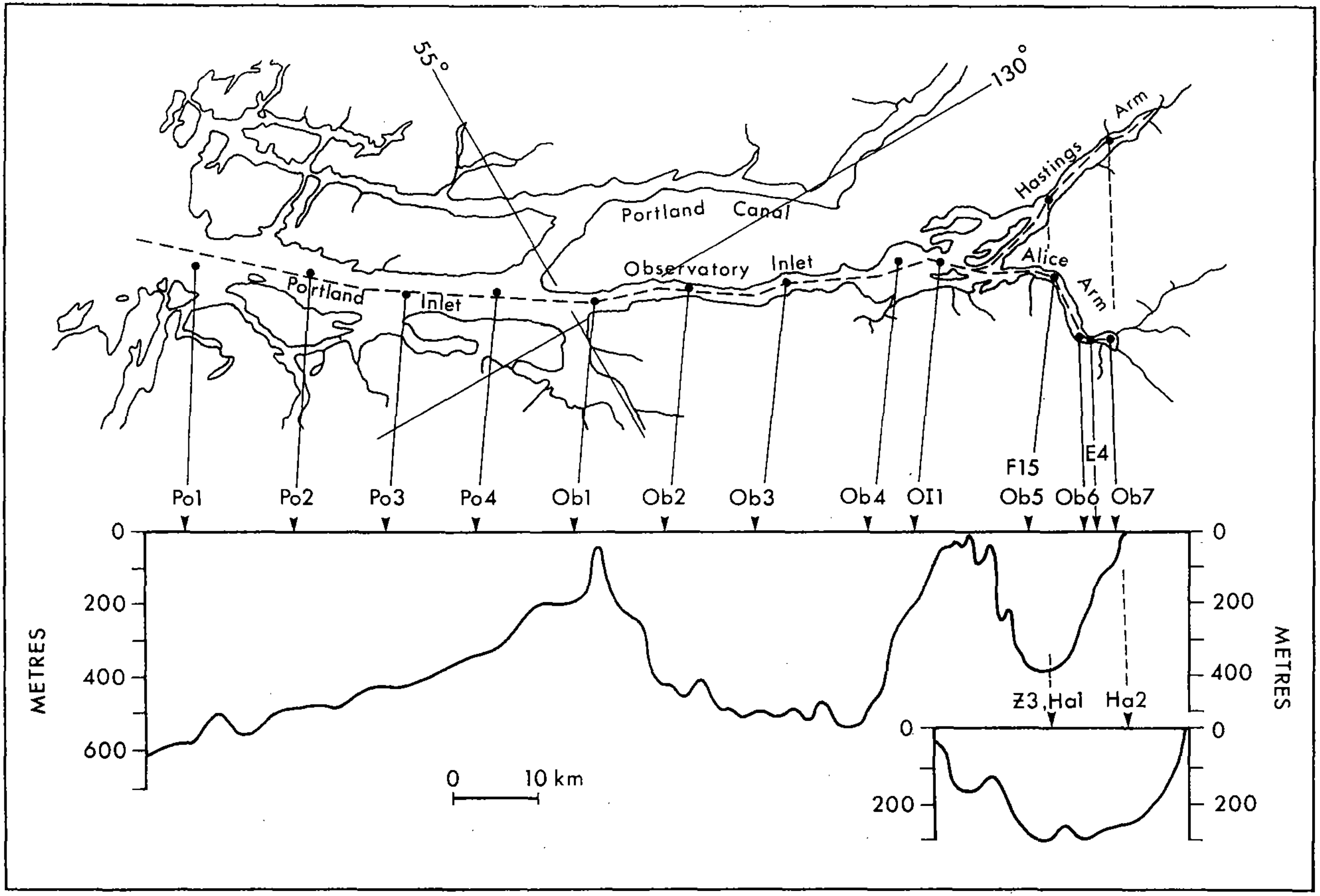


Figure 2.1 Plan view and longitudinal section of Portland Inlet to Alice Arm, showing station locations.

2.2 Climatology

The climate of the Alice Arm area is influenced for most of the year by the Pacific Ocean, a source of low-pressure systems which move eastward onto the coast with their associated fronts. The frequency of these frontal systems peaks in the autumn producing a maximum mean monthly precipitation in October. The September to March period tends to be overcast with heavy precipitation and strong winds, while periods of high pressure in the summer months tend to produce clearer, drier, and calmer conditions. The high topography surrounding Alice Arm and the adjoining inlets tends to funnel the winds in either an up-inlet or down-inlet direction.

The maritime influence produces mild winters and cool summers, however the climate also has many characteristics of a continental-type climate. During the winter months cold arctic air, accompanied by strong northerly winds, is frequently funnelled down the inlets to the coast, and winter snowstorms deposit approximately 40 percent of the total precipitation. The 1941-1970 temperature normals for British Columbia (Canada, Department of Environment, 1971) show an annual cycle in the mean monthly air temperature at Alice Arm which has a minimum in January of -6.1° C, a maximum in July of 14.4° C, and an annual mean of 4.4° C (Fig. 2.2). The total precipitation normals for the same period show a peak in October of 352 mm and a minimum in June of 58 mm (Fig. 2.2). The total normal annual precipitation includes 1253 mm of rain and the water equivalent of 7930 mm of snow.

No long-term wind observations have been made that would permit the determination of wind normals at Alice Arm. The closest station with long-term records is at Prince Rupert, but it is a sheltered station (Kendrew and Kerr, 1955), and the wind observations are not representative of the winds in Alice Arm and the adjoining inlets. As in other inlets on the Pacific Coast of British Columbia, it is expected that local winds are influenced by topography and blow either up or down the inlet (Bell and Kallman, 1976). The stronger winds in the summer months are probably directed up-inlet, however the strongest winds probably occur in the winter and are directed down-inlet. Strong up-inlet winds are generated by active Pacific storms or sea breeze effects. The required conditions for strong outflow winds are

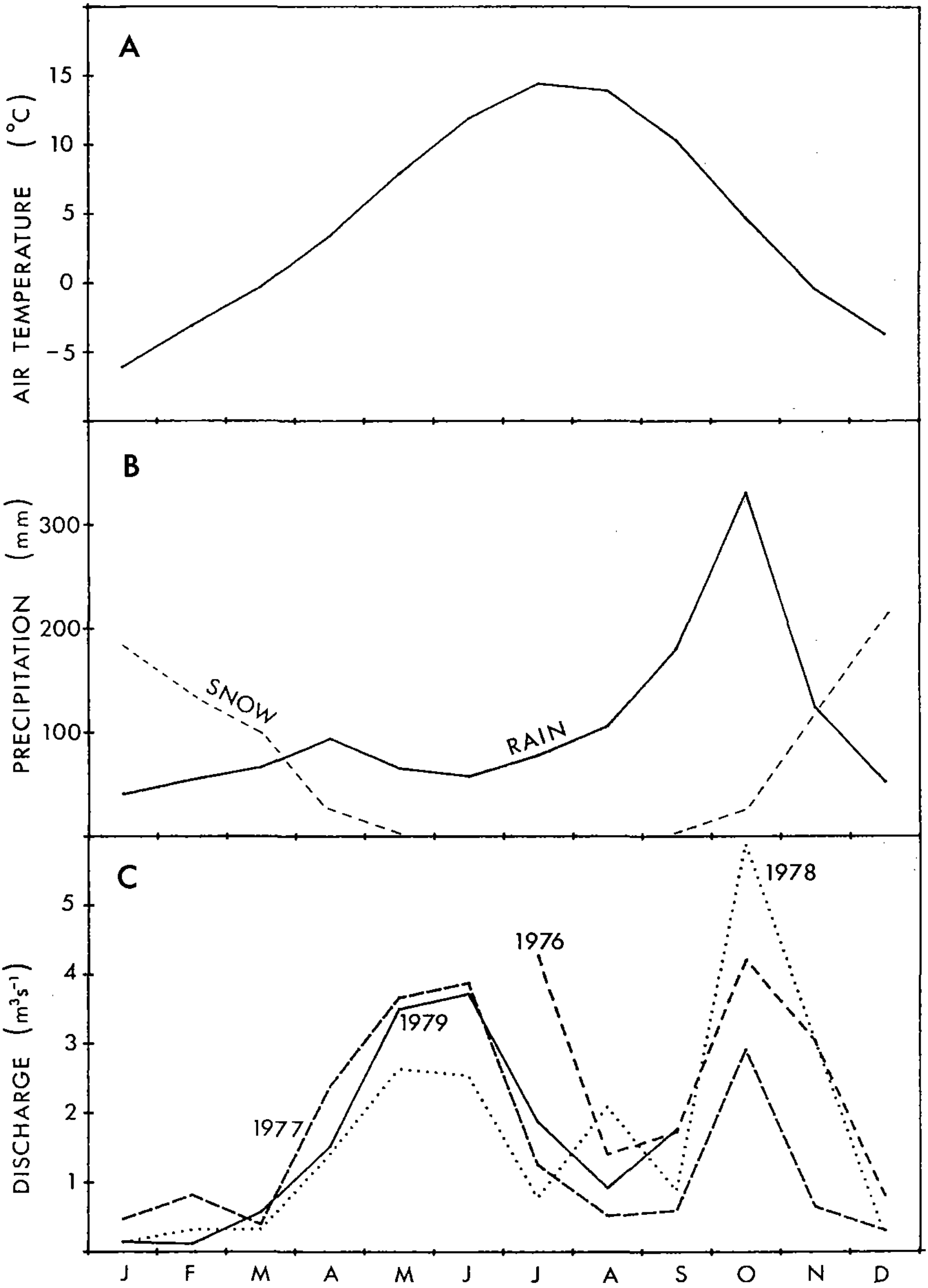


Figure 2.2 A. Alice Arm mean monthly air temperatures, (1941-1970);
B. Alice Arm mean monthly precipitation as rain and the water equivalent of the snow (1941-1970);
C. Mean monthly Lime Creek gauged discharge.

both meteorological and topographical, and include the presence of a high-pressure system over the central and northern interior of British Columbia, with a steep barometric gradient to direct arctic air to the west and south along the narrow NE-SW oriented fjords to the coast. These conditions are frequent during the winter, and the snow-covered uplands also add their katabatic influence (Phillips, 1977). These outflow winds are known to be important in Portland Canal and Observatory Inlet (Kendrew and Kerr, 1955), where winds in excess of 50 ms^{-1} have been observed by shipping. Since Alice Arm trends E-W it is not known how important these outflow winds are locally.

Figure 2.3 shows the prevalence of up-inlet and down-inlet winds and their annual cycle in the N-S trending Kitimat area 150 km to the southeast. The Kitimat anemometer is also in a sheltered location so that the absolute speeds are not representative of the over-water speeds in the inlets, however, the directions are representative of the seasonal variation in up-inlet and down-inlet winds.

A meteorological station located on the Lime Creek delta at Kitsault continuously recorded wind speed and direction, air temperature, and precipitation for the period 23 June, 1978 to 22 June, 1979 (Buckingham, 1980). The average wind speed for the year was 2.2 ms^{-1}, with a maximum monthly mean speed of 3.2 ms^{-1} in July, 1978. These low speeds indicate that either the anemometer was located in a relatively sheltered location, or the topography surrounding Alice Arm shelters it from strong winds. The maximum gust (2-second duration) of 41.8 ms^{-1} was recorded from the south on 1 November, 1978, at which time the mean wind speed (15-minute average) was 21 ms^{-1}.

The wind and air temperature records display an obvious diurnal influence from March to mid-September (Fig. 2.4). In the early-morning a weak land breeze blowing down-inlet persists until late-morning when, as a result of rising air temperatures over the land, the wind reverses to a moderate sea breeze blowing up-inlet. The up-inlet winds continue until late-evening when, with falling air temperatures, the wind reverses to a land breeze again. This diurnal cycle was most obvious in July and August 1978 when the prevailing sea breeze averaged approximately 10 ms^{-1} and the land breeze, 2 ms^{-1}.

	J	F	M	A	M	J	J	A	S	O	N	D
N	53	45	31	17	14	8	9	13	21	25	36	45
NE	14	11	12	8	12	5	5	5	9	12	22	16
E	2	2	4	4	4	3	4	2	3	4	2	2
SE	1	2	5	8	6	7	7	8	8	5	2	6
S	23	30	39	53	52	64	62	61	45	44	30	21
SW	6	5	6	8	11	11	11	8	9	6	6	6
W	0	1	1	1	1	1	1	1	1	1	0	1
NW	0	0	0	0	0	0	0	0	1	0	0	1
CALM	1	4	2	1	0	1	1	1	3	3	2	2
MEAN SPEED (ms^{-1})	5.2	3.7	3.2	3.1	3.1	3.3	3.2	3.0	2.8	2.8	3.4	3.9

Figure 2.3 Kitimat (Townsite), percent frequency wind direction and mean wind speed by month (1967-1975).

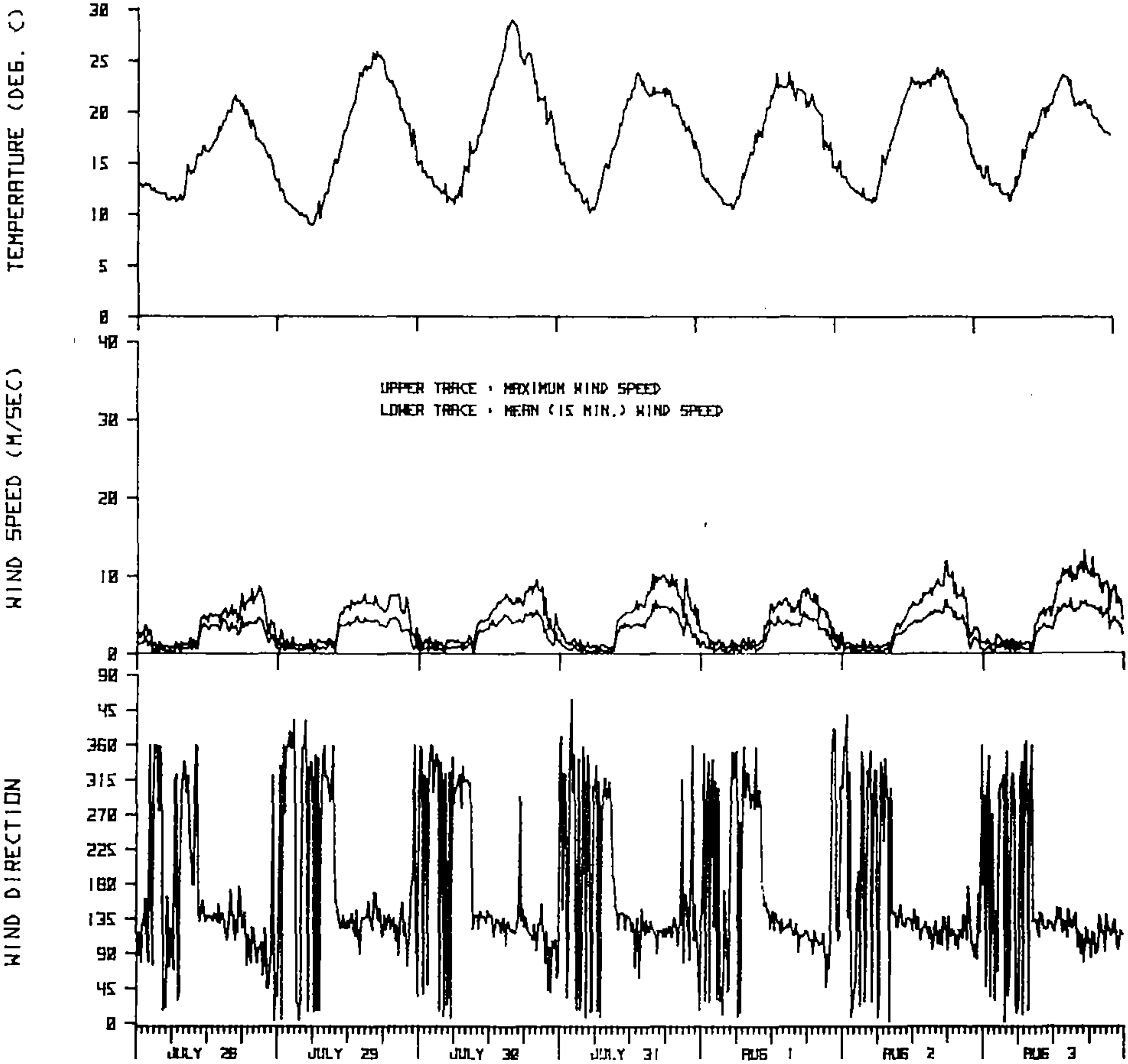


Figure 2.4 Observed air temperatures and wind speeds and directions at Kitsault, 28 July - 03 August, 1978.

The diurnal variation in September was occasionally obliterated by storms and the period of daily outflows became longer and the inflows shorter and weaker. By October 1978 the prevailing winds were down-inlet, a condition which persisted until May 1979 when the prevailing winds were again directed up-inlet.

2.3 Freshwater Inflow

A total land area of 793 km^2 drains into Alice Arm primarily through a series of rivers and creeks which are glacially fed and enter the Arm near the head (Fig. 1.2). The largest of these, the Kitsault and Dak Rivers, with a total drainage area of 454 km^2 (57%) join and enter the northern extremity of the Arm. The next largest basin (131 km^2) is drained by the Illiance River and Clary Creek which also enter the Arm at the head. A minor basin (10 km^2) drained by Wilauks Creek and located between the two major sources completes the freshwater inflows over the delta at the head of the Arm. Lime Creek (40 km^2) and Roundy Creek (21 km^2) enter the southern side of the Arm, approximately 2.5 and 4.0 km respectively from the head. A total of 656 km^2 or 83 percent of the total drainage area empties into Alice Arm upstream of an imaginary N-S line across the Arm at Pearson Point approximately 4 km from the head.

The only stream flow data that are available are for Lime Creek, which has been gauged since July 1976. The monthly mean gauged discharges have been plotted in Figure 2.2 for the available data from July, 1976 to September, 1979 (Canada, Department of Environment, 1977; 1978; unpublished data). The average discharge for this 39-month period was 1.74 $m^3 s^{-1}$. The annual cycle of freshwater discharge appears to have two peaks: one in May-June, associated with the spring melt, which results from thawing temperatures, and one in October, associated with increased precipitation, before the winter freeze-up.

Since the Lime Creek gauge records the discharge from 5 percent of the total land area draining into Alice Arm, an estimate of the total discharge entering the Arm can be obtained by multiplying the observed discharges by a factor of twenty. This leads to an average total freshwater inflow of

34.8 m^3s^{-1}, with a monthly minimum in February, 1979 of 2.2 m^3s^{-1}, and a monthly maximum in October, 1978 of 118 m^3s^{-1} during the observation period. These estimates are in reasonable agreement with those of Foster (1976) who simulated the freshwater discharge from precipitation records and observed discharges from other drainage basins in the vicinity of Alice Arm. Foster predicted upper, lower, and most-probable mean monthly discharge values. The prorated Lime Creek data tend to the lower limits determined by Foster, but are within his limits; the minor peaks that he predicted for December and February were not observed during the three year period (1976-1979).

The observed daily freshwater discharges from Lime Creek for the period July, 1976 to September, 1977 are plotted in Figure 2.5.

2.4 Tides

Within Portland Inlet and Observatory Inlet, the barotropic tide closely approximates a standing wave with a lag of less than 15 minutes between Prince Rupert on the coast and any location up the Inlets to the mouth of Alice Arm (Canada, Fisheries and Oceans, 1981). The tides within Alice Arm are delayed by approximately 20 minutes relative to the tide times outside the constricted mouth, but it is expected that the tides within the Arm also approximate a standing wave with times of high or low waters everywhere the same within the Arm.

The tides are of the mixed type, mainly semi-diurnal. The mean tidal range in Alice Arm is 5.0 m but the large fortnightly component reduces the range to less than 2 m at neap tides and increases the range to approximately 8 m at spring tides (Fig. 2.6).

The tides were not observed during any of the observation periods. Hence all quoted tides are the predicted values from the Canadian Tide and Current Tables.

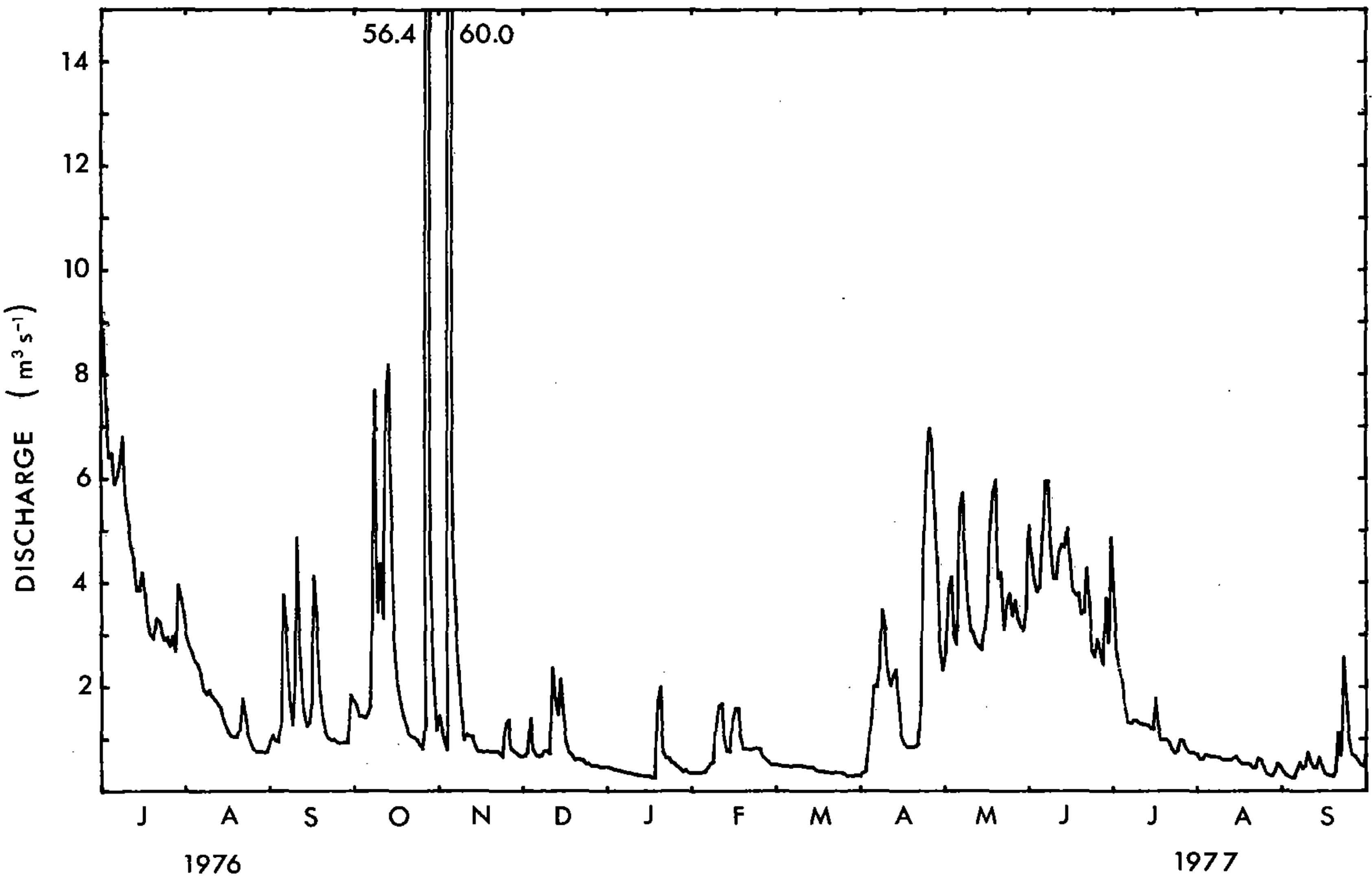


Figure 2.5 Lime Creek gauged daily discharge, July 1976 - September 1977.

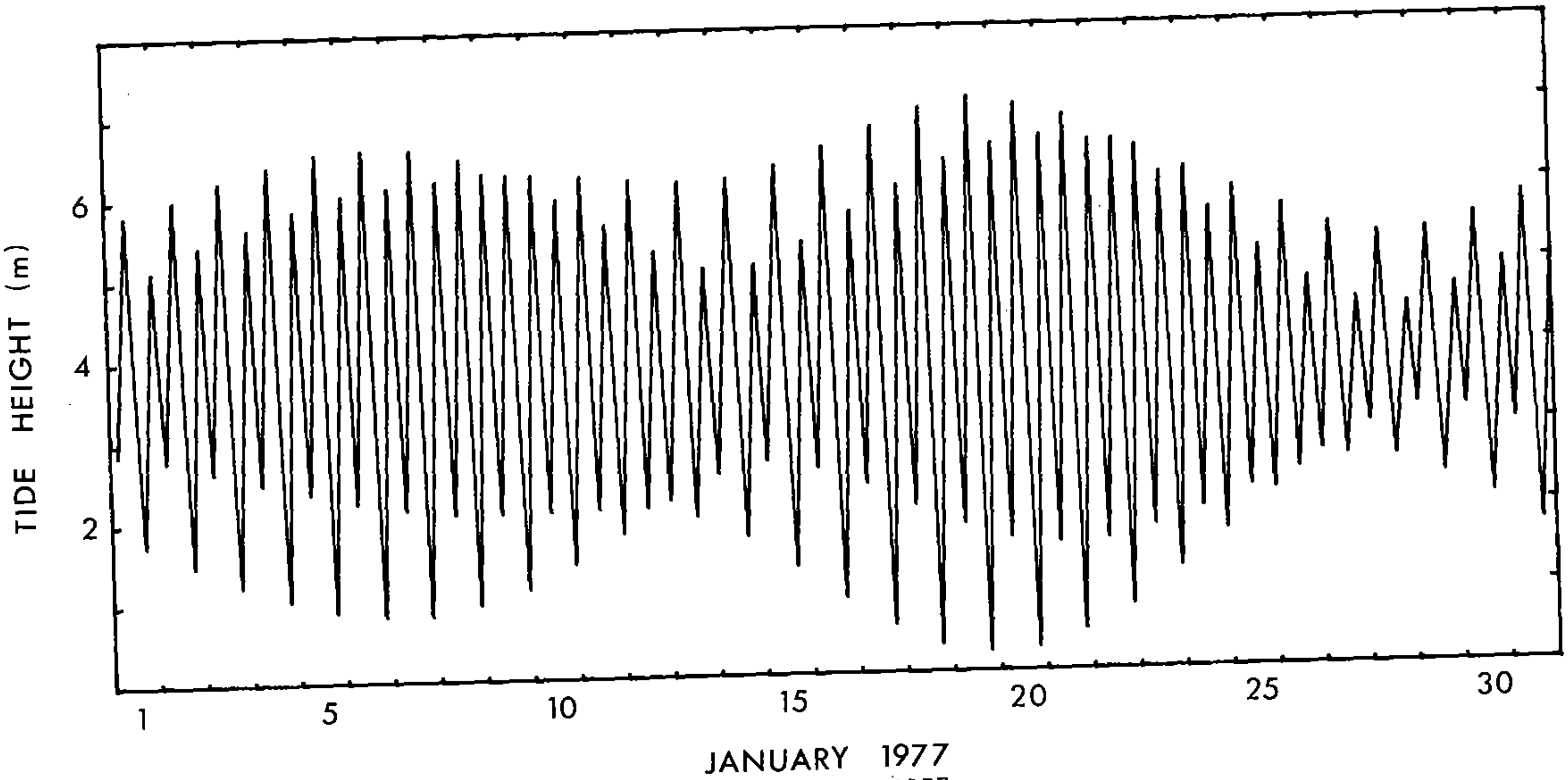


Figure 2.6 Prince Rupert predicted tides, January 1977.

3.1 Data

Oceanographic data collected in Alice Arm over the past 30 years have been assembled and analyzed. The Institute of Oceanography, University of British Columbia has reported hydrocast data from the Alice Arm area (UBC, 1953 and 1967) taken in July 1951 and May 1966. These data include temperature, salinity, and dissolved oxygen at standard depths to the bottom at stations Po1, Po2, Po3, Ob1, Ob2, Ob3, Ob4, Ob5, Ob6, Ob7, Ha1, Ha2 (Fig. 2.1). In 1974 under the direction of Dr. J.L. Littlepage, Dobrocky Seatech began a three year study of the Alice Arm area for the Climax Molybdenum Corporation. These data have been published in a series of reports listed in Appendix A and have been summarized by Webster (1977) and Littlepage (1978). The data include hydrocasts of temperature and salinity at standard depths and bottom dissolved oxygen made at irregular intervals between 1974 and 1977 at stations including OI1, F15, E4, Z3 (Fig. 2.1). From August 1976 to September 1977 Aanderaa recording current meters with temperature and conductivity sensors were moored at station F15 at approximately 10, 185, and 365 m and at station E4 at approximately 5, 53, and 97 m. These depths represent local near-surface, mid-, and near-bottom depths.

In October 1977 and May 1978, the Pacific Geoscience Centre lowered a heat probe through the water column and into the bottom sediments to obtain temperature profiles in the deepest part of Alice Arm near station F15 and in Observatory Inlet (T. Lewis, unpublished data). In May and October 1980, Environmental Protection Service occupied a series of hydrocast stations in the Alice Arm area including sites near stations F15 and E4 (Fig. 3.1). Temperature, salinity, and transmittance were observed at standard depths in May and continuously over the water column in October (D. Goyette, unpublished data). Most of the sampling techniques have been reported along with the data and will not be repeated here.

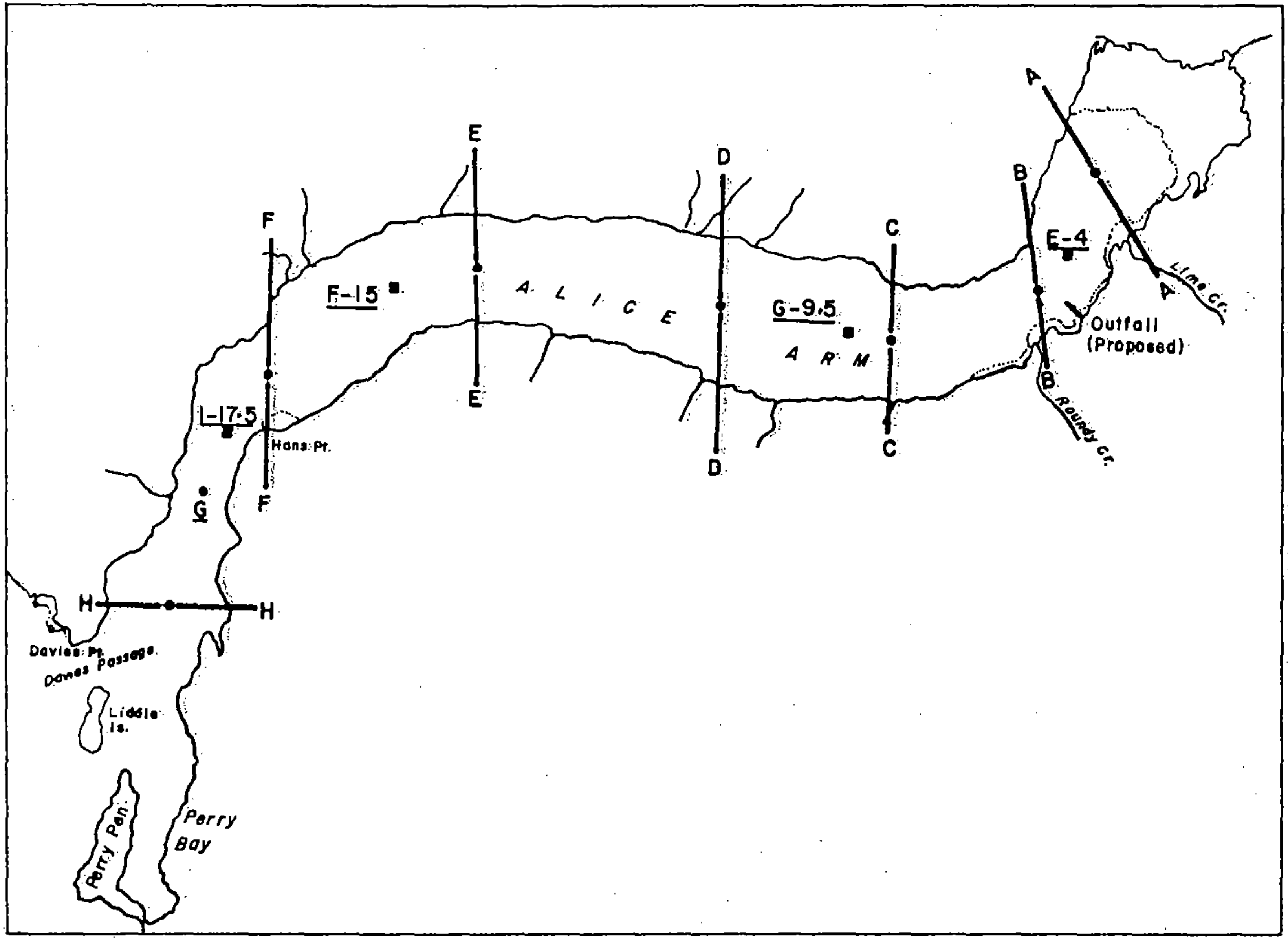


Figure 3.1 Environmental Protection Service station locations.

The data base is heavily biased to the summer period between May and October. December 1976 and March 1977 observations are the only winter data available.

3.2 Temperature - Salinity Distributions

Longitudinal sections of temperature, salinity, and density plotted from a series of stations along Alice Arm that were occupied over a period of a few hours display depth variations in the contours of the water properties along the Arm. Such behaviour is indicative of internal waves. As will be shown later from other data, internal waves are an important and common feature of Alice Arm. Any determination of horizontal gradients from a series of stations observed over a period of hours is questionable in the presence of internal waves. Since the longitudinal dimension of the Arm and the horizontal gradients of water properties are relatively small below sill depth, stations in the central, deepest part of Alice Arm (near station F15) should be representative of conditions in the fjord.

The temperature, salinity, and density profiles at stations near F15 are plotted in Figures 3.2 to 3.5 for each observation period. The most obvious feature of the profiles is a low density layer of warmer, less saline water at the surface for observations between May and October. Near the surface, both temperature and salinity change rapidly with depth and the sigma-t attains 90 percent of its maximum value at a depth of 20 to 30 m. Below this sharp surface pycnocline, the vertical gradients in the water properties rapidly decrease with depth. The December 1976 and March 1977 data do not display marked vertical gradients near the surface. This is as expected from the annual cycles of freshwater inflow and air temperature.

The profiles indicate significant variability in the water properties at all depths over the 30 year observation period. Since most of the data are widely separated in time, it is not possible to interpolate between observations and determine the time and scale of the water exchanges or mixing processes. Many fjords have an annual cycle of bottom water renewal followed by vertical mixing by turbulent diffusion (Gade and Edwards, 1980). As a first attempt, the water properties were plotted by month,

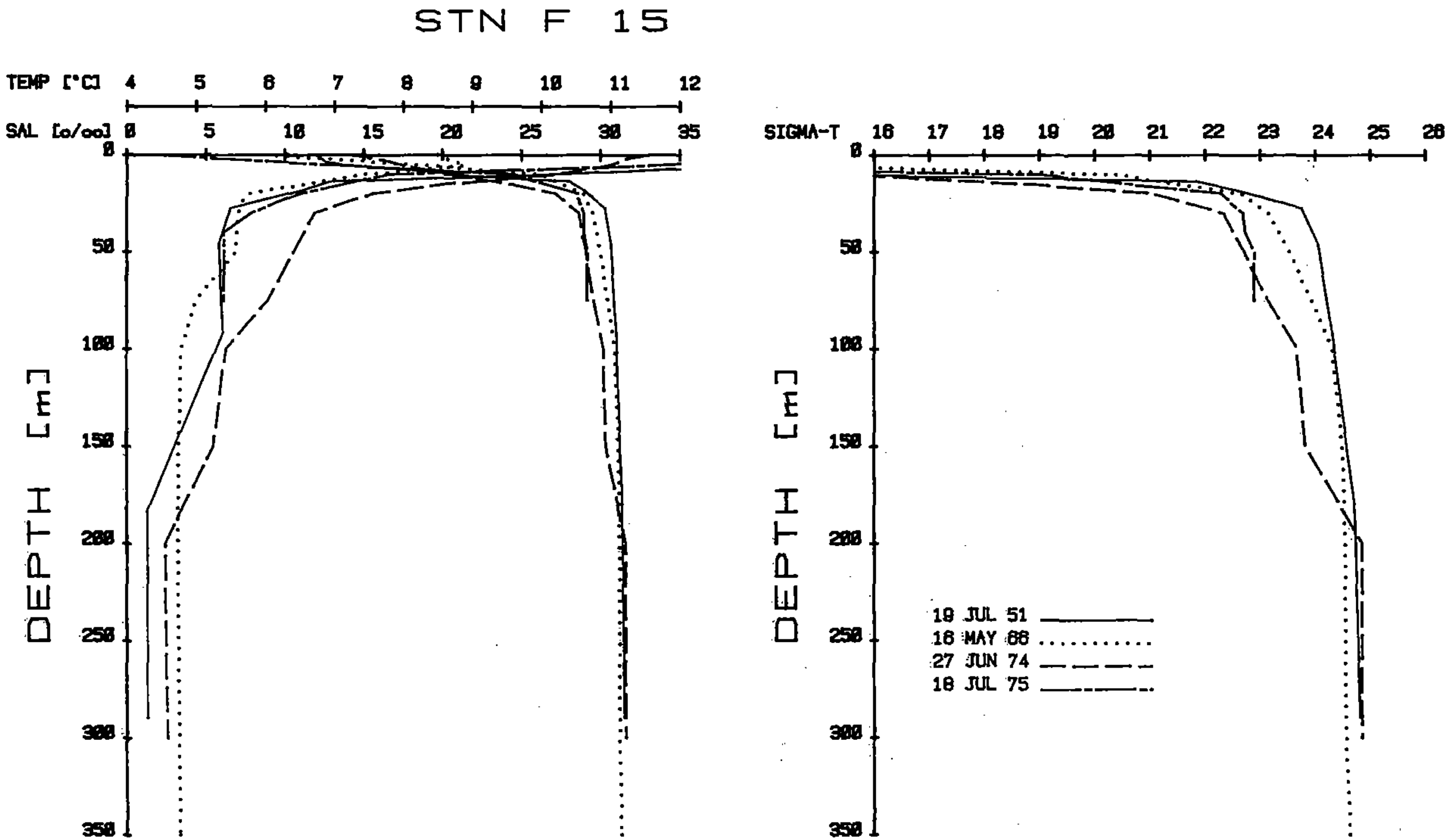


Figure 3.2 Temperature, salinity, and density profiles at F15; 19 July 1951, 16 May 1966, 27 June 1974, and 18 July 1975.

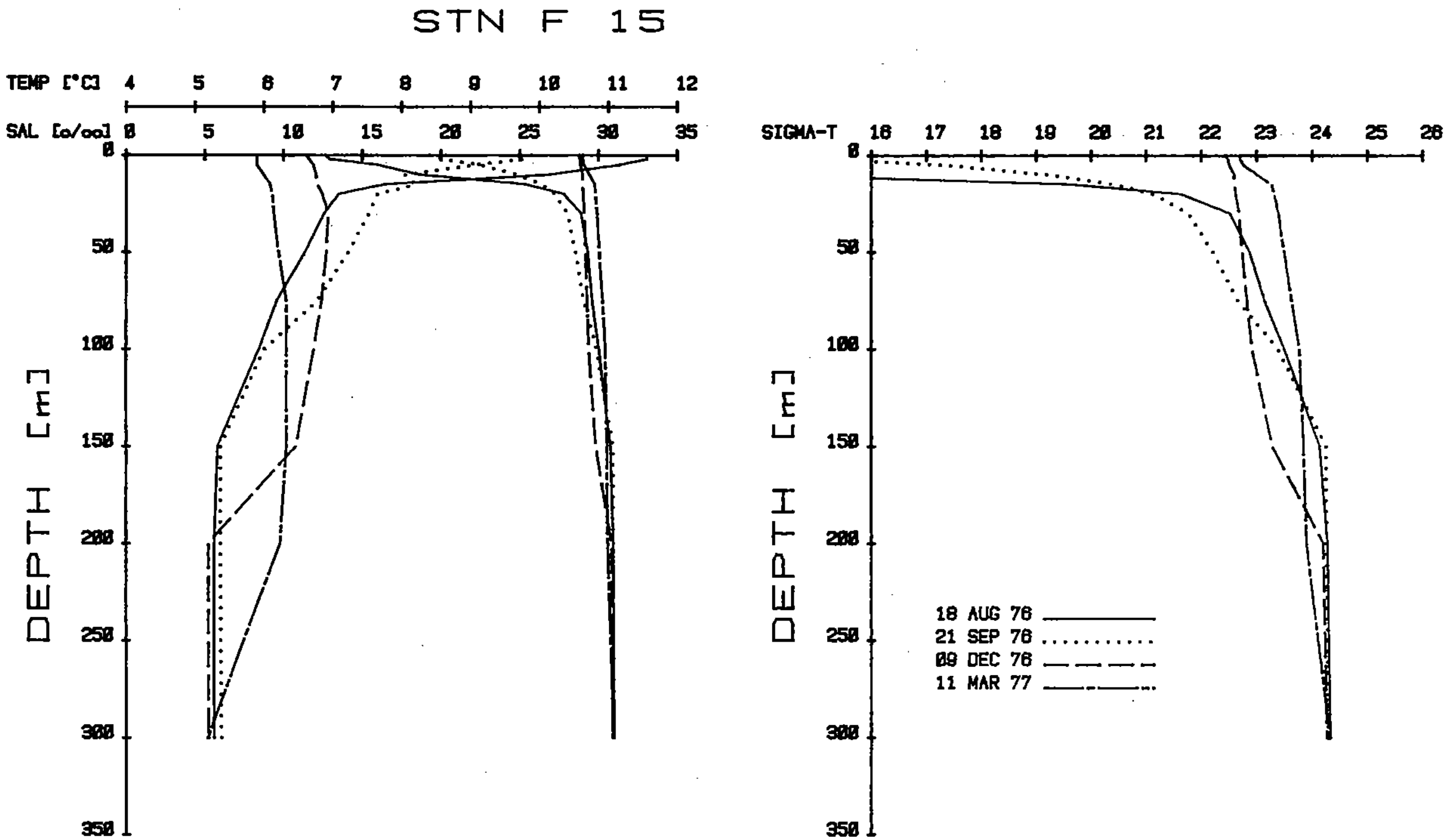
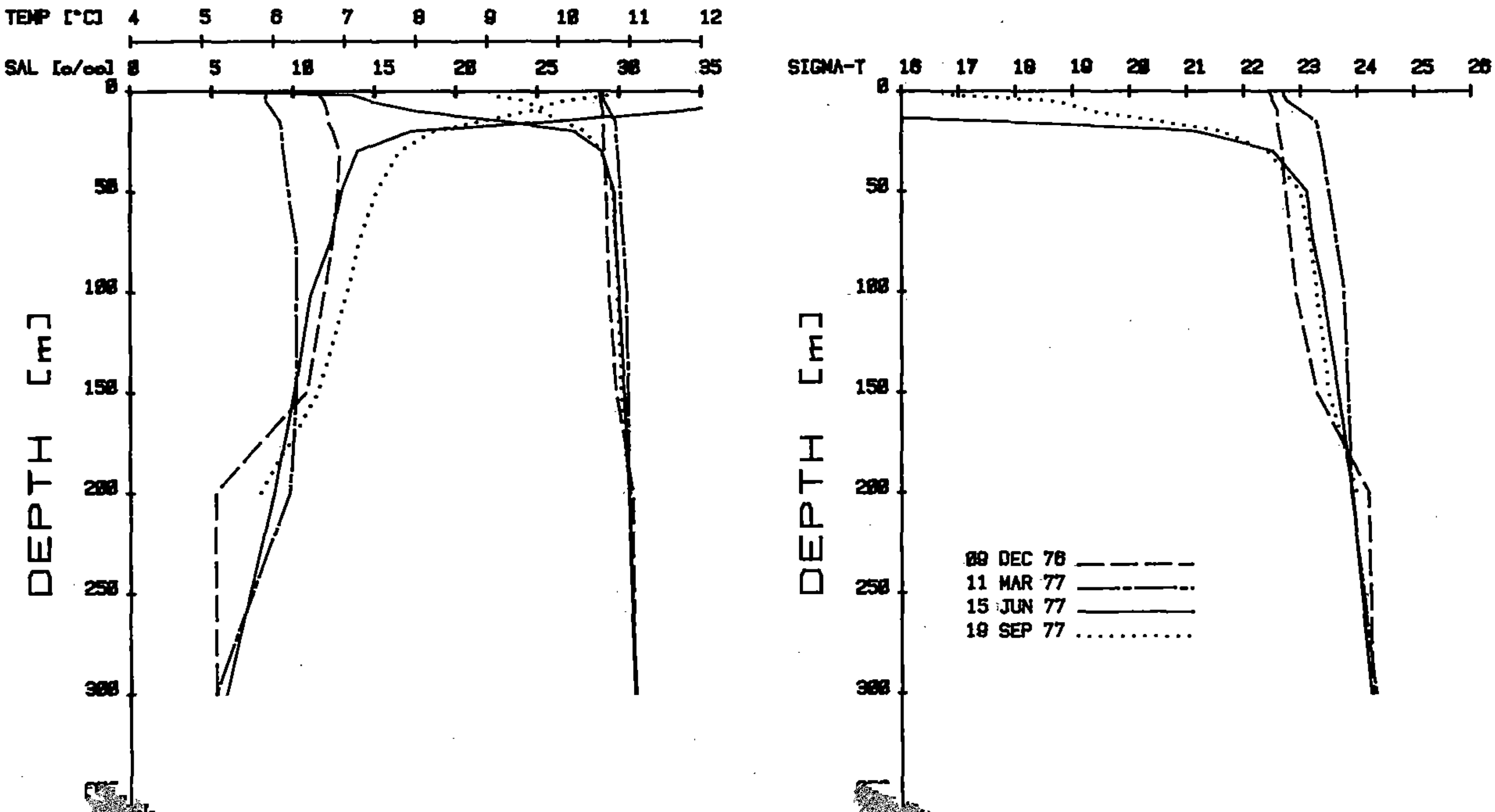


Figure 3.3 Temperature, salinity, and density profiles at F15; 18 August1976, 21 September 1976, 09 December 1976, and 11 March 1977.

STN F 15


TEMP [°C] 4 5 6 7 8 9 10 11 12
SAL [o/oo] 0 5 10 15 20 25 30 35
SIGMA-T 16 17 18 19 20 21 22 23 24 25 26
DEPTH [m]
0
50
100
150
200
250
300
09 DEC 76
11 MAR 77
15 JUN 77
19 SEP 77

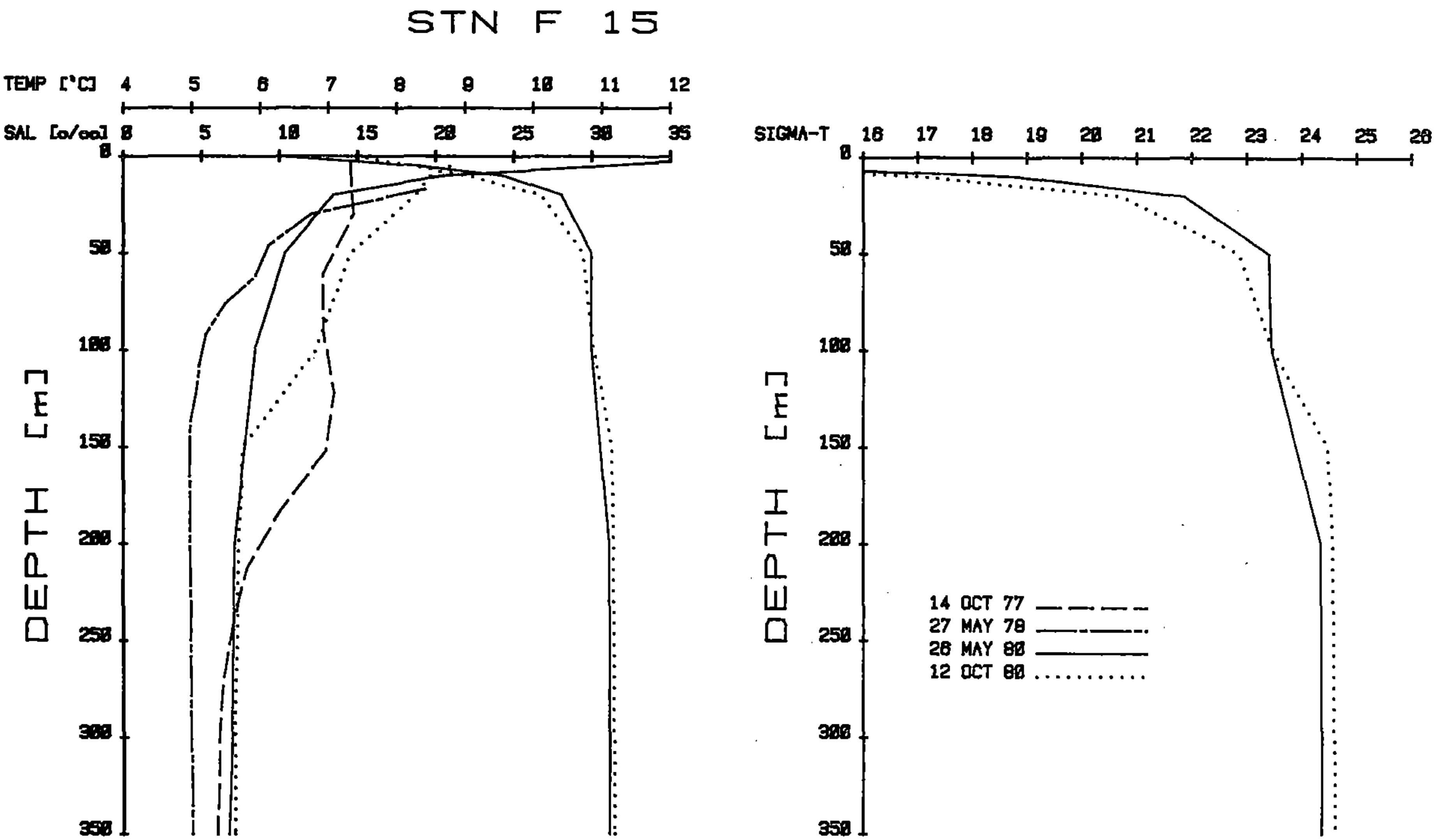


Figure 3.5 Temperature, salinity and density profiles at F15; 14 October 1977, 27 May 1978, 26 May 1980, and 12 October 1980.

irrespective of the year of observation, for each depth. The plots display an apparent random scatter indicating the absence of a regular annual cycle in Alice Arm.

Changes in water types are most graphically indicated in Figures 3.2 to 3.5 by the temperature and density profiles. The bottom (>200 m) temperatures are at low extremes and densities at high extremes in July 1951, June 1974, and May 1978 (no salinities were observed in May 1978 and hence there is no density profile). The prime mechanism by which bottom densities are increased in fjords is an influx of dense water from outside of the sill. One other period of significant density increase occurred between December 1976 and March 1977 above the 200 m level. During the same period the density decreased below 200 m. In fact the bottom density decreased from September 1976 until at least June 1977. A slow decrease in density such as this, usually indicates vertical mixing by turbulent diffusion.

Observations along the Arm indicate the presence of longitudinal gradients in the surface temperature, salinity, and layer thickness from the head and the freshwater sources to the mouth. With distance from the source, the freshwater becomes more diluted with sea water entrained from below but the internal waves prevent accurate determination of the gradients from the data available.

The only sampling period which permits a detailed examination of the dynamics of Alice Arm is from August 1976 to September 1977. The Aanderaa recording current meter data were supplemented by six hydrocasts at irregular intervals during the fourteen-month period. Figure 3.6 presents the contoured salinity time series as observed at station F15. The diagram was constructed primarily from the hydrocast data but the salinity data from the Aanderaa meters were used to assist in the interpolation. Since the temperature gradients below sill depth are relatively small, the salinity time series is a good approximation of the density time series.

The most obvious feature of this diagram is the increase in salinity between December 1976 and March 1977 in the surface 200-m layer as previously seen in the profiles of Figure 3.3. This indicates that in late December or

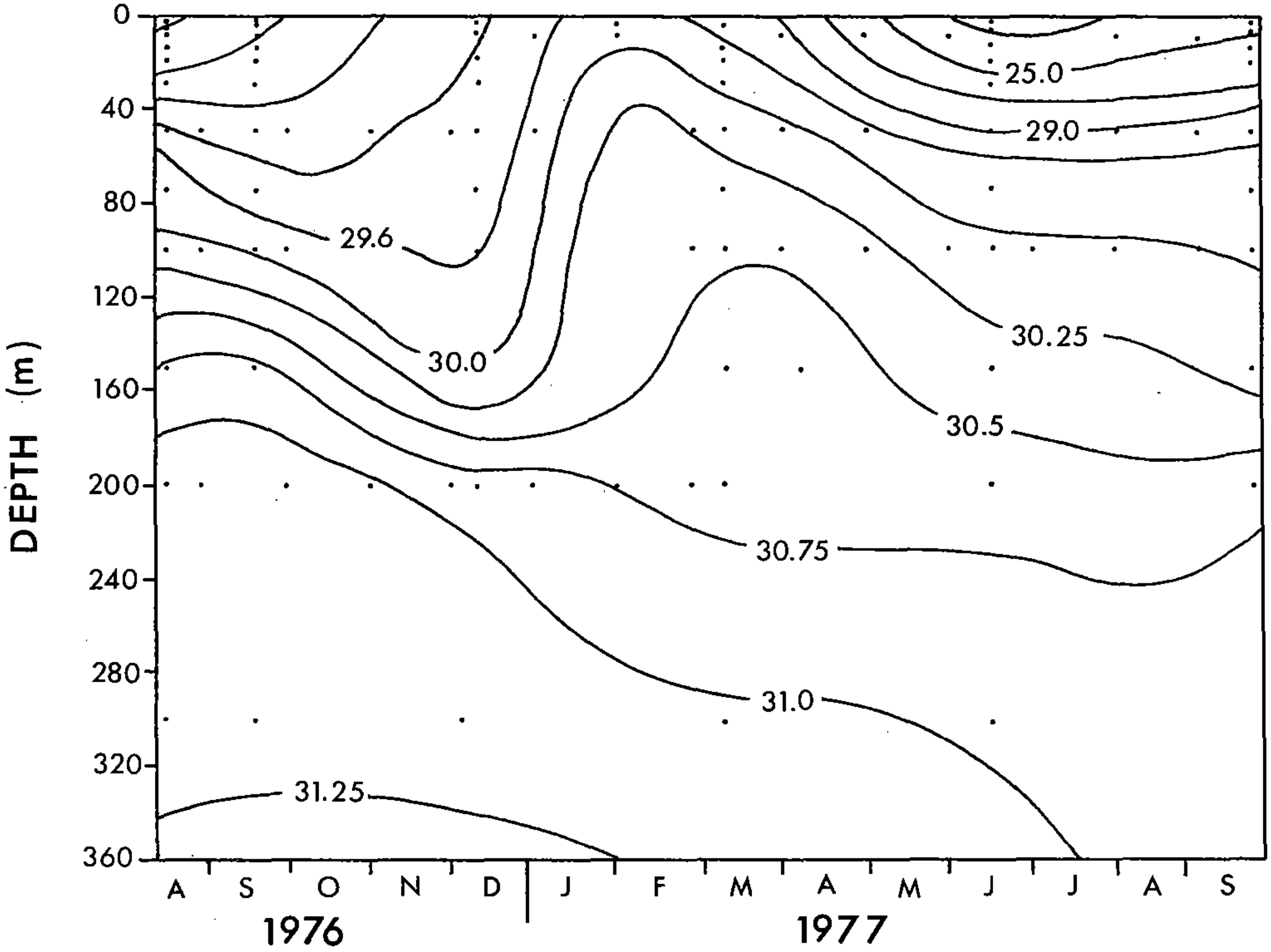


Figure 3.6 Time-depth contours for salinity at station F15; August 1976 to September 1977.

early January, there was an influx of saline water into the Arm. For the rest of the observation period the salinity at any depth gradually decreased with time.

If it is assumed that the salinity decrease was caused by vertical turbulent diffusion, the average vertical coefficient of turbulent diffusion, K_z, can be calculated for any layer from the salinity time series. Since horizontal salinity gradients are negligible below sill depth, the turbulent diffusion equation reduces to

$$\frac{\partial s}{\partial t} = K_z \frac{\partial^2 s}{\partial z^2}$$

If it is further assumed that the rate of turbulent diffusion was constant between hydrocast observations and did not vary with depth, the partial differential equation can be solved using finite differences. Vertical coefficients of turbulent diffusion calculated in this fashion were typically of the order of 10^{-4} to $10^{-3} m^2 s^{-1}$ below a depth of 80 m. The data do not permit a detailed determination of the temporal or spatial variations in the rates of turbulent diffusion. The calculated values are typical of those found in other marine environments and do not indicate exceptionally high or low levels of vertical turbulent mixing below the sill in Alice Arm.

Vertical mixing tends to be constrained as the vertical density gradient increases. The density versus time plots of Figure 3.7 display the monthly density values at 40 m intervals over the water column as interpolated from the observed temperature and salinity data. The density gradient or static stability increases with the separation of the lines on the plots. During the single year of observations the stabilities displayed an annual cycle with very low stabilities approaching neutral conditions in the winter to early spring, and more stable conditions at other times of the year. The stability of the surface 40 m layer peaked in the June-July 1977 period at $2.7 \times 10^{-4} m^{-1}$ and was at a minimum of approximately $10^{-6} m^{-1}$ from December 1976 to March 1977. The stability of the 40 to 160 m layer was at a maximum of $3.0 \times 10^{-6} m^{-1}$ in September 1976, approached neutral conditions in January-February, and increased to a maximum of $2.6 \times 10^{-5} m^{-1}$ in August 1977.

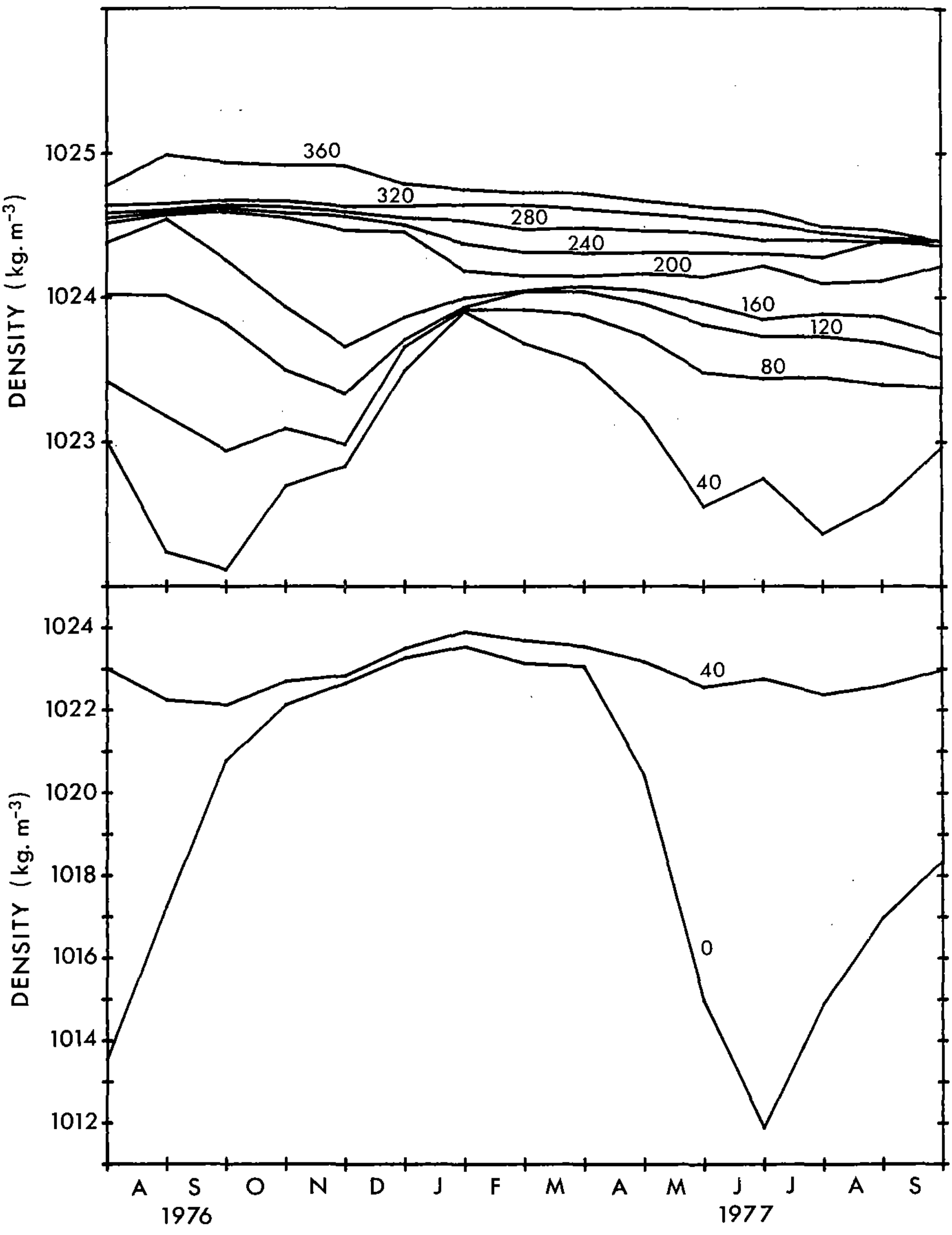


Figure 3.7 Density versus time at 40 m intervals over the water column, August 1976 to September 1977.

The stability of the water below 200 m was always relatively low and approached neutral conditions with values of $3.3 \times 10^{-6} m^{-1}$ or less. Although an annual cycle was not pronounced, the stability near the bottom peaked in mid-winter approximately five months after the stability peak in the upper waters. The layer from 160 to 200 m appeared to be a transition zone which displayed the characteristics of the upper layer until January 1977, and then displayed the characteristics of the deep waters until the end of the observations.

The stabilities of the observation period are significantly altered by the influx of water in early January and may not be typical of all years. However, the indicated annual cycle is to be expected considering the annual variation in freshwater inflow. The indication is that the restoring forces acting on a parcel of water that is displaced vertically by internal waves or tides are at a minimum during the winter and late spring. Therefore mechanical mixing of the water column is most easily accomplished at this time.

The static stability indicates the resistance to vertical displacement and hence vertical mixing, but Alice Arm is a dynamic rather than a static system and the existence of current shears must also be considered. Some of the kinetic energy of the currents is lost to turbulent energy which, in turn, contributes to vertical mixing and is converted to potential energy. The energy available for mixing in Alice Arm varies with time and with depth. A measure of the dynamic stability is the Richardson number which is a function of the static stability which suppresses vertical mixing and the current shear over the water column which enhances vertical mixing. Since the velocity profiles were not observed in detail, it is not possible to calculate the Richardson numbers. The magnitudes of both the density gradients and the current shears can vary significantly with depth and locally may be much larger than indicated by the average over a 40 m layer.

The salinity observations were used to estimate the total amount of salt contained in Alice Arm at monthly intervals. The total salt content versus time curve is very similar to the density of the surface 20 m layer versus time curve. The change in salinity of the surface layer over the year is an order of magnitude greater than any other layer. Since the density is directly proportional to the salt content it is to be expected that the two curves would be similar. The annual cycle of salt content inversely follows the cycle of freshwater inflows.

The potential energy or the amount of energy required to pile up the water above the bottom was calculated for each month during the observation period. The potential energy values followed the total salt content values and had a maximum of 7.778×10^{15} Joules at the end of January after the saline influx to 200 m, and a minimum of 7.760×10^{15} Joules at the end of June 1977 after the spring runoff. The change in potential energy over the year due to changes in the salt content is approximately one quarter of the potential energy change over a tide cycle due to a change in surface elevation.

3.3 Oxygen Distribution

Dissolved oxygen has been observed less frequently than temperature and salinity. In July 1951 the water was saturated at the surface and decreased to approximately 60 percent saturation or 4.5 ml/l at 20 m and below. In May 1966, the bottom water had increased to 5.5 ml/l dissolved oxygen or greater than 75 percent saturation and in June 1974 the bottom water was greater than 5 ml/l or 70 percent saturation. Since then only bottom oxygen values have been observed. During the 1976-1977 observation period the dissolved oxygen at 300 m in Alice Arm decreased from 4.5 ml/l in August 1976 to 3.9 ml/l in March 1977 and then increased to 4.4 ml/l in June before decreasing to 4.0 ml/l again in September 1977.

The observed dissolved oxygen content of the bottom waters of Alice Arm is always relatively high indicating frequent bottom water renewals. If the data from 1976-1977 are typical, the oxygen utilization is of the order of 1 to 2 ml/l per year. Saturation values at the observed temperature and salinity are of the order of 7 ml/l. Since the water replacing the bottom water during a renewal may not be surface water which is saturated with dissolved oxygen, the renewal events must occur most years or at least every second year, for the dissolved oxygen content of the bottom water to remain above 4 ml/l and usually closer to 5 ml/l.

3.4 Currents

Fjord circulation is usually thought to be characterized by a net outflow in the upper layer composed of the river inflow and entrained saline water, and a diffuse, weak inflow in the deeper water. If it is assumed that the prorated fresh water inflow from land drainage that enters the Arm near the head, remains in the surface 22.5 m layer and contributes a net seaward flow to that layer, the average surface layer residual current is $1.8 \times 10^{-3} ms^{-1}$. Therefore, it would take an average of 140 days for an object in the surface layer to travel from the head of the Arm to the sill. This is a gross over-simplification of the flushing mechanism and yields a greatly exaggerated flushing time for the surface layer. Saline water is entrained into the surface layer along the length of the Arm and augments the net seaward flow. For example, if the average salinity of the surface layer at station F15 were 25 $^{o}/_{oo}$ a volume of saline water equal to approximately five times the volume of freshwater inflow per tidal cycle would have been entrained from below. Under these conditions a volume of water six times as large as the freshwater inflow would be advected through the local cross-section in the same time period. As more saline water is entrained into the surface layer, the residual flow is increased and the flushing time of the surface layer is decreased. The freshwater inflow and the vertical entrainment vary with time and hence the flushing time will also vary significantly over the year.

The currents as observed in Alice Arm during 1976-1977 were highly variable in magnitude and direction and did not consistently display an obvious fjord-like circulation. Departure from the idealized circulation can be caused by fluctuations in the freshwater inflow, wind stress on the surface, and tides. Table 3.1 presents a summary of the observed currents at the six current meter locations. The mean speed and direction varies significantly with the observation period and hence it is not meaningful to quote the means. Figure 3.8 shows the low pass filtered currents at 10 m at Station F15 resolved onto N-S and E-W axes. The low pass filter (Godin, 1972) removes the diurnal and higher frequency fluctuations which are due primarily to the tide. The plot indicates significant variability at time scales of days to months. However, it does not display an annual cycle which might be related to the freshwater inflow.

TABLE 3.1 Summary of Observed Currents

Location	Depth (m)	Median (ms^{-1})	Maximum (ms^{-1})	Net flow bias
F15	10	0.10	0.75	down inlet
	182-190	0.03	0.20	up inlet
	360-374	0.015	0.40	down inlet
E4	5-10	0.12	0.75	down inlet
	51-55	0.03	0.45	up inlet
	97-105	0.04	0.48	down inlet

Winds were only recorded on Alice Arm from April 15 to September 20, 1977 while the current meters were moored. During this period there was usually a diurnal landbreeze-seabreeze cycle but the winds were generally light and no major wind events were recorded. The shallowest current meters were at a depth of 10 m. It was not possible to determine the importance of local wind forcing on the circulation of Alice Arm since the currents at this depth were not significantly influenced by the light winds recorded during the current observations. Moreover, the variations in the currents caused by the semi-diurnal tidal forcing and the associated variation in depth of the meters with the tide masked any wind forcing.

The fluctuations at the various time scales do not persist for long periods but tend to be transient in nature. Therefore it is not possible to describe typical conditions since variability is typical. Over the observation period the predominant scales had periods of approximately 1 to 3 hours, 6 hours, 12 hours, and 2 weeks. The recording interval was 0.25 hours so very high frequency fluctuations were not observed. Semi-diurnal tidal motions were observed at all depths at times, while at other times they were not detected at some depths. The phase relationship of the semi-diurnal tidal currents at different depths also varied with time and with respect to the barotropic tide. At times the phase relationship of the tidal currents reversed from the surface layer to mid-depth and again from mid-depth to the bottom. At other times two adjacent depths

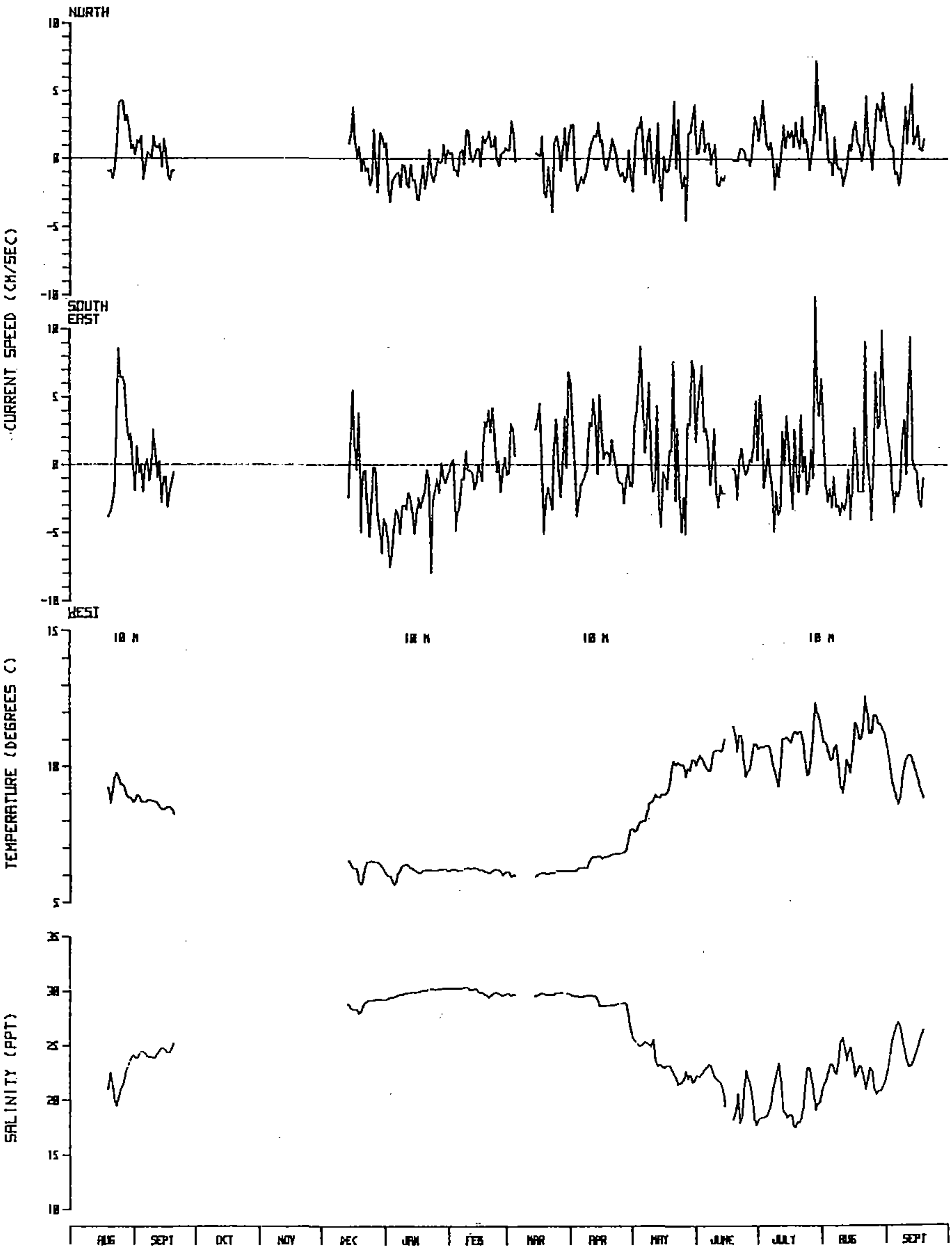


Figure 3.8 Low pass filtered Aanderaa current meter data from station F15 at 10 m, August 1976 to September 1977.

were in phase and the third 180° out of phase or the phase varied with depth and time. Since it is not possible to generalize about the currents in Alice Arm, the observed currents will be illustrated by means of selected examples.

A comparison of the surface currents at the two stations in mid-September 1976 (Fig. 3.9) reveals a phase lag in the currents at E4 relative to F15. This lag may be caused by the freshwater inflow near E4 which delays the flood tidal currents and causes them to occur over a shorter period and have greater magnitude than the ebb currents. Another possible explanation is the variation in depth of the current meters which are fixed relative to the bottom. As the tide rises and falls above them, the near surface current meters sample a different depth in a layer that usually has large vertical gradients. This effect would be accentuated by internal tides, the presence of which are indicated by other data. Surface currents at both stations are dominantly semi-diurnal but the surface currents at E4 also have quarter-diurnal and higher frequency components. At mid-depth at E4 the currents at the beginning are predominantly semi-diurnal but the amplitude is attenuated over the week to the level of the higher frequencies. The mid-depth currents are 180° out of phase with the surface currents and resemble a reflection of the surface currents; the ebb currents are of greater amplitude and shorter duration than the flood currents. At the bottom the quarter-diurnal component prevails at the beginning of the week but degenerates into high frequency fluctuations by the end of the week. The energy decreases significantly with depth and over the week, especially at mid-depth.

A few days later the semi-diurnal component is overshadowed by quarter-diurnal and higher frequency fluctuations, at most depths (Fig. 3.10). At E4 the semi-diurnal component of the surface and mid-depth tidal currents is still out of phase, but by the end of the week the surface currents have a dominant quarter-diurnal component that is not as evident at mid-depth. The bottom currents still are characterized by high frequency fluctuations but there is evidence of a semi-diurnal component that is 180° out of phase with the mid-depth fluctuations. However, the up-inlet flow is interrupted

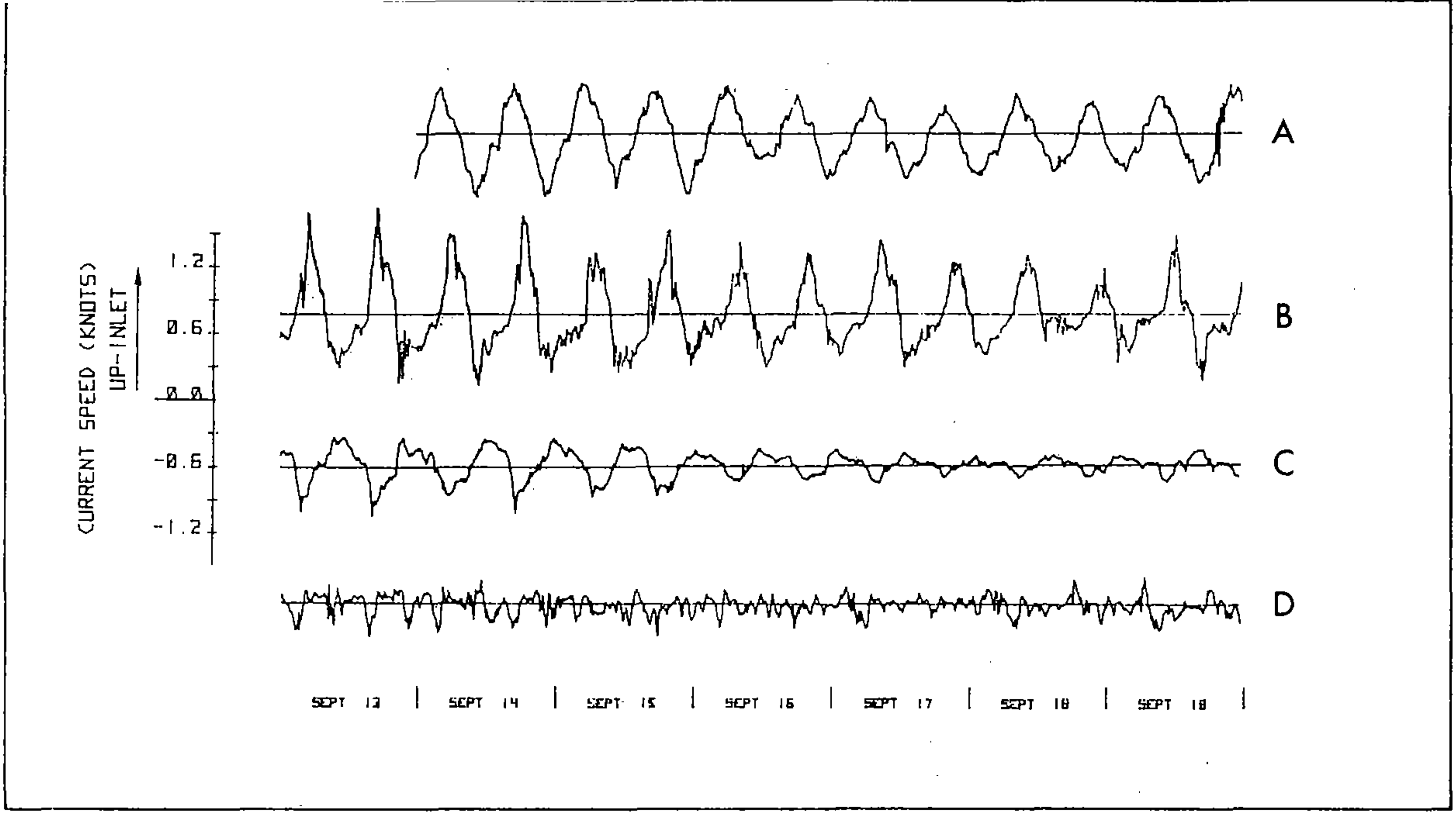


Figure 3.9 Observed currents in Alice Arm, 13-19 September 1976: A. F15-10m, B. E4-5m, C. E4-53.5 m, D. E4-97 m.

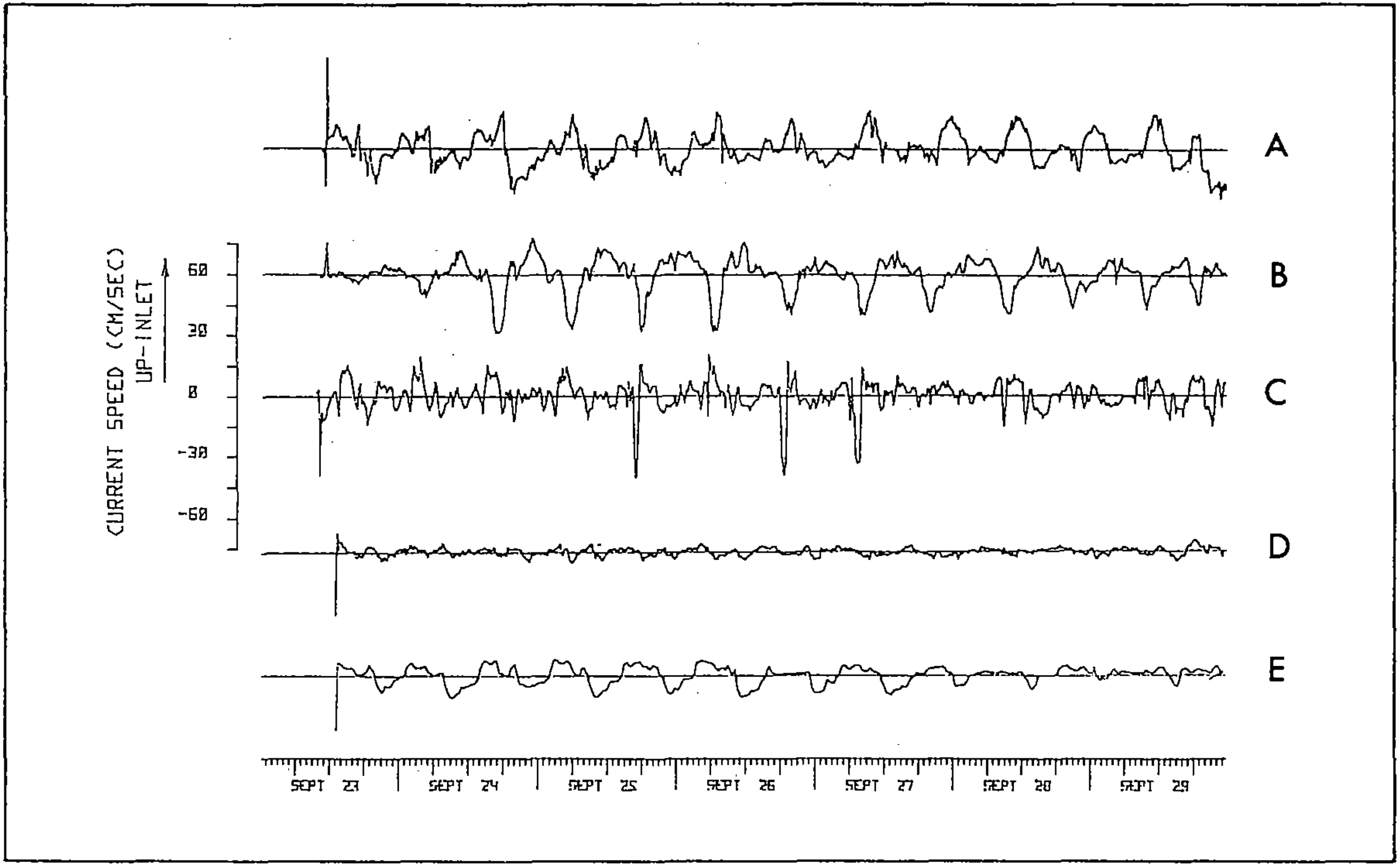


Figure 3.10 Observed currents in Alice Arm, 23-29 September 1976: A. E4-10m, B. E4-51 m, C. E4-97 m, D. F15-182.25 m, E. F15-359.5 m.

by a brief (~1 hour) but intense (~0.40 ms^{-1}) pulse of down-inlet flow. This down-inlet flow occurs at the mid-point in time between the predicted high water and low water. At station F15 the mid-depth currents are strongly quarter-diurnal in nature with little energy, but the bottom currents are semi-diurnal and in phase with the surface currents at station E4.

The same depths display a similar relationship six weeks later (Fig. 3.11). The down-inlet surges at the bottom at E4 again occur at the predicted mid-ebb. These surges and the presence of semi-diurnal components at depth tend to coincide with times of spring tides but are observed at other times as well.

The transient nature of the currents is very apparent at the time of the intermediate water renewal in January 1977. The influx of water is first detected by the temperature and salinity sensors of the meter at 189.3 m at F15 on January 4, 1977. The currents at this depth prior to the influx were very weak with minor semi-diurnal and some high frequency fluctuations. On January 4 a quarter-diurnal component became apparent but after a week it had diminished and semi-diurnal fluctuations persisted undiminished for weeks afterwards. The data from the F15 bottom meter at this time is questionable but the bottom meter at E4 after a relatively quiet period began to record a dominant semi-diurnal signal in mid-January with an amplitude of approximately 0.15 ms^{-1}.

The low pass filtered currents at E4 do not display any change at the time of intermediate water renewal. The low pass filtered bottom currents at F15 are directed up-inlet for the first two weeks of January but the magnitude of the flow is not unlike that of many other periods. The mid-depth currents do display an unusually strong (0.02-0.05 ms^{-1}) net up-inlet flow for most of January. A second period of up-inlet net flow at mid-depth occurs in early February.

The salinities tend to reach maximum values at the slack water following up-inlet flow however there are many exceptions. At times the salinities and temperatures were strongly quarter-diurnal while the currents were semi-diurnal or vice versa. At the surface at E4 the

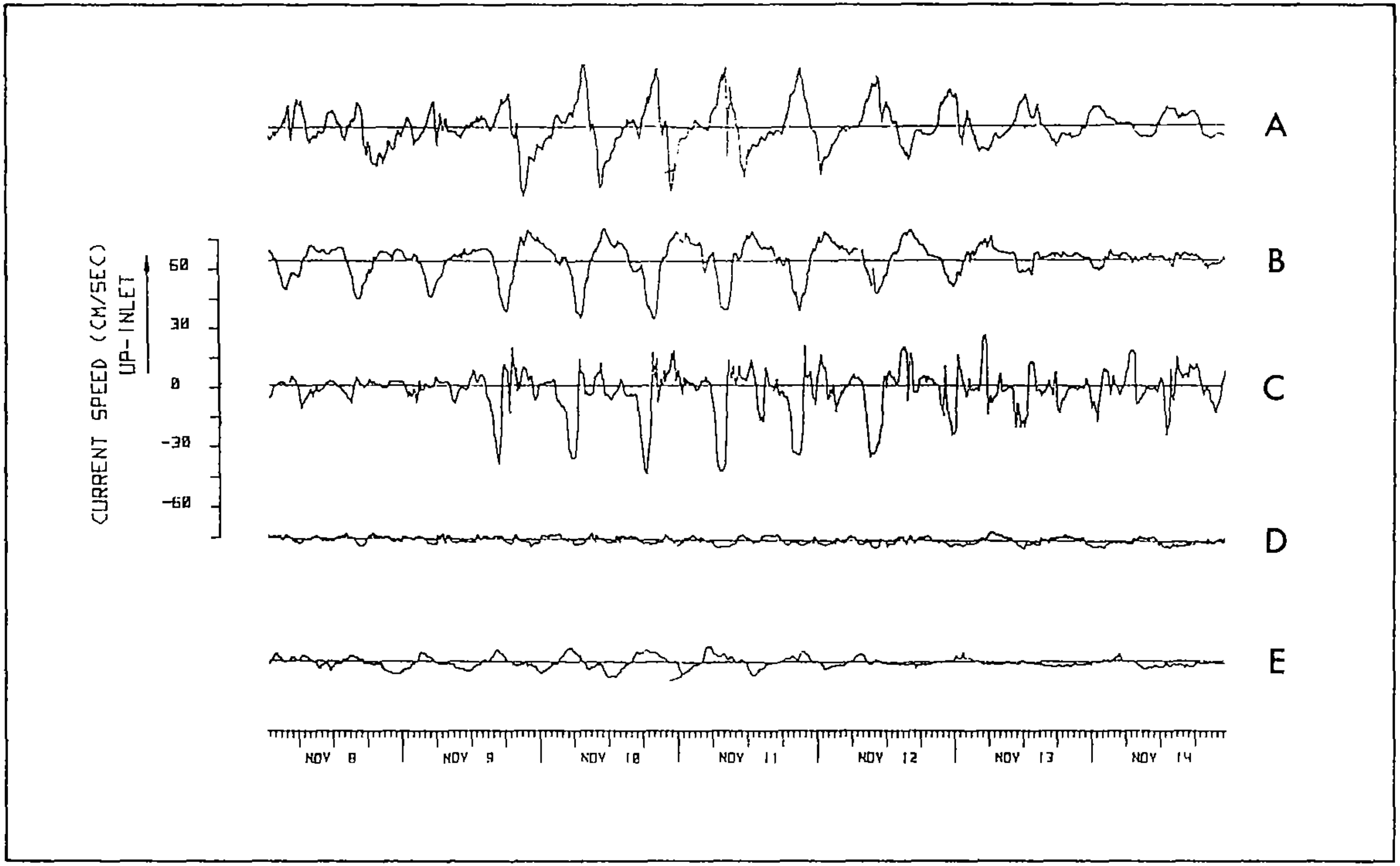


Figure 3.11 Observed currents in Alice Arm, 8-14 November 1976: A. E4-10 m, B. E4-51 m, C. E4-97 m, D. F15-182.25 m, E. F15-359.5 m.

salinity was frequently at a minimum at slack water after flood. This indicates that the flood tide tends to hold the freshwater inflow back and thicken the fresher surface later at the head of the Arm. The down-inlet surges at the bottom at E4 (Figs. 3.10; 3.11) are relatively fresh, warm water, indicating that they are composed of downwelled water. An examination of the hydrocast data taken at E4 on 21 September, 1976 indicates that, if the profiles remained unchanged, the water associated with the down-inlet surges at 97 m on 26-27 September could have originated at a depth of 64-72 m, if it did not mix with other waters and at shallower depths if it entrained water as it was downwelled.

There is other evidence that the head of the Arm is a region of active processes. In June 1974, a volume of dye which had been diluted with methanol and ambient seawater to approximate the density of the receiving waters was injected at 30 m off Lime Creek at mid-flood (Goddard, 1975a). The released patch is calculated to have been slightly denser than the ambient density, yet it was detected in the surface waters at most sample sites at the head of the Arm 13 to 17 hours later. Although it is difficult to adjust the density of a solution accurately, the methanol and dye mixture which was denser than the receiving waters was diluted in the ratio 1:60.7 with the receiving waters before release. Such a dilution would reduce any density differences between the dye mixture and the receiving waters to a very small value. The small volumes of dye and methanol (1 gallon and 0.4 gallons, respectively) could have been measured accurately while the accurate measure of the seawater (85 gallons) was not critical. If the water used in the dilution was not pumped from the proper depth of 30 m, and the mixture proved to be buoyant, it would have reached its equilibrium level near the depth from which the water was pumped. Since the vertical density gradient in the surface 30-m layer was relatively large, minor errors in the density adjustment of the dye mixture were not critical.

The low pass filtered temperature and salinity data at the surface displayed an annual cycle as expected plus a strong fortnightly component driven by the tides (Fig. 3.8). The data at other depths do not display the fortnightly signal or any other fluctuation. In contrast they display a slow variation of small amplitude over the year.

The reversal of the semi-diurnal tidal currents with depth indicates the presence of internal tides. The transient nature of the observed currents and the variations in the speeds and directions of the low pass filtered currents also indicate the presence of internal waves with the ratios of the amplitudes of the baroclinic modes varying with time. Further evidence of internal waves is seen in a series of hydrocasts made by EPS at the middle of the CC section in May 1980(Fig. 3.12). The station was occupied five times over a tide cycle and the minimum, maximum and calculated mean profiles for temperature, salinity, and density are shown. It can be seen that significant variations are present throughout the 250 m water column. A number of nodal points are evident which separate layers of widely fluctuating density. For example at 100 m the internal wave height is greater than 60 m. Time series observations by EPS in October 1980 display similar though less intense internal wave activity.

It appears that internal wave activity is prevalent in Alice Arm. The dominant modes vary with the density structure and hence because of the transient nature of the currents cannot be calculated because the density profile is not known accurately at most times. Stigebrandt (1976) has noted the important contribution to turbulence by the breaking of internal waves in Oslofjord. It has been determined that the coefficient of vertical turbulent diffusion in Alice Arm is not abnormally large. But if the vertical mixing is primarily a result of breaking internal waves at the sloping boundaries, the vertical mixing locally may be much more intense in the region of the breaking waves. When the internal waves break their energy increases the level of turbulence which in turn causes locally intense vertical mixing and, hence, a locally large coefficient of vertical turbulent diffusion. The mixed water spreads out horizontally into the interior of the fjord and the vertical mixing that occurred primarily at the boundaries is averaged over the entire fjord. The apparent vertical mixing and coefficient of vertical turbulent diffusion calculated in the interior of the fjord are therefore much less than the local values near the boundaries in the presence of breaking internal waves.

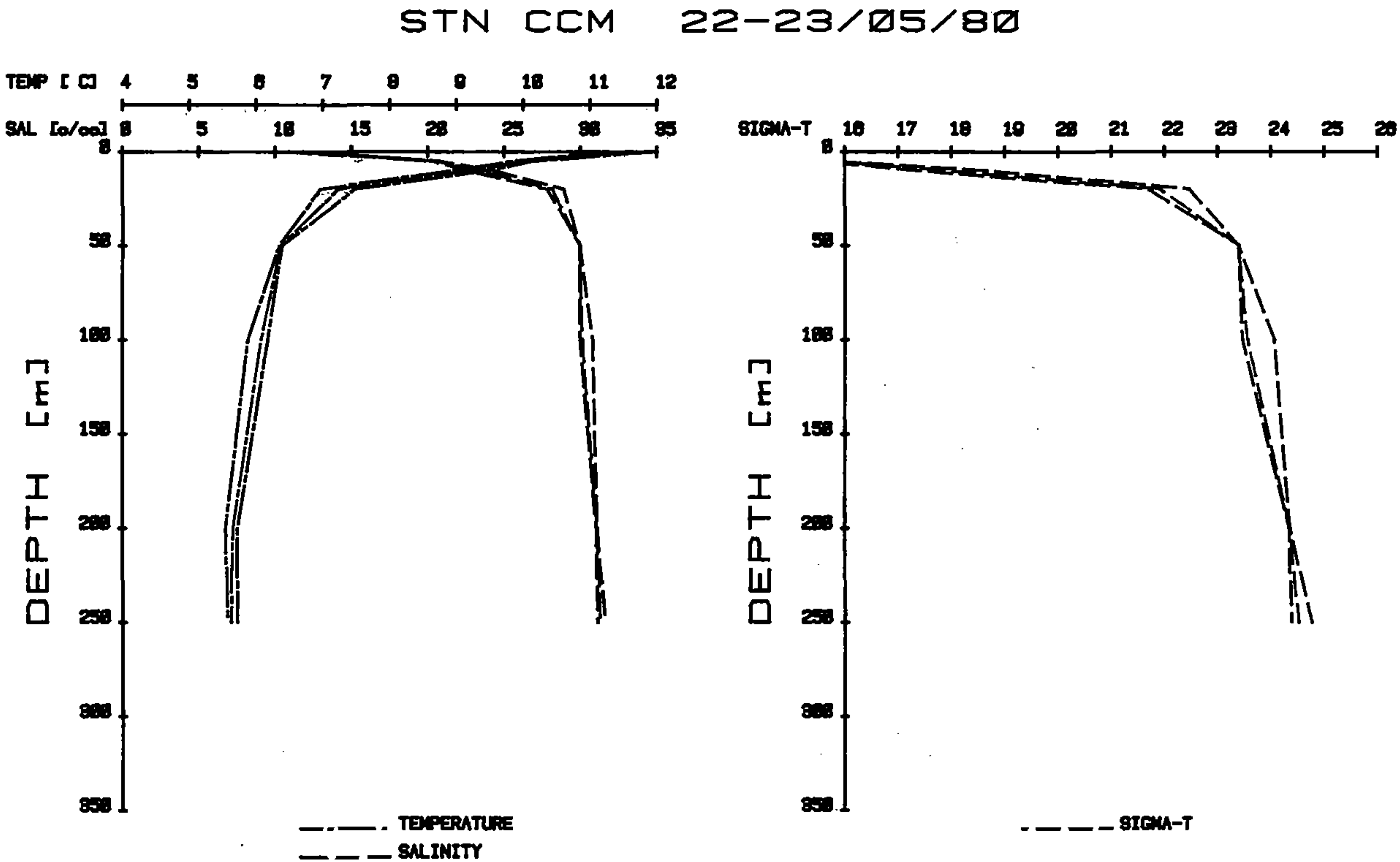


Figure 3.12 Observed minimum and maximum and calculated mean temperature, salinity, and density profiles over a tide cycle at the middle of section CC, 22-23 May 1980.

3.5 Deep Water Renewal

The deep water renewal of Alberni Inlet, Vancouver Island has been shown to occur at times of coastal upwelling when dense coastal water is elevated above sill depth and flows into the Inlet to replace less dense resident water (Bell, 1976; Beak Consultants, 1979; D. Stucchi, private communication). Coastal upwelling indices (Bakun, 1973), based on calculations of offshore Ekman surface wind transport from surface atmospheric pressure data at six hour intervals, are available at three degree latitude intervals along the Pacific coast including the region off the northwest tip of the Queen Charlotte Islands, centred at 54^{o}N, 134^{o}W. Upwelling along the Pacific coast of North America normally occurs during the summer months with a maximum period and magnitude off Southern California. In the vicinity of the Queen Charlottes, the coastal upwelling indices normally indicate very brief and weak upwelling in the summer and strong downwelling in the winter (Bakun, 1973).

Figure 3.13 shows the seven day running means of the coastal upwelling indices for the Queen Charlotte region between July, 1976 and September, 1977. During the period of intermediate water renewal in January, 1977 there is no upwelling indicated but there is a relaxation of a downwelling event which had persisted for at least two weeks. Downwelling relaxation has been observed to trigger deep water renewal in Alberni Inlet (D. Stucchi, private communication). However there were a number of relaxation periods during the winter and the one coinciding with the intermediate water renewal was not the most marked event, and hence was unlikely to have caused the influx of saline water into Alice Arm.

A comparison of the temperature, salinity, and dissolved oxygen values at comparable depths in Hastings Arm and Observatory Inlet (Appendix B) reveals significant differences at most of the observation times. This indicates that the sills separating the three bodies of water limit the renewal events and cause events of different magnitudes and at different times in the three bodies of water. This would indicate that local processes are more important than the processes off the coast.

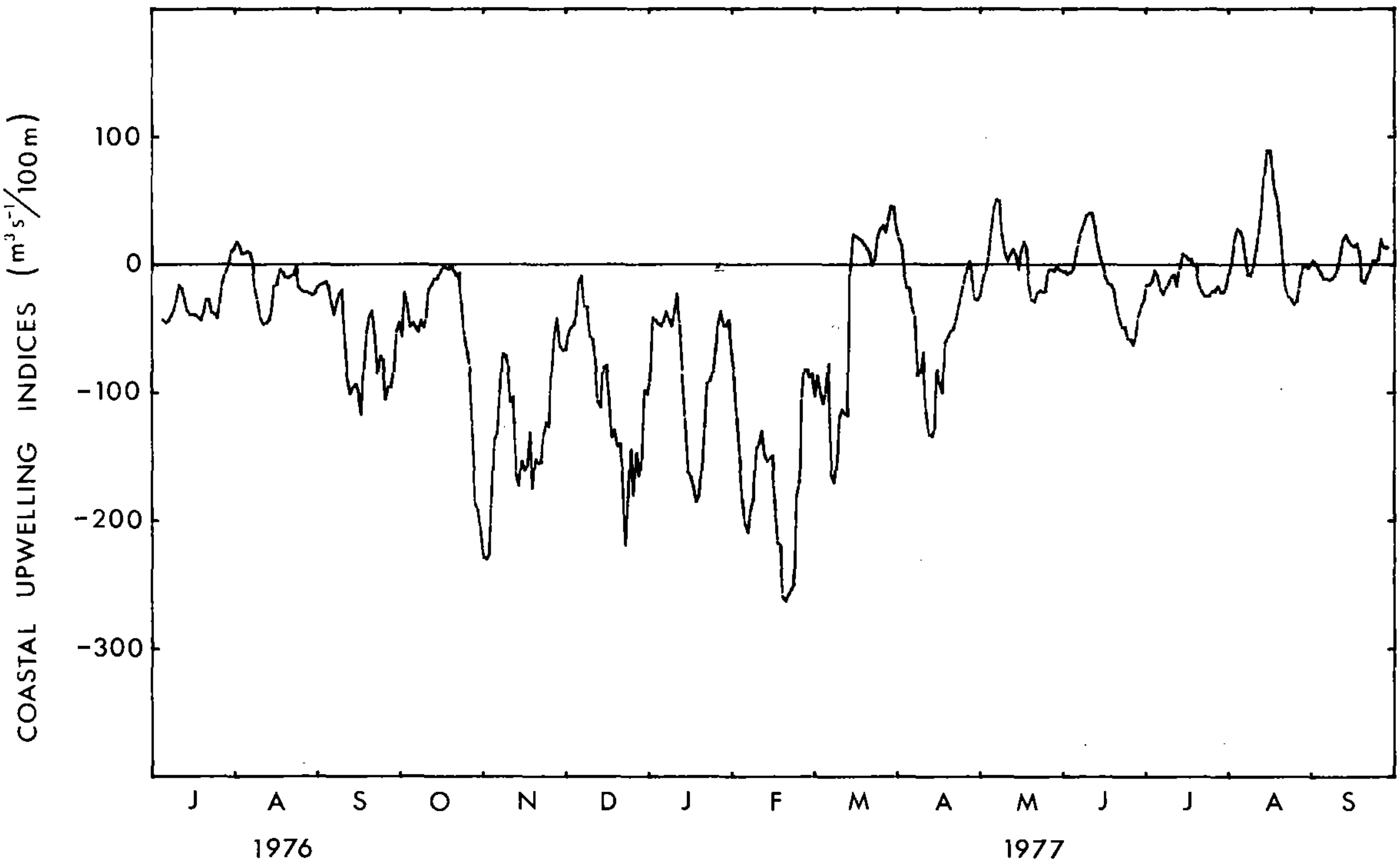


Figure 3.13 Seven day running means of the coastal upwelling indices at 54°N, 134°W, July 1976 to September 1977.

The coastal upwelling indices may correlate well with bottom water renewal in Observatory Inlet, which is separated from Portland Inlet by a 50 m sill, but insufficient data exist to verify that relationship.

A local wind stress blowing along a body of water will cause the surface to slope up in the downwind direction. Assuming steady state conditions, from hydrostatic pressure considerations, if the water is composed of two layers with different densities, the interface between the two layers will slope up in the opposite or upwind direction. From December 30, 1976 to January 05, 1977, the winds observed at Green Island off the mouth of Portland Inlet were from the northeast at speeds of 13 to 20 ms^{-1} and averaged $\sim$17 ms^{-1} for the first four days (Atmospheric Environment Service, unpublished data). This was a major atmospheric outflow event, and the down-inlet winds in the confines of Observatory Inlet would likely have been much stronger. Using the hydrocast data of December 10, 1976, the conditions in Observatory Inlet can be approximated by a 40 m layer of density 1022.8 kgm^{-3} overlaying a bottom layer of 1024.0 kgm^{-3}. If it is assumed that the wind in the confines of Observatory Inlet was twice the speed of that observed at Green Island, it can be calculated that the interface between the upper and lower layers could have been elevated approximately 35 m at the northern end of the Inlet off the mouth of Alice Arm. Therefore, in this region water from as deep as 55 m could have been raised above the sill at the entrance to Alice Arm. The T-S plot of Figure 3.14 shows that on December 10, 1976 the water type at 200 m in Alice Arm when mixed with the water type at 50 m in Observatory Inlet in the ratio of 43 percent to 57 percent could have produced the water type observed at 200 m in Alice Arm on March 11, 1977. Over this period the water at 150 m and above increased in density but the water at 200 m decreased in density. This indicates that the influx of dense water flowed down the inside of the sill under the force of gravity and displaced the resident water upwards. The negatively buoyant plume would have entrained water as it flowed down the inner slope of the sill and caused locally intense mixing. Apparently the momentum of the gravity flow caused it to overshoot its equilibrium depth, which is estimated to have been approximately 180 m, and mix down and entrain and displace water to a depth of at least 200 m.

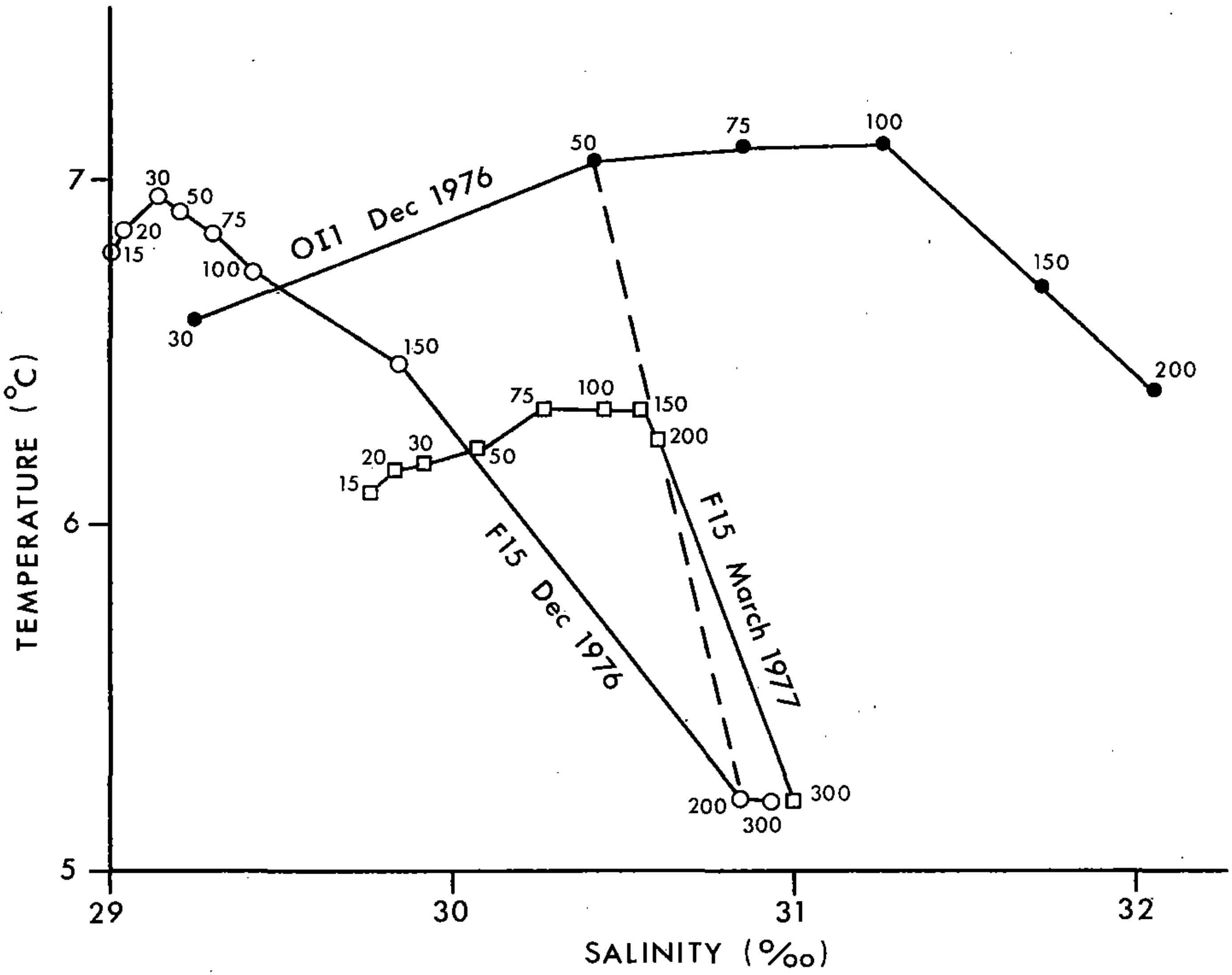


Figure 3.14 Temperature - salinity diagram of Alice Arm and Observatory Inlet water indicating the possible source of the intermediate renewal of January 1977.

Figures 3.4 and 3.5 indicate a major deep water renewal event in Alice Arm between October 1977 and May 1978 that extended right to the bottom and may have involved the entire water column. H. Gade (private communication) has pointed out that during some renewal events in Norwegian fjords, the water is flushed more than 100 percent. Only the autumn and spring temperature profiles are available and at both times there was no water in Observatory Inlet as cold as that which existed at depth in Alice Arm in May. Hence the renewal must have occurred in the December to February period when the upper layers are at their minimum temperatures.

It was hoped that the temperature profiles in the sediments would reveal the nature and timing of the renewal. The low thermal conductivities of the sediments cause them to possess a record of the temperature of the water that has been in contact with them in the past. This record extends back for a year or more. The sediment temperature profile of October, 1977 can be modelled by a slowly increasing bottom water temperature over the past year (T. Lewis, private communication). This is in agreement with the temperature-salinity data which indicate a period of slow changes in the bottom waters caused by vertical turbulent diffusion from August, 1976 until June, 1977 or later. During that period the density of the bottom water slowly decreased as a result of a slow increase in temperature and a slow decrease in salinity.

Attempts to model the May, 1978 sediment temperature profile by a single step decrease in temperature failed (T. Lewis, personal communication). This indicates that the renewal was not a single intense event over a short period of time. Unfortunately the sediment temperature profile can be modelled in an infinite number of ways by two or more step decreases of varying magnitudes and times. It is therefore not possible to determine the timing and scale of the renewal events and relate them to the local winds.

Indications are that the bottom water renewal of Alice Arm occurs in the winter which is typical of shallow sill fjords (Gade and Edwards, 1980). It probably occurs most winters but the scale of the renewal varies from year to year with complete renewals some years and partial renewals other years. Only the timing of the partial renewal of January 1977 is known. It occurred near spring tides, a few days after an intense atmospheric outflow began and persisted for the order of days.

Daily sea-surface observations at Langara Island reveal above average temperatures during the winter of 1976-1977 (Dodimead, 1980; Giovando, 1978, 1980). Although the sample size is small there does appear to be a correlation between the bottom temperatures of Alice Arm and the Langara Island sea-surface temperature. Since the winter decrease in the Langara Island surface temperature is related to upwelling winds with a northerly component, and the bottom water renewal of Alice Arm has been seen to be triggered by northerly outflow winds, this relationship would be expected.

3.6 Surface Wind Waves

The fetches for surface waves generated by a wind stress within Alice Arm are very limited. The maximum E-W fetch is approximately 10 km while the maximum N-S fetch is only 4 km. Assuming a wind speed of 25 ms^{-1} and employing the SMB wave hindcast equations (CERC, 1977), it can be calculated that after one hour the waves would be fetch limited with significant wave heights and periods of 2.0 m and 5.35 s for E-W winds or 1.4 m and 4.3 s for N-S winds.

The only direction from which waves of significant magnitude could propagate into Alice Arm from outside is the southwest. Waves generated by a southwest wind blowing up Observatory Inlet could originate in Chatham Sound with a maximum fetch of 125 km. Again assuming a 25 ms^{-1} wind, after 6 hours the waves would be fetch limited with significant height and period of 5.5 m and 9.2 s. Such long period waves would probably break over the shallows in Observatory Inlet south of Alice Arm but it is apparent that large magnitude waves could propagate onto the sill area of Alice Arm from the southwest.

4.1 Natural Sediments

The total annual sediment load introduced into Alice Arm by the Kitsault and Illiance Rivers, which drain 74 percent of the basin, has been estimated to be 3.56×10^5 tons per year, most of which is transported by the rivers at times of peak discharge in the spring and autumn (Western Canada Hydraulic Laboratories, 1978). In comparison, the proposed mill production of 12,000 tons per day would introduce 4.38×10^6 tons per year, or approximately ten times the natural sediment input.

The natural sediment flows into the surface waters of the Arm with the freshwater, and the particles begin to settle through the water column. The settling rate of the particles increases with particle size (Table 4.1), so natural sorting occurs as the freshwater layer is advected along the Arm.

TABLE 4.1 Settling Velocities Determined from Stokes Equation for Spherical Particles of Density 2700 kg m^{-3} in seawater.

Diameter	Settling Velocity				
1 μm	0.65 x 10^{-6}	ms^{-1}	=	0.056	m day^{-1}
2 μm	2.6	"	=	0.22	"
4 μm	10.4	"	=	0.90	"
8 μm	41.7	"	=	3.6	"
16 μm	167.0	"	=	14.0	"
32 μm	667.0	"	=	58.0	"
64 μm	2670.0	"	=	230.0	"
128 μm	0.011	ms^{-1}	=	38.0	m hr^{-1}
256 μm	0.043	"	=	150.0	"
512 μm	0.17	"	=	10.0	m min^{-1}
1024 μm	0.68	"	=	41.0	"
2048 μm	2.7	"	=	164.0	"

The median diameter of the sediments rapidly decreases from coarse sands in the shallow water near the river mouths to fine silts or clays in the depths approximately 2 km from the river mouths (Littlepage, 1978). A sediment sample from a depth of 380 m at Station F15 was found to contain 52 percent clay and 44 percent silt (Goddard, 1975b).

The settling velocities of the very fine fraction are so small that large quantities remain in suspension in the surface layer as it is advected along the inlet. Observations in May and October, 1980, display no significant increase in transmittance along the length of the Arm. Transmittance was at a minimum of approximately 10 percent at the surface and increased to 50 percent at depths of 15-20 m. The transmittance reached a maximum of approximately 75 percent at depths near 30 m and remained relatively constant through mid-depths, but usually decreased to less than 50 percent in the bottom 25-m layer. These observations were made at times when the freshwater inflow is usually at a maximum and hence the surface turbid layer is likely near to its maximum thickness. The turbidity at these times would have been primarily caused by suspended particulate matter introduced from the rivers and not caused by plankton. The near-bottom turbidity maximum or nepheloid layer is commonly observed in marine environments.

If the natural sediments were distributed uniformly over the bottom of Alice Arm, the estimated input would lead to an average sedimentation rate of 0.6 cm yr^{-1}. However, submarine slides down the steep sides of the fjord focus the bulk of the sedimentation on the central depths of the Arm, where the natural sedimentation rate has been estimated to be 2 cm yr^{-1} (D. Goyette, private communication). The areal distribution of the rates of sediment accumulation has not been observed in sufficient detail to determine a budget for the naturally introduced sediments. However, the transmittance observations indicate that a significant portion of the very fine fraction is advected out of the Arm in the low-salinity surface layer.

If the residual flow, which is calculated from the estimated average freshwater discharge, and the settling velocities in Table 4.1 are used, it can be determined that only clay particles of 2 μm diameter or less would still be in the surface 22.5-m layer after the 140-day transit time from the head to the sill. Maximum discharge conditions would decrease the transit time by a factor of approximately four, but only increase the diameter of particles which remain in the surface layer by a factor of two. Since the transmittance observations indicate a significant suspended load in the surface layer throughout the Arm, the residual flow model based on freshwater inflow only must be an oversimplification of the surface layer dynamics. The down-inlet residual flow in the surface layer is augmented by saline water entrained from below which can increase the flow by at least an order of magnitude. The resulting decrease in residence time and the vertical mixing driven by the tidal currents cannot be ignored.

A further complicating factor that affects the settling rates of the particles is the process of flocculation. When clay particles come into contact with each other in a saline environment they tend to stick together and form flocs of larger diameter than the individual particles (Kranck, 1973), with correspondingly greater settling velocities. When bottom sediments containing a clay fraction are analyzed it is very difficult to determine the true particle size distribution because the flocs will break down when dried, when mechanically sieved, or when suspended in a laboratory settling tube.

4.2 Tailings

The tailings generated by the proposed milling operation will have essentially the same characteristics as the tailings from the previous operation. The size distribution of the design grind for the proposed operation is listed in Table 4.2 (Western Canada Hydraulic Laboratories, 1978) along with the size distribution of tailings remaining at the Kitsault mine site from the earlier operation (Dempsey and Ernst, 1976). The mean density of the tailings is 2700 kg m^{-3} and the design solids concentration in freshwater is 34.3 percent by weight, yielding a slurry density of 1275 kg m^{-3} (Western Canada Hydraulic Laboratories, 1978). It is this slurry which will be injected into Alice Arm at a depth of 50 m.

TABLE 4.2 Tailings Size Distribution

Classification	Size Range (μm)	Design Grind	Previous Tailings
Gravel	>2000	-	1%
Very coarse sand	2000 - 1000	-	3%
Coarse sand	1000 - 500	2%	8%
Medium sand	500 - 250	14%	20%
Fine sand	250 - 125	33%	26%
Very fine sand	125 - 62.5	23%	20%
Coarse silt	62.5 - 31		9%
Medium silt	31 - 15.6		6%
Fine silt	15.6 - 7.9		3%
Very fine silt	7.9 - 3.9		1%
Clay	<3.9		2%

A comparison of the ultra-fine fraction of particles (1.56 - 15.8 μm diameter) from various sources in the Alice Arm region with those of the previous tailings (Littlepage, 1974) determined that the suspended particles from Kitsault River, Lime Creek, Alice and Hastings Arms surface waters, and the previous tailings are all identical in size composition (Table 4.3).

TABLE 4.3 Ultra-fine Particles from Various Sources

Diameter (μm)	B.C. Moly. tailings	Kitsault River	Lime Creek	Alice Arm surface	Hastings Arm surface
1.56 - 1.97	15.0%	15.1%	15.0%	14.7%	15.7%
1.97 - 2.48	13.3	13.3	13.6	12.8	13.5
2.48 - 3.13	12.2	12.3	12.4	11.8	12.4
3.13 - 3.94	11.2	11.1	11.2	11.0	11.5
3.94 - 4.96	10.0	10.1	10.0	10.3	10.4
4.96 - 6.25	9.0	8.9	8.9	9.1	9.2
6.25 - 7.88	7.8	7.9	8.3	8.3	8.0
7.88 - 9.93	7.4	7.2	7.8	7.3	6.8
9.93 - 12.51	7.4	7.2	7.5	7.6	6.1
12.51 - 15.76	7.0	7.0	5.9	7.1	6.3
1.56 - 15.76	100.0	100.0	100.0	100.0	100.0

4.3 Dispersal of the Tailings

The tailings from the previous operation were discharged into Lime Creek and hence flowed into the surface layer near the head of Alice Arm alongwith the freshwater discharge from the Creek. During periods of low stream flow the resulting mixture of tailings and freshwater would have been more dense than the sea water in the Arm and the tailings plume would have descended through the water column. However, during peak runoff periods, the mixture would have been less dense than the receiving waters and would have spread over the surface of the Arm. Such conditions exist during approximately 20 percent of the year. Figure 4.1 shows the areal distribution of the tailings based on zinc/molybdenum analysis of the surface sediments. The tailings are detectable from the edge of the shallow delta at the head of the Arm to a location 8.5 km down inlet from Lime Creek, where the water depth is at a maximum. The area of tailings deposition from the previous operation is confined to Alice Arm and tailings have not been detected beyond the sill separating the Arm from Observatory Inlet (Canada, Department of Environment, 1980).

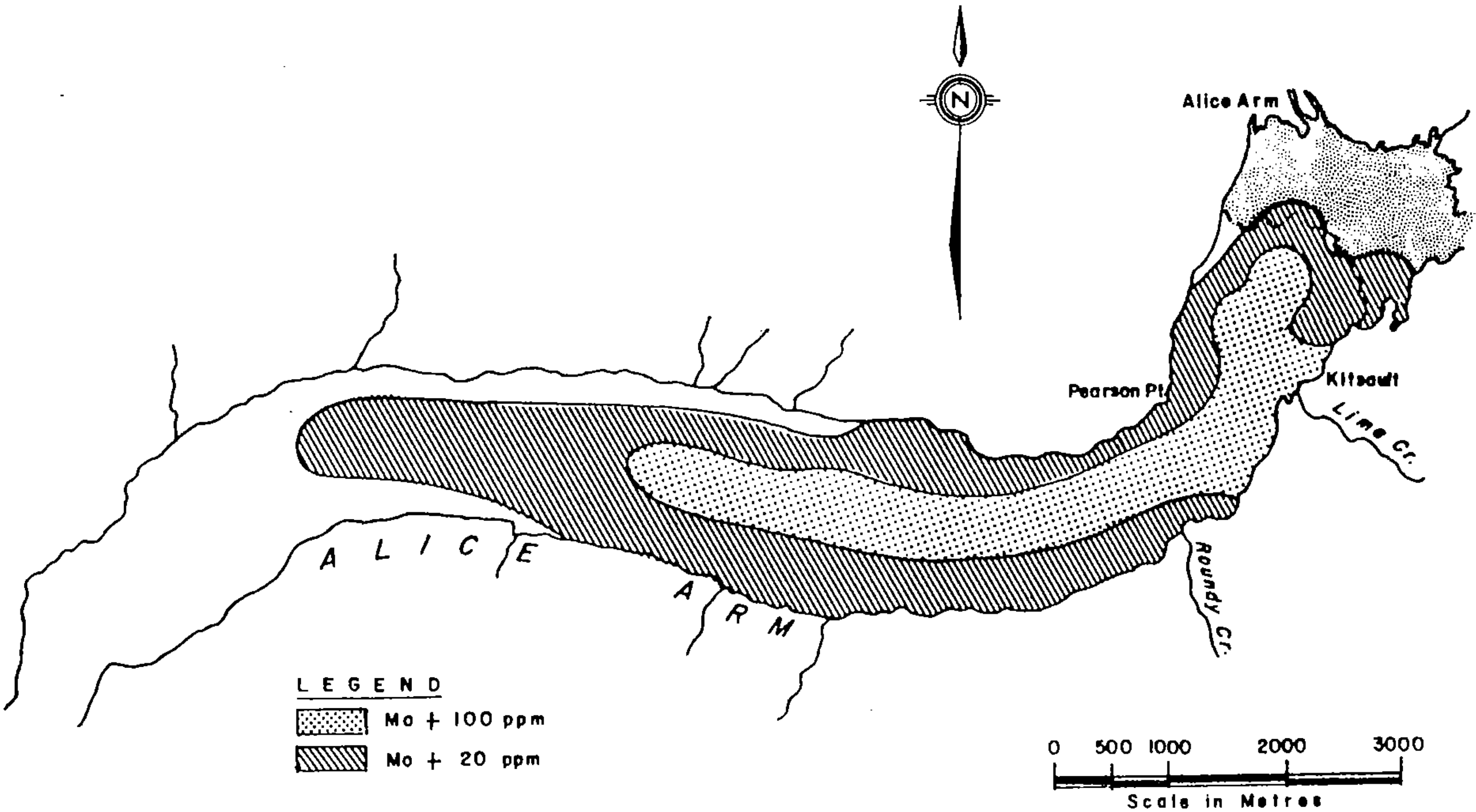


Figure 4.1 Areal distribution of previous tailings based on zinc/molybdenum analysis of surface sediments.

The tailings from the proposed operation are to be introduced into Alice Arm via a pipeline from the mill which will terminate on the bottom of the Arm between the mouths of Lime Creek and Roundy Creek, at a depth of 50 m below the surface (Fig. 1.2). The density of the slurry will be greater than the receiving waters and hence the tailings are expected to descend as a plume through the water column. The coarsest particles will settle quickly out of the plume and hence the density of the plume will decrease with time. The density of the plume will be further reduced by entrainment of sea water, but the plume will remain more dense than its surroundings and continue to sink, although at a reduced rate (Western Canada Hydraulic Laboratories, 1978).

The tailings are not expected to contain large concentrations of clay particles, however flocculation was observed to occur in the laboratory tests of tailings from the previous milling operation (Western Canada Hydraulic Laboratories, 1978). Flocculation would tend to reduce the very fine fraction of the tailings and speed up the settling rate of the tailings.

Since the tailings are introduced below the sill and are expected to sink as a descending plume, it appears that the tailings would settle to the bottom of the Arm and remain within the sill. However, there are a number of processes which could disturb this simple approach to the fate of the tailings:

a) Entrained air - air entrained in the tailings slurry would form bubbles in the effluent after release from the outfall. These air bubbles would float fine particles to the surface of the Arm to produce a surface boil and slick. A de-aeration tank placed in the pipeline, just before the outfall terminus, has been designed to allow the escape of air from the slurry prior to its release. If the de-aeration tank functions properly a buoyant plume of fine tailings particles is not expected to be a problem.

b) Ambient currents - in the absence of any ambient currents the dense tailings plume would descend along the bottom under the force of its initial release momentum and gravity. The presence of ambient currents would cause the descending plume to be deflected and the turbulent energy associated with these currents would tend to slow down the settling rates of particles. The currents would, therefore, cause the particles to be distributed over a larger area.

The non-tidal residual flow near the proposed release location averages less than 0.01 ms^{-1} in the up-inlet direction at 50 m, and less than 0.02 ms^{-1} in the down-inlet direction at 100 m. These residual flows are not constant, but fluctuate in both magnitude and direction with the forcing parameters. Superimposed on the residual flow is an up- and down-inlet tidal excursion of less than 2 km per tide, that is associated with the tidal currents which average less than 0.1 ms^{-1}. At times either up- or down-inlet surges of 0.4 ms^{-1} magnitude and one- to two-hour duration were observed at E4 at depths of approximately 51 and 97 m. These currents could significantly deflect the tailings plume and advect the tailings into the head of the Arm where vertical mixing has been observed to be more intense. The increased level of turbulence in this region would cause the tailings to remain in suspension for longer periods and hence increase the probability of them being mixed up into the down-inlet flow of the surface layer.

Since the tailings are expected to descend from their 50 m release depth, the local horizontal currents below 50 m cannot advect the tailings out of the Arm past the 20 m sill at the mouth. However, the imaginary line at Hans Point, beyond which the tailings are not allowed to pass, has a sill depth of approximately 210 m. During November 1976, a residual flow of 0.04 ms^{-1} or more was observed to persist for more than 4 days at a depth of 97 m at E4. If it is assumed that this residual flow is vertically and horizontally coherent, the settling velocities of Table 4.1 can be used to determine that tailings particles of 32 μm diameter or less would not have settled below the 200 m sill depth before being advected past Hans Point. The distances over which currents are coherent is difficult to assess - the current meter at 182 m at F15 did not record significant residual flow in any direction at that time. Since turbulence will also tend to keep particles in suspension, the size and quantity of particles that will pass through the permit boundary due to a combination of advection and eddy transport cannot be estimated by a simple model employing the settling velocities only.

c) Upwelling - the dynamic process of raising bottom water to the surface, called upwelling, is a mechanism that would transport tailings into the surface layer. Upwelling can occur in a fjord as a result of a wind stress that pushes the surface water downwind and elevates bottom water at the upwind end, or as a result of a bottom-water renewal which displaces the resident water up and out of the fjord. Upwelling near the head of Alice Arm and the outfall, caused by a wind blowing down-inlet, is more likely to bring tailings to the surface than upwelling near the mouth. However, if the light winds observed in 1978-79 (Buckingham, 1980) are representative of the wind stress over Alice Arm, it is not likely that wind-driven upwelling occurs either at the head or the mouth inside Alice Arm. Upwelling was observed to occur off Lime Creek from a depth of 30 m in June 1974 (Goddard, 1975a). It is not known if upwelling occurs regularly in this area, but this event occurred at a time when it was unlikely to have been driven by deep-water renewal. Deep-water renewal in Alice Arm has been observed to occur over relatively short periods of time. The upwelling associated with the intermediate water renewal of January 1977 raised water at an estimated rate of at least 3 m day^{-1}. Using Table 4.1, it can be seen that an upwelling velocity of this magnitude would cause suspended particles of less than 8 μm to rise rather than settle. It is not known how representative the time scale of this renewal was, but is is apparent that renewal events can elevate at least the fine fraction of the tailings. Gade and Edwards (1980) have noted that the water displaced by intruding water is more likely to take the direct route up and out of the fjord than to follow the classic circulation pattern of first being advected along the bottom to the head of the fjord and then up and out. Hence, as was assumed for the January 1977 renewal, the upwelling is a general feature of the fjord rather than being concentrated at the head.

d) Vertical turbulent diffusion - the coefficient of vertical turbulent diffusion has been calculated from salinity time series below 80 m in the middle of Alice Arm to be of the order of 1-10 x 10^{-4} $m^2 s^{-1}$. Values such as these are typical of average marine environments and suggest that vertical turbulent mixing would not contribute significantly to the vertical transport of tailings from deep water. However, if the vertical diffusion is driven by internal waves breaking at the boundaries (Stigebrandt, 1976), the local vertical mixing at the boundaries could be much larger and cause resuspension and vertical transport of tailings.

e) Resuspension - in addition to the possibility of sediments being advected out of the disposal region before they are deposited on the bottom, there is the possibility that sediments may be resuspended and redistributed subsequent to their initial sedimentation. Sediments are resuspended if the shear stress on the bottom exceeds a critical value, which depends on the diameter of the sediments and whether or not the sediments are cohesive. If the sediments contain a significant fine fraction, they become more consolidated with time and hence more resistant to scour. Although the sediments in the depths of Alice Arm contain a large clay fraction, they apparently remain cohesionless. It was noted that during reconnaissance surveys of the bottom by submersible the vehicle motion readily stirred up bottom sediments without coming into contact with the sediments (D. Goyette, private communication).

The critical shear stress can be expressed as a critical velocity at a fixed height above the bottom, if a number of assumptions are made (Graf, 1971). The critical velocity is at a minimum of approximately 0.2 ms^{-1} for particles of 100-600 μm diameter and increases to approximately 0.5 ms^{-1} for diameters of 15 and 3200 μm. The near bottom velocity can be considered to be the vector sum of the water current and the orbital velocity associated with surface gravity waves. The observed currents 10 m above the bottom at E4 and F15 exceeded 0.2 ms^{-1}, less than 1 percent and 0.1 percent of the time respectively, and never exceeded 0.5 ms^{-1}. However, it should be recalled that the recorded speeds are averages over 15 minute periods. The currents were seen to have large amplitude fluctuations at the highest detectable frequencies and would be expected to possess significant energy at higher frequencies as well. Therefore, the instantaneous speeds may be much larger than the recorded averages. Since the shear stress is proportional to the square of the current speed, the maximum instantaneous values may be significantly underestimated. From the calculated wave climate, the only locations where surface gravity waves could induce significant orbital velocities near the bottom are in the shallows over the delta area at the head and the sills (20 and 42 m) near the mouth. The region of the sills also experiences much larger tidal currents than the bottom near E4 or F15. Canadian Hydrographic Service Chart 3793 indicates maximum surface currents of 0.50 - 0.75 ms^{-1} over the shallow sills. Calculations of the average flow through the cross-sectional area over the sill based on the intertidal volume of the Arm yield similar velocities. Therefore, the flow over the sill is expected to be dominantly barotropic and the large velocities near the bottom scour the sills and leave the coarse sediments that are found there. In the depths of the Arm the critical velocity is seldom exceeded, and resuspension of sediments is not expected to be an important process.

In other fjords, large magnitude currents associated with buoyant or negatively buoyant jets that penetrate along the bottom on flood tides have been observed on the inner slope of the sill (Stucchi, 1980). No current observations were made on the inner slope of the Alice Arm sill, so there is no direct evidence of how important this process may be. The sediment distribution indicates that currents prevent fines from accumulating on the inner slope of the sill to a depth of 230 m. Therefore, if tailings were to pass the Hans Point Permit boundary and were deposited on the inner slope of the sill, they would eventually be resuspended. If the penetrating jet were vigorous enough, the resuspended tailings could be upwelled to the surface and transported out of the Arm (Stucchi, 1980).

The near bottom shear in the currents is important in keeping particles in suspension. The transmittance observations indicated an increase in turbidity in the bottom 25 m layer. Hence, although resuspension of bottom sediments by water currents is unlikely, the bottom 25 m layer has a higher concentration of suspended sediments which could be advected along the bottom or upwards with deep water renewal.

f) Slides - submarine slides are common on the edge of the Mississippi Delta and other areas of rapid deposition (Coleman and Garrison, 1977; Prior and Coleman, 1979). The sedimentation rate and the slope of the delta front at the head of fjords indicate a high probability of submarine slides (D.B. Prior, private communication). Submarine slides and turbidity currents have been observed in many fjords and are thought to be common in the fjords of British Columbia, Alaska, New Zealand, and Norway. A major slide which generated large amplitude surface waves in Kitimat Inlet in 1975 has been reported and compared with other slides in other fjords (Murthy and Brown, 1979). Canadian Hydrographic Service Chart 3793 indicates two areas of conspicuous landslides on the south shore of Alice Arm. Sub-bottom profiles and sand-shell-organic matter layers found in cores indicate that slides or turbidity currents are common in Alice Arm (B.D. Bornhold, private communication). These submarine events may be triggered by landslides, seismic activity, or submarine slope failure. On November 03, 1976 the current meter 10 m above the bottom at F15 recorded a current spike of almost 0.5 ms^{-1} towards 039°T for approximately 1 hour. This isolated current surge was probably a turbidity current. A turbidity current of this magnitude and duration could redistribute a large quantity of sediments. It would primarily transport sediments to greater depths, but it would also resuspend a significant quantity of sediments along its path. If upwelling were to occur at approximately the same time, the resuspended material could be transported out of the disposal area.

The accumulation of tailings in the vicinity of the outfall is likely to create conditions favourable to frequent submarine slides. Based on observations in Rupert-Holberg Inlet (A. Hay, personal communication), these tailings slides would be expected to occur weekly or more frequently and resuspend large quantities of tailings as they travel down the side of the fjord.

g) Buoyant tailings plume - the tailings slurry will be mixed with saline water from Alice Arm before injection at 50 m depth. The dilution rate and the depth of the water used in the dilution (and hence its density) are not known. If the water is taken from the near surface, it will have a density significantly less than the water at 50 m or below, especially in the late spring to autumn period. When the tailings slurry is released into the Arm, the largest particles will begin to settle out of the plume, and the density of the plume will decrease. Although no detailed calculations can be made, there is a possibility that the plume may become buoyant and begin to rise. The existence and the amount of plume rise will depend on the volume and the density defect of the water used in the dilution. Plume rise could be minimized by using water from a depth of 50 m or more in the dilution process.

5.0 COMPARISON WITH OTHER TAILINGS DISPOSAL SITES

Down and Mill (1978) presented a review of the disposal of mine and mill wastes at sea. Half of their examples were fjord disposal sites and included three in Norway and one in British Columbia (Rupert-Holberg Inlet). Takenouti, Natsume, and Miyata (1979) investigated the sinking and diffusion of bauxite residue injected 30 m below a barge in the Pacific Ocean off Japan. Hatfield and Williams (1976) summarized the possible environmental effects of disposing mine tailings into Strathcona Sound, Baffin Island by a comparision of the Sound with two exsiting fjord disposal sites: Qaumarujuk-Agfardlikavsa Fjord, Greenland and Rupert-Holberg Inlet, British Columbia. Both of these latter fjord disposal sites have been studied in detail. The most recent papers on the circulation of the former are by Asmund (1980) and Nielson and Ottesen Hansen (1980). The Boca de Quadra and Smeaton Bay areas of Alaska, 80 km to the west of Alice Arm, are being considered for the disposal of tailings from a proposed molybdenum mining operation and are under investigation (Burrell, Niebauer, and Nebert, 1980).

The Rupert-Holberg Inlet has been studied in detail (Johnson, 1974; Drinkwater and Osborn, 1975; Stucchi and Farmer, 1976; Stucchi, 1980; Waldichuk and Buchanan, 1980). The tailings are disposed as a slurry of density 1200-1400 kgm^{-3} at a depth of 50 m in Rupert Inlet but are frequently resuspended by tidal turbulence and upwelling at the junction of Rupert and Holberg Inlets, in the vicinity of Quatsino Narrows. The resuspension appears to be most intensive on the flood tide near springs. The resuspended material has been deposited in the intertidal areas of Rupert-Holberg Inlet and has been advected out of the system through Quatsino Narrows on the ebb tide.

Table 5.1 compares Alice Arm with the Rupert-Holberg Inlet system. The sill depth and volumes of the two inlets are approximately the same but Alice Arm is much deeper and the tailings are to be injected near

TABLE 5.1 Comparison of Alice Arm with Rupert-Holberg Inlet

		Alice Arm	Rupert-Holberg Inlet
Sill depth (m)		20	18
Maximum depth (m)		386	170
Volume ($10^6 m^3$)		3700	5400
Tidal Prism ($10^6 m^3$/flood tide)	- average	130	170
	- large	210	260
Freshwater inflow ($10^6 m^3$/6.2 hour)	- minimum	0.05	-
	- average	0.78	3.1
	- maximum	2.6	10.3

the head rather than near the sill as in Rupert Inlet. Approximately 3.4 times as much tailings are introduced into Rupert Inlet with 75 percent less than 74 μm as compared to the Alice Arm design grind with approximately 34 percent less than 74 μm. It has been found that very fine particles (<3 μm) do not settle but remain in suspension in Rupert-Holberg Inlet.

Pickard (1963) noted that Rupert Inlet appeared to experience an unusually high level of mixing. Stucchi (1980) has noted that in Rupert-Holberg Inlet the bottom water properties have large seasonal variations (4^oC and $3^o/oo$), the water column is vertically well-mixed, and the deep water has a high dissolved oxygen content. Bottom current velocities greater than 1.5 ms^{-1} are frequently observed at the foot of the sill at 145-m depth and within one kilometre of the sill. In modelling the tidal jet issuing from Quatsino Narrows on a flood tide, Stucchi (1980) identified two types of flow: a buoyant jet which can penetrate well below the sill depth and to the bottom for high densiometric Froude numbers, and a negative jet that penetrates to the bottom. In both cases the jet entrains significant quantities of water and resuspends and upwells tailings.

In contrast, in Alice Arm the seasonal variations in the bottom water were small (much less than 1^oC and $1^o/oo$), the water column is stratified, but dissolved oxygen values are high. The bottom currents recorded at the foot of the sill at 360 m and 5 km from the sill were always less than 0.25 ms^{-1} except for the brief surge thought to be caused by a turbidity current. Although bottom water renewal would take the form of a negative jet, the flow would probably be quite dissipated as a result of the water that it would entrain by the time it reached the foot of the Alice Arm sill. Buoyant jets are not likely to penetrate to the bottom of Alice Arm since an extremely high densiometric Froude number would be required for it to occur (Stolzenbach, Adams, and Harleman, 1973; Shirazi and Davis, 1974). Buoyant jets may partially penetrate the water column and contribute to mixing in the intermediate waters of Alice Arm. The current meter at 185 m at station F15 does not show any evidence of a penetrating buoyant jet but it may be too far from the sill to observe it. However, it is not likely to be an important process since the vertical turbulent diffusion is not unusually high.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Although insufficient data exist to resolve the long-term, typical scales of motion within Alice Arm, the data do indicate some important dynamic processes that contribute to the circulation and mixing of Alice Arm. Oceanographic data taken at widely separated times over the past 30-year period display moderate variability in the properties of the bottom water of Alice Arm (1.5 ^{o}C and 1 ^{o}/oo). The high concentration of dissolved oxygen at depths (always greater than 50 percent saturation) indicate regular renewals of the water below the sill depth where the oxygen consumption is estimated to be 1-2 ml/l per year. Long-term variation in the sparse data base mask any obvious annual cycle.

A partial renewal to a depth of approximately 200 m was observed in January 1977 and a total renewal occurred a year later between October 1977 and May 1978. Renewal events of variable magnitude are believed to occur most years in the winter time, as in other shallow silled fjords. The renewal event of January 1977 coincided with a period of strong outflow winds and spring tides. It is hypothesized that the down-inlet wind stress on the surface of Observatory Inlet caused upwelling off the sill of Alice Arm. The upwelled water was denser than the upper waters of Alice Arm and it flowed down the sill into the Arm on the flood tide as a negatively buoyant plume. The plume overshot its equilibrium level of approximately 180 m and mixed down to a depth of more than 200 m (approximately the depth of the innermost sill). The renewal of the following winter was not a single event, but rather a series of two or more events. The scale and timing of these influxes cannot be determined from the data. Although large magnitude currents were not observed at the time of the 1976-1977 partial renewal, caution must be exercised in extrapolating to renewal events in other years. There is evidence that the 1976-1977 winter was atypical and hence the observed renewal event may well have been atypical. However, renewal events are not as vigorous or as frequent in Alice Arm as they are in

Rupert-Holberg Inlet. The fine sands down the sill slope to a depth of 230 m indicate higher velocity currents than at greater depths but not regularly exceeding 0.5 ms^{-1}.

Buoyant jets are not as likely to penetrate to the bottom of Alice Arm as they do in Rupert-Holberg Inlet. The innermost sill in Alice Arm with a depth of 210 m may influence the boundary separation point of buoyant and negatively buoyant plumes flowing down the sill of Alice Arm. The penetration of the 1976-1977 partial renewal may have been limited to approximately a 200 m depth by the presence of the deep sill.

The tailings which will be introduced at a depth of 50 m in the form of a negatively buoyant plume are likely to descend to the deepest parts of the Arm under the influence of gravity. While the plume is descending, it will be deflected by the ambient currents. Considering the settling velocities of the tailings and the observed currents, there is a high probability that the finer fraction of the tailings will remain in suspension long enough to be transported by advection and turbulent diffusion over the 210 m sill at the boundary of the permitted disposal area while still remaining within the Arm.

If the tailings are to be transported out of Alice Arm, they must be raised from their injection depth of 50 m to a level above the 42 m depth of the sill at the mouth. The vertical coefficient of turbulent diffusion below a depth of 80 m as calculated from the time series salinity observations of 1976-1977 in the middle of the Arm is 1-10 X 10^{-4} m^2s^{-1}. These values are not unusually large and are not large enough to overcome the gravitational settling velocities of all but the finest tailings. In Rupert-Holberg Inlet, tailings of less than three micron diameter do not settle but remain in suspension. The turbulence in Alice Arm is less energetic than that in Rupert-Holberg Inlet and hence the diameter of permanently suspended particles may be less.

The spectral content of the currents as observed at the six locations in 1976-1977 is highly variable in space and time. The predominant scales had periods of 1 to 3 hours, 6 hours, 12 hours, and 2 weeks. The semi-diurnal and quarter-diurnal modes are the most prevalent but additional higher order tidal modes caused by interactions of the M_2 tide with itself are also prevalent.

The recording current meter data and hydrocasts at a fixed location over a tide cycle indicate that internal waves driven by the tides commonly exist with semi-diurnal and quarter-diurnal periods. The three current meters at both locations frequently recorded three layer flow. Vertical oscillations as large as 60 m were observed over a tide cycle at a depth of 100 m near the head of the Arm. If internal waves are an important source of turbulence, the vertical mixing may be much more intense near the boundaries where the internal waves break than indicated by the diffusion coefficients calculated in the middle of the Arm.

The reduced transmittance of the bottom 25 m layer indicates that increased turbulence near the bottom caused by current shears or breaking internal waves keeps particulates in suspension. Since the size distribution of the tailings will be similar to the natural sediments, the concentration of suspended tailings will also increase near the bottom. Therefore it is not necessary for a renewal event to be so vigorous as to resuspend deposited tailings. A near bottom concentration of suspended tailings will be present which could be upwelled with the water being replaced.

The head of Alice Arm was observed to be an area of active processes. A dye tracer with neutral to negative buoyancy introduced at a 30 m depth off Lime Creek was observed to have upwelled into the surface waters at the head of the Arm after one tide cycle. Up- and down-inlet surges of up to 0.4 ms^{-1} were observed at mid-depth and near the bottom in the vicinity of the tailings outfall. The down-inlet surges which occurred at predicted mid-ebb were composed of relatively fresh, warm water indicating that they were downwelled waters.

The observed presence of large amplitude internal waves and upwelling near the outfall indicates that it is probable that at times tailings will be elevated above the release depth. Since their settling velocities are smallest, the fines will be more likely to upwell. Once in the turbulent surface layer, a portion of the fines will most probably remain in suspension and be flushed from Alice Arm.

However, the questions still remain: what portion of the tailings will reach the surface layer, and once in the surface layer what portion of the tailings will be flushed out of Alice Arm? Unfortunately, there is a series of interrelated mechanisms by which tailings remain suspended or are resuspended, and by which the suspended tailings are raised to the surface and flushed from the Arm. The frequency of occurrence of the individual processes cannot be determined from the existing data base and hence the joint probability of tailings being raised to the surface and flushed from the Arm cannot be quantified. The only neutrally buoyant dye release at depth off Lime Creek indicated upwelling. It is not known if such upwelling occurs regularly or if an error in the experiment resulted in a buoyant dye mixture. Internal waves are usually present in Alice Arm but it is not known if the waves break on the sloping bottom at the head and cause large local vertical mixing rates. The data do indicate that the region around the outfall at the head of the Arm is an area of active, non-linear processes that should be examined in more detail. Similarly, the inner slope of the sill should be studied in further detail. No current data exist from this area in Alice Arm but studies in other fjords including Rupert-Holberg Inlet (Stucchi, 1980) have shown that processes on the inner slope of the sill contribute significantly to bottom scouring, upwelling, and vertical mixing.

The probability of tailings being upwelled into the surface layer could be reduced by lengthening the outfall pipeline and injecting the tailings at a greater depth. Upwelling events would then have to persist for a longer period of time or be more intense in order to elevate the tailings the additional distance to the surface. Since the frequency distributions of upwelling durations or magnitudes are not linear, a doubling of the release depth would reduce the probability of upwelling to the surface by a factor of more than two. However, there may not be any depth at which the tailings could be released that would totally remove the possibility of tailings being upwelled to the surface.

Additional studies should focus on the non-linear processes that were apparent in the region of the outfall at the head of the Arm, and on the dynamics of the inner slope of the sill. Another observation programme extending over a minimum of a one-year period should be undertaken. Hydrocasts or CTD profiles should ideally be done monthly at six to eight stations spaced along the axis of Alice Arm, and at a minimum of one station in Observatory Inlet. In addition to temperature-salinity observations, dissolved oxygens should be observed at standard depths over the water column rather than merely at the bottom. Current meters, complete with temperature and conductivity sensors should again be moored at a minimum of two locations: one mooring in the head of the Arm (E4 again) and one on the inner slope of the sill (say on the 150 m depth contour). This time the meters should be at similar depths (say 10 m, 50 m, and 100 m at both locations, and a near-bottom meter at the sill mooring), so that the horizontal coherence can be investigated. The sampling interval should be a maximum of 15 minutes. The resolution of the temperature and conductivity sensors should be improved over the last observations since the fluctuations at depth are relatively small. A thermistor chain at both stations, centred at sill depth, would assist the interpretation of the dynamics of the near-surface layer. Other concurrent environmental data should include local winds, tides, and freshwater inflow, preferably from the Kitsault River.

Now that tailings are being injected into the Arm, transmittance observations of the plume will be simpler to execute than dye injections at depth. The trajectory of the tailings plume should be observed monthly to determine if plume rise or upwelling is a problem.

Echo sounding observations of the depth of the pycnocline along the axis of the Arm, especially in the vicinity of the sill and the head, would be useful in the study of internal waves, and could be done on the return trip after occupation of the monthly hydrocast stations.

Data analysis should focus on a better understanding of the mechanism of deep-water renewals, the processes present on the inner slope of the sill, and the generation and dissipation of internal waves. The second time series over the winter period should permit a better understanding of the magnitude, duration, and forcing of deep-water renewals. The current meter on the inner slope of the sill will permit an analysis of the currents present in this region and the frequency of penetration by buoyant or negatively buoyant jets. The regular determination of the density profiles will permit the calculation of the possible internal wave modes, which can then be compared with the observed currents at the three or four depths. Energy present in the internal waves should be calculated, and estimates made of the energy lost by breaking internal waves.

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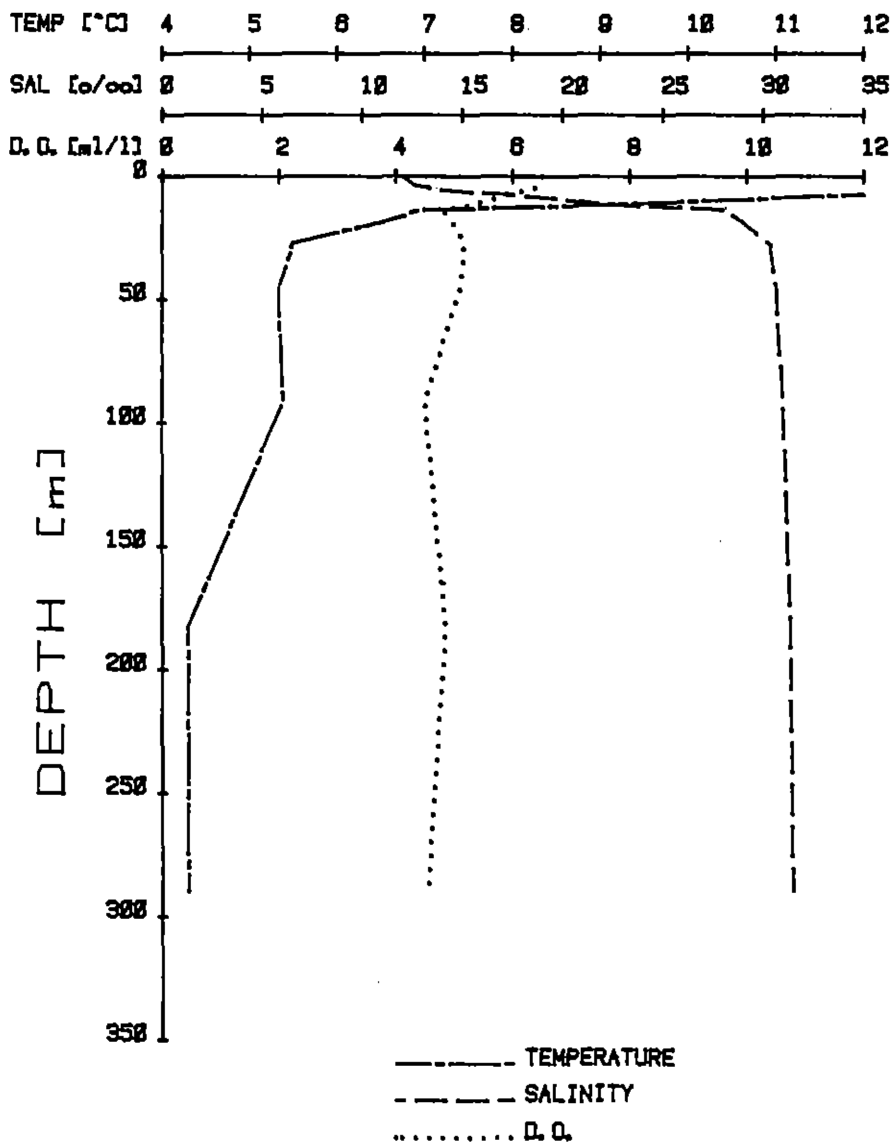

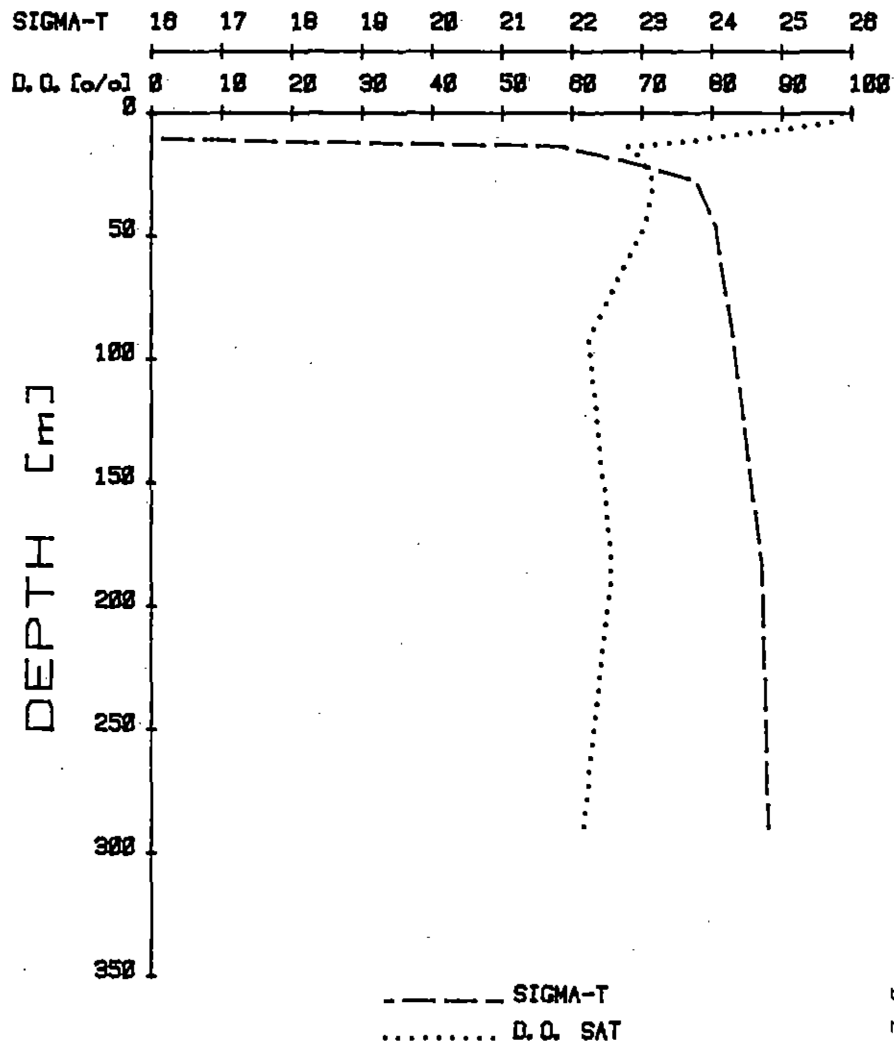

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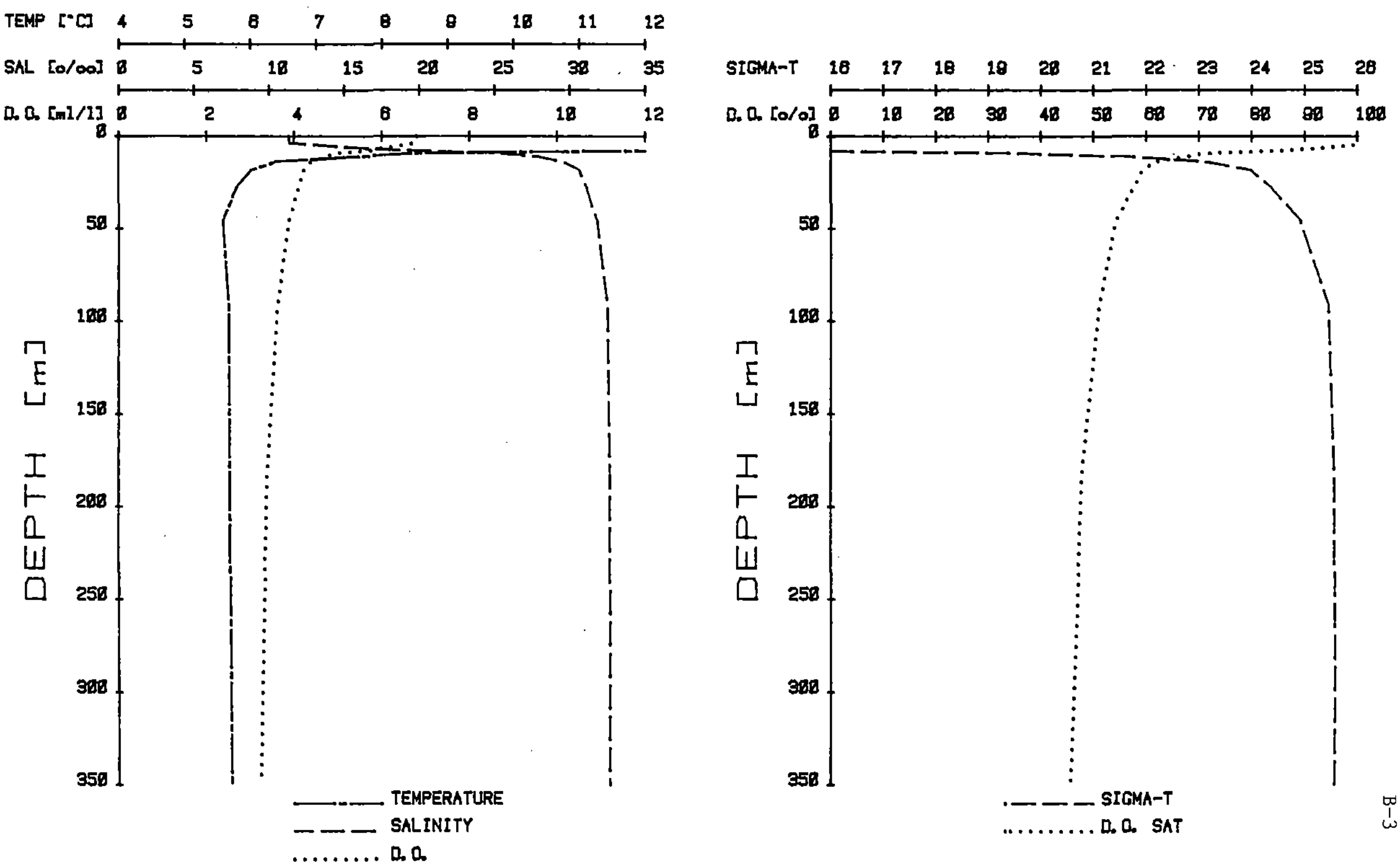

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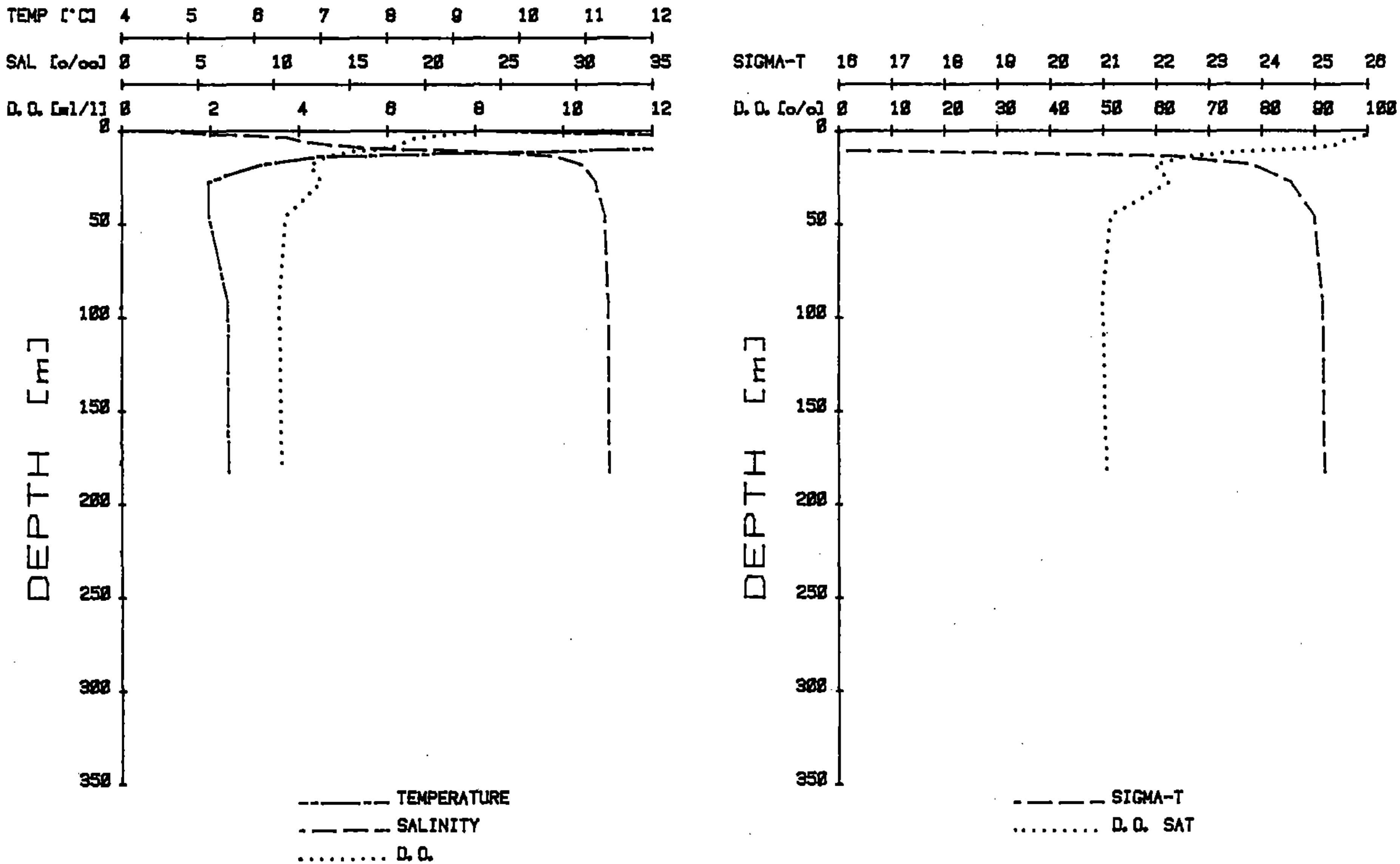

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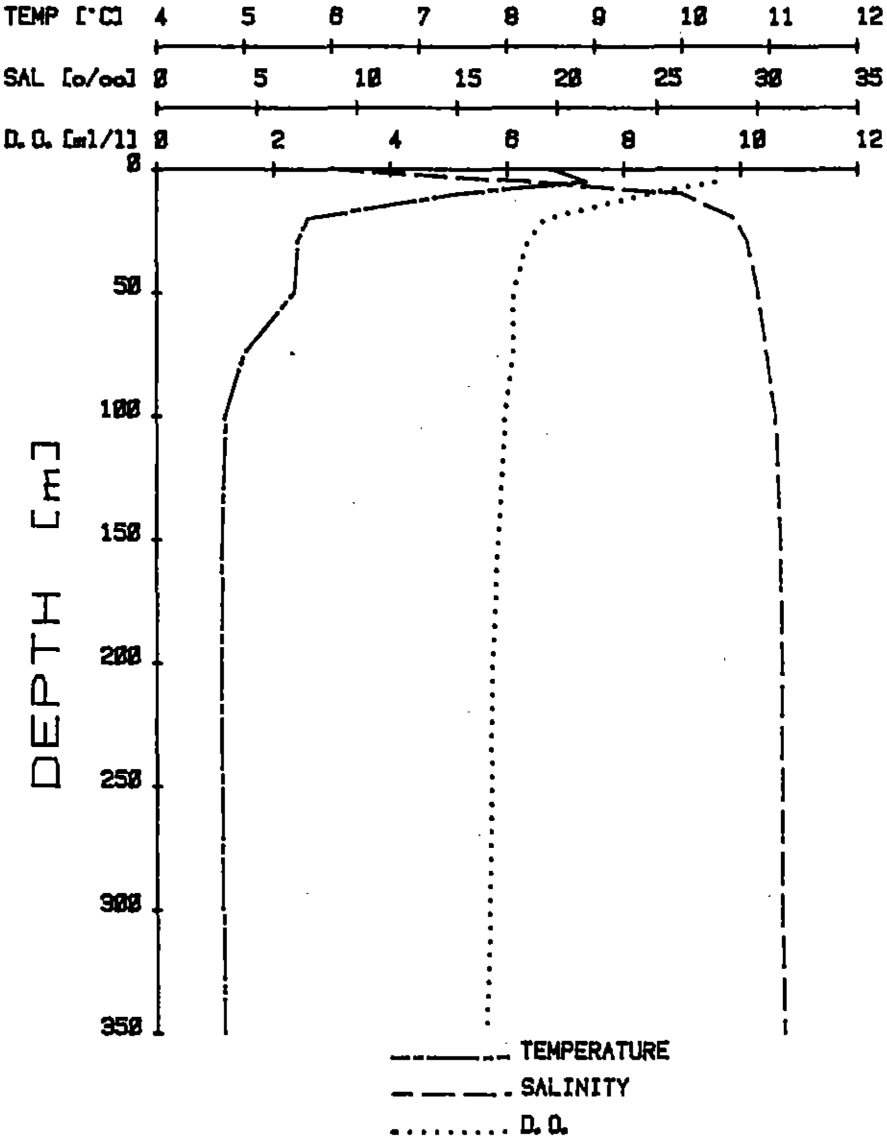

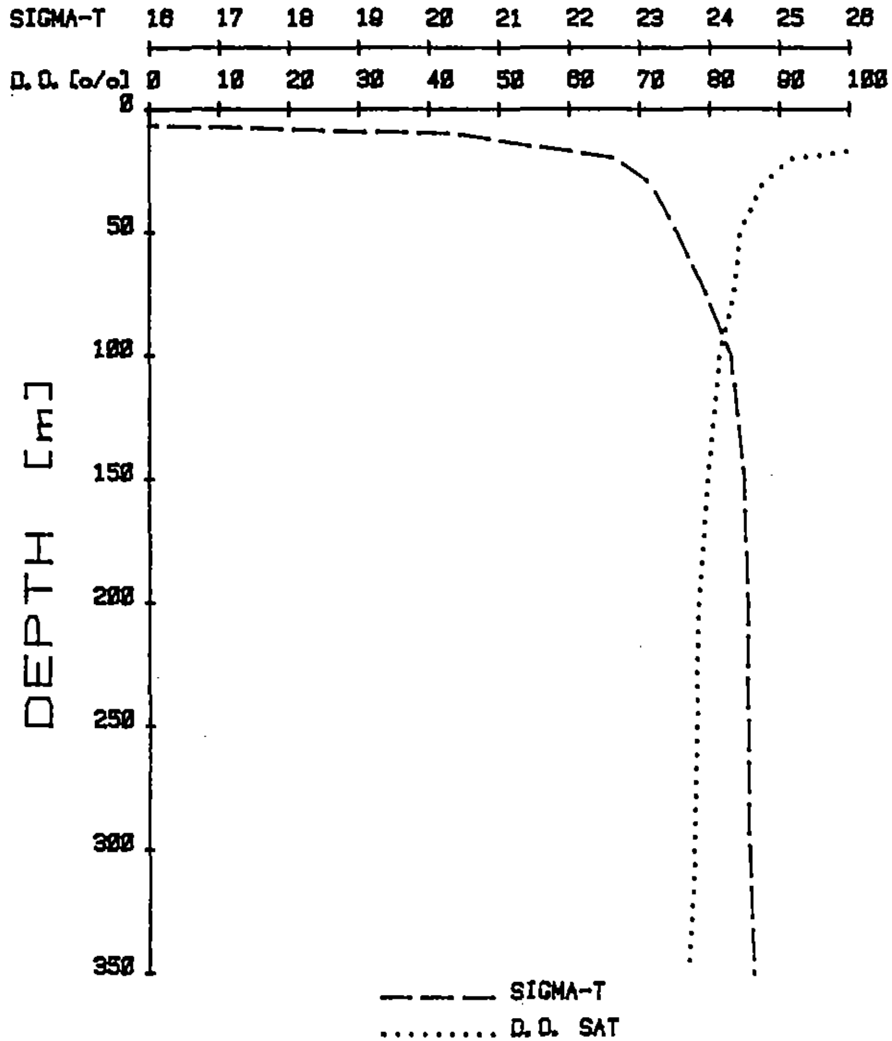

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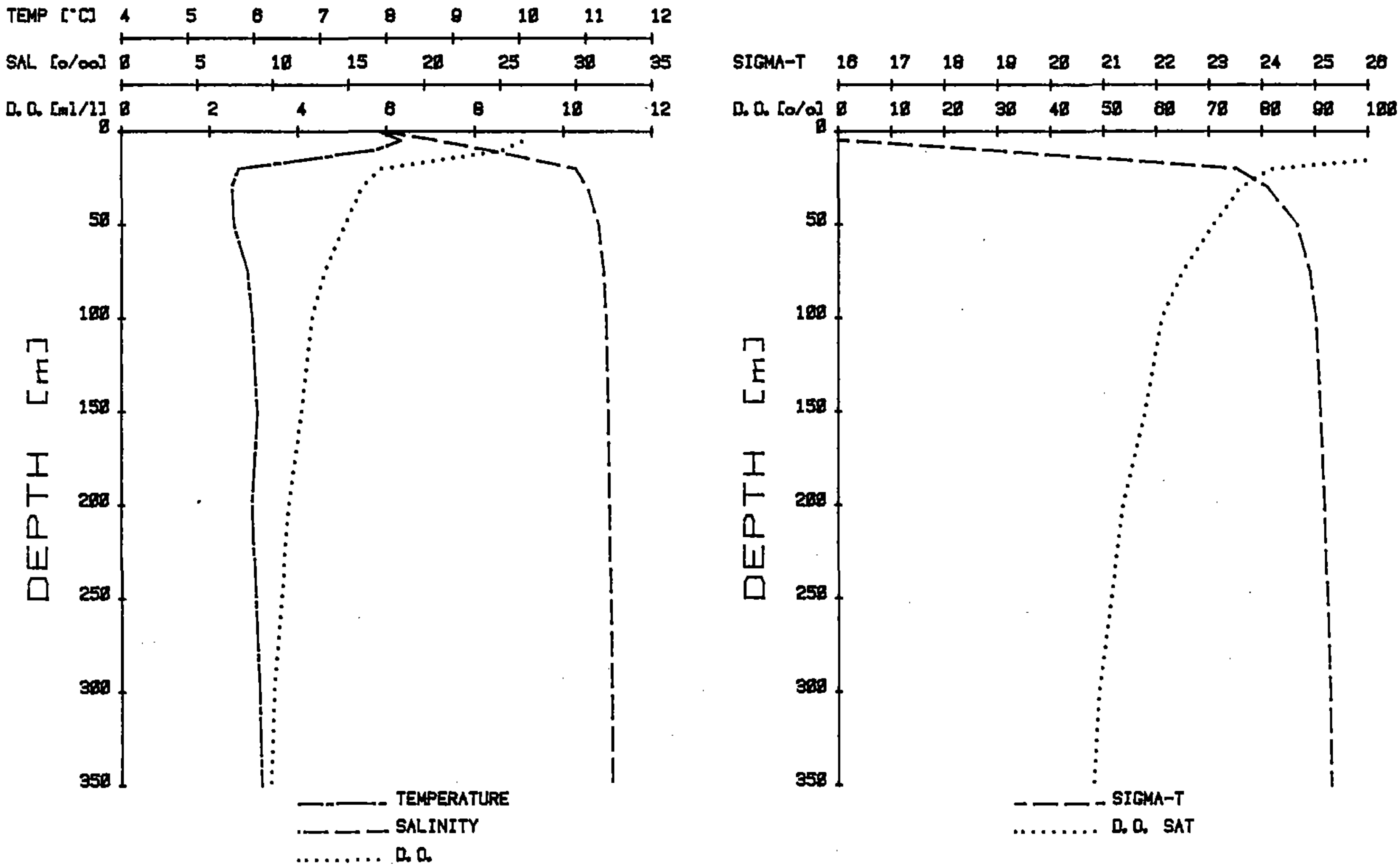

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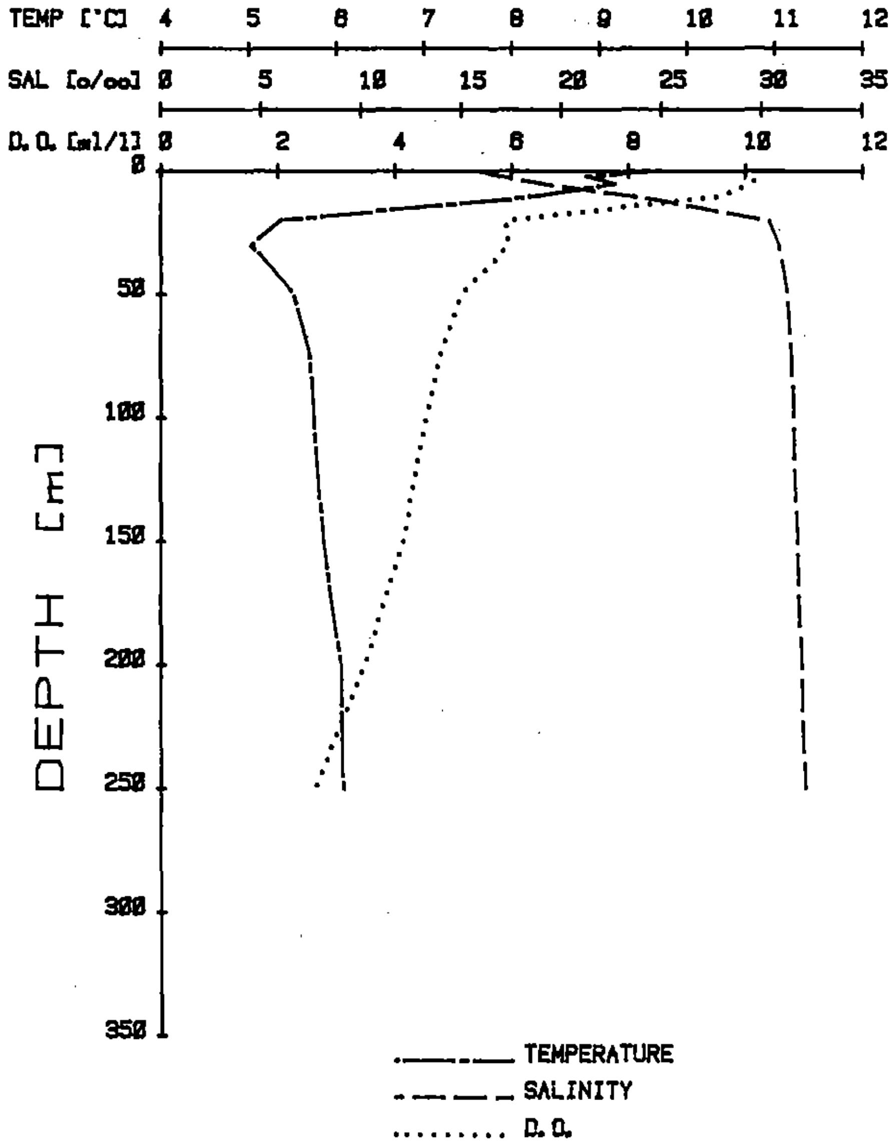

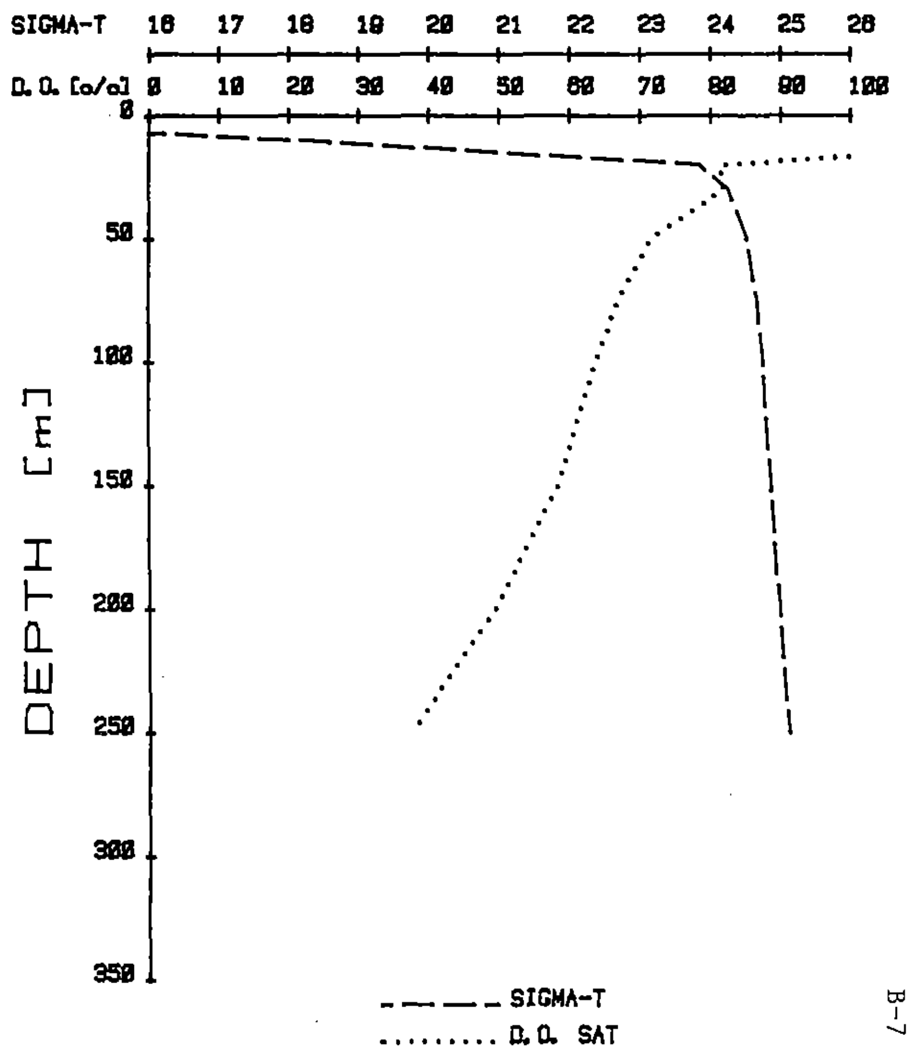

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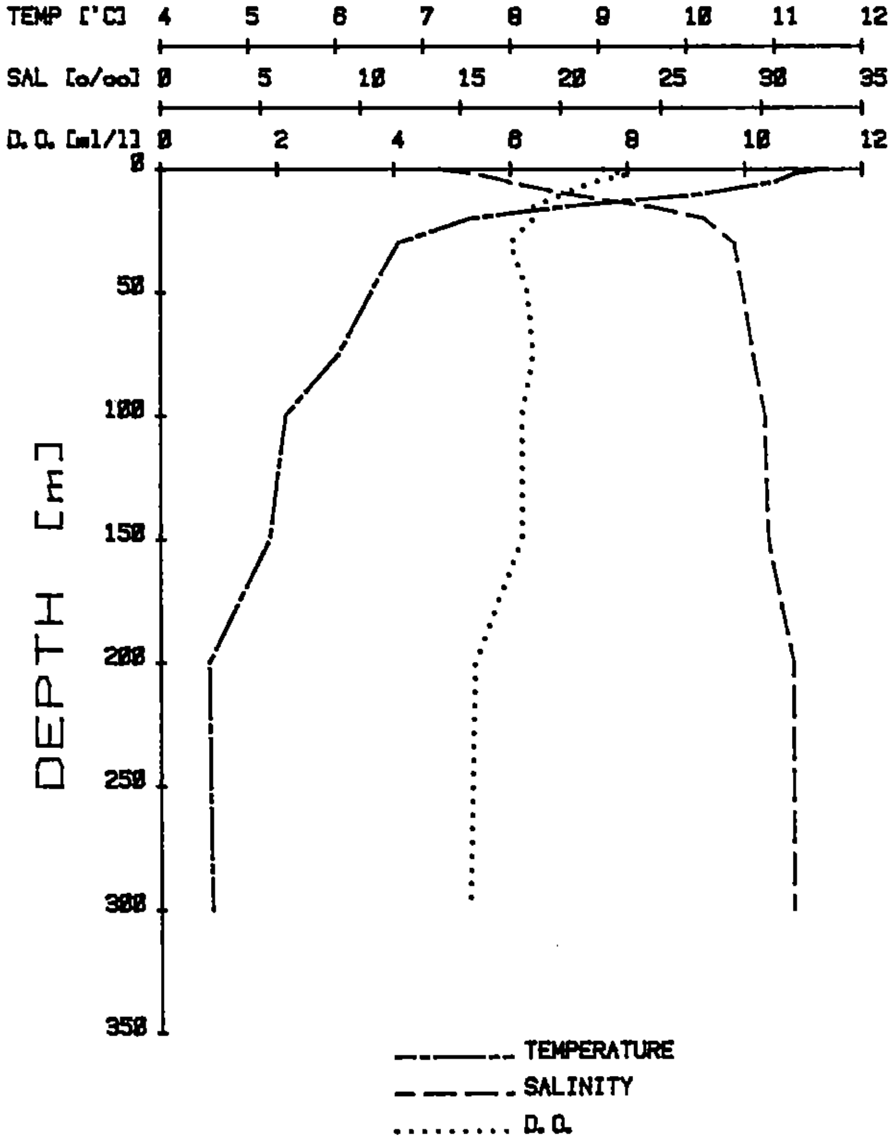

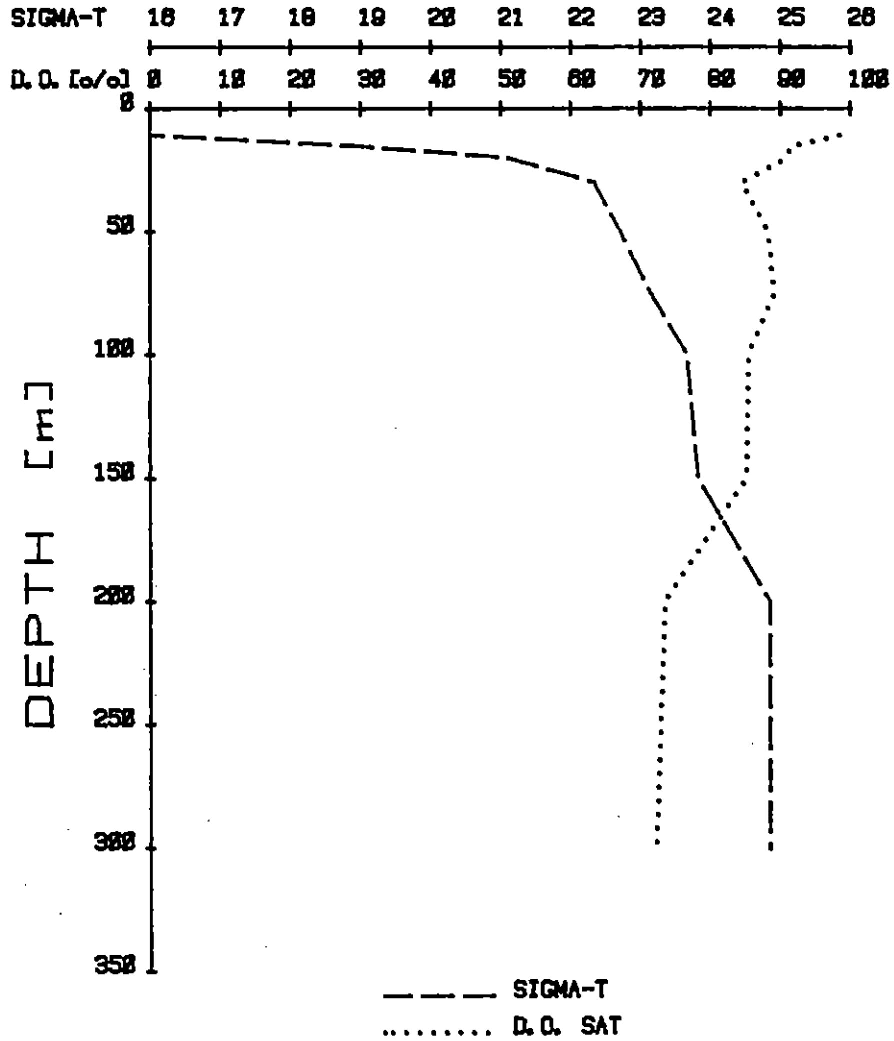

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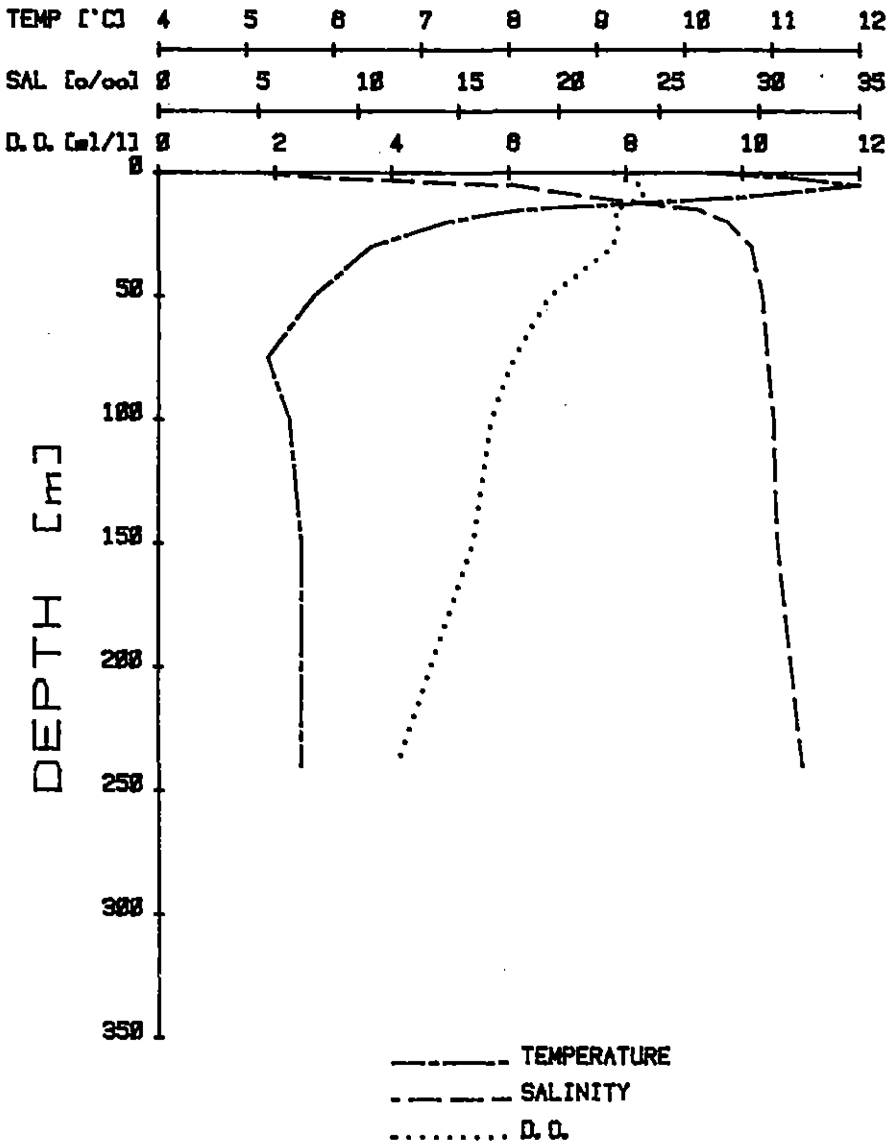

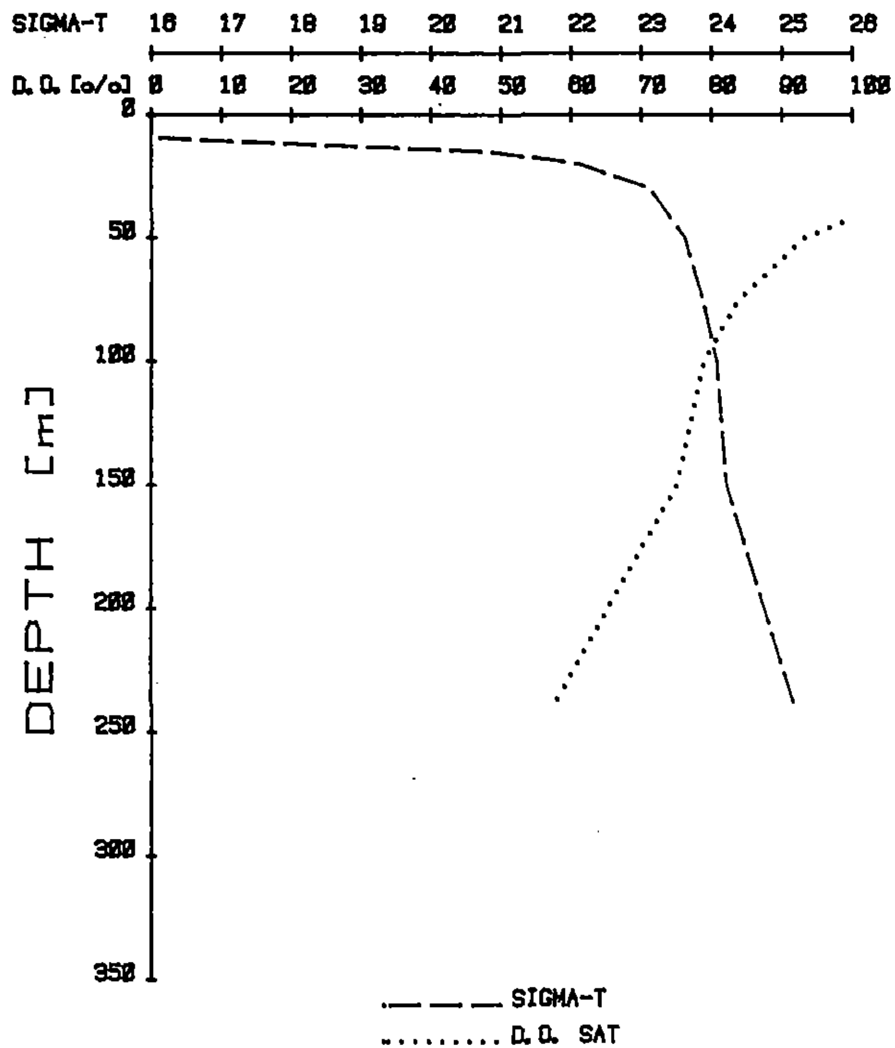

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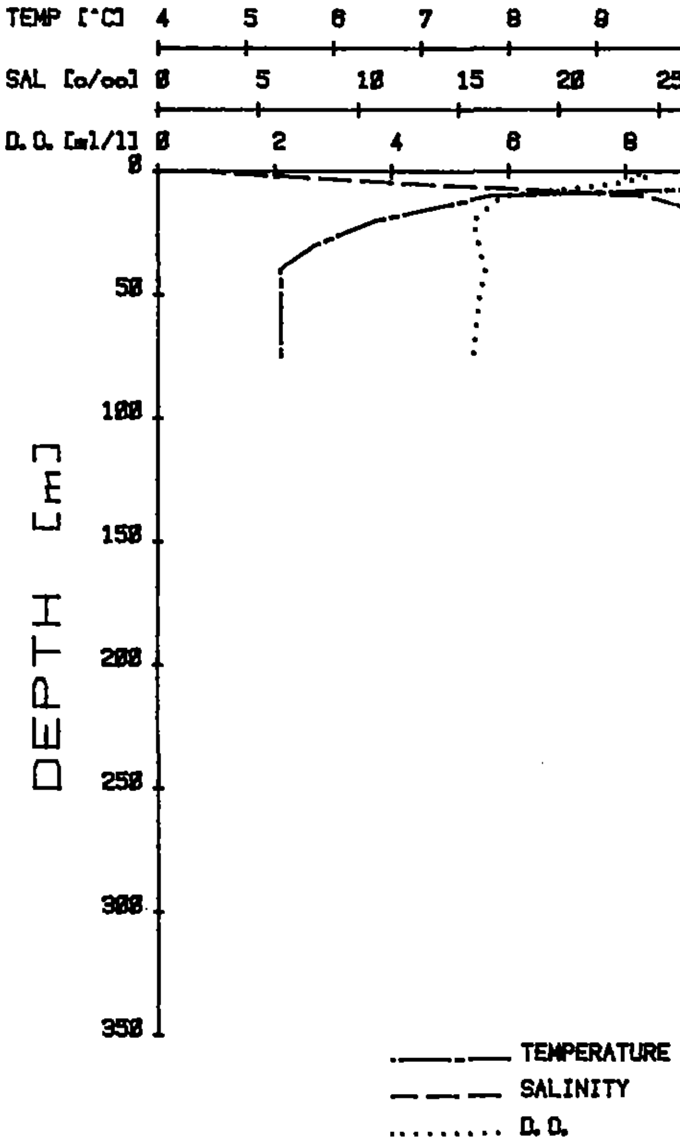

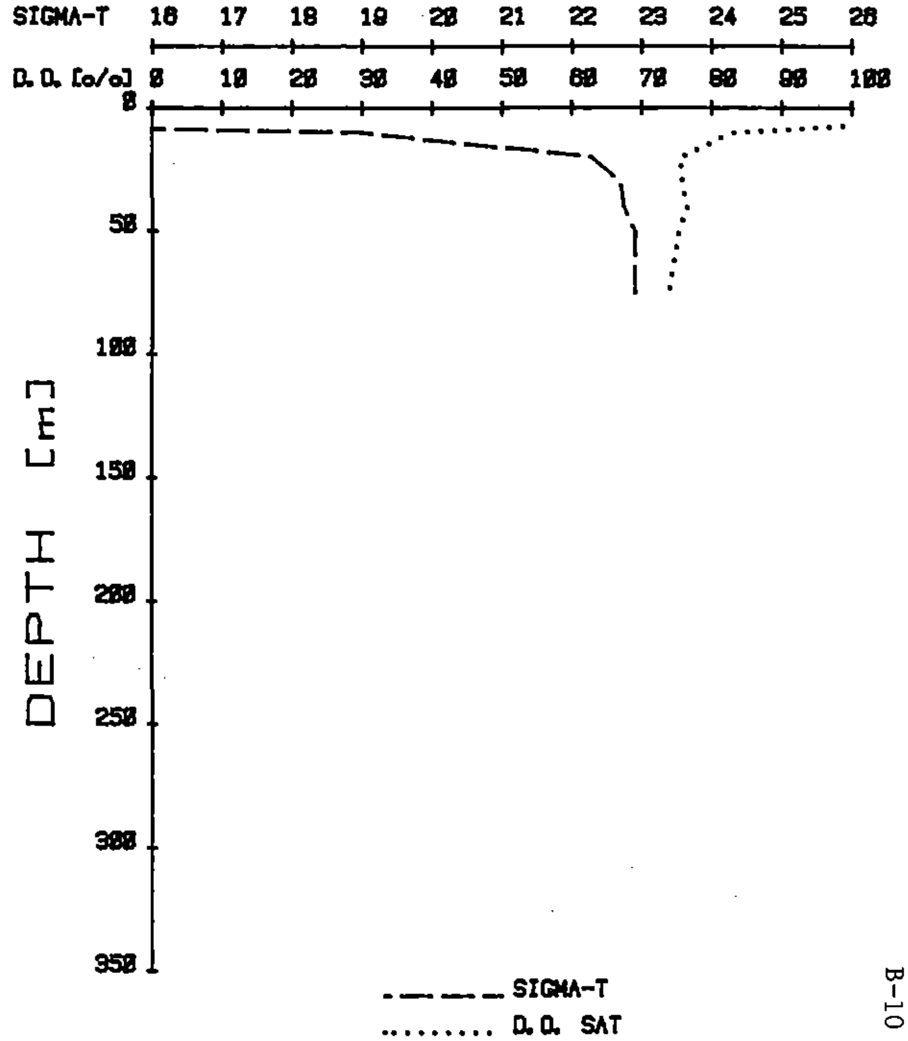

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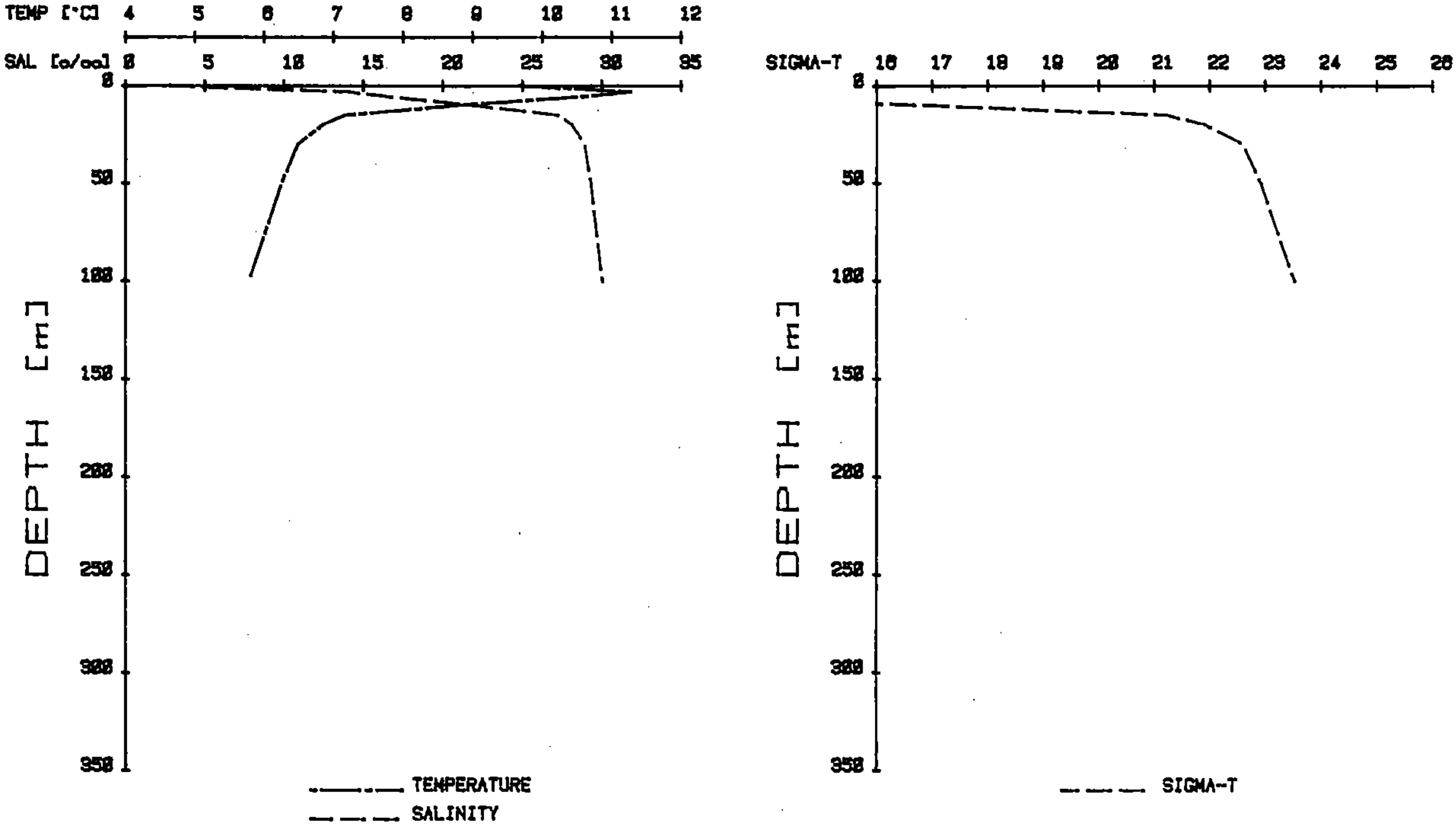

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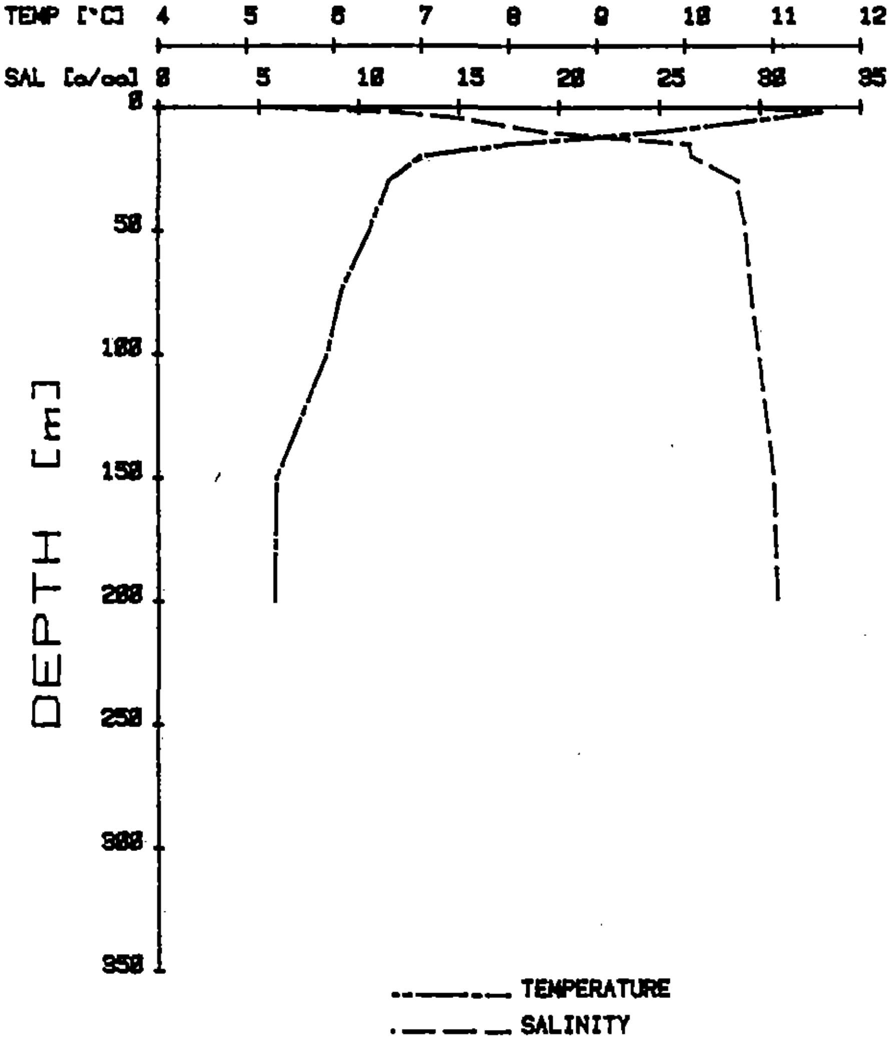

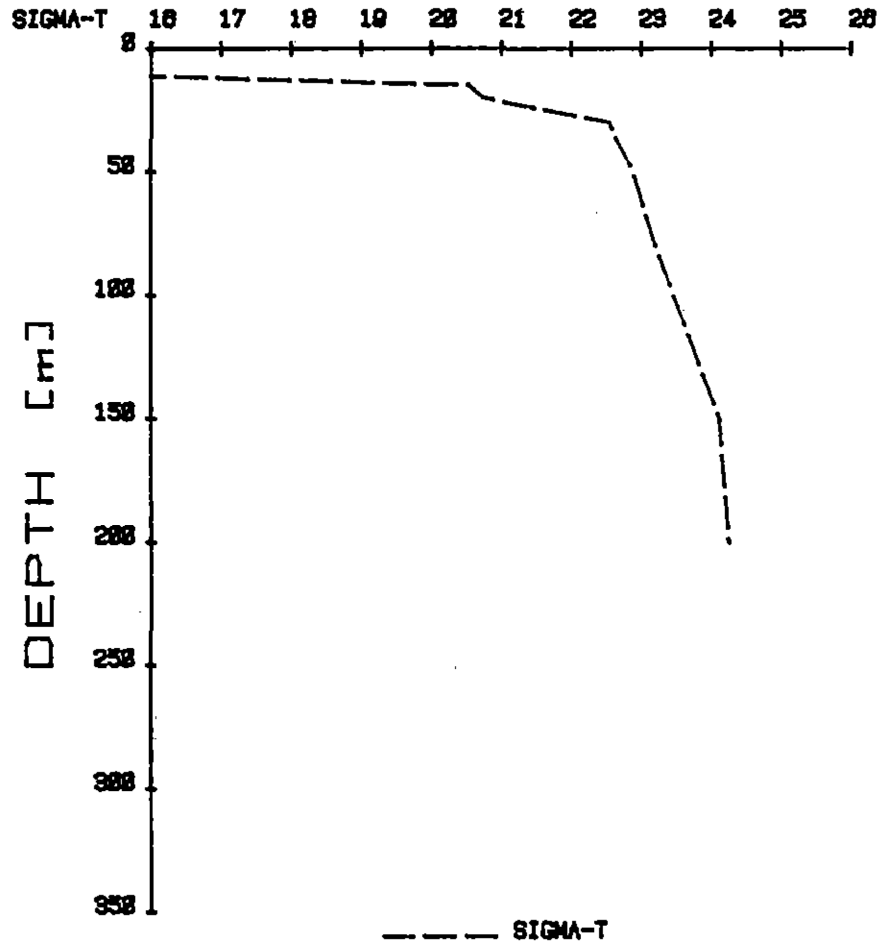

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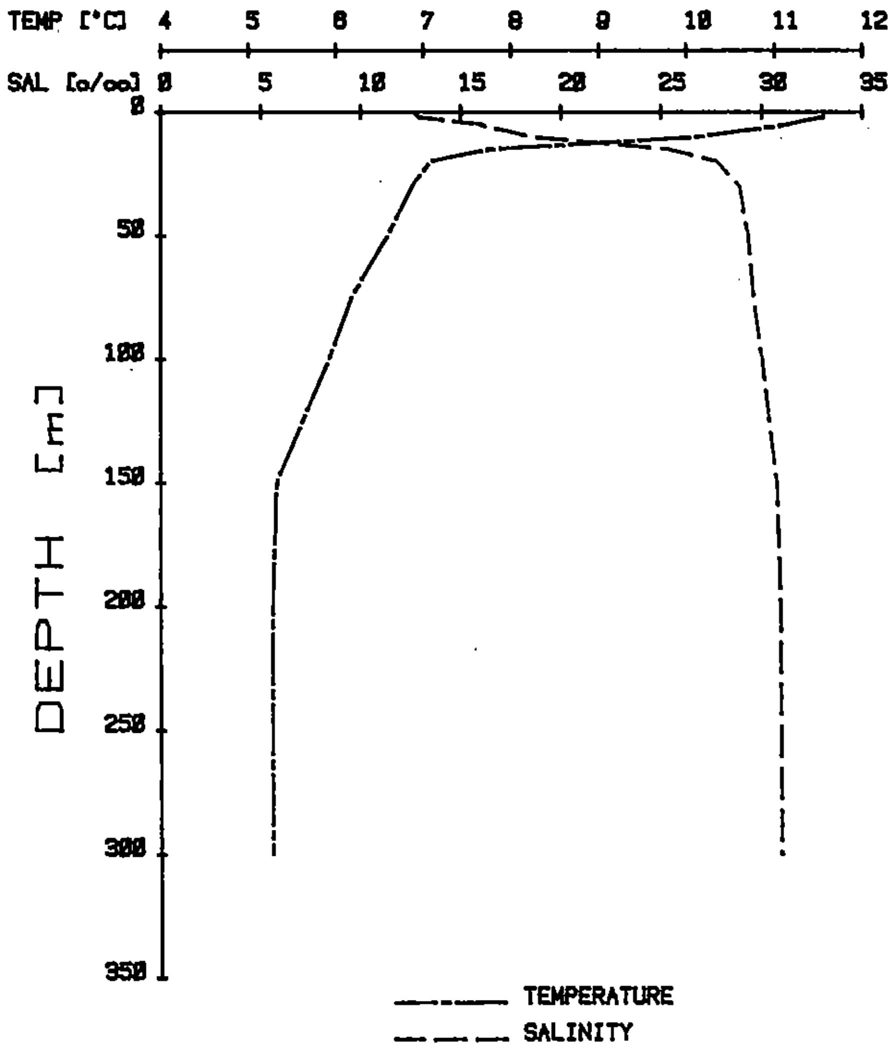

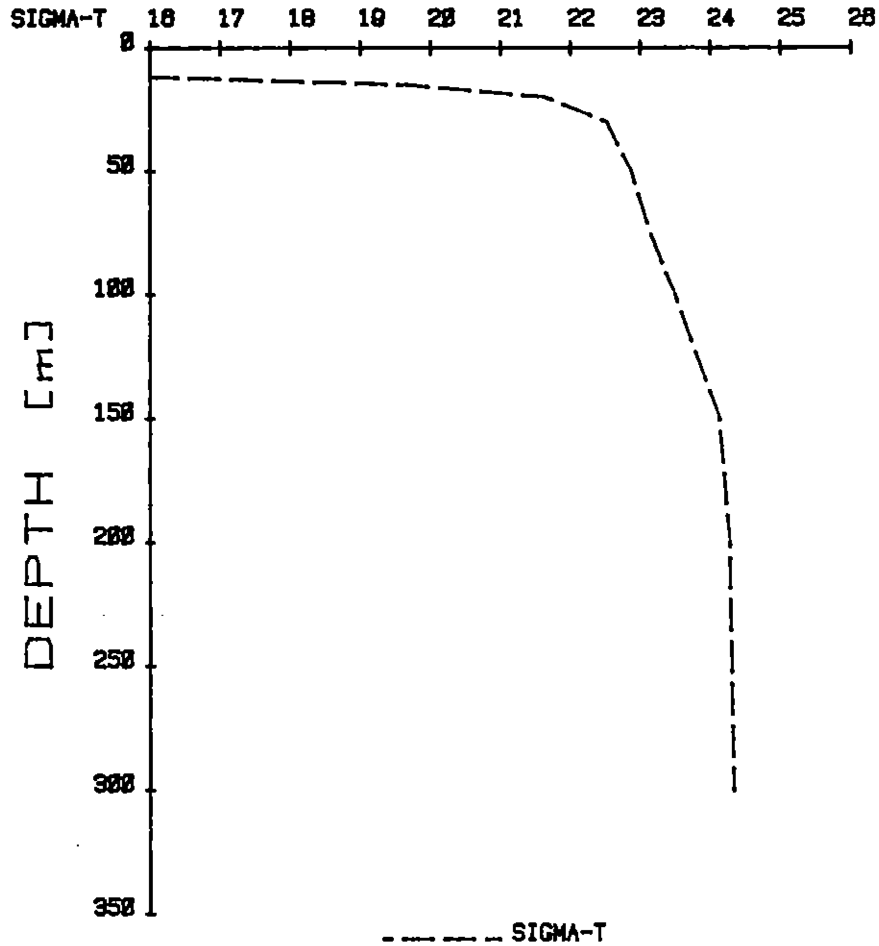

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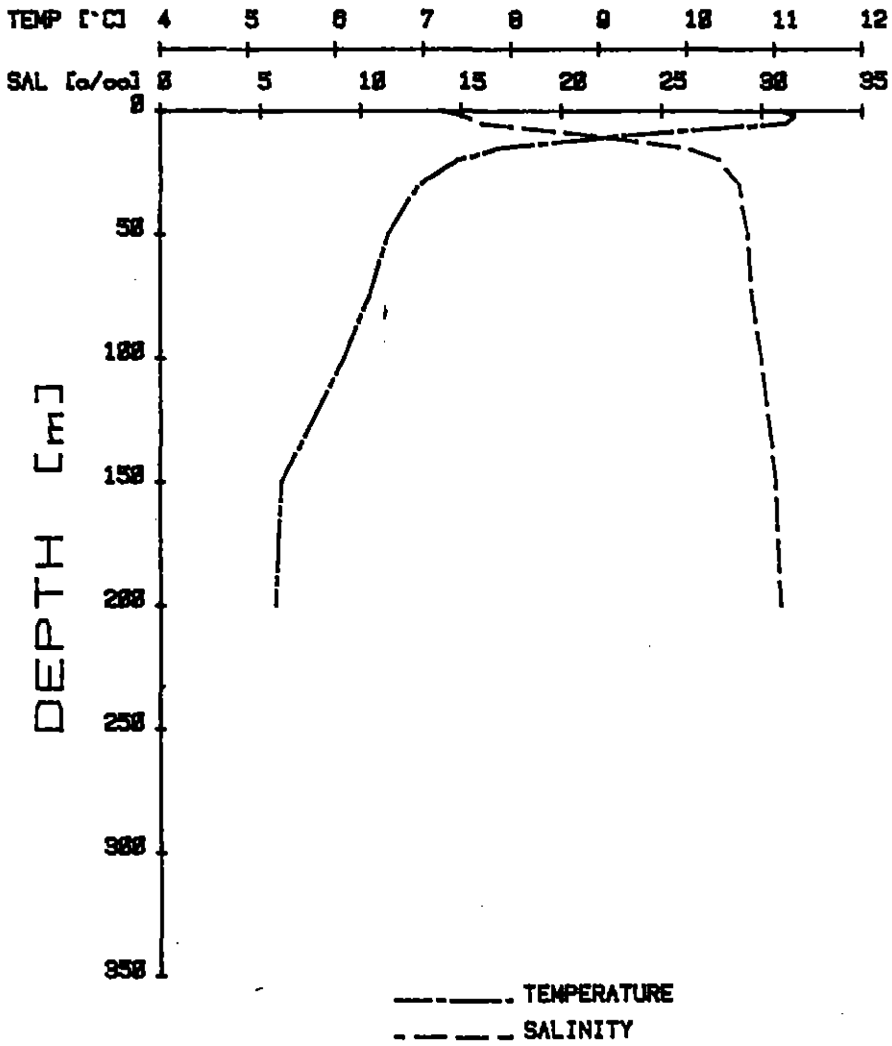

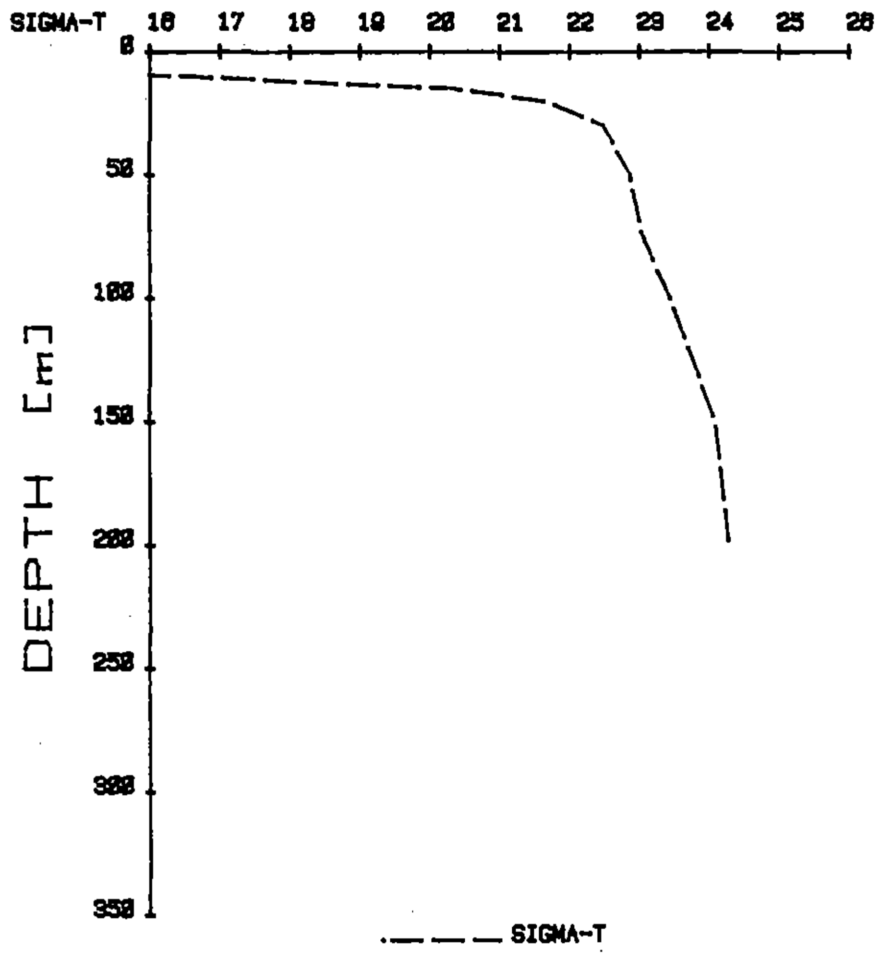

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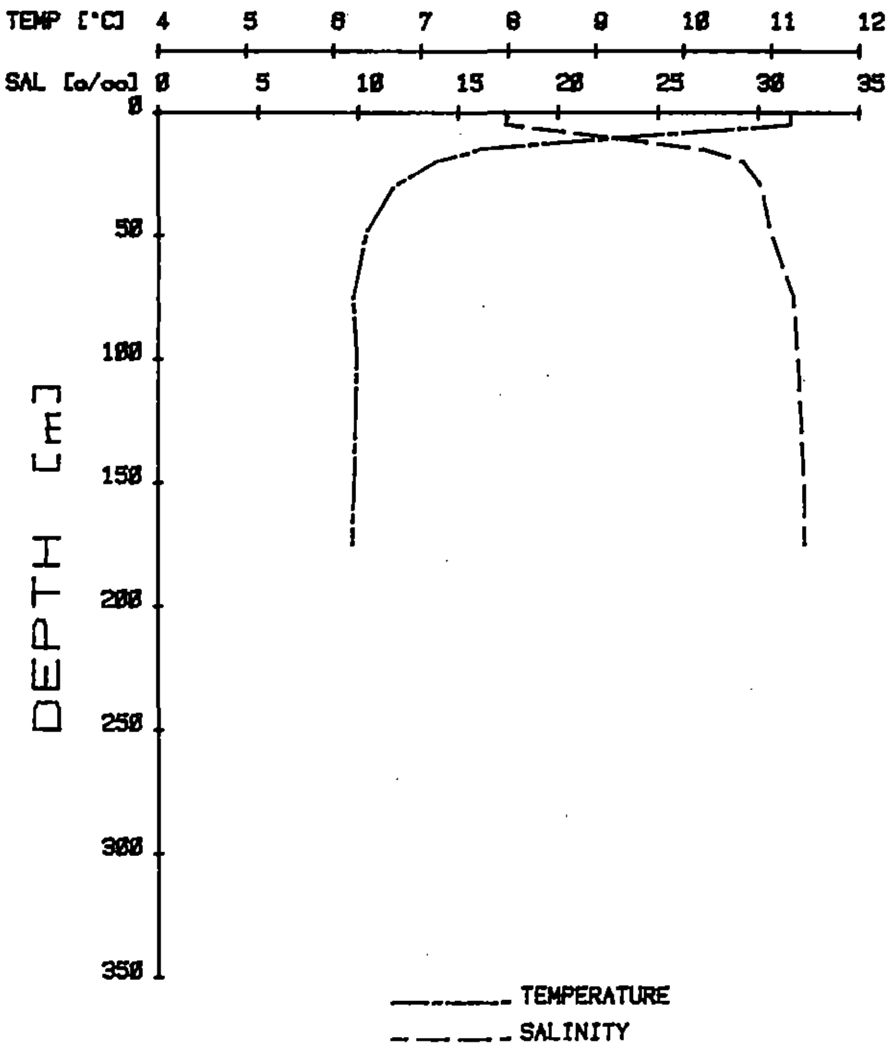

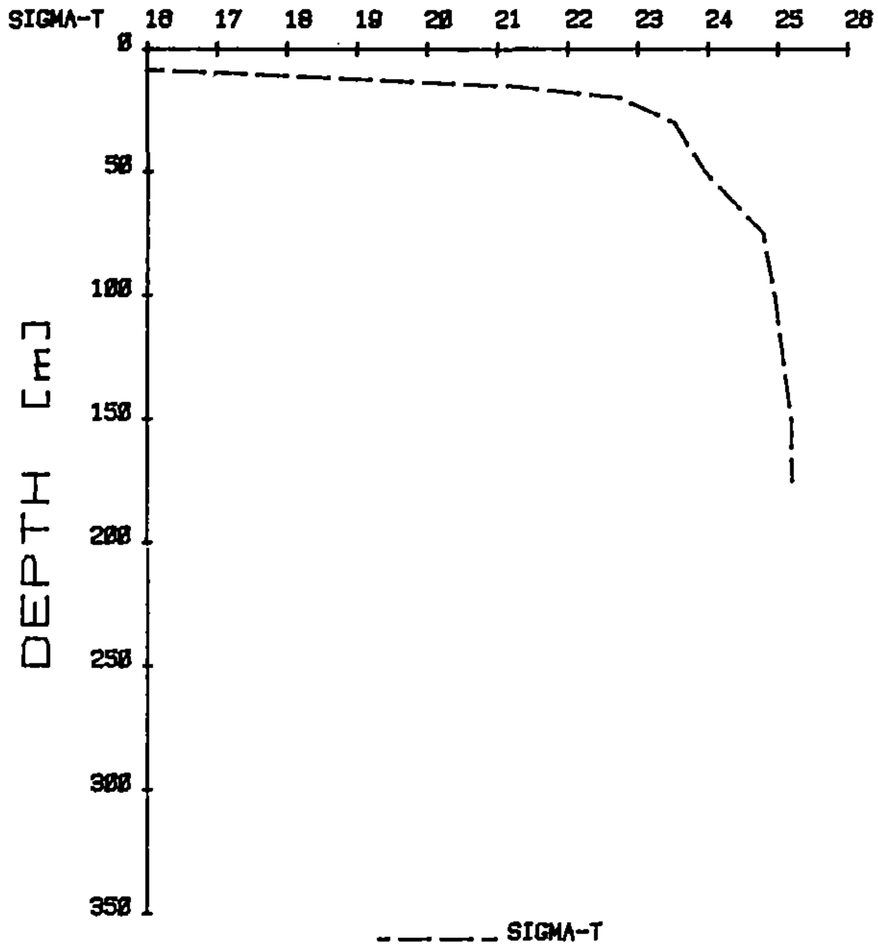

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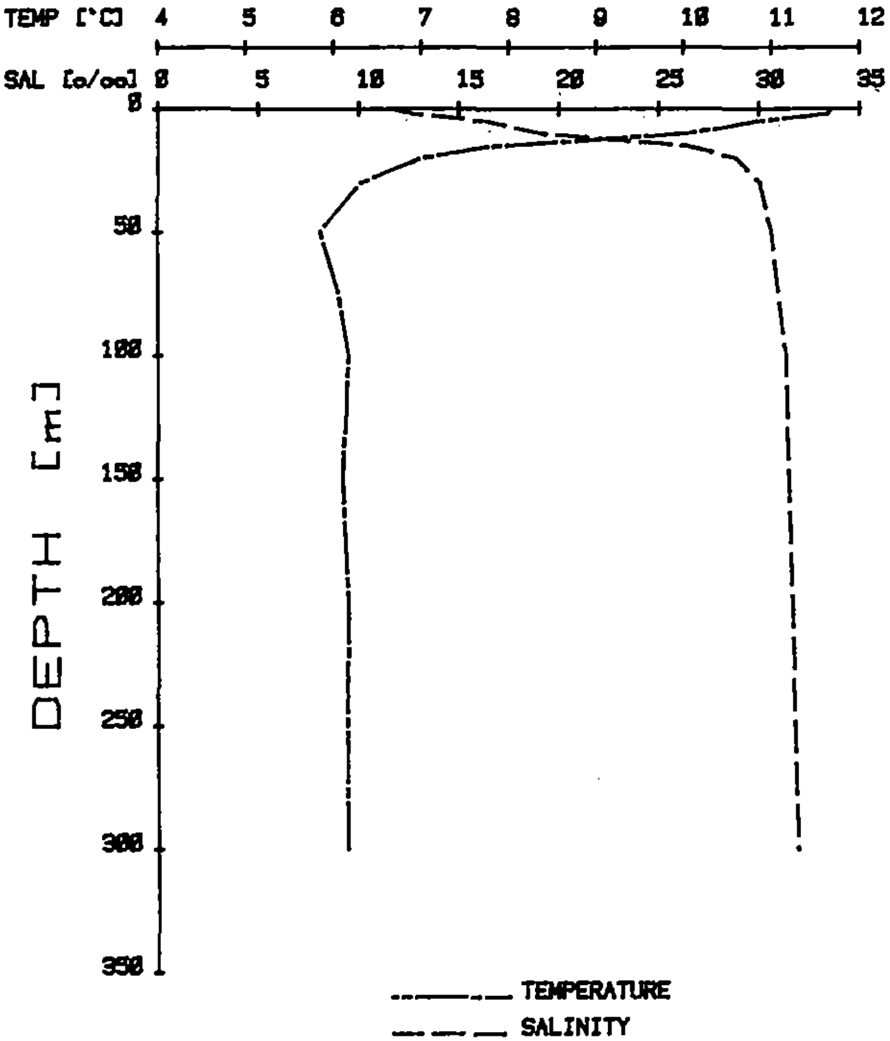

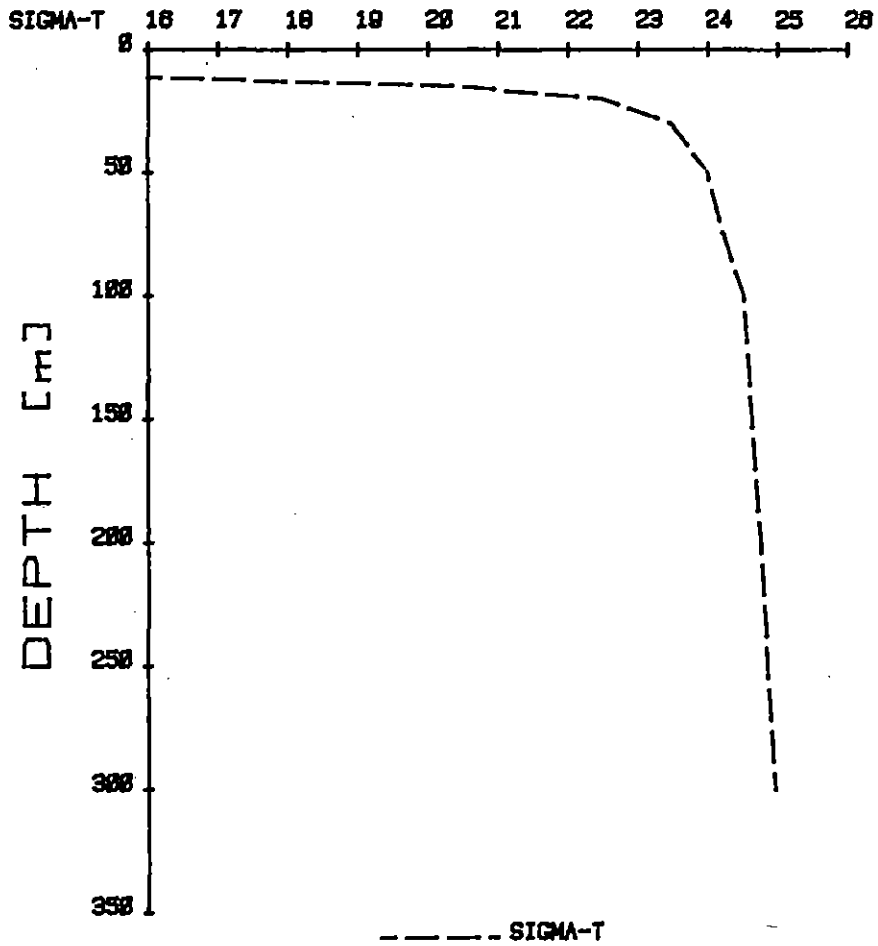

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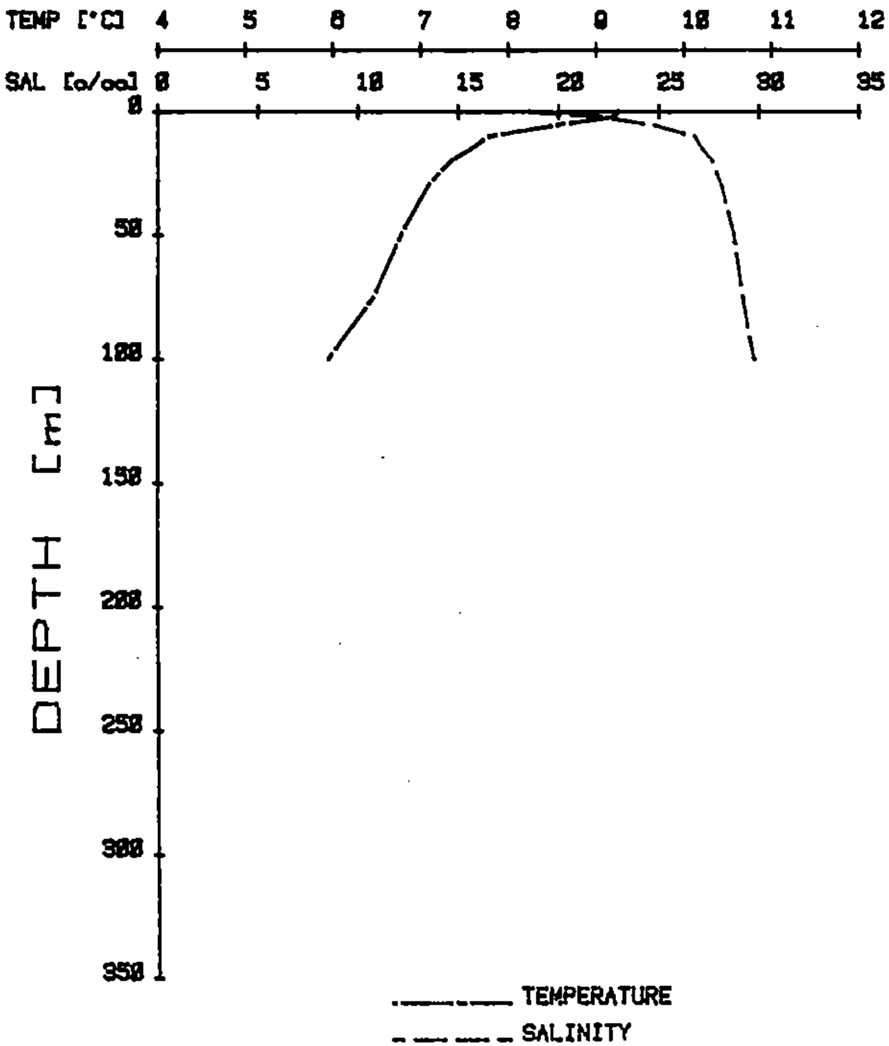

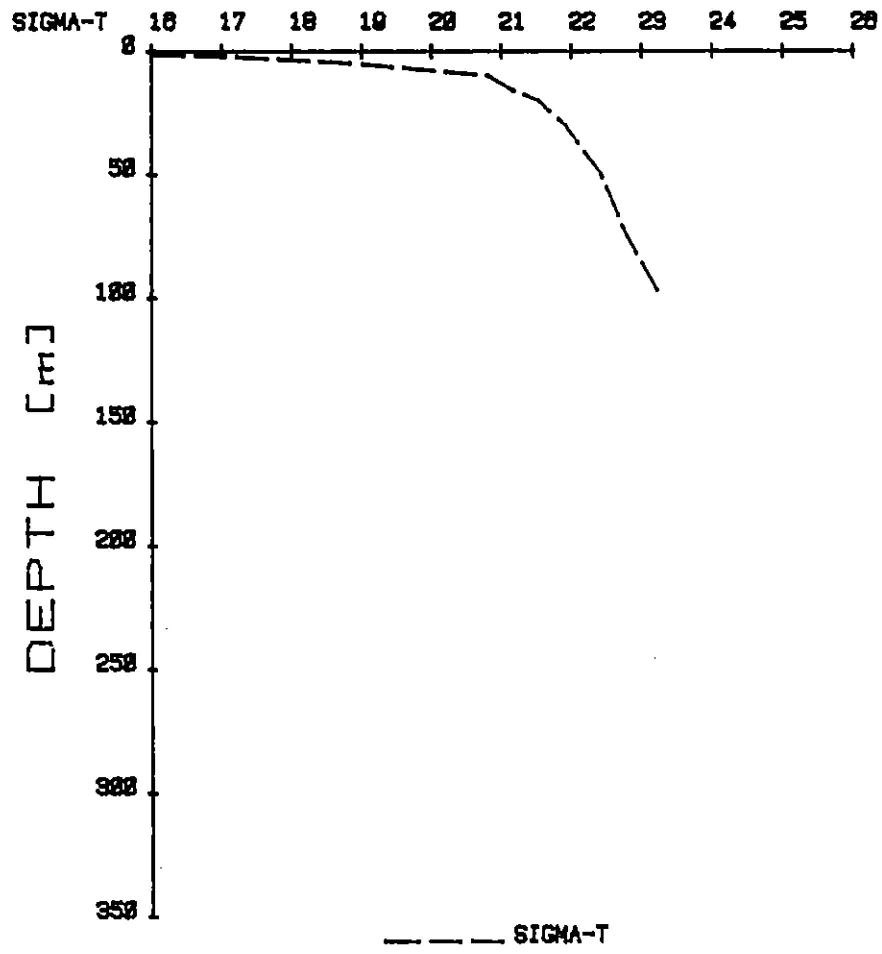

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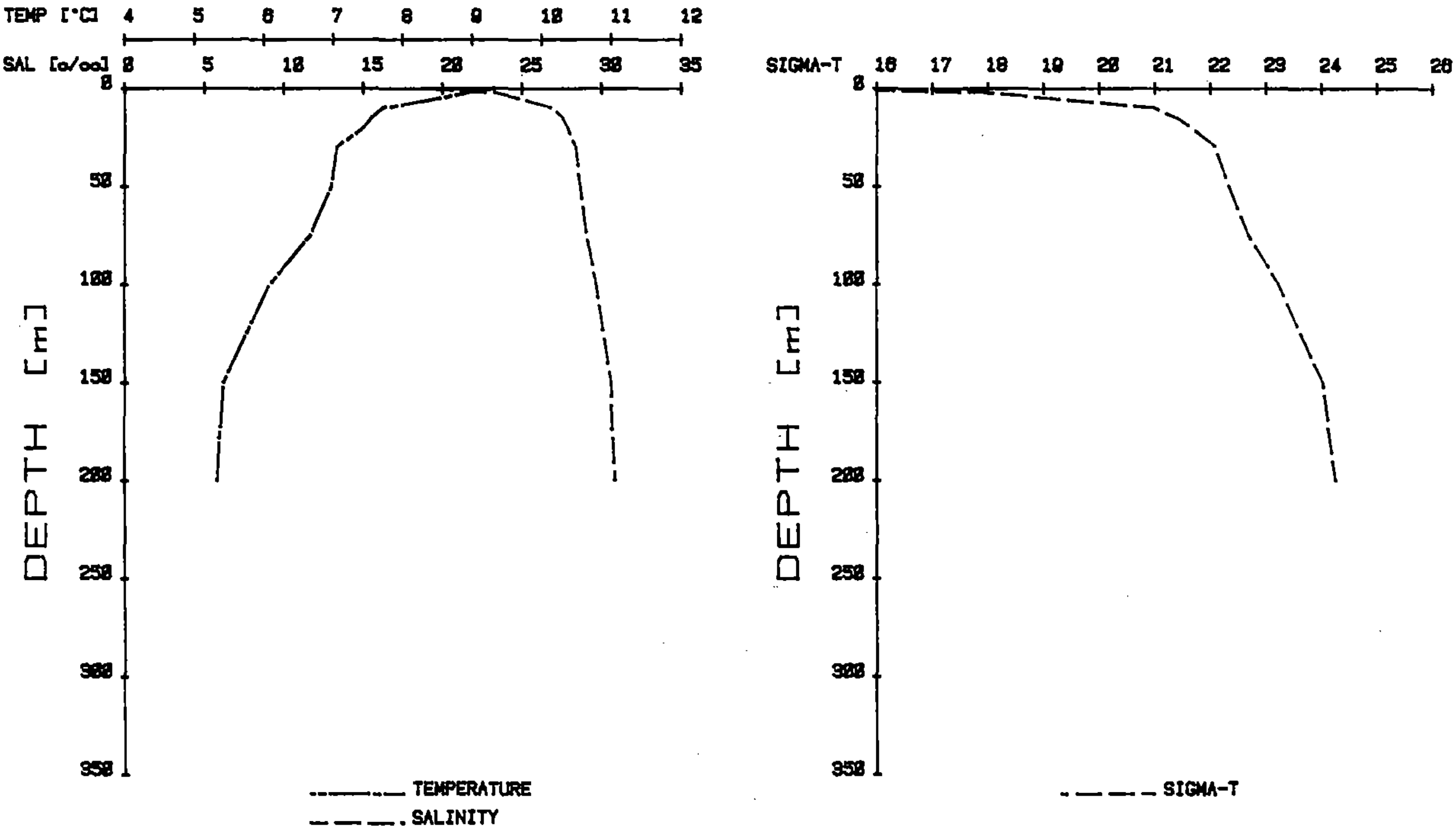

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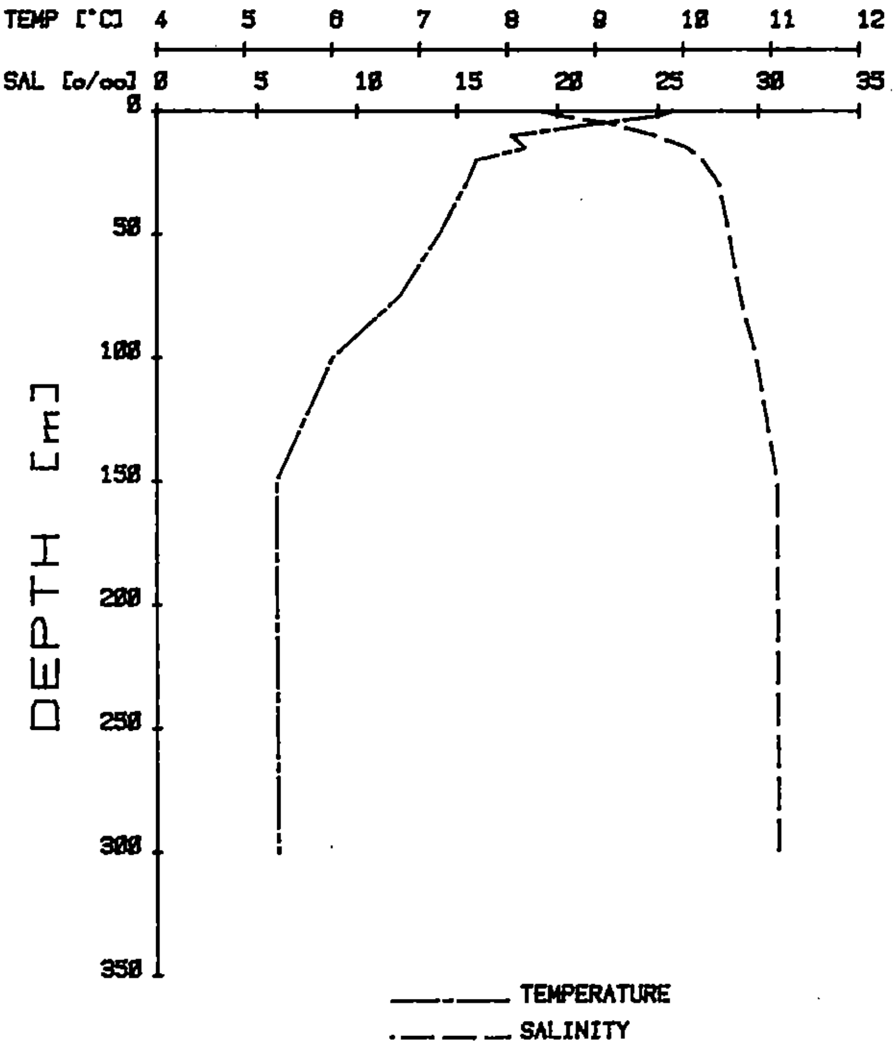

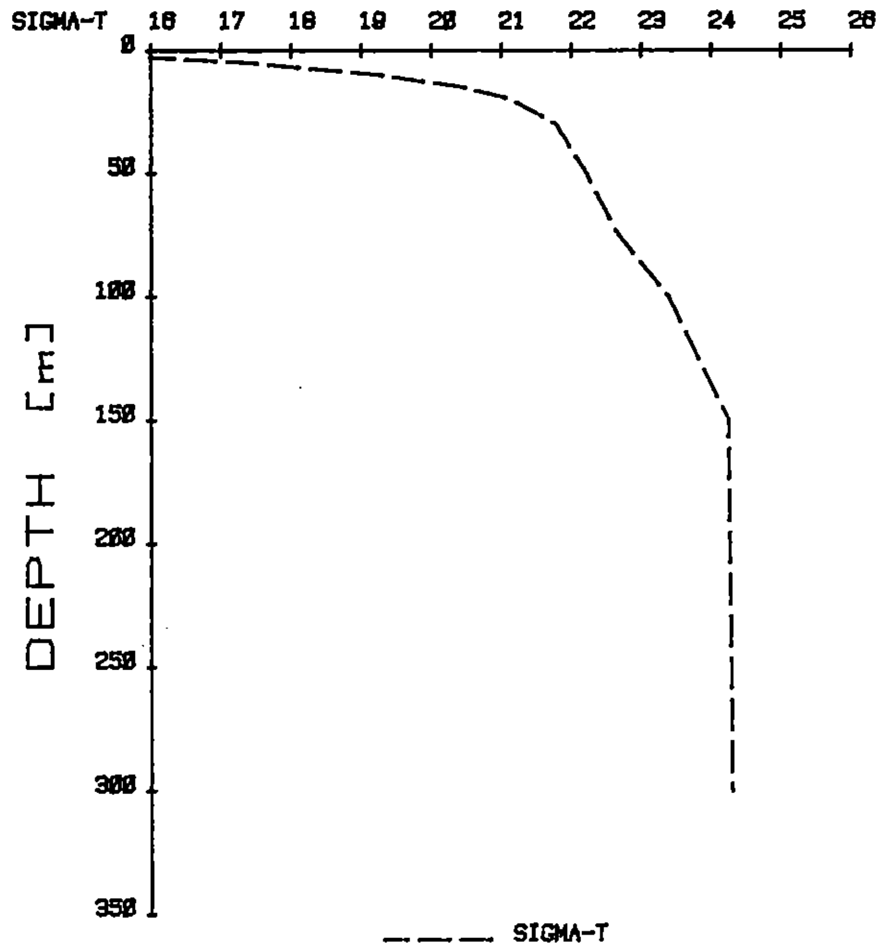

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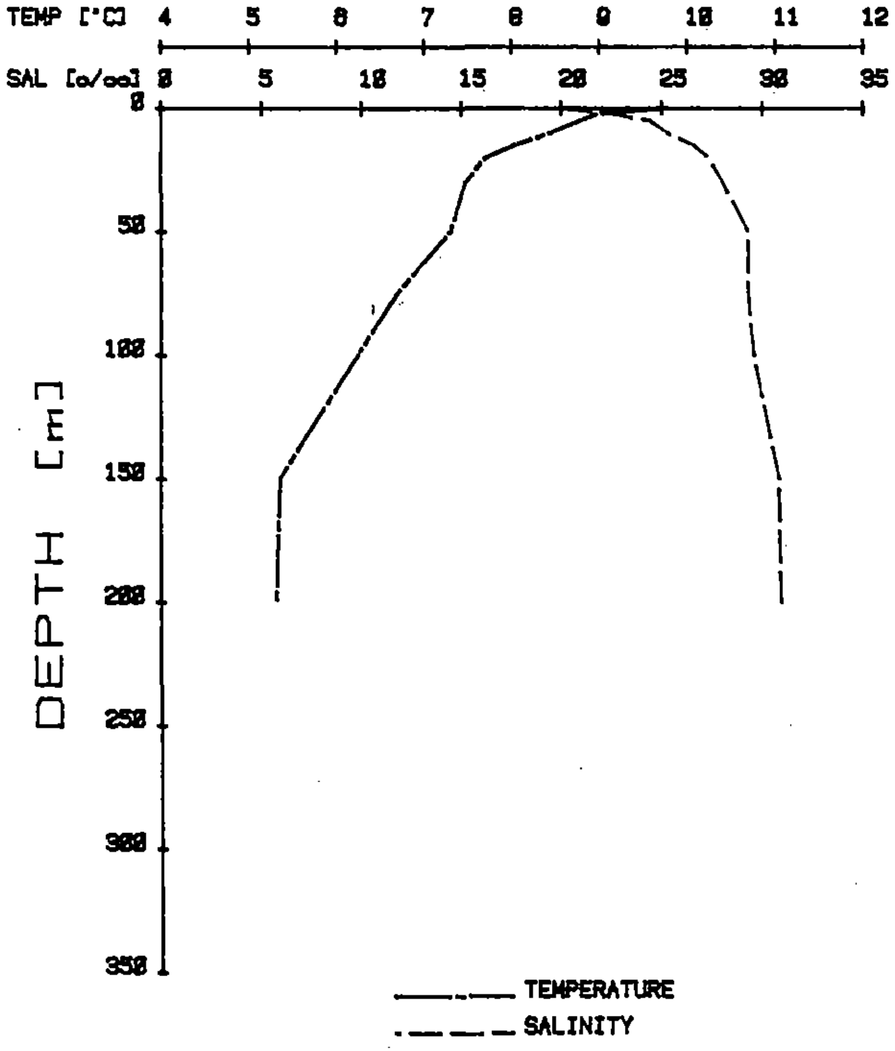

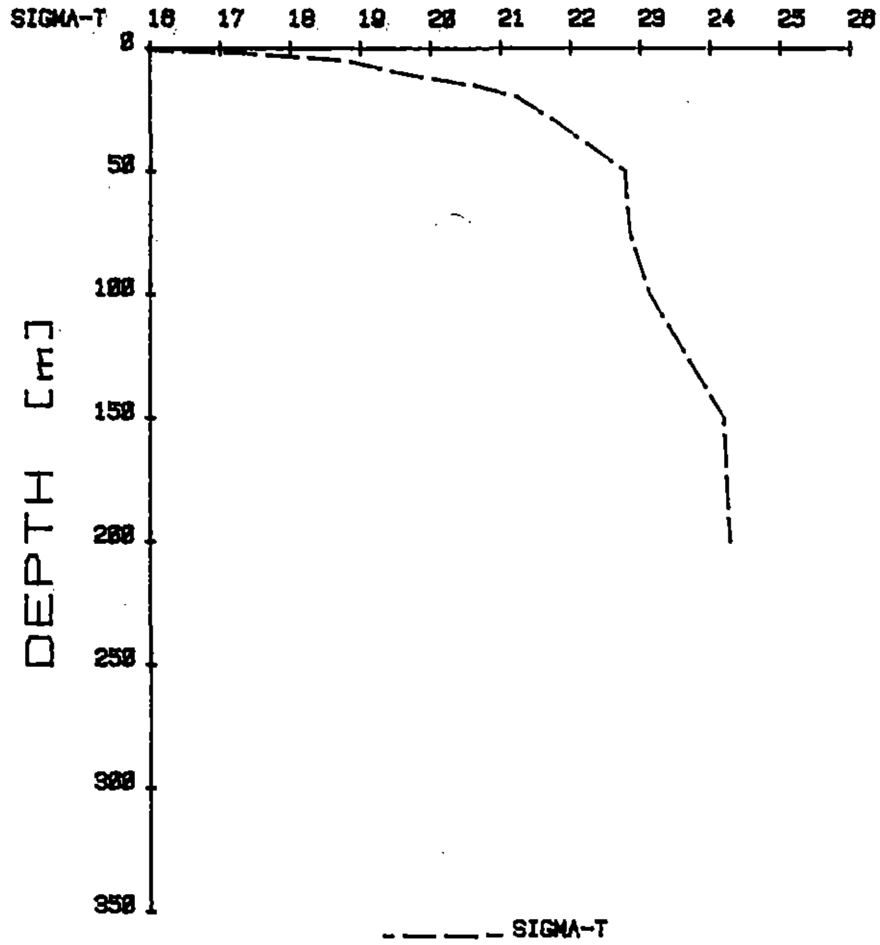

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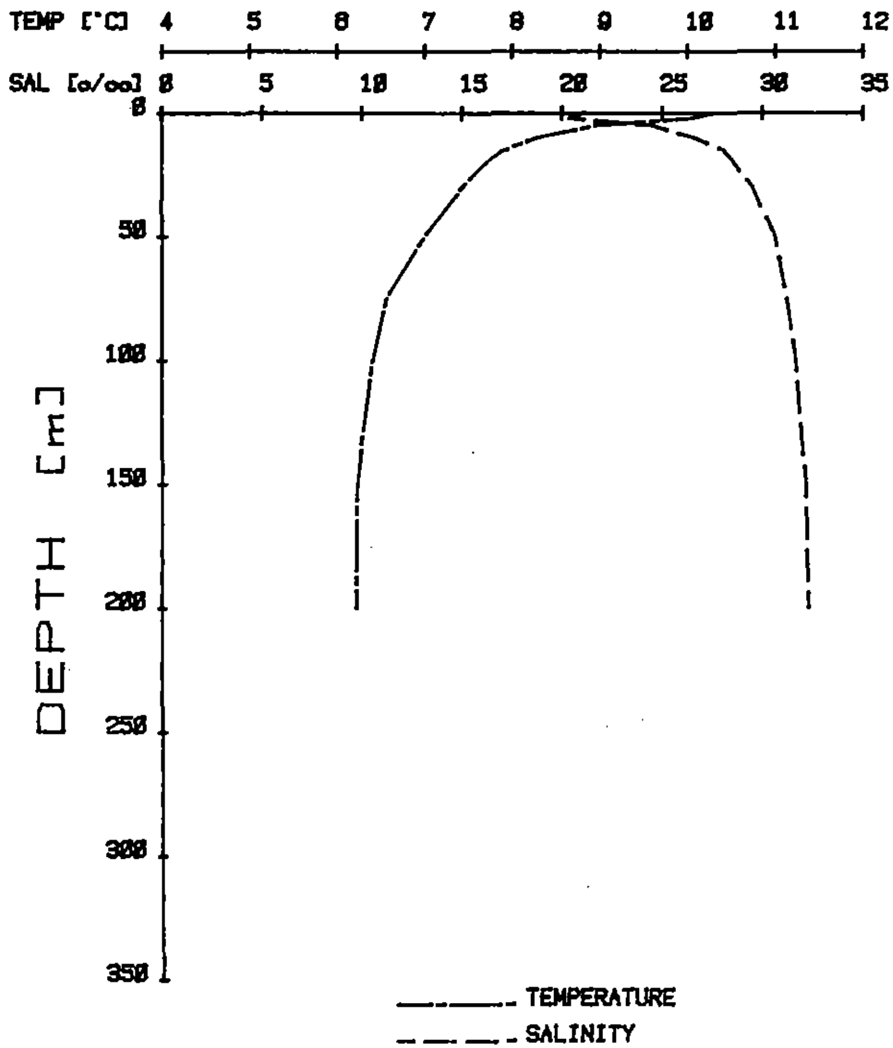

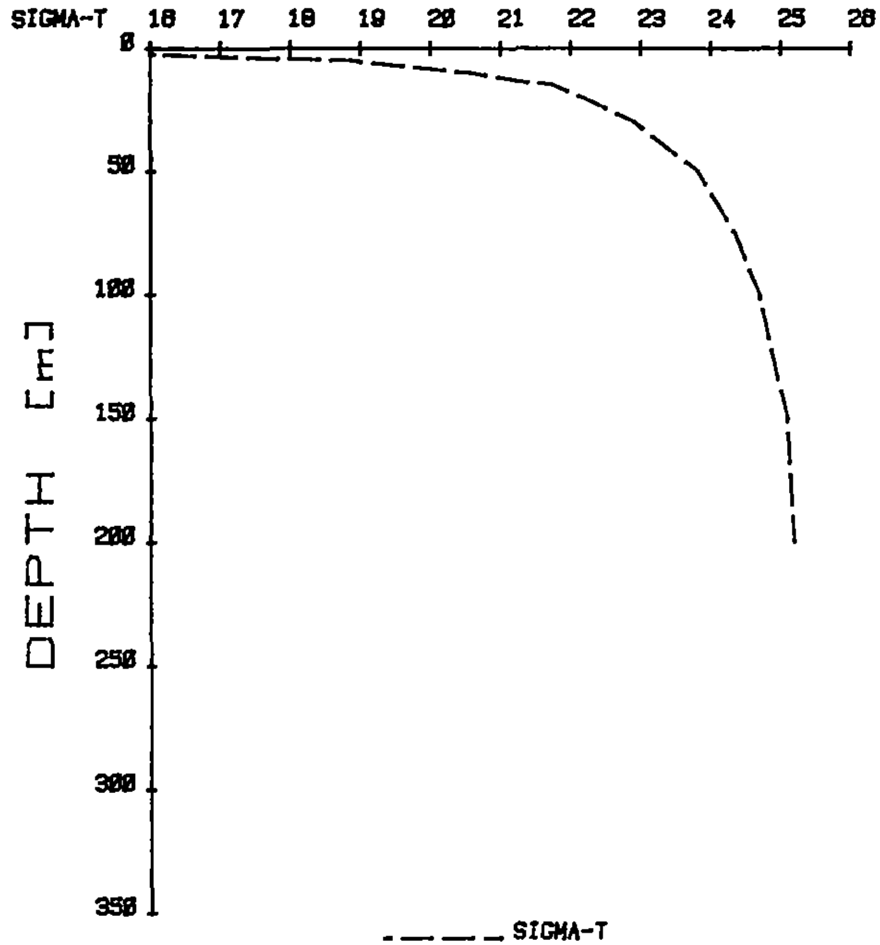

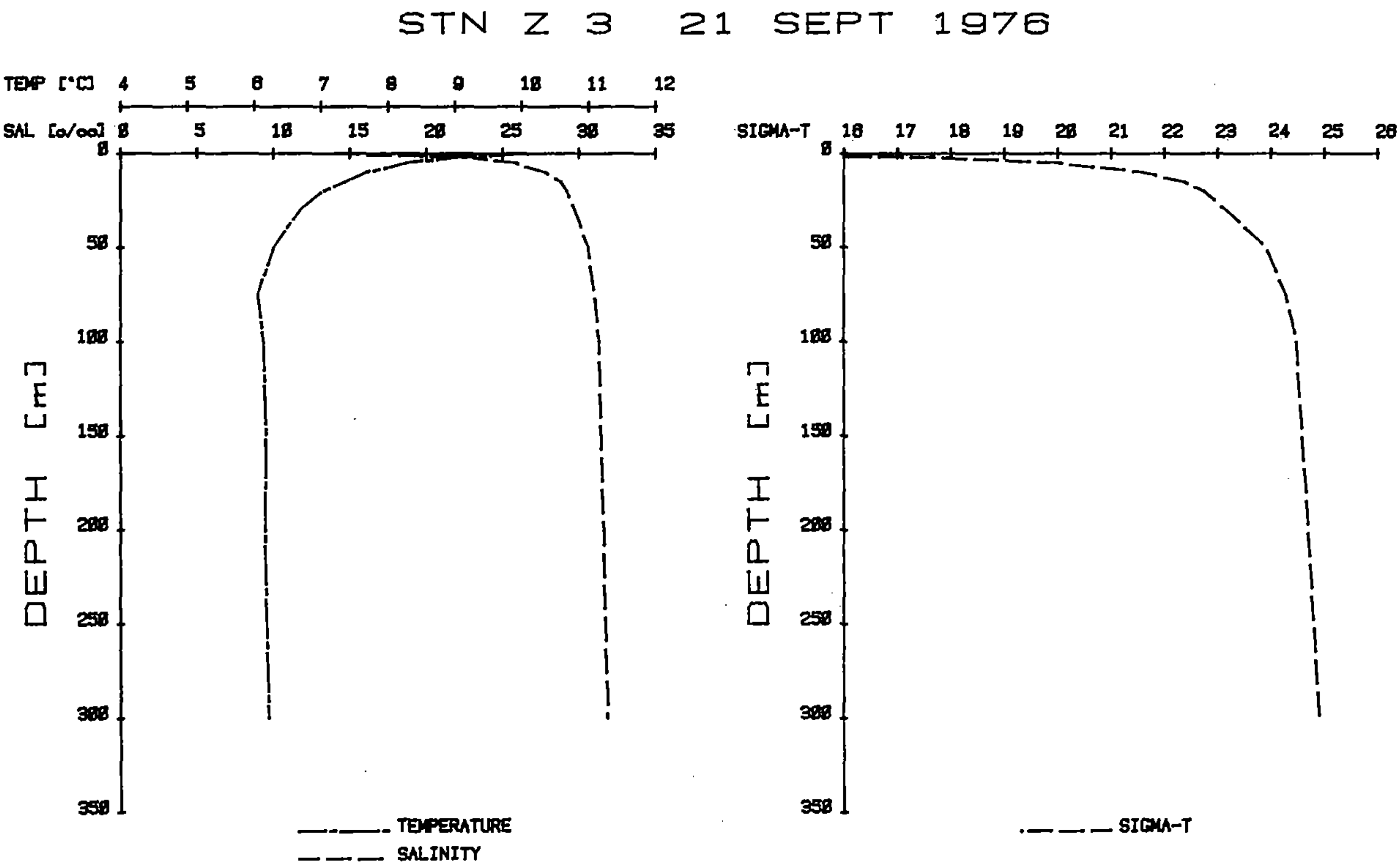
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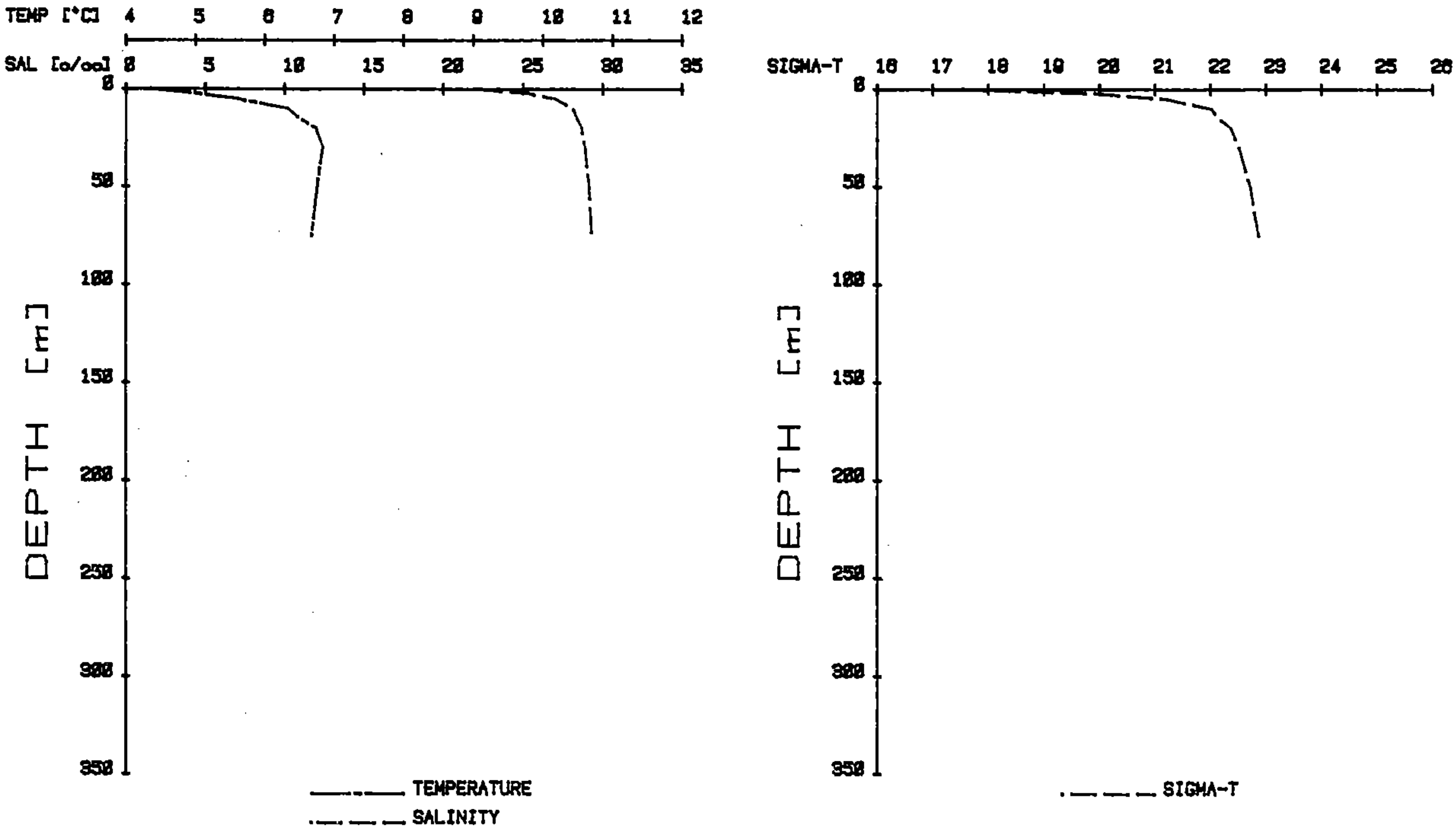

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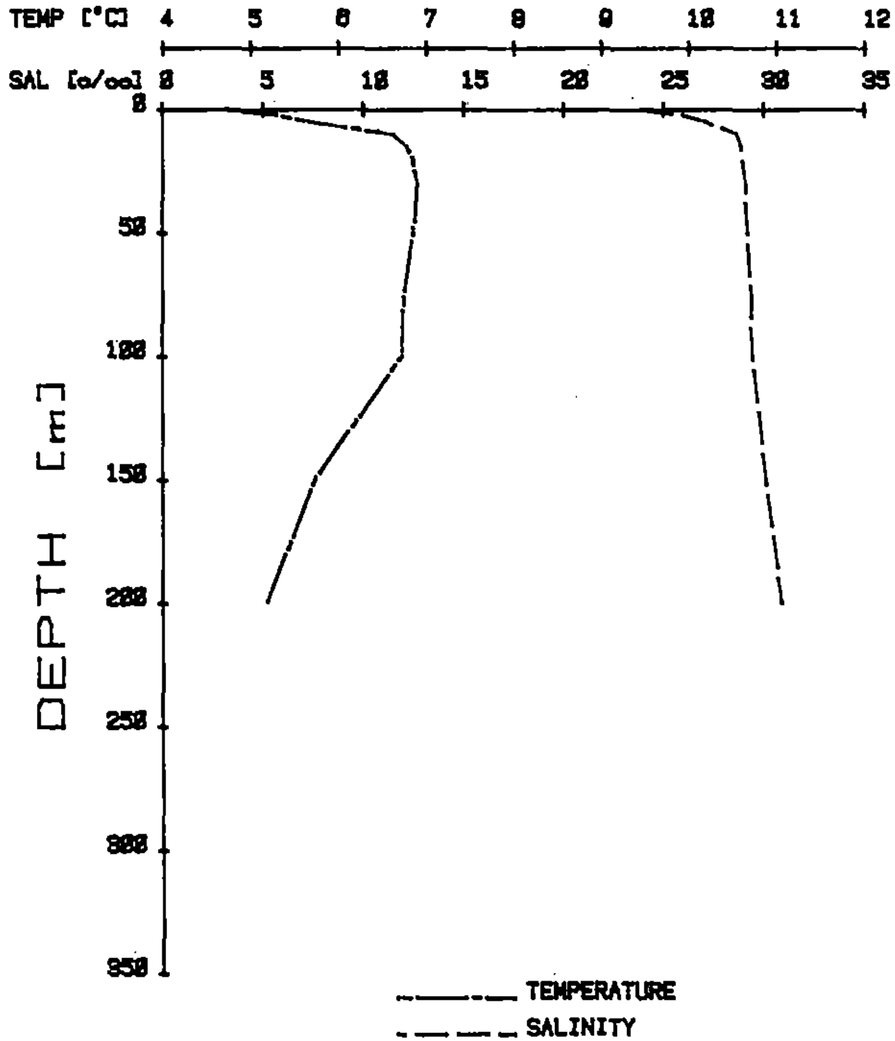

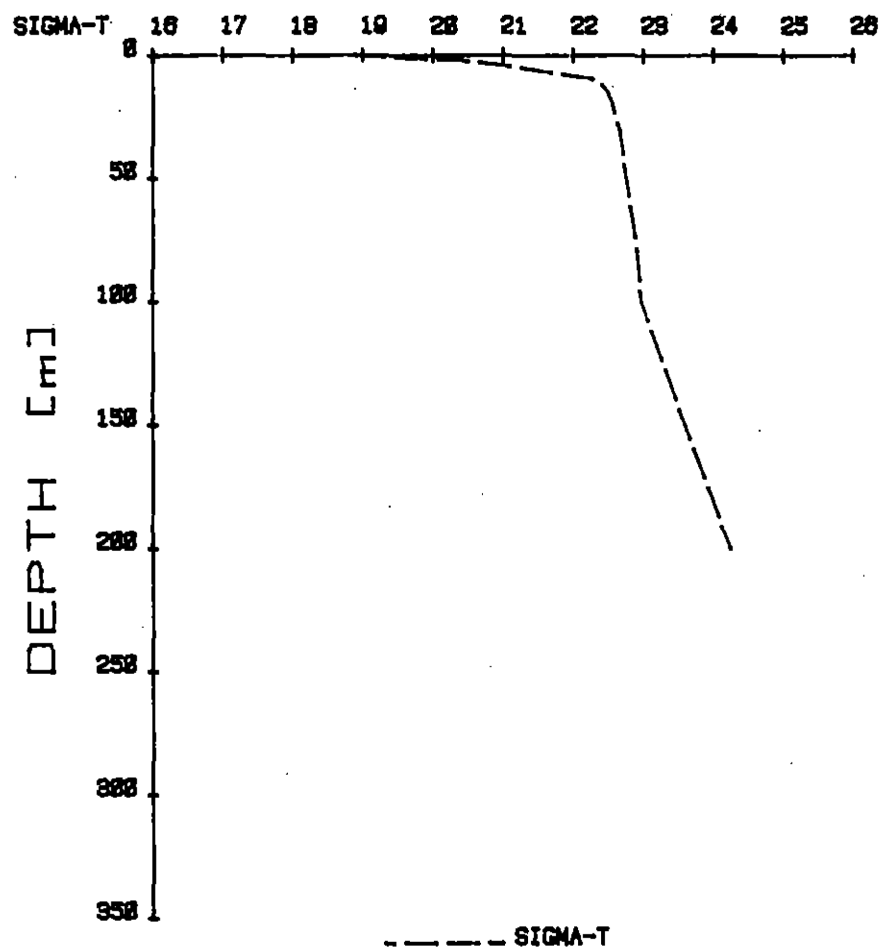

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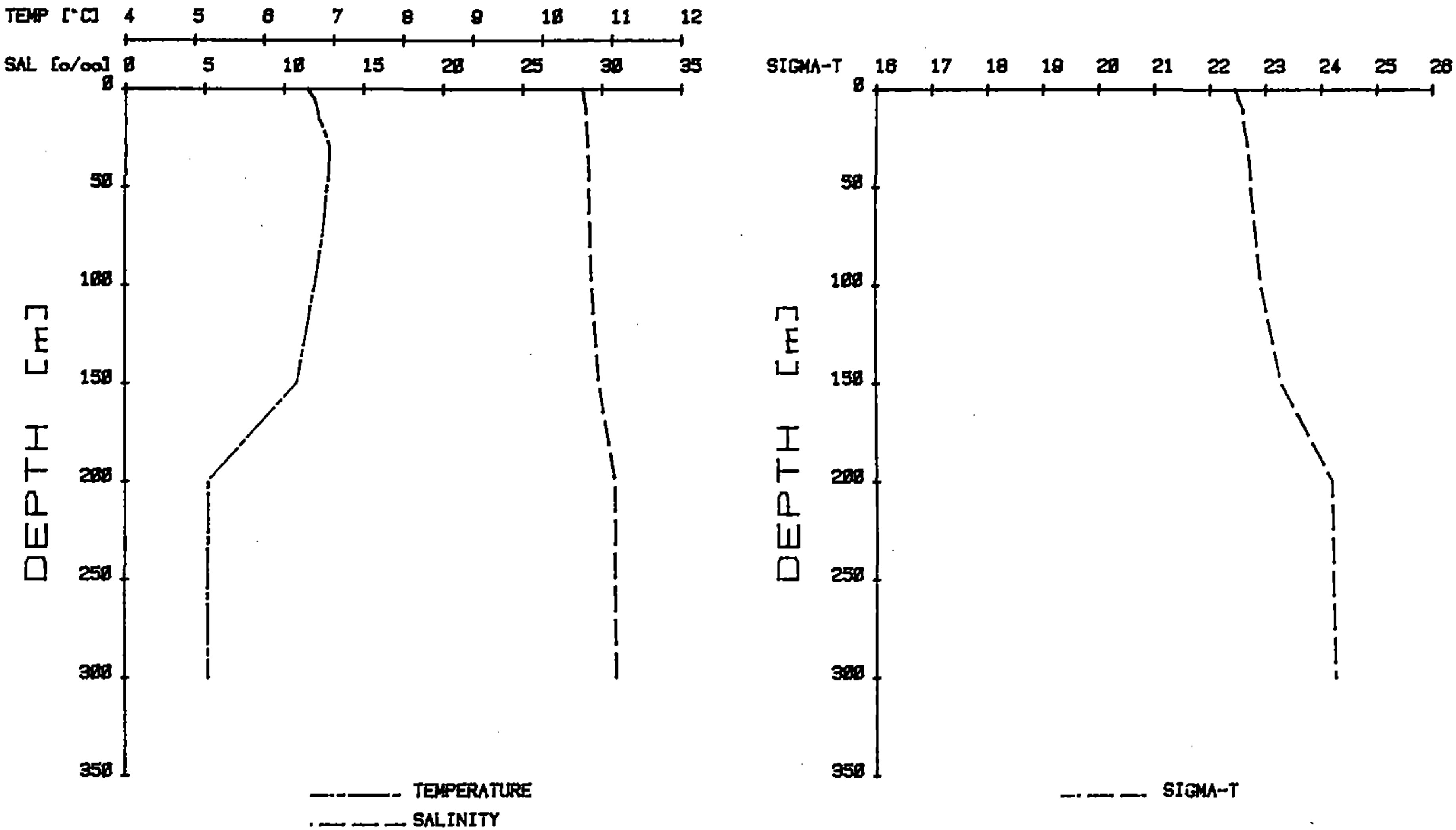

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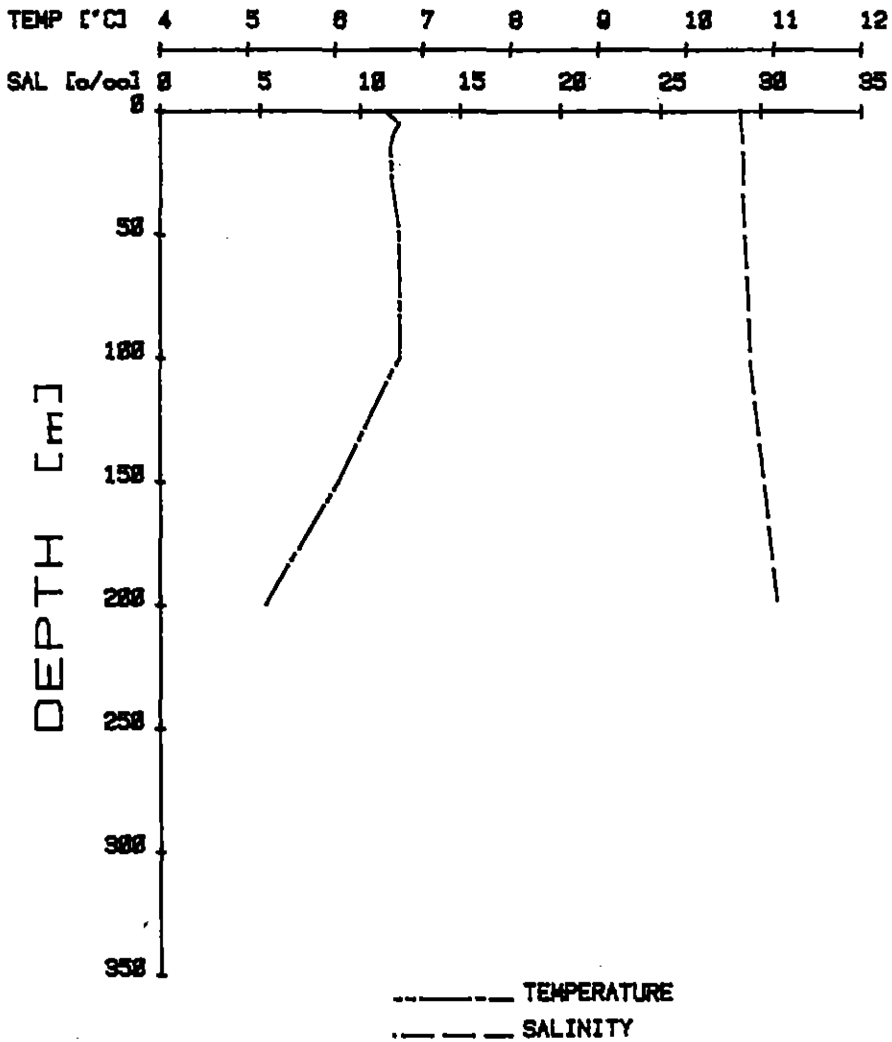

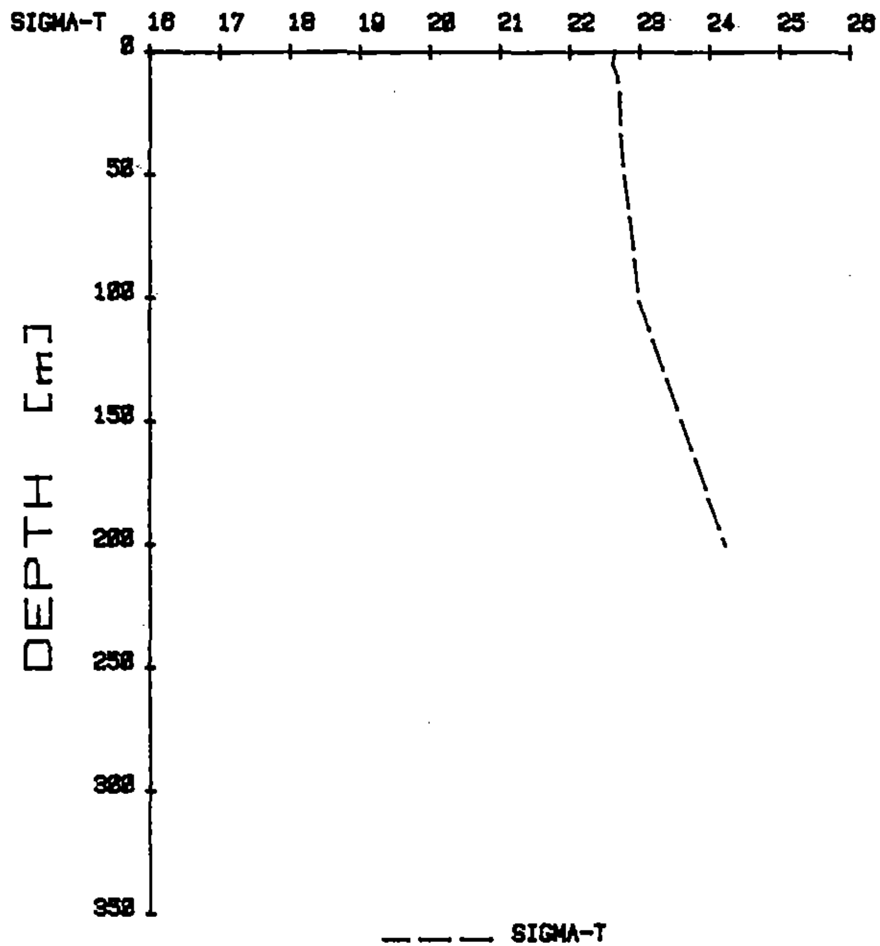

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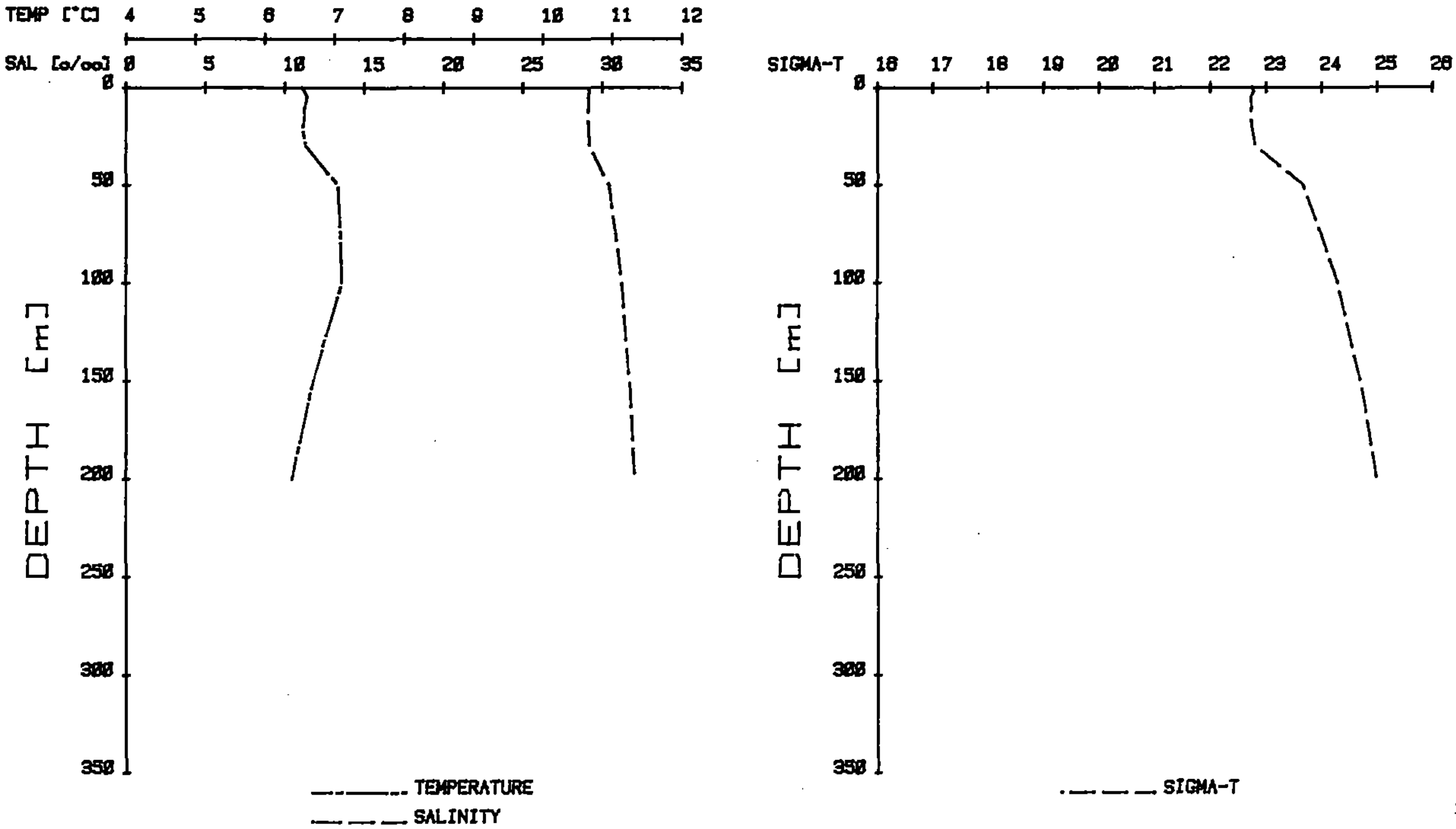

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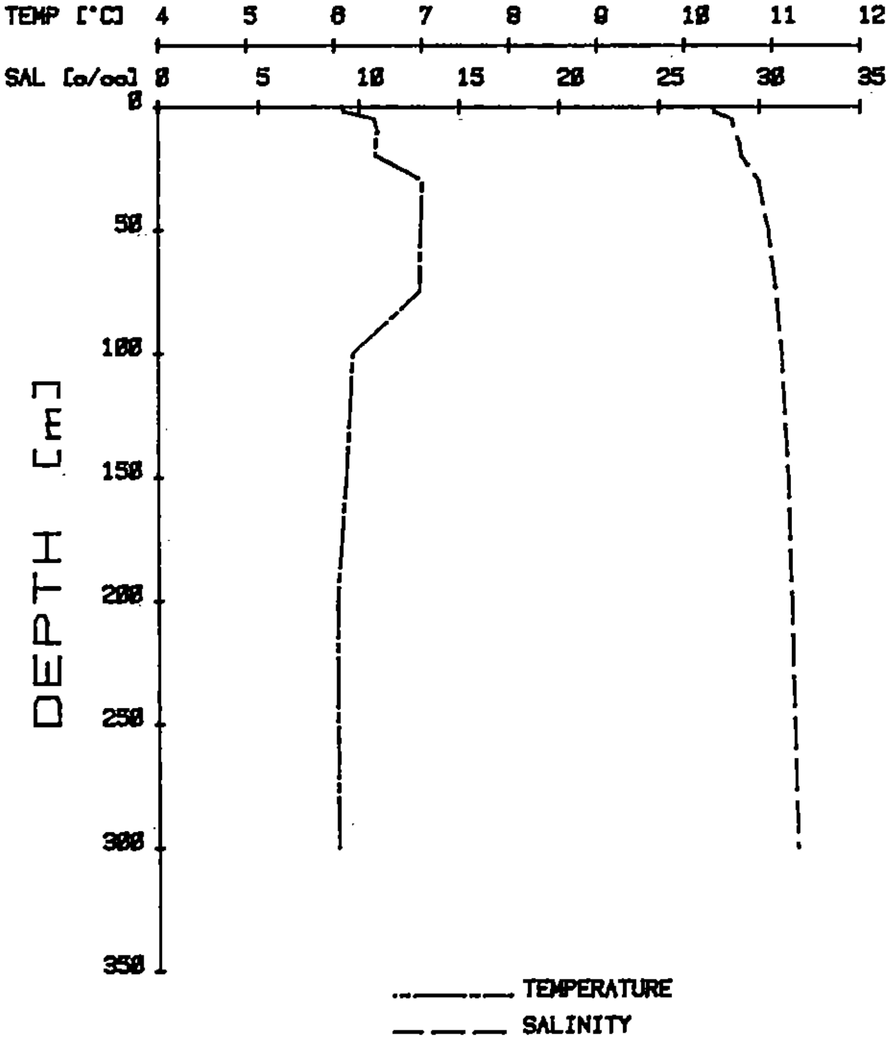

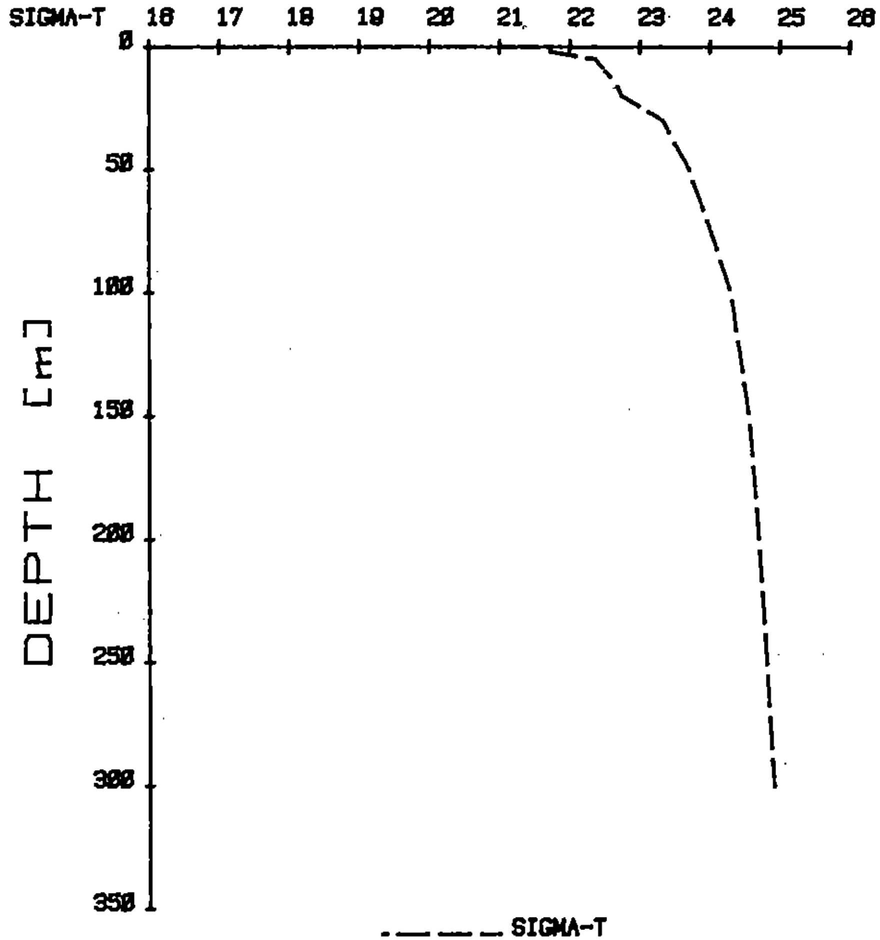

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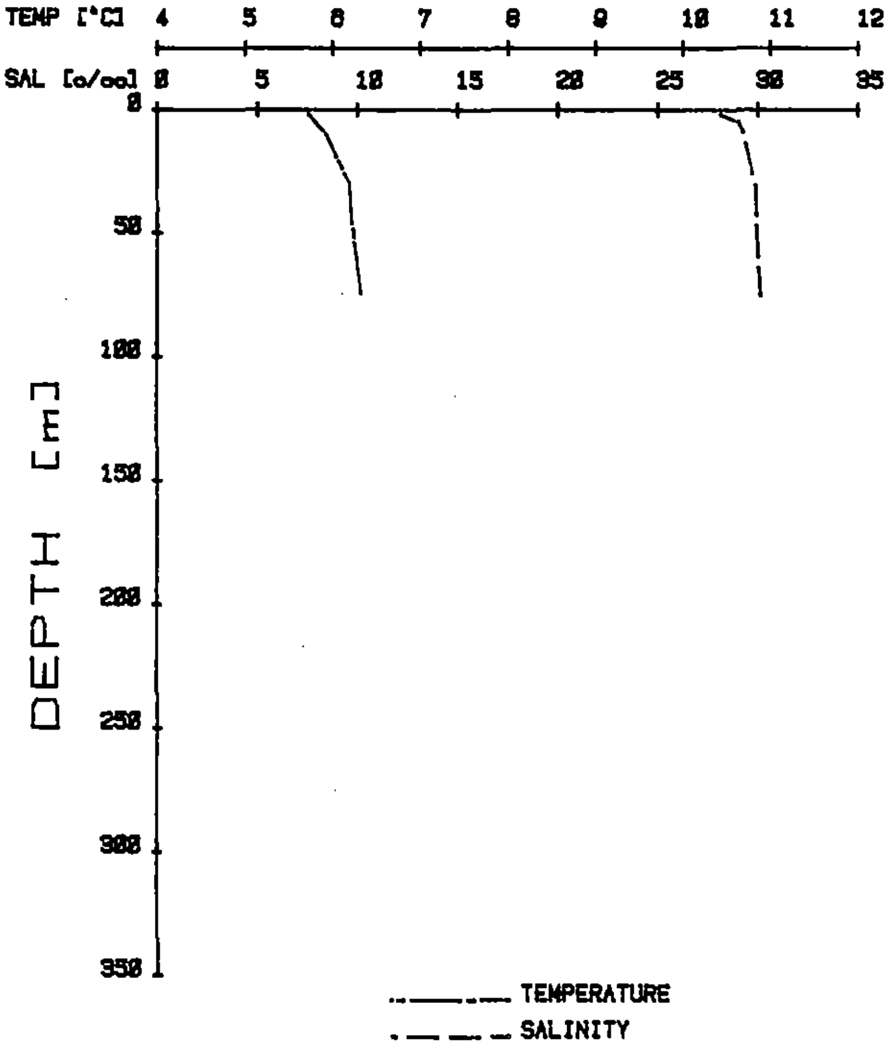

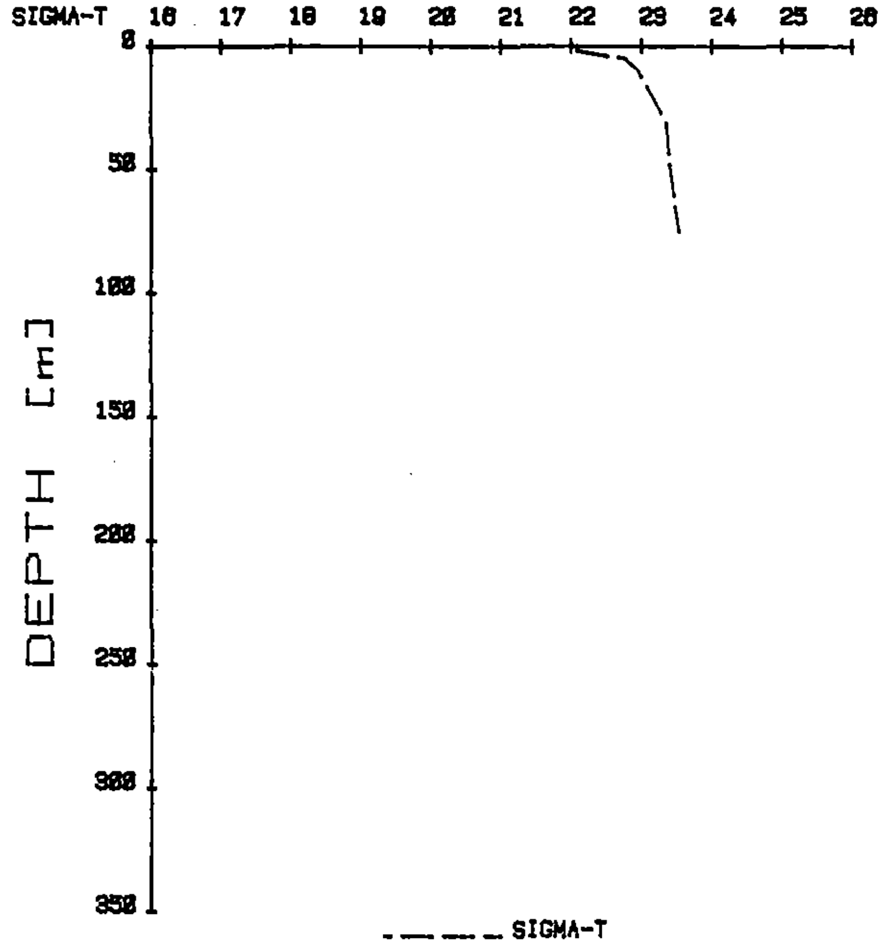

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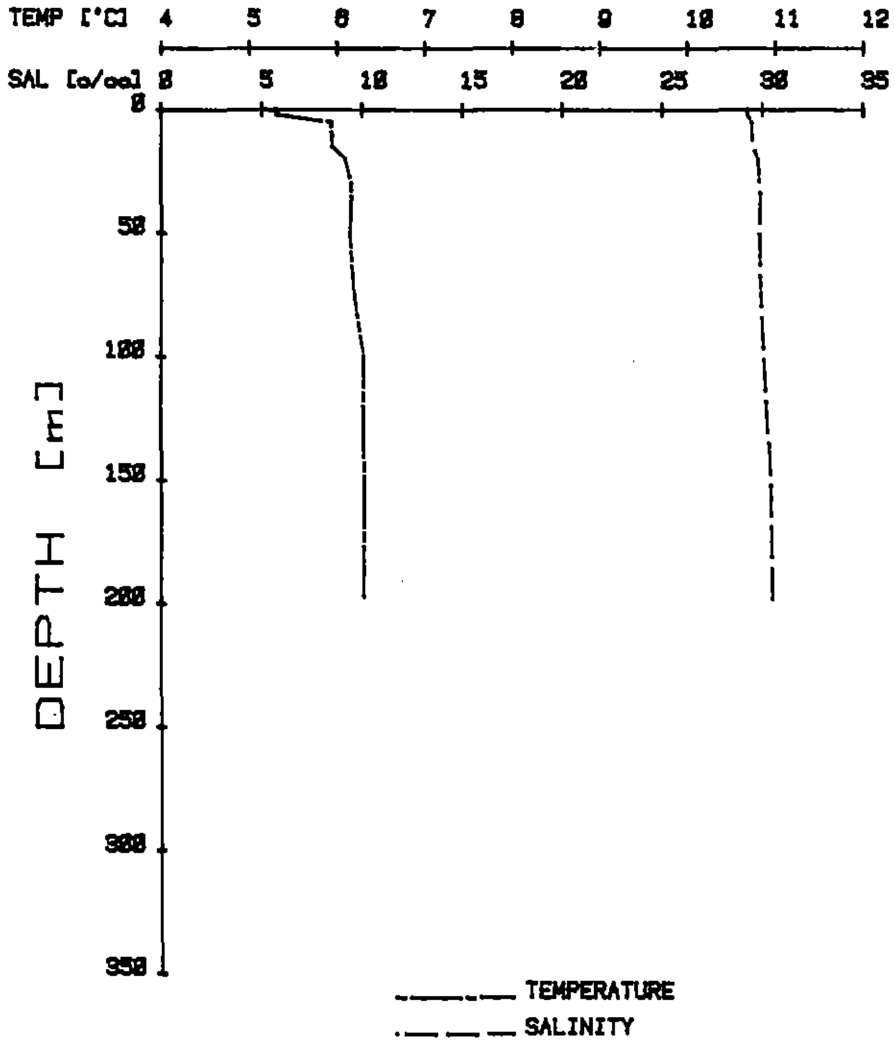

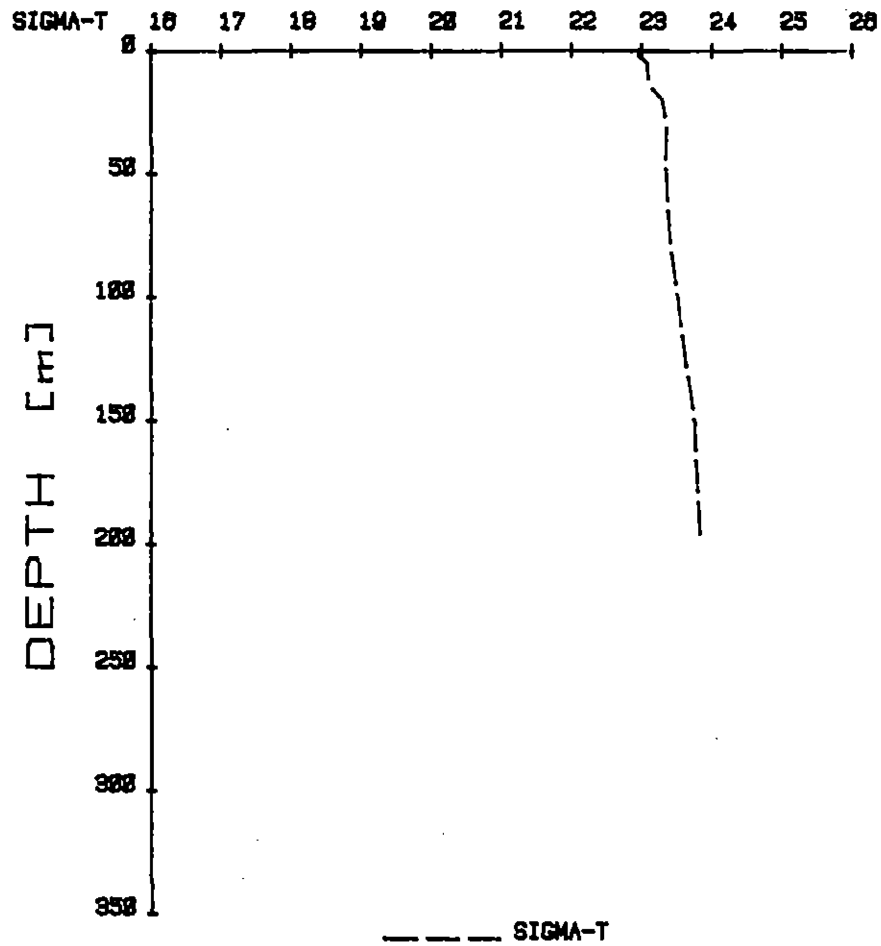

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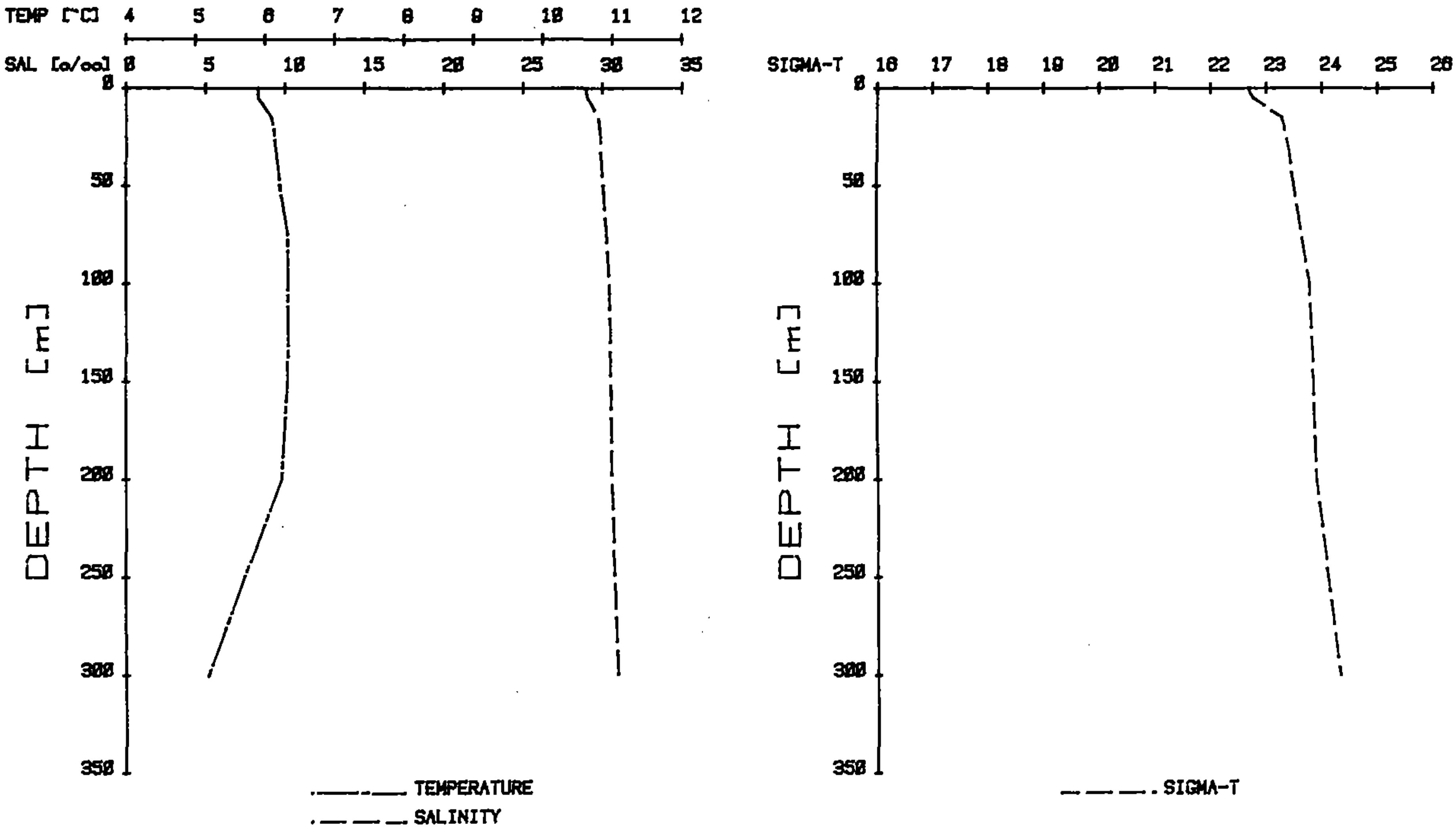

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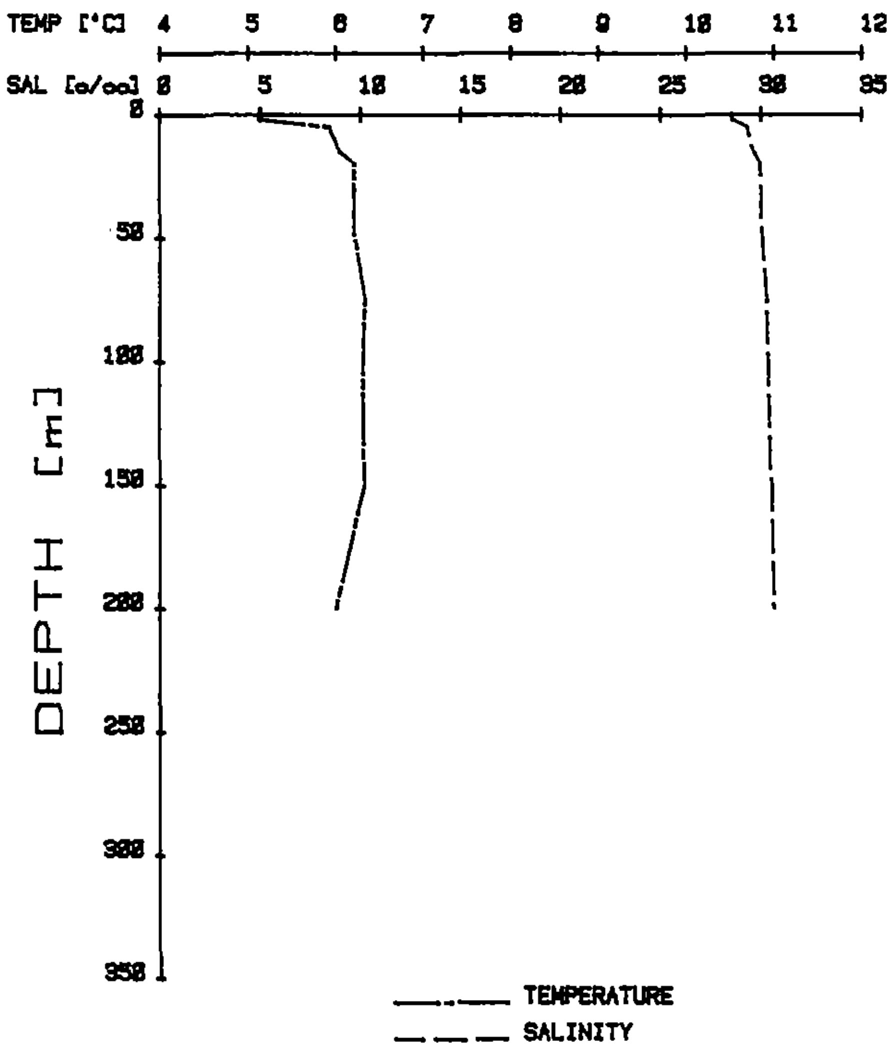

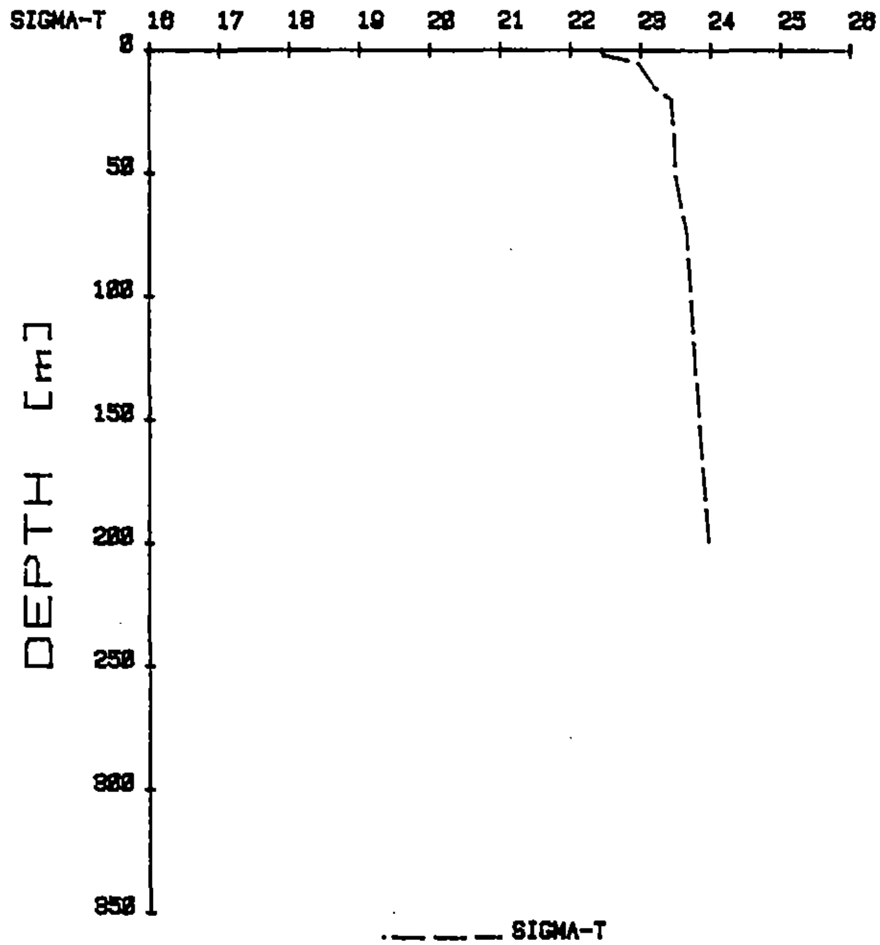

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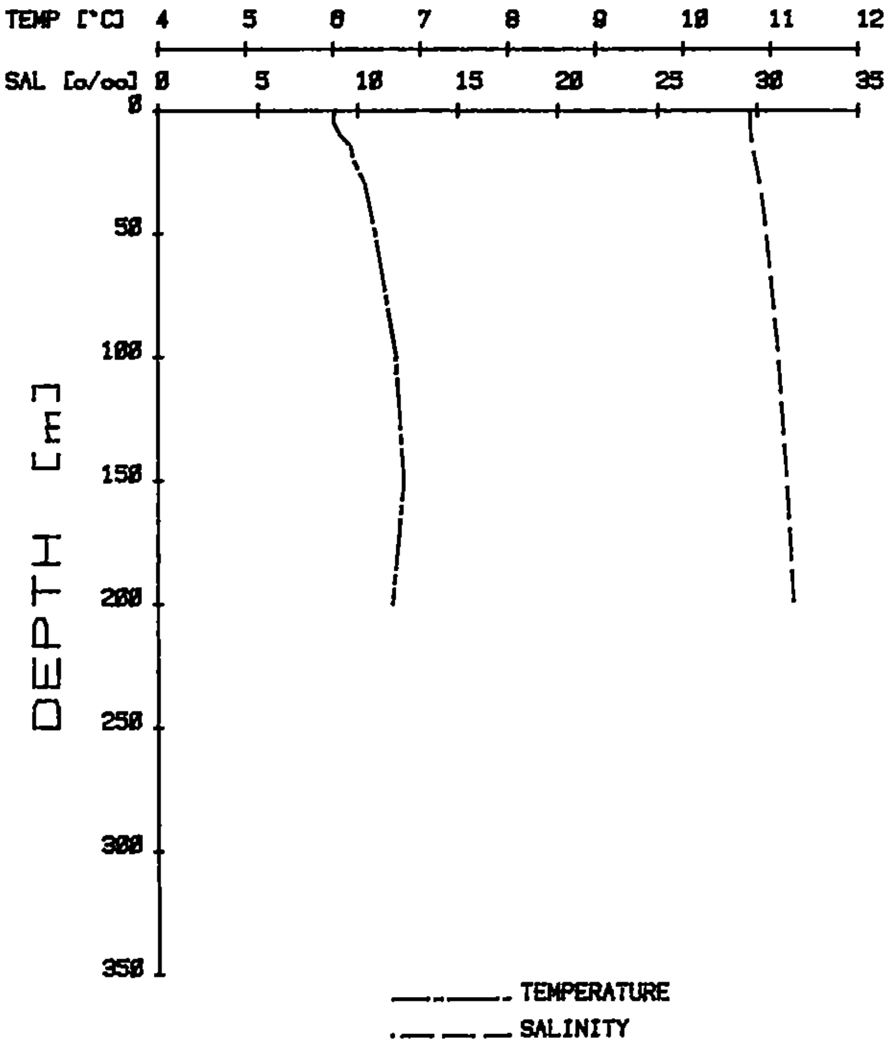

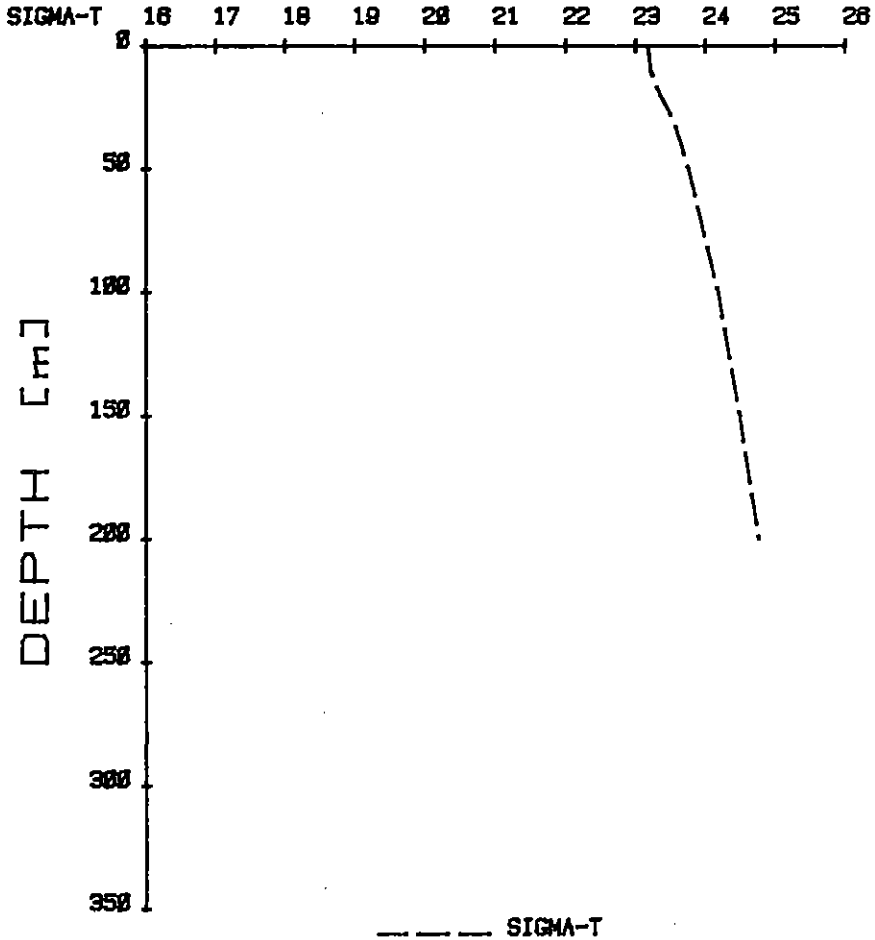

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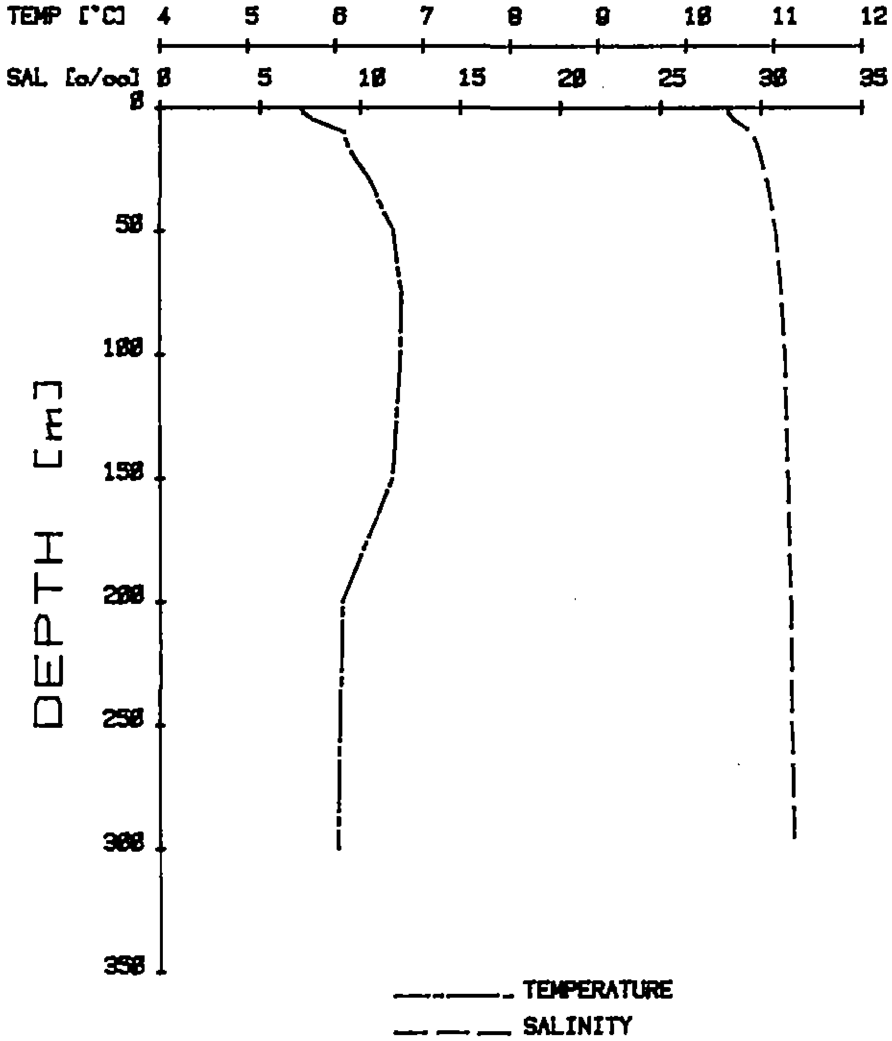

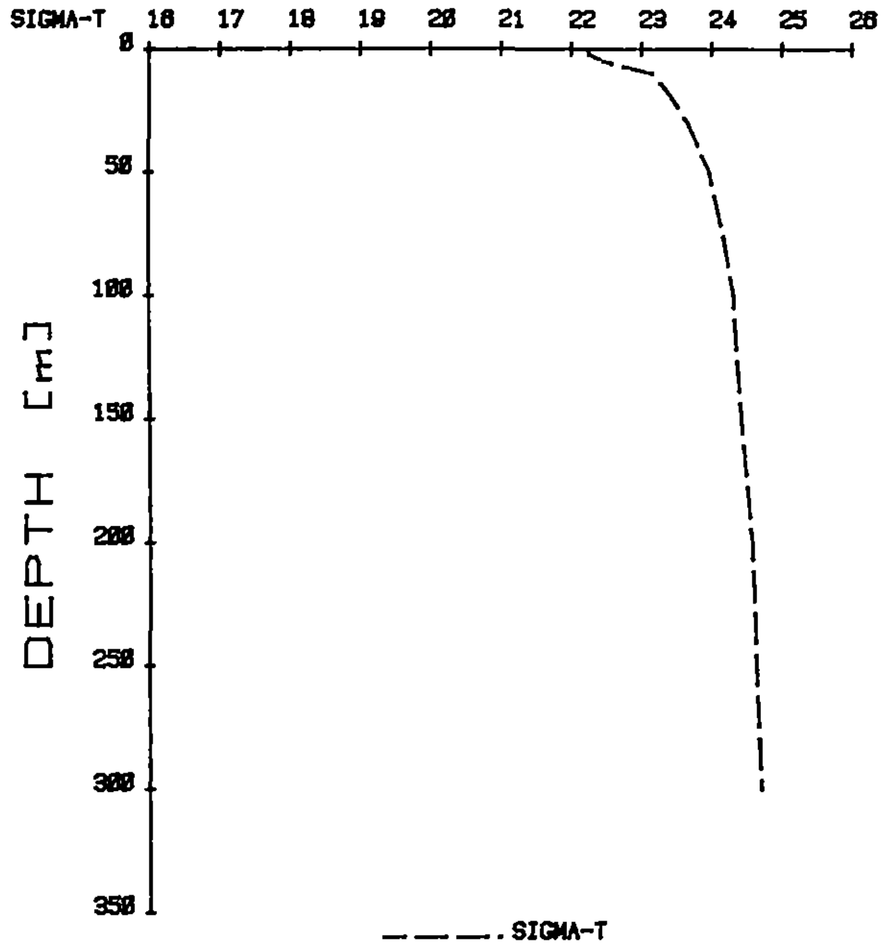

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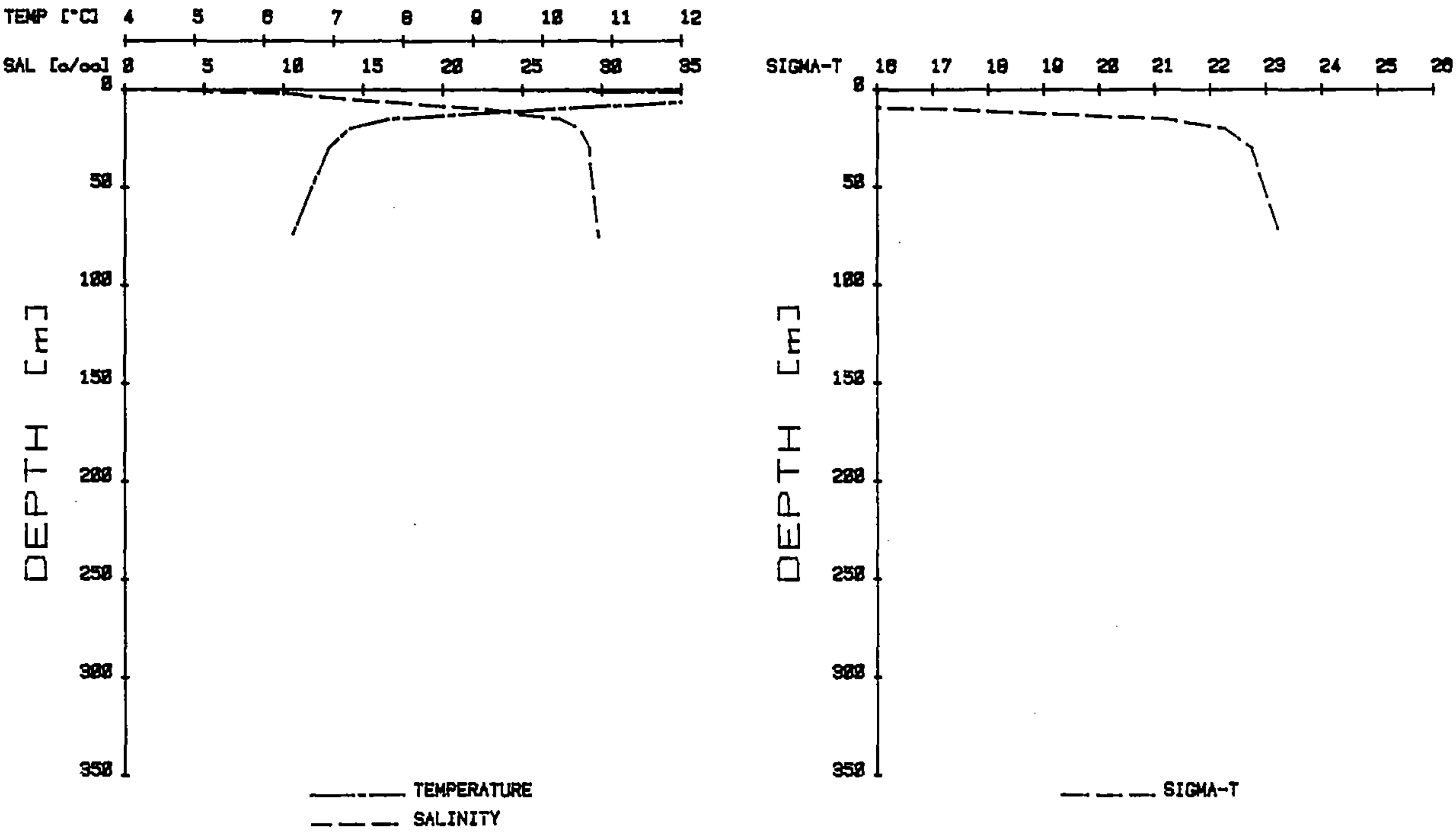

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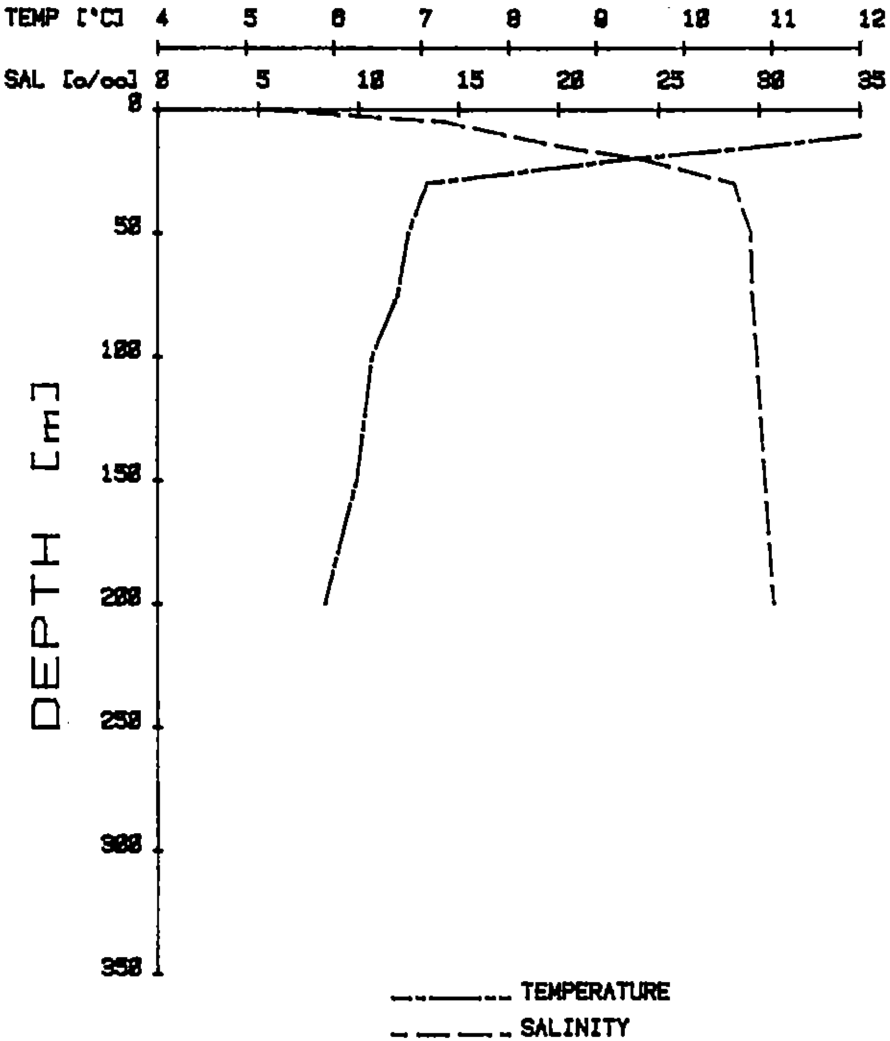

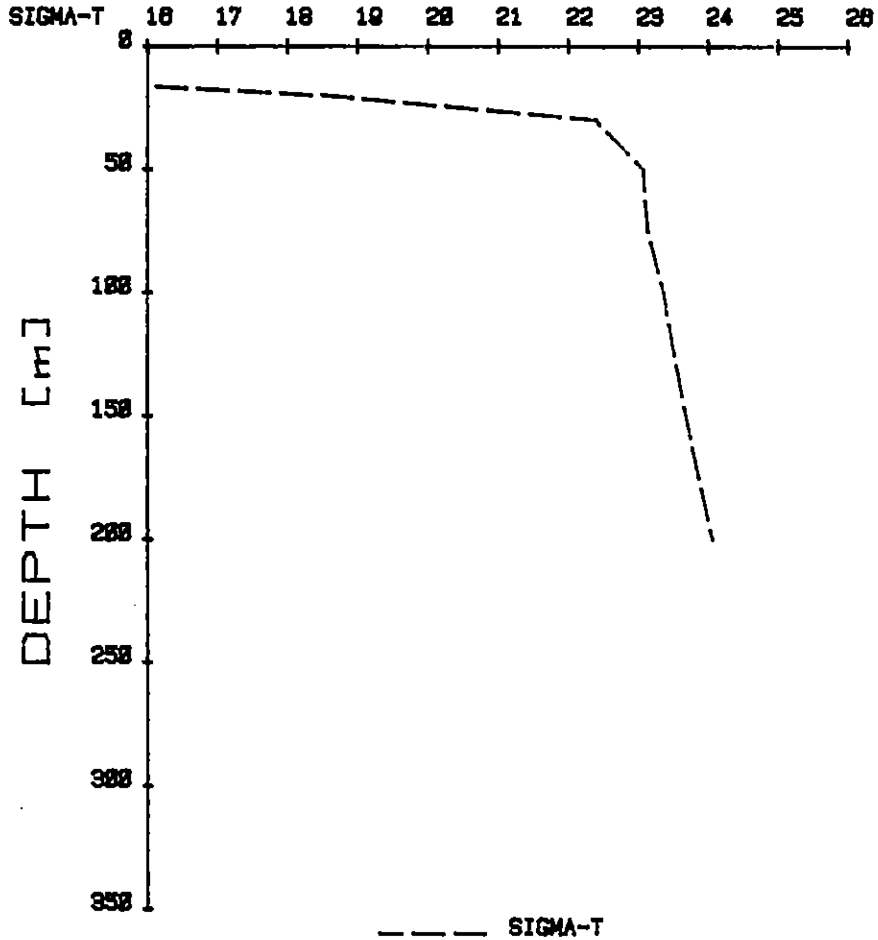

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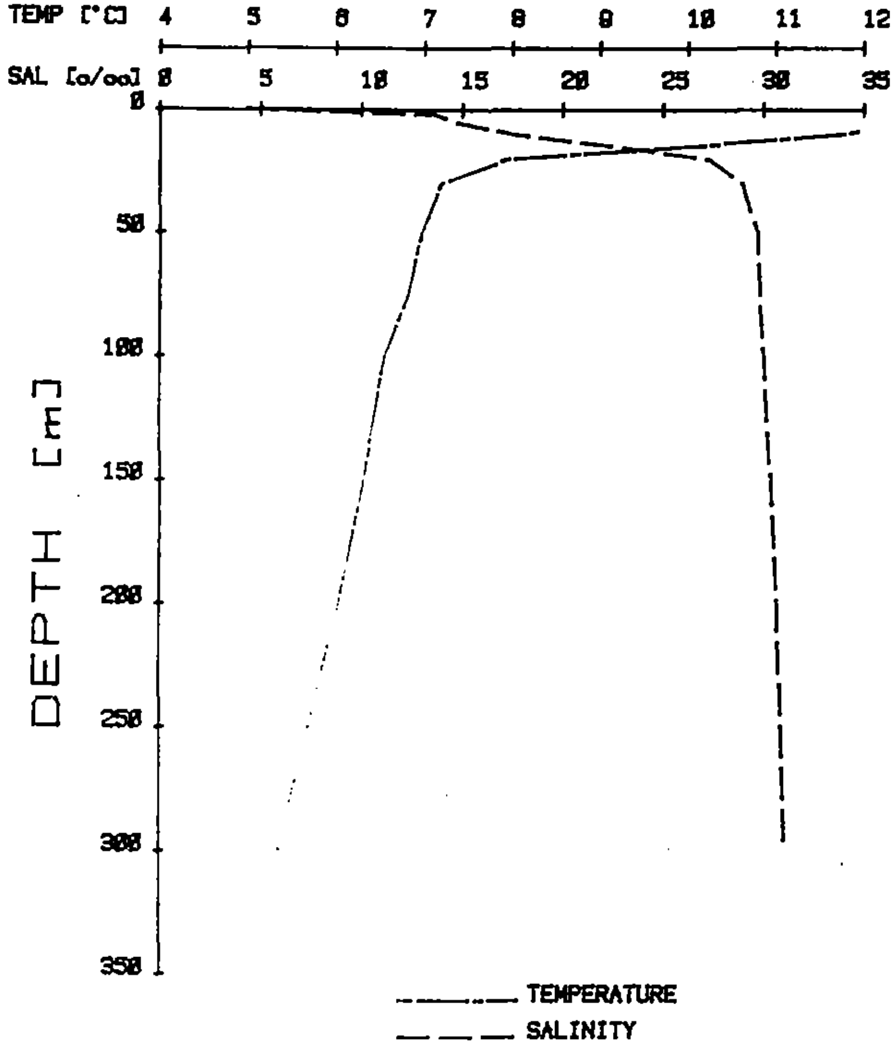

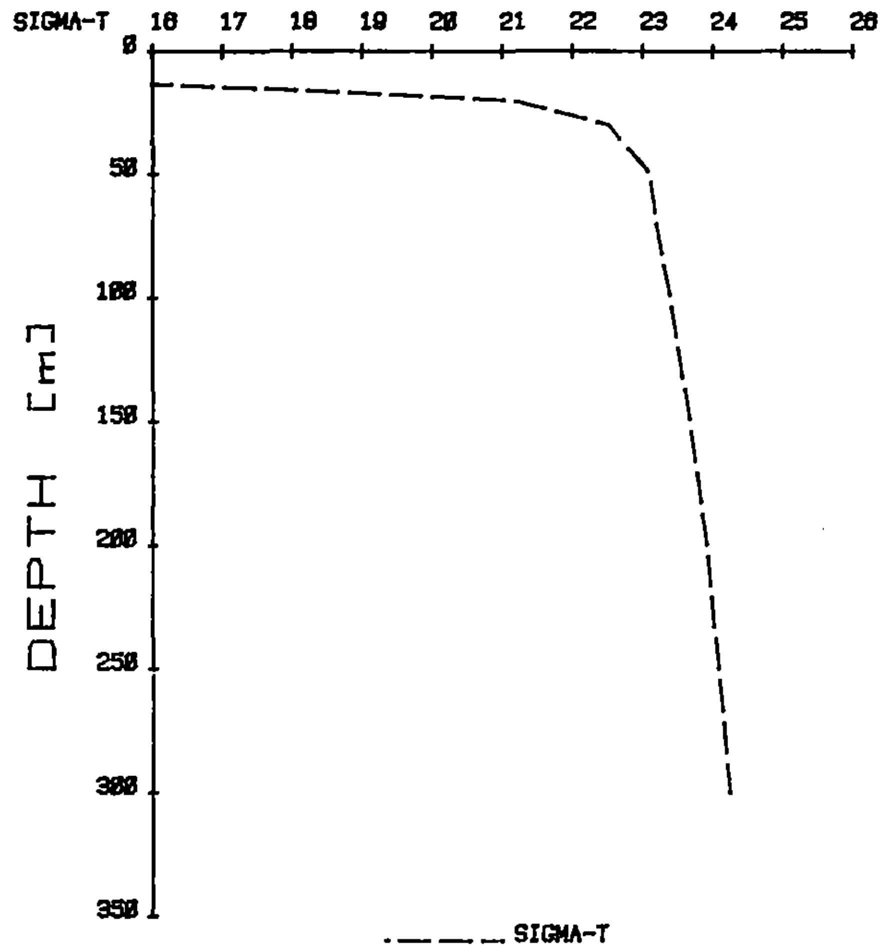

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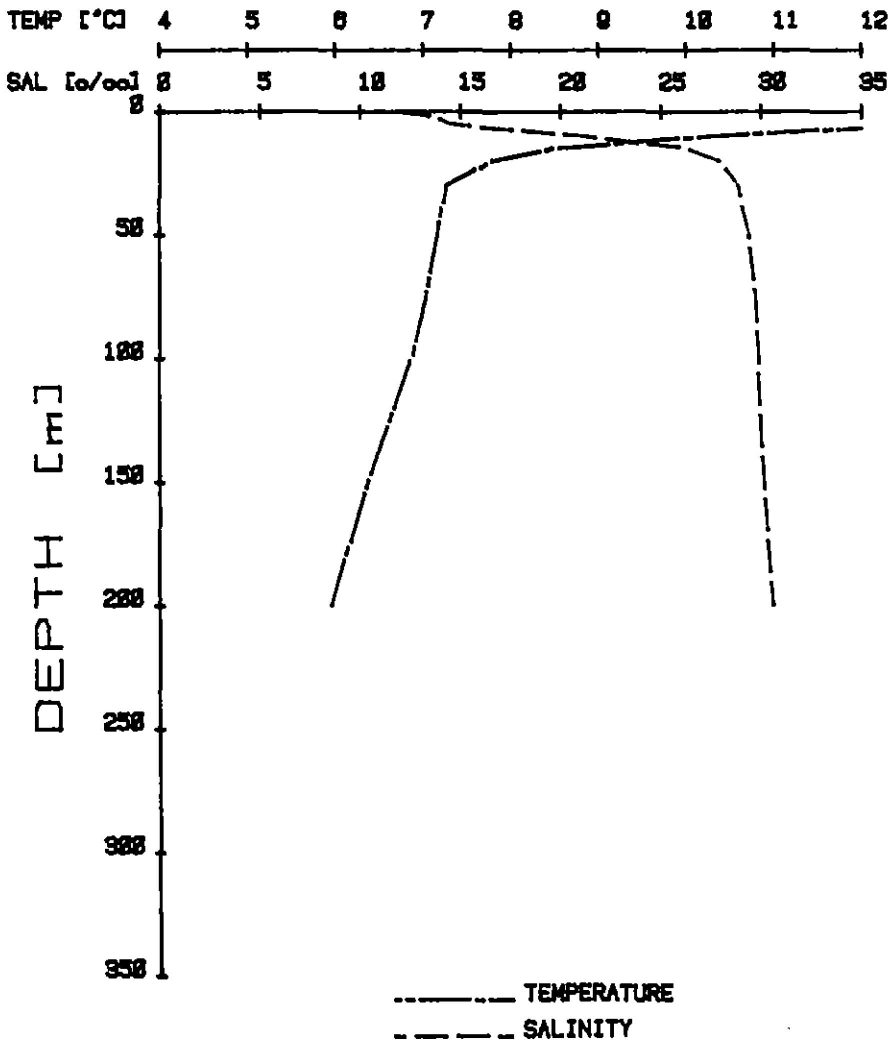

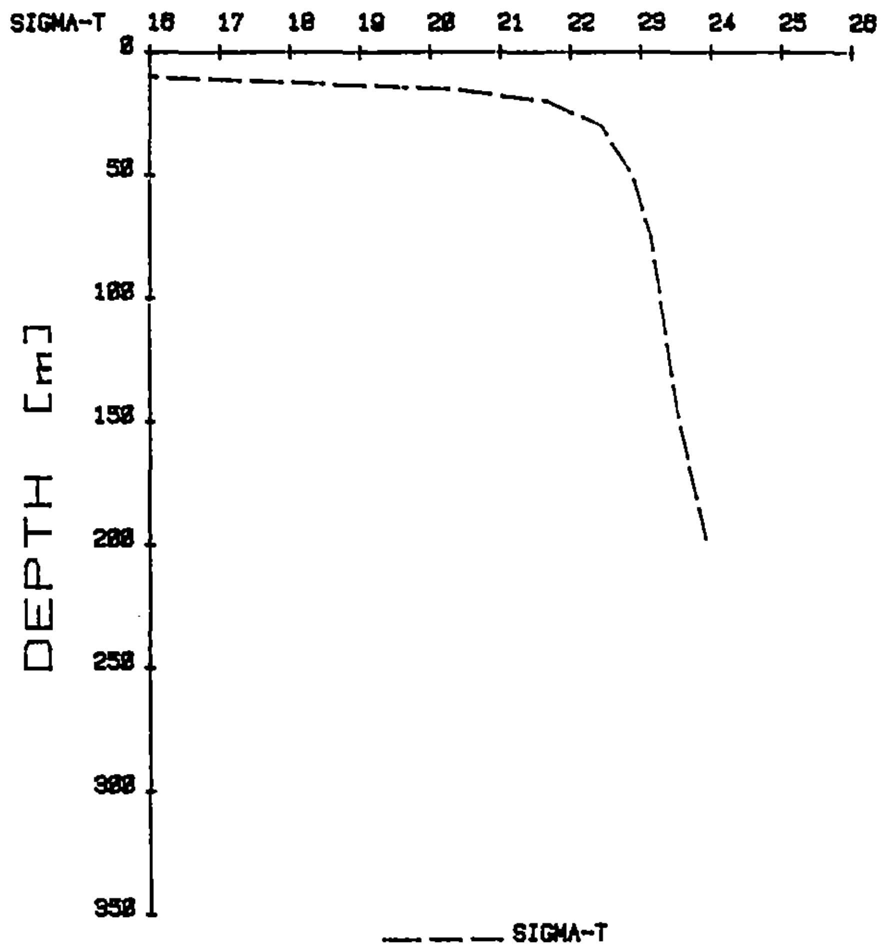

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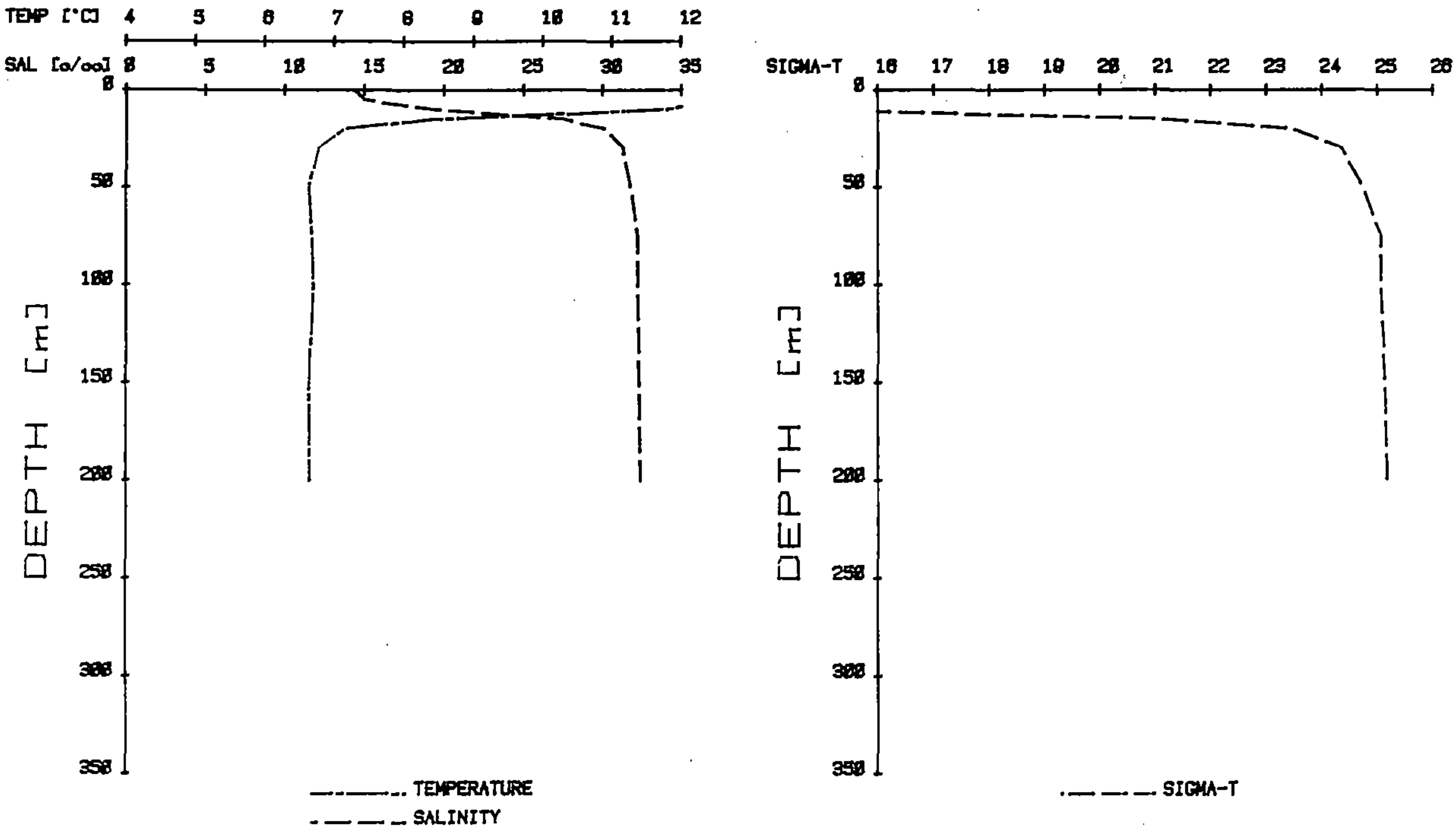

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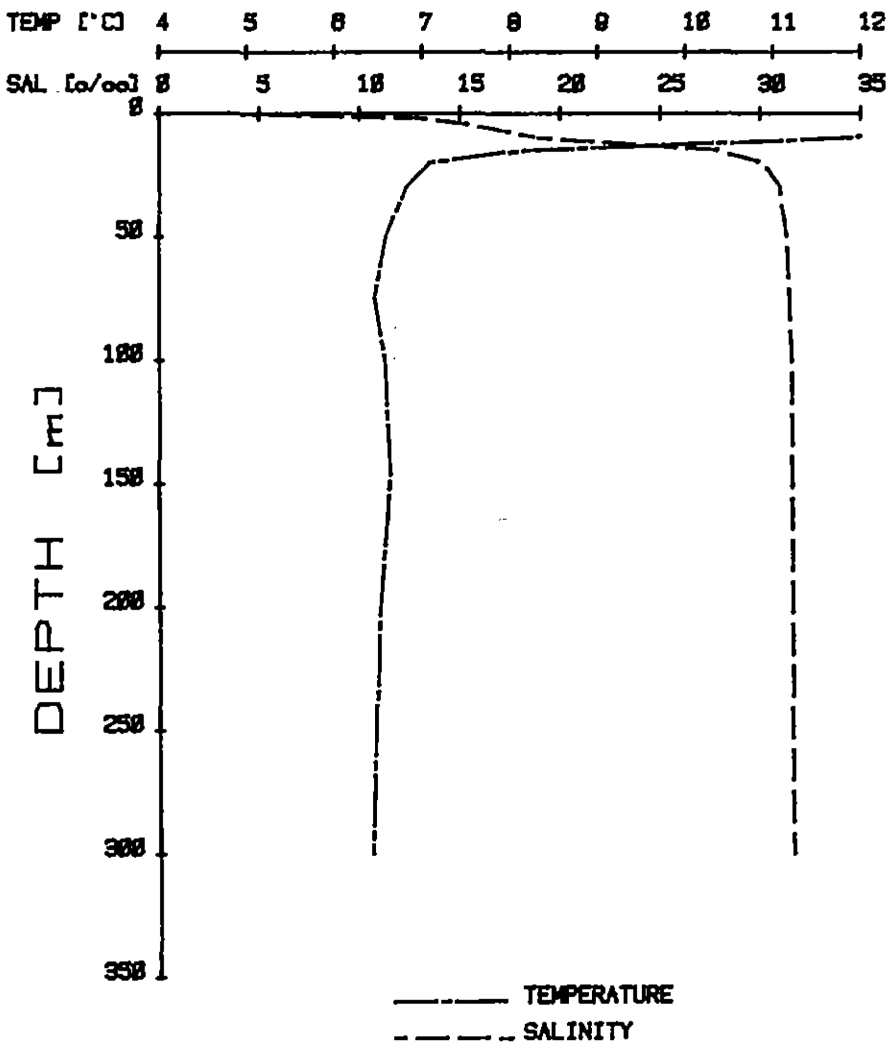

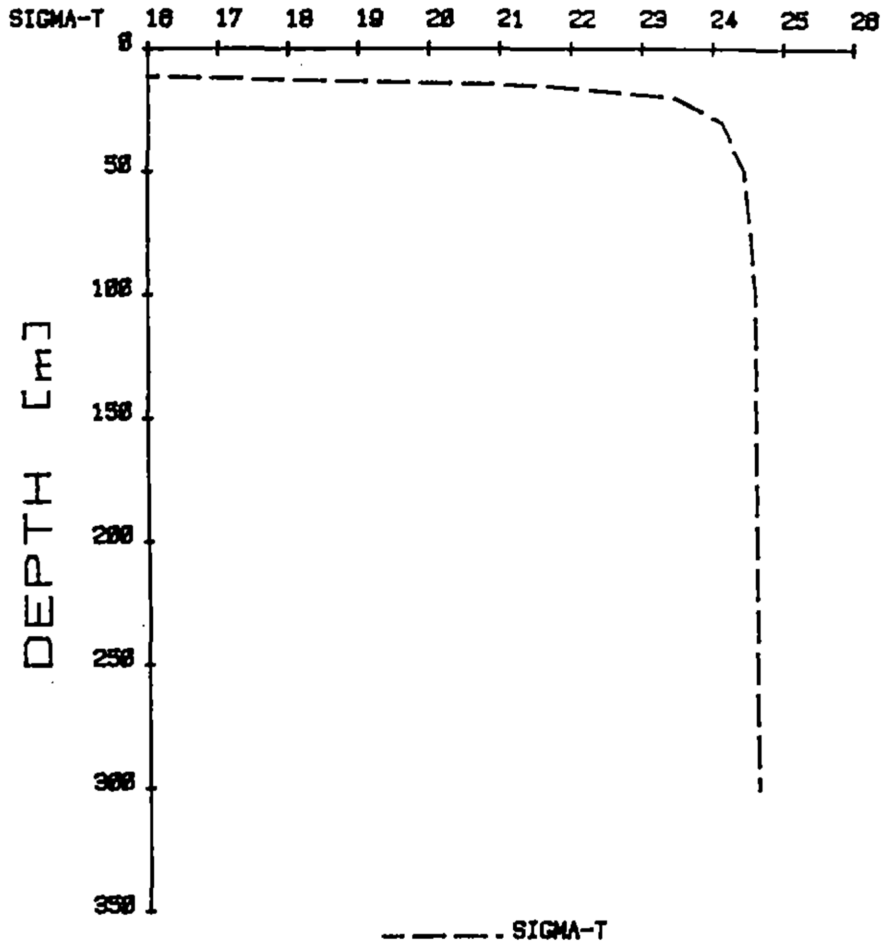

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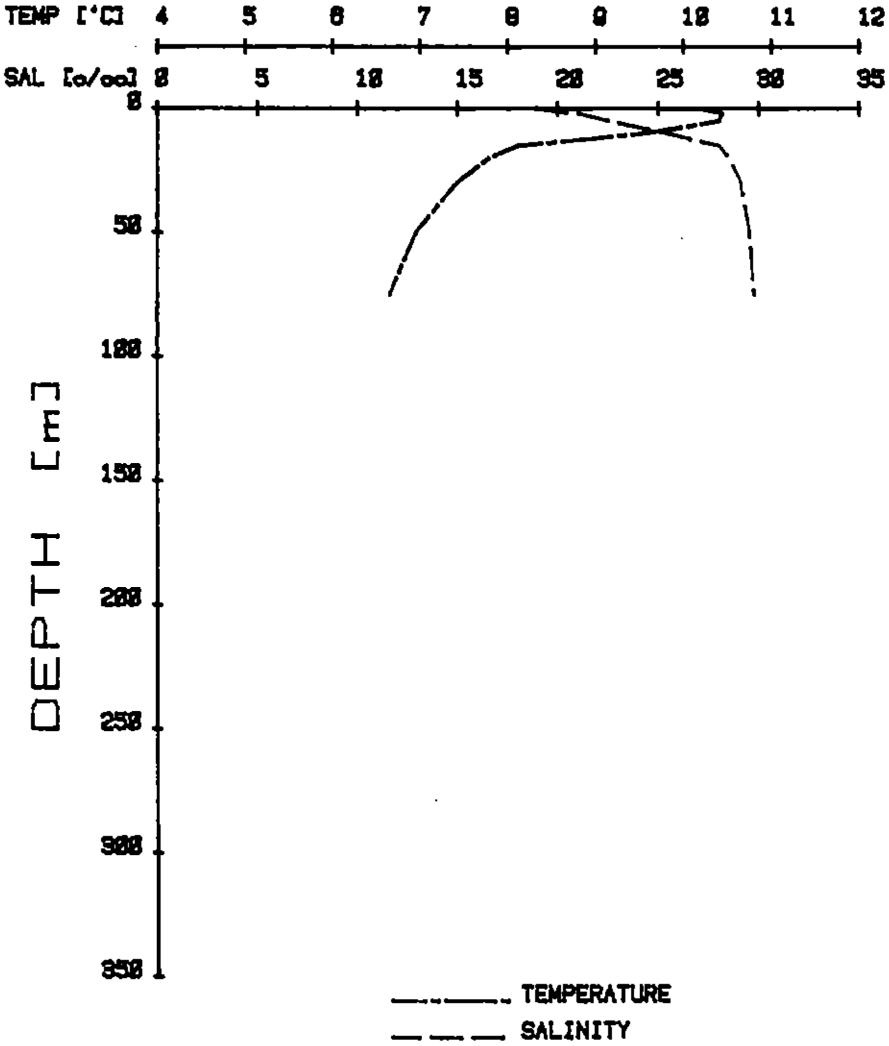

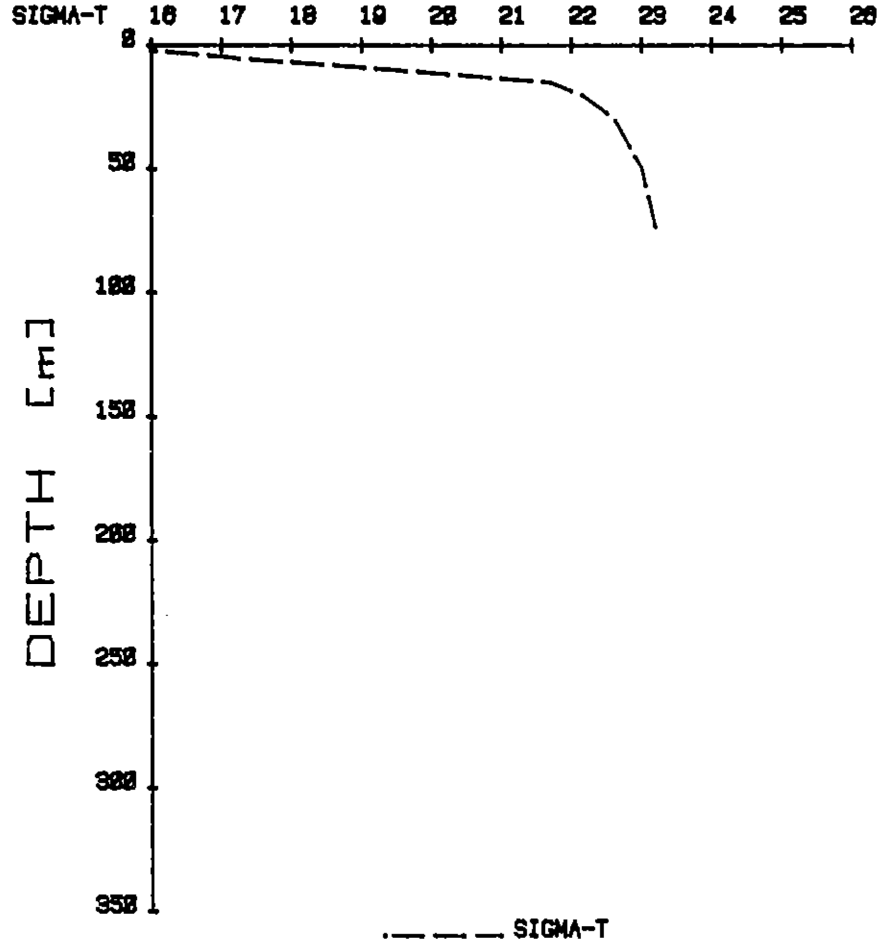

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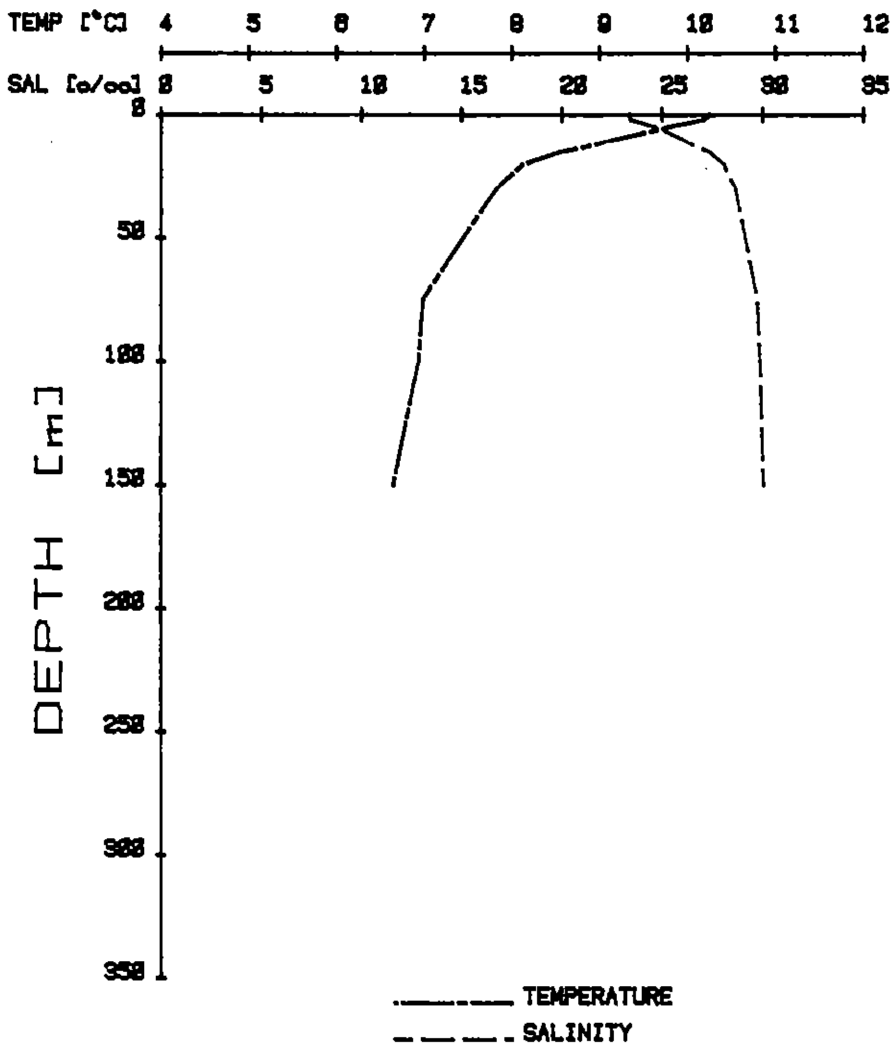

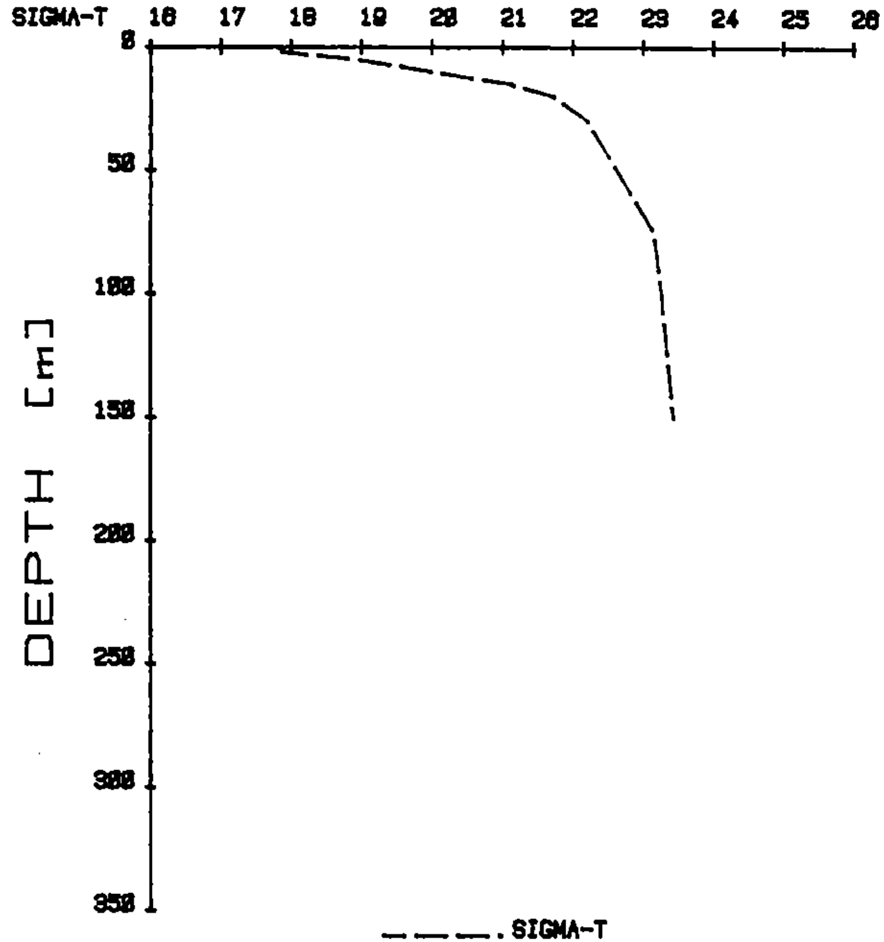

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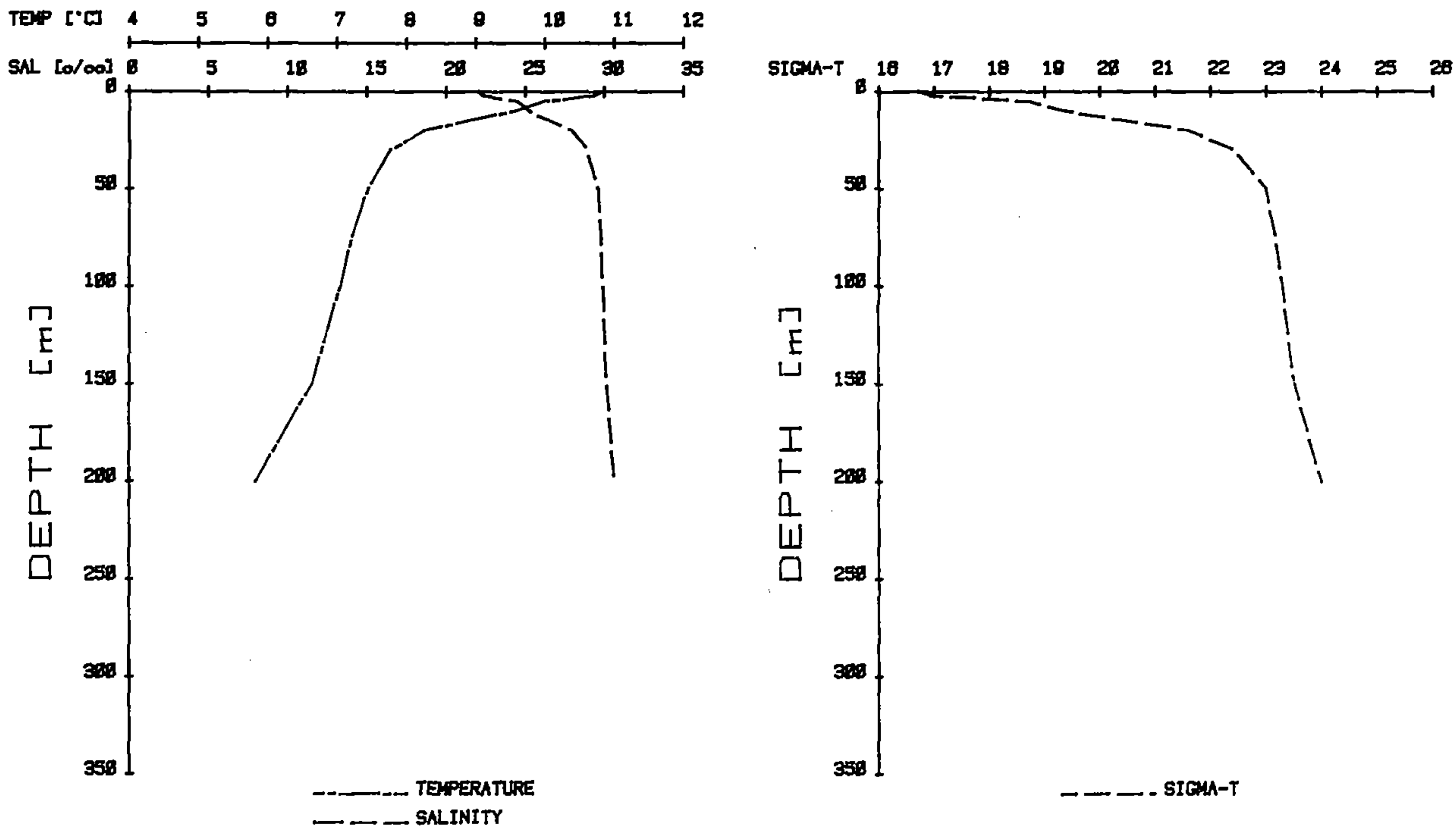

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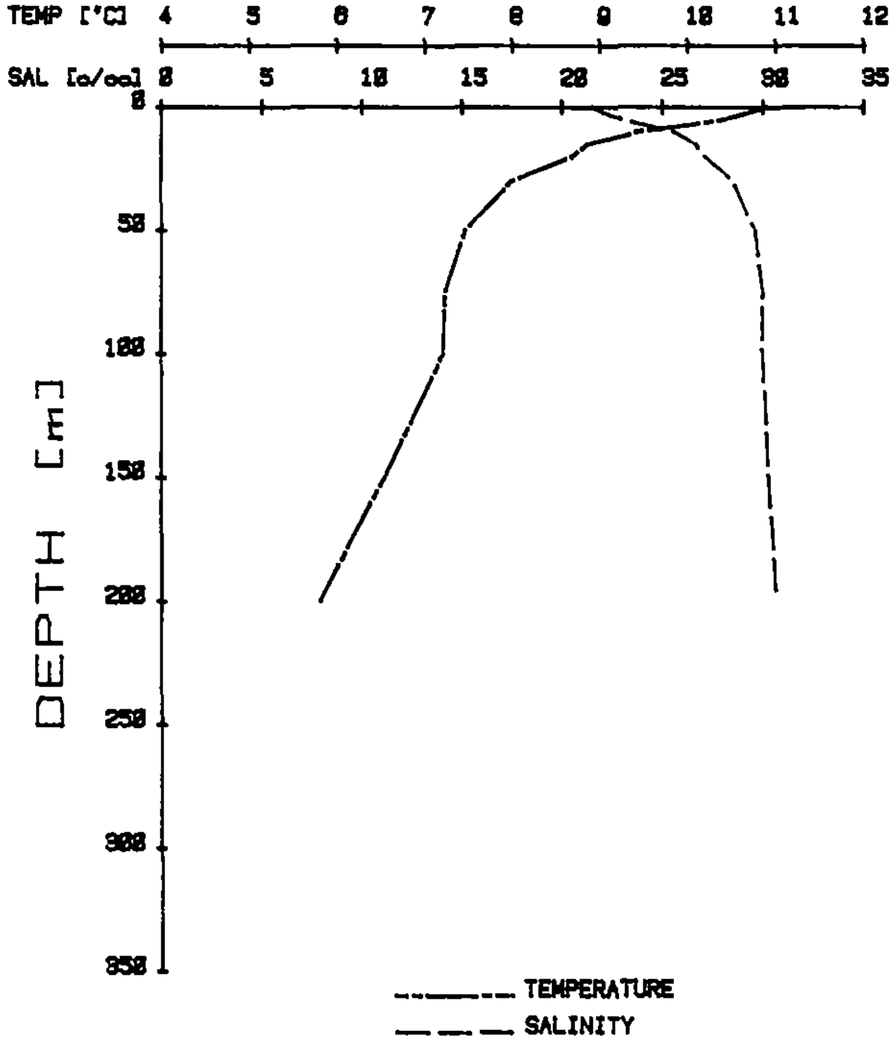

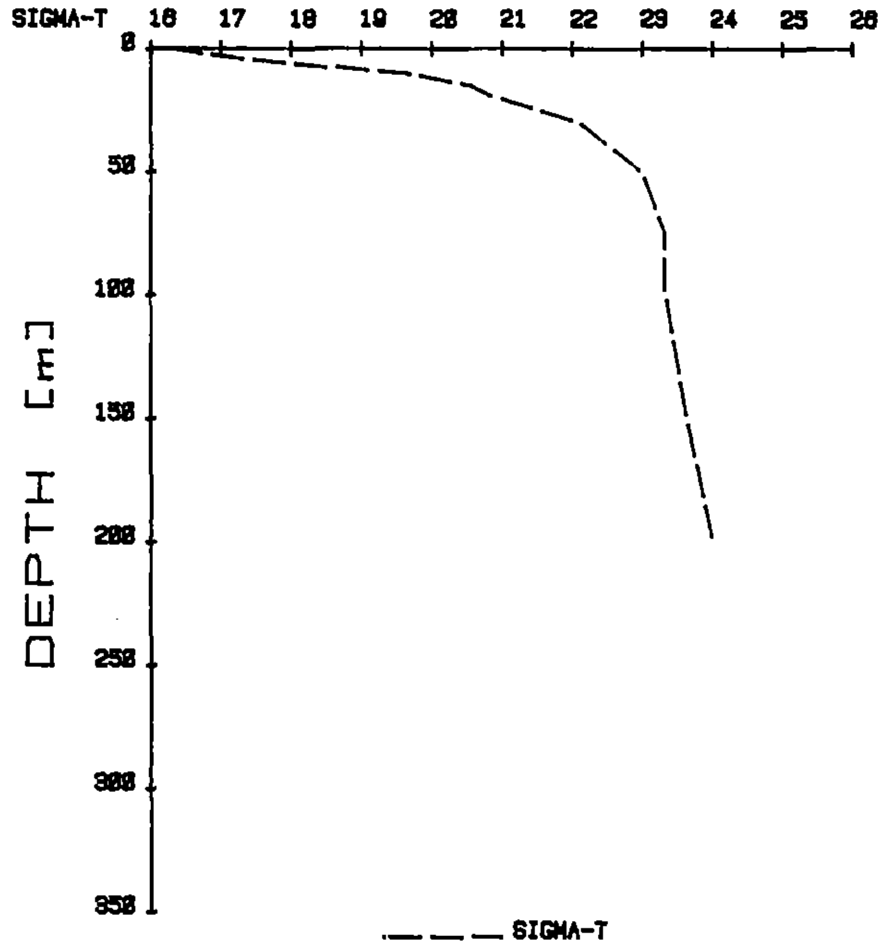

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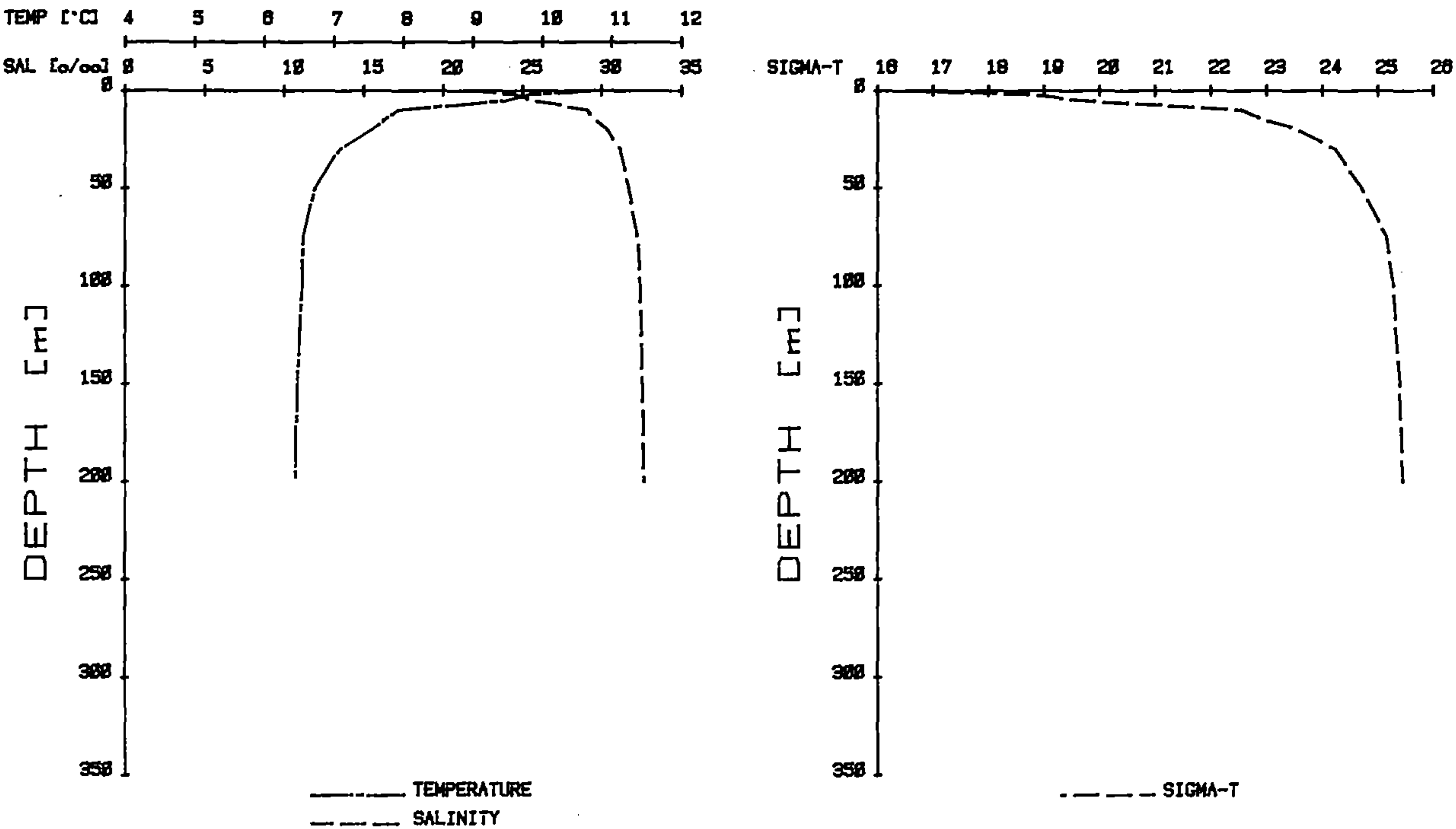

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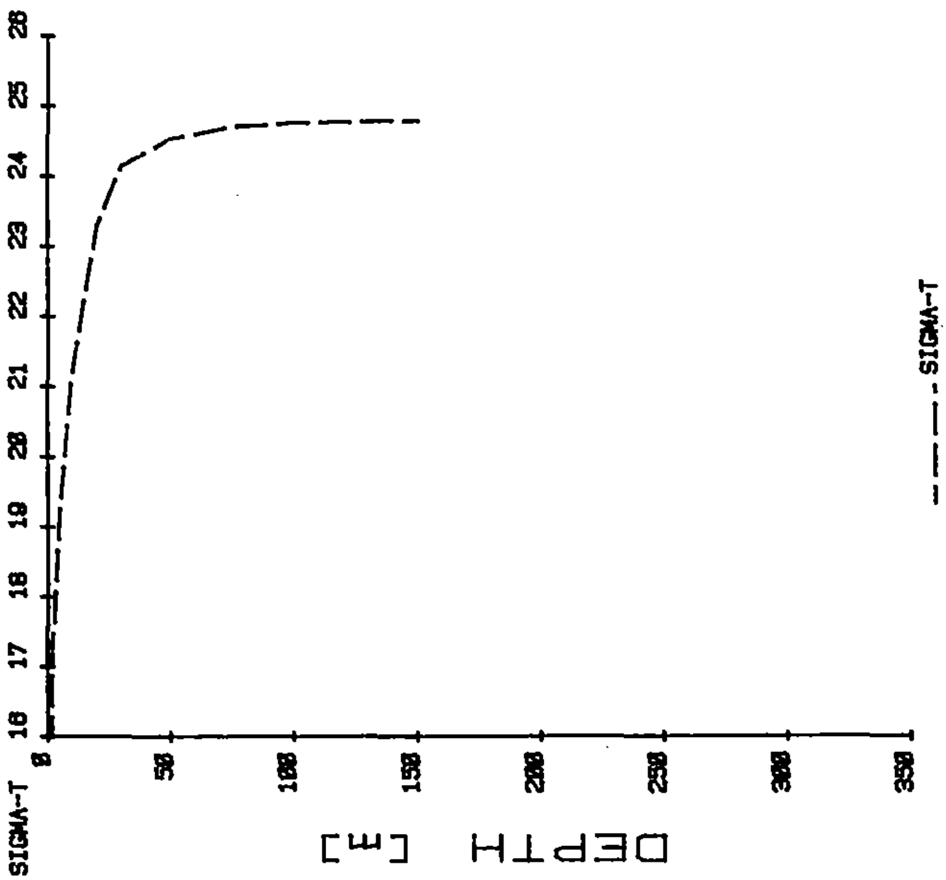

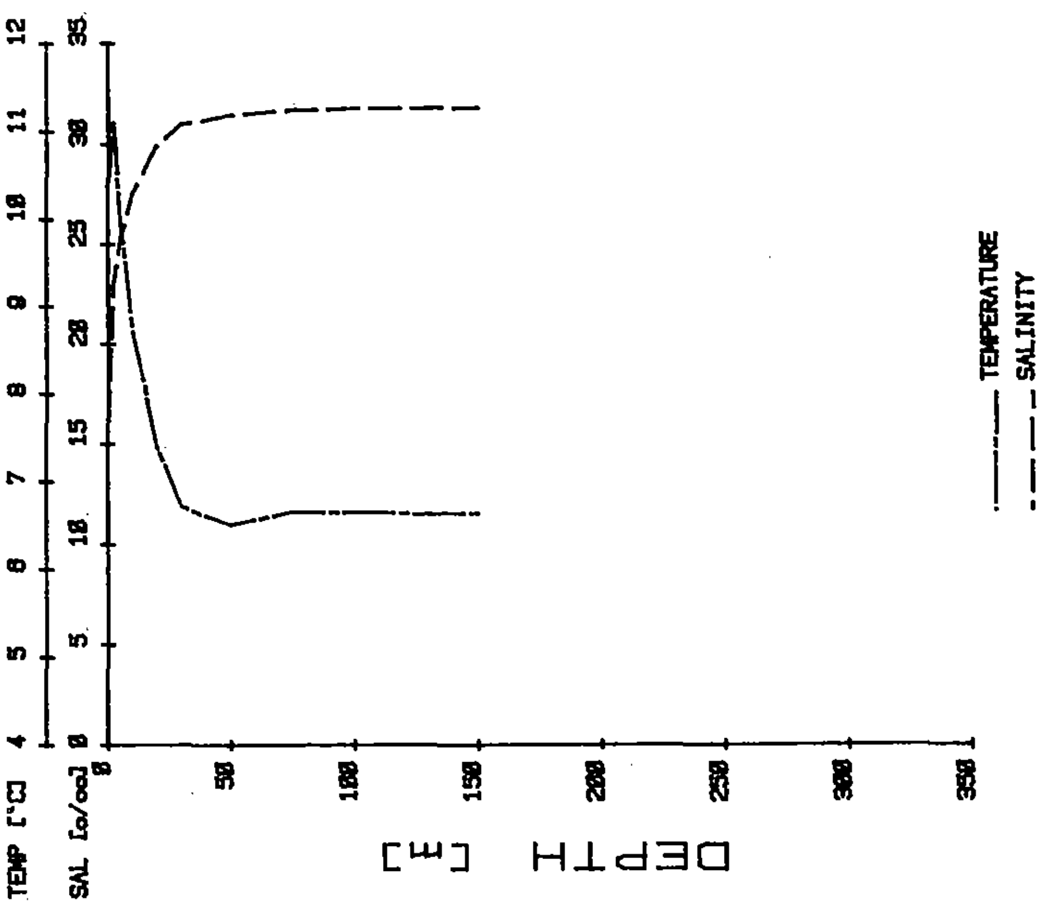

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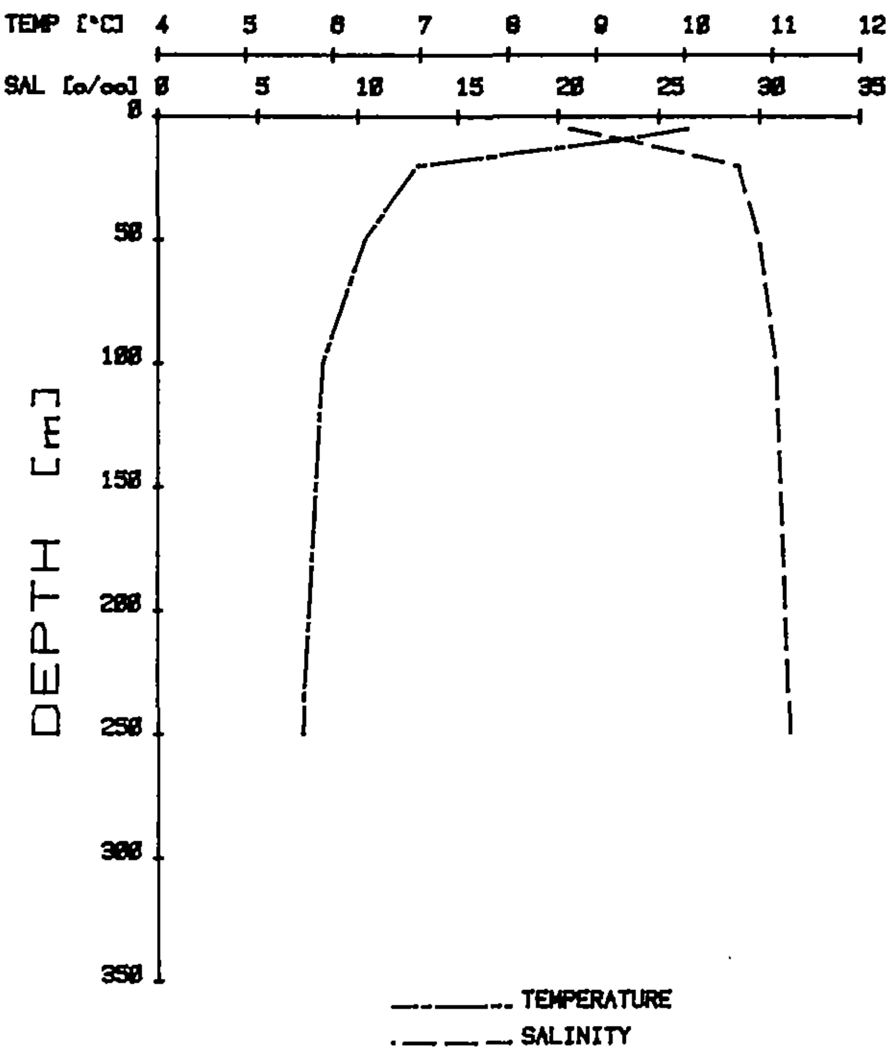

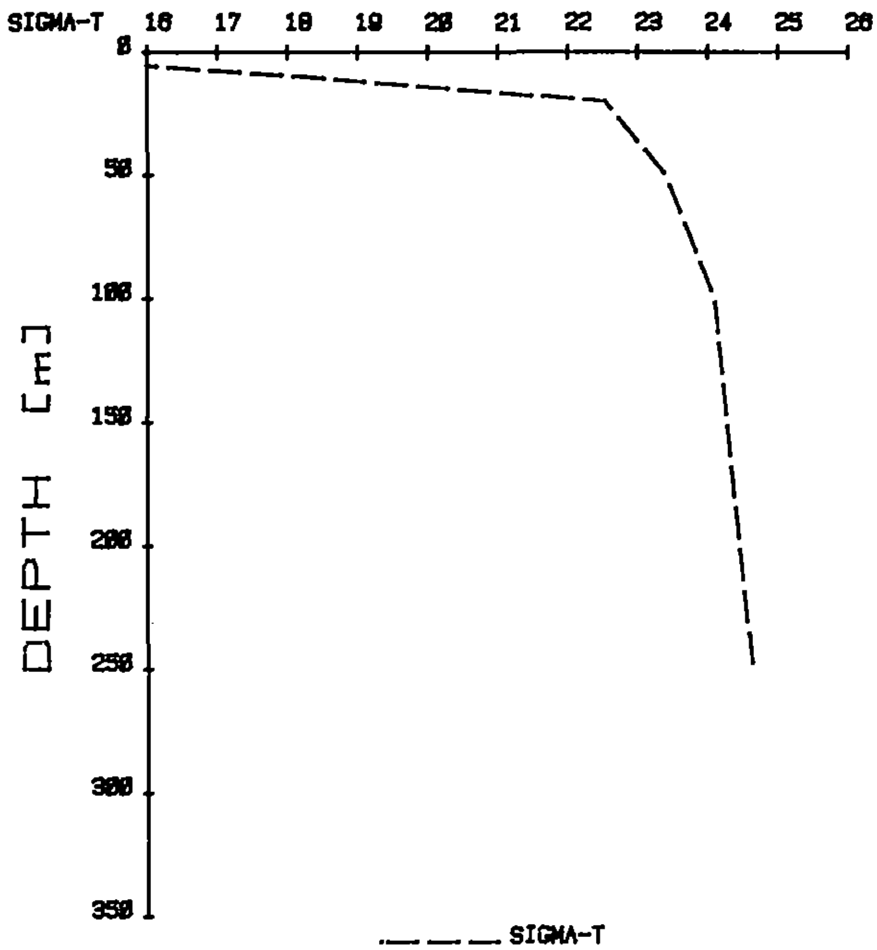

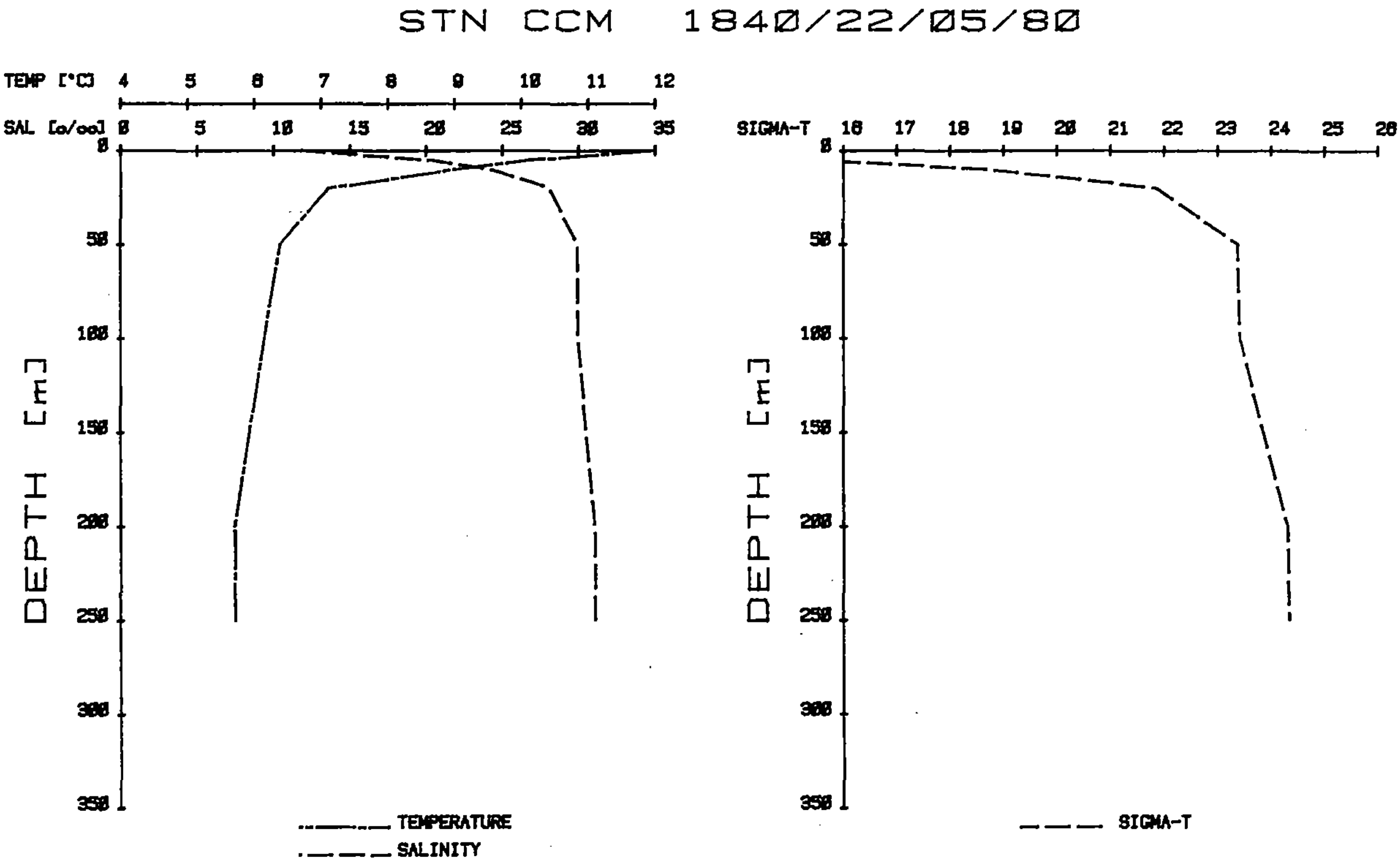
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SAL [o/oo] 0 5 10 15 20 25 30 35
SIGMA-T 16 17 18 19 20 21 22 23 24 25 26
0
50
100
150
200
250
300
350
DEPTH [m]
TEMPERATURE
SALINITY
SIGMA-T

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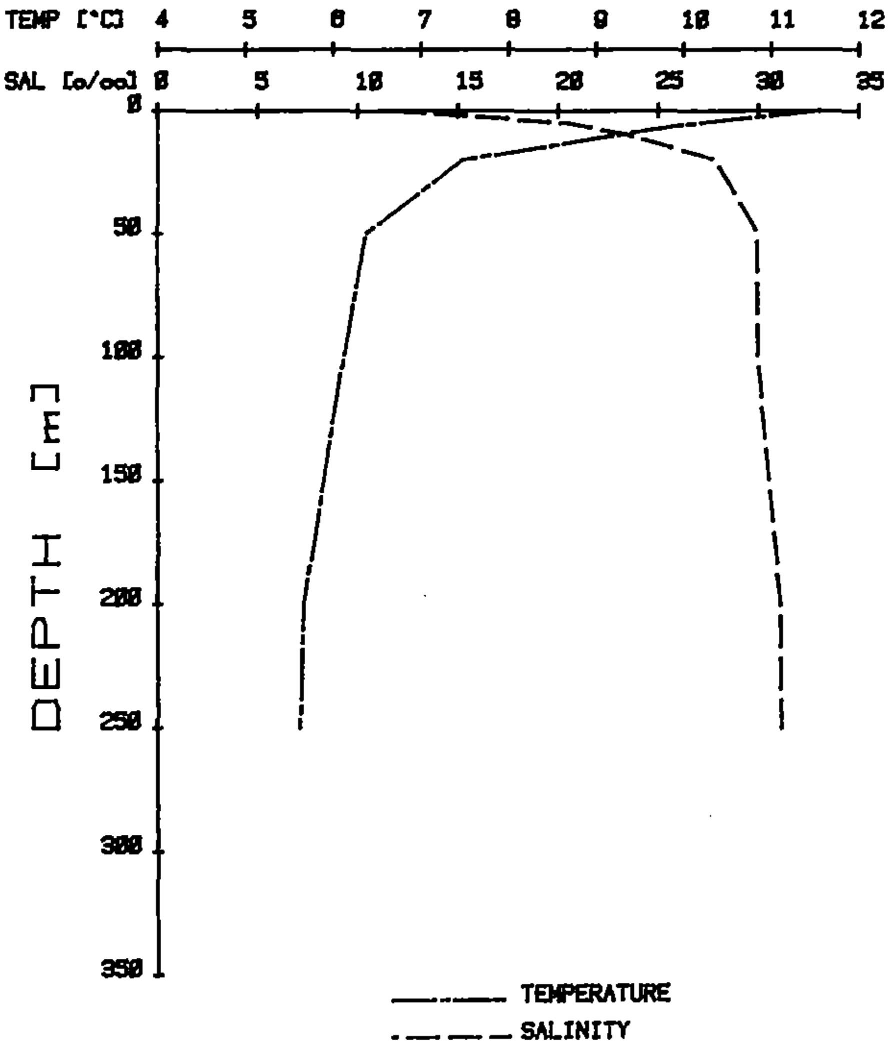

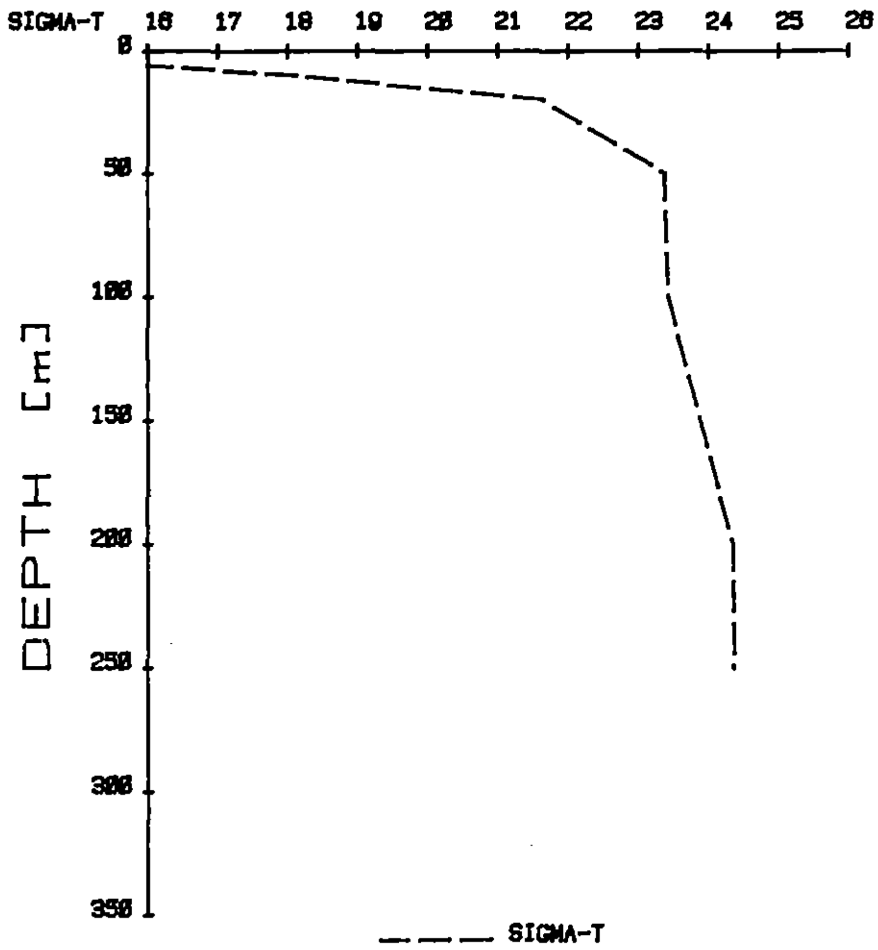

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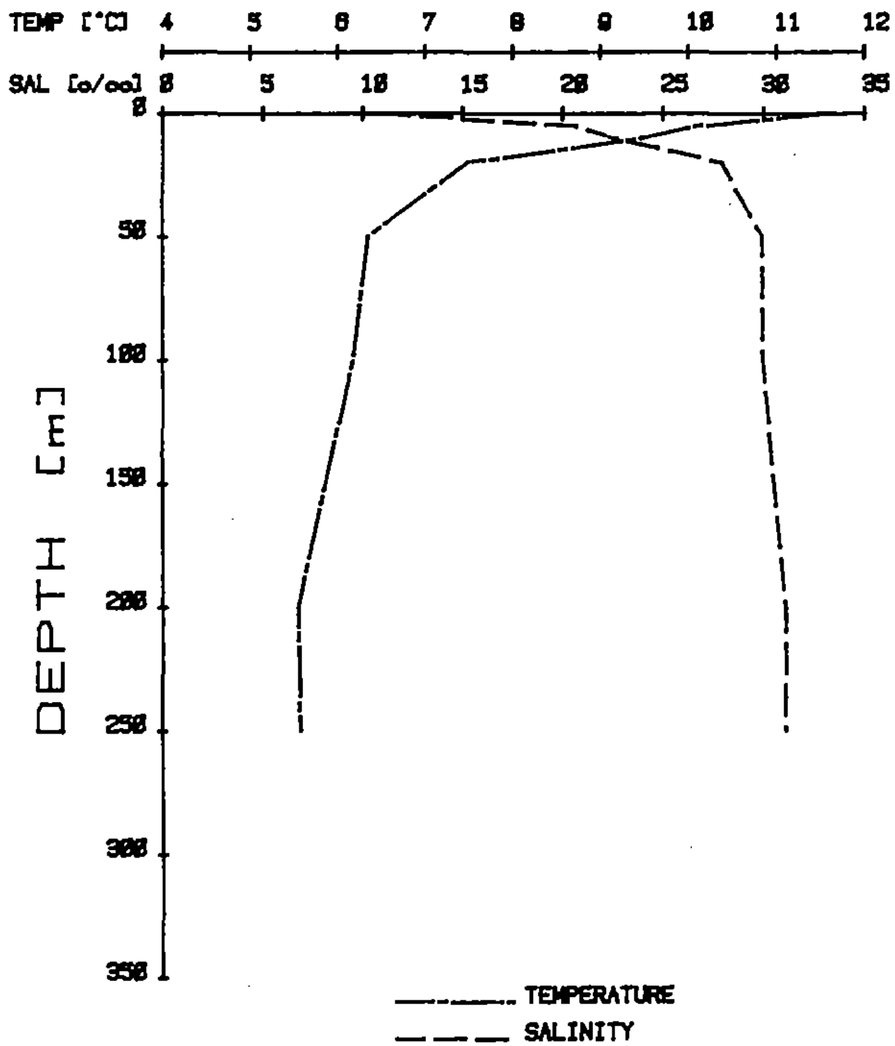

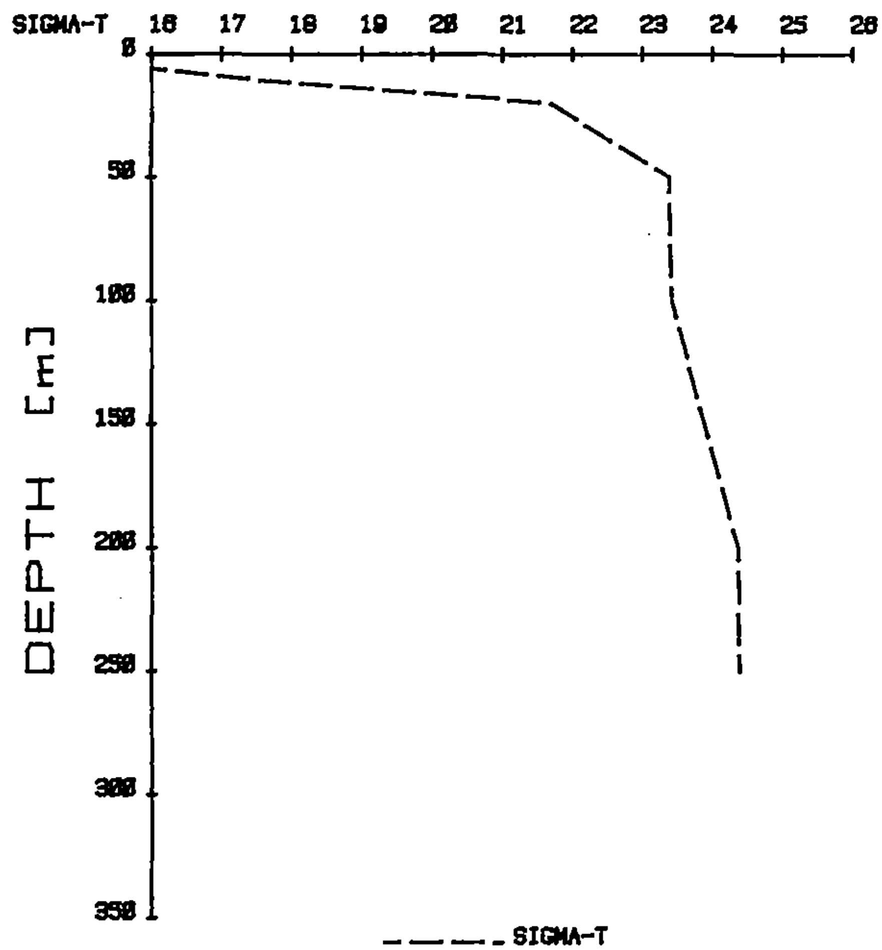

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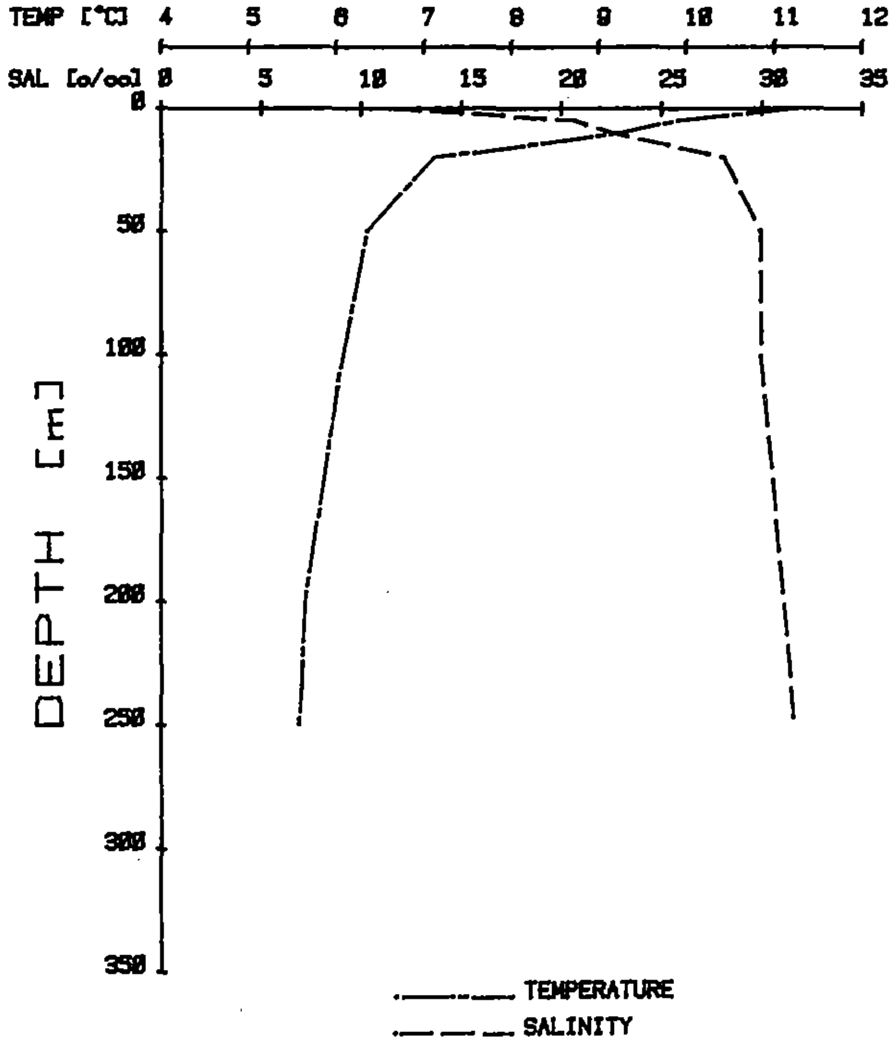

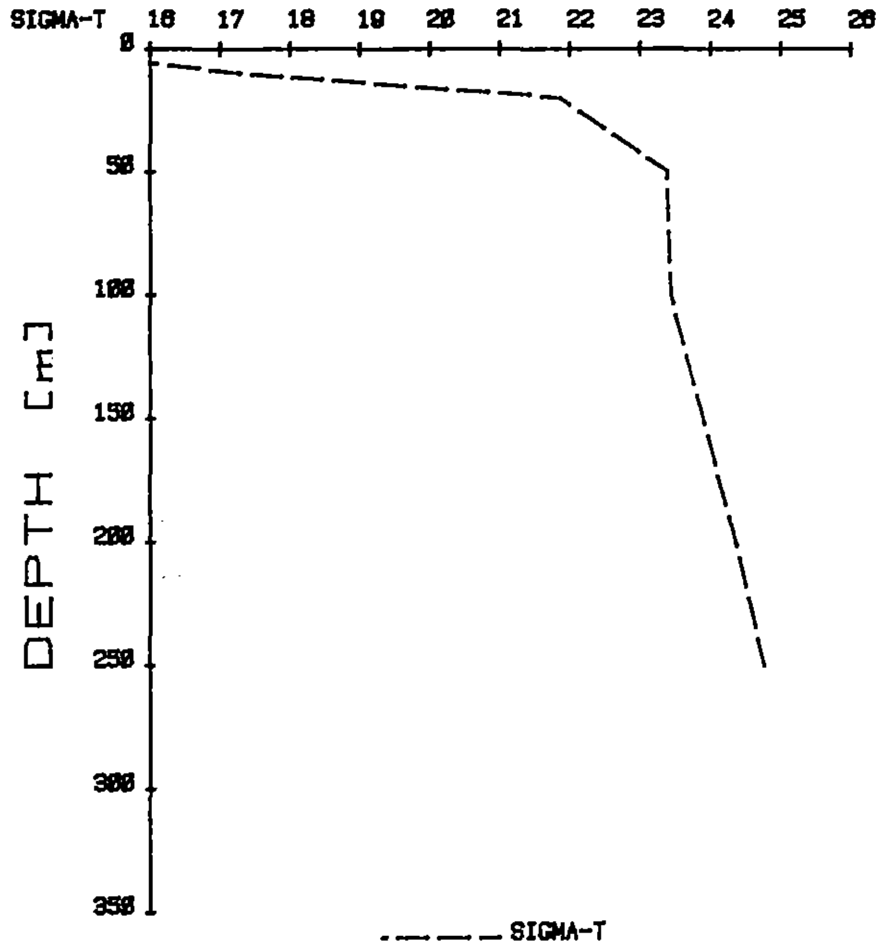

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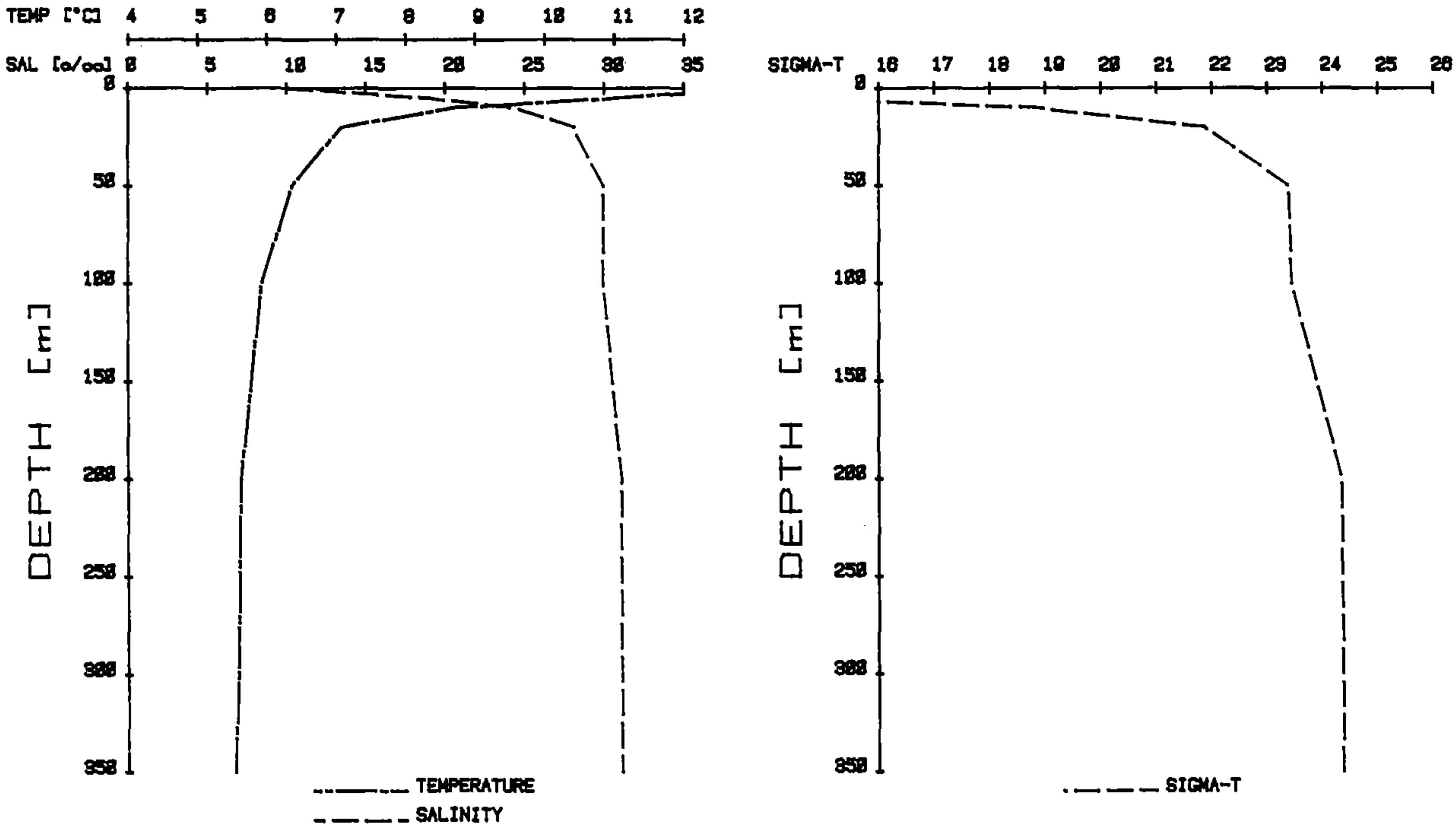

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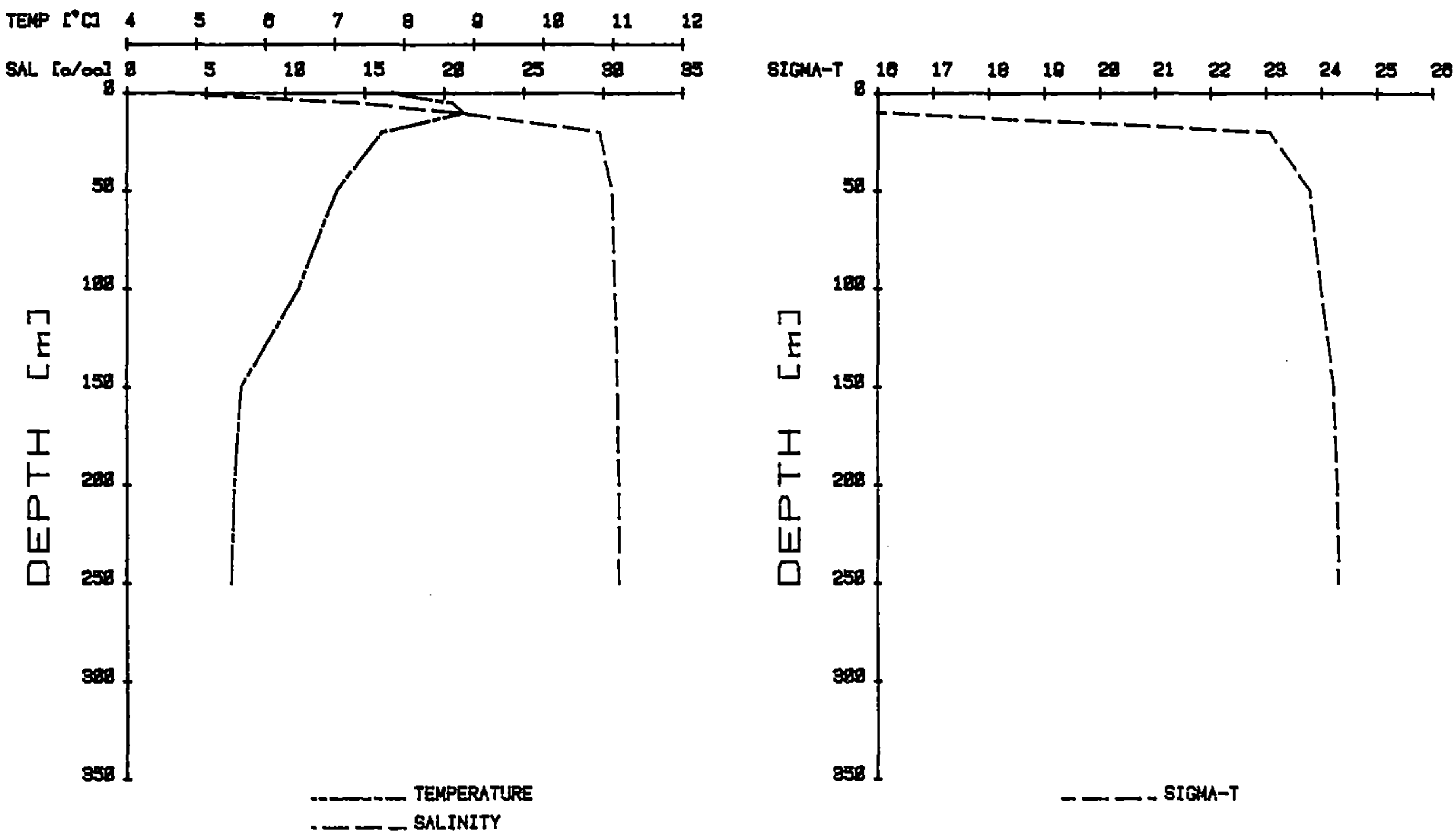

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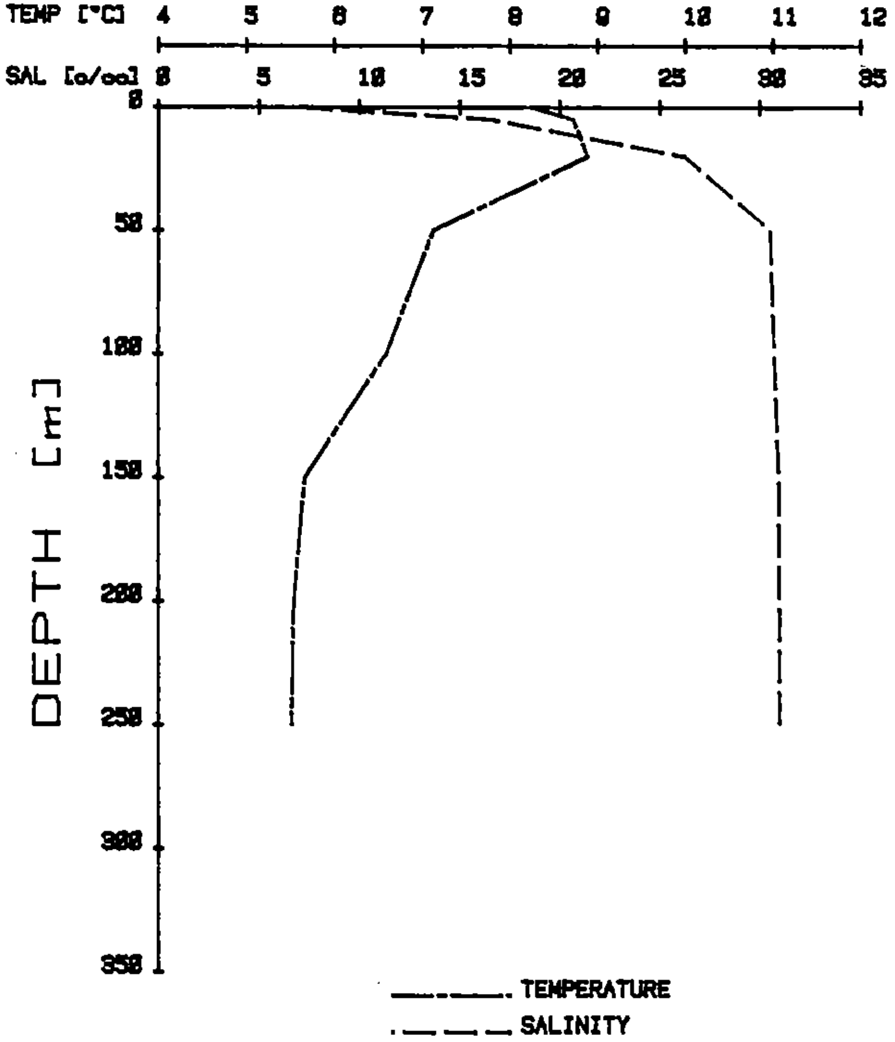

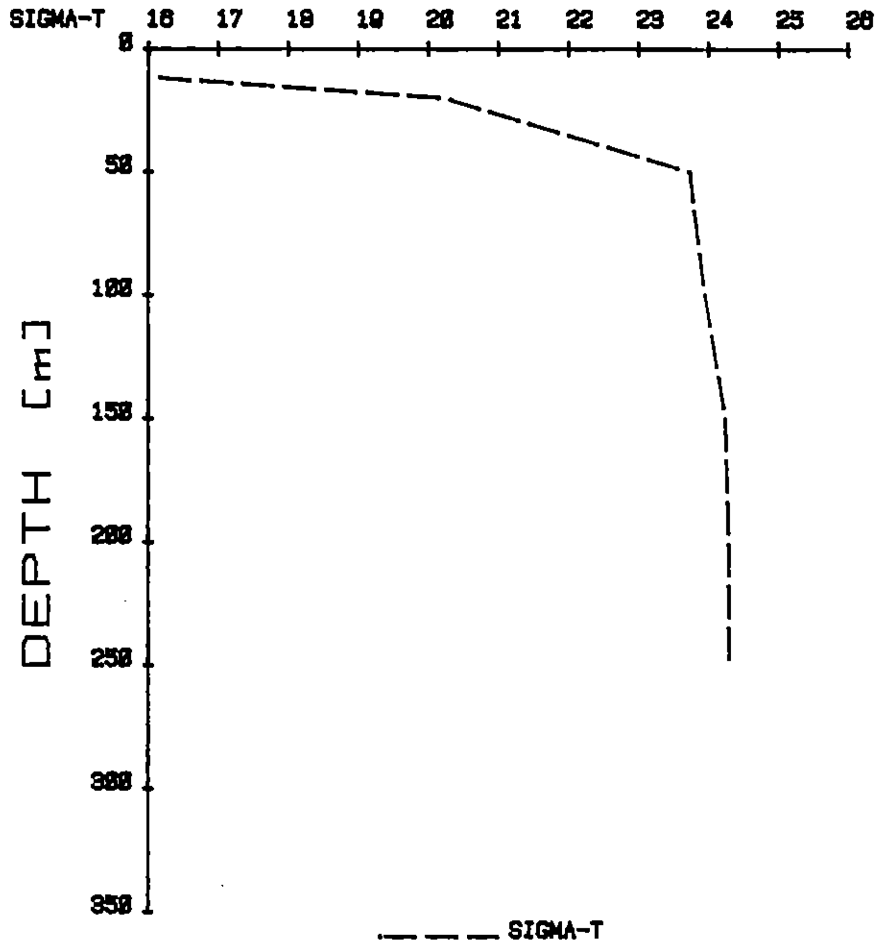

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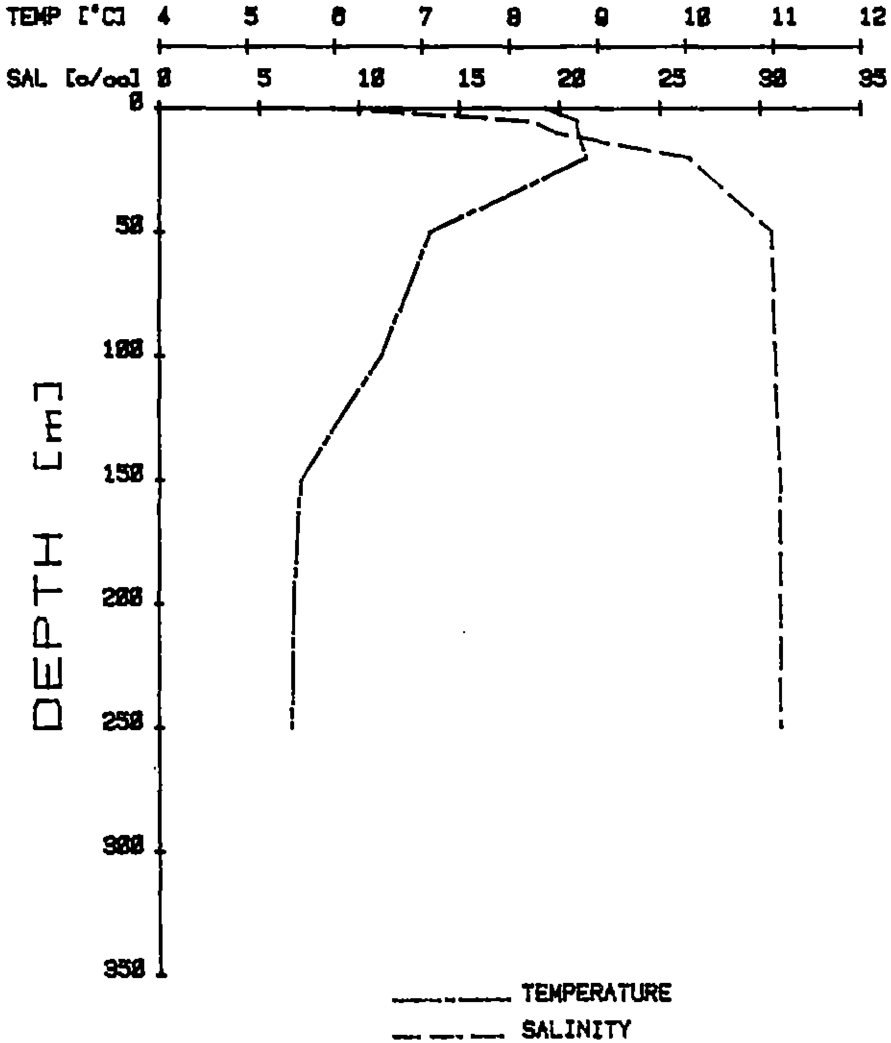

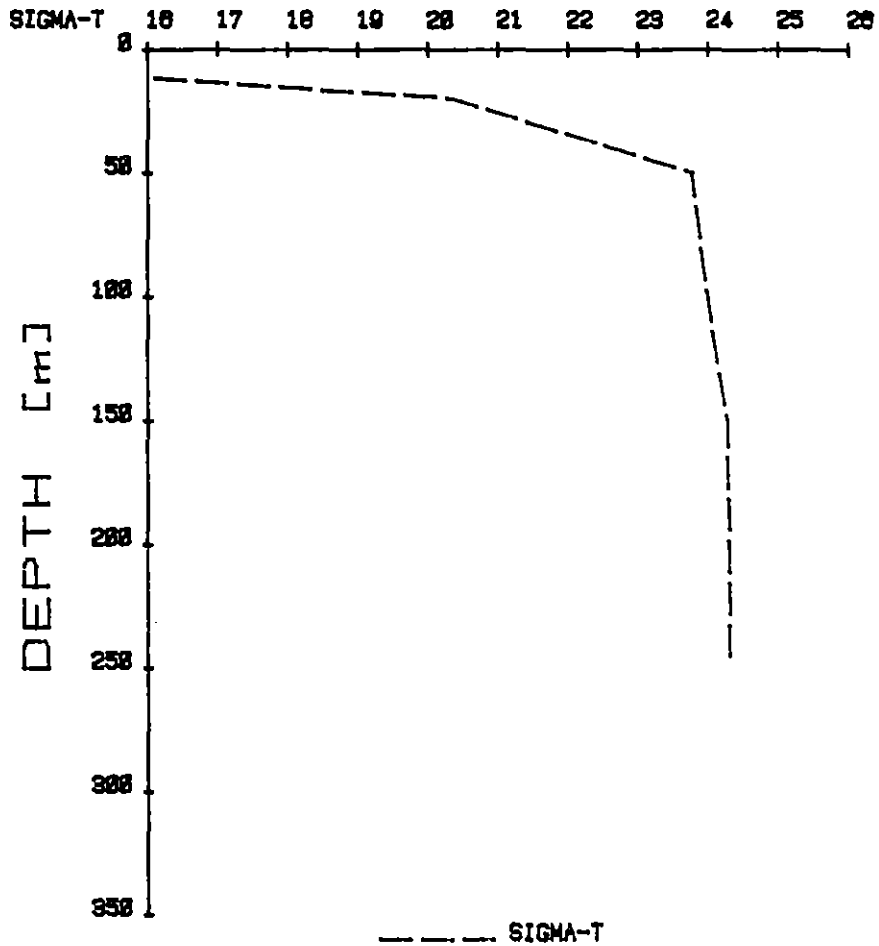

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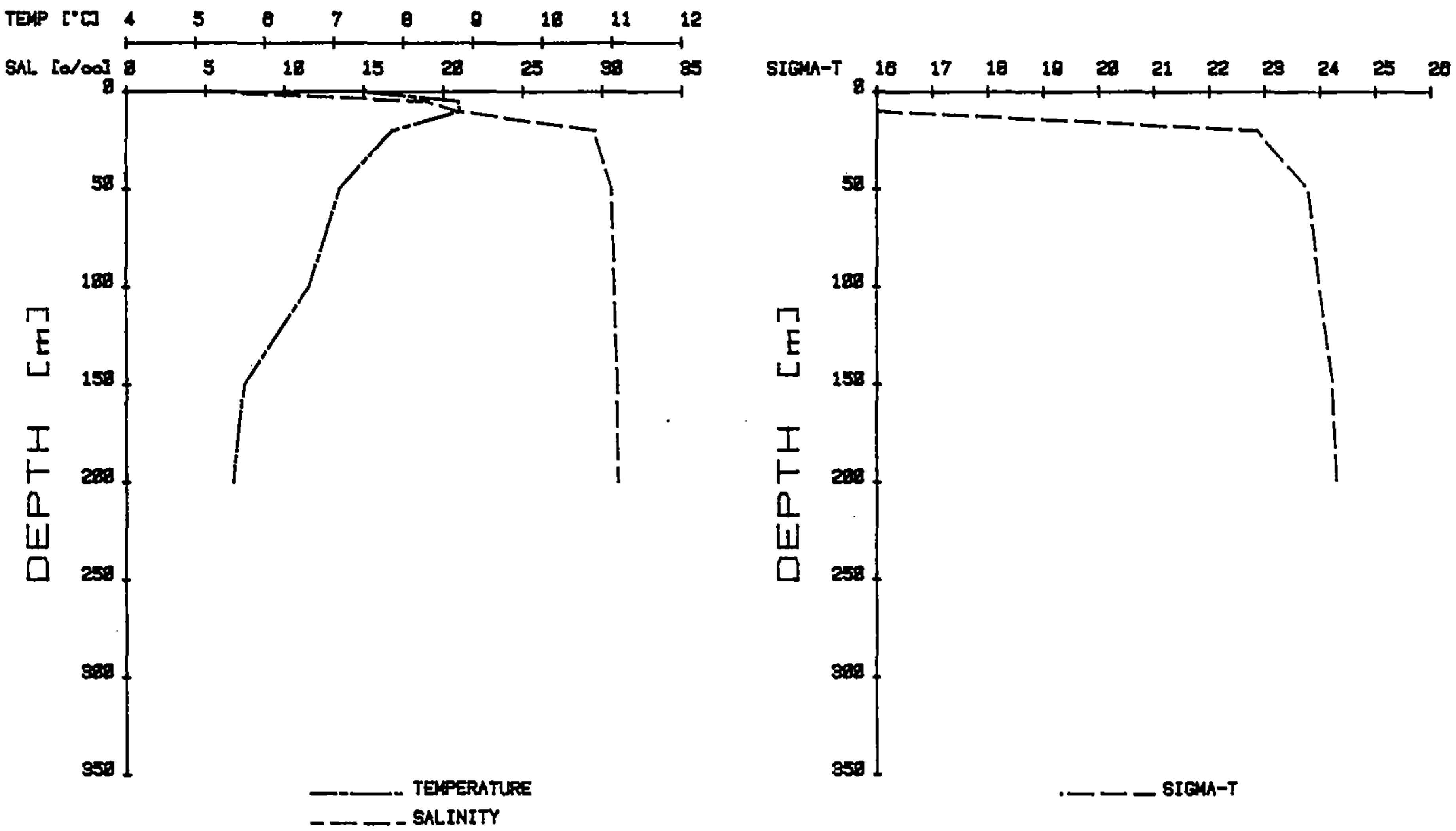

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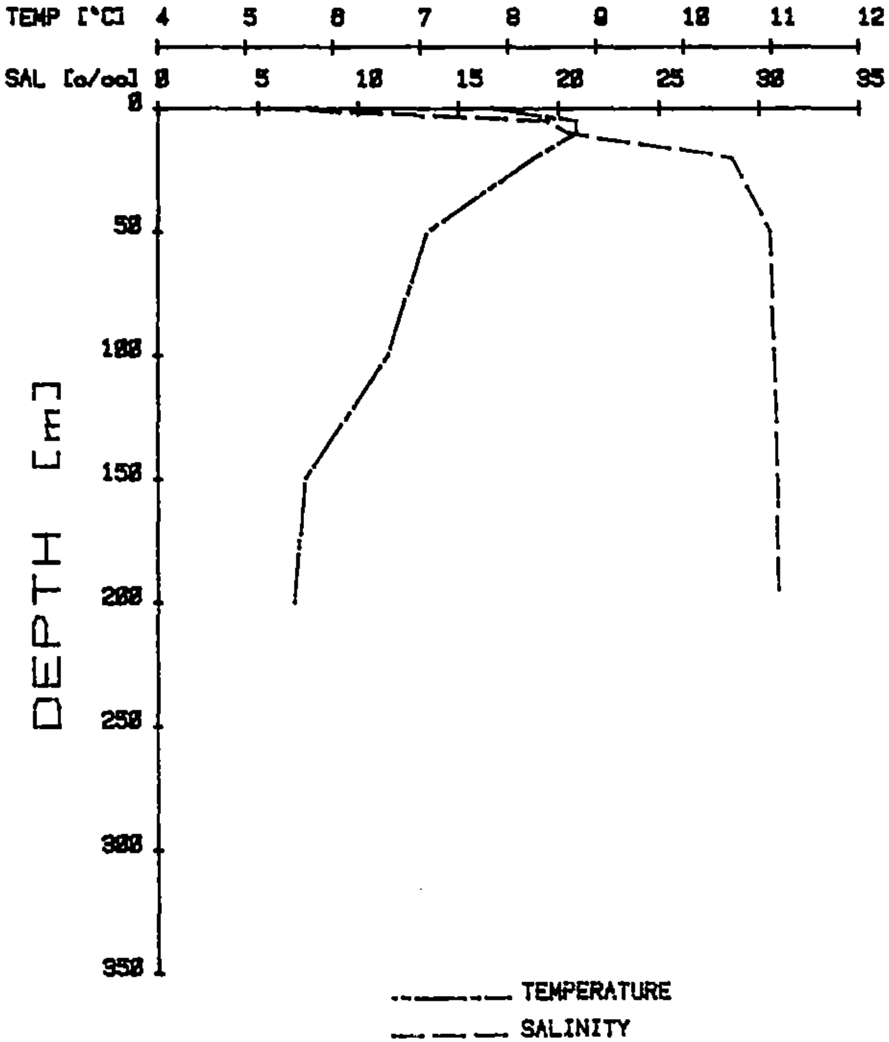

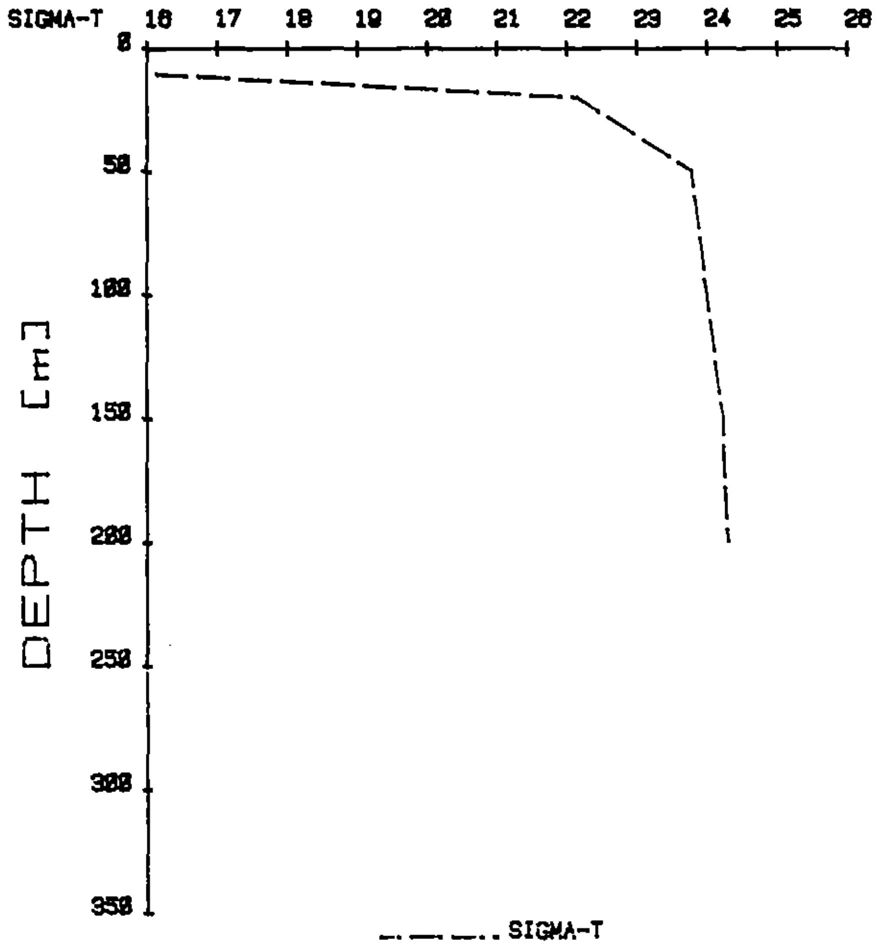

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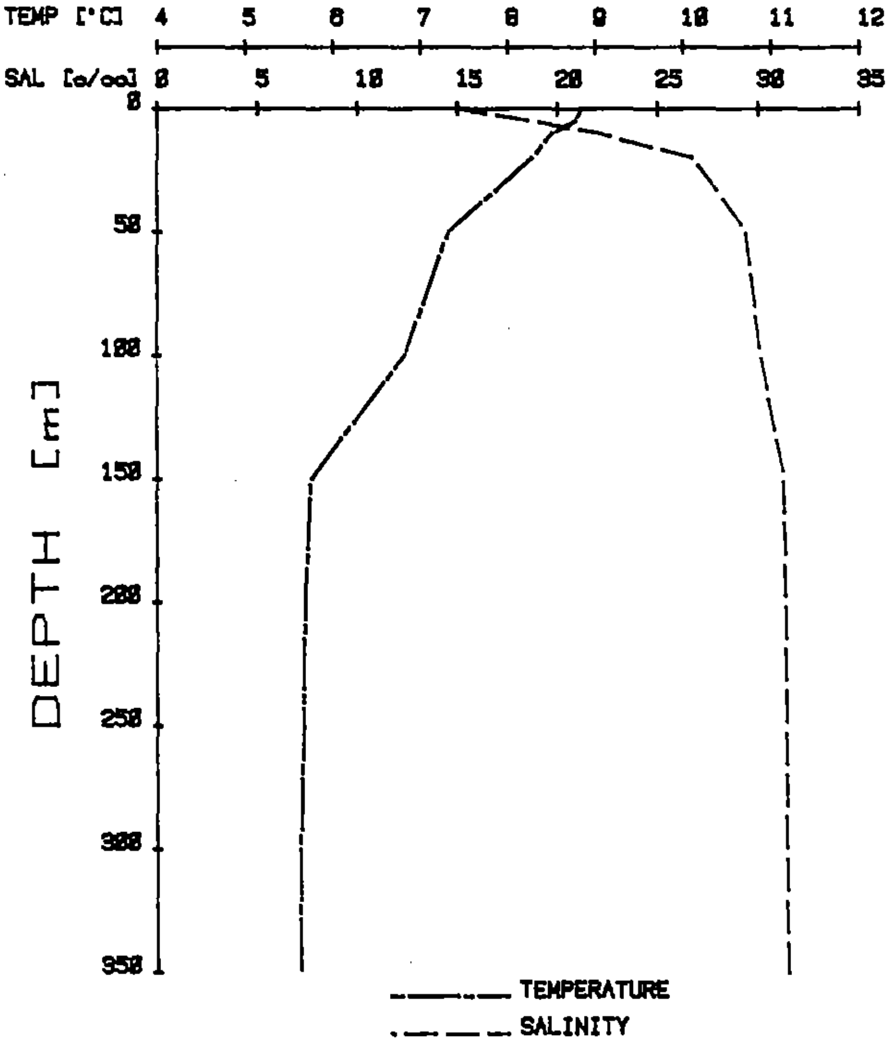

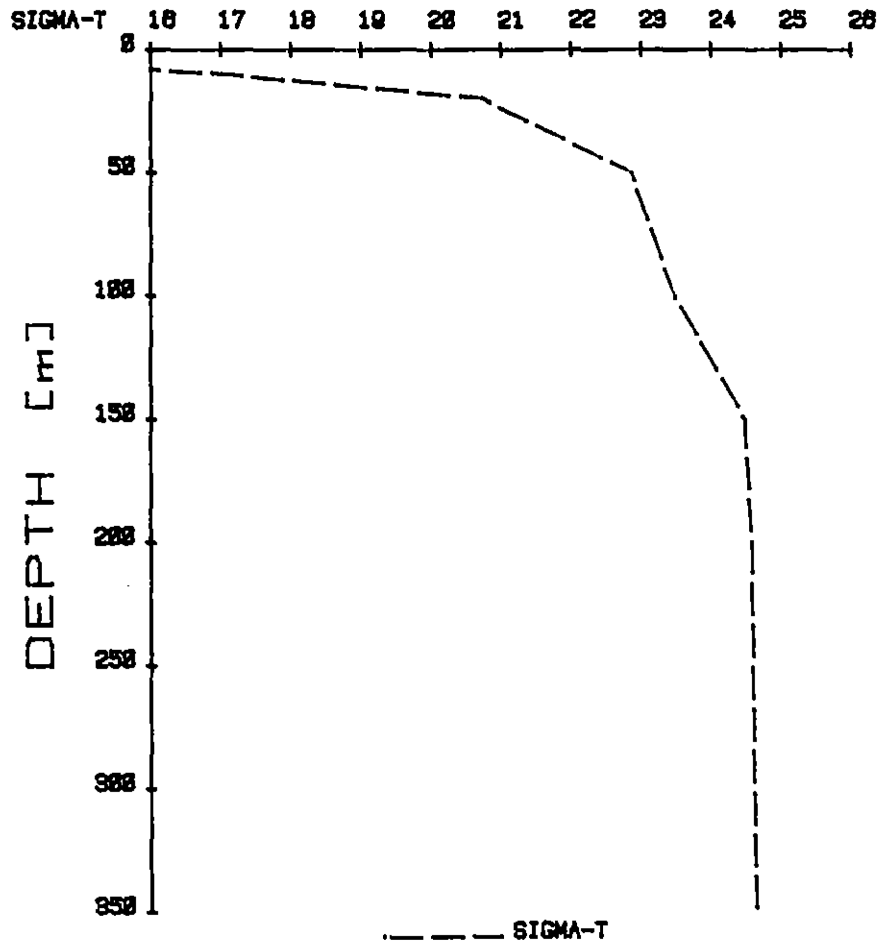

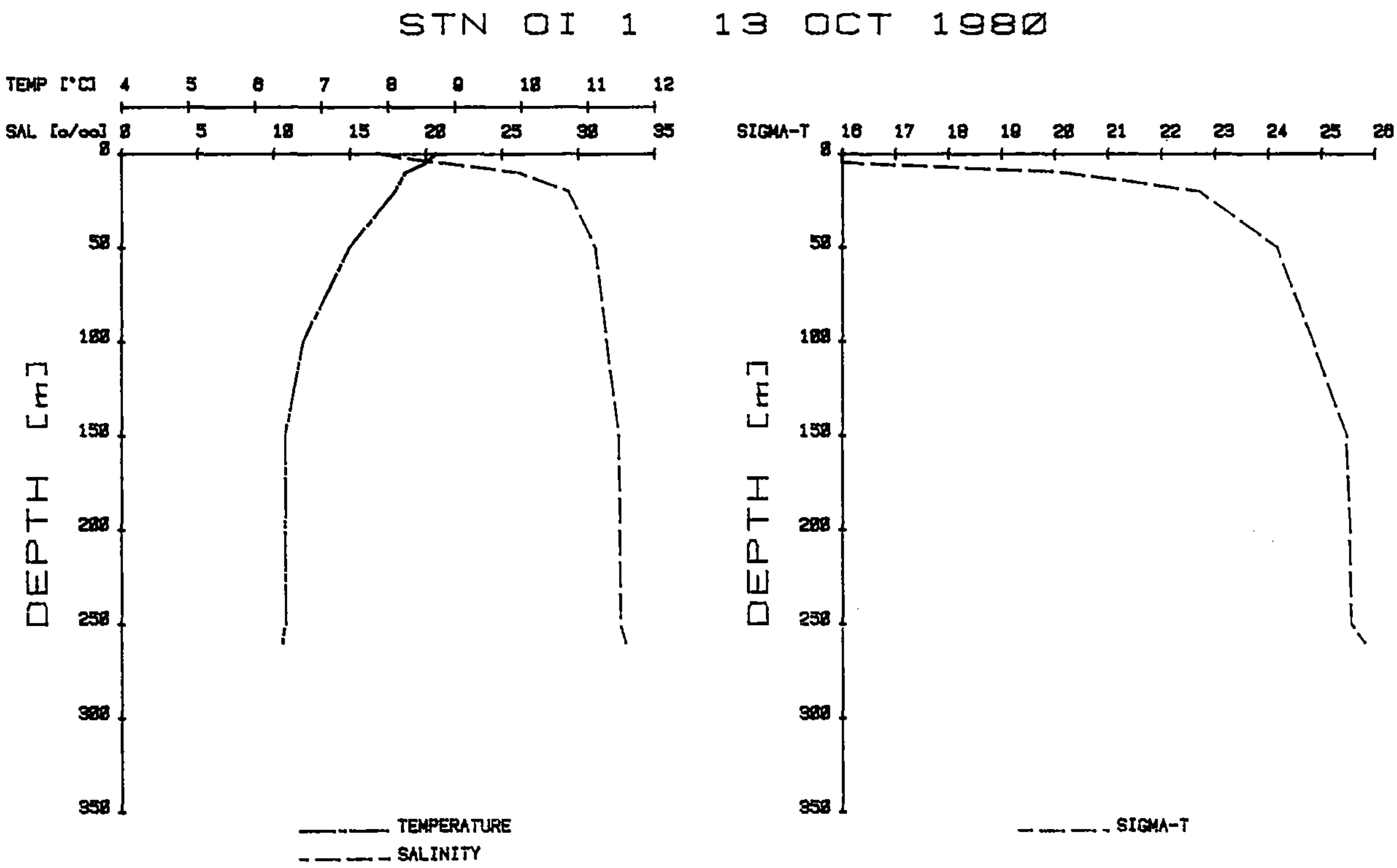
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SAL [o/oo] 0 5 10 15 20 25 30 35
DEPTH [m]
0 50 100 150 200 250 300 350
TEMPERATURE
SALINITY
SIGMA-T 16 17 18 19 20 21 22 23 24 25 26
DEPTH [m]
0 50 100 150 200 250 300 350
SIGMA-T

APPENDIX C - CRITIQUE OF DYE RELEASE EXPERIMENTS

Subsequent to the primary study of the deep-water flow and exchange processes in Alice Arm, the dye experiments of June, 1974 (Goddard, 1975) were examined in more detail. The fact that a dye tracer released off Lime Creek at a depth of 30 m was reportedly observed at the surface twelve hours later (Goddard, 1975) has serious implications for the disposal of the mine tailings near this location. The following is an assessment of the scientific techniques used in the dye experiments. Since it was the experiment of 29-30 June, 1974, that indicated upwelling from a depth of 30 m, only the analysis of that experiment will be reported in detail.

As reported by Goddard (1975), a mixture of 1 gal. rhodamine WT dye, 0.4 gal. methanol, and 85 gal. of seawater pumped up from a depth of 30 m (100 ft.) was prepared and pumped back down to a depth of 30 m (100 ft.) at the same location off Lime Creek at 2030 on 29 June, 1974. Goddard reported that dye was detected in the surface waters at all but one of thirteen sites near the head of the Arm (both up- and down-inlet from Lime Creek) which were sampled the next day on 30 June between 0930 and 1340.

Assuming a density of 1150 kg m^{-3} for the rhodamine WT dye (Littlepage, 1980) and 810 kg m^{-3} for the methanol (CRC Press, 1980), a mixture of the two in the stated ratio would lead to a density of 1053 kg m^{-3}. This density is greater than that of seawater of normal salinity, and certainly greater than all densities observed in Alice Arm. Hence dilution with ambient seawater would reduce the density difference between the dye solution and the receiving waters, but the density of the dye mixture would continue to be greater than the receiving waters.

The density of the seawater used to dilute the dye mixture was not observed, nor were any temperature-salinity observations made on the day of the dye release. A series of hydrocasts at stations along the axis of Alice Arm on 26 and 27 June, 1974 (Goddard, 1974) recorded densities at a 30 m depth of 1022.1 to 1022.5 kg m^{-3}. The 30 m depth was near the bottom of a sharp pycnocline, with densities less than 1017 kg m^{-3} at the surface.

Internal waves may have altered the depth of the pycnocline, but it is not likely that the densities and density profiles changed significantly during the following three days, and hence the observations are a good estimate of the conditions during the dye experiment. Therefore, even if the seawater used in the dilution had been pumped from a shallower depth than the release depth of 30 m, the density stratification would have caused the dye to reach an equilibrium depth near the depth from which the water had been pumped. Such an error could reasonably be assumed in the order of a few metres, but could not account for the presence of dye on the surface of the Arm.

The density of the dye mixture may have been reduced as a result of heating during the mixing process at the surface. The decrease in density from this source would have been minor, and again could not account for the presence of dye above the pycnocline at the surface. Therefore, it must be assumed that unless the experiment deviated markedly from the reported account, the density of the dye mixture closely approximated the ambient density at the release depth, and hence the dye did not rise to the surface as a result of buoyancy forces.

The use of rhodamine dyes as tracers in the marine environment is common practice, and the technique is well documented (Carpenter, 1960; Pritchard and Carpenter, 1960; Feuerstein and Selleck, 1963; Krauel, 1972). Rhodamine dye is a fluorescent material with an absorption spectrum which peaks at 550 nm (1 nm = 10^{-9}m) and an emission spectrum which peaks at 575 nm. The dye can be strongly excited to fluorescence by the 546 nm green line of mercury. Goddard (1975) reports that the light source used in the Turner Model III fluorometer was the far ultraviolet GE-T4T bulb, which has its major emission wavelength at 254 nm and useful output at 297, 313, 405, 436, and 546 nm mercury lines. The lamp is not a continuous spectrum light source, but emits useful energy at the stated mercury lines, and is recommended for rhodamine dye detection (Turner Associates, 1972). Goddard reports that the primary filter inserted between the light source and the sample was a narrow band-pass type, with peak transmission at 546 nm, which essentially isolates the green line of mercury from the light source, and hence the sample was irradiated by the exciting mercury line only. The secondary filter inserted between the sample and the detector was also a narrow band-pass type, with peak transmission at 590 nm. Although there is overlap in the transmission bands of these two filters between 555 and 570 nm, the transmission is minor and the overlap is not coincident with the 546 nm mercury line. Therefore, no wavelengths from the source lamp should have been transmitted through both filters to the detector. However, if impurities in the source lamp introduced emission at wavelengths between 555 and 570 nm, suspended material in the sample may have reflected this light into the detector to be recorded as apparent low-level fluorescence. Naturally-occurring materials in turbid waters normally fluoresce at wavelengths longer than rhodamine dye (Carpenter, 1960; Krauel, 1972). It is not known what the emission spectrum of the glacial flour in Alice Arm was at the time of the dye studies. No vertical profiles of background fluorescence were made prior to the release of dye, so it is not known if the suspended material in Alice Arm was excited by the 546 nm mercury line or if it fluoresced at wavelengths that would be passed by the secondary filter.

The fluorescence of rhodamine dye is temperature dependent and decreases 2.3 to 2.9 percent per degree Celsius increase in temperature (Pritchard and Carpenter, 1960; Feuerstein and Selleck, 1963; Krauel, 1972). Although a vertical temperature gradient of approximately 4°C existed in the surface 30-m layer, no simultaneous temperature observations were made with the fluorescence observations. However, the warmer waters at the surface would have reduced the fluorescence, and hence the temperature effect could not have been the source of the fluorescence peaks observed at the surface.

If the experiment had been performed under more scientifically controlled conditions, the results would have been more conclusive. Proper efforts were made to create a neutrally buoyant dye source, but the observational techniques did not follow those recommended in the literature previously cited. A more complete survey of background fluorescence should have been undertaken prior to the release of dye. The problems associated with dye studies in turbid waters are well-documented, yet no efforts were made to assess the effects of the high concentrations and large gradients of glacial flour in Alice Arm. The temperature effect is also well-reported, but no temperature observations were made. The dye samples were pumped through a long hose, which introduced a delay in the order of three minutes and tended to smear the dye peaks so that the maximum fluorescence was reduced. There is evidence that the pumping rate varied with time, but very few quantitative measures of the lag were recorded. Under such circumstances, it would have been better to have lowered the hose intake in a series of steps, rather than continuously at the rapid rate of 15 to 25 m/minute.

In summary, because of the many unknowns, it cannot be definitely determined whether or not rhodamine dye was observed at the surface on 30 June, 1974, twelve hours after dye was released at a depth of 30 m off Lime Creek in Alice Arm. The 3 to 5 fluorometer unit peaks observed on the surface were not major peaks, and may not have been above background variability. Littlepage (private communication) has recently simulated such "peaks" in the laboratory, using turbid waters. But since this was done under dissimilar conditions, it cannot be used to explain the Alice Arm observations. Krauel (1972) found that different source lamps or the same lamp at different times produced different results.

Therefore, in conclusion, it is suggested that additional dye studies be undertaken, but that more scientifically acceptable techniques be employed. Or, to quote from page 6-5 of the report:

> Now that tailings are being injected into the Arm, transmittance observations of the plume will be simpler to execute than dye injections at depth. The trajectory of the tailings plume should be observed monthly to determine if plume rise or upwelling is a problem.

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