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DEPARTMENT OF ENERGY

TRANSPORT AND TRANSFER RATES IN THE WATERS OF THE CONTINENTAL SHELF

MASTER

Annual Report

August 1979

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APPENDIX The Appendices, while part of this Annual Report, are bound separately from the report and only a limited quantity have been made. Requests for copies of any of the individual appendices should be made directly to the authors or to the Principal Investigator.

1. Malone, T.C. and M.B. Chervin, The production and fate of phytoplankton size fractions in the plume of the Hudson River, New York Bight. Limnol. Oceanogr. 24 (1979), 683-696.

2. Li, Y.-H., H.W. Feely and P.H. Santschi, ^{228}Th-^{228}Ra radioactive disequilibrium in the New York Bight and its implications for coastal pollution. EPSL 42 (1979) 13-26.

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5. Santschi, P.H., D. Adler, M. Amdurer, Y.-H. Li and J. Bell. Thorium isotopes as analogues for particle reactive pollutants in coastal environments. Submitted to EPSL.

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7. Biscaye, P.E., S.R. Carson and G. Mathieu. Excess radon in shelf and slope waters of the New York Bight (abbreviated abstract) DOE workshop on "processes determining the input, behavior and fate of radionuclides and trace lements in continental shelf environments" 7-9 March 1979.

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ABSTRACT

Since the last Annual Report we have analyzed samples and data from previous cruises with a view to understanding those biological, chemical and physical processes which affect energy-related pollutants in the marine environment of the continental margin. We have carried out two cruises designed to expand our sample base, measure the time variability of several transfer processes, and to test specific hypotheses on the mechanisms for processes which effect exchange of continental margin with open ocean waters.

We have made progress in understanding the relative roles of nutrients and light in controlling the productivity of important primary biomass (and hence, particle) producers.

We have made progress in understanding the influences of phytoplankton populations on distribution of inorganic nutrients, dissolved oxygen and particulate organic matter. In addition, preliminary results from field work during 1979 support the hypothesis that most diatom production on the shelf sinks to the bottom where it enters benthic food chains or provides seed populations for subsequent blooms.

By studying radionuclides in water column and in sediments we have obtained the following important conclusions:

1) Using the natural radionuclides pairs ^{234}Th-^{238}U, and ^{228}Th-^{228}Ra, we have been able to show definitely that the removal mechanisms of thorium isotopes from the coastal waters is mainly through the uptake by resuspended sediment particles (Appendices 4 and 5). Therefore, the higher the sediment resuspension rate near shore, the faster the removal rate of thorium isotopes (Appendix 2).

2) From the radionuclide spike experiments performed in the microcosms simulating Narragansett Bay (Appendix 5) and from the monitoring of Th isotopes removal rates both in the microcosms and the Bay (Appendix 3), we conclude that thorium isotopes are good proxy for the other particle reactive elements like Fe, Cr, Pb, Po, Hg, ^{241}Am (and probably Pu) with regard to their removal behavior in coastal waters.

3) The distribution coefficients of minor alkaline and alkaline earth elements (Cs, Rb, Sr, Ba, Ra) decrease one to two orders of magnitude from a fresh water to sea water medium (Appendix 6). Therefore, if a reactor releases these elements in radioactive forms into rivers, they will be adsorbed by the river-borne suspended sediments first, but a significant fraction will be desorbed again in any estuarine environments.

4) In coastal environment, $^{239,240}Pu$ can be easily re-introduced back to water column as a fine colloidal particle (<0.45μm) by the re-suspension processes of bottom sediments (section 2.3).

Major progress has been made on the analysis of hydrographic data from all previous cruises and to evolve a comprehensive picture of the stratification of the waters of the New York Bight. The relation between our seasonal data set and the historical data has been evaluated with particular emphasis on features large enough to be distinguished in historical serial bottle casts such as the cold pool. Our STD and CTD data sets permit distinction of small scale features and, from these data, hypotheses have been evolved (and, to some degree, tested) concerning the importance to the replenishment of shelf water by processes of isopycnal mixing across the shelf/slope front. Isopycnal mixing also appears to play some role in the mixing of properties across the seasonal thermocline on the shelf.

Of particular significance is the salinity maximum which develops in the upper part of the seasonal pycnocline. The removal rate of this pycnocline S-max is determined to be about one month. This would provide enough salt to convert the observed river input into "average" shelf water salinity.

In the lower part of the seasonal pycnocline an oxygen maximum develops, presumably induced by a chlorophyll maximum. The O_2-max is used to determine an upper limit to K_z (vertical mixing coefficient), of about 0.2 cm^2/sec.

The CO_2-H_2O equilibration system required for the preparation of samples for oxygen isotope analysis has been completed and runs of laboratory standard samples indicates that we will be capable of an order of magnitude better precision than heretofore. Analysis of a limited sample set for tritium suggests that it will be an extremely useful tracer of water mass origins because of variability of input waters as a function of latitude. We have therefore collected a set of samples over a much broader latitude range to exploit this.

Work has continued in the use of radon as a tracer of small scale water motions and mixing in the definition of the source function needed for modelling the data, in actual modelling of the data, and in defining the range of variability of the radon distributions.

The major advance in the use of radon as a tracer came with this summer's field program in which we found that the anomalous low-radon zone in the near bottom waters of the slope and rise extends as far south as Cape Hatteras. This therefore, appears to be an extensive feature emphasizing its importance in indicating a mechanism whereby water (and associated pollutants) may be mixed away from the continental margin into the oceanic interior. On this cruise we also obtained a synoptic data set for the evaluation of shelf/slope water exchange as well as data and samples for primary productivity, zooplankton distributions and samples of water, sediment, suspended particles and fecal material for analysis of natural and man-made radionuclides.

1.0 INTRODUCTION

1.1 Objectives

The long term goal of our work on the continental shelf and particularly in the New York Bight is to understand and to quantify the processes that govern the transport and dispersal of energy-related pollutants introduced to those waters by man's activities. To this end we have, since the inception of our shelf program, attempted to integrate the efforts of the Lamont Geochemistry and Physical Oceanography groups and have, more recently incorporated Biological Oceanography into the program. Each of these disciplines brings to the program a data set to be integrated with and to complement the others, as well as an ability to focus on one or more of the processes affecting the fate of pollutants more effectively than the other disciplines. It is therefore useful to briefly summarize the processes affecting the introduction and fate of energy-related pollutants, and to indicate both those processes, to the understanding of which we can make a contribution by one or more techniques, as well as those for which we at present have no applicable analytical technique in any of the disciplines.

Figure 1.0/1 is a schematic cross section of the Bight from the Hudson River to the middle of the continental slope. In the lower left corner is a plan view of the New York Bight as defined by the shoreline and by the 50 and 200 m isobaths. A number of production, removal, mixing and regeneration processes are schematically portrayed primarily by arrows which are numbered. In Table 1.0-1 are listed the processes represented and a brief identification of observational and analytical techniques available to the Lamont Geochemical, Biological and Physical groups which will aid in understanding how polllutants are dispersed through and removed from the New York Bight.

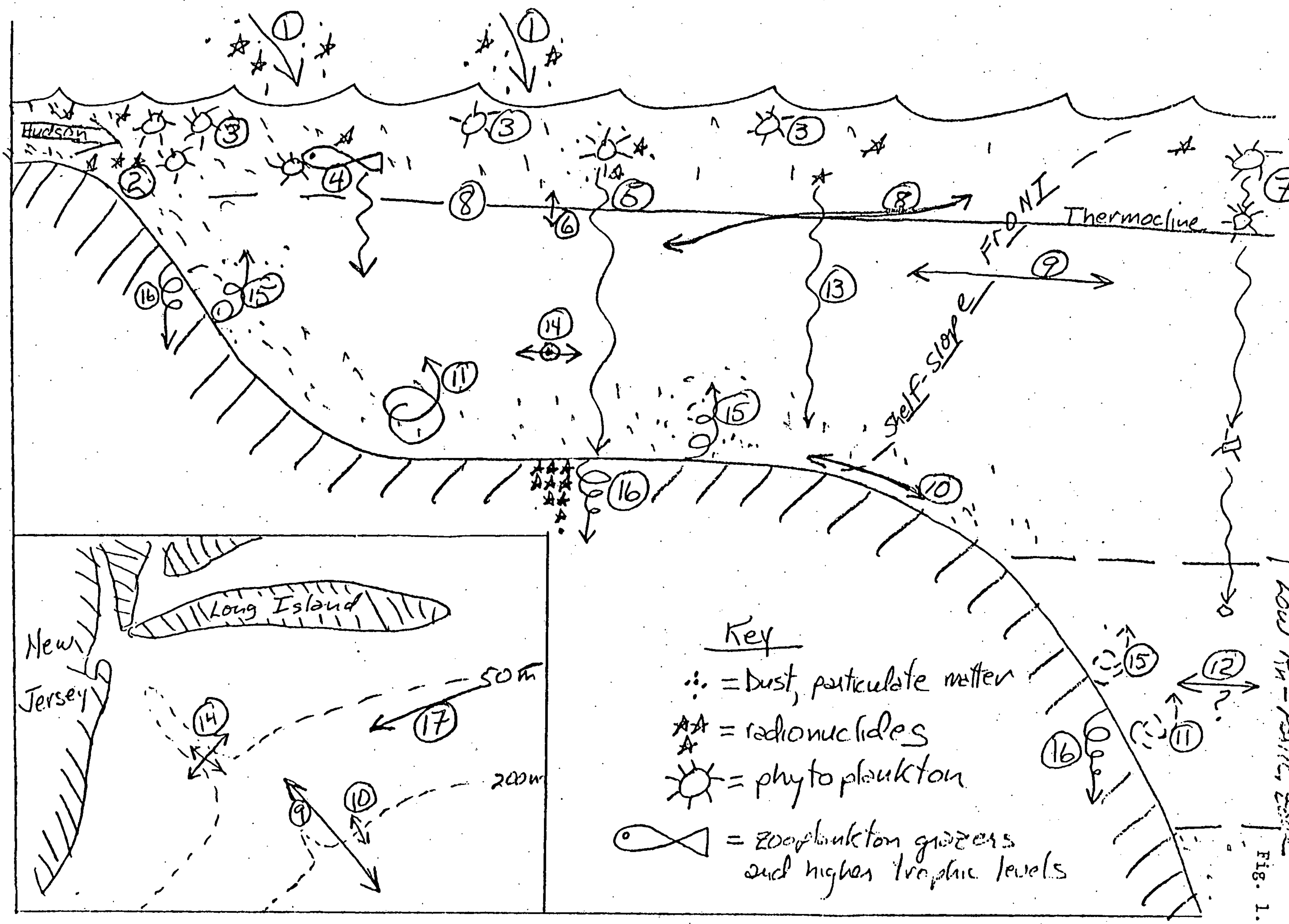
Hudson
Thermocline
FRONT
shelf-slope
Long Island
New Jersey
50m
200m
Key
= Dust, particulate matter
= radionuclides
= phytoplankton
= zooplankton grazers and higher trophic levels

Fig. 1.0-1

Table 1.0-1

No.	Process	Observational or Analytical Techniques
1	Atmospheric infall of dust and radionuclides.	Literature
2	Input of radionuclides and nutrients from the Hudson River & Barnegat Bay.	Work of Simpson, et al., at Lamont; nutrient chemistry, α, β, γ-counting.
3	Phytoplankton production and biomass.	Fluorescence (chlorophyll a), C-14 techniques for productivity.
4	Grazing & fecal pellets	Zooplankton tows and microscopic analysis.
5	Transport of radionuclides from surface waters on sinking particulates.	^{234}Th, ^{228}Th, ^{210}Po, $^{239,240}Pu$ in the water column.
6	Vertical mixing across the thermocline.	Rn^{222}, oxygen and nutrient budgets.
7	Decomposition of sinking dead phytoplankton & resultant nutrient regeneration (or cycling).	Nutrient chemistry including O_2 analysis; Microscopic examination of filtered particulate matter.
8	Isopycnal mixing through the thermocline.	Hydrography
9	Cross front exchange.	Hydrography, ^3H
10	Benthic layer exchange (Slope water instrusions)	Hydrography, ^3H
11	Near Bottom Vertical Mixing	Rn^{222}
12	Mixing regime on slope producing low Rn zone (possibility of rapid horizontal or isopycnal mixing.)	Rn^{222}, Ra^{228}, ^3H
13	Fluxes of particles & radionuclides to the sediments.	Sediment Traps on Slope; sedimentation rate determination by Pb^{210} integrated total Cs^{137}, $Pu^{239,240}$ activities in the sediment column.
14	Horizontal mixing or eddy diffusion cross shelf & long shelf.	Rn^{222}

No.	Process	Observational or Analytical Technique
15	Particulate resuspension & chemical regeneration	Suspended particulate measurements ^{228}Th, ^{228}Ra, ^{210}Pb, $^{239,240}Pu$ in water column.
16	Sediment mixing and accumulation.	^{234}Th, ^{210}Pb, ^{14}C, ^{137}Cs, $^{239,240}Pu$ profiles in sediment columns.
17	Long shelf advection	$^{18}O/^{16}O$, ^{3}H.

These arrows, representing processes, are referred to subsequently by these numbers.

Although the project must necessarily reflect some of the administrative and budgetary organization along classical disciplinary lines (geochemistry, physical-and biological-oceanography) conceptually the scientific approach to understanding the fate of energy-related pollutants in continental shelf waters is organized according to processes. This is reflected in the division of this report (as well as the renewal proposal) into three scientific sections deailing with; 1.0) Processes associated with Suspended Solids; 2.0) Processes Associated with Sediments; and 3.0) Spreading of Water Characteristics and Species in Solution (processes involving water and dissolved constituents). Within these sections there is a mixture of geochemical, biological and physical aspects to almost every proposed study. Nor can one ignore cross-disciplinary aspects of the major section with each other.

The work over the past contract year reported here represents increasing integration of the several disciplines in both the reduction and analysis of older data as well as in the design of the field efforts for obtaining new data and samples. We have, for example, added a capability in zooplankton studies in the person of Dr. Jean Stepien who worked with the geochemistry group in the design and implementation of the experiments on rates of zooplankton fecal production and removal of radionuclides to fecal material. We have also made a modest (and gratifyingly successful) beginning in the business of moored instruments and samplers in which the physical oceanographers and geochemists designed an experiment to gain several kinds of information related to understanding the origin of the low-radon zone along the continental slope and rise. These and aspects of our progress are reported briefly (with the exception of section 4.1.3 - "New York Bight Stratification) in this part of the report. The more detailed and definitive results are given in the several appendices which, although a formal part of the Report, are bound separately. These represent results of our work in the past year in the form of papers published, in press, submitted and, in retrospect as we should have done with the extensive report on New York Bight Stratification in section 4.1.3, in preparation.

In the following section we list those accomplishments of the past contract year which bear very specifically to DOE's mandate and goals in the marine environment and which may aid DOE project management in relating achievement to mandate.

1.2 Accomplishment of DOE Goals

The following statements and conclusions represent accomplishments during the past year toward our long-term goal of understanding by what processes and at what rates pollutants are dispersed and transported through and removed from the New York Bight. We believe these accomplishments are particularly pertinent to the mandate and goals of DOE in the marine environment.

- During much of the year the waters of the continental shelf are divided into two relatively well-mixed reservoirs which are separated vertically by strong gradients in physical, chemical and biological characteristics. The rate of a number of processes affecting the fate of pollutants within the reservoirs depend on the rate at which mixing occurs between the two reservoirs. From field data we have made estimates of this important mixing rate using three different approaches -- radioactive tracer (^{222}Rn), nutrient demand by phytoplankton and rate of oxygen production by phytoplankton.

- Two processes control the rate of removal of reactive pollutants from the water column -- adsorption on resuspended sediment particles and incorporation into living organisms and sinking of organic debris (dead organisms, fecal matter). We have found that different parts of the shelf and slope regime are characterized by varying rates and degrees of effectiveness of these processes. For example, in the near shore the former process is dominating.

- Measurements of plutonium on sediment cores and on suspended particulate material suggest that this very toxic element may not be removed from the system once it is accumulated in the sediments, but may be remobilized into the water column as colloidal particles. Evidence by coworkers at Lamont suggests that plutonium may even be transported back into the Hudson Estuary from the shelf.

- The microcosms experiments prove that thorium isotopes are good proxy for other reactive elements like Fe, Cr, Hg, Am, Po, Pb with regard to their removal behaviors.

- Measurements of radioactive tracers in sediment cores from a large area of fine-grained sediment on the shelf (the "mud hole") indicates that these sediments are a zone of net accumulation of reactive pollutants. However, because we always observe a plume of resuspended sediment being carried away from this area, it must also be an intermediate source of reactive pollutants. Similar measurements on sediment cores from the adjacent slope indicate that, although those sediments are a sink for reactive pollutants, slumping of sediments distorts the record making measurement of a steady-state rate of accumulation difficult.

- Water from the open ocean (slope water) which is relatively pollutant-free exchanges by mixing in a cross-shelf direction along isopycnal surfaces with shelf water on the time scale of about one month.

- From measurements of excess ^{222}Rn, we have determined that a zone of near-bottm water adjacent to the continental slope and rise, in which rapid mixing apparently takes place, extends from the Hudson Canyon as far south as Cape Hatteras. This zone is important because it represents a potential locus of dispersion of pollutants from the continental boundary out into the interior ocean.

2.0 PROCESSES ASSOCIATED WITH SUSPENDED SOLIDS

2.1 Introduction

Because of the close association of most reactive pollutant species with particulate matter it is extremely important to understand what processes produce and destroy or remove suspended solids from the system and to attempt to measure the rates at which these processes occur. Our approach has been to measure total suspended particulate matter and important components of it, e.g., particulate organic carbon and nitrogen, to study the primary and secondary planktonic generators of suspended solids, and to use natural and man-made radioactive tracers to measure the rates at which generation and removal rates occur. In addition, we have begun this year the use of sediment traps as collectors of suspended solids. Four traps were deployed on the mooring in the low radon zone in June and recovered in August so results are not yet available to report. We are aware of the controversy that currently surrounds the use of sediment traps to measure vertical fluxes of particulate material. We feel, however, that there are oceanic regimes in which calculated fluxes are reasonable approximations of actual particulate fluxes and that in these and perhaps other regimes, they represent one of the only cost effective means of obtaining sufficiently large samples of suspended particles on which to make radionuclide measurements. The following sections deal with the biological and then the radionuclide measurements on particulate matter.

2.2 THE PRODUCTION AND FATE OF PHYTOPLANKTON BIOMASS

Introduction

Phytoplankton productivity is the major source of particulate organic matter in the New York Bight. As such, evaluation of the processes that influence the production and fate of phytoplankton biomass is critical to the understanding of particulate fluxes and associated transport of pollutants. Phytoplankton influence time- and space-dependent distributions of particulate matter through growth (#3 in figure 1.0/1) sinking (#5 and #7), resuspension (#15), fecal pellet production (#4) and vertical migrations.

Previous research (1977 and 1978 Annual Reports: Walsh et al., 1978; Malone and Chervin, 1979) has shown that phytoplankton biomass is often an important component of total suspended solids, particularly during the late winter and spring in the plume of the Hudson River and along the outer shelf. During the summer when the seasonal thermocline is present, phytoplankton biomass is low and productivity is closely coupled with grazing and nutrient fluxes into the euphotic zone. This is reflected in the distribution of biomass with respect to major nutrient reservoirs. Thus, the chlorophyll a maximum found near the pycnocline during the summer across most of the shelf can be interpreted to indicate the importance of vertical nutrient fluxes from bottom waters. From previous research we have concluded that spatial variations in euphotic zone productivity are mainly caused by changes in biomass.

Nutrient supplies to the euphotic zone are dependent on regeneration rates within and physical processes that mix nutrients into the euphotic zone from nutrient pools associated with the benthos, estuaries and deep slope water (cf. Walsh et al., 1978). Our primary objective during the

August, 1978, cruise (CH78-BT) was to determine the influence of the summer pycnocline on the flux of nutrients from bottom water into the euphotic zone (#6 in fig.1.0/1) and to understand how the vertical distribution of phytoplankton biomass modifies this flux.

We planned to compare estimates of vertical eddy diffusion based on nutrient demand by phytoplankton and radon distributions. However, radon distributions below the pycnocline were too variable and calculations of eddy diffusivity were not possible (section 4.3). We will attempt another comparison from our June, 1979, cruise.

Methods

Stations were occupied from mid-shelf to the shelf-break from 13-19 August, 1978, (Fig.2.2/1). Phytoplankton productivity (^{14}C uptake, 24-hr sunlight incubations), chlorophyll a, and nutrient concentrations were measured in conjunction with radon and CTD profiling as previously described (1977, 1978 Annual Reports).

Apparent coefficients of eddy diffusion (K_z) for nitrate were calculated by the equation

$$K_z = F/(dN/dz)$$

where F = nitrate uptake ($\mu g\ cm^{-2}\ sec^{-1}$)

dN/dz = gradient of nitrate ($\mu g\ cm^{-4}$)

and K_z = $cm^2\ sec^{-1}$.

F was calculated from primary productivity integrated from the 1% light depth to the top of the nutricline. Carbon production was converted to nitrogen demand using a N:C ratio of 0.13 which is the mean ratio for particulate matter in the chlorophyll a maximum. F (and K_z) will be overestimated to the extent that phytoplankton were taking up ammonia rather than nitrate. However, ammonia concentrations were consistently less than 0.5 μg-at liter^{-1} and no vertical gradients were observed.

Results and Discussion

The 1% light depth was between 45 and 50 m (mean = 46 m) and vertical profiles of chlorophyll a specific productivity (PP_{Chl} = mg C [mg Chl·d]$^{-1}$) were similar at all stations (Fig.2.2/2).Surface inhibition was observed and PP_{Chl} was light saturated at light levels of 22% to 8% in the pycnocline. Calculations of F were based on PP_{Chl} between the 1% light depth and the 8% light depth.

Chlorophyll a concentrations were less than 0.5 μg liter^{-1} in the upper 20 m of the water column throughout the study area. Concentrations increased to a maximum of 1-10 μg liter^{-1} 35 to 45 m below the surface near the base of the pycnocline (Fig.2.2/3).The maximum was located above the 1% light depth in the upper reaches of a gradient in nitrate concentrations. This nutricline was always deeper than the pycnocline. An oxygen maximum was situated just above the chlorophyll a maximum.

Nitrate concentrations in the range of 1 to 4 μg-at liter^{-1} were typical of surface waters above the nutricline during 15-16 August when chlorophyll a concentrations in the maximum were about 1 μg liter^{-1} (Fig. 2.2/3). As the chlorophyll a content of the maximum began to increase the nitrate content of water above the nutricline decreased rapidly (Fig. 2.2/3 & 4).Since chlorophyll a concentrations and PP_{Chl} above the nutricline showed little or no increase, it is likely that the increase of chlorophyll a in the maximum reduced the flux of nitrate into the surface so that existing demand exceeded supply.

During most of the cruise vertical profiles of PP_{Chl} (Fig. 2.2/2 and dissolved oxygen indicated that the chlorophyll a maximum was produced and maintained by photosynthetic growth, increases in the chlorophyll a content of the maximum during the last day of the cruise, however, were often too rapid to have been a consequence of photosynthetic growth (Fig. 2.2/3). The chlorophyll a maximum was associated with the 25.5 isopycnal at all shelf stations (Fig. 2.2/5) which roughly coincided with the upper boundary of the cold pool. Given the cross-shelf distribution of isopycnals relative to depth across the shelf (Gordon, et al., 1976), the development of a chlorophyll a maximum in association with a particular isopycnal could reflect isopycnal mixing of nutrients from bottom water at shallow depths into the euphotic zone of deeper water columns or from high salinity shelf-break water.

Our conclusion is supported by calculations of eddy diffusivity (Table 2.2/1). K_z varied from 0.2 to 3.1 $cm^2\ sec^{-1}$ which is consistent with values calculated from measured uptake rates of nitrate (Eppley et al., in press; King and Devol, 1979). Vertical eddy diffusion coefficients calculated from radon distributions at the base of the thermocline during the May 1977 cruise in the New York Bight, however, were in the range of 0.05 - 0.5 $cm^2\ sec^{-1}$ (see Section 4.3.3), which indicates that the higher values of K_z reported here are most likely also related to horizontal processes.

K_z was independent of vertical stability ($E = [\Delta \text{sigma-t}/\Delta z] \times 10^3$) when less than 0.5 $cm^2 sec^{-1}$. Above 0.5 $cm^2 sec^{-1}$, K_z was a negative power function of E (Fig. 2.2/6). Our relationship appears to conform to that found by King and Devol (1979) in the eastern tropical Pacific. Combining their data with ours gives the following least square regression equation ($r = 0.95$, $P < 0.005$):

$$K_z = 330\ E^{-1.45}$$

Welander (1968) proposed two cases for the relationship between K_z and E.

When turbulence is caused by vertical shear, K_z is proportional to $E^{-0.5}$. When horizontal mixing processes are important, K_z is proportional to $E^{-1.0}$. The exponential constant derived from our data and those of King and Devol argue for horizontal mixing as being the dominant process, i.e., isopycnal mixing.

K_z less than 0.5 at low E correspond to F values of less than 25 while those greater than 0.5 correspond to values greater than 30 (Table 1). F would be underestimated if N:C or the chlorophyll a content of the maximum were underestimated. The latter is a distinct possibility since chlorophyll a profiles were based on samples from discrete depths and stations with low F were characterized by the small number of depths sampled or low chlorophyll a concentrations in the maximum. Thus, it is quite possible that the actual maximum was not sampled leading to an underestimate of chlorophyll a and F as a consequence. It is also possible that K_z was primarily a function of local vertical shear at these stations.

Conclusions

The distribution of phytoplankton biomass during the stratified summer regime is characterized by low surface concentrations with a chlorophyll a maximum associated with the pycnocline. Walsh et al. (1978) observed similar distributions of nitrate and concluded that storm events are required to transport sufficient nitrate across the pycnocline. Our results suggest that isopycnal mixing may provide an alternate mechanism for mixing nutrient rich water into the euphotic zone. In addition, as hypothesized by Anderson (1969), the development of such chlorophyll maxima has a regulatory effect on phytoplankton productivity in the surface layer by limiting the vertical flux of nutrients.

Figure Legends

Fig. 2.2/1. Station locations for 13-19 August, 1978 CH78-BT Cruise in New York Bight.

Fig. 2.2/2. Primary production per unit chlorophyll (PP_{Chl}, μg C $[Chl]^{-1}$ day^{-1}) with depth measured during CH78-BT Cruise, 13-19 August, 1978. ⊢⊣ Represent standard errors.

Fig. 2.2/3. Representative profiles showing the time course of variation in vertical profiles of sigma-t (——), Chl a (●—●, μg l^{-1}) and nitrate (▲---▲, μg-at l^{-1}) for two reoccupied areas 13-19 August, 1978 in New York Bight (West Stas: Aw, Bw, Ca, Dw; East Stas: Ae, Be, Ce, De) A ⟶ D represents increasing time. 1% - represents 1% light depth, Depth - meters.

Fig. 2.2/4 Relationship between integrated surface layer nitrate concentration ($[NO_3]_{SL}$, μg-at l^{-1}) and the concentration of Chl a in the maximum layer ([Chl]max, μg l^{-1}) for CH78-BT Cruise, N.Y. Bight, 13-19 August, 1978.

Fig. 2.2/5 Relationship between chlorophyll concentration relative to that of maximum layer ([Chl]/[Chl]max) and sigma-t during CH78-BT, 13-19 August, 1978. Note that the #15 in upper right corner indicates number of data points associated with the 1.0 [Chl]/[Chl]max value.

Fig. 2.2/6 The relationship between apparent coefficients of eddy diffusion (K_z, $cm^2 sec^{-1}$) and the stability of the water column associated with the nutricline (E, Δ sigma-t/Δ Z x 10^3). Values calculated for N.Y. Bight areas sampled during CH78-BT Cruise indicated as ● and ■. ■ values deleted from regression analysis. ⊙ indicate values calculated by King and Devol for tropical Pacific waters.

Fig. 1.

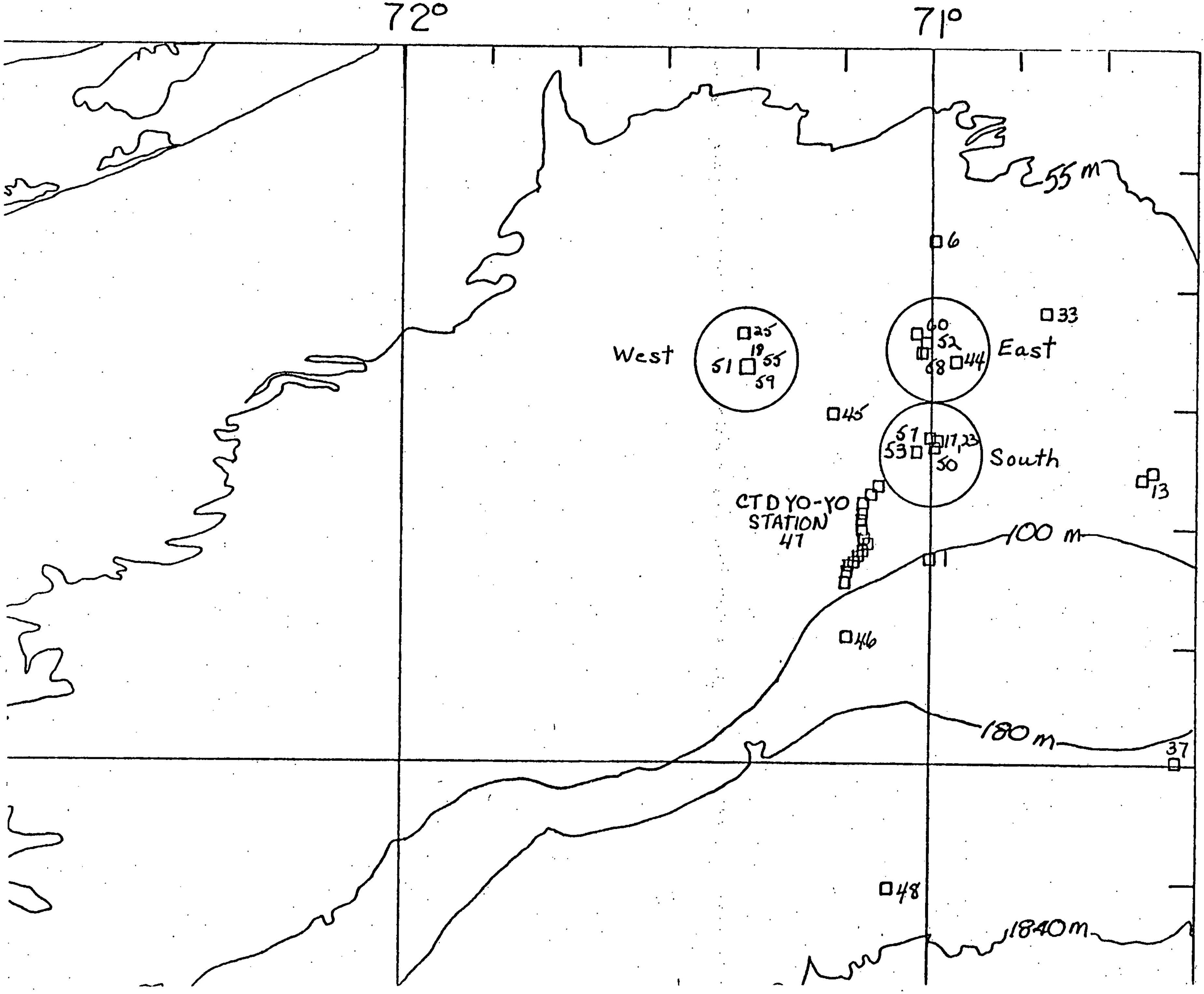

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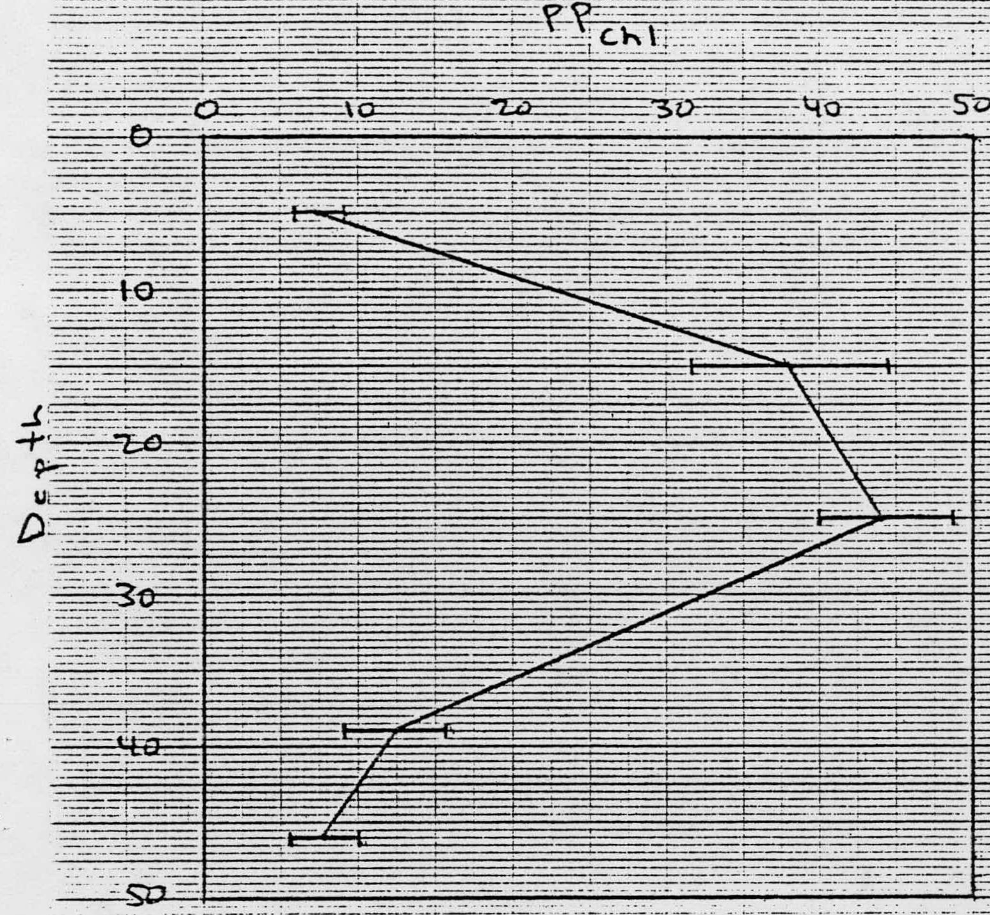
Fig 2.2/1

Fig. 2.2/2



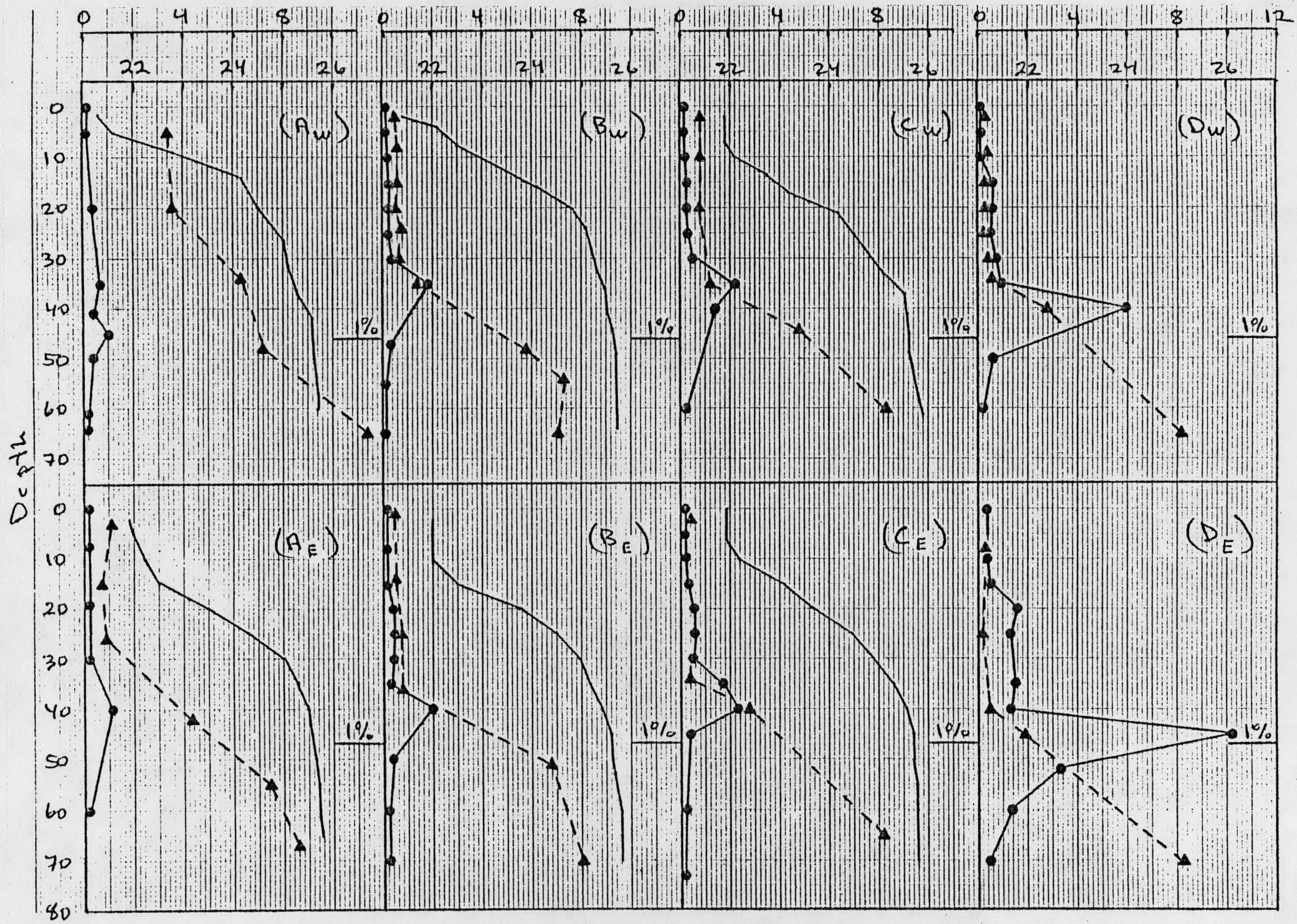

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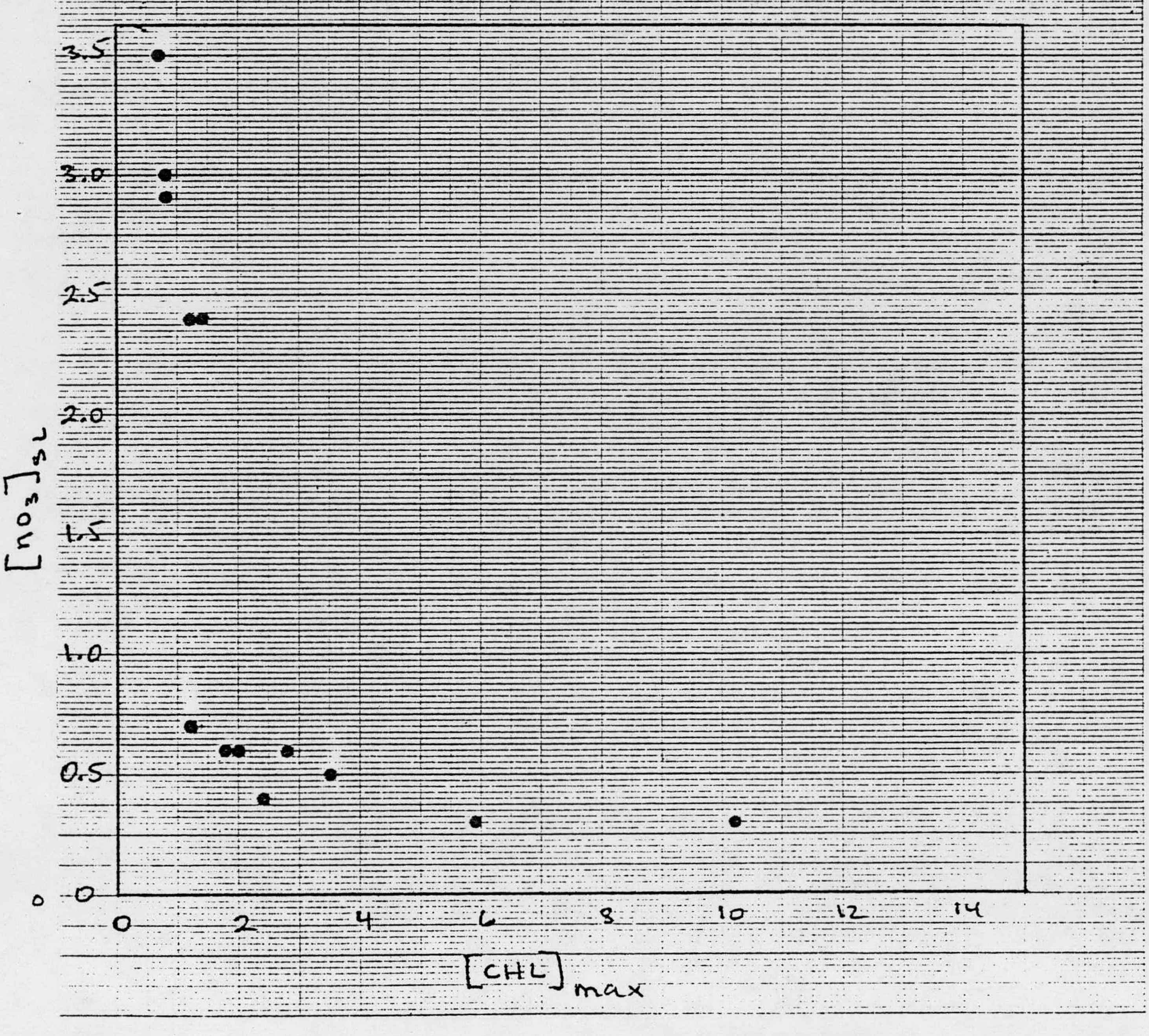
Fig. 22/4

CH78-BT

August 1978

Mid-shelf



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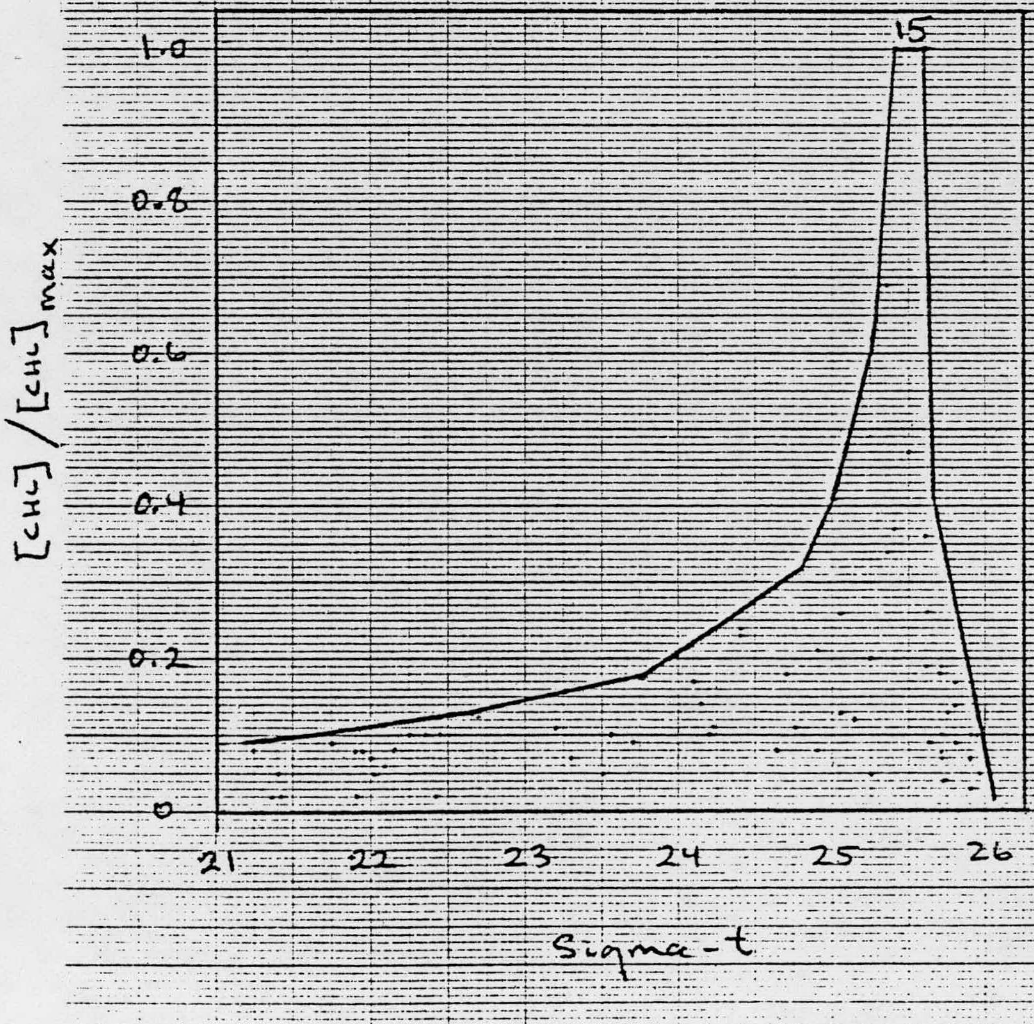
15
1.0
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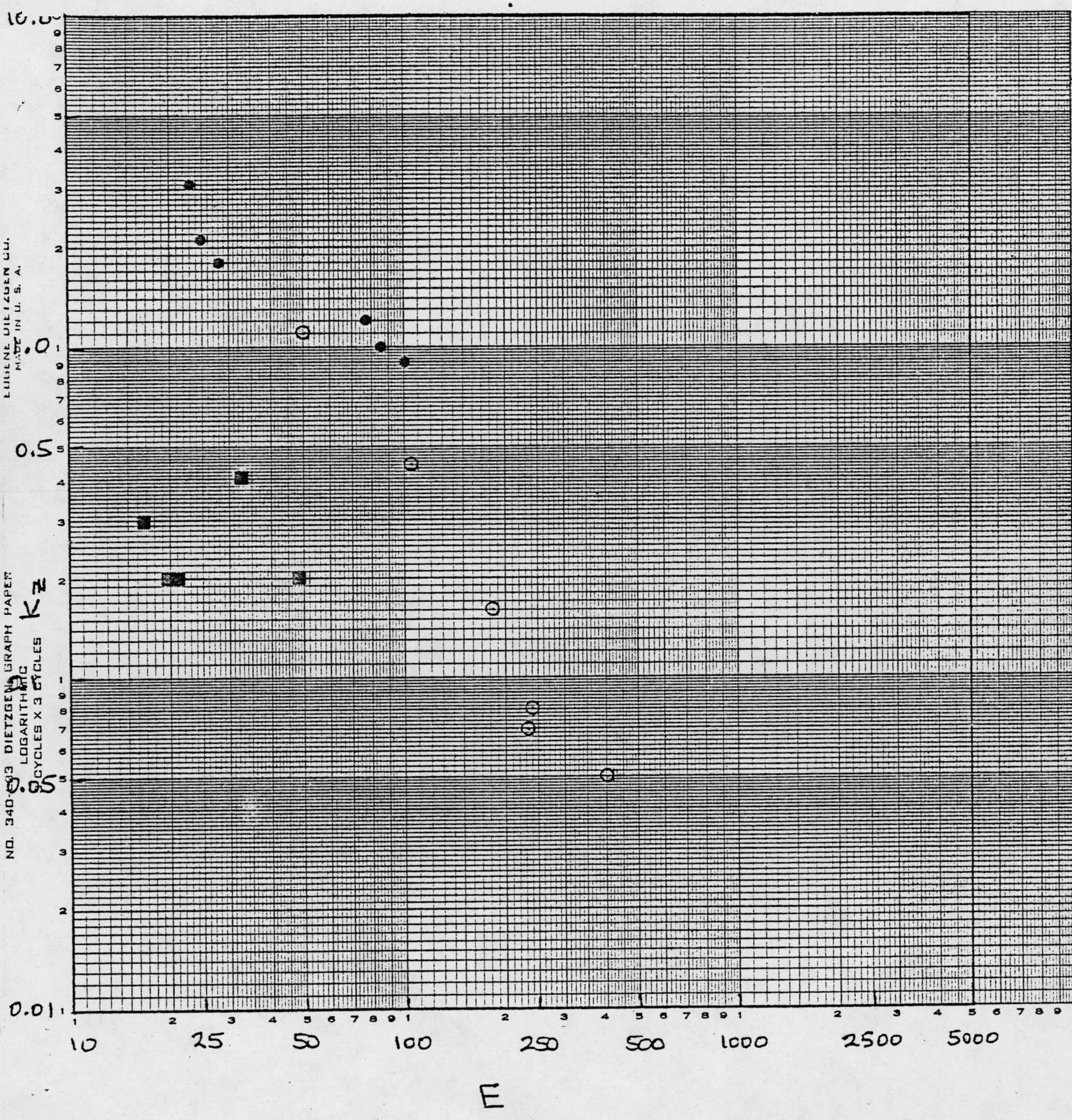
Sigma-t

Fig. 22/6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LOGARITHMIC
CYCLES X 3 CYCLES

Table 2.2/1. Apparent coefficients of eddy diffusion (K_z, cm^2 sec^{-1}) for nitrate calculated from nitrate flux (F, mg m^{-2} day^{-1}) and the nitrate gradient ($\Delta N/\Delta z$, mg m^{-4}), and stability (E, [Δ sigma-t/Δ z] x 10^3) of the water column associated with nutricline for stations occupied during CH-BT, 1978 Cruise in New York Bight.

Location		Sta.	F	$\Delta N/\Delta z$	K_z	E
Shelf	Water	13	3.24	.21	1.8	27.9
		33	2.96	.37	0.9	100.7
		47	1.88	1.27	0.2	21.0
	South	17	2.46	.92	0.3	16.6
		57	1.42	.93	0.2	19.9
	West	18	3.43	.32	1.2	-
		25	4.50	.25	2.1	77.2
		51	4.18	.23	2.1	24.6
		59	5.95	.67	1.0	85.2
	East	52	2.05	.55	0.4	33.2
		60	3.57	.40	1.0	-
Slope	Water	37	4.58	.17	3.1	22.9
		46	.46	.23	0.2	48.8
		48	1.24	.54	0.3	-

Literature Cited (Section 2.2)

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Welander, D. (1968) Theoretical forms for the vertical exchange coefficients in a stratified fluid with application to lakes and seas. Acta R. Soc. Sci. Litt. Gothob. Geophys. 1:1-26.

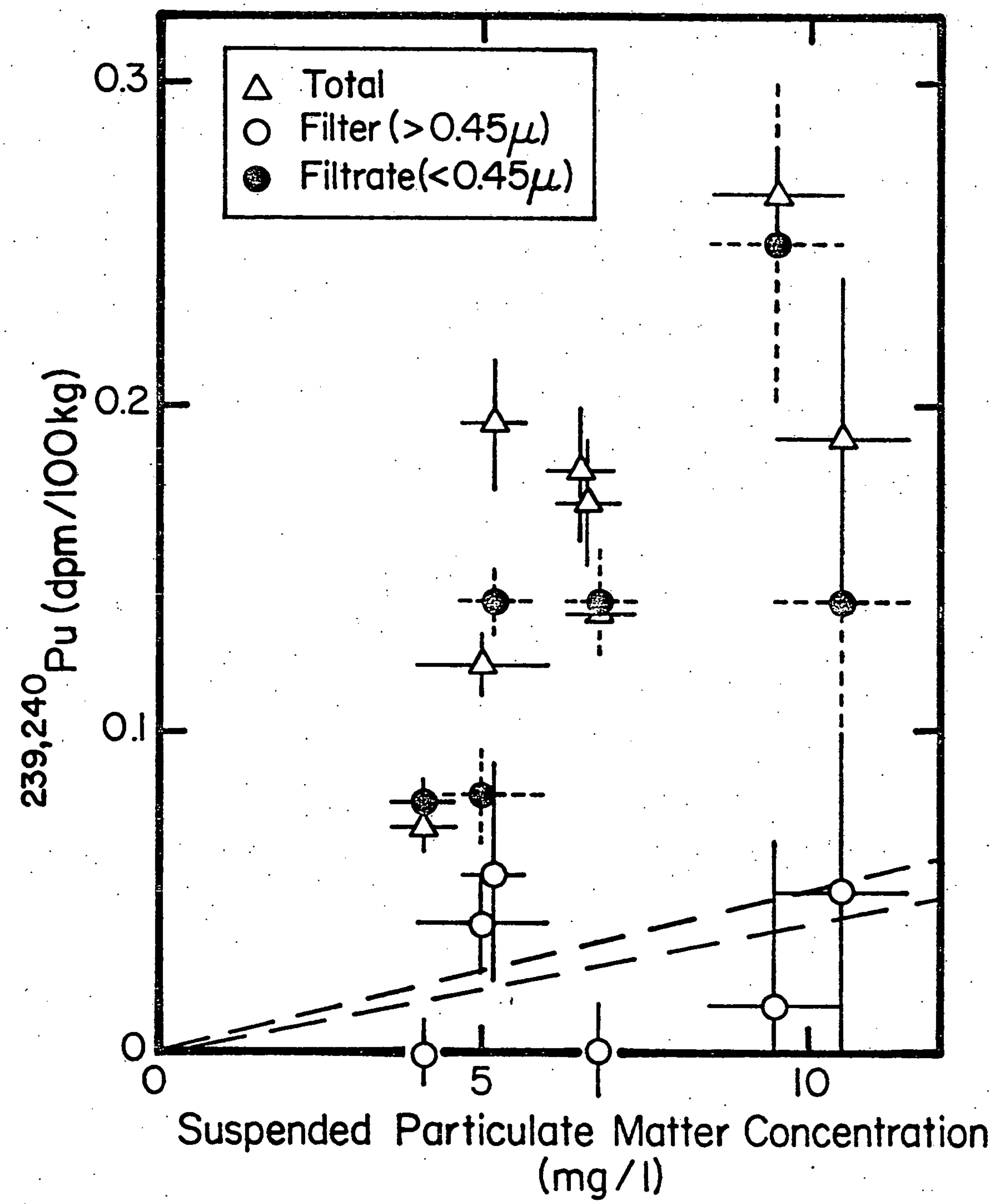
2.3 NATURAL AND MAN-MADE RADIONUCLIDES IN THE WATER COLUMN

Since our early work showed that the removal rate constants of ^{228}Th from the water column by settling particles increase from the slope water toward the inner shelf water (Appendix 2: ^{228}Th-^{228}Ra radioactive disequilibrium in the New York Bight and its implications for coastal pollution, EPSL 42 [1979] 13-26), we chose Narragansett Bay to study in detail the removal mechanisms of ^{228}Th and ^{234}Th from the near shore environment. The work done so far is summarized in Appendix 3: "Natural radionuclides in the water of Narragansett Bay" EPSL (in press). The main conclusion is that the removal rates of ^{228}Th and ^{234}Th from the water column of Narragansett Bay are governed mainly by the rate of sediment resuspension (Process #15, Fig. 1.0/1) with fast removal (Process #5, Fig. 1.0/1) at higher sediment resuspension rate (therefore at higher suspended particle concentrations). However, the total suspended particle concentrations in Narragansett Bay are usually an order of magnitude higher than in the waters of the New York Bight. Therefore, the relative importance of removal mechanisms by resuspended particles in the New York Bight is not yet certain as compared to other possible mechanisms, e.g., sinking of zooplankton fecal pellets (Process #4, Fig. 1.0/1). As proposed last year we attempted to collect fecal pellet samples and also measure the fecal pellet production rates during the RACACA cruise this year. With the data on concentrations of various radionuclides in the fecal pellets and on production rate of fecal pellets, we hoped to estimate the removal rate of various radionuclides by the sinking fecal pellets and compare it with the removal rate of ^{234}Th obtained from ^{234}Th/^{238}U ratio during the cruise. This would give us total vs. fecal pellet removal rates and permit a distinction between the relative importance of one vs. all mechanisms combined.

The quantities of zooplankton fecal pellets actually produced during the in vitro experiments on RACACA were disappointingly small. It is therefore questionable whether or not we will be able to adequately measure their ^{234}Th concentrations.

In Narragansett Bay, we also measured $^{239,240}Pu$ concentration in; 1) unfiltered water samples (total); 2) filtrate (<0.45μm; and 3) the filter (>0.45μm) calculated as the difference between tottal and filtrate). The results are plotted against the particulate matter concentration in Fig. 2.3/1. The dashed lines in the figure represent the expected concentration of plutonium on the filter, assuming that the particulate matter on the filter consists of non-size-fractionated resuspended surface sediments. The total plutonium concentration in the water column increases almost linearly with increase of suspended particulate matter concentration but is much higher than the expected value from resuspension of the Bay sediments alone. The interesting fact is that most of the plutonium in the water column is in the filtrate (passed through 0.45 μm pore size filter), probably in colloidal forms as suggested earlier by Rees et al. ("Dispersion of plutonium from contaminated pond sediments", Environ. Sci. Tech. 12, 1978, p. 1085-1087). The implication is that plutonium can be redispersed from sediments into the water column as discrete colloids or as hydrolytic species adsorbed onto colloidal sediment particles in the near shore environment. It is often assumed that, once removed to the sediments from the water column, reactive pollutants are largely out of the system (except for involvement with benthic organisms) and are mixed and buried downwards. Our data (as well as data by Olsen on sediments of the Hudson Estuary and Bowen at WHOI) suggest that this is not true and must be considered in the study of what happens to plutonium in the marine environment.

Fig 2.3/1



Total
Filter (>0.45μ)
Filtrate(<0.45μ)
0.3
0.2
0.1
0
^{239,240}Pu (dpm/100kg)
0
5
10
Suspended Particulate Matter Concentration
(mg/l)

Part of our ^{234}Th-^{238}U and ^{228}Th-^{228}Ra data from the CAPE HENLOPEN cruise, May 1977, are given in Appendix 4 ("Removal rates of ^{234}Th and ^{228}Th from waters of the New York Bight", preliminary draft). Our radiotracer experiments in microcosms simulating Narragansett Bay (supported separately by EPA and the Bay itself (supported in part by DOE) show that ^{228}Th, ^{210}Po, ^{210}Pb, ^{241}Am, Fe, Hg, Cr and Sn all behave very similarly with regard to their removal from the water column and to their physical form in the water column. A large fraction of these elements are associated with the suspended particles (see "The fate of trace metals in Narragansett Bay, Rhode Island , Radiotracer experiment in microcosms" by P.H. Santschi, Y.H. Li and S. Carson, accepted by Estuarine & Coastal Marine Science, and Appendix 5: "Thorium isotopes as analogues for particle-reactive pollutants in coastal environment", submitted to EPSL). Therefore, the removal rate constants of ^{234}Th and ^{228}Th obtained in the New York Bight may also be applied to the above-mentioned other elements.

As a continuation of our earlier work ("The flux of ^{226}Ra from estuarine and continental shelf sediments", EPSL 37, 1977, p. 237-241), we measured Ba concentration in the Hudson estuary waters and performed some additional desorption experiments of ^{226}Ra and Ba from the Hudson River sediments by mixing with sea water. The results are given in Appendix 6 ("Desorption of Ba and ^{226}Ra from the river-borne sediments in the Hudson estuary, EPSL, 1979). The major conclusions are: 1) the pronounced desorption of Ba and ^{226}Ra as well as other alkaline earth and alkaline elements like ^{90}Sr, Ca, ^{137}Cs, ^{134}Cs from river-borne sediments in estuaries can be explained quantitatively by the drastic decrease in the distribution coefficients of these elements from a fresh to a salty water medium, and 2) the desorption in estuaries can augment the total global river fluxes of dissolved Ba and ^{226}Ra by at least one and nine times, respectively.

3.0 PROCESSES ASSOCIATED WITH SEDIMENTS AS SINKS FOR RADIONUCLIDES AND OTHER POLLUTANTS

3.1 Introduction

Because many highly reactive pollutants are associated with suspended particulate matter (SPM) which will eventually settle or be carried to the bottom, what subsequently happens to this material must concern us since arrival at the bottom does not necessarily mean simple burial and removal from the system. To what extent does sediment get resuspended from the bottom (process 15, Fig. 1.0/1) versus getting mixed downward with older sediment by bioturbation (process 16, Fig. 1.0/1) and, perhaps, other processes? What are the rates of sediment mixing (bioturbation) and how do they vary with different geographic locations and sedimentation regimes? What are the areas adjacent to the continent where sediment and its assoicated pollutants is actively accumulating versus passing, in steady state, through sedimentation, resuspension and transport elsewhere?

We have begun approaching these questions with a theoretical study of sediment mixing as reported last year. Testing of models however, requires data from actual sediments and we obtained our first cores for analysis last year during the "Boue Trou" cruise. At that time we used two different borrowed box corers both to obtain cores and to test which corer we wanted to build or buy. Based on that cruise we have built a Soutar-type, two-spaded corer as modified by Turekian and his students. This particular design of the Soutar corer has not been used in a frame and, although largely successful in this mode in shallow water, is less successful in deep water as we learned during this year's RACACA cruise. We are therefore in the process of designing and building a frame in which the corer will be suspended, which will sit on the bottom and constitute a stable platform, and from which the corer will penetrate the sediment.

Results on sediment mixing from our first cores are given in the following section.

3.2 Results from "Boue Trou" Box Cores

Four box cores were collected from the continental shelf ("mud hole") and slope roughly along 71°W longitudinal line (Fig. 3.2/1) during the CAPE HENLOPEN cruise, August 1978. The cores were sectioned on shipboard and analyzed for several radionuclides from the U-Th decay series and for $^{239,240}Pu$, ^{238}Pu and ^{137}Cs. The preliminary results are plotted in Figures 3.2/2A to 3.2/2D.

At steady state, the depth profile of excess ^{234}Th (= $^{234}Th-^{238}U$) can be expressed by

$$C = C_o \exp\left(-z \cdot \sqrt{\lambda/D_m}\right) \qquad (1)$$

where C_o = concentration of $^{234}Th_{ex}$ at surface

z = depth

λ = decay constant

D_m = sediment mixing coefficient by bioturbation.

D_m values obtained from $^{234}Th_{ex}$ data of four cores (Table 3.2/1) show that the "mud hole" cores have very high bioturbation rate ($D_m = 0.12 \pm 0.02 \times 10^{-6}$ cm^2/sec), comparable to that in Long Island Sound (Turekian <u>et al.</u>, 1978). Even in the slope region, D_m is high (30 to 40 x 10^{-9} cm^2/sec) as compared to the Atlantic deep ocean cores (2 to 6 x 10^{-9} cm^2/sec) reported by Turekian <u>et al.</u>, (1978).

The $^{210}Pb_{ex}$ (= $^{210}Pb-^{226}Ra$) data can be interpreted by two extreme models: the first model assumes that there is continuous sediment accumulation but no sediment mixing below the bioturbated surface layer (about 2 to 7 cm thick here), i.e.,

$$C = C_o \exp\left(-z \cdot \lambda/S\right) \qquad (2)$$

where C_o = $^{210}Pb_{ex}$ concentration in the mixed surface layer

S = sedimentation rate (cm/yr)

The sedimentation rates obtained by this model are high in the "mud hole" cores (0.2-0.3 cm/yr) (Fig. 3.2/2A and 3.2/2B). In the cores raised from the slope, however, (Fig. 3.2/2C and 3.2/2D) S varies with depth. The $^{210}Pb_{ex}$ profile from HBC-3 (Fig. 3.2/2D) even gives a mid-depth maximum. Both facts strongly suggest frequent slumping of sediments in the slope area.

The second model assumes that there is no actual net accumulation of sediments and that sediment mixing by bioturbation operates below the surface mixed layer as well. Therefore, the ^{210}Pb profile below the surface mixed layer can also be expressed by equation (1) (assuming constant D_m with depth).

D's obtained by this $^{210}Pb_{ex}$ model at depth are smaller than D_m obtained by $^{234}Th_{ex}$ in the surface mixed layer in the "mud hole" cores but of the same order of magnitude. The deep penetration of $^{239,240}Pu$ in the "mud hole" cores (Fig. 3.2/2A and 3.2/2B) strongly favors the second model in the "mud hole" region. A D_m of 0.04 to 0.1 x 10^{-6} cm^2/sec can adequately fit the $^{239,240}Pu$ profiles. In reality one cannot exclude the possibility of finite sediment accumulation in the "mud hole" area. If there is finite sedimentation, then our D_m obtained by $^{210}Pb_{ex}$ is a maximum. The apparent sedimentation rates obtained from the first $^{210}Pb_{ex}$ model are maxima since ^{210}Pb can be mixed downward by bioturbation also. As soon as ^{137}Cs analysis is completed, we will model ^{137}Cs, $^{239,240}Pu$ and $^{210}Pb_{ex}$ data by assuming the proper input function of ^{137}Cs and $^{239,240}Pu$ and D_m as function of depth, using our numerical advection-diffusion-decay model. The results will provide us more quantitative answers as to the mobilities of ^{137}Cs and $^{239,240}Pu$ through the pore water in the sediments

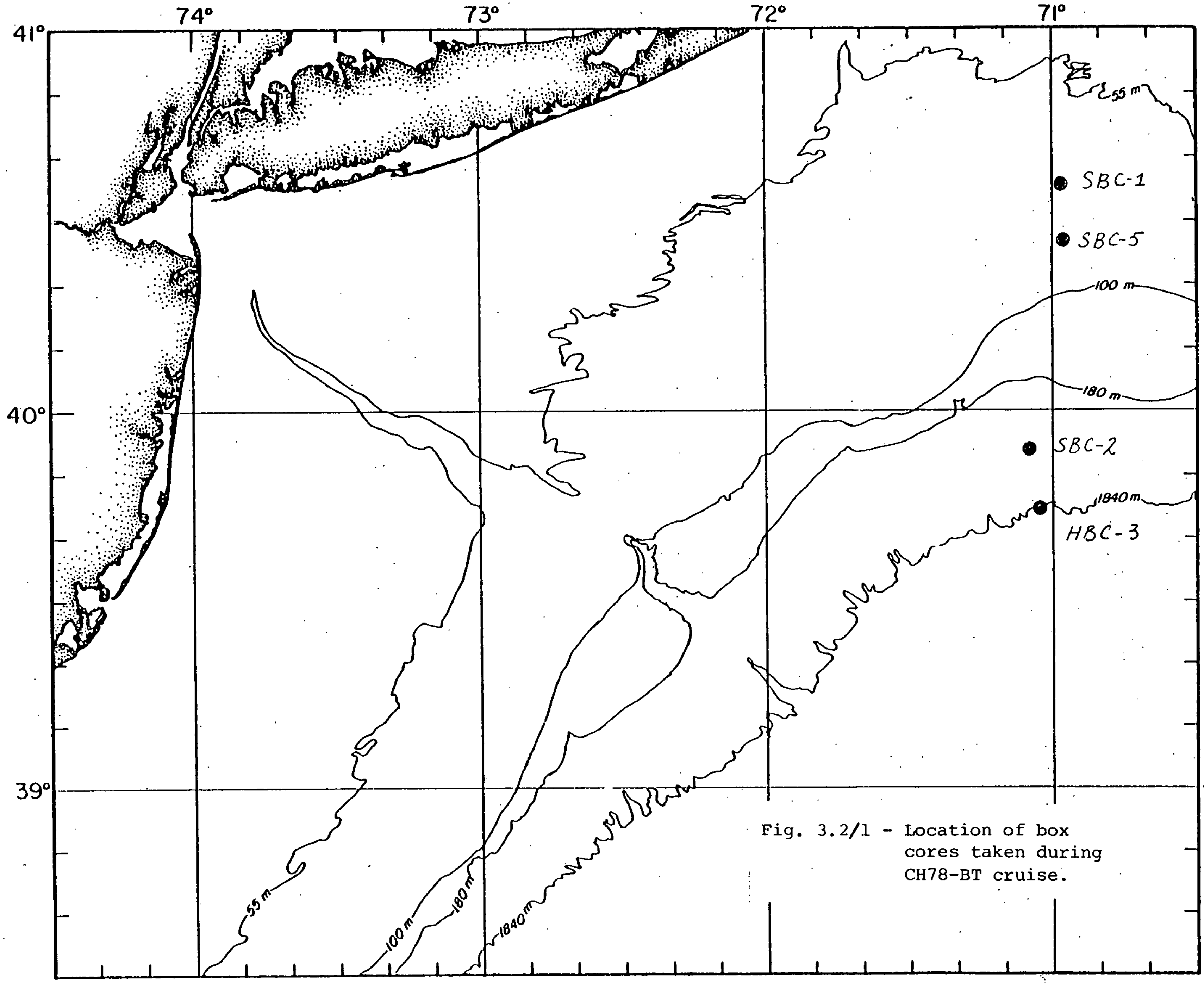


Fig. 3.2/1 - Location of box cores taken during CH78-BT cruise.

Fig. 3.2/1

Fig. 3.2/2 A

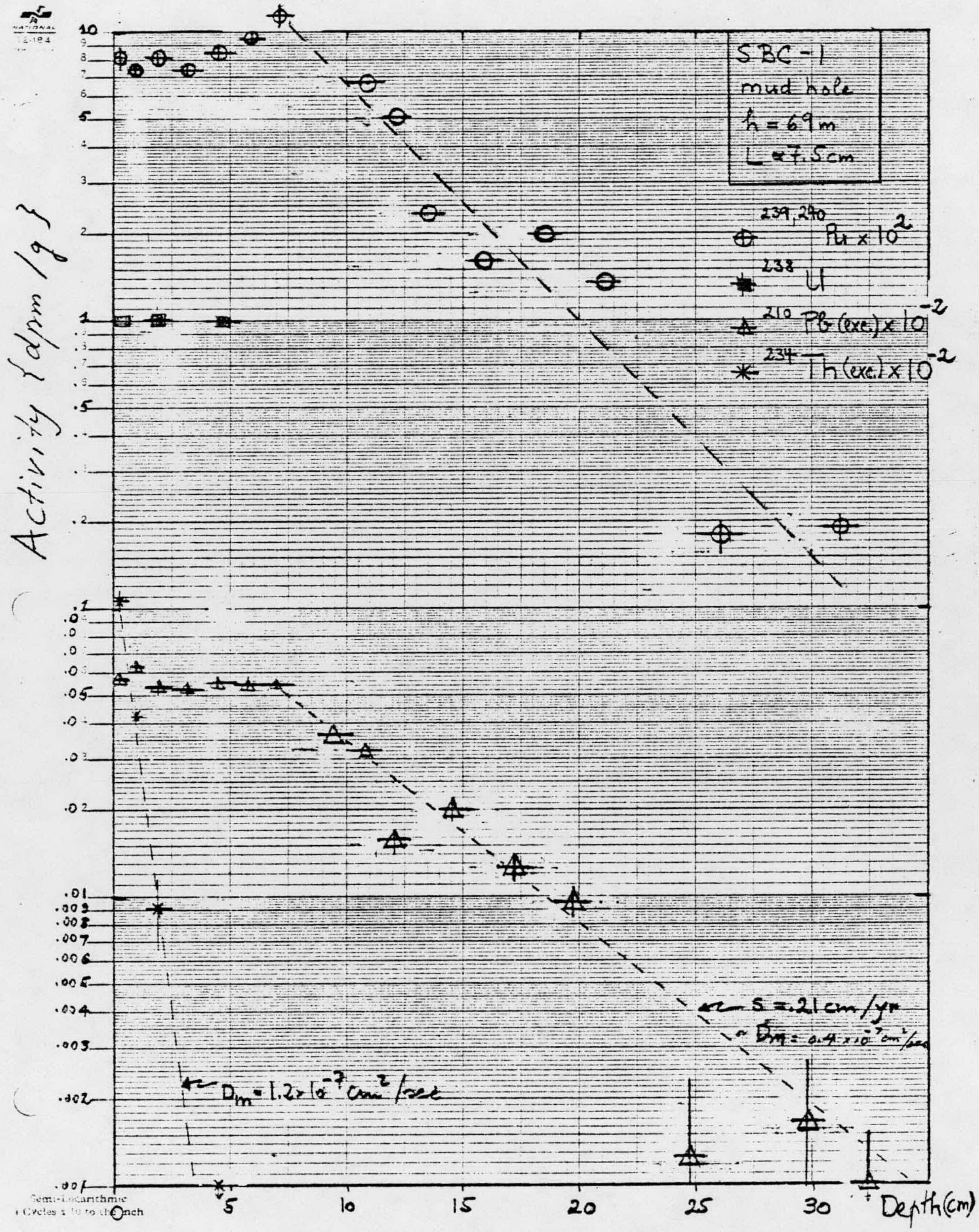
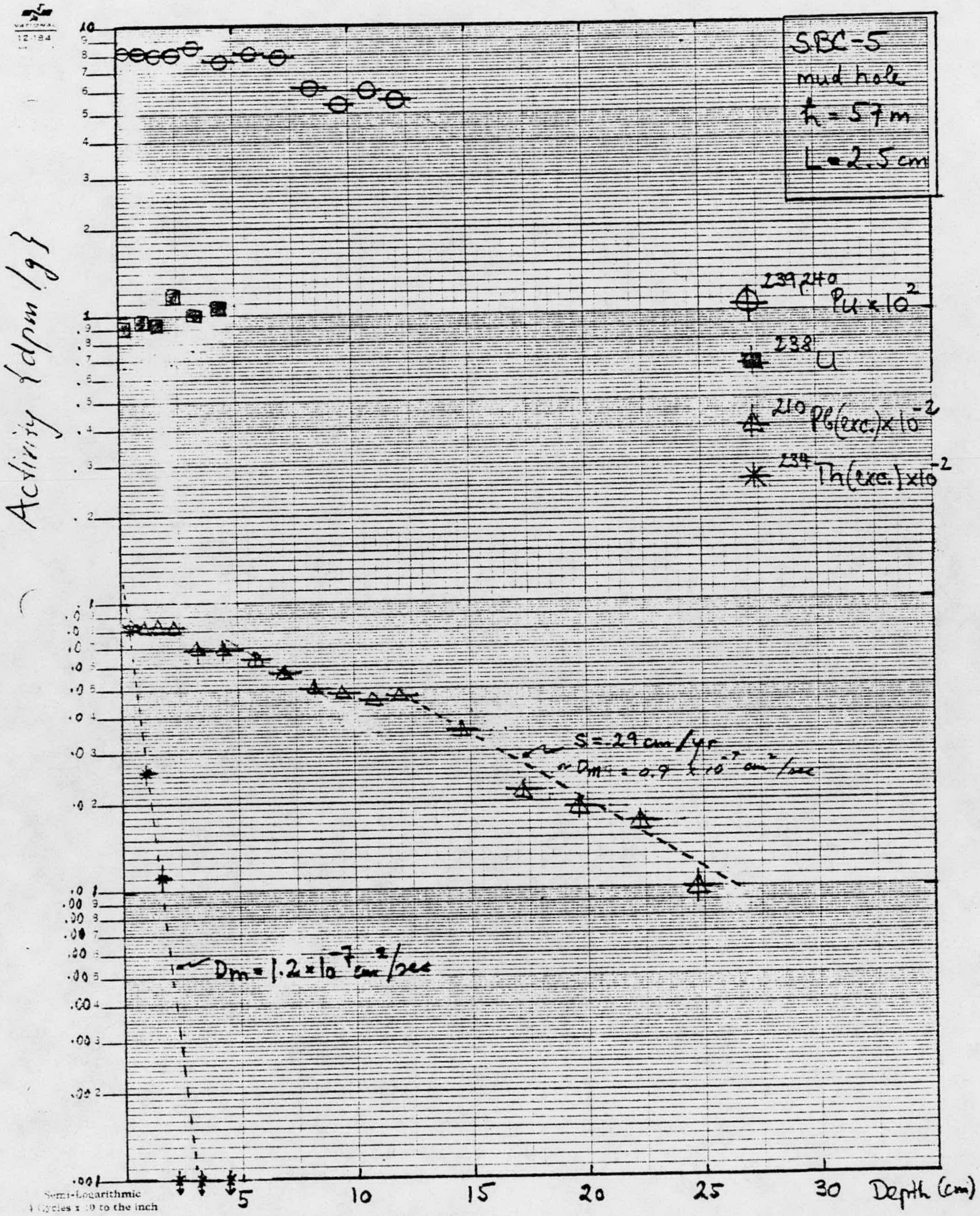
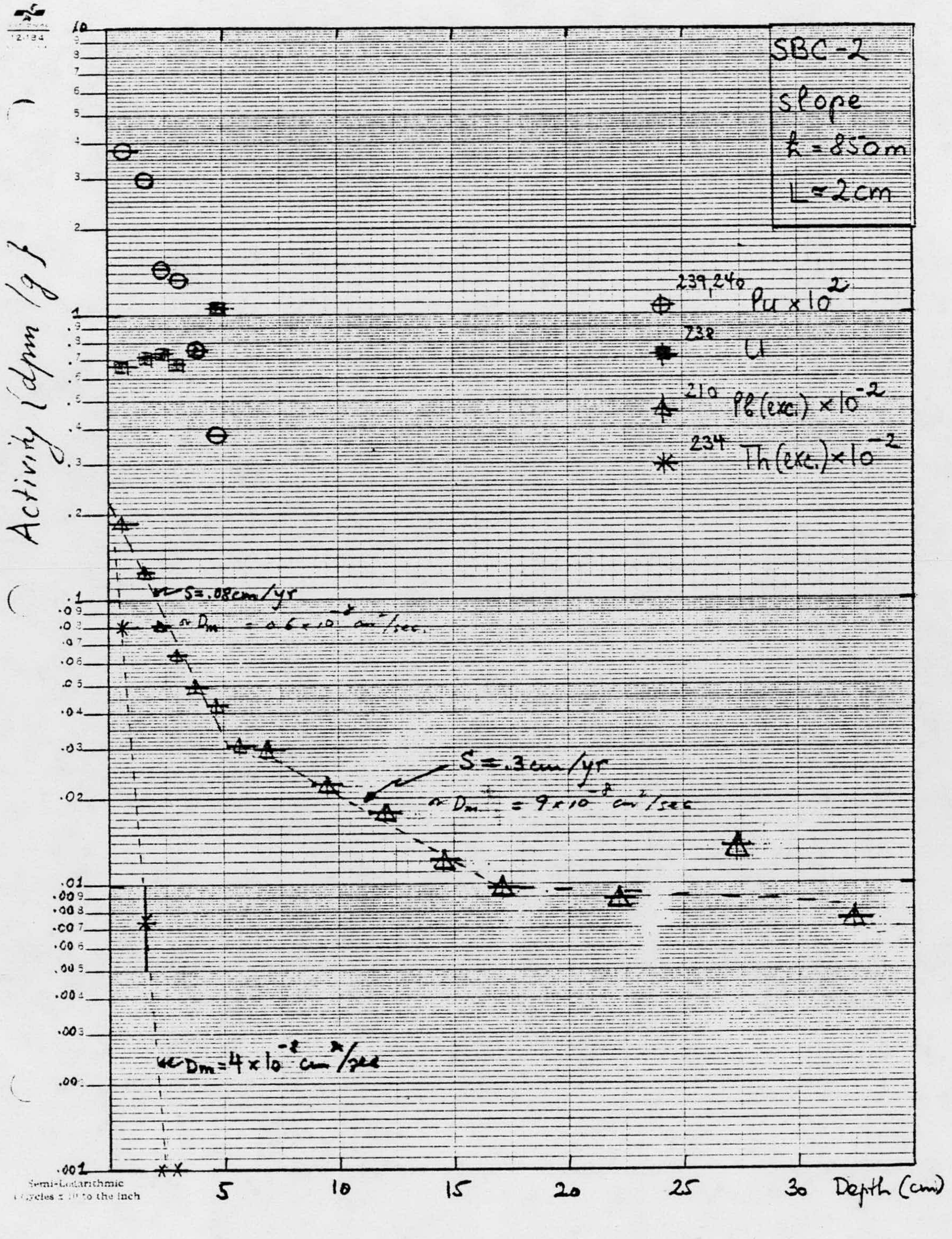

SBC-1
mud hole
h = 69m
L ≈ 7.5cm
239,240 Pu x 10^2
238 U
210 Pb (exc.) x 10^-2
234 Th (exc.) x 10^-2
Activity {dpm/g}
S = .21 cm/yr
Dm = 0.4 x 10^-7 cm²/sec
Dm = 1.2 x 10^-7 cm²/sec
Depth (cm)
0
5
10
15
20
25
30
Semi-Logarithmic
Cycles x 10 to the inch

Fig. 3.2/2B



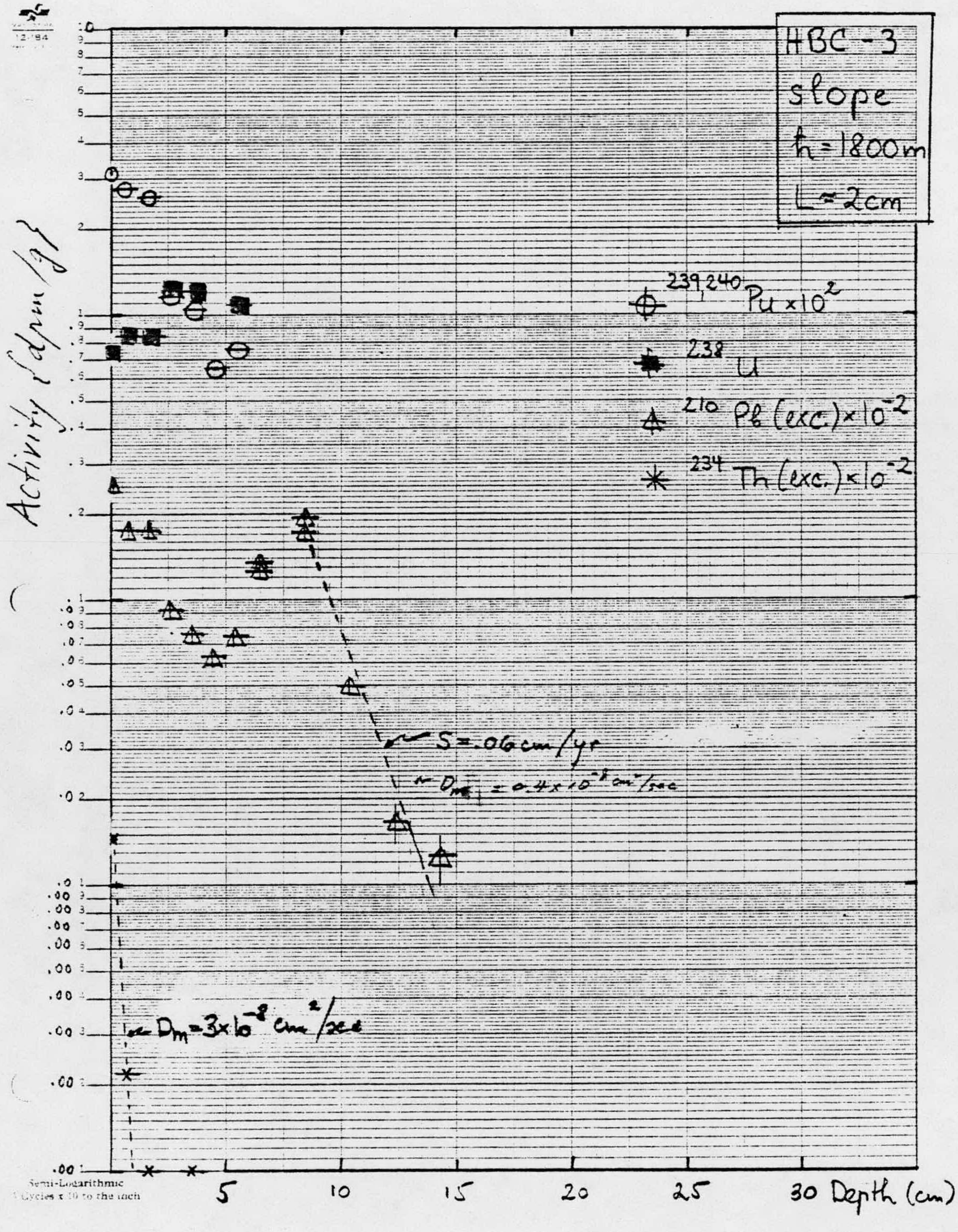
SBC-5
mud hole
h = 57m
L = 2.5 cm
239,240 Pu × 10^-2
238 U
210 Pb(exc.) × 10^-2
234 Th(exc.) × 10^-2
Activity {dpm/g}
S = .29 cm/yr
Dm = 0.9 × 10^-7 cm²/sec
Dm = 1.2 × 10^-7 cm²/sec
Depth (cm)
5
10
15
20
25
30
Semi-Logarithmic
4 Cycles x 10 to the inch

Fig 3.2 /2C



SBC-2
slope
h = 850m
L ≈ 2cm
239,240 Pu × 10^2
238 U
210 Pb (exc.) × 10^-2
234 Th (exc.) × 10^-2
S = .08cm/yr
S = .3cm/yr
Dm = 9 × 10^-8 cm^2/sec
Dm = 4 × 10^-8 cm^2/sec
Activity (dpm/g)
Depth (cm)
5
10
15
20
25
30
Semi-Logarithmic

Fig 3.2/2D



HBC-3
slope
h=1800m
L≈2cm
239,240 Pu ×10^2
238 U
210 Pb (exc.)×10^-2
234 Th (exc.)×10^-2
Activity (dpm/g)
S=.06cm/yr
Dm=3×10^-8 cm^2/sec
5
10
15
20
25
30 Depth (cm)
Semi-Logarithmic

and bioturbation rates as function of depth.

The total inventories of $^{234}Th_{ex}$ ($\Sigma^{234}Th_{ex}$ in Table 3.2/1) in the "mud hole" cores are roughly equal to what one would have expected from the overlying water column of 60$\pm$10 m (assuming $^{234}Th/^{238}U$ activity ratio of about 0.4$\pm$0.1 in the water column), while the total inventories of $\Sigma^{239,240}Pu$ (Table 3.2/1) and ΣPb_{ex} are about twice the expected values from the atmospheric inputs ($\sim$ 35 dpm $^{210}Pb/cm^2$ and 0.4 dpm $^{239,240}Pu/cm^2$). The "mud hole" sediments therefore appear to be effective sites for accumulating reactive pollutants. Although there appears to be net accumulation of these pollutant tracers in the "mud hole", we also know from studies of SPM in the water column that the "mud hole" constitutes the source area for a plume of SPM being advected "downstreams" (southwest) along the shelf. The extra sources of ^{210}Pb and $^{239,240}Pu$ for the "mud hole" sediments are probably the surface open ocean waters which contain high concentration of ^{210}Pb and $^{239,240}Pu$, or inputs from river runoffs. However, Simpson et al. (1979) have shown that river input of $^{239,240}Pu$ into the New York Bight is too small to be significant. In fact, based on a comparison of radionuclides in sediments of the Hudson estuary, New York Harbor and the Bight, Olsen (1979) concludes that there is net movement of radionuclides from the Bight into the harbor.

The two slope cores have accumulated only 12 to 25% of the direct atmospheric $^{239,240}Pu$ inputs so far. Apparently most of the $^{239,240}Pu$ is still in the overlying water column. In order to assess fully the importance of the slope sediments as sinks for pollutants, we need more extensive sample coverage. We obtained two more cores from the slope to the sourh during the RACACA cruise, but we really need more cores for comparison.

Table 3.2/1. Apparent sedimentation rates, sediment mixing rates and inventories of radionuclides in the New York Bight cores.

Box core #	Location Lat. N	Long. W	Water Depth (m)	D_m by $^{234}Th_{ex}$ (cm^2/sec)	D_m by $^{210}Pb_{ex}$ cm^2/sec)	S(cm/yr) by $^{210}Pb_{ex}$	$\Sigma^{234}Th_{ex}$	$\Sigma^{210}Pb_{ex}$	$\Sigma^{239,240}Pu$
SBC-1	40°36'	70°59.7'	69	$1.2x10^{-7}$	$0.4x10^{-7}$	0.2	6.7	58	0.93
SBC-5	40°27.8'	70°58.6'	57	$1.2x10^{-7}$	$0.9x10^{-7}$	0.3	3.9	76	0.87
SBC-2	39°59'	71°05'	850	$4x10^{-8}$	$0.6x10^{-8}$	0.08	0.3	80	0.05
HBC-3	39°44.5'	71°02.4'	1800	$3x10^{-8}$	$0.4x10^{-8}$	0.06	7.9	75	0.09

Literature Cited (Section 3.2)

Turekian, K.K. et al. (1978) Bioturbation in deep sea deposits: Rates and Consequences. Oceanus 21, 34-41.

Simpson, H.J. et al. (1979) Transport of plutonium by rivers, Transuranic elements in the environment (ed. W.C. Hanson).

Olsen, C. (1979) Radionuclides, sedimentation and the accumulation of pollutants in the Hudson estuary. Ph.D. Thesis, Columbia University.

4.0 SPREADING OF WATER CHARACTERISTICS AND SPECIES IN SOLUTION

4.1 Hydrographic and Physical Mixing Processes

4.1.1. Introduction

A descriptive study "New York Bight Stratification" by Gordon, Houghton and Aikman of the Lamont DOE sponsored data sets prior to 1978 has begun and is nearly in first draft stage. The study deals in a comprehensive form with the water type thermohaline structure of New York Bight waters. The work is needed to provide a foundation for more quantitative mixing models for the New York Bight. Its goals are primarily to define the significant advective-dispersive processes. A discussion of the results is given in section 4.1.3.

During the 1978-79 contract period, data analysis progress was reported at the 1978 Annual Workshop on Physical Oceanography of the Middle Atlantic and New York Bights, hosted by Virginia Institute of Marine Sciences (VIMS) in Williamsburg, Virginia (Appendix 8), and the Posmentier-Houghton paper "Fine-structure instabilities induced by double diffusion in the shelf/slope water front" was published in the "green" JGR [83(C10): 5135-38, 1978] (Appendix 9).

The data report for the August 1978 cruise on CAPE HENLOPEN (cruise "Boue Trou") was distributed.

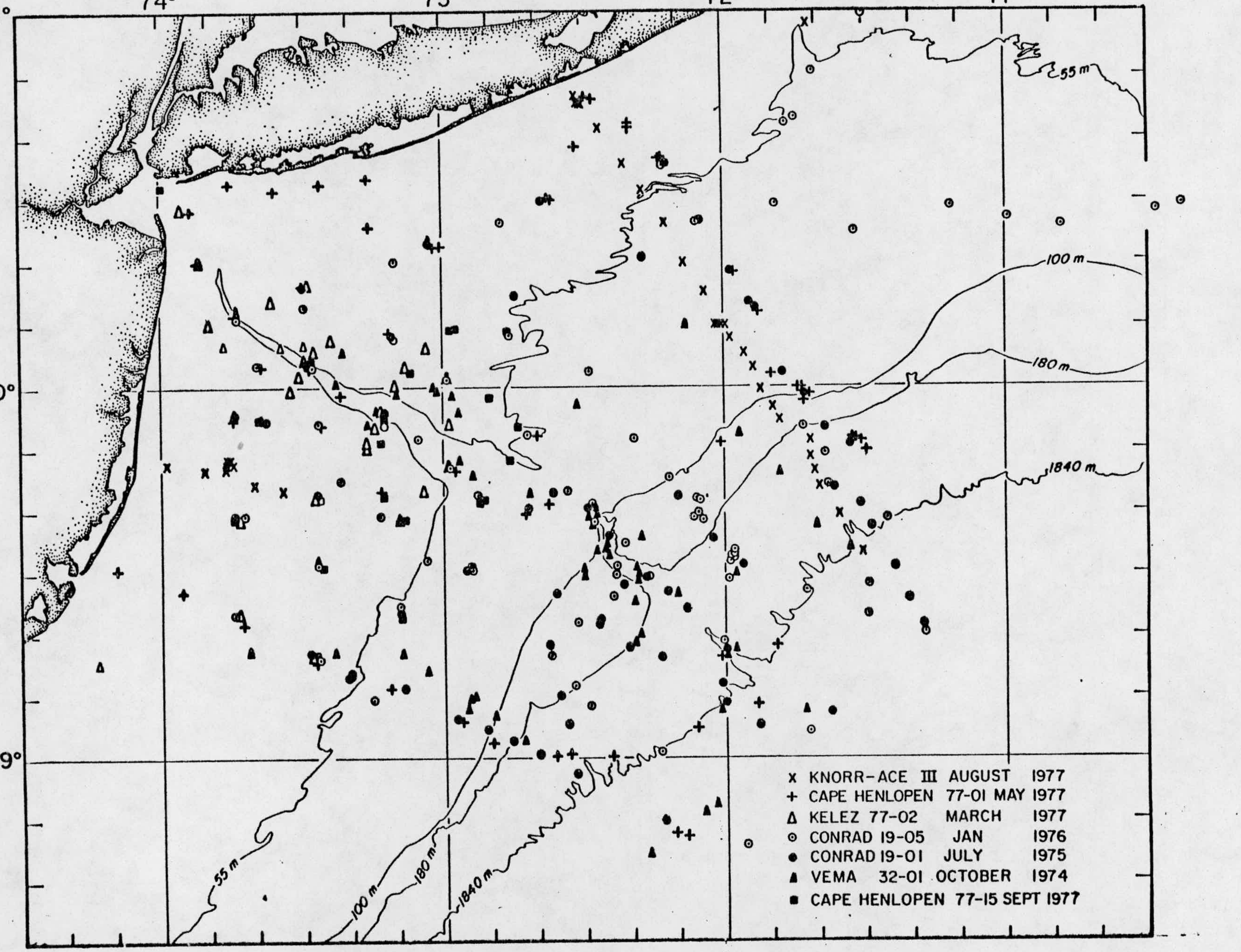
4.1.2. Data Processing

As reported last year, all data reports have been distributed to the DOE investigators at Lamont. The August 1978 data collected on the CAPE HENLOPEN "Boue Trou" cruise was distributed in October 1978. Preliminary analysis of these very significant data is included in section 4.1.3.

The CTD-O_2 hydrographic data has not yet been officially released. This would be done when the data is run through the full data processing system presently being developed for handling our Antarctic data set. This system is essentially the same as the one developed at Woods Hole Oceanographic Institution. It is likely that it will be ready for our New York Bight data later in 1979. In any case, the large gradients encountered in the New York Bight permit the first level of data processing and display (the distributed data reports) to meet nearly all our needs. The study of the finest scale of vertical structure (less than 1 meter) would benefit from the next level processing.

4.1.3. Data Analysis

Models for New York Bight shelf water replacement patterns and rates are being developed. The formulation of the models is based on the interpretation of the Lamont data set collected in the New York Bight from 1974-1977 (Fig. 4.1-1), in conjunction with the full set of historical data. The Lamont hydrographic station data, consisting of continuous measurement with depth of the thermohaline and oxygen stratification, allows for recognition of lateral exchange processes to a much greater



74°
73°
72°
71°
41°
40°
39°
55 m
100 m
180 m
1840 m
X KNORR-ACE III AUGUST 1977
+ CAPE HENLOPEN 77-01 MAY 1977
Δ KELEZ 77-02 MARCH 1977
⊙ CONRAD 19-05 JAN 1976
● CONRAD 19-01 JULY 1975
▲ VEMA 32-01 OCTOBER 1974
■ CAPE HENLOPEN 77-15 SEPT 1977

Fig. 4.1-1

level of resolution than that permitted by the historical serial cast hydrographic data. We are therefore able to evaluate the importance of various processes and more suitably incorporate them within our model (discussed below). The results should prove of value in interpreting the DOE geochemical and biological data sets.

In 1978 our field work was designed to address specific problems of shelf and slope zone exchange processes. The August 1978 data set is unique in that it provides a closely spaced line of CTD hydrographic stations across the shelf-slope frontal zone. The data are now being used to better describe the nature and the variability of the fine scale thermohaline structure characteristics of the frontal zone, with the objective to more realistically parameterize type of cross frontal exchange.

Several specific results, which are being included in the developing study "New York Bight Stratification", are:

(1) The upper third of the seasonal pycnocline acts as a guide for shoreward spreading of saline slope water. (Process #9, Fig. 1.0/1). It is determined that the pycnocline S-max must be renewed in a time scale of about one month. If this is correct, then the pycnocline S-max represents the major salt input to the inner and middle shelf region.

(2) Near the base of the pycnocline over the outer shelf and slope region seaward spreading of the cold pool water dominates. The cold pool water is also attenuated by vertical mixing.

(3) Significant influx of North Atlantic Central Water (NACW) occurs over the floor of the outer continental shelf. (Process

#10, Fig. 1.0/1). On mixing with the cold pool water (within the bottom well-mixed layer) it spreads seaward within the linear T/S layer between the pycnocline and the well-mixed layer.

(4) Gulf Stream warm core eddies adjacent to the slope apparently shallow the water properties over the slope. In this way the warm core eddies may allow introduction of slightly deeper, cooler-less saline NACW onto the outer shelf floor than would normally be the case. The warm core eddies also increase the volume of warm-saline, less dense water available to spread into the seasonal pycnocline of the shelf, which may amplify input into the pycnocline S-max layer.

(5) The exchange across the shelf-slope front associated with the seasonal pycnocline (Process #10, Fig. 1.0/1) may not be totally isopycnal, since double diffusion processes appear to be active - though we have not yet evaluated the significance of double diffusion relative to other cross frontal exchange processes.

(6) The end of winter properties of the cold pool water vary markedly from year to year. The initial density of the cold pool water (its February condition) may determine its mixing fate for the rest of the year; after cold winters or years of low river input the cold pool water is denser and so can mix isopycnally with the more voluminous sub-pycnocline waters of the slope zone, whereas after warmer winters or high river input the cold pool water is less dense and may mix primarily with the small volume of lower pycnocline waters of the slope. In the latter situation the cold pool waters may be a bit more persistent.

(7) The oxygen maximum characteristics of the summer shelf pycnocline are presumably a product of high photo-synthesis relative to outward diffusion of the oxygen. Using a diffusive one-dimensional (vertical) model and oxygen production rate keyed to concentration of measured chlorophyll, a K_z is calculated for the lower portions of the summer pycnocline. Values range from 0.2 to 2 cm^2/sec.

The following sections are excerpted from the draft study being written of "New York Bight Stratification" by Gordon, Houghton and Aikman. Some of the material presented in the 1977 and 1978 Report on interleaving fine structure, and on the pycnocline salinity-maximum, will be expanded and included in the study for publication, and will not be repeated here. Following the discussion of "New York Bight Stratification" study is a preliminary analysis of the "Boue Trou" August 1978 data.

"New York Bight Stratification"

A.L. Gordon, R.W. Houghton and F. Aikman III

(A) Vertical Profiles and Horizontal Distributions of Thermohaline Properties

This section will be expanded from the material presented in our 1977 and 1978 DOE Annual Report. The principal objectives of this introductory section to the paper are review of a. the thermohaline structure, b. the relation of water masses to the density field, c. the seasonal variability of the water mass distribution, and d. the large scale thermohaline form of the shelf-slope frontal zone.

(B) Thermohaline Stratification

Again this section will be an expanded form of the material presented in our last two DOE reports, though some additions are included. The principal objective of this section of the paper is to define thermohaline regions of the New York Bight into Inner Shelf, Middle Shelf, Outer Shelf (seaward of the foot of the shelf-slope front), and Slope regions (where low salinity water rests over the North Atlantic Central Water). Each region has unique stratification features which are discussed and related to each other.

The seasonal variability of the stratification characteristics is also discussed. Figure 4.1-2 shows the evolution of the thermohaline characteristics of the water column in May and August 1977 at the same position over the water shelf off Long Island. For the sake of brevity of this Report, no discussion is presented now - the figure should be helpful to the reader in following the discussion of the T/S structure presented below.

(C) Temperature-Salinity Relation

The T/S relation of the CTD and STD points clearly show the seasonal nature of the thermohaline stratification. The

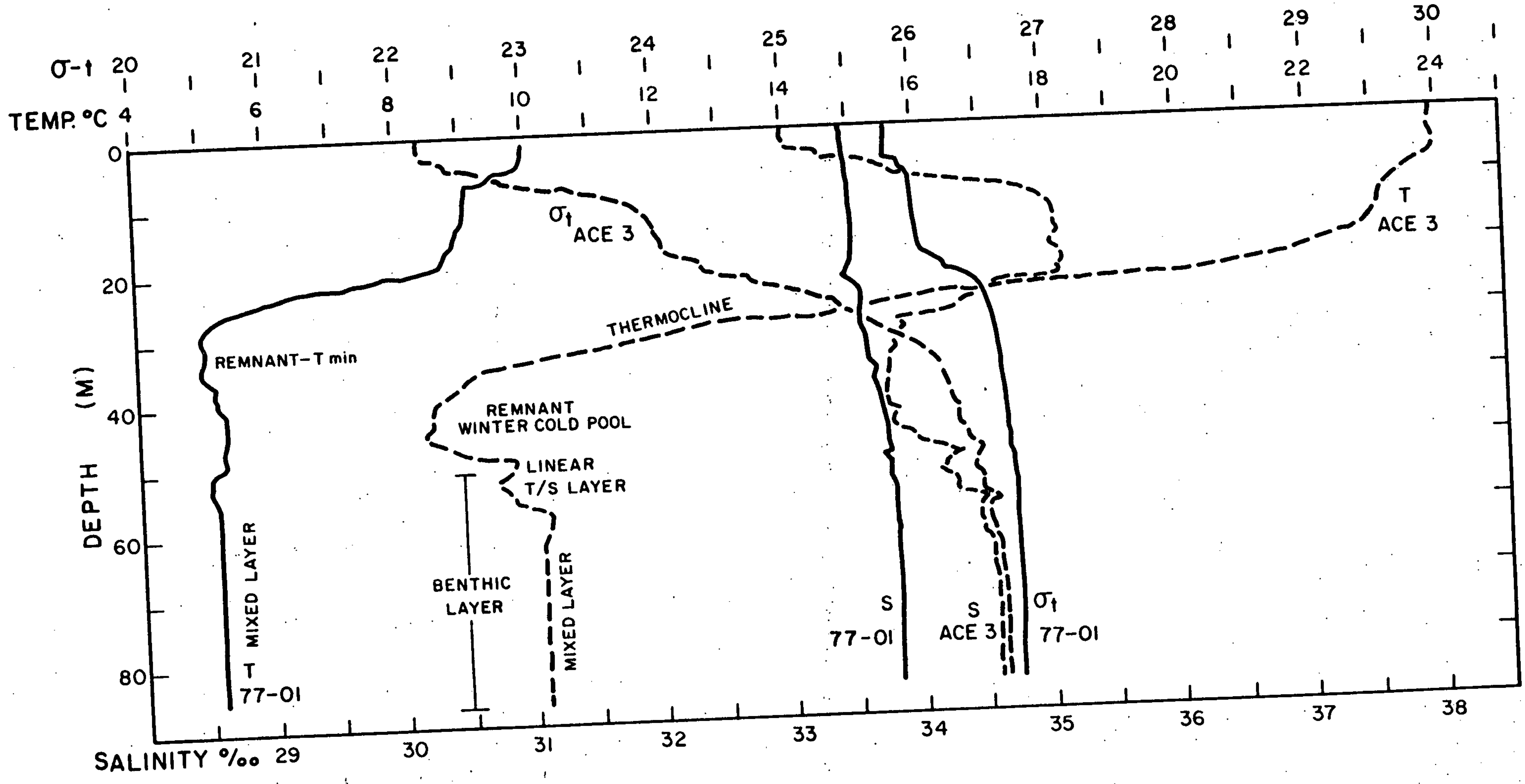

σ-t
TEMP. °C
DEPTH (M)
SALINITY ‰
σt ACE 3
T ACE 3
THERMOCLINE
REMNANT-T min
REMNANT WINTER COLD POOL
LINEAR T/S LAYER
BENTHIC LAYER
MIXED LAYER
T 77-01
S 77-01
S ACE 3
σt 77-01

Figure 4.1-2

simple "seven" shape of the winter T/S relation is preserved to some extent in the warmer months as the cloud of T/S points migrates to warmer temperatures, establishing the summer T/S pattern. A schematic of the large scale water mass distribution is given in Figure 4.1-3 as a guide.

In recognition of the strong seasonal signal, the T/S relations will be discussed in a monthly chronological order rather than in the chronological order in which the data were obtained. Since interannual variations are large, care must be taken in not "overgeneralizing" the results. Using the historical data as a guide, that problem can be minimized.

January 1976 -

The January 1976 T/S relation (fig. 4.1-4a,b) represents the winter situation, though on the average the full extent of the winter is expected in February. We note however that February 1976 was an anomalously warm month, which induced early stratification, which may have been responsible for the anoxic condition developed later in 1976 in the New York Bight (Walsh et al., 1978). Therefore the January 1976 data may represent the maximum winter extreme for 1976.

The T/S relationship below the salinity maximum (S-max) in the slope regime near 13°C and 35.6 ‰ defines the continental slope modification of the Islen 1936 North Atlantic Central Water (NACW) as discussed by McLellan (1957). This modification shifts the NACW curve towards lower salinity at nearly all isotherms.

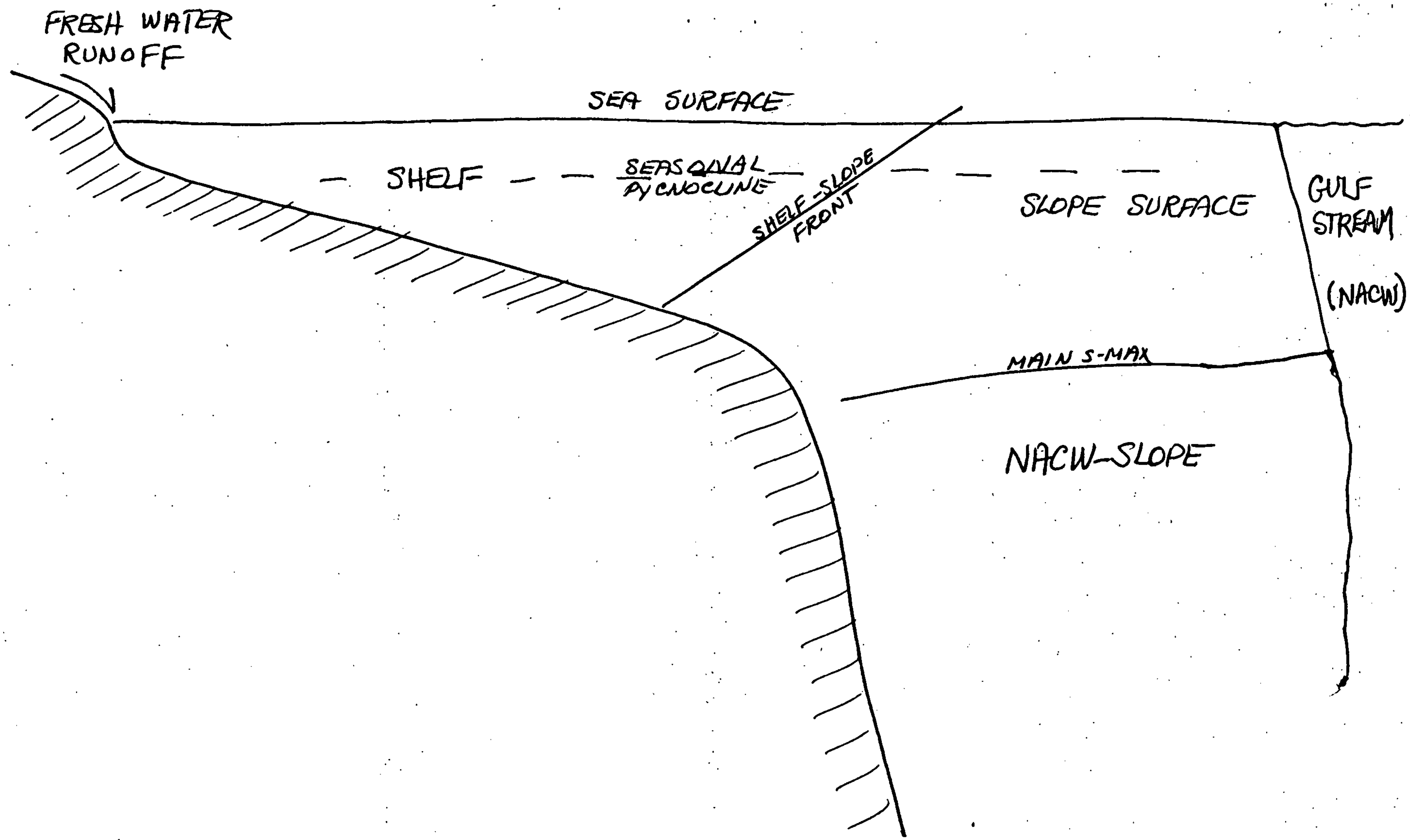

FRESH WATER RUNOFF
SEA SURFACE
SHELF
SEASONAL PYCNOCLINE
SHELF-SLOPE FRONT
SLOPE SURFACE
GULF STREAM
(NACW)
MAIN S-MAX
NACW-SLOPE

Figure 4.1-3

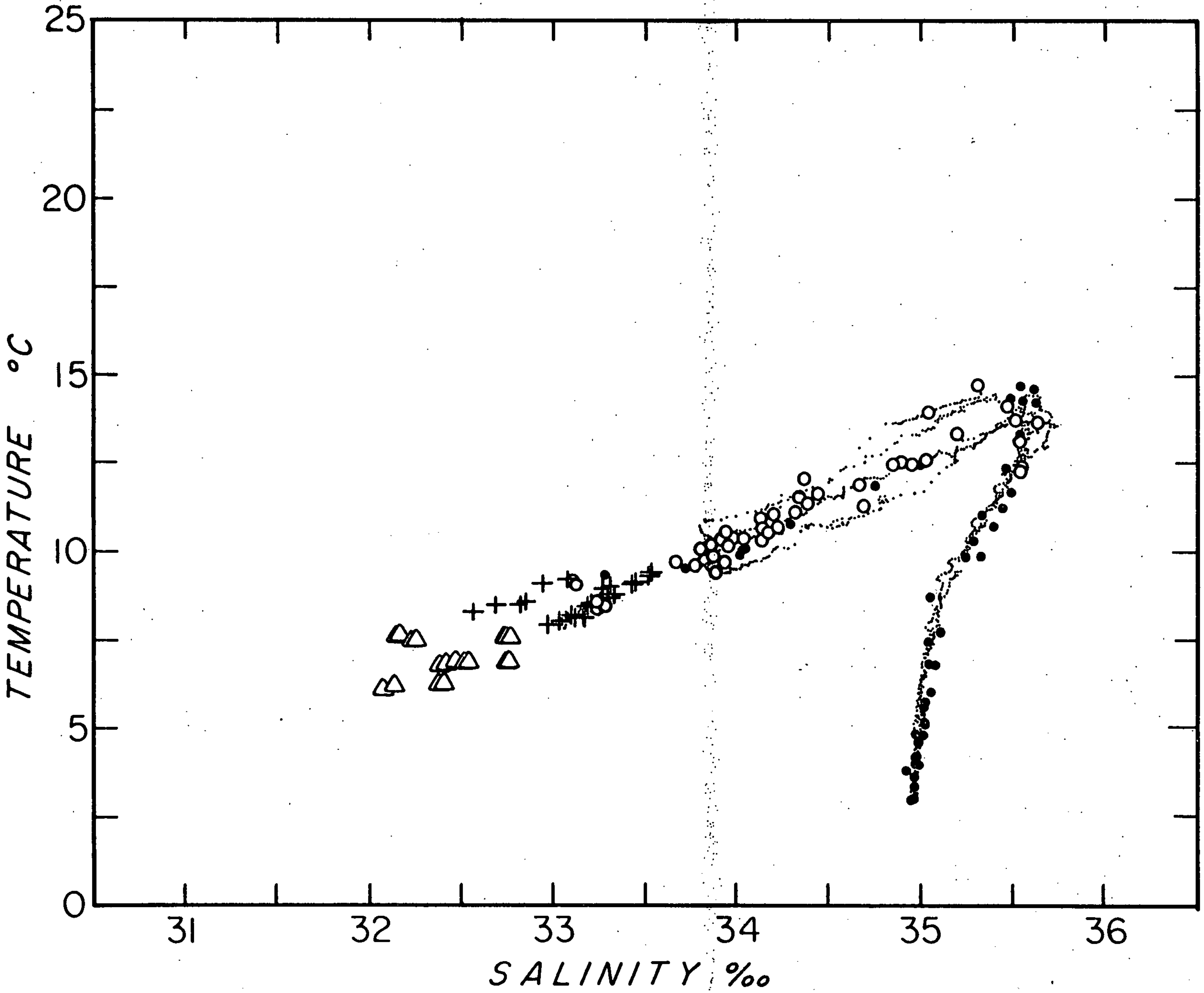


Figure 4.1-4a

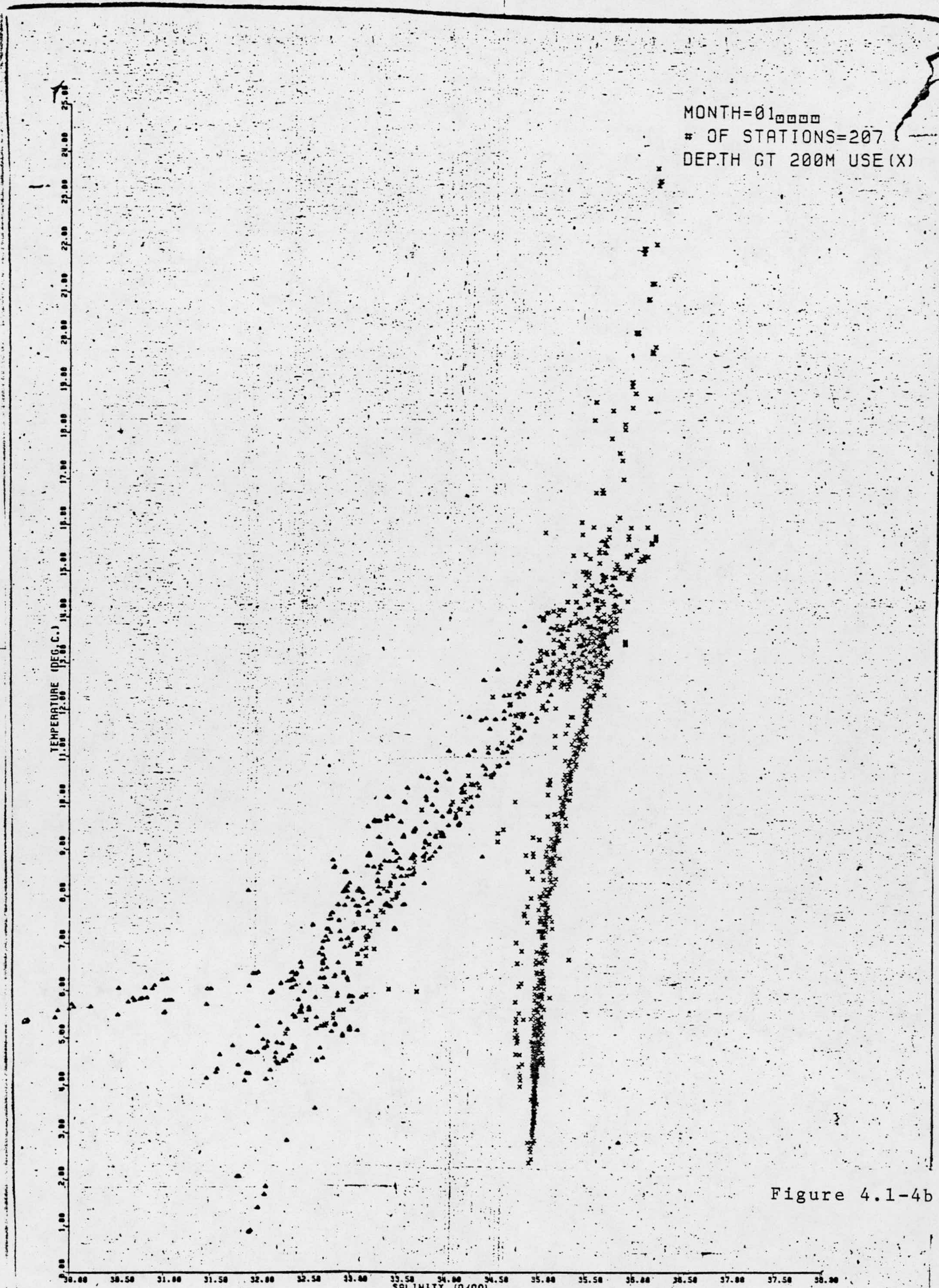

MONTH=01
# OF STATIONS=207
DEPTH GT 200M USE(X)
TEMPERATURE (DEG.C.)
SALINITY (O/OO)

Figure 4.1-4b

Gordon et al. (1976) discussed the various slope changes observed in the NACW-slope T/S relation, as evident in the October 1974 VEMA data set; this discussion is equally valid for the other data sets, since seasonal variability has an insignificant influence below the slope S-max.

The position of the T/S-max point on the NACW-slope T/S relation defines the deepest and densest water influenced directly by the continental shelf water. It is noted that an anomalous (relative to the NACW-slope T/S curve) condition occurs when volumes of more concentrated NACW water are introduced to the slope region by warm-core Gulf Stream rings in the slope region of the New York Bight (discussed below). The S-max marking the top of the NACW-slope water will be called the main S-max to differentiate it from the salinity maximum layers observed in the shelf water. Presumably, the main S-max is free to "slide" along the NACW-slope T/S curve, depending on variability in the density of the shelf component, or in the processes which mix it into the slope regime.

At depths above the main S-max the January 1976 T/S points fall along a nearly straight T/S line, suggestive of simple two-point mixing. The observed T/S relation is colder at any isohaline and/or saltier at any isotherm than would be expected were the water at the main S-max position to mix with the freezing point river water introduced at the western boundary. The sense of the displacement is expected, since the local sea to air heat loss implies that temperature is non-conservative in the active mixed layer (Fig. 4.1-5). The difference of the observed winter T/S curve from a

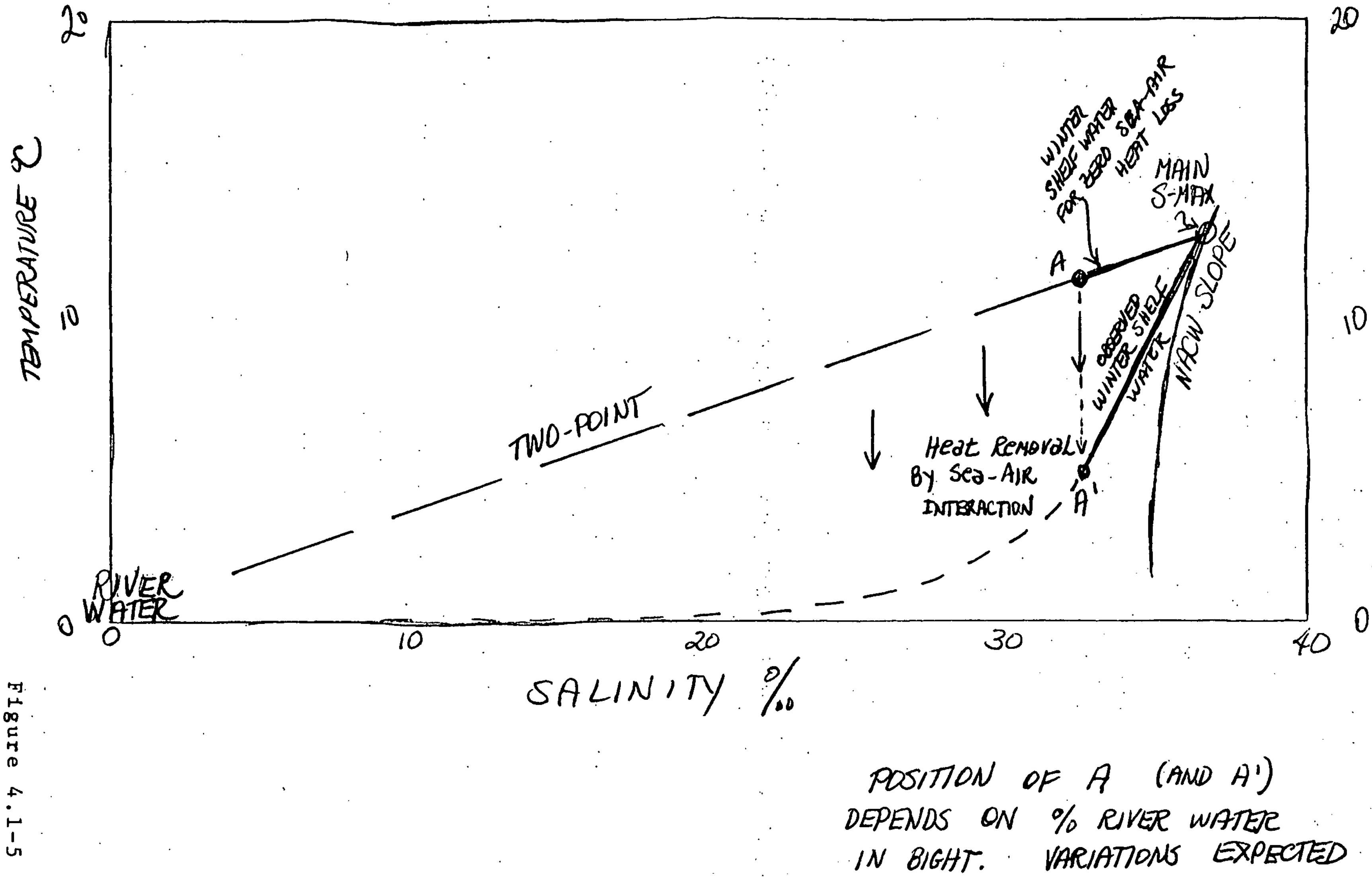

20
10
0
TEMPERATURE °C
RIVER WATER
TWO-POINT
WINTER SHELF WATER FOR ZERO SEA-AIR HEAT LOSS
MAIN S-MAX
A
A'
Heat Removal By Sea-Air INTERACTION
OBSERVED WINTER SHELF WATER
NACW SLOPE
0
10
20
30
40
SALINITY ‰
POSITION OF A (AND A') DEPENDS ON % RIVER WATER IN BIGHT. VARIATIONS EXPECTED

Figure 4.1-5

simple conservative slope water-riverine mixing line cannot simply be a product of the non-conservative salinity effect induced by excess evaporation over precipitation. The salinity excess (difference of observed salinity to the salinity expected from the simple two-part slope-riverine mixing) at an isotherm is about 3-6°/₀₀, which requires evaporation excess over precipitation of many meters, far above any reasonable value. Bunker and Worthington (1976) show an annual evaporation of 100 cm for the New York Bight, which is close to the average annual precipitation in New York City [Climate of New York, from Climatography of the United States, No.60-30, U.S. Dept. of Commerce], which should be representative of the regional precipitation. The average E-P is near zero.

The segment of the water column for each station above the main S-max, or seafloor in the case of the stations on the continental shelf, is used to determine the heat deficiency relative to simple two-point (winter riverine water at 0°C, 0°/₀₀, and the main S-max Θ/S point at 13°C, 35.6°/₀₀) conservative mixing. That is the straight T/S relation that would develop if the sea-air heat exchange in the New York Bight were zero.

The distribution (Fig. 4.1-6) indicates maximum heat deficiency over the middle and outer shelf of between 3 to 4×10^4 cal/cm^2. The Hudson Channel and Canyon regions are particularly high. The decreased deficit landward of the inner 3.0×10^4 cal isopleth is due to the shallowness of the water column, whereas the decrease seaward of the outer 3.0×10^4 cal isopleth is most likely the result of attenuated mean sea-air temperature differences and

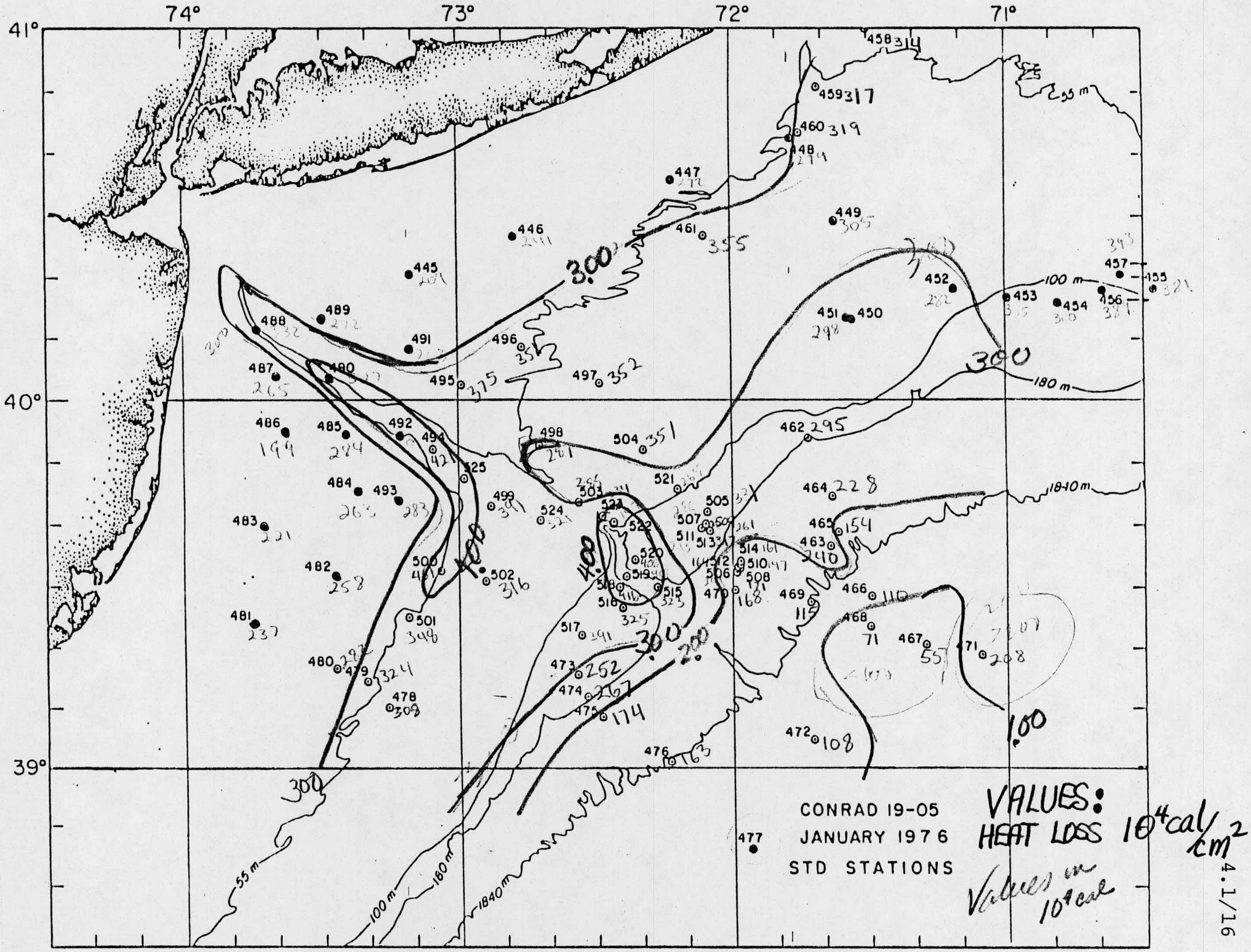

74°
73°
72°
71°
41°
40°
39°
55 m
100 m
180 m
1840 m
CONRAD 19-05
JANUARY 1976
STD STATIONS
VALUES:
HEAT LOSS $10^4 cal/cm^2$
Values in 10^4 cal

Figure 4.1-6

increased air mass humidity due to air mass modification by the oceanic heat and water source.

The heat deficit can be explained by sea to air heat loss after the seasonal thermocline (this includes summer heat of the riverine water) is essentially removed. Inspection of the historical data set indicates that this occurs by the end of November. The heat deficit must be accomplished by sea-air heat loss in approximately two months. The daily average heat loss is approximately 400 to 650 cal/cm^2/day over the shelf, and 150-250 cal/cm^2/day over the slope. Hopkins and Garfield (1979) determined the total heat loss in the Gulf of Maine during the 1974-75 winter had a daily average of 200-500 cal/cm^2/day.

The above determination is carried out in an effort to conceptually address the question of gradient T°:S°/₀₀ ratio of the basic 'end-of-winter' T/S curve of the shelf water and slope surface water. Ocean to atmosphere heat flux steepens the T/S ratio or gradient. Naturally annual variations in the percentage of riverine and saline NACW-slope water present at the end of winter would vary the T/S length (i.e. salinity range) of the shelf and slope surface water in T/S space.

A characteristic winter shelf water salinity of 33.5°/₀₀ represents a 93% input of NACW-slope water in the shelf water volume with 7% of river water. A 10% increase in river water content (caused by increased river input or increased river water residence time) would lower the average shelf water salinity by 0.27°/₀₀. Therefore, assuming the winter sea-air heat flux has no annual variation, the winter shelf water T/S ratio would vary due to differences in river water residence time.

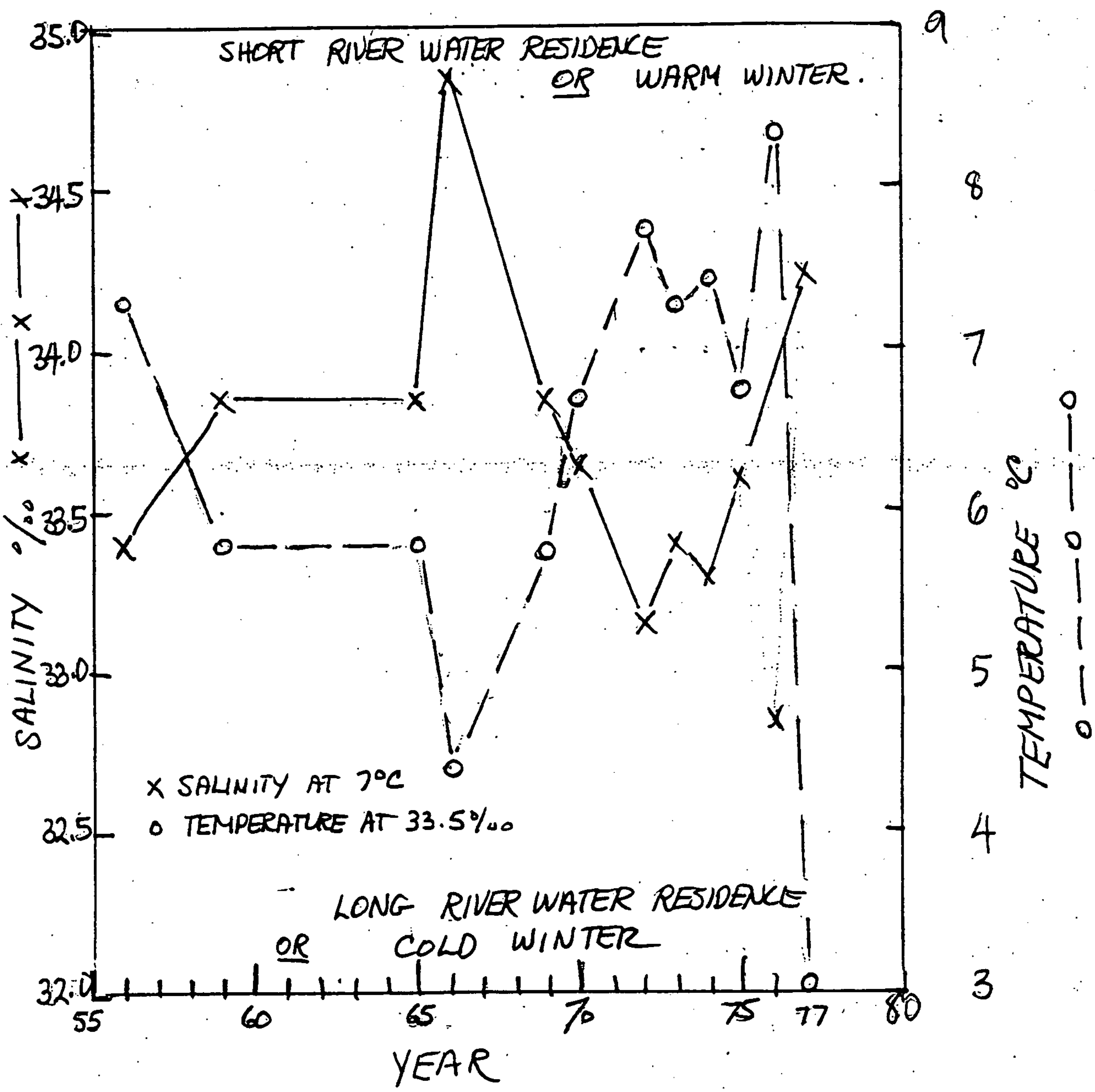
In summary: It is expected that the magnitude of the T/S gradient and the mean T/S characteristics of the shelf water of the end of winter shelf and slope surface water is due to a combination of: a) Sea to Air Heat Flux - colder winters would induce a steeper T/S gradient;

b) River Water Residence Time - decreased residence volume of river water due to decreased river runoff or increased onshore flux of NACW-slope water would induce a steeper T/S gradient;

c) T/S Position of Main S-Max - the saline end member T/S point may vary.

The variability in end of winter (February-March) shelf water characteristics are studied to determine the extent of shelf water T/S gradient variability. The temperature at the 33.5°/₀₀ isohaline and salinity at the 7°C isotherm are plotted for 12 years, for which the NODC file has data between 1956 and 1977 (fig. 4.1-7). Naturally, either method a) or b) can be used to explain the variability. The winter severity and river runoff data may suggest which process, a) or b), is more important. A major potentially important factor, which is not included in winter severity or river runoff, is item c): the possible variability in slope water intrusions which could influence the river water residence time.

The ΔT range at the 33.5°/₀₀ is about 5.5°C, with a mean variation of 3°C. This would be representative of a heat content variability (using a 50m water column, which is characteristic of the winter period mixed layer) of 1.46×10^4, which is



SHORT RIVER WATER RESIDENCE OR WARM WINTER.
LONG RIVER WATER RESIDENCE OR COLD WINTER
× SALINITY AT 7°C
o TEMPERATURE AT 33.5‰
SALINITY ‰
TEMPERATURE °C
YEAR
35.0
34.5
34.0
33.5
33.0
32.5
32.0
9
8
7
6
5
4
3
55
60
65
70
75
77
80

Figure 4.1-7

about 40% of the January 1976 value. The salinity range at 7°C is about 1°/₀₀, suggesting a variability in river residence time of about 20%.

[The correlation between the T/S gradient and data on winter severity and river runoff will be investigated shortly].

Ketchum and Corwin (1964) find a good relation between mean salinity of the shelf water to the 60 m isobath and average river flow of the six months prior to the hydrographic observations.

After March the surface water is heated and the cold bottom water on the shelf becomes the remnant cold pool or winter water. This water slowly mixes out, though remnants survive the whole summer period. The fate of the winter water, that is the rapidity with which it mixes with the surrounding water, may be related to its condition at the end of winter. This hypothesis is developed below, after the seasonal evolution of the T/S relation is discussed.

May 1977 -

Development of the seasonal pycnocline is well underway by May (fig. 4.1-8a, with fig. 4.1-8b showing the historical data set for May), as T/S points of the shelf and slope surface water are lifted off the winter T/S base line. The slope and shelf waters are separated by an intense shelf break frontal zone, which now clearly shows up in T/S space. The coldest cold pool water observed was 3°C below any value found in the historical data set,

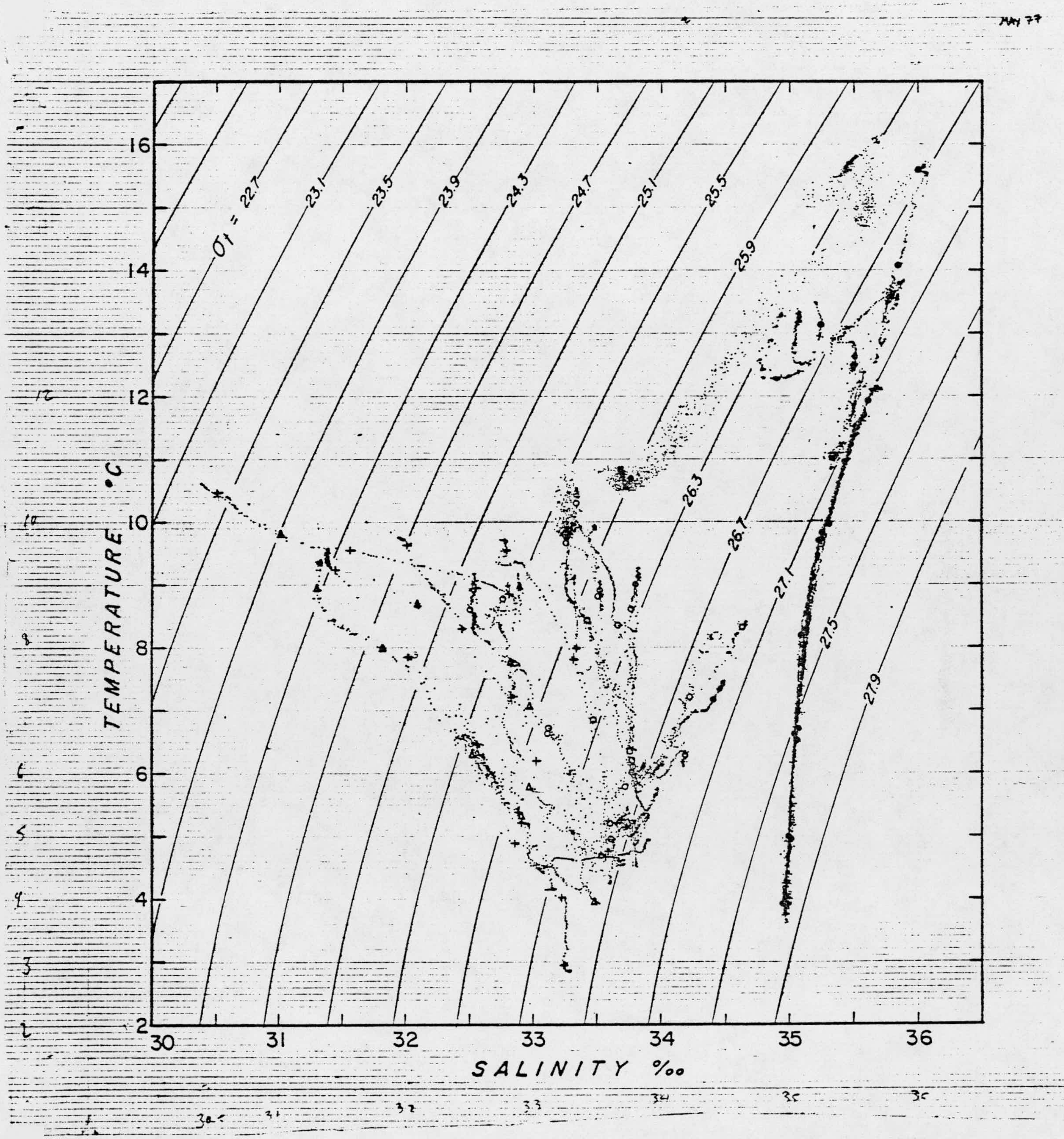

MAY 77
σ_t = 22.7
23.1
23.5
23.9
24.3
24.7
25.1
25.5
25.9
26.3
26.7
27.1
27.5
27.9
16
14
12
10
8
6
4
2
TEMPERATURE °C
30
31
32
33
34
35
36
SALINITY ‰

Figure 4.1-8a


MONTH=05
# OF STATIONS=251
DEPTH GT 200M USE(X)
TEMPERATURE (DEG.C.)
SALINITY (O/OO)

Figure 4.1-8b

which may be expected from the severity of the 1976-77 winter. Temperature and salinity increase near the shelf floor is similar to the winter base line, but at higher temperatures (about 1°C) than observed in March 1977 [shown in figure 4.1-12 , suggesting warming (about 0.8°C) and/or salinity (about 0.2°/₀₀) decrease].

The shelf T/S curves at temperatures above the winter base are nearly isohaline, though often the warmest section at the sea surface shows a pronounced decreasing salinity as temperature warms. This is expected, since at these elevated temperatures the river input is concentrated into a density region in which no slope water exists, and hence there is a diminished availability of highly saline water, assuming isopycnal processes are an effective mode of exchange.

The slope water above the main S-max shows many inversions, as the lower salinity shelf water mixes with the slope water. The pronounced concavity (area A on the T/S diagram, Fig.4.1-8a) is induced by seaward mixing of the cold pool water, fed by the large reservoir situated on the sea floor at the middle continental shelf. The rapid cooling and decreased salinity at the surface is seaward spreading of the shelf surface water, unopposed by an isopycnal saline input.

The water layer below the T-min is called the benthic layer over the shelf, and subsurface water over the slope (where it is underlain by the main S-max rather than the seafloor). This layer is shown in the preceding section on thermohaline stratification (Fig. 4.1-2). The benthic layer is composed of two parts: a lower homogeneous mixed layer, and a layer of near-linear T/S characteristics between the T-min and bottom mixed layer. The T/S relation suggests that the linear T/S layer is composed of a mixture of cold pool water and the main S-max water.

July 1975 -

The July 1975 T/S relation (figure 4.1-9a) and historical July data (figure 4.1-9b) show the fully developed seasonal stratification. The vertical thermal gradients are remarkably strong over the continental shelf, with a total temperature range of 18°C in the characteristic middle shelf depth of 50 meters.

The inner and middle shelf form the low salinity component above the cold pool water. The slope surface water forms the high salinity component. The outer shelf and some middle shelf stations show a pronounced salinity maximum near the 24.3 to 24.7 σ-t level (area B on figure 4.1-9a). Over the outer shelf this S-max is essentially slope surface water. Since it occurs in the upper section of the seasonal pycnocline, it is called the pycnocline S-max. It is obviously a layer dominated or at least significantly influenced by slope surface water.

The slope surface water above the main S-max is relatively saline, though markedly decreased surface salinity is observed, presumably as low density river influence spreads seaward within the surface mixed layer.

Relatively low salinity is also observed in the slope region just above the main S-max, often accompanied by a T-min in the density level 26.3 σ-t. The low temperature and salinity characteristics point to an origin within the remnant cold pool

JULY

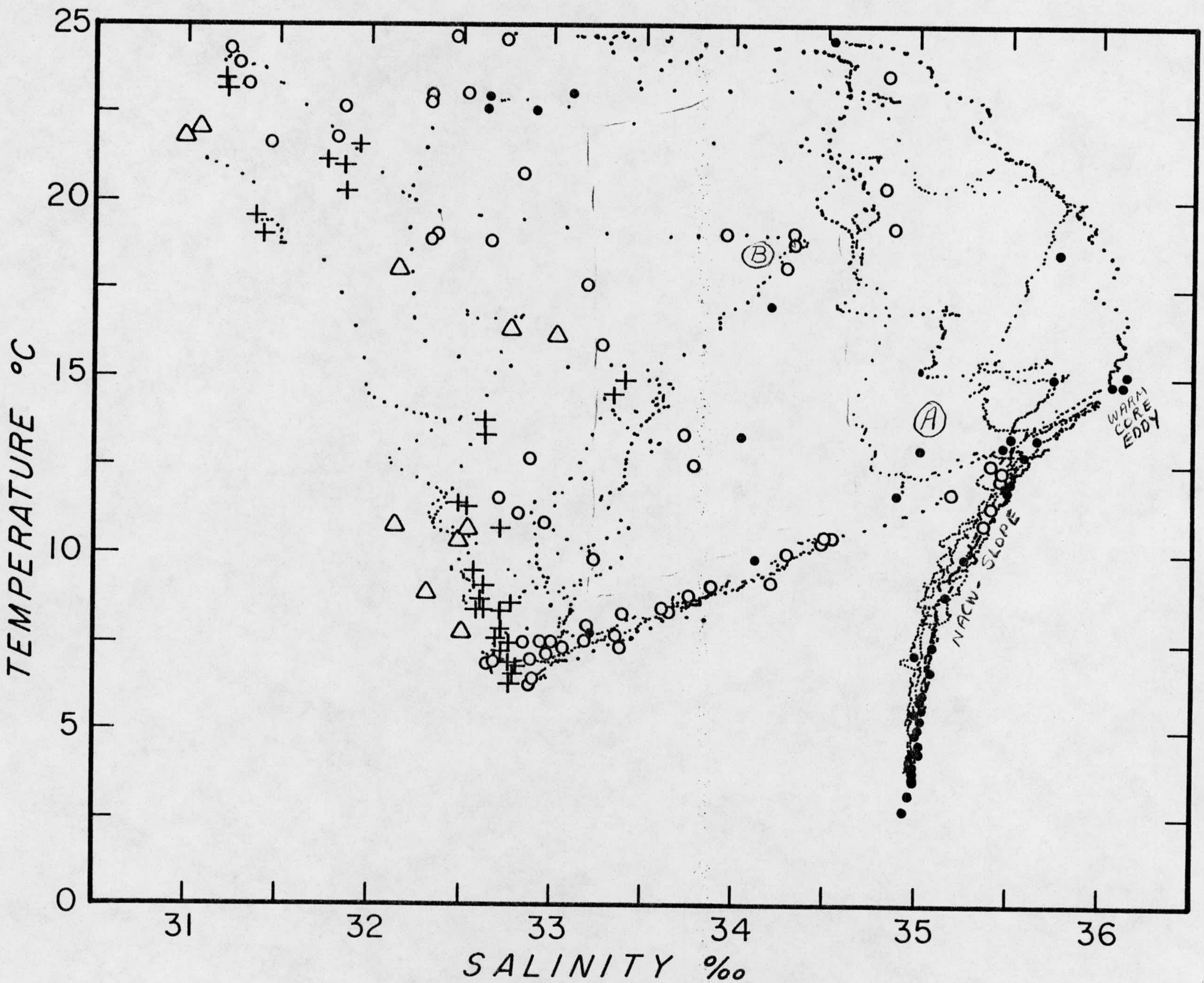


Figure 4.1-9a

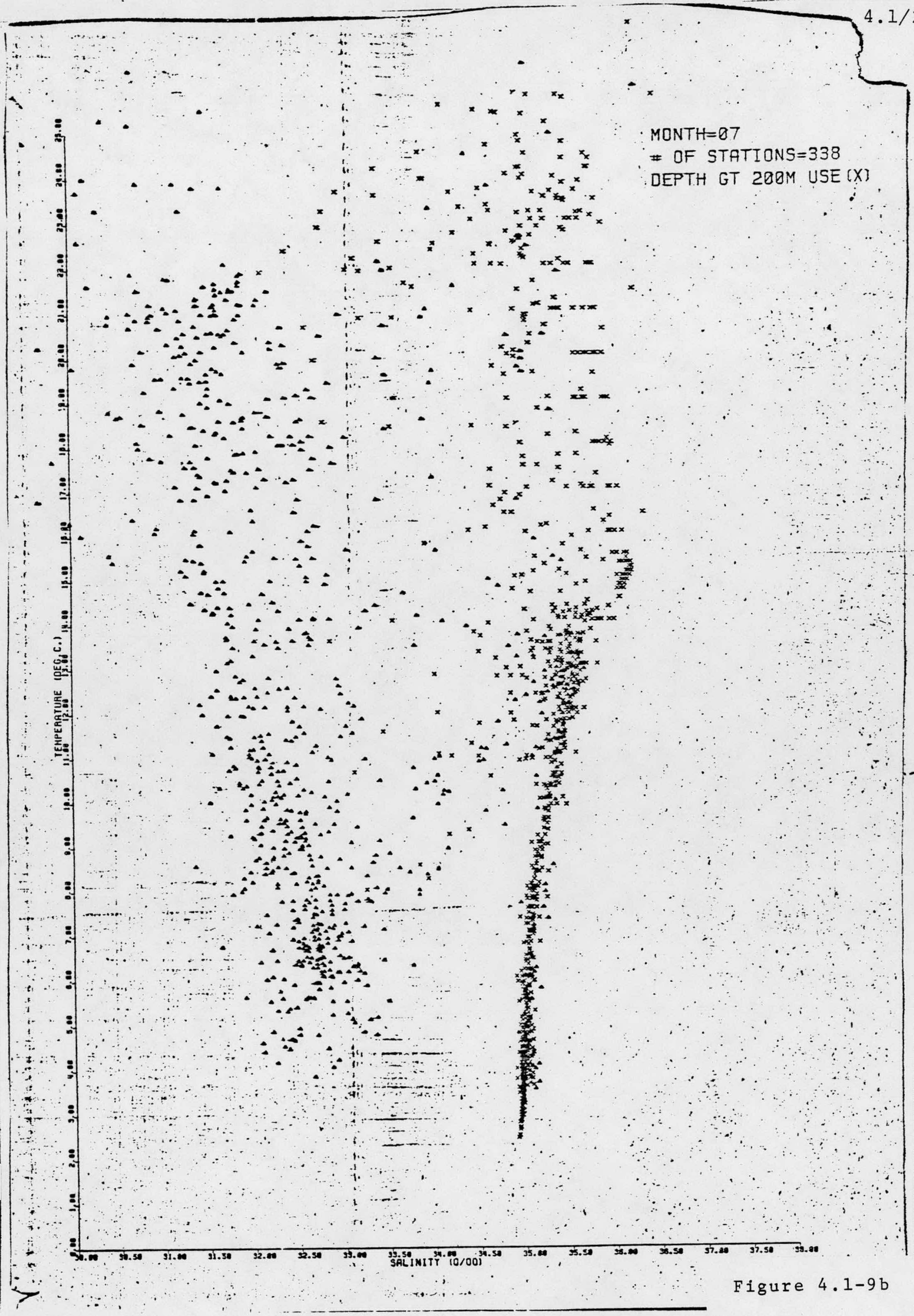

MONTH=07
# OF STATIONS=338
DEPTH GT 200M USE (X)
TEMPERATURE (DEG.C.)
SALINITY (O/OO)
30.00
30.50
31.00
31.50
32.00
32.50
33.00
33.50
34.00
34.50
35.00
35.50
36.00
36.50
37.00
37.50
38.00

Figure 4.1-9b

and benthic layer on the continental shelf. The benthic layer over the outer shelf in July 1975 falls in the 26.3 σ-t level and hence provides the most likely isopycnal source of the slope water S-min layer at the base of the slope pycnocline, rather than the main body of cold pool water.

In a uniform distribution of data an oceanic front is indicated by a low density of T/S points (or low volume of water in the frontal T/S area). The low density of data points in the boxed area of Figure 4.1-9a, pierced only by the pycnocline S-max, marks the shelf-slope frontal zone. Hence the pycnocline S-max represents significant cross-frontal exchange.

In July 1975 a volume of very saline water was observed over the slope (Fig. 4.1-9a). This is identified as a warm core eddy and is discussed below.

August 1977 -

The August 1977 cruise T/S relation and historical T/S for August (Fig. 4.1-10a,b) is similar to the July characteristics. The inner, middle shelf water above the seafloor T-min forms the low salinity (31.5-33.5°/oo) component over an impressive temperature range (9° to 22°C). The slope surface water over the main S-max forms the saline (34.5-35.3°/oo) component.

Between the two components are few data points, though cross-over between components occurs over the outer shelf and at some stations over the middle shelf. The outer and some middle shelf waters show the dominant slope water traits, marked by a S-max near 20-22°C and 23.9-24.7 σ-t levels (area B on fig. 4.1-10a), Aug 77

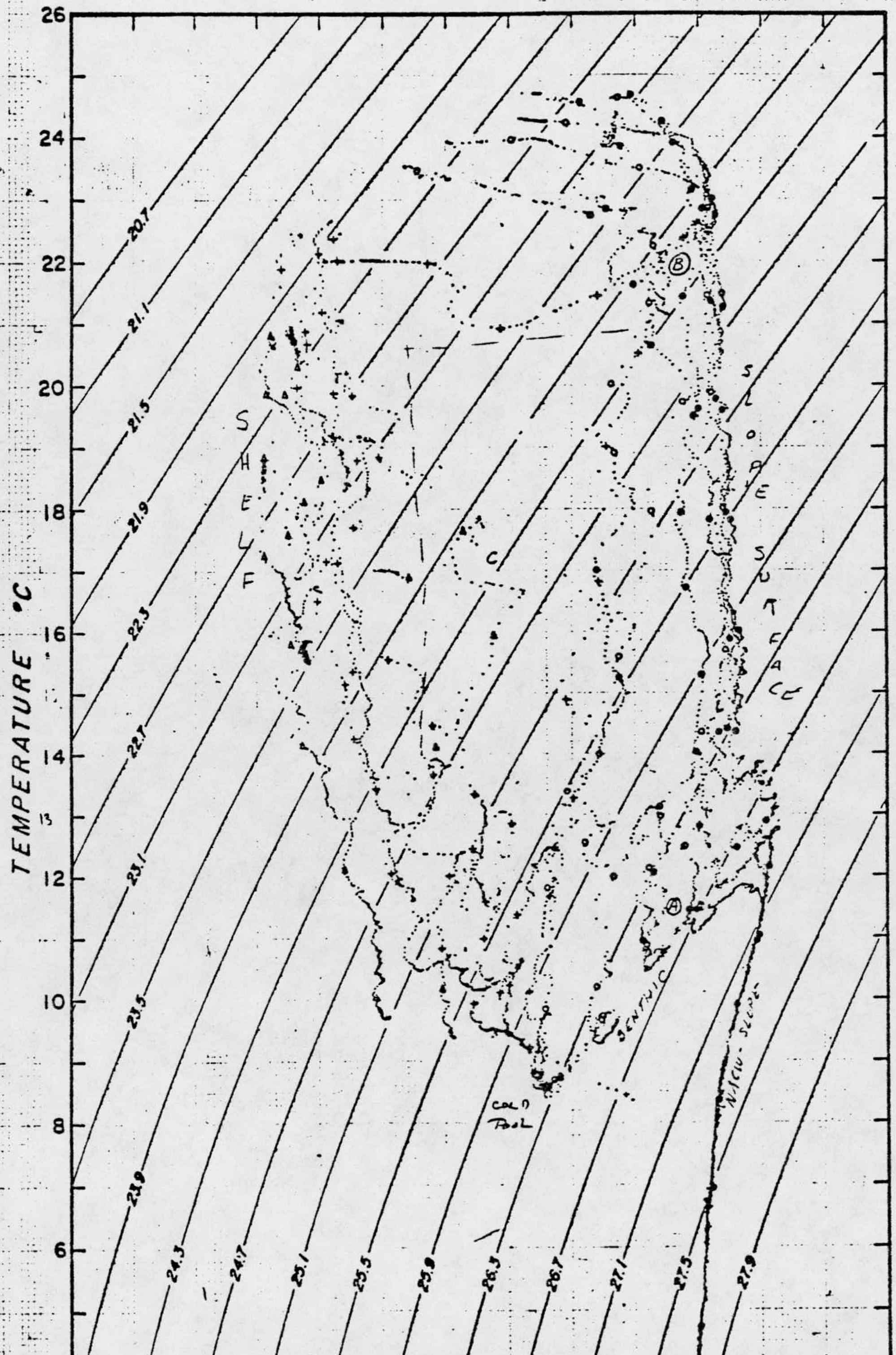


Figure 4.1-10a

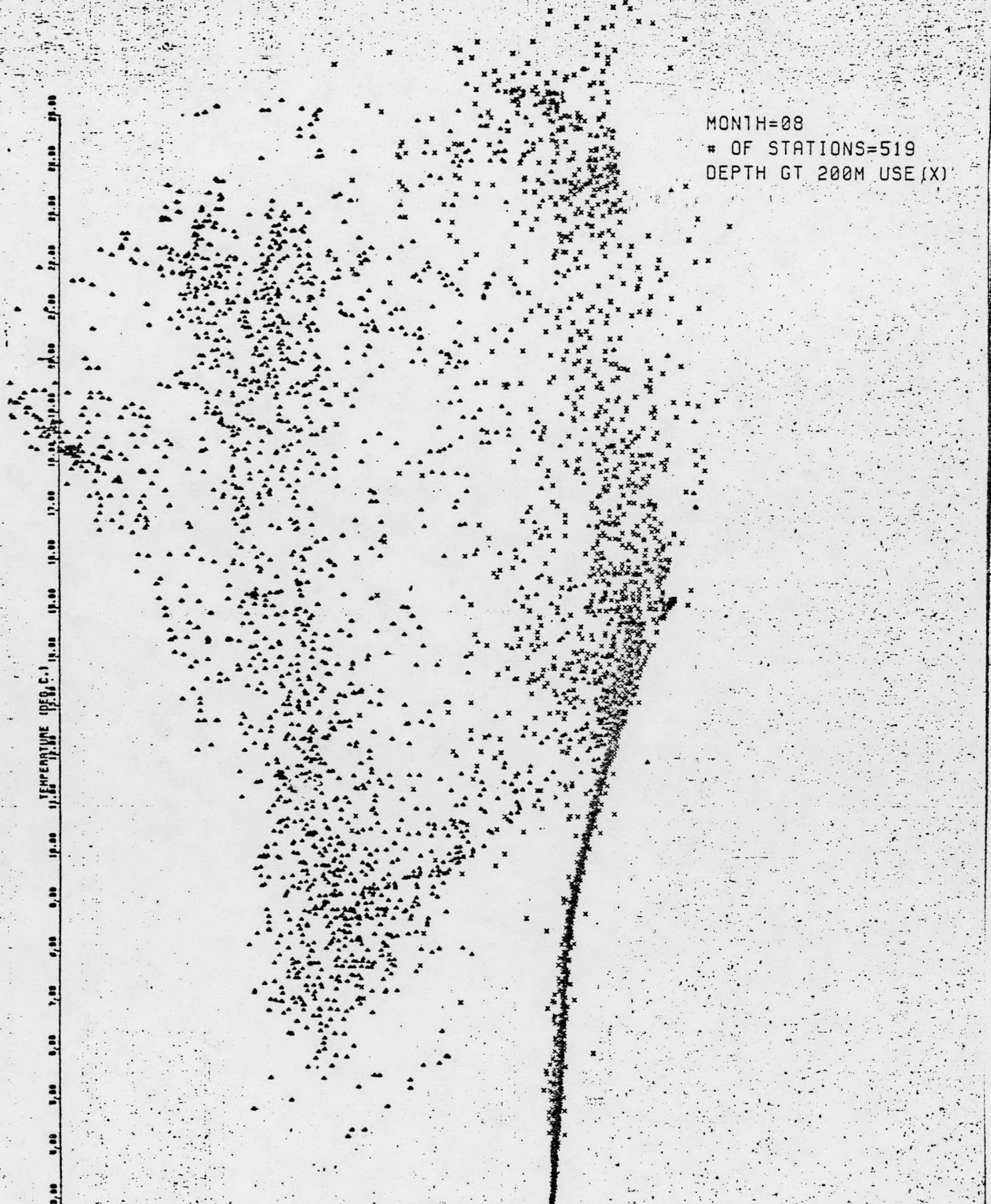


Figure 4.1-10b

in the upper pycnocline, with dominant shelf water characteristics at the pycnocline base marking the seaward extension of the T-min winter remnant cold pool waters near 26.3-26.7 σ-t levels.

The slope water has two T/S areas influenced by the shelf water: the surface low salinity layer, and a low salinity layer in the same σ-t levels marking the seaward T-min extension.

The inner shelf T/S relation of station 17 displays some excursions into the T/S void between the shelf and slope water. While this excursion (area marked C on fig.4.1-10a) occurs at 16-18°C, its density is 23.9-24.7 σ-t which is identical to the density range of the slope water dominated pycnocline S-max. This is taken as evidence that shoreward isopycnal spreading of slope waters characteristic in the upper pycnocline extends to the inner shelf regions.

The August section does not show a well developed shelf-slope frontal zone. However, the near void of T/S points in the boxed region is suggestive of a frontal region. As in the July 1975 situation, the pycnocline S-max represents significant cross frontal exchange.

October 1974

The VEMA 32:01 data obtained in October 1974 is shown in T/S space on figure 4.1-11a, with the historical data shown in figure 4.1-11b. The October 1974 oceanography has been discussed by Gordon et al., 1974.

In October the surface mixed layer deepens as heat is removed by the atmosphere. The lower layers of the thermocline

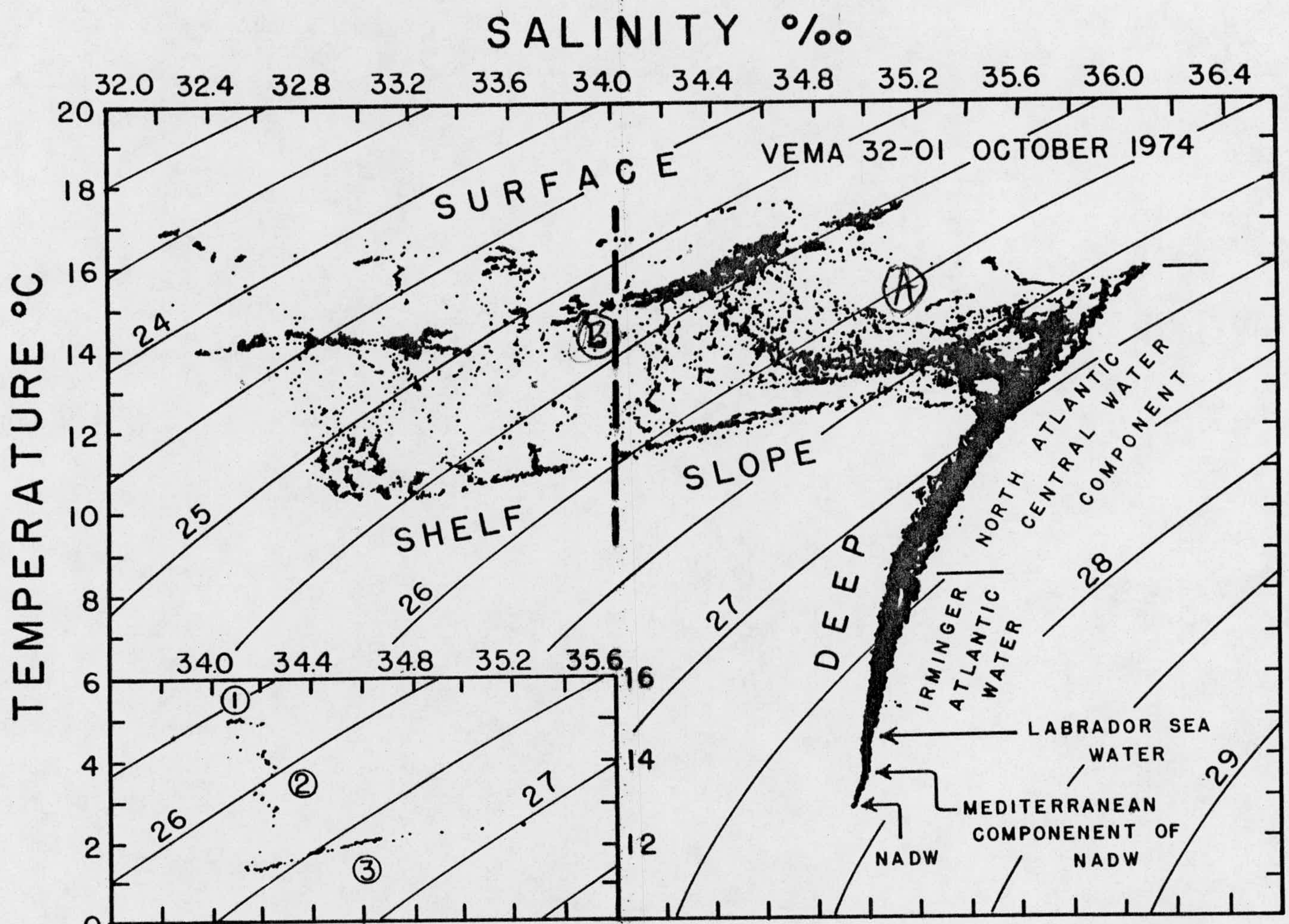


Figure 4.1-11a

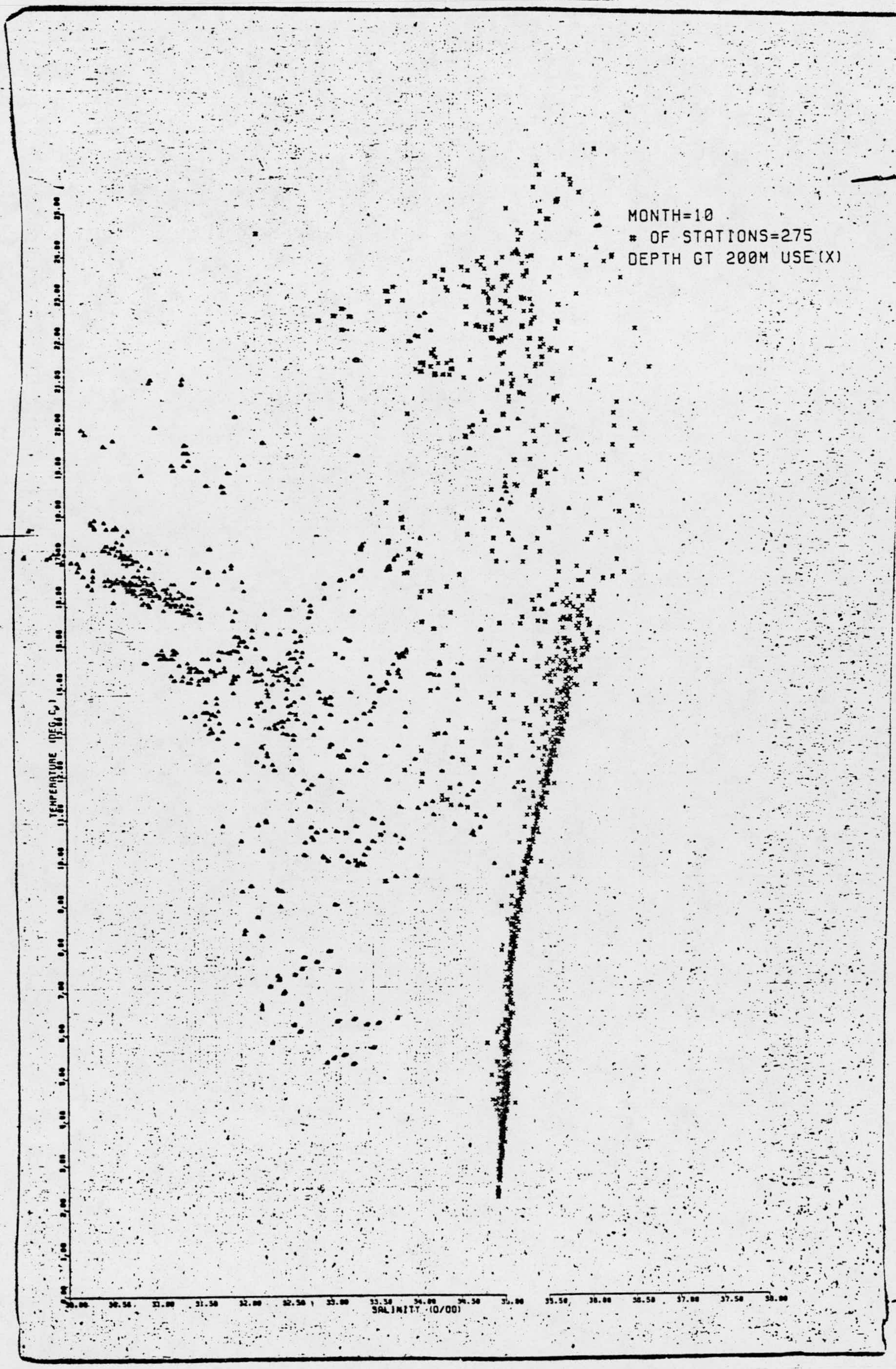


Figure 4.1-11b

remain. Not until late in November is the summer thermocline removed.

The subsurface S-min of the slope region marking the seaward extent of shelf water into the slope pycnocline (area A of Fig. 4.1-11a) remains, as does the outer shelf remnant of the pycnocline S-max (area B of Fig. 4.1-11a). Low salinity surface water is observed throughout the area as the accumulated river water in the summer upper mixed layer is mixed downward by the autumnal convection.

(D) Cold Pool Water

A distinctive hydrographic feature of the New York Bight is the pocket of cold water, called the cold pool, found near the shelf break during the summer. Whether the cold pool is the remnant of local winter cooled water, or whether it is renewed from the Gulf of Maine, is a continuing controversy. We have used the historical data sets along with our own data sets to investigate the formation and dissipation of the cold pool.

During April and May the shelf cold water is capped by a rapidly forming pycnocline. The near shore water is heated to the shelf floor by wind and tidal mixing. The cold pool is bound seaward by slope water.

Few data sets are sufficiently detailed and synoptic to assess the structure and seasonal evolution of the cold pool. The best available is that of Colton et al. (1968), which covers the Gulf of Maine and the northern New York Bight for the years 1965-66. Although the station grid is not sufficiently fine to rule out advection of cold water from the Gulf of Maine via the Great South Channel between the Nantucket shoals and Georges Bank, this is not likely since the coldest cold pool temperatures are persistently found in the New York Bight near the Hudson Canyon.

The mean circulation in the New York Bight has now been evaluated from the long term MESA moorings (Mayer et al., 1979). The near bottom circulation is weaker, 25-40 km/month to the southwest, and contains greater interannual variability than originally suspected (Beardsley et al., 1976). At times the bottom flow reverses direction to the northwest. These results suggest that for the months of May to September when the cold pool is such a distinct feature the bottom water near the Hudson Canyon originated most likely during the previous winter within the New York Bight.

The longevity of the cold pool, therefore, would seem to depend primarily on local mixing processes. In 1965 the cold pool persisted through September, while in 1966 it disappeared in August, in spite of the fact that the March (winter) conditions were similar both years. In 1965 the seasonal evolution of the cold pool in T-S space was very close to being isopycnal, whereas in 1966 the evolution was more isohaline. It is suggested that both vertical and isopycnal mixing processes are important, but to varied degress of relative intensity in different years. In 1966 the cold pool evolution was nearly isopycnal until mid summer, when weakening of the pycnocline results in a vertical flux of heat, sufficient to severely attenuate the cold pool.

Ketchum and Corwin (1964), studying the cold pool evolution in 1957 to 1959, also find the T/S changes are produced by a combination of vertical and horizontal (isopycnal) processes, and the ratio between the two values from year to year.

In 1977 there were four sets of data from which the evolution of the cold pool water and of the linear T/S component of the benthic layer can be defined (Fig. 4.1-12; Fig. 4.1-1 shows the station positions). The linear T/S line slowly warms and its gradient becomes less steep (smaller T:S ratio). At 33.5°/₀₀ the total temperature increase amounts to over 6°C. Warming is expected, since there is no source of cold water to maintain the cold pool water, as local convection stops by April and any possible connection with Gulf of Maine Intermediate Water (which Hopkins and Garfield, 1979, suggest is the source of the New York Bight cold pool water) is apparently cut off.

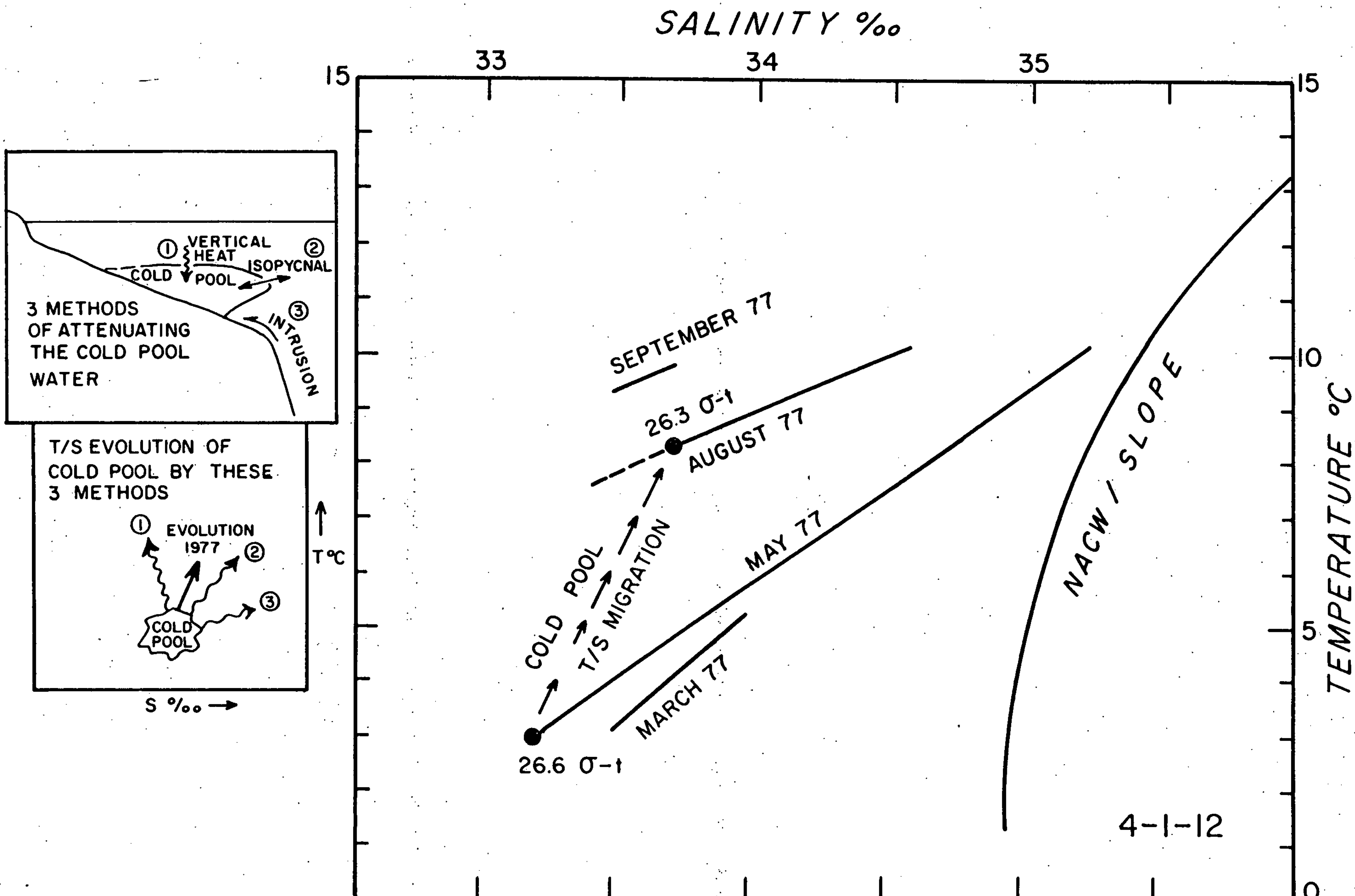
Warming or attenuation of the cold pool water can come about in three ways (represented schematically in Fig. 4.1-12):

1. vertical flux of heat across the pycnocline;
2. isopycnal mixing with slope surface water;
3. benthic layer intrusions of NACW-slope water.

The cold pool water must be mixed or replaced (a question of the scale of the exchange as the distinction of advection and diffusion blurs) by warmer water. Certainly some loss is expected by the isopycnal process (item 2), since the T/S evolution of the cold pool water is either isopycnal (1965), or nearly so (1966 and 1977), and a significant concavity in the slope water T/S relation (area A in previous T/S figures) is observed just above the main S-max. However, vertical flux of heat is also of some importance, in that the cold pool density does decrease somewhat. The vertical heat flux is given by:

$$C_p K_z \frac{\Delta T}{z} = \text{downward heat flux cal/cm}^2\text{/sec}$$

Using a characteristic $C_p K_z$ of 0.1 cal/°C·cm·sec (as suggested by



SALINITY ‰
33
34
35
15
15
10
5
0
TEMPERATURE °C
SEPTEMBER 77
26.3 σ-t
AUGUST 77
MAY 77
MARCH 77
COLD POOL
T/S MIGRATION
26.6 σ-t
NACW / SLOPE
4-1-12
① VERTICAL HEAT
② ISOPYCNAL
③ INTRUSION
COLD POOL
3 METHODS OF ATTENUATING THE COLD POOL WATER
T/S EVOLUTION OF COLD POOL BY THESE 3 METHODS
EVOLUTION 1977
T °C
S ‰

Figure 4.1-12

the radon results) and a summer thermocline of $7.7x10^{-3}$ °C/cm, a heat flux of $7.7x10^{-4}$ cal/cm^2/sec is determined. This is enough heating to warm 20 meters of water by 1°C/month, which is about the warming rate at the 33.5°/₀₀ isohaline observed in 1977.

While cold pool water is exchanged with slope water in near isopycnal process, significant attenuation by cross isopycnal, effective vertical mixing with the surface and pycnocline shelf waters is expected. The K_z=0.1 may represent an upper limit, since the isopycnal process supplies some of the heating.

Because of the large perturbation in the position of shelf/slope water front, and the similar scale size of the horizontal gradients and turbulent motion, a comparable number for lateral mixing is difficult to calculate and probably meaningless. Yet, these lateral processes are an important means by which the bottom water on the shelf is modified.

Mixing of cold pool waters with benthic layer intrusions (item 3) may not be important as a source of heat/salt to mix with the cold pool water, but it is important in inducing the near linear T/S layer below the cold pool T-min extension.

The foot of the shelf-slope front over the outer shelf is marked by increasing temperature and salinity as the seafloor is approached. This must be maintained by slope water intrusions. The extrapolation of the linear T/S relation characteristics of this component of the benthic layer shows it to meet the NACW-slope T/S curve near the local main S-max point, suggesting this is the probable source. The other low salinity mixing component is the cold pool water. Since the cold pool water does not become substantially more saline, the cold pool volume does not incorporate the NACW-slope water. The mixture, expressed by the linear T/S benthic layer, must move seaward.

It is concluded that the main body of the cold pool water is both made warmer by vertical mixing and made warmer and saltier by isopycnal process. As to which is dominant is not known, though yearly variation in relative importance is expected. In addition, the cold pool water volume may be reduced as sections calve into the slope region (Wright 1976), and as volumes mix with benthic intrusions of saline water and spread seaward.

The initial density of the cold pool water may be critical in determining its fate in the stratified period. When it is dense it would interact with the more voluminous sub-pycnocline slope waters, and hence may be mixed isopycnally) at a more rapid rate with the warmer-more saline slope water. When the cold pool water is less dense, it would be in isopycnal communication with the small volume lower pycnocline on the shelf and hence can be a more persistent feature.

The density typical of the lower pycnocline on the slope is 25 to 26 σ-t, with 26-27 σ-t being more typical of the sub-pycnocline (but above the main S-max) layer. A σ-t unit change in the cold pool density would be accompanied by a 6°C variation in the end of winter cold pool temperature (at 33.5°/oo). This is about the maximum variation observed since 1956 (fig. 4.1-7).

Therefore it is possible to develop some model for cold pool evolution during the summer based on its initial end of winter density.

(E) <u>Cross Shelf Mixing Model</u>

The New York Bight T/S structure for the various periods covered by the DOE field work suggests patterns of cross-shelf exchange processes. Naturally, inter annual variability and long shore processes may be of some importance in modifying these generalities. The overall pattern of cross shelf circulation is given in schematic form in figure 4.1-13. It represents an update of the cross shelf exchange pattern, first presented by Gordon et al., 1976.

The structure of the winter T/S shelf and slope surface water is discussed in the January 1976 section above and is not to be repeated here.

The stratified pattern is dominated, away from the upper and lower turbulent boundary layers, by isopycnal processes. The slope surface water dominates the upper part of the shelf pycnocline, manifested by the pycnocline S-max. The cold pool waters or linear T/S layer of the benthic layer dominate the lower or base of the pycnocline of the outer shelf and slope surface water.

This dominance may be explained by the varied volumes of water between isopycnal surfaces. In a pycnocline where the vertical density gradient is large the volume (depth increment) between isopycnal surfaces is less than the volume between the same isopycnal surfaces, where they fall outside (above or below) the pycnocline. Therefore, the T/S properties of the large volume of water would dominate the properties of the small volume within the pycnocline. Molinelli (1978) used a similar argument in explaining a thermohaline feature near the Antarctic polar front.

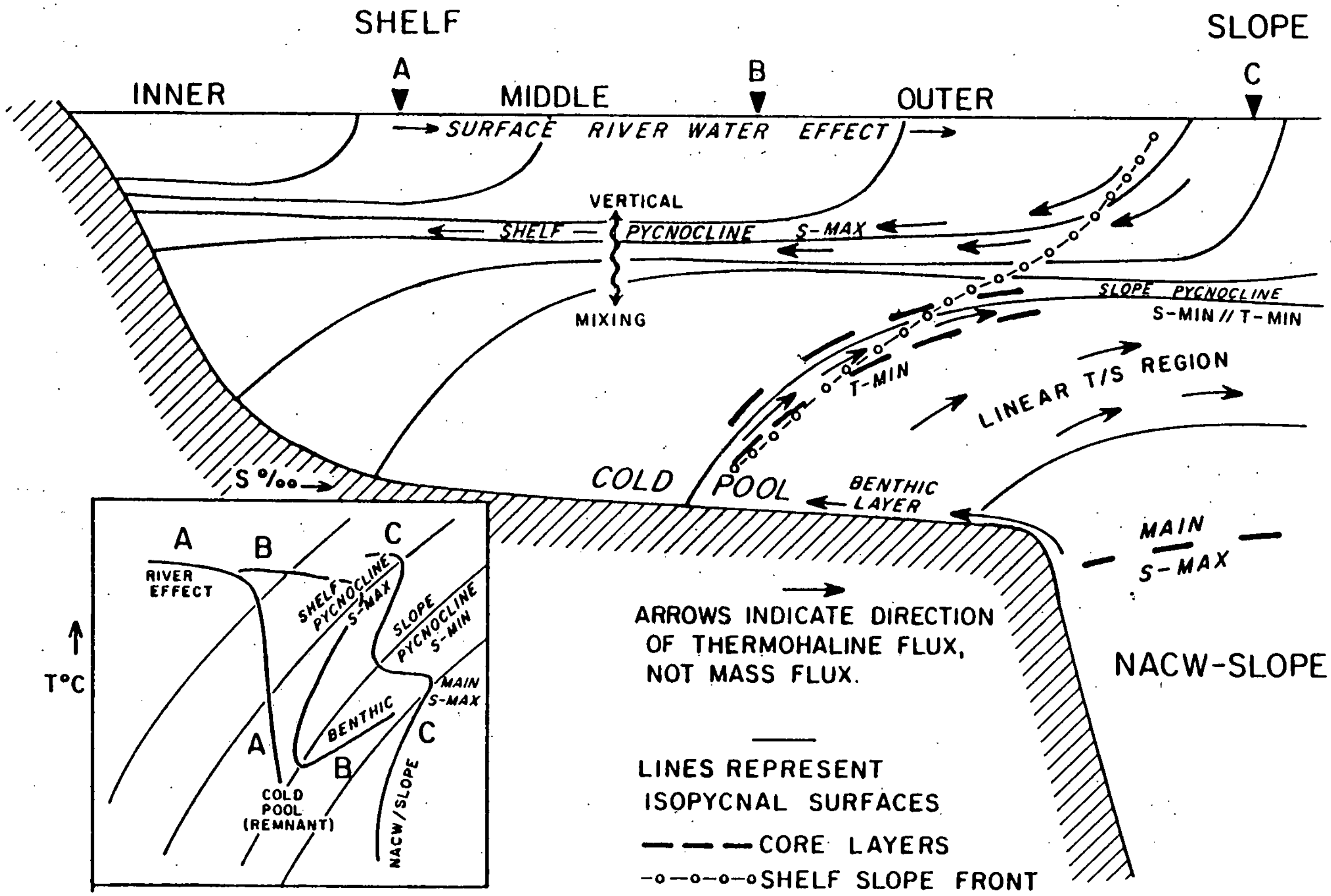

SHELF
SLOPE
INNER
A
MIDDLE
B
OUTER
C
SURFACE RIVER WATER EFFECT
VERTICAL
SHELF
PYCNOCLINE
S-MAX
MIXING
SLOPE PYCNOCLINE
S-MIN // T-MIN
T-MIN
LINEAR T/S REGION
S ‰
COLD POOL
BENTHIC LAYER
MAIN S-MAX
NACW-SLOPE
ARROWS INDICATE DIRECTION OF THERMOHALINE FLUX, NOT MASS FLUX.
LINES REPRESENT ISOPYCNAL SURFACES
CORE LAYERS
SHELF SLOPE FRONT
T°C
RIVER EFFECT
SHELF PYCNOCLINE S-MAX
SLOPE PYCNOCLINE S-MIN
MAIN S-MAX
BENTHIC
COLD POOL (REMNANT)
NACW/SLOPE

Figure 4.1-13

The isopycnals composing the shelf pycnocline are of lower density than those composing the slope pycnocline (Gordon et al., 1976). The shelf pycnocline isopycnals enter the above pycnocline layer over the slope. The sub pycnocline isopycnals of the shelf enter the lower pycnocline levels of the slope. In this way the shelf pycnocline thermohaline is subjected to a dominant slope influence, and the slope pycnocline is subjected to a shelf influence.

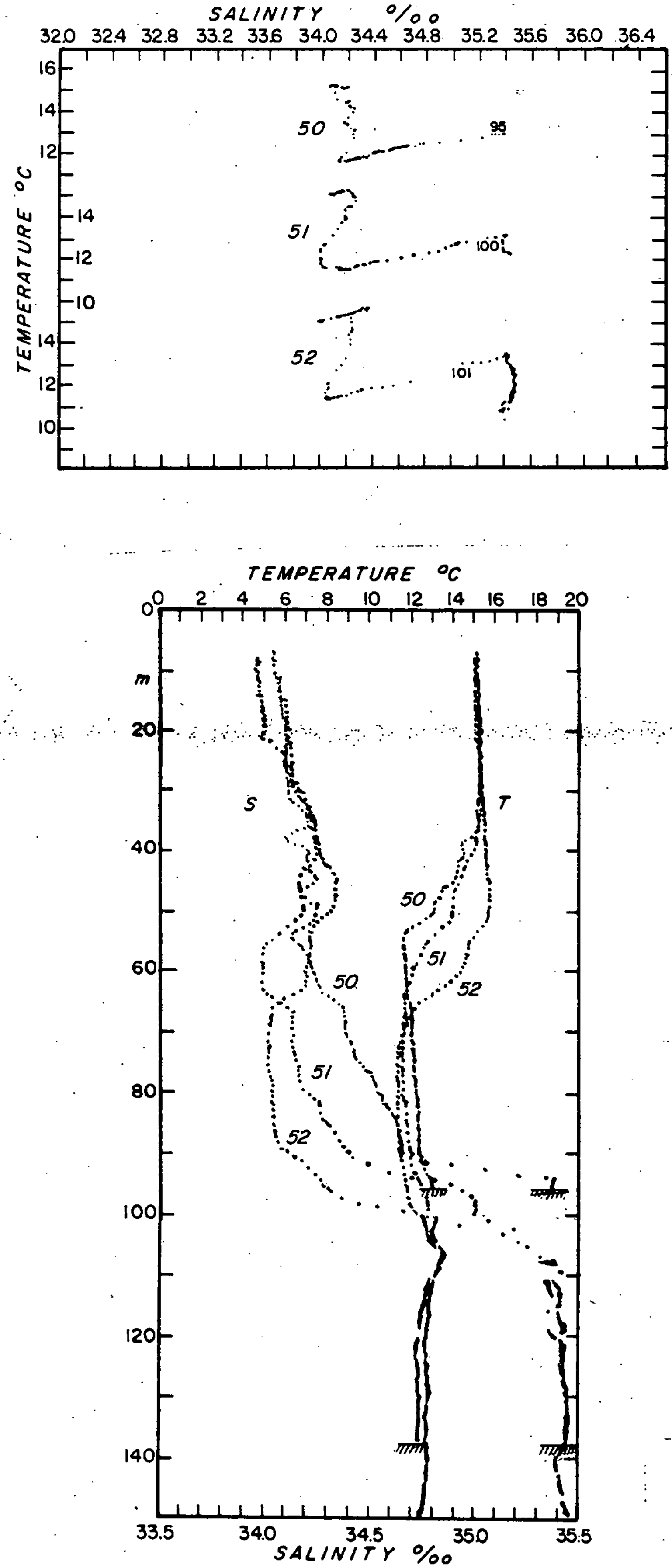
Since the tilt of the isopycnals relative to the pycnocline is not extreme, the slope water induced pycnocline S-max lies in the upper shelf pycnocline and the shelf water induced S-min lies in the lower, near the base of the slope, pycnocline. When the pycnocline S-max extends far inshore (e.g., station 17 of August 1977 data), it is found to be deeper within the pycnocline. If our data set extended further seaward in the slope zone, it is probable that the shelf water influence would occur at shallower pycnocline layers.

Yearly variability in the relative tilt of isopycnals to the pycnocline is expected. The layer below the seaward cold pool extension (marked by an S-min, or isohaline layer, occasionally with a T-min near the base of the seasonal pycnocline of the slope), in which the temperature and salinity increase to the seafloor, over the outer shelf below the foot of the shelf-slope front, or to the main S-max marking the top of the NACW-slope water, is a mixture of remnant winter water and the waters characteristic of the main S-max layer, as discussed above. The cross-shelf exchange pattern in this layer is hypothesized to be shoreward flow of the saline slope water component over the floor of the outer shelf within the lower, well mixed segment of the benthic layer, mixing with the colder less saline shelf water component to form the linear T/S segment of the benthic layer, which spreads seaward.

The saline slope water component is normally found at depths below the shelf break (as shown on the cross-shelf sections shown in section A), hence enhanced vertical mixing and/or upwelling over the shelf break is expected. An internal wave origin for this phenomenon is discussed by Wunsch (1968), and Wunsch, Hotchkiss and Millard (1978).

During the VEMA cruise in 1974, many stations were occupied near the head of the Hudson Canyon. The thermohaline structure of three of these stations (Fig. 4.1-14) shows similar T/S properties of the benthic layer's linear T/S segment. However, they occur at greater depth (about 10 meters deeper) over the Canyon than over the floor of the outer shelf. This suggests upwelling amounting to many meters occurs at least near the Hudson Canyon head.

The benthic layer process may only be responsible for salt introduction into the outer shelf region, since the foot of the shelf-slope break remains nearly fixed to the 60 to 80 meter isobaths. The path of the seasonal evolution of the cold pool thermohaline properties in T/S space lies between isohaline and isopycnal lines, indicating that its demise is principally caused by vertical and isopycnal mixing.



VEMA 32-01
October'74

Figure 4.1-14

(F) The Pycnocline Salinity Maximum

The primary quasi-steady state method of salt introduction to the middle and inner shelf is apparently the seasonal pycnocline S-max, which is integrated into the rest of the water column by vertical mixing, particularly during the autumnal convection.

The salt introduction to the pycnocline S-max represents a cross frontal transfer of slope surface water in approximate isopycnal fashion. It is probable that at the front small scale processes, acting on the thermohaline fine-structure, are not totally isopycnal, as double diffusion may be important (Joyce et al., 1978; Posmentier and Houghton, 1978). In this way the slope salinity is "stepped-down" to a slightly higher density value over the shelf than its slope water source.

As mentioned in last year's report, the pycnocline S-max ends abruptly at a position near the 60-m isobath, close to the foot of the shelf-slope front. Shoreward of this, the pycnocline S-max presence is more sporadic. This prompted the suggestion in last year's report of a mid-shelf front. The significance of the sudden change in the pycnocline S-max near the 60-m isobath is not clear.

An estimation of the significance of salt introduction by the pycnocline S-max can be made as follows -

Vertical mixing acting on the pycnocline S-max would broaden and attenuate the salinity maximum vertically, assuming no renewal. The standard deviation, σ (thickness scale) of the S-max is related to K_z and t (time) by:

$$\sigma^2 = 2 K_z t \text{ (equation 1.26 of Csanady, 1973)}$$

Using a K_z of 0.1 cm^2/sec, the σ would increase with time (from a δ function):

t	1 day	10 days	30 days
σ	1.3 m	13 m	39 m

Therefore, since the pycnocline S-max is characteristically about 10 meters thick, its time scale of renewal must be less than one month.

The pycnocline S-max is at least 1°/₀₀ above the shelf component (see group T/S, particularly for July 1975 and August 1977, where the S-max is about 34°/₀₀, while the shelf water outside of the S-max is near 33°/₀₀ or less).

U ing a 10 meter characteristic thickness of the pycnocline S-max covering one third of the shelf area, then each monthly renewal inputs 5×10^6 gms of excess salt per centimeter of distance along the shelf-slope front, or 1.93 gms salt/sec per centimeter along the shelf-slope front.

The average stream flow onto the shelf of the Mid Atlantic Bight is 47 cm^3/sec per centimeter of coast (Bumpus, 1973). A mixture of this runoff with 1.93 gms salt would "make" seawater with a salinity of about 41°/₀₀. The induced salinity is about 65°/₀₀ in excess of the average shelf water salinity. This may be responsible for the apparent decrease of river water content in the direction of flow to the southwest (Ketchum and Keen, 1955; Bumpus, 1973).

While the above estimation is about 20% above the average shelf salinity, in view of the gross approximations used in this estimate it is significant. Hence, the salt introduction by the pycnocline S-max could be a key factor in compensating for the fresh water input in a steady state condition.

In winter, isopycnals are sloped steeply and no shelf pycnocline occurs. Isopycnal exchange of slope water to the middle shelf is not possible. However, during the winter, cross frontal exchange by small scale processes may continue, but the salt is carried shoreward by non-isopycnal process. The cross-shelf salinity gradient, coupled with a lateral mixing coefficient, may transfer the salt shoreward. Hence, in summer, cross-frontal salt flux feeds salt into the pycnocline S-max, whereas in winter the cross frontal salt flux spreads shoreward by non-isopycnal processes in the full depth of the water column, due to the much larger K_z winter value.

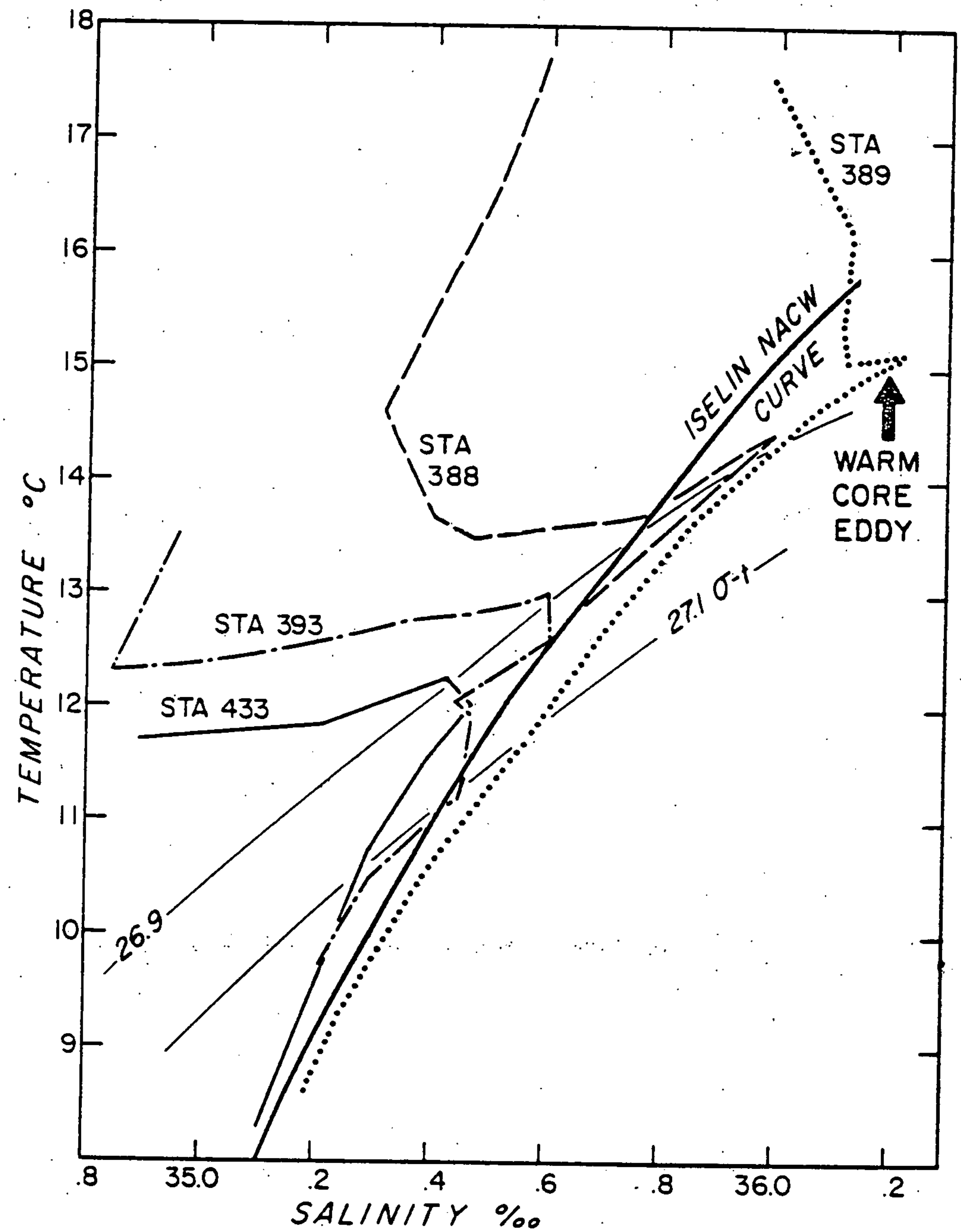
Voorhis, Webb and Millard (1976) determine cross frontal transfer by thermohaline fine structure (small scale exchange) of 1.5×10^{10} gms salt/day·km (1.74 gm/sec·cm), near the value calculated above. In view of the approximations made in the above determinations, as well as in the Voorhis et al. estimates, the agreement is quite good. Voorhis et al. point out that the cross-frontal zone salt transfer by the fine structure can compensate the river input, to form average shelf water.

Smith (1978) suggests that low frequency flux of salt across the shelf-slope front is significantly larger than the small scale exchange value of Voorhis et al. (1976); though one wonders whether, if the actual length of the convoluted front were taken into account, would the total salt transfer by the small scale processes be significantly larger than Voorhis et al. values?

(G) Warm Core Eddy - July 1975

The warm core eddy observed over the slope south of Hudson Canyon during the July 1975 CONRAD cruise, which was briefly mentioned in last year's report, has been studied in more detail. The eddy core has been winter cooled and is distinguished by being located to the right of Iselin's NACW line in a T-S diagram (see Fig. 4.1-15).

The position of the eddy, denoted by the topography of the 15° isotherm shown in Fig.4.1-16, coincides with that shown on the NAVOCEANO Frontal Analysis maps and has a diameter of approximately 100 km centered near station 384. A temperature section from the center to the shelf (Fig.4.1-17) shows the deep mixed core of the eddy with isotherms rising steeply up the slope. Temperature sections derived from other cruises when eddies were not present show roughly horizontal isotherms over the slope, with negligible seasonal fluctuations below 150 m. Using this average thermal structure we calculated the thermal anomalies shown in Fig.4.1-18. The maximum anomaly of 8°C at 400 m depth is comparable to the anomaly structure of cyclonic rings (Hagan et al., 1978). However, along the slope upward isotherm displacements of 40-70 m produce temperature anomalies of -1 to -2°C. These displacements which are greatest where the eddy intersects the slope, are most likely upslope Ekman veering in a bottom boundary layer and not just internal wave distortion. It does, however, seem curious that this boundary effect extends 150 m or more above the shelf floor. A model of the bottom boundary layer by


STA
389
STA
388
ISELIN NACW
CURVE
WARM
CORE
EDDY
STA 393
STA 433
27.1 σ-t
26.9
TEMPERATURE °C
18
17
16
15
14
13
12
11
10
9
.8
35.0
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.6
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36.0
.2
SALINITY ‰

Figure 4.1-15

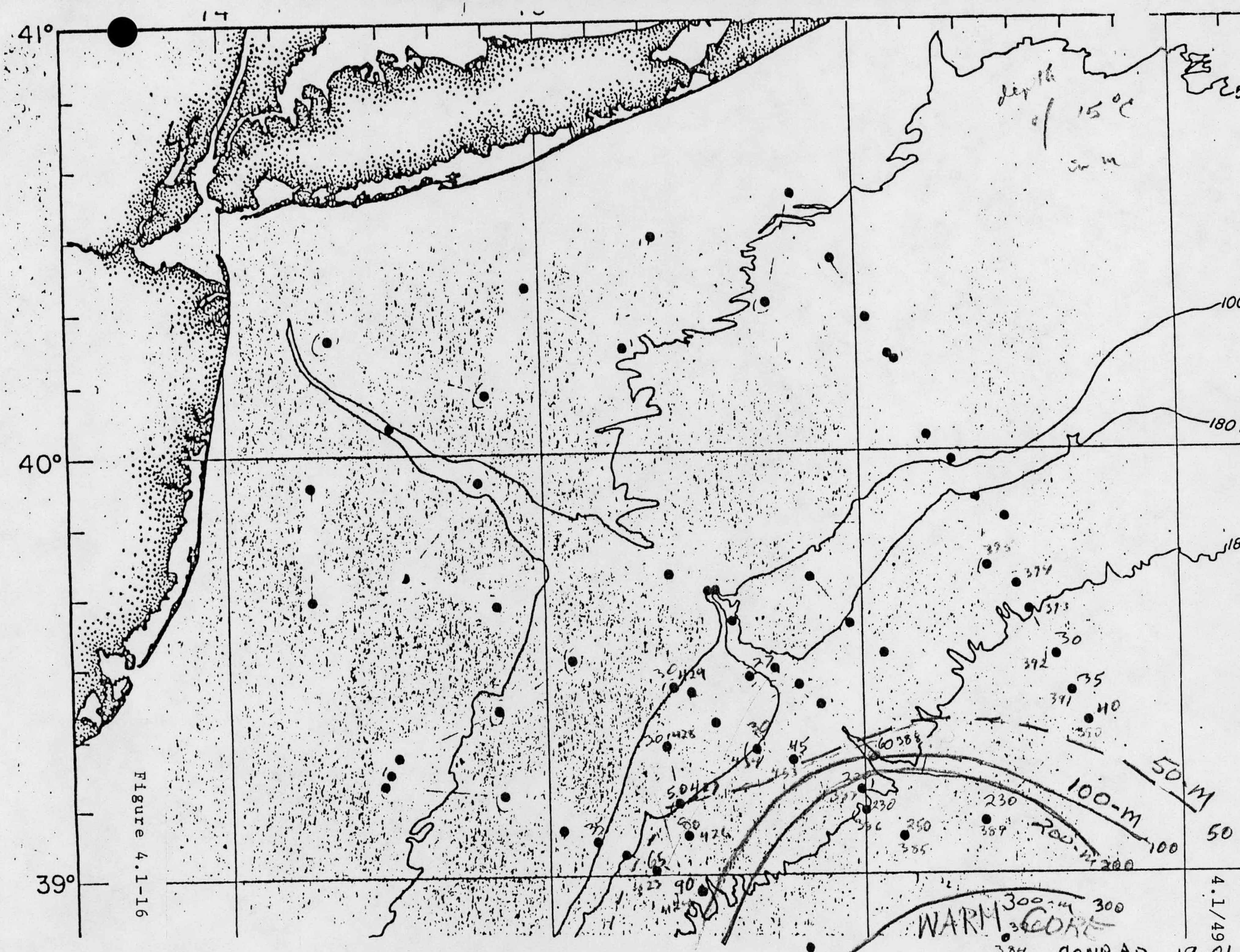
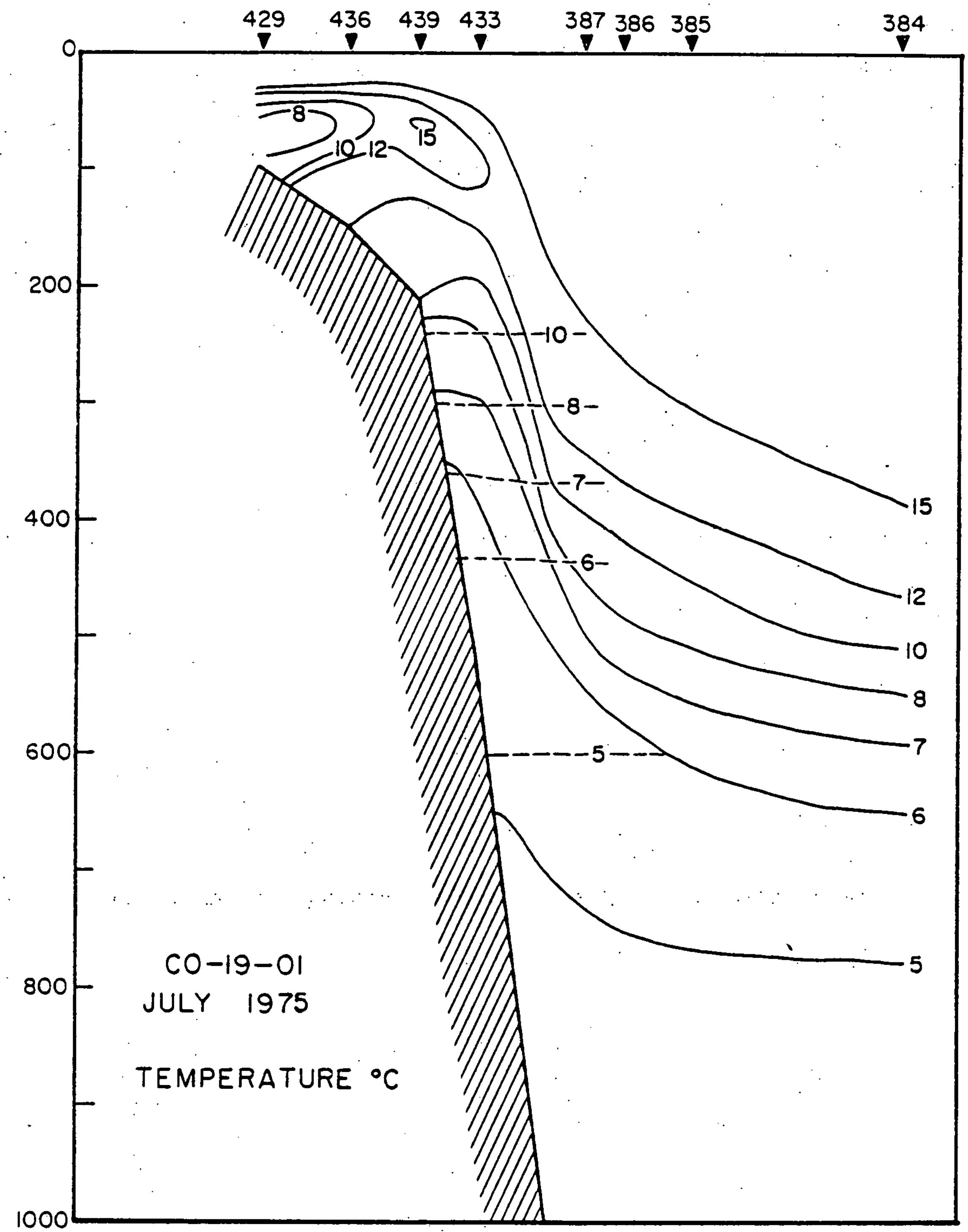


Figure 4.1-16

CONRAD 19-01



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8
10 12
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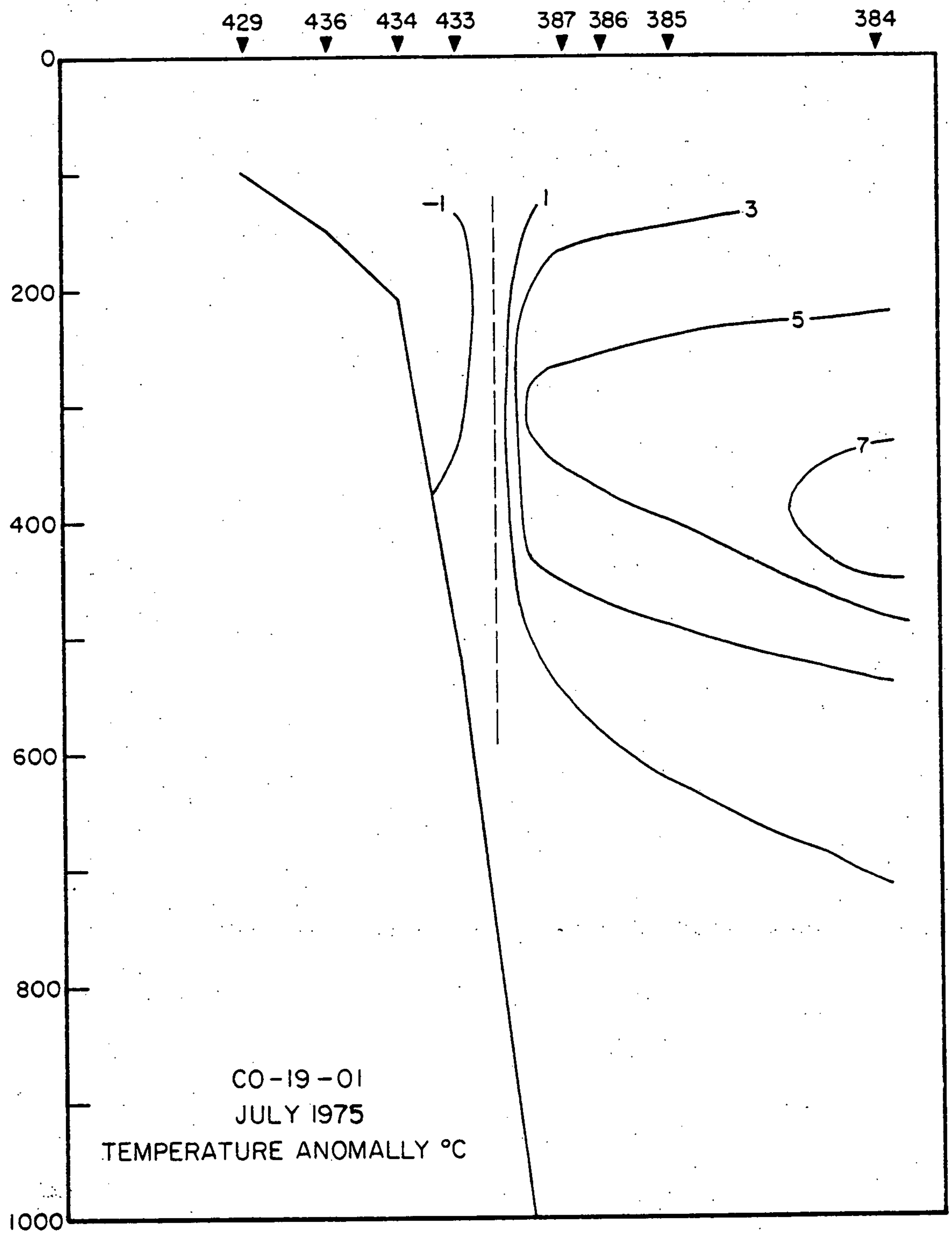
CO-19-01
JULY 1975
TEMPERATURE °C

Figure 4.1-17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434
433
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386
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384
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200
400
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800
1000
-1
1
3
5
7
CO-19-01
JULY 1975
TEMPERATURE ANOMALLY °C

Figure 4.1-18

Weatherly and Martin (1978) for an interior flow of 0.15 m s^{-1} shows a distinct bottom layer with thickness of 9 m for a stratified water column with $N_o=1.25x10^{-2}s^{-1}$, but a more ambiguous layer 50-70 m thick for an unstratified water column, i.e. $N_o=0$. In our case the stratification on the slope is weak, $N_o=4x10^{-3}s^{-1}$, but the interior flow is larger. Saunders (1971) has measured currents .40-.70 m s^{-1} in a warm core eddy. If currents of this magnitude can penetrate the slope region then bottom boundary layers greater than 100 m are possible. However, the temperature profile over the slope, e.g. Sta.433 (Fig.4.1-15), does not show a well mixed region at the bottom.

Our primary interest in these warm core eddies is to determine their role in heat and salt exchange onto the shelf. Because of the apparent upslope flow the temperature on the floor at the shelf-slope break will drop when a warm core eddy is incident on the slope. The S-max also moves upslope, distorting the base of the shelf-slope front. The salinity of the shelf water is so variable that it is impossible with our limited data set to determine whether this results in a net flux of salt onto the shelf.

The primary decay mechanism of Gulf Stream rings is thought to be isopycnal exchange from the core to the surrounding water (Lambert, 1974; Cheney and Richardson, 1976). Such processes are evident in the T-S diagram shown in Fig.4.1-15. Normally shelf water mixes with slope water on or slightly fresher than the NACW curve at 100 m depth. The T-S plot for Sta. 388 crosses the NACW line on the p=26.9 σ_t surface which passes into the eddy core (Sta. 389). The 27.0 σ_t density surface which normally is horizontal over the slope and intercepts the shelf between 120-175 m now dips down to 400-500 m in the eddy core. Thus the shelf waters can communicate isopycnally with a much larger volume of warm saline water.

The role of these warm core eddies in the salt balance in the shelf waters is uncertain. To balance the fresh water input onto the shelf requires approximately 2000 km^3/y. of 35°/oo slope water (Wright, 1976; Gordon, 1977, abstract at 1977 Mid Atlantic Bight Workshop). An equivalent amount of salt is derived from 1940 km^3/y of 36°/oo warm core eddy water. The upper 200 m of an eddy with 50 km radius has a volume of 1560 km^3. Since there is an average of at least 3 eddies incident on the slope per year they alone, if their water is mixed onto the shelf, could easily modify the salt balance.

We observe intrusions of shelf and slope water off and onto the shelf at the perimeter of the eddy similar to but smaller in magnitude to those reported by Morgan and Bishop (1977). The data does not permit an accurate estimate of flux rates. We expect that warm core eddies are more effective at extracting shelf water off the shelf by entrainment than driving slope water onto the shelf, since the turbulent kinetic energy is greater in the eddy than on the shelf and the salinity maximum at 1000 m is below the more energetic currents near the surface of the eddy. The degree to which these intrusions are mixed to produce a net exchange of salt onto the shelf has yet to be evaluated. Given the infrequency of warm core eddies and the fluctuation of salinity on the shelf, one can only speculate on the relative importance of eddy induced shelf-slope water exchanges compared to isopycnal mixing that persists at the shelf-slope front throughout the year.

(H) Temperature-Oxygen Relation

During most of the DOE cruises samples for oxygen concentration determinations were obtained. The T/O_2 relation for October 1974, July 1975, January 1976, August 1977, is given in Figure 4.1-19a,b,c.

Two points are now developed: (1) the migration of the T/O_2 portion of the shelf remnant winter water toward lower oxygen during the stratified period; and (2) the occurrence of a super-saturated layer in the summer thermocline, strongest at near 12°-16°C in July 1975 and above 16°C in August 1977.

(1) The oxygen of the bottom water on the middle shelf in January 1976 is at the saturation level of about 7 ml/l. In July 1975 it is near 7 ml/l, 5 ml/l in August 1977, and in October 1974 it is near 4 ml/l. Assuming the decrease in bottom water oxygen begins with initiation of stratification in late March, an average oxygen decrease of 0.5 ml/l-month (April 1 to September 30) is suggested.

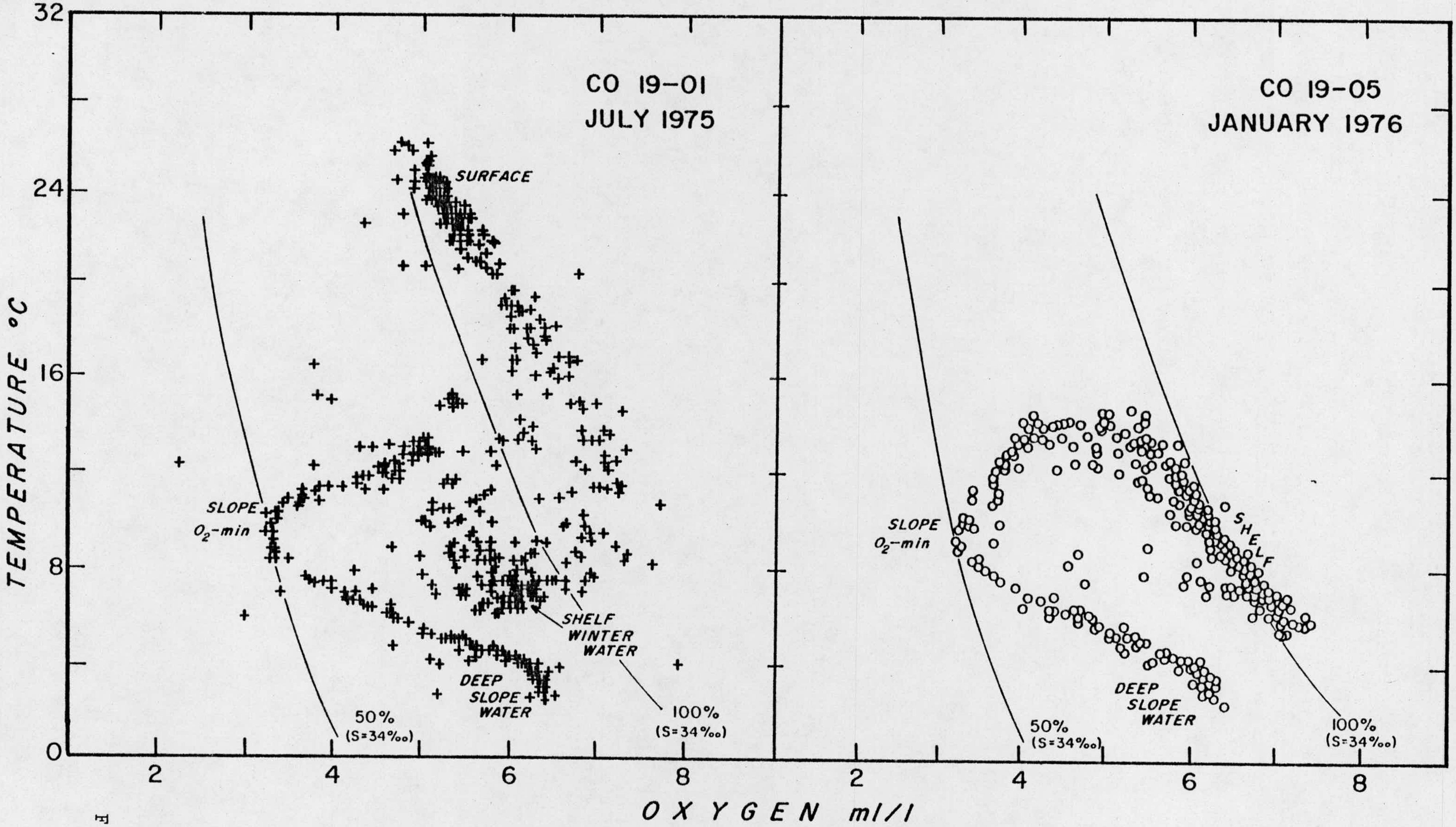


Figure 4.1-19a

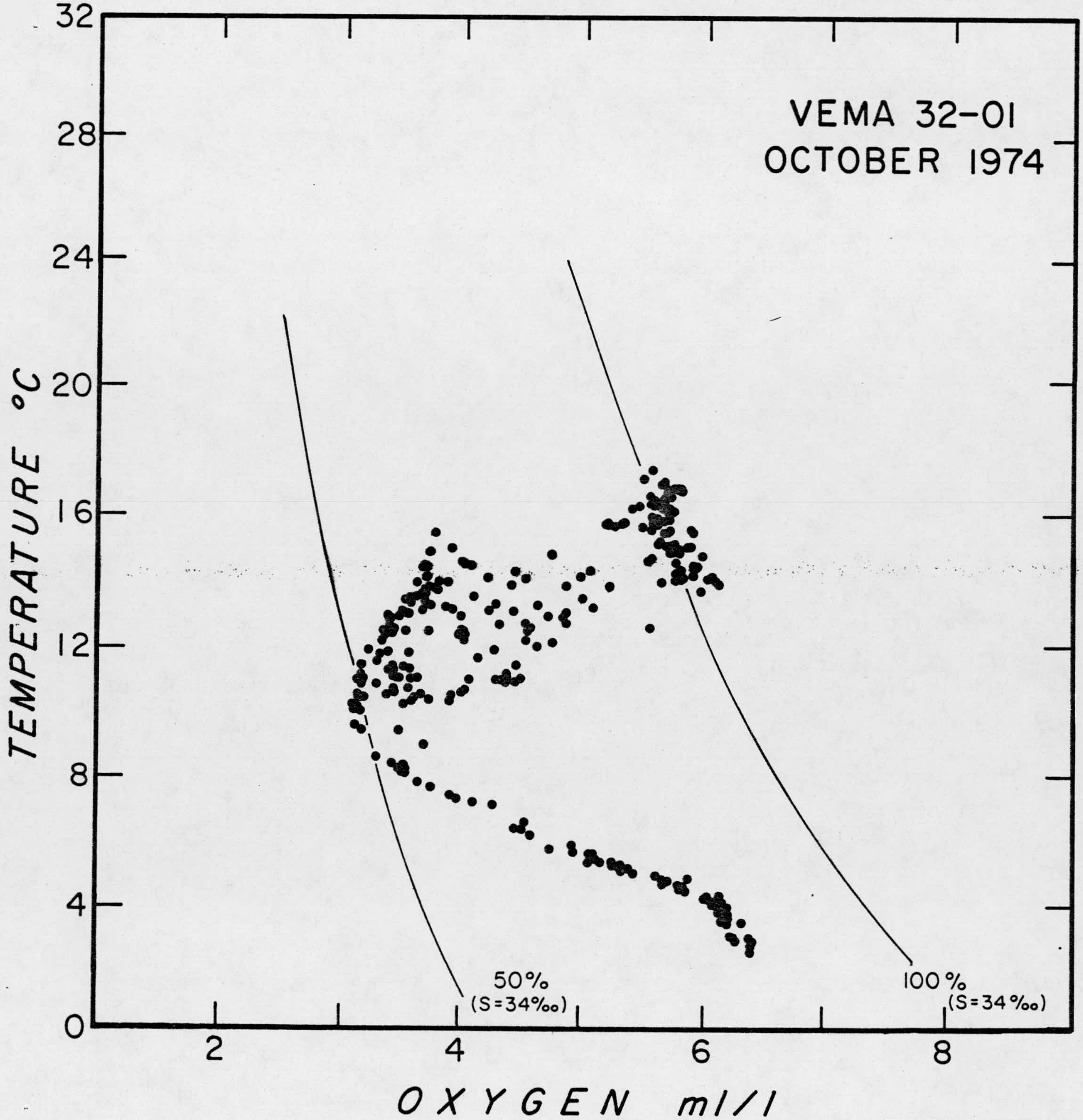


Figure 4.1-19b

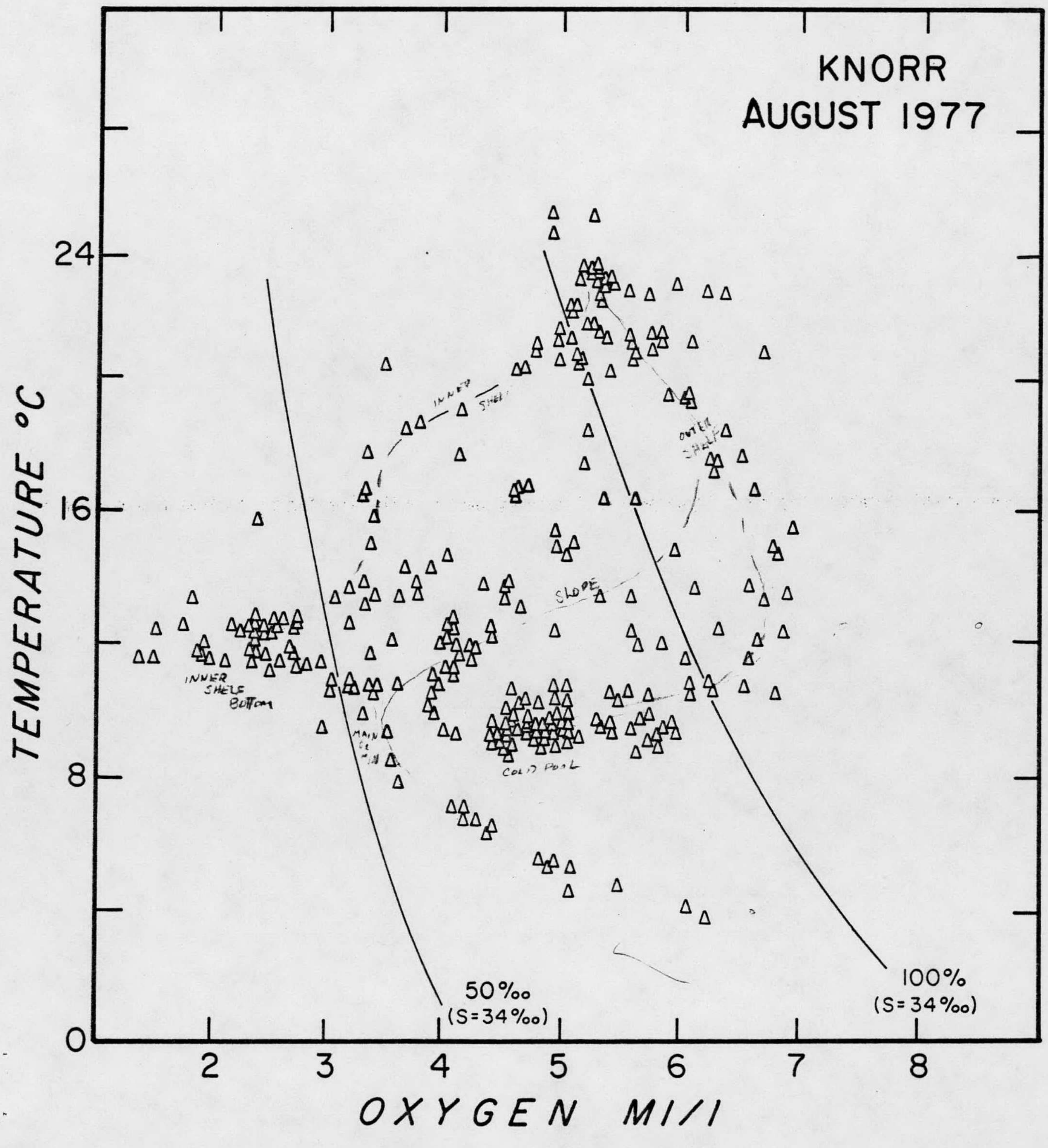


Figure 4.1-19c

Since oxygen is introduced into the bottom water of the middle shelf by vertical diffusion and isopycnal exchange, the observed bottom water decrease is less than the consumption rate due to oxidation of bottom organisms. Hence, the actual oxygen utilization in the bottom layer of the middle shelf is in excess of 0.5 ml/l·month.

The oxygen of the bottom water over the inner shelf, sampled in August 1977, is significantly below the middle shelf bottom water oxygen (about 3 ml/l less). A decrease of about 1 ml/l·month for the inner shelf is suggested (April to August). Higher degree of oxygen utilization on the inner shelf is the probable cause. Again, vertical diffusion oxygen input to the inner shelf bottom water indicates that the actual oxygen utilization in the inner shelf bottom waters is greater than 1 ml/l·month.

(2) The supersaturation in the summer thermocline amounts to 115 to 120% of full saturation. An example of oxygen versus depth, displaying the thermocline O_2-max, is given in figure 4.1-20. The O_2-max is believed induced by a chlorophyll maximum within the shallow shelf thermocline. The high increase of stability restricts the vertical outflux of dissolved oxygen produced by photosynthesis. The stability of the seasonal pycnocline chlorophyll maximum in the face of tidal induced turbulence can be determined using the formulation of Pingree et al., 1978.

$$E = \log_{10} \frac{C_D \frac{4}{3} \pi U_o^3}{h}$$

where U_o is the mean tidal current, h is the water depth and C_D is the drag coefficient (taken as 2.5×10^{-3} by Pingree et al).

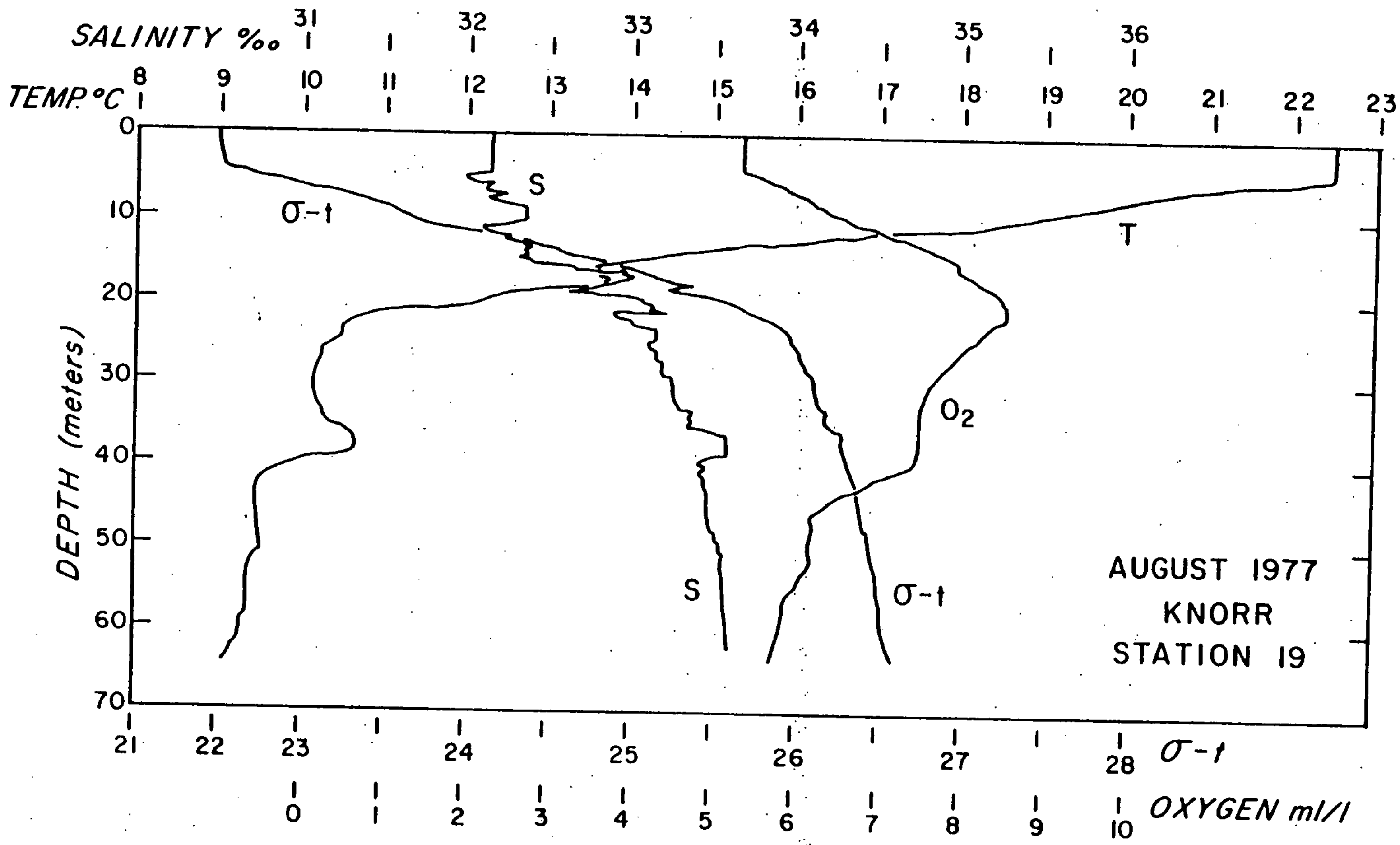

SALINITY ‰
TEMP. °C
DEPTH (meters)
σ-t
S
T
O_2
AUGUST 1977
KNORR
STATION 19
OXYGEN ml/l

Figure 4.1-20

For the northwest European shelf Pingree et al (1978) show that the chlorophyll maximum is persistent when E lies between -1 and -2.

The typical U_o are 8 to 20 cm/sec for the inner shelf (Hansen, 1977). Using 10 cm/sec, E=-2.7; using 20 cm/sec E=-1.8. Hence a chlorophyll maximum is expected in the New York Bight (assuming the same E range applies to the New York Bight).

The appropriate E range is dependent on the vertical density gradients, which in conjunction with the local K_z provide the nutrients.

The loss of the oxygen from O_2-max by vertical diffusion can be estimated for a steady state situation from production rate, determined by observed carbon production (also see the Biology section, in which a companion determination is carried out).

The vertical diffusion equation for steady state is

$$\nabla \cdot \frac{K_z}{\rho} \nabla C + J = 0$$

where J is the O_2 generation rate. If K_z is constant the equation becomes

$$K_z \frac{d^2 O_2}{dZ^2} = -J$$

The carbon uptake is 20 ugm C (1.67×10^{-6} moles C) per day per one ugm/liter of chlorophyll. The range of chlorophyll in the New York Bight thermocline is 1 to 10 ugm/l.

Uptake of 1.67×10^{-6} moles carbon/day liberates 1.67×10^{-6} moles O_2 per day, or 1.93×10^{-10} moles O_2/sec. This converts to 4.32×10^{-7} ml/l·sec of oxygen per unit ugm/l of chlorophyll.

The total range of J is

$$J = 4.32x10^{-7} \text{ to } 4.32x10^{-6} \text{ ml/l·sec}$$

The value of K_z was calculated for five stations in the August 1977 data set. The $\frac{d^2O_2}{dZ^2}$ were determined from the CTD-O_2 data (oxygen corrected for sensor drift using the water bottle data). The results are

Station	chlorophyll concentration ugm/l 1	10
16	0.1	1.0
17	0.137	1.37
18	0.09	0.9
19	0.231	2.31
20	0.175	1.75
Average	0.147	1.47

Hence a range of 0.15 to 1.5 for K_z is necessary to diffuse vertically the oxygen produced in the thermocline. This range is quite similar to that determined using nutrient flux, presented in the Biology section.

Since the oxygen maximum is in the lower part of the pycnocline, this K_z is believed representative of the lower pycnocline. The upper pycnocline is stronger and lower K_z is expected. The K_z=0.1, used for the T/S section, may be representative of the minimum K_z in the summer water column.

This concludes discussion of the results of "New York Bight Stratification".

BOUE TROU - August 1978

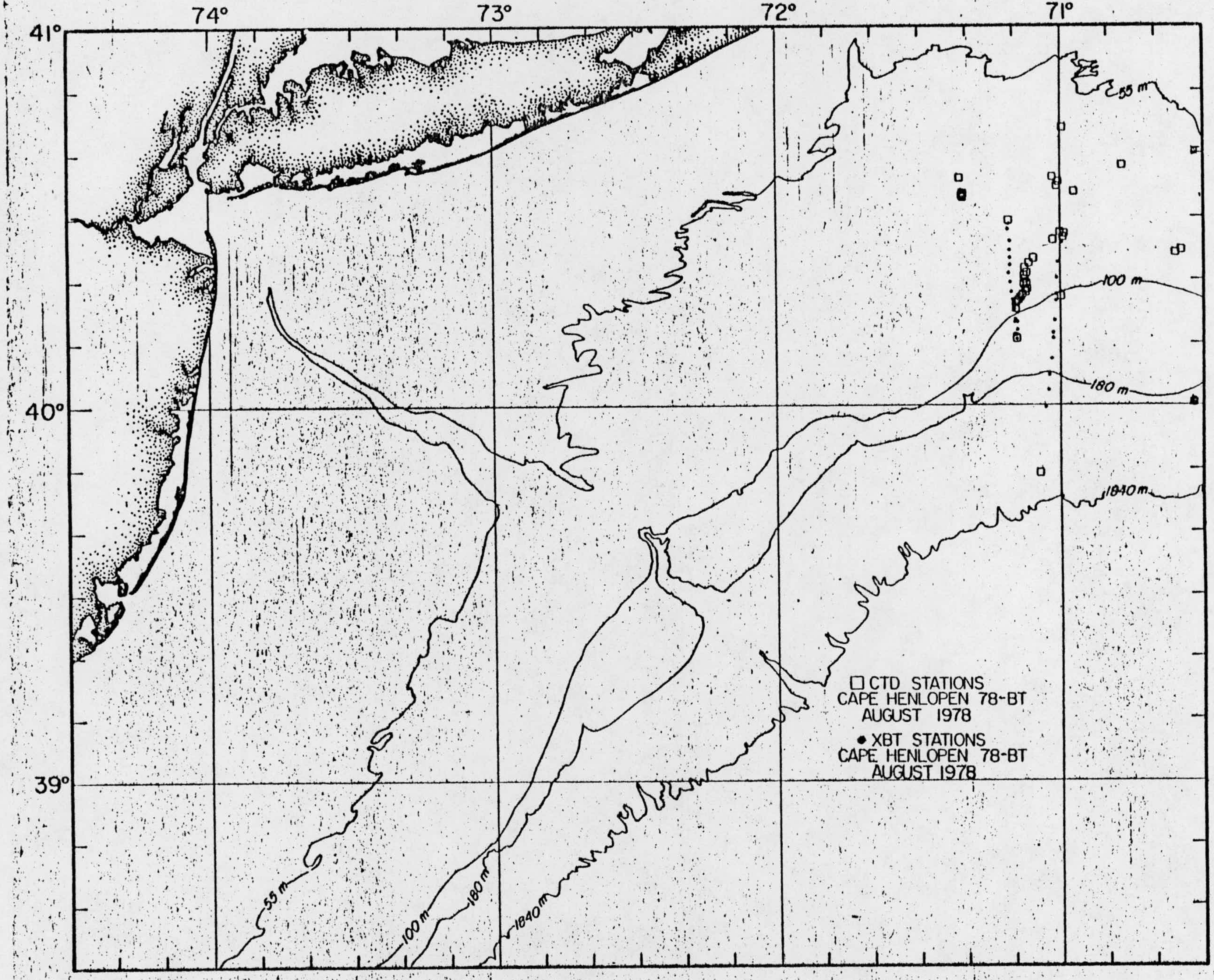
The field work in August 1978 was designed to meet two objectives; mapping sediments and checking for time variability of the excess radon in the mud hole south of Rhode Island and studying the interleaving structure at the shelf/slope water front. The former consisted of widely spaced stations shoreward of the 80 m isobath , the latter consisted of two parallel XBT lines surrounding a line of closely spaced CTD stations from a drifting boat (see Fig. 4.1-21.).

Stratification typical of summer conditions was encountered during the cruise. Surface temperatures 23-25°C extended throughout the region over a strong pycnocline at 20m depth. Beneath the pycnocline cold pool temperatures of 6-7°C were recorded. Although colder than previous years, these are well within the range observed in the historical data. Within the coold pool no temperature fine structure is observed.

We use the 8 and 11 isotherms to demarcate the frontal zone separating the shelf and slope waters. Fig. 4.1-22 shows the intersection of this front on the shelf floor. As anticipated it follows the contours of the 80-90 isobaths.

The XBT sections shown in Fig. 4.1-23 and 24 show the complex interleaving fine structure at the shelf/slope front. The slope water intrusion up the slope under the edge of the cold pool results in a T-minimum layer at 50-60 m depth. The region of intense interleaving extends 10 km seaward from the terminus of the cold pool. We were encouraged at the persistence of this structure and our ability to navigate the ship back into the band of fine structure.

The XBT spacing was sufficient to resolve interleaving structures some of which are continuous over 10 km. Aliasing of the internal


74°
73°
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71°
41°
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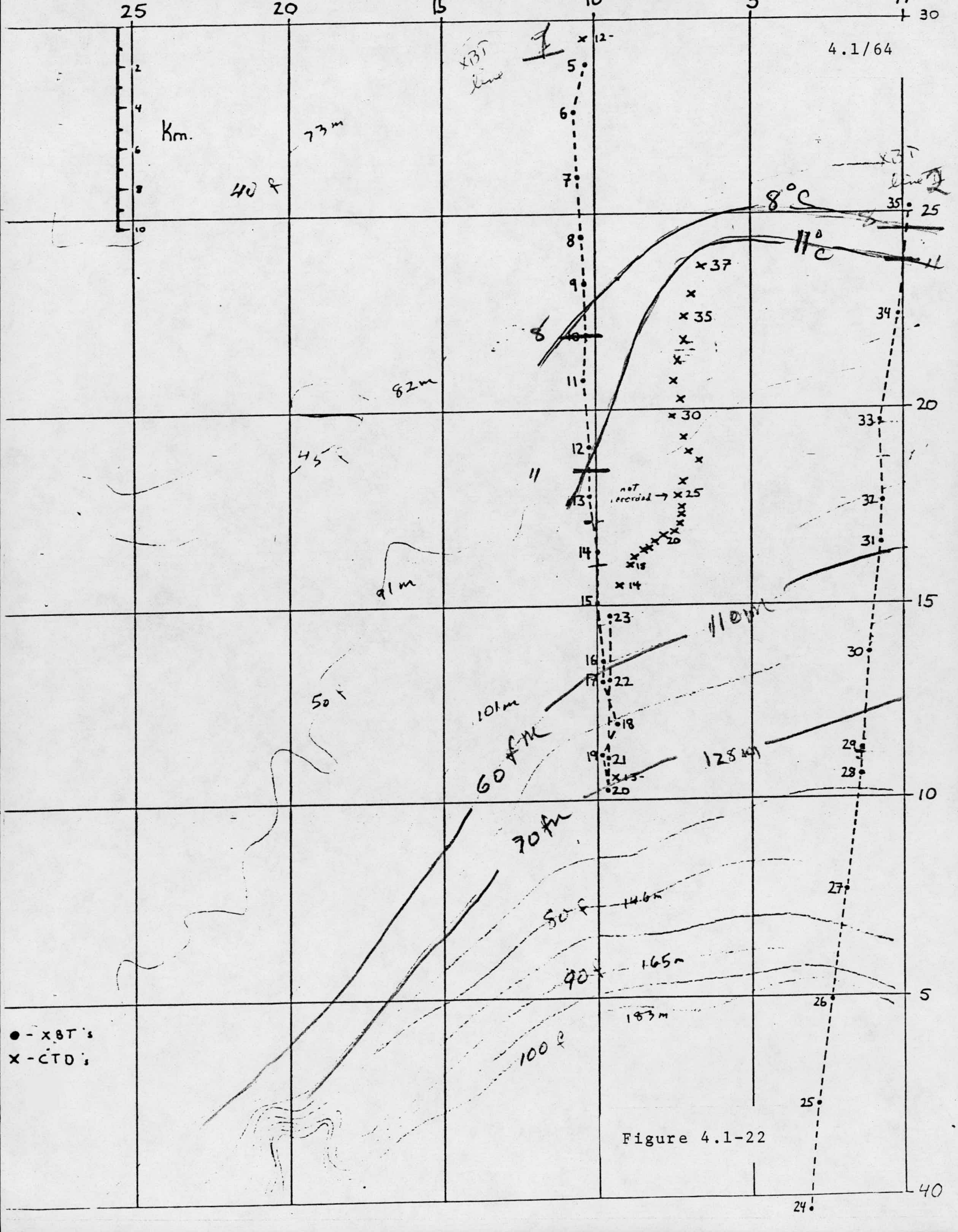
39°
55 m
100 m
180 m
1840 m
55 m
100 m
180 m
1840 m
□ CTD STATIONS
CAPE HENLOPEN 78-BT
AUGUST 1978
• XBT STATIONS
CAPE HENLOPEN 78-BT
AUGUST 1978

Figure 4.1-21



25
20
15
10
5
71
30
25
20
15
10
5
40
Km.
XBT line I
XBT line II
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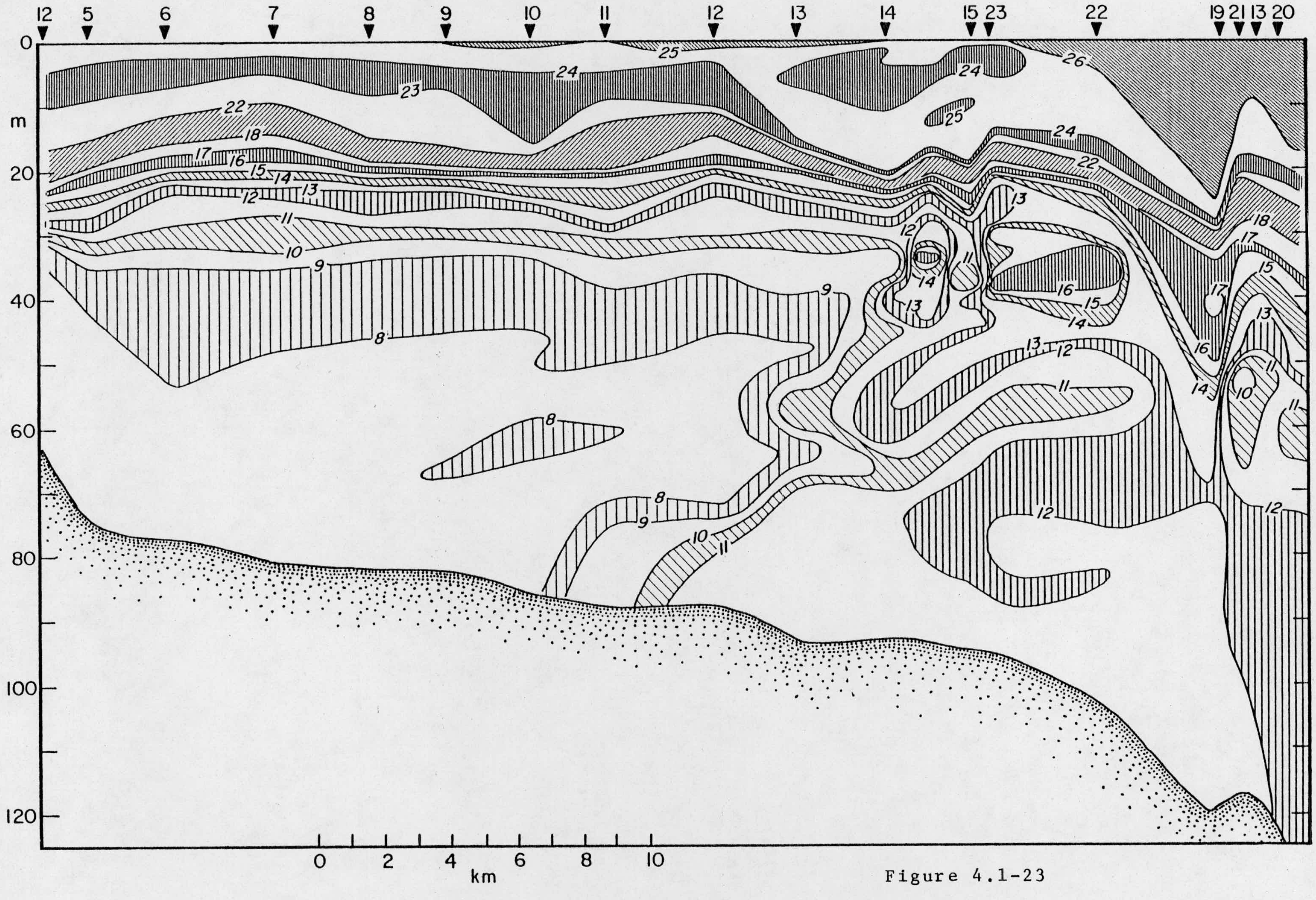
11°C
40 f
50 f
60 fm
70 fm
80 f
90
100 f
73m
82m
91m
101m
110m
128m
146m
165m
183m
not recorded
● - XBT's
X - CTD's

Figure 4.1-22


12 5 6 7 8 9 10 11 12 13 14 15 23 22 19 21 13 20
0
m
20
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26
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18
17
16
15
14
13
12
11
10
9
8

Figure 4.1-23

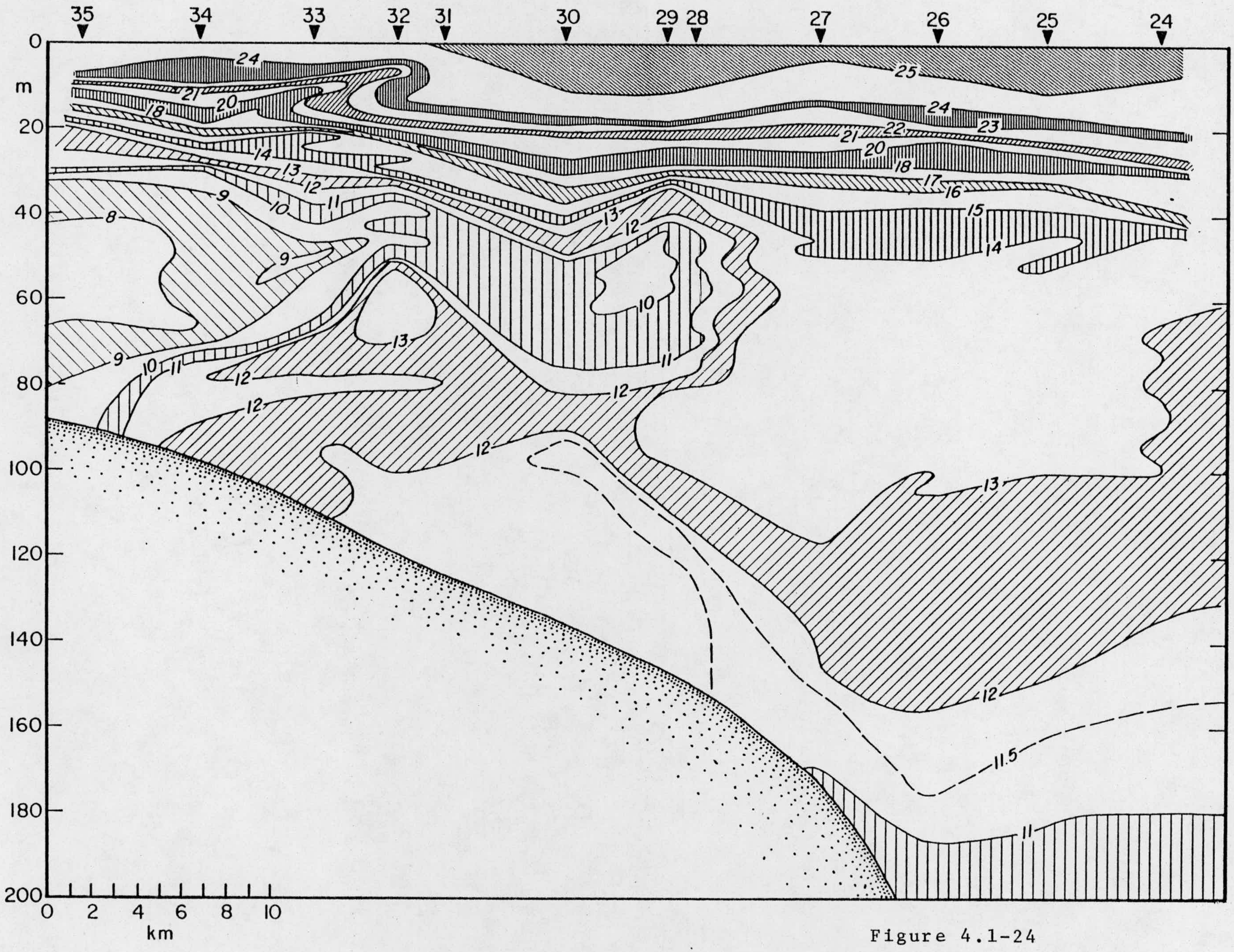

35
34
33
32
31
30
29
28
27
26
25
24
m
0
20
40
60
80
100
120
140
160
180
200
0
2
4
6
8
10
km
25
24
23
22
21
20
18
17
16
15
14
13
12
11
10
9
8
11.5

Figure 4.1-24

wave motion can account for irregular 10-20 m vertical displacements of the structure. There was evidence of much smaller structure and isolated parcels of water.

This smaller scale structure was resolved on the section of closely spaced CTD stations. After completing XBT line 1, we steamed back into the region where fine structure had been previously observed and began CTD casts every 1/2 hour from a drifting ship. From CTD station #15 to #20. The ship drifted slowly parallel to the isobath with an average spacing of 400 m. The ship then started to drift on shore at the same speed. After station 25 the drift speed increased, lengthening the station spacing to 900 m. The temperature section shown in Fig.4.1-25 reveals a complex structure of interleaving intrusions in a highly stratified regime. Some of the apparently isolated parcels of water may be connected by 3-dimensional structures. The salinity structure is compensating, so that the density gradients are vertical, even across the frontal boundary seaward of the cold pool.

A composite T-S diagram of all of these CTD stations (Fig.4.1-26) shows some useful organization, in spite of the apparent confusion. The cold pool and seasonal warming of shelf and slope water are evident. The latter produce isohaline thermoclines. Also the transition between shelf and slope water occurs along "preferred" isopycnals.

For greater clarity the CTD stations are divided into three groups which have distinct T-S patterns (see Fig.4.1-27,28&29). The inner stations 37-34 (see Fig.K) pass through the cold pool, but also have intrusions of slope water along the 24.5 σ_t surface. Never before have we seen such extremes of water type at a single station. The middle stations #33-26 (Fig.4.1-28) feature a thick halostad between 24.5-26 σ_t as a result of seasonal heating of slope water. The outer stations

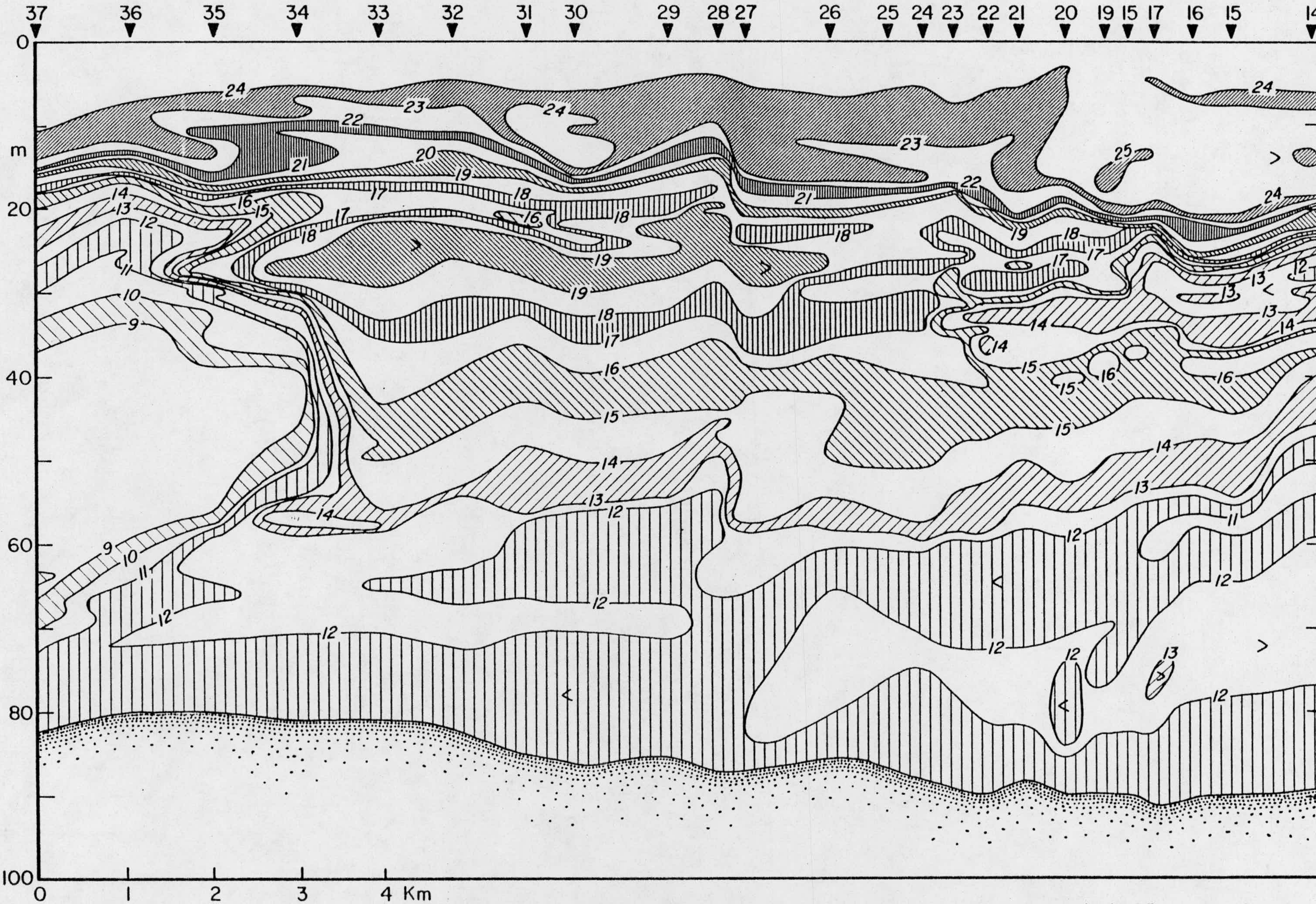
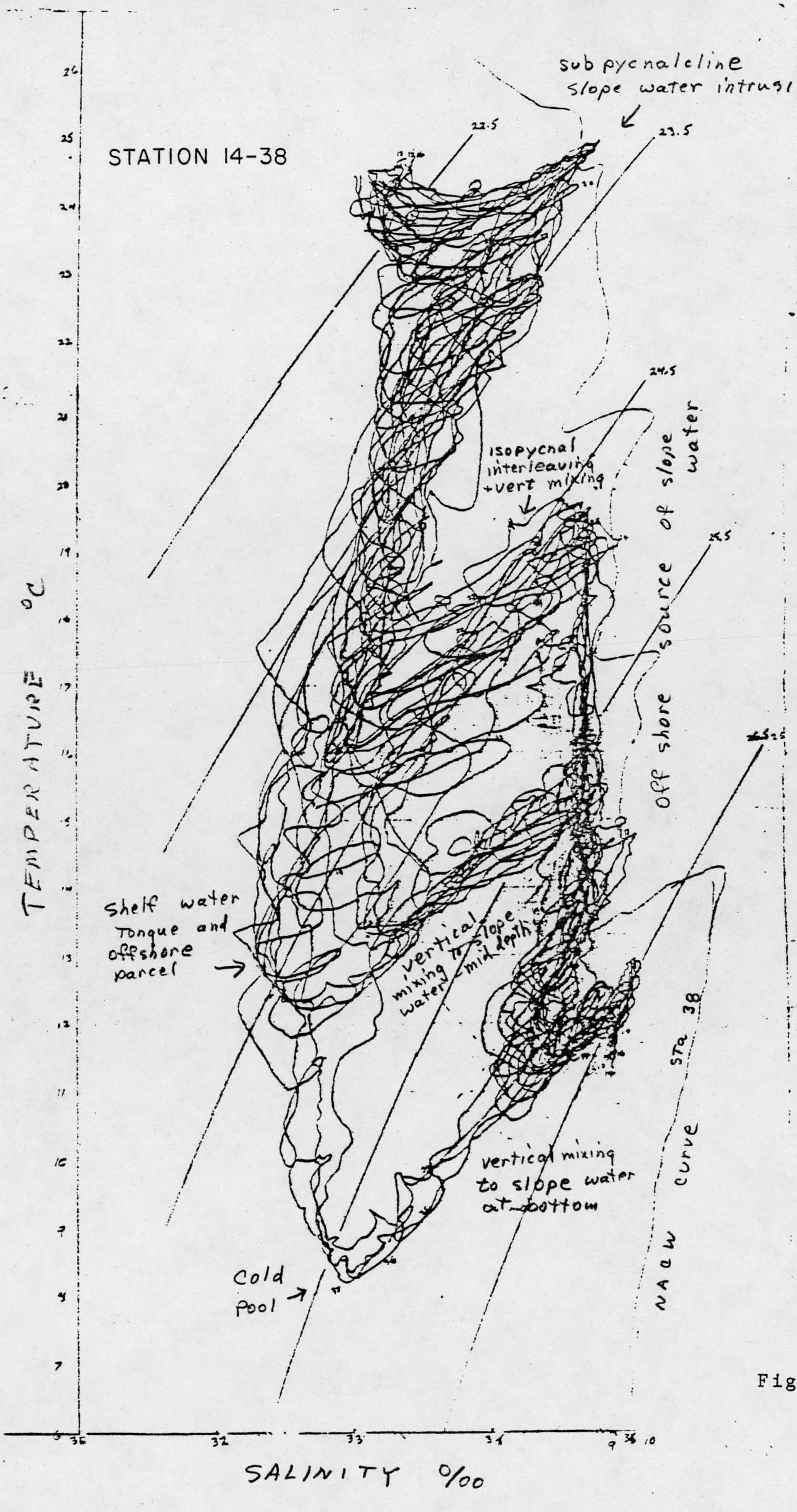

37 36 35 34 33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 15 17 16 15 14
0
m
20
40
60
80
100
0 1 2 3 4 Km

Figure 4.1-25



STATION 14-38
sub pycnalcline slope water intrusion
isopycnal interleaving +vert mixing
Off shore source of slope water
Shelf water Tongue and offshore parcel
vertical mixing to slope water mid depth
vertical mixing to slope water at bottom
Cold Pool
NACW curve
STA 38
TEMPERATURE °C
SALINITY o/oo

Figure 4.1-26

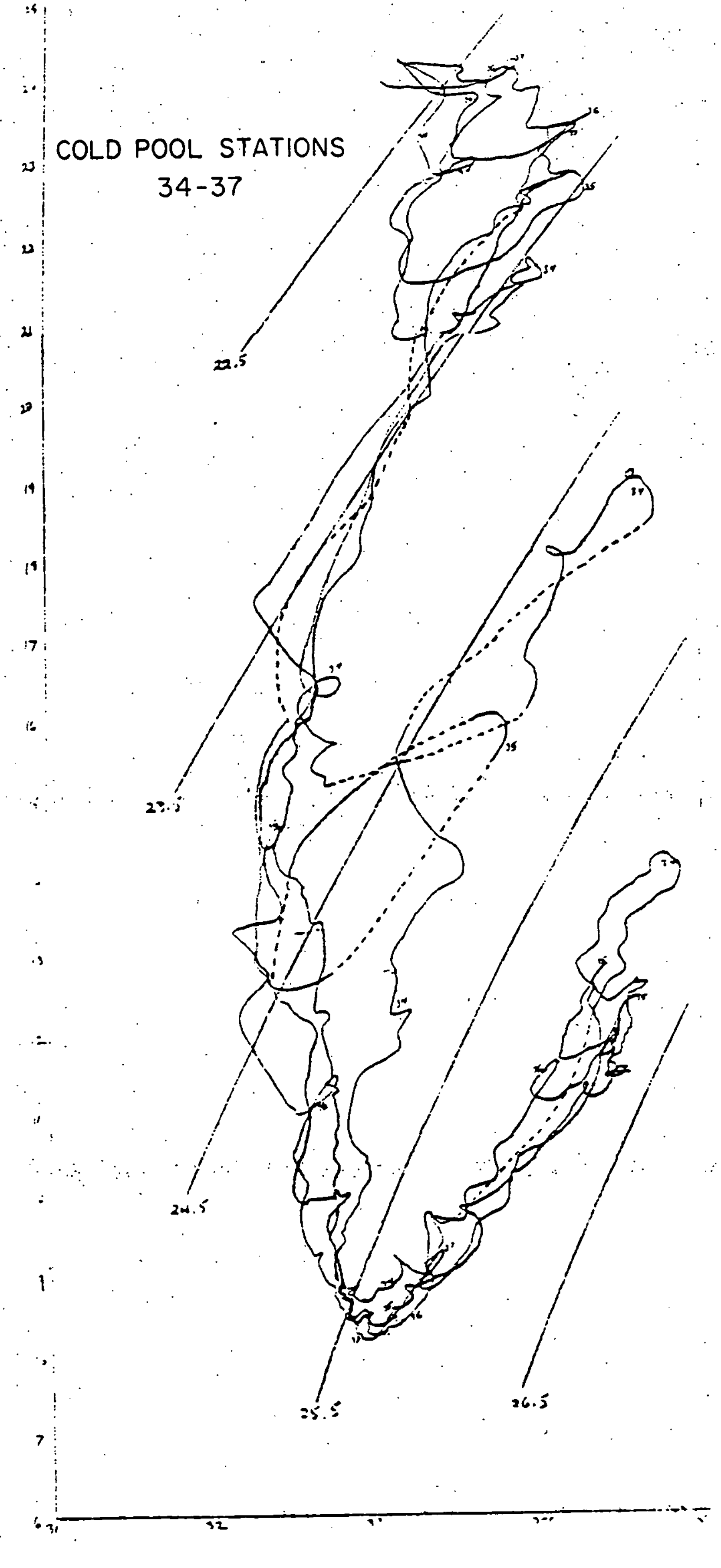


Figure 4.1-27

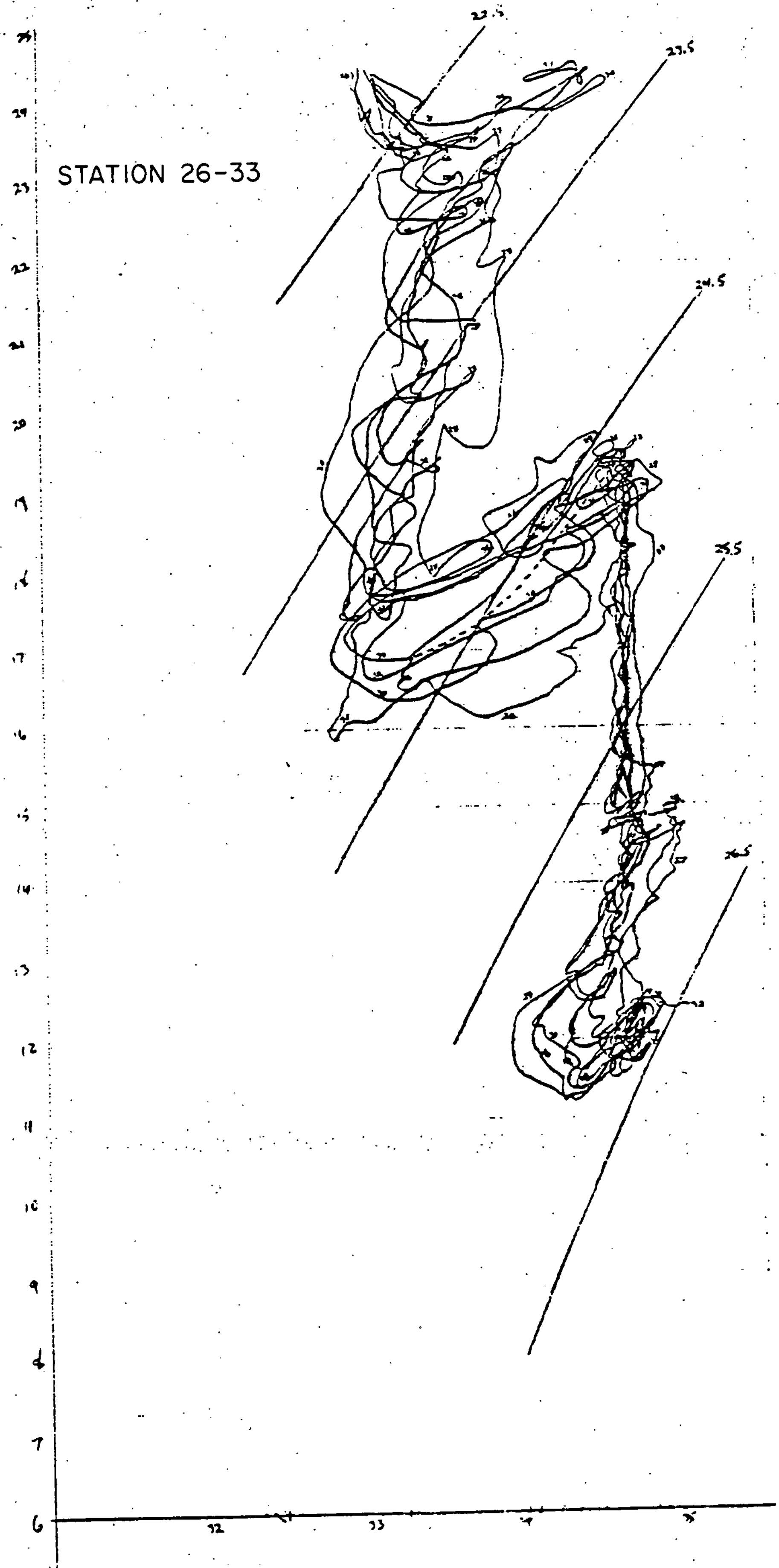


Figure 4.1-28

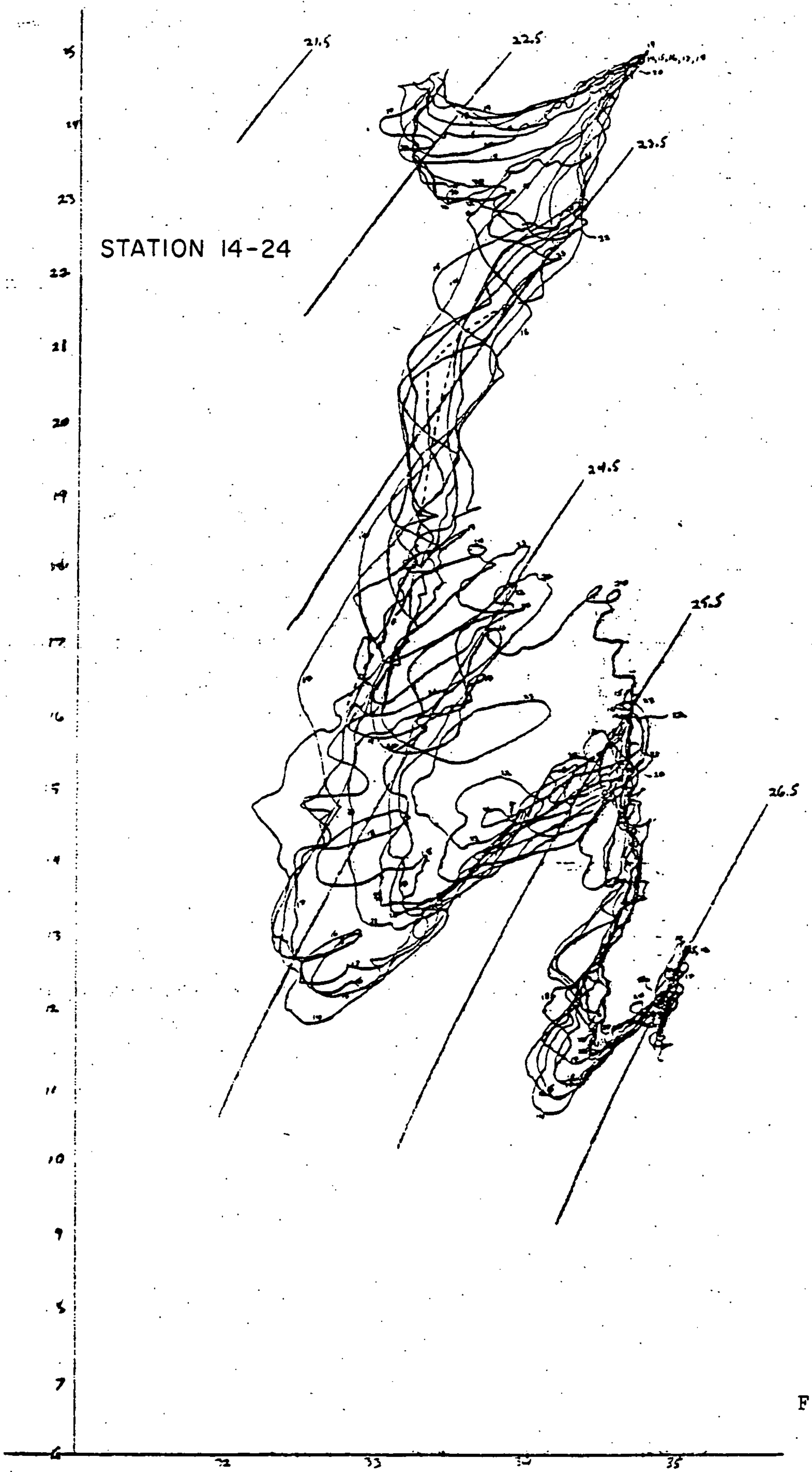


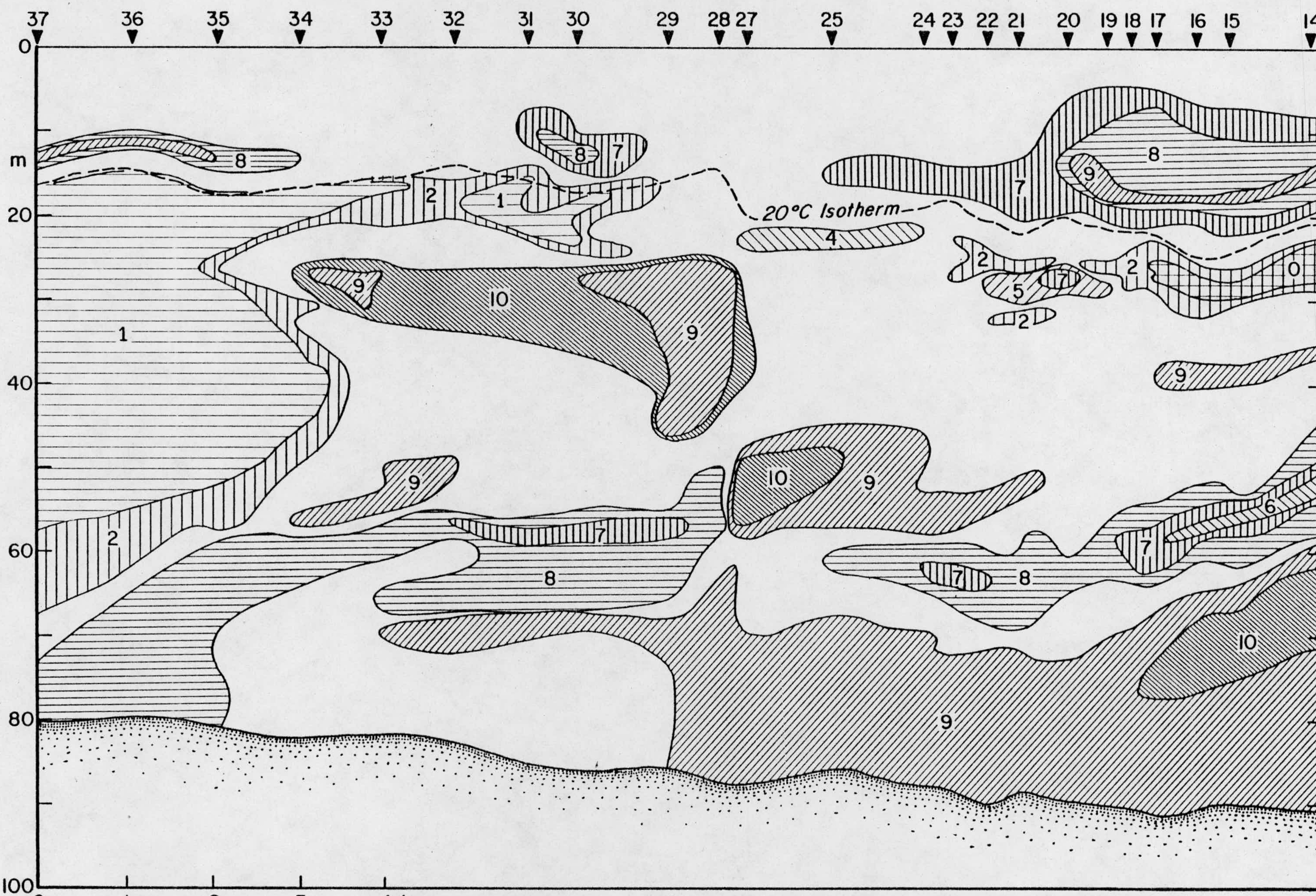
Figure 4.1-29

#24-14 (Fig.4.1-29) have a transition from shelf to slope water at a greater depth. In the absence of vertical mixing this transition would be infinitely sharp and along an isopycnal.

Using these T-S diagrams we can construct a section (Fig.4.1-30) of this frontal region showing the distribution of water types on a scale of 1 = shelf and 10 = slope. A thin tongue of shelf water extends just below the 20°C isotherm 5 km seaward of the cold pool. Above the cold pool is a detached parcel of shelf water. Between Sta.14 and 23 is a layer of shelf water which may be attached to the inner tongue by a three-dimensional structure.

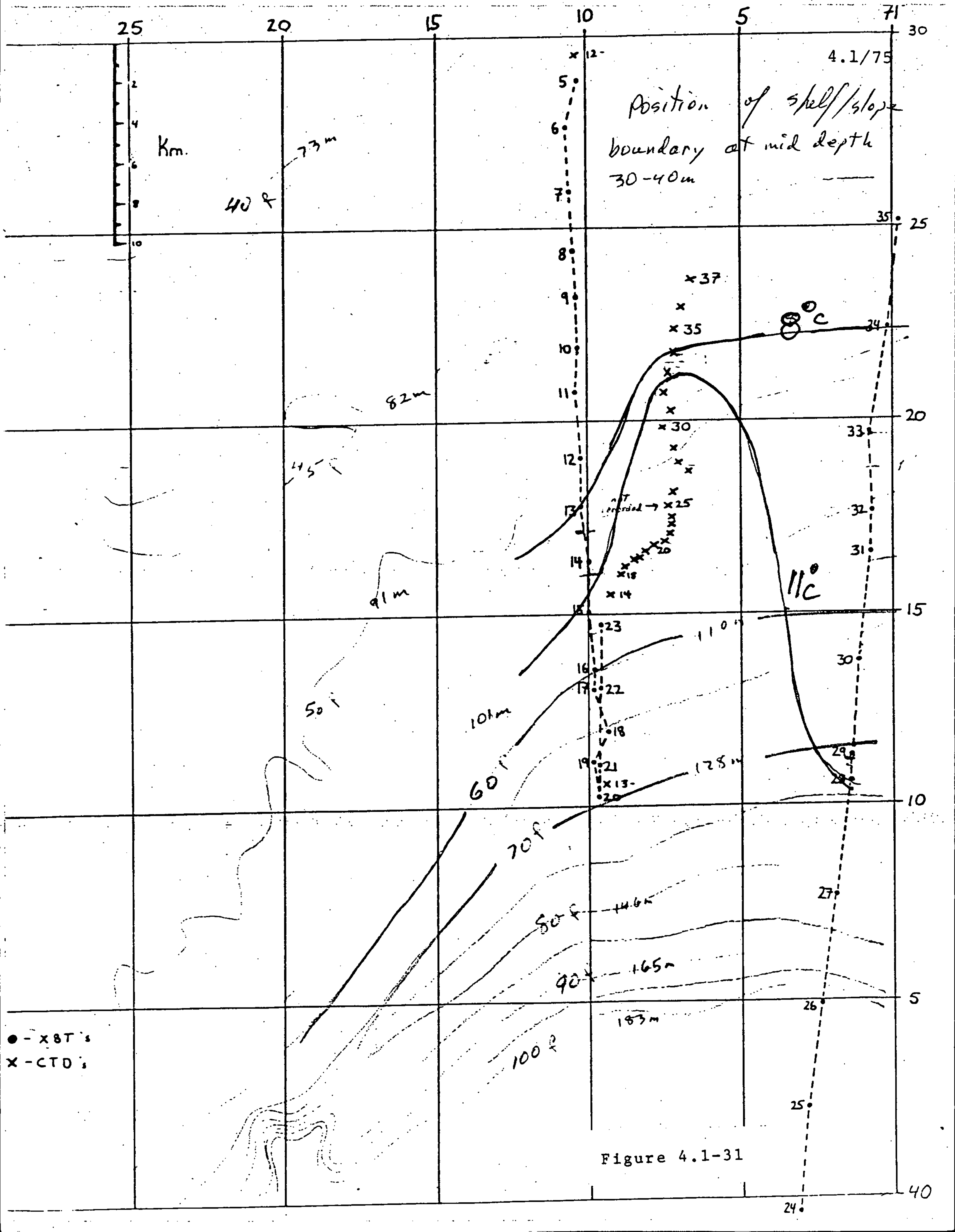
The position of the shelf-slope boundary at mid depth (30-40m), the depth of the cold pool T-min is shown in Fig.4.1-31. In contrast to the shelf bottom (Fig.4.1-22), this boundary does not follow the bathymetry. The cold pool is pushed 5-8 km shelfward on the CTD line as compared to the two XBT lines. This convoluted boundary has alongshore scales of 10-20 km. The picture we get of the shelf/slope front is a region with 5-10 km scale intrusions, detached parcels and meanders with sharp vertical and horizontal boundaries between distinct and sharply contrasting water types. It's clear that a study of the space and time evolution of these structures poses a formidable sampling problem.

We have attempted a preliminary investigation of whether double diffusion could be the predominant mechanism in the vertical mixing of these intrusions. According to Stern (1967), a cold, fresh intrusion should become more dense in time as it mixes with warm, salty water. A T-S plot of the locus of the core of the cold water tongue at 20 m shows it becoming less dense as it moves off the shelf. All intrusive



37 36 35 34 33 32 31 30 29 28 27 25 24 23 22 21 20 19 18 17 16 15 14
m
0
20
40
60
80
100
20°C Isotherm
0 1 2 3 4 km

Figure 4.1-30



25
20
15
10
5
71
30
25
20
15
10
5
40
4.1/75
Km.
Position of shelf/slope boundary at mid depth 30-40m
73m
40 f
82m
45
91m
50 f
101m
60 f
70 f
110m
128m
146m
50 f
165m
90 f
183m
100 f
8°C
11°C
• - XBT's
x - CTD's

Figure 4.1-31

layers coherent over 4 or more stations were tested and none unambiguously confirmed the double-diffusive hypothesis. It would not be surprising if other mixing mechanisms competed with double diffusion to produce a complex situation.

To study the slope/shelf frontal mixing, either large scale surveys such as the one we have undertaken on the 1979 RACACA cruise, or a time series of the small scale structure is required. The field work in 1978 confirmed the existence and persistence of small scale features on the frontal boundary. The data provides a wealth of detail, which we are continuing to analyze and which is invaluable in constructing a realistic design for future field work.

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4.2 Oxygen Isotopes as Tracers of Water Mass origins on the Continental Shelf

The rationale for the use of oxygen isotopes as a tracer of water mass origins has been explained in detail in the previous report and proposal. Its potential is based on the isotopic variation in continental waters flowing into the Atlantic shelf as a function of latitude. Realization of this potential, however, depends on achievement of sufficient analytical precision to distinguish between two isotopically-distinct sources after they suffer varying degrees of dilution and mixing in the waters of the continental shelf. The rationale and our initial results (using both oxygen isotopes and hydrogen/deuterium as tracers) based on our analytical capabilities as of one or two years ago have just been published (Torgersen, T., 1979, Isotopic composition of river runoff on the U.S. East Coast; Evaluation of stable isotope versus salinity plots for coastal water mass identification. Jour. Geophys. Res., V. 84, (No. C7), p. 3773-3775) and appears as Appendix 10.

Since Torgersen's work we have imporved our analytical capabilities through the addition at our laboratory of a new gas-source mass spectrometer under support of other projects, and by the construction of a new CO_2-H_2O equilibration system, largely with support of this contract. The new CO_2-H_2O equilibration system for 0-18 analysis of sea water which was developed with funds from NSF-OCE-77-25976 for R. Fairbanks as well as from this contract has just been tested. The analytical precision is better than $\pm$0.04 per mill based on multiple analyses of our laboratory standard NADW-1 (see Table 4.2/1). This precision can be achieved routinely and is approximately an order of magnitude better than the precision of the system previously used at Lamont.

Currently, 6 samples can be equilibrated simultaneously and analyzed per working day.

All three water types (South Atlantic Bight, Mid-Atlantic Bight and Georges Bank) can be readily distinguished by the improved ^{18}O system at salinities less than 34 per mill, thus covering the range of shelf waters. We are currently analyzing surface water samples along a north-south transect from our July 1979 cruise which we anticipate will include the entire range in ^{18}O values we might expect in our studies of the New York Bight. Our next objective is to analyze vertical profiles covering several seasons in the New York Bight to determine the origin of the "cold pool" water below the thermocline in the New York Bight. We do not know whether this water represents remnant water of New York Bight origin from the previous winter, or represents a continuous flow of cold water from the George's Bank area (i.e., isotopically light). See Section 4.1 and particularly p. 4.1/33 ff. for a discussion of cold pool hydrography).

Table 4.2/1 Replicate Analysis of Laboratory Standard NAWD-1

LDGO #	EQUIL. TIME (MIN.)	DELTA 0-18 @ 20.0°C W/WET-1
4092 6/29/79	225	1.82±.02
4093	247	1.87±.02
4094	284 Min. Equi. Time	1.90±.02
4095	319	1.95±.01
4096	330	1.93±.03
4097	350	1.92±.01
4120 7/3/79	1175	*1.81±.01
4121	1195	1.93±.02
4122	1217	1.93±.03
4123	1239	1.95±.02
4124	1266	1.95±.02
4125	1331	1.95±.02
4140	1121	1.90±.03
4180	2572	1.93±.02
	$\bar{x}$*elim =	1.93±.016

4.3 Radon-222 as a Tracer of Water Motions and Mixing.

4.3/1 Introduction

Work on the use of radon as a tracer of meso-scale water motions and mixing has proceeded along several lines as described in the three following section. This work is largely the Ph.D. thesis project of Steve Carson who has increasingly taken charge of aspects of the problem. Related studies of radon fluxes in Narragansett Bay are included in his thesis work and where relevant are disucssed in this report. No specific report is given on the work on dissolved ^{226}Ra because measurements during the past contract year have not altered the value of $10.5 \pm .5$ dpm/100ℓ reported last year for dissolved radium-226 in shelf water in the spring. More samples of slope water were collected during the RACACA cruise to provide needed data for radium in slope waters. In addition we began testing a technique for recovering the radium from sea water while at sea to preclude the cumbersome (and expensive) problem of having to ship whole water samples back to Lamont for analysis and then the problem of storing them once here. Results from the RACACA cruise on radon in the "low-radon zone" of the continental slope and rise are given below under Section 5.0 FIELD WORK rather than here since they are just preliminary results. The sections following deal with the problem of modelling source functions of ^{222}Rn from bottom sediments, the results of last years attempts on the Boue Trou cruise to quantify short-term variability in radon distributions, and modelling of excess radon distributions to yield mixing coefficients. The paper by Biscaye, Olsen and Mathieu describing some of the early results of the distribution of radon (and suspended particulate matter) in the New York Bight has been published as part of a symposium volume and is included as Appendix I.

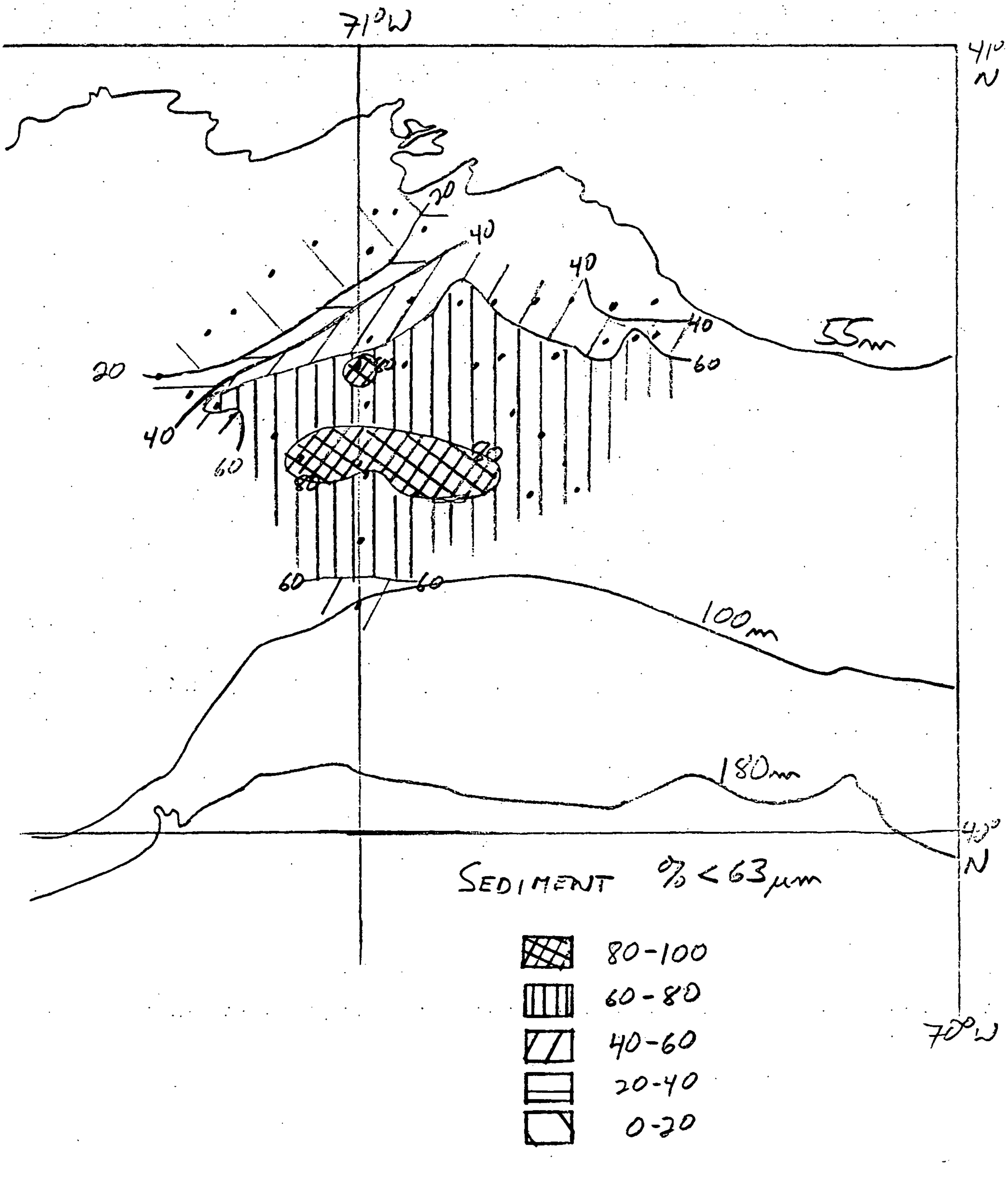


Figure 4.3-1 Weight percent less than 63 μm of sediment collected on cruise Boue Trou.

4.3.2 Radon-222 source function

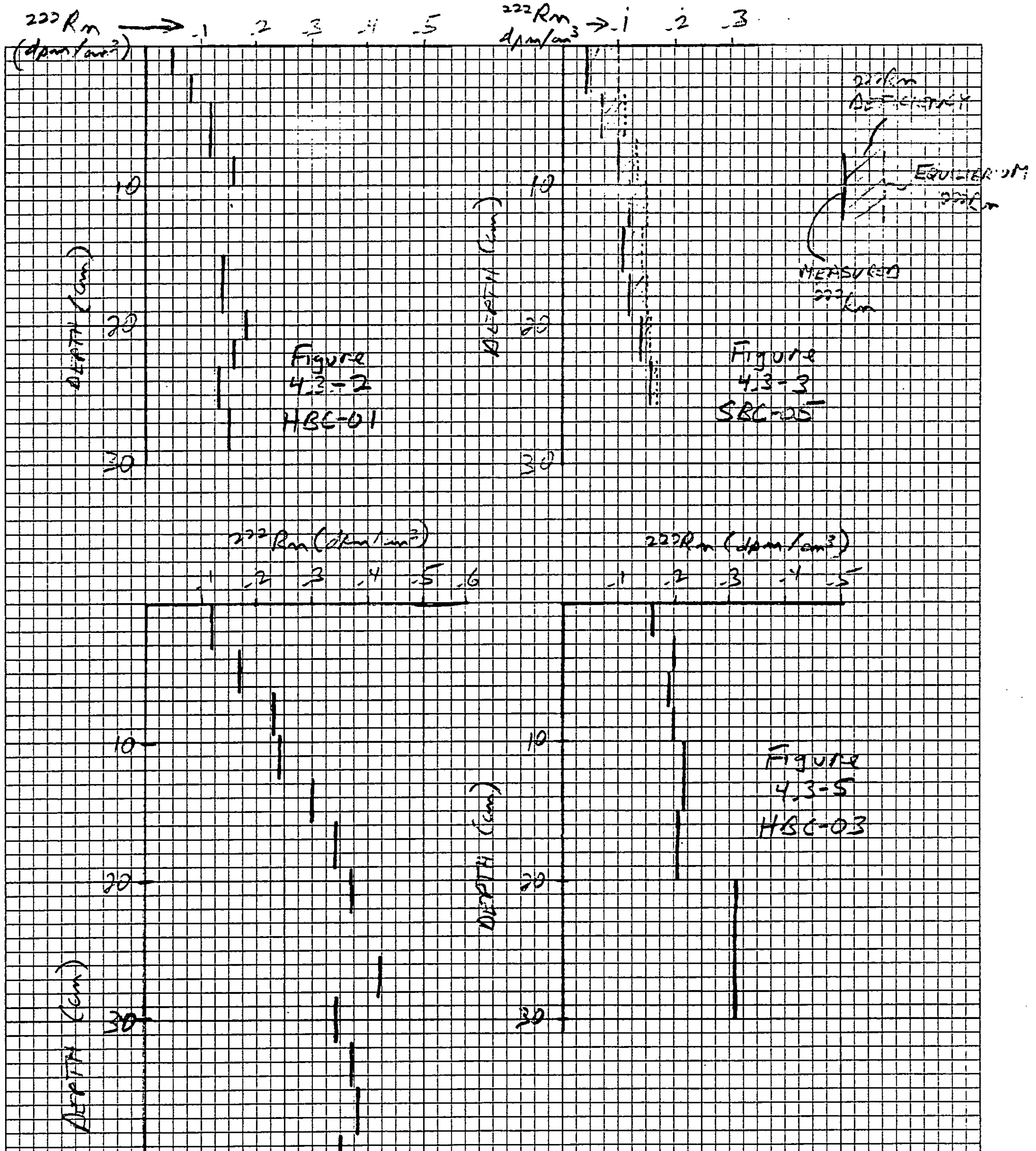
As discussed in previous reports the production of ^{222}Rn in the sediments can be related to the percentage less than 63 μm sediments in most areas of the Bight. Different relationships between those parameters have been determined for two regions: 1) the "mud hole" area where our sample density was limited to a single traverse in January 1976, and 2) the rest of our study area excluding an anomalous region south of the Hudson Shelf Channel. On cruise CH-78-BT of August 1978, 44 grab samples were collected in a portion of the "mud hole". These have been analyzed for grainsize distribution (Fig.4.3/1). These data can be used in conjunction with the known ^{222}Rn production vs. % < 63μm relationship to refine our knowledge of the source function for ^{222}Rn in that area.

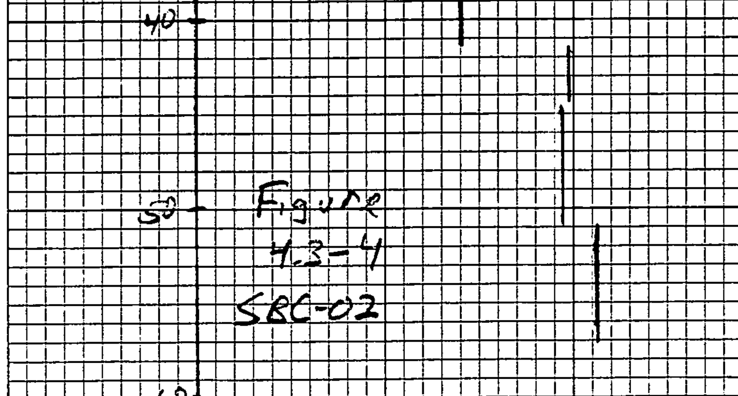
Four box cores were also successfully collected and analyzed for ^{222}Rn on the cruise in August 1978 to obtain estimates of radon fluxes by measuring radon deficiency in the upper sediment column. Two cores were collected with a one meter square box corer designed by Hessler and borrowed from F. Grassle of Woods Hole Oceanographic Institution. One of these was collected from the "mud hole" and another from the slope at a water depth of 1800 m. Both of these box cores were subcored with a 2 1/8" 1D core liner and the subcores were sectioned at 2 to 5 cm intervals. The sections were placed into jars with 100 mℓ of seawater, sealed and stripped of ^{222}Rn by bubbling He through them with our extraction system.

The other two cores were collected with a ∿20 cm square box corer originally designed by A. Soutar and borrowed from K.K. Turekian of Yale University. These cores were collected from the "mud hole" and from the slope at a water depth of 850 m. These cores were sectioned by means of "windows" that can be opened in the side of the corer, a modification of Soutar's design made by the Yale group. Starting from the top of the core a 1-1/4 inch window would be opened and stainless steel or brass plates would be pushed horizontally into the core at the base of that window to divide off the upper one inch. A two-inch section of 2 1/8 ID core liner was then pushed downward into the sediment and stopped by the plate in order to collect a 1-1/4 inch long section. The procedure was repeated down the length of the core with 1-1/4- or two-inch sections collected. These sections were also placed in jars and stripped.

By this method profiles of ^{222}Rn were determined in these cores (Figures 4.3/2 to 4.3/5). In order to obtain estimates of fluxes from these data it is necessary to determine the equilibrium concentration of radon in the same sections, i.e., the concentration that would be found in the sediments if there were no loss to the overlying water. This is determined by measuring ^{222}Rn on the sections in the lab after sufficient time has been allowed for the re-growth of the radon from the decay of ^{226}Ra. The difference between the total amount of equilibrium ^{222}Rn in the core and the total amount of ^{222}Rn measured on the ship is the radon deficiency of the sediments and is equivalent to the flux of ^{222}Rn out of the sediments to the overlying water column.

The measurement of equilibrium ^{222}Rn has been completed on one core from the "mud hole" (SBC-05 and is shown in Figure 4.3/3 . The deficiency calculated for this core is in the range of 0.90-1.3 dpm/cm^2. The large range results from problems with blanks of the bubbler system being used which are currently being assessed and corrected. If the equilibrium ^{222}Rn distribution of core SBC-05 is applied to the shipboard ^{222}Rn distribution of core HBC-01 also from the "mud hole", a simular flux is also determined. If the overlying water column received Rn only from these sediments, the standing crop of ^{222}Rn in water above the core sites should be equivalent to the deficiencies. These fluxes compare favorably with





Figures 4.3-2 thru 5
Radon-222 in cores collected on cruise Boue Trou.

Equilibrium radon and deficiency shown for SBC-05.

the highest standing crops measured at or near the two sites, although most standing crops measured in the water column were much lower. This is reasonable since the cores were collected in relatively fine grained areas which would be the major source of ^{222}Rn. Thus the fluxes from these sediments would be expected to be among the greatest fluxes on the shelf in the Bight. The variability of the standing crops (discussed further in section 4.3.3) indicates significant interaction between waters from areas of high radon fluxes and those with lower fluxes.

Although the ^{226}Ra in the slope cores has not yet been determined, it can be seen from the shapes of the ^{222}Rn profiles that the fluxes from those sediments would be significant and probably larger than those of the "mud hole". The deficiency in the core at 850 m appears to be especially large. This confirms previous work on grab samples of sediment that the low radon zone is indeed highly anomalous in that it seems to have higher fluxes of ^{222}Rn from the sediments than those in the "mud hole", while the overlying water column of the slope shows much lower standing crops than that above the "mud hole". We had hoped to obtain many more cores from slope sediments but problems with our box corer (described in 3.0 and 5.2) kept us to only two new cores.

Many samples collected on the CH-BT cruise and on a short cruise on the R/V KELEZ in November of 1978 for laboratory processing. Three six-inch subcores and large volumes of sediment for constructing "cores" were collected on CH-BT in order to do flux measurements in the laboratory. Because these sediments all have high percentages of the fine grained component, large volume samples of sand from "normal" and "anomalous" radon production areas as well as sediment from the Hudson shelf channel were collected in November, 1978, from the R/V KELEZ.

Portions of the samples collected in November were frozen for later analysis of chemical properties in an attempt to understand the cause of the anomalous region of radon production. In this region relatively coarse grained sediments show unusually high levels of ^{222}Rn production. We have found that the fraction of these sediments that is greater than 63 μm has higher concentrations of ^{226}Ra that can produce diffusable ^{222}Rn than other sands of the Bight. This is somewhat anomalous in itself in that ^{226}Ra is generally associated with the fine grained sediment fraction.

Considerable work has been done in conjunction with another grant directed toward an understanding of the fluxes of radon from sediments and the techniques for measuring such fluxes. The work has been done in Narragansett Bay, in tanks simulating Narragansett Bay and with 6" cores collected from the Bay. In the Bay fluxes have been measured by two methods. One is by covering a portion of the sediments with a chamber and measuring the concentration of the radon initially and then after a few hours of incubation. The second is by determining deficiences in diver-collected cores. The two techniques gave comparable results in the Bay, although the deficiency must be considered a lower limit due to the fact that the length of core collected did not span the entire deficient zone.

In the tanks a third technique was used in addition to the two used in the Bay. This involved the measurement of the standing crop of ^{222}Rn in the tanks. With the knowledge of gas exchange rates determined from other experiments the flux from the sediments could be calculated. The techniques utilizing the chamber and the standing crop measurements showed comparable values. The sediment deficiency technique, however, indicated significantly higher fluxes than those determined from the other techniques. This could be the result either of problems with the coring technique or of inhomogeneities of the sediments.

Since the technique of measuring the standing crop in the tanks should give the most reliable results, these intercomparison experiments indicate that the chamber technique is also good. The measurement of radon deficiencies in cores, however, seems to overestimate the actual flux. Problems with the sediment radon deficiency measurements were also noted on the RACACA cruise as discussed in section 5.2.1. Experiments designed to test the analytical procedures of that technique are being carried out.

Experiments with 6" Bay cores maintained in the laboratory were designed to test the effects of benthic organisms important in the Bay on the fluxes of dissolved substances out of the sediments. Unfortunately, the results of these experiments were highly erratic and nothing could be said about the influence of the organisms on radon fluxes. Fluxes did not compare well with the Bay measurements. This indicates that there are major problems with the technique that must be corrected before it can be applied to the Bight sediments that have been collected for laboratory flux experiments.

Seasonal measurements with the chambers and of standing crops in the tanks show that the highest ^{222}Rn fluxes occur in the fall and the lowest in the winter. The seasonal change is only about a factor of two or three. These results are consistent with the lower total standing crops found below the thermocline in our Spring 1977 cruise compared to our summer 1975 cruise and fall 1977 cruise. This seasonal change may be the result of changes in benthic activity. Another indicator of the possible influence of benthic activity on the flux of ^{222}Rn from sediments is that Narragansett Bay tanks that were spiked with oil and as a result showed depressed benthic communities also showed fluxes lower by a factor of three than control tanks.

Clearly the problem of estimating radon fluxes is not a simple one and requires more effort.

4.3.3 Radon Variability in the Water Column; Results from "Boue Trou"

An attempt was made on our cruise CH 78-BT in August 1978 to characterize the time variability of radon distributions in the waters above the "mud hole". This was done in order to determine whether the radon profiles can indeed be considered steady state and thus can be used in modeling vertical and horizontal mixing rates. Three sites were selected for repeated occupation over several days. Two sites were located within the "mud hole" where variability would be expected to be the least because the sites were surrounded by sediments which should have similar fluxes of radon. The third site was at the eastern edge of the "mud hole" where there is a strong gradient in the flux and thus a high degree of variability in the water column could be expected.

All parameters which can be used to characterize the radon profile were highly variable at all three sites. The standing crops varied by a factor of 2 to 4. The heights above bottom to which excess radon was observed varied by at least a factor of 2. The maximum concentrations observed varied by up to a factor of 1-1/2. Qualitative changes in the shapes of profiles were dramatic. In many cases the variability could be correlated with temperature, salinity and density changes. In other instances any such relationship was much more elusive. Thus it was found that in this area at least at that time, the radon distribution is highly variable and would be inadequate for use in understanding vertical mixing.

We do not feel, however, that this indicates that all of the data we have collected in the Bight is so highly variable. This area showed evidence of intrusions and considerable interleaving of various water types. This is due largely to the depth and to the proximity to the shelf slope break at the chosen sites. In our other cruises, which focused on the inner- and mid-shelf in the region of the Hudson Shelf Channel, the lower water column of many stations appears better mixed and less subject to intrusion. Thus it is felt that at such stations ^{222}Rn can still be a useful tool in the understanding of mixing processes.

4.3.4 Modelling of Excess Radon Distributions - Last years report included a discussion of preliminary analysis of radon data in terms of vertical and horizontal mixing coefficients. Work in the past year has focused on a more rigorous treatment of the radon data particularly in an attempt to measure mixing across the pycnocline. The importance of obtaining estimates of mixing across this boundary is discussed from the biological viewpoint in Section 2.2 and from the physical viewpoint in Section 4.1. The following discussion deals with data from the May 1977 and July 1975 cruises when there were both frequent well-mixed bottom water conditions and a well-developed thermocline.

Most profiles from May 1977 (CH 77-01) show a very similar shape that can be related to the density structure of the water column. In the bottom mixed layer where T, S and σ_T show no vertical gradient, the concentrations of excess radon are high and have low gradients. At the base of the pycnocline or at stratification below the pycnocline the excess radon concentration decreases rapidly with distance above bottom often decreasing to zero within a few meters. This characteristic shape suggests that a two-layer model of vertical diffusion can be applied to most profiles and that all of the data can be used together to calculate average values of the vertical diffusion coefficient within each layer.

In order to use all of the data together the concentrations had to be normalized because concentrations within the lower mixed layer varied from station to station. The first step in the normalization process was to determine the average height above bottom to which excess radon was observed simply by selecting the midpoint of the high gradient portion of the profile. The standing crop of each profile was then divided by the average height in order to determine the mean concentration of the profile. In some cases the calculated mean concentration differed somewhat from the concentration of the well mixed portion of the radon profile due either to sampling resolution or to near bottom concentrations that were much higher than the rest of the mixed layer concentrations. In those cases the normalization was done both with the calculated mean concentration and that estimated from the profile. All concentrations in each profile were then normalized by dividing the mean concentration of the profile.

The normalized data were then plotted relative to the mean height. That is, the mid point of the high gradient region of the profile was chosen as the zero level and the normalized concentrations of all profiles were plotted at the appropriate distances above or below that level. This was done so that all of the data points from the upper stratified layer would fall together.

The model applied to the data was that presented by Sarmiento et al. (1976) in which a constant value of K_z is assumed for each layer. Other assumptions include steady state conditions for radon and no horizontal processes. The equation for the upper layer is

$$C(Z_1) = C_b \exp [-Z_1/Z_1^*]$$

where Z_1 is the distance above the boundary between the two layers, $C(Z_1)$ is the concentration at Z_1, C_b is the concentration at the boundary and $Z_1^* = \sqrt{K_{Z1}/\lambda}$, K_1 is the vertical diffusion coefficient for the upper layer and λ is the decay constant of radon. The equation for the lower layer is

$$C(Z_2) = \frac{C_b}{2} (1+Z_1^*/Z_2^*) \exp [Z_2/Z_2^*] + \frac{C_b}{2} (1-Z_1^*/Z_2^*) \exp [-Z_2/Z_2^*]$$

where Z_2 is the distance below the boundary between layers, $C(Z_2)$ is the concentration at Z_2, $Z_2^* = \sqrt{K_{Z2}/\lambda}$ and K_{Z2} is the vertical diffusion coefficient in the lower layer. In order to use the model graphically, values for the height of the boundary between the two layers and the concentration of radon at the boundary (C_b) were determined visually from the plotted data. The average height of the boundary appeared to be 2-1/2 meters below the midpoint of the high gradient region (i.e., the mean height). Values of .9 and .95 were used for the normalized concentration at the boundary.

Model curves showing radon concentration vs. height above the boundary were plotted for the upper layer with various values of K_{Z1} and compared with the normalized data. All of the data that showed a two-layer structure fell within the K_{Z1} range of 0.05 to 0.5 cm^2/sec. For those stations in which the upper layer was associated with the bottom of the pycnocline the data fell within the more limited range of 0.05 to 0.3 cm^2/sec.

Using a value of 0.1 cm^2/sec for K_{Z1} as a reasonable average, model curves in the lower layer were calculated and plotted for several values of K_{Z2}. Many of the profiles could not be adequately explained by the simple model in which K_{Z2} is constant. For those that did fit the model, however, a range of 10 to 100 cm^2/sec was indicated for K_{Z2}.

A similar approach was also applied to the data of July 1975 (RC19-01) in which a two-layer structure is also apparent in the profiles. The lower layer of most profiles, however, show more variability than do those of May 1977. When plotted together, the normalized data of the lower layer in July 1975 show much more scatter than those of May 1977 and the assumptions of the model do not seem to apply. In the upper layer, however, most of the data fall again within the range of 0.05 to 0.5 cm^2/sec for K_{Z1}. One profile suggests a K_{Z1} of up to 1 cm^2/sec.

The ranges found for the value of K_Z at the base of the pycnocline during May 1977 and July 1975 are identical to the range found by the application of a similar model to individual profiles as described in last year's report. For some individual profiles the value of K_{Z1} are lowered slightly by the new approach of using all of the normalized data together because the vertical resolution is improved relative to studying individual profiles.

The fact that the normalized data for May 1977 plotted closely together indicates that the general assumption of a two-layer structure is reasonable for that period. The data from July 1975 are more variable but they also suggest that a two-layer structure exists. The assumption of a constant K_{Z2} is probably not valid. Variations in K_{Z2} from station to station would also cause scatter in the data.

The lower layer data from July 1975 indicate that lower layer mixing is very complex and may be affected by horizontal diffusion and advection. Many of the profiles show concentration maxima well above the bottom.

This was also the case for the data from September 1977 (CH77-15C) to which the model seemed inapplicable. The lower layer was even more variable than in July 1975 and the upper layer often seemed to intersect with the surface mixed layer of the water column in which radon is deficient.

The great degree of variability in the lower layer could be the result of the scale at which mixing occurs. The radon concentration at a given location could be highly variable in time due to parcels of high and low radon water that are large relative to the sample volume moving both vertically and horizontally through the location. In order to understand completely the complexities of the lower layer and, hopefully, to model the mixing processes, a study of time variability is essential. It is possible that with a long enough series of data collected at one location the average profile could be used to calculate an average vertical diffusion constant as in Biscaye and Ettreim (1974). We did do a limited time variability study on the RACACA cruise in June and are proposing a more detailed study for the next contract year.

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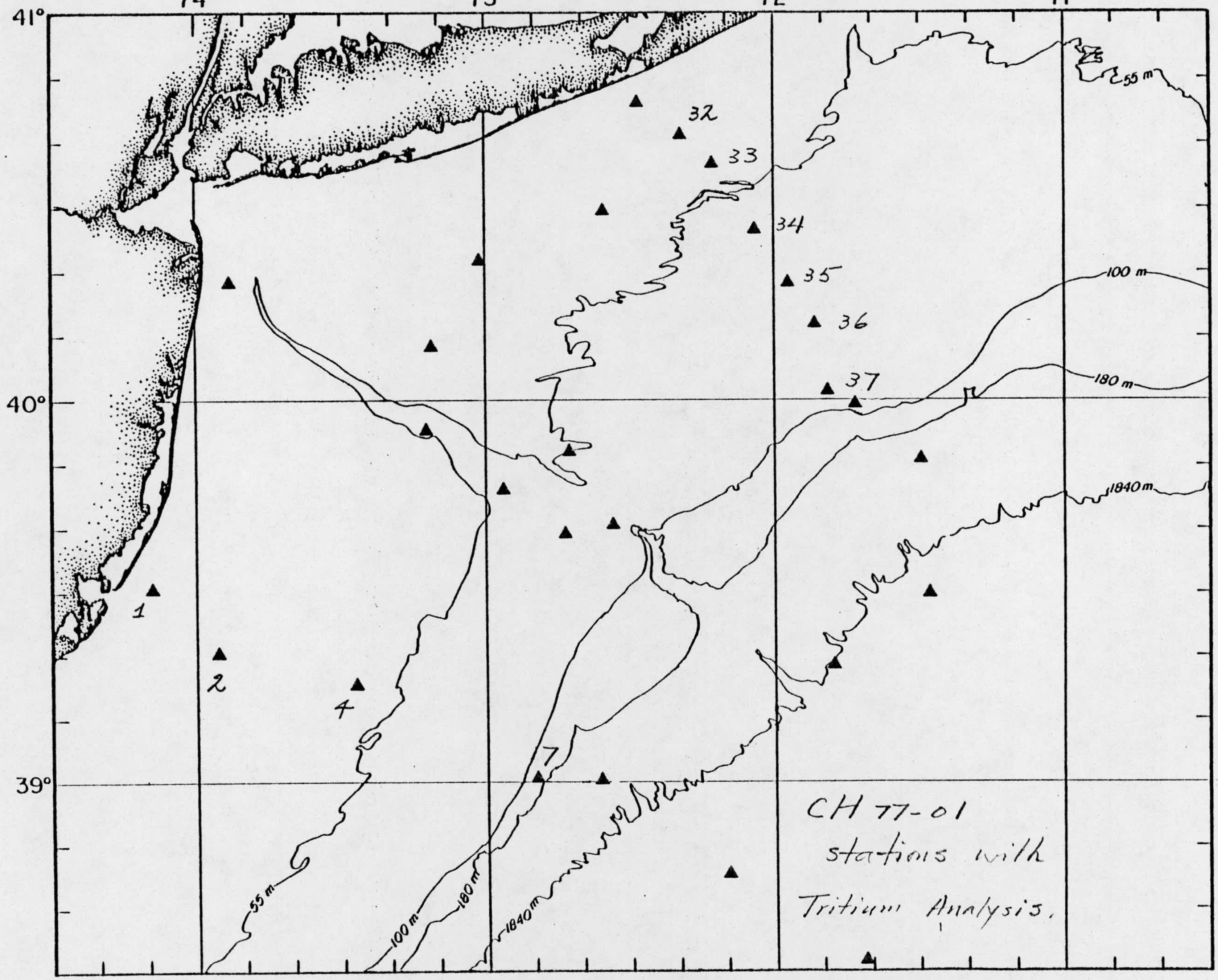

74°
73°
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40°
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1
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32
33
34
35
36
37
CH 77-01
stations with
Tritium Analysis.

4.4 Tritium as a Tracer of Water Masses on the Continental Shelf

Shelf water samples (at depth less than 110 m) obtained along two cross sections north and south of Hudson Canyon during the CH 77-1 cruise, May 1977,(Fig. 4.4-1) were analyzed for tritium content. The preliminary results are shown in Fig. 4.4-2. In general, the northern samples contain about 2 T.U. more than the southern samples at the same salinity, reflecting the fact that the higher the latitude in the northern hemisphere, the higher the tritium concentration in rivers and in the surface ocean. The results bear out our suggestion that tritium can serve as an excellent tracer of water masses on the continental shelf. Becuase the RACACA cruise covered a much larger range of latitude than previous cruises, we are able to obtain a set of samples for tritium analysis which covers a much larger range of tritium values. By knowing the tritium inputs from rivers and the change in tritium concentration from north to south in the Mid-Atlantic Bight, we can estimate the shelf-slope water exchange rate.

5.0 FIELD WORK

Since last year's report (July 1978) we have had two cruises. The first, on RV CAPE HENLOPEN last August was actually part of the last contract year's program and funding but had to be scheduled after the report. The scientific results of that cruise have been included throughout this report. A brief summary is given below.

The second was carried out on RV CONRAD in June of this year and, having just been conpleted, only preliminary results are given below.

5.1 CAPE HENLOPEN, "Boue Trou" (Mud Hole)

As implied by the name, this cruise was carried out primarily in the area of the Mud Hole, that extensive anomaly of fine-grained sediments which covers much of the continental shelf south of Block Island-Nantucket. The primary scientific objective of the cruise was to measure in one location the temporal variability of a number of the features and parameters heretofore measured primarily on an areal or geographic basis in the New York Bight. From the physical oceanographic viewpoint, this meant variability in water-mass characteristics, particularly features reflecting injection into the outer shelf waters of slope waters along isopycnal surfaces. Geochemical variability was in terms of some of the natural radioactive tracers such as radon-222, thorium-234, -228, etc., and the parameters (apparent vertical mixing, removal rates) calculated from them. The biologists were looking for primary productivity variability and, in connection with the estimation of mixing across the pycnocline from radon-222, wanted to independently estimate mixing from cross-pycnocline nutrient gradients and productivity rates.

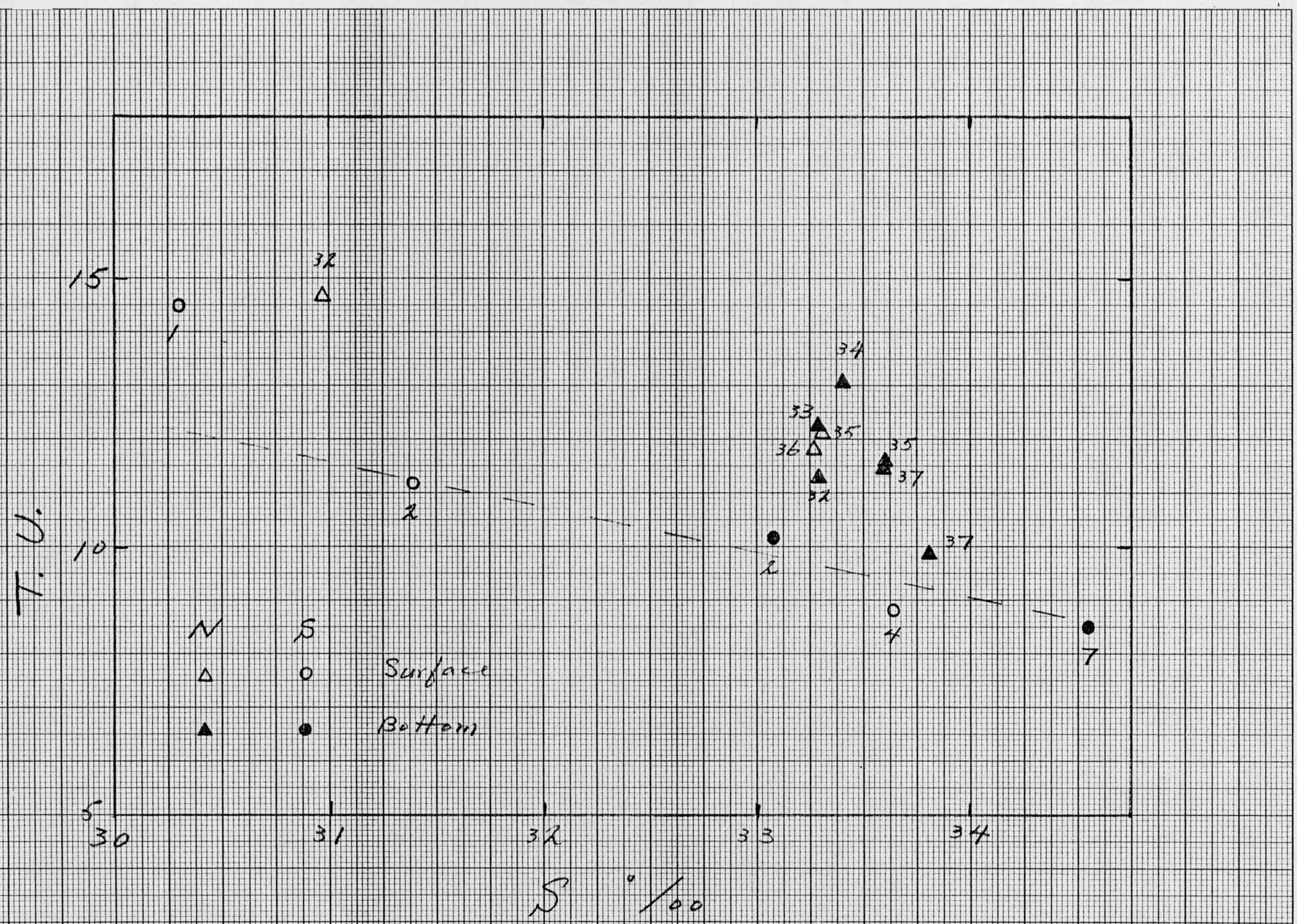

Fig. 4.4/2. Tritium (T.U.) vs. salinity plot of New York Bight shelf waters. (CH77-01, May 1977)

Fig. 4.4/2

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An additional objective and important reason for siting the cruise in the Mud Hole, was to test two different types of box corers. To study the rates of removal of pollutants from the water column into the sediments, one must obtain sediment cores in which the surface sediment is collected undisturbed. Box coring is the only method currently available with even a reasonable chance of success at this. We tested two different designs of box core, one borrowed from Fred Grassle at WHOI and the other from Karl Turekian at Yale. The WHOI corer was the Hessler-type with a single space which is used by most benthic biologists. While we obtained cores successfully with this unit, it is very massive, to the point of being dangerouse to try to use in any kind of sea, and yields much more mud than we need for geochemical measurements. The Yale corer was modified after a design by Andy Soutar of Scripps, is much smaller, easier to take samples from and we also obtained cores successfully with this unit. Based on this experience, we built a box coerer patterned after the Soutar/Yale design.

5.2 CONRAD "RACACA" (C22-08)

Previous years' field efforts under DOE support on the continental shelf/slope have all been focused in the area of the New York Bight and covering a sector on the order of a hundred miles either side of New York City at the coast and the order of several tens of miles either side of the Hudson Canyon. During these cruises we repeatedly observed phenomena, particularly at and beyond the shelf break, which provoked the question of their existence and intensity elsewhere. We were funded this year to pursue the geographic extent of these observations in a cruise focussing on the shelf break, slope and upper continental rise from Hudson Canyon south to Cape Hatteras. The cruise was originally scheduled from New York to New York but, because of Coast Guard regulations concerning the proportion of American nationals in a U.S. flag vessel's crew on departure from a U.S. port, St. Georges, Bermuda was the beginning and ending port (11 June - 2 July). The extra costs of transporting our scientific gear and personnel to and from Bermuda was borne by L-DGO from institutional funds. Our DOE project also benefitted from the addition of 6 days of shiptime from the Office of Naval Research. Dr. Bill Ryan of L-DGO is supported by ONR to study submarine canyons of the North American east coast. Because of various problems in ship schedules, the most profitable use of Ryan's ONR ship support was to add it to our DOE leg. This permitted us to do some work in the Baltimore Canyon and to compare our results there with those obtained in previous cruises in the Hudson Canyon. The cruise as scheduled and funded by DOE alone was designed to cover inter-canyon areas and would not have had time to work in the Canyon itself.

The objectives of the cruise were, 1) to document the extent of the low-radon, low-particles zone in the near-bottom waters of the contintental slope and rise and to learn the relationship between the distribution and intensity of this zone and the topography (bathymetric gradient) and the underlying sediments; 2) to measure the concentration, size frequency and distribution and obtain large (sediment trap) samples of suspended particulate matter (SPM) and hydrographic characteristics in this zone compared to those in overlying and underlying water; 3) to test the hypothesis that a pumping mechanism, related to internal waves of tidal frequency, is dynamically responsible for the low-radon zone; 4) to obtain box cores of sediments underlying and adjacent to the zone; 5) to obtain a synoptic data set of shelf front/upper slope water mass characteristics to determine the degree of shelf/slope water exchange across the front and obtain samples for tritium and oxygen isotope analysis for comparison; 6) to measure primary productivity, nutrients, biomass relationships at the biologically-active shelf/slope boundary and to further test the relationship of these with radionuclide (thorium-234) removal rates and to compare these rates against direct (*in vitro*) measurement of radionuclide removal of zooplankton fecal pellets.

Starting with last year's CAPE HENLOPEN cruise we adopted the custom of naming our DOE cruises in addition to the more logical, but pedestrian, Lamont numbering system. Hence last year's "Boue Trou" in the region of the "Mud Hole". In view of this year's objectives strongly focusing on radon and the role of fecal matter in pollutant removal, the name RACACA evolved from the first two letters of radon and the name used by parents and children (in a number of languages) for feces, "caca" (from the Latin, *cacare*, to void, as excrement).

The cruise having just been completed, we cannot completely assess the degree to which these objectives were achieved. The sampling and measurement program, with two exceptions, was a success with the following distribution of casts throughout the stations shown in Fig. 5.0/1: 84 CTD profiles; 49 XBT profiles; 78 30 liter water bottle casts for radon, SPM; 3 water bottle profiles for radium-228; 28 nephelometer profiles; 34 bottom camera stations; 31 continuous (surface 50 m) profiles of chlorophyll *a* and temperature; 27 zooplankton tows; 50 surface-water samples for thorium isotope analysis; 2 box cores; 25 surface sediment grab or gravity core samples.

The two exceptions to successful sampling were the zooplankton collections for fecal production experiments (we just could not net enough plankton to produce enough fecal material), and the box coring. We had decided to build the Soutar-type corer based on last year's experience on "Boue Trou" where the corer was successful on almost every cast. These casts, however, were mostly in shallow water. We had not had time to complete the design of the frame in which the corer itself is hung, but based on last year's success, without a frame, we tried the corer out on RACACA. Conclusion -- you need the frame in deep water. We obtained two successful box cores out of some dozen attempts, but these appeared to be almost fortuitous in view of evidence on most other attempts that the corer was not hitting the sediment vertically and appeared to be falling on its side. We designed a jerry-rigged frame and, with an enormous effort beyond the normal call of duty, Capt. Olander and his crew constructed one out of scrap steel. Unfortunately we did not have time to adequately test or use the corer with frame because, by the time it was finished, we were operating off Hatteras where surface drift from the Gulf Stream was so large as to cause even the frame to kite and drag on its side along the bottom.

The results of RACACA are not finished nor are those of the several disciplines integrated with each other. We provide below, however, a summary of major shipboard results in the form of a brief report from each discipline.

5.2.1 Geochemistry: Low Radon Zone. On previous cruises we have consistently observed a zone of anomalously low radon concentrations and standing crops in the near bottom waters of the continental slope adjacent to the New York Bight. This zone extends, as near as we could determine, from the shelf-slope breakdown to ∿2000 m with the lowest values at about 1000 m. It also appeared to be associated with a zone of low SPM concentrations, as measured on filtered samples.

The track of RACACA was designed to determine the long-slope extent of the low-radon zone, study its relation to bathymetry and gather data to resolve questions about possible causes of the zone. Seven cross-slope transects with 4 to 14 stations per transect were occupied from south of the Hudson Canyon to south of Cape Hatteras. Several stations were also occupied between transects. The transects were selected to study regions of varying bathymetry. One transect was located in the Baltimore Canyon region (Fig. 5.0/1).

A thermistor chain with sediment traps was moored at center of the low radon zone (∿ 1300 m water depth) on the first transect south of the Hudson Canyon. Data from the chain will enable us to evaluate the importance of a tidal pumping mechanism for removal of radon from near the bottom to areas where larger scale mixing can take place as discussed in last years proposal. Such a mechanism would be evidenced by increased separation of isotherms at high tide. (The mooring was successfully recovered on 5 August on C22-10 and, while the thermistor chain measurements appeared to record properly, the data are not yet available. The four sediment traps operated properly and collected considerable SPM which is being processed now).

Low concentrations and standing crops of radon were found at at least a few stations on every transect. Standing crops integrated up to 100 m above bottom of 0.1 dpm/cm^2 or less were found at one station in each transect except those in the Baltimore Canyon. Such values are on the order of 10% of that expected from sediment production and fluxes. The depth of the minimum in radon standing crop was variable. It was found at ∿1100 m in the first three transects (Baltimore Canyon and northward), between 500 and 1000 m in transects 4 and 5 (between Baltimore Canyon and north of Cape Hatteras) and at 1300 - 1800 m on either side of Cape Hatteras. In general the minimum occurred at the midpoint of the steepest section of the slope with the exception of transect 1 where the upper 300 m was the steepest part of the transect (minimum at ∿1100 m). This suggests some relationship between the low radon zone and the inclination of the slope. The nature of that relationship, if it really exists, is not clear because, even where the inclination of the bottom appears to be fairly constant over a large depth range, the observed radon is variable over that range with the lowest values occurring at the midpoint.

In most cases fairly low values are found all the way up to the shelf so there appears to be no clear upper bound to the zone on the slope.

If a standing crop of 0.5 dpm/cm^2 is taken as an arbitrary indicator of the extent of the low radon zone it can be seen that the lower (deepest water) limit is highly variable. Such a standing crop was found as shallow as 900 m in transect 4. In most transects 0.5 dpm/cm^2 in not reached until 1100-1400 m depth. Some stations taken between transects at ∿1250 m depth show a range of standing crops from 0.14 to 0.52 dpm/cm^2, indicating the variability of the location of lower bound. Better comparisons of standing crops with bathymetry can be made after the bathymetry of our cruise track and final navigation are reduced.

As mentioned above previous surveys suggested that a low SPM concentration zone is associated with the low radon zone. Preliminary results from RACACA indicate that this is not true. The SPM standing crops (integrated up to 100 m above bottom) showed a maximum just above or right at the observed radon minimum. From that maximum seaward the SPM standing crops decreased rapidly and then remained relatively constant below about ∿1300 m in the northern transects. The southern transects showed a slight increase below 2000 m yielding a slight minimum between 1500 and 2000 m (which is deeper than the radon minimum in these transects). There is no obvious correlation between low radon and low particles as previously observed and in fact in transect 4 the SPM standing crops shows a maximum at the depth of the radon minimum. The SPM standing crops below 1500 m are greater in the southern sections than in the northern sections. As we found previously in the upper Hudson Canyon, in the upper Baltimore Canyon both anomalously low radon and very high SPM standing crops coexist.

Due to techinical difficulties (reviewed above) only two box cores were obtained on which radon profiles were measured. One core taken at 850 m depth shows a radon deficiency of 1.0-1.5 dpm/cm^2 (preliminary estimate). This should be equivalent to the flux of radon in $atoms/cm^2/min$ and to the total standing crop expected above the sediment. The radon standing crop in the water at this station was $\sim$.12 dpm/cm^2. The core collected at 1800 m penetrated mud more deeply ($\sim$80 cm) and showed large radon deficiencies down to $\sim$70 cm. This result is questionable since it is not likely for radon to migrate from that depth except under conditions of strong irrigation. At present we have no explanation for these results and are checking them against analytical procedures.

5.2.2. Physical Oceanography. Seven lines of closely-spaced CTD-O_2 hydrographic stations nearly perpendicular to the continental margin isobaths were obtained during the RACACA cruise. The seaward front of the relatively cold and fresh remnant of the winter water column is a striking feature in all sections. The cold core of the winter water increases in temperature towards the south from less than 5°C (characteristic of the New York Bight) to about 6°C in sction IV (around 37-38°N lat.). The cold core water at Section V (near 36°N Lat.) is slightly below 6°C, reversing the long-shore trend which, however, continues to almost 10°C off Cape Hatteras.

The Cape Hatteras section is quite different from the northern sections in many ways, notably in the continuous and rapid seaward increase in isotherm depth. This is due to proximity of the Gulf Stream as the zone of slope water is "pinched out" between the shelf water and Gulf Stream.

Isotherms and isohalines in the slope water intersect the continental slope as approximately horizontal surfaces except at Cape Hatteras and in the northernmost section (I) where a weak warm-core eddy is apparently centered near CTD station #3.

The data set provides a synoptic picture of the long-shore variations in the outer shelf, shelf-slope front and slope water zones of the entire Middle Atlantic Bight. The data will permit study of shelf-slope interactions as well as provide the water-mass (stratification) data over the slope water characteriezed by deficient radon concentrations.

5.2.3. Biological Oceanography - Sampling was conducted to determine the distribution and abundance of phytoplankton and zooplankton populations, and to estimate primary production of waters overlying the shelf-break and slope from the Hudson Canyon to Cape Hatteras. Stations were occupied along transects across the slope from approximately the 80 M water depth to the base of the slope as well as one transect across the shelf of the New York Bight to a water depth of 25 M. Water was collected in conjunction with the physical oceanography and geochemical sampling program for measurements of chlorophyll a (chl a), particulate organic carbon and nitrogen, size frequency distributions of suspended particles, dissolved inorganic nutrients (ammonia, nitrate, phosphate and silicate), ATP, phytoplankton enumeration and identification, phytoplankton production estimate, and copepod gut fluorescence. In addition, vertical profiles and surface mapping of in vivo chl a fluorescence were obtained using a submersible pump and the ship's seawater system. Primary production estimates were made using a simulated in situ incubator and standard methods of ^{14}C uptake. Quantitative oblique and discrete depth tows were made for estimates of zooplankton abundance and biomass in shelf and slope waters. Experiments were run on shipboard to evaluate the rate of production of fecal pellets by copepods and to obtain adequate amounts of zooplankton fecal materials for radionuclide analysis. The radionuclide analyses are to be performed by the geochemical group.

Preliminary results are available for chl a distribution and primary production estimates, but further laboratory analysis is necessary for an evaluation of the rest of the measurements. Surface chl a concentrations were less than 0.1 μg L^{-1} in both shelf and slope waters. In slope waters maximum concentrations of 0.1 - 0.5 μg L^{-1} were found in the thermocline.

At the shelf-break and along the one shelf transect maximum concentrations were 1 and 5 μg L^{-1}, repsectively, and were associated with the top of a cold pool of water (<6°C). The chl max was dominated by netplankton (>20 u) on the shelf and at the shelf-break, and by nanoplankton (< 20 u) in slope waters.

Primary production estimates were highest on the shelf, essentially 1 mg C $m^{-2}day^{-1}$ for both the nanoplankton and netplankton fractions. At the shelf-break and in slope waters netplankton primary production was substantially lower whereas nanoplankton production was not as reduced. Calculations of production per unit biomass, however, indicated that variations in production were more related to variations in biomass rather than growth rate. Except for netplankton at the shelf-break, production per unit biomass was generally high everywhere ranging from 92 - 225 μg C $[chl]^{-1}day^{-1}$ and 54 - 202 μg C [chl]-1 day^{-1} for nanoplankton and netplankton, respectively. At the shelf-break netplankton chl a was maximal at the bottom of the euphotic zone and production per unit biomass was reduced to 5.3 μg C $[chl]^{-1}$ day^{-1}. Thus, phytoplankton populations in the areas sampled were turning over rapidly. Doubling times on the order of less than a day were calculated for all euphotic areas (assuming a C:Chl = 47) except for the netplankton at the shelf-break where the estimate of turnover time was approximately 6.5 days.

Since variations in netplankton and nanoplankton primary production were primarily related to variations in chl a, the decrease in netplankton productivity in slope waters probably reflects influences of environmental factors other than those which directly affect growth, i.e., resuspension of seed populations, sinking and grazing. The importance of resuspension and sinking is suggested by the presence of netplankton diatoms in sediments.

A sample was obtained during the cruise from the surface of a box core collected from 800 M. A small subsample was inoculated into culture media and placed in a constant temperature (16°C) light incubator. Within one week an extremely diverse and dense group of large celled and chain-forming pelagic diatoms grew up.

While quite preliminary, this observation supports the hypothesis that high and variable rates of diatom production in continental shelf waters relative to the open ocean is, at least in part, a consequence of the sinking and dark survival characteristics of diatoms (Malone, in press). The longer cells remain in suspension, the greater the probability that they will be removed from shelf environments. Diatom production is high in shelf waters because they tend to be retained on the shelf due to relatively high sinking rates and the seasonal cycle of thermal stratification which restricts diatom blooms to winter and early spring when grazing pressure is low (Malone & Chervin, 1979 ; Malone, in press).

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Malone, T.C. Algal Size and Phytoplankton Ecology. In Physiological Ecology of Phytoplankton. Ian Morris, Ed., Blackwell (in press).

Malone, T.C. and M. Chervin. (1979). The production and fate of phytoplankton size fractions in the plume of the Hudson River, New York Bight. Limnol. Oceanogr. 24, 683-696.

6.0 PAPERS, TALKS AND ABSTRACTS

What follows is an update of the list of talks, abstracts and papers produced and in preparation since the July 1978 Annual Report.

Papers Published, in Press or Submitted

Biscaye, P.E., Olsen, C.R., and Mathieu, G, 1978, Suspended particulate matter and natural radionuclides as tracers of pollutant transports in continental shelf waters of the eastern U.S.: First American-Soviet Symposium on Chemical Pollution of the Marine Environment, Odessa, USSR; K.K. Turekian and A.I. Simonov; EPA-600/9-78-038, p. 125-147.

Cook, R. and Li, Y.-H. A model for sediment mixing, submitted to EPSL.

Kadko, D. Thorium-230, radium-226 and radon-222 in abyssal sediments. (EPSL, in press).

Kaufman, A., Y.H. Li, and K. Turekian. The removal rates of ^{234}Th and ^{228}Th from waters of the New York Bight, submitted to EPSL.

Li, Y.-H., Feely, H.W. and Santschi, P.H. ^{228}Th-^{228}Ra radioactive disequilibrium in the New York Bight and its implication for coastal pollution. Earth Planet. Sci. Lett. 42 (1979) 13-26.

Li, Y.-H. and Chan, L.H. Desorption of barium and ^{228}Ra from riverborne sediments in the Hudson estuary. Earth Planet. Sci. Lett. 43 (1979) 343-350.

Malone, T.C. and Chervin, M. The production and fate of phytoplankton size fraction in the plume of the Hudson River, New York Bight. Limnol Oceanogr. 24(4) (1979) 683-696.

Olsen, C.R., Biscaye, P.E., Simpson, H.J., Trier, R.M., Kostyk, N., R.B. Bopp, Y.-H. Li and H.W. Feely, Reactor-released radionuclides and Fine Grained Sediment Transport and Accumulation Patterns in Barnegat Bay, New Jersey and Adjacent Shelf Waters. Estuarine & Coastal Marine Science, in press.

Posmentier, E.S. and Houghton, R.W. Fine structure instabilities induced by double diffusion. J. Geophys. Res.

Santschi, P.H., Li, Y.-H. and Bell, J. Natural radionuclides in the water of Narragansett Bay. EPSL (in press).

Santschi, P.H., D. Adler., M. Amdurer., Y.H. Li, and J. Bell. Thorium isotopes as analogues for reactive particle pollutants in coastal environments. Submitted to EPSL.

Papers in Preparation

Biscaye, P.E., Carson, S. and Mathieu, G. Radon-222 as a radioactive tracer of water mixing processes on the New York Continental Shelf; seasonal variability.

Biscaye, P.E., Carson, S. and Mathieu, G. Anomalous zone of low radon-222 and suspended particulate matter in near-bottom waters of the upper continental slope, New York Bight.

Gordon, A.L., Houghton, R.W. and Aikman, F. New York Bight stratification.

Li, Y.-H., Santschi, P.H. and Trier, R. The geochemical behavior of $^{239,240}Pu$ in coastal waters.

Li, Y.-H. *et al.* ^{228}Th-^{228}Ra radioactive disequilibrium in the New York Bight, Part II.

Li, Y.-H. Oceanic mean residence time of elements revisited.

Malone, T.C., Chervin, M. and Neale, P. Characteristics of particulate size fractions in the water column of the New York Bight.

Talks and Abstracts

Houghton, R.W., Gordon, A.L. and Aikman, F., III. The cold pool - why does is persist? NOAA Workshop, Nov. 1978.

Li, Y.-H. Is continental shelf a sink for pollutants? Invited talk at WHOI, Nov. 17, 1978.

Malone T., Phytoplankton biomass and the 1976 ceratium tripos bloom in the New York Bight. ASLO, June 19-22, 1978.

Malone, T., Oxygen depletion in the New York Bight - plankton processes. ASLO, June 18-21, 1979.

DOE workshop on "Processes determining the input, behavior and fate of radionuclides and trace elements in continental shelf environment." March 7-9, 1979. Biscaye, P.E. Suspended particulate material, radionuclides and trace elements in continental shelf environments." Li, Y.-H., Removal rates of highly reactive trace elements in coastal waters.