# Water quality monitoring in Massachusetts and Cape Cod Bays: April-August 1992.

Massachusetts Water Resources Authority

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# FINAL REPORT

# WATER QUALITY MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: APRIL - AUGUST 1992

by
John R. Kelly
Carl S. Albro
John T. Hennessy

prepared by:
Battelle Ocean Sciences
397 Washington Street
Duxbury, MA 02332
(617) 934-0571

prepared for:
Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Boston, MA 02129
(617) 242-6000

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WATER QUALITY MONITORING IN MASSACHUSETTS BAY AND CAPE COD BAYS:
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CONTENTS

CONTENTS *(Continued)*

CONTENTS *(Continued)*

LIST OF APPENDICES



**Note to reader: Appendices A-L are bound separately from this technical report. to request the Appendices, contact the MWRA and ask for one of the MWRA Miscellaneous Publications entitled "APPENDICES TO WATER QUALITY MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: APRIL-AUGUST 1992"**

## LIST OF TABLES

## LIST OF FIGURES

## PREFACE

This report provides a description and summary of data collected for the Massachusetts Water Resources Authority Water Quality Monitoring during 1992. The authors played the primary role in report preparation including: data processing, interpretation, and presentation of survey objectives and findings. A larger group of individuals are gratefully acknowledged for tremendous efforts in the field, in the laboratory, in data analysis, and in report production. This group included:


Dr. Peter Doering, University of Rhode Island, who coordinated all aspects of the nutrient metabolism sampling and provided results of data analyses and modeling of metabolism. He was assisted by Laura Reed, Edwin Requintina, and Eric Klos.

Dr. Jefferson Turner and David Borkman of the University of Massachusetts - Dartmouth, who performed phytoplankton and zooplankton sampling and analyses and provided interpretative assistance.

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Ellie Baptiste, of Battelle Ocean Sciences, helped develop and manage the database and prepared some of the appendices for this report. Carole Peven and Lisa Ginsburg prepared many of the graphic results for the report.

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# WATER QUALITY MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: APRIL-AUGUST 1992

## EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA) is implementing a long-term monitoring plan for the future MWRA effluent outfall that will be located in western Massachusetts Bay. The purpose of monitoring is to verify compliance with the discharge permit and to assess the potential environmental impact of effluent discharge into Massachusetts Bay. To help establish the present conditions as a baseline, Battelle will be conducting twenty-two water-quality surveys throughout Massachusetts Bay and Cape Cod Bay during 1992 for the MWRA. These water-quality surveys are to provide data on water properties, including nutrients and other parameters of importance relative to eutrophication.

This report encompasses the surveys from late Spring through mid-Summer, covering all surveys from early April to the middle of August. Included are results, from two months (April and June), of a "combined" survey. Each combined survey included stations located in the "nearfield," an approximately 100 $km^2$ region whose center is near the middle of the proposed outfall diffuser line, and the "farfield," defined as all other stations sampled in Massachusetts and Cape Cod Bays that fall outside the nearfield region. Also included are results from five separate surveys conducted only in the nearfield during the time period. The report briefly provides background information on the water quality surveys and objectives and describes field, laboratory, and data analysis procedures. Results by survey then are presented and discussed in some detail. Survey activities and major results are summarized here.

### Overview of surveys

Measures of physical, chemical, and biological properties in Massachusetts Bay and Cape Cod Bay were made. Sampling was performed at predetermined stations, following the monitoring plan developed by the MWRA. Included were twenty-one nearfield stations in a regular grid around the proposed outfall location in Western Massachusetts Bay. Also included were twenty-five farfield stations; most of these were along transect lines set to provide description of water quality north, south, east, and west of the nearfield. Some stations were also to characterize selected areas, such as along the axis of Stellwagen Basin, near Race Point off Provincetown at the tip of Cape Cod, and at two exit points from Boston Harbor.

There were two main types of stations: nutrient/hydrography stations and biology/productivity stations, both in the nearfield and the farfield. A variety of supplemental measurements were made at the latter type of station to provide intensive description of water quality.

There were two principal modes of sampling. Vertical profiles were made, using sensors and bottles to sample throughout the water column at a station. In the nearfield, horizontal towing also was conducted, in which instruments sampled the water column while oscillating from near surface to near bottom along prescribed transects.

The purpose of measurements was to determine *in situ* concentrations for most parameters and provide data on rates of several important processes. Sampling was performed using three general methods: (1) *in situ* sensors and electronic, or in one case (light) manual, data recording; (2) whole-water samples retrieved from depth by closing bottles, or in some cases, by pumping; (3) towing of a net to obtain samples of zooplankton. From (2) and (3), laboratory analyses were performed to provide precise

determinations of chemical or biological parameters and results were input to the MWRA monitoring database.

**Overview of major results**

The surveys have been highly successful; results have allowed useful and detailed characterization of physical, chemical, and biological properties in the nearfield and farfield regions. The major environmental features in Massachusetts and Cape Cod Bays were revealed by the April and June surveys. By June the two Bays had some distinct features in terms of biology, chemistry, and physics.

Nutrients were within the range, and followed geographic and seasonal patterns, previously measured in the Bays. In general, as the season progressed, normal thermally-induced stratification of the water column ensued. Except for the shallow waters where physical energies still kept the water column slightly mixed, results showed a layering of warmer surface water above the cold bottom waters, with a sharp transition zone of temperature and seawater density (the "pycnocline") between layers. The surveys covered a period where the last remnants of a prolonged winter-spring bloom were noted as a *Phaeocystis* bloom spread throughout both Bays. As this population waned and sank from the surface layers during April, stratification sharpened and helped create a low nutrient surface layer underlain by a higher nutrient bottom water layer, as expected. In general, these conditions encouraged growth of organisms able to assimilate nutrients where they were more abundant (the pycnocline or below, or near inshore sources), and lead to a growth of a dinoflagellate species, *Ceratium*, that was pronounced in Cape Cod Bay, but not Massachusetts Bay. It was notable that stratification, nutrients, and chlorophyll were interrelated and in coastal areas with less distinct stratification, different vertical distributions of many parameters were seen compared to deep-water stations.

As in our first report for 1992 (Kelly *et al.* 1992), it was convenient to examine results by contrasting variability of physical, chemical (nutrients), and biological parameters. The features of variability for each were as indicated by the following synopses.

***Physical variability.*** Conditions generally changed from early April to summertime (by June) from well-mixed or weakly-mixed vertically to strongly stratified. There were weak, but characterizable, horizontal gradients from shore. Water mass distinctions between shallow coastal and more offshore waters were possible, as were distinctions between Cape Cod and Massachusetts Bays. For example, Cape Cod Bay (compared to Massachusetts Bay) surface waters flipped from being colder in April (continuing the February-March trend) to warmer in June. With respect to the nearfield, one can infer from the data that a surface water mass occasionally impinged on nearfield from the north during this season. Advection and mixing of coastal water of obvious Boston Harbor origin with offshore water also was documented within the nearfield region, particularly at the southwestern corner. This advection and mixing was strongly connected to tidal oscillations, as repeatedly demonstrated by analysis of each survey. In the nearfield, where repeated sampling occurred on several days of a survey and where synoptic data were gathered during horizontal towing, results showed that short-term and small-scale variability was high, and at times fronts in the center of the field were detected. But under relatively calm conditions in mid-summer a fairly uniform nearfield, in terms of physical parameters, was seen often.

***Chemical (nutrients) variability.*** Nutrients followed physics with respect to offshore/inshore distinctions, tidal dynamics, latitudinal patterns, and most significantly, vertical stratification. It was usually possible to make some geochemical distinction between coastal and offshore waters and Massachusetts Bay vs. Cape Cod Bay stations by virtue of either the quantity or quality of nutrients. There was a persistent

signal of nutrients in waters ebbing from Boston Harbor, often more detected in organic N than in dissolved inorganic N, but patterns with salinity were not as striking as during colder months. A most interesting feature of regional variability was the difference in both April and June in the silicate concentration of waters in Cape Cod Bay vs. Massachusetts Bay. As for physics, apart from higher nutrient variability at inshore stations and near the strong source for the region (Boston Harbor), the principal nutrient variability was in the vertical dimension. In a sense, water depth, as much or more than geographic position, seemed to influence dissolved nutrients concentrations of N, P, and Si. Surface waters were, small exceptions noted, uniformly low in nutrients for most of the period, and concentrations built up underneath the pycnocline throughout the summer. Interestingly, we appeared to document an interruption of the seasonal progression in mid-July, where some mixing and disruption of the nearfield occurred, altering some vertical patterns of nutrients and chlorophyll. Notably, this disruption seemed to be followed by a quick reestablishment of striking vertical gradients.

***Biological variability.*** Regionally, in contrast to some physical and nutrient distinctions (both horizontal and vertical) that were evident in April, there were no species differences in the phytoplankton community at different stations. Rather, a dominant, nearly mono-specific, presence of *Phaeocystis* was seen throughout the Bays. The concentration of cells was not strikingly related to dissolved nitrogen, but a correlation with total N was seen. In contrast to April, the regional physical and chemical distinctions between Cape Cod Bay and Massachusetts Bay that were evident in June were accompanied by a biological difference with respect to phytoplankton species. In Cape Cod Bay, a deep subsurface chlorophyll maximim was primarily a dinoflagellate, *Ceratium*, which was not among the dominant organisms in Massachusetts Bay. Volumetric production rates and $P_{max}$, a measure of production potential under non-limiting surface light irradiance conditions, had considerable variability across stations and depths. The degree to which net production can be modeled was in part related to chlorophyll biomass. Chlorophyll varied substantially over time, station, and depth. May was the period of lowest chlorophyll on average. High summer chlorophyll was routinely associated with inshore water, and found close to the surface; in the case of the nearfield, high chlorophyll time-variability was related to the (presumed) tidal dynamics also affecting nutrients and physical parameters. In many instances, high chlorophyll was seen quite deep in the water column, and in general it appeared to track the pycnocline location as well as perturbations to it. From high-resolution data, it was apparent that chlorophyll may often be distributed very patchily throughout the nearfield.

**Initial conclusions on monitoring design**

The station sampling design and array of sample analyses were able again to distinguish regions of the Bays having only very small differences in their parameter values. Repeated casts at a selection of stations showed that results at deeper or more mid-Bay stations were highly repeatable when made hours apart. In contrast, the coastal stations showed considerably more short-term variability in all parameters. The sampling for all measures in the nearfield was more powerful than in the farfield. Accordingly, results showed much fine-scale variability in the nearfield; higher resolution in parts of the nearfield may be required for adequate baseline characterization, however, because changes there occurred within a tidal cycle, as well as over periods of days.

# 1.0 INTRODUCTION

This report is the second synthesis report for the water quality portion of the 1992 Massachusetts Water Resources Authority Outfall Monitoring Program. It includes physical, chemical, and biological data from early April and June combined nearfield-farfield surveys and from five other nearfield-only surveys running from late April to the middle of August 1992. The report structure is as follows.

1. Background information on the water quality surveys
2. Description of field, laboratory, and data analysis procedures
3. Results by survey, in chronological order
4. Discussion of the physical and chemical properties of the water, the water-column/nutrient dynamics, and the relationship between biological parameters and water properties/nutrient dynamics
5. Summary of the 1992 [spring-summer] season — water properties and ecological dynamics.

Recognizing the need for dissemination of monitoring data and information, this report is intended to be a summary and preliminary synthesis of information. Survey plans were prepared for each survey to provide important operational details required to conduct each survey. Summaries of each survey were given in survey reports that have been submitted to the MWRA; these should be consulted for pertinent details, for example, on sampling tracks and samples obtained at each station. Appendices of data from the surveys covered in this report, listed in the Table of Contents, are attached as a separate volume of this report. Further interpretation of this information, and information gathered over the remainder of 1992, will be given in an annual report that will be prepared under a separate contract.

## 1.1 Background

The Massachusetts Water Resources Authority (MWRA) is implementing a long-term monitoring plan (MWRA, 1991) for the future MWRA effluent outfall that will be located in Massachusetts Bay (see Figure 1-1). (Note that all tables and figures are at the end of each chapter). The purpose of the monitoring is to verify compliance with the discharge permit and to assess the potential environmental impact of effluent discharge into Massachusetts Bay. To help establish the present conditions with respect

to water properties, nutrients, and other important parameters of eutrophication, Battelle was contracted to conduct twenty-two water-quality surveys throughout Massachusetts Bay during 1992 for the MWRA. A detailed description of the monitoring and its rationale are given in the Effluent Outfall Monitoring Plan (MWRA, 1991). The technical approach used to implement the water quality portion of this monitoring plan is presented in the Quality Assurance Project Plan (QAPjP), Shea *et al.* (1992). The QAPjP describes the technical activities performed at sea and in the laboratory, data quality requirements and assessments, project management, and a schedule of activities and deliverables.

## 1.2 Survey Objectives

The objectives of the water quality surveys are discussed in detail in the MWRA Effluent Outfall Monitoring Plan (MWRA, 1991) and are summarized below.

**Physical Oceanography**

- Obtain high-resolution measurements of water properties throughout Massachusetts Bay
- Use vertical-profile data on water properties at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (10s of km) and temporal (seasonal) variability in water properties and to provide supporting data to help interpret biological and chemical data
- Use high-resolution, near-synoptic, water-property measurements along transects within the nearfield area for analysis of smaller-scale spatial (km) and temporal (semi-monthly) variability in water properties, and develop a three-dimensional picture of water properties near the future outfall.

**Nutrients**

- Obtain nutrient measurements in water that is representative of Massachusetts and Cape Cod Bays
- Use vertical-profile data on nutrients at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (10s of km) and temporal (seasonal) variability in nutrient concentrations and to provide supporting data to help to interpret biological data
- Use vertical-profile data on nutrients along transects of closely-spaced stations within the nearfield area for analysis of smaller-scale spatial (km) and temporal (semi-monthly) variability in nutrient concentrations, and develop a three-dimensional picture of the nutrient field near the future outfall.

**Plankton**

- Obtain high-quality identification and enumeration of phytoplankton and zooplankton in water that is representative of Massachusetts and Cape Cod Bays
- Use vertical-profile data on plankton at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (10s of km) and temporal (seasonal) variability in plankton distribution.

**Water Column Respiration and Production**

- Using water that is representative of Massachusetts and Cape Cod Bays, obtain a reasonable estimate of the rates of water-column respiration and production as a function of irradiance.

**General**

- Evaluate the utility of various measurements to detect change or to help to explain observed change
- Provide data to help to modify the monitoring program to allow a more efficient means of attaining monitoring objectives
- Use the data appropriately to describe the water-quality conditions (over space and time) in Massachusetts and Cape Cod Bays.

## 1.3 Survey Schedule for 1992 Baseline Water Quality Monitoring Program

The original survey schedule for the 1992 Baseline Water Quality Monitoring Program is shown in Figure 1-2. February and March combined nearfield-farfield cruises were reported in Kelly *et al.* (1992). No nearfield survey was conducted in late March due to weather. A combined nearfield-survey was conducted as planned in early April (7-14) and also in June (22-26). Nearfield surveys were conducted as planned in late April (29-30), May (19-20), mid-July (15-16), late July (29-30) and in mid-August (12-13).

## 1.4 Summary of Accomplishments during early April to mid-August

A high percentage of planned stations were completed, data electronically recorded, and samples obtained. For the two combined surveys, *in situ* measurements were taken and samples were collected at the stations shown in Figure 1-3 for laboratory analyses to obtain the following types of data.

- Dissolved inorganic nutrients: nitrate, nitrite, ammonium, phosphate, and silicate
- Chlorophyll *a* and phaeopigments in extracts of filtered water
- *In situ* fluorometric measurements of chlorophyll, optical-beam transmittance (attenuation), light irradiance, salinity, temperature, and dissolved oxygen
- Total suspended solids and dissolved oxygen in discrete water samples
- Organic nutrients: dissolved carbon, nitrogen, and phosphorus; particulate carbon and nitrogen
- Phytoplankton and zooplankton identification and enumeration
- Rates of water-column respiration and production vs. irradiance from shipboard incubations.

For the nearfield surveys in general, the first day was dedicated to vertical profiling, including collection of the following data

- Dissolved inorganic nutrients: nitrate, nitrite, ammonium, phosphate, and silicate
- *In situ* fluorometric measurements of chlorophyll, optical-beam transmittance (attenuation), light irradiance, salinity, temperature, and dissolved oxygen
- Chlorophyll *a* and phaeopigments in extracts of filtered water, as well as oxygen samples for titration, all to be used to calibrate *in situ* readings
- Phytoplankton samples for archival purposes.

The second day of a nearfield survey was dedicated to high-resolution "tow-yo" profiling. A towfish containing *in situ* sensors (as above, minus irradiance) was performed along nearfield tracks set between the vertical stations with the towfish oscillating from near the surface to near the bottom as

the ship progressed at about 4 kt. There are 8 standard legs for towing. Four legs form the outer box (see Figure 1-3), covering about a 40 km track (Stations N01P-N04P-N07P-N10P). The inner track has as its corners stations N12, N15, N17 and N19. Not all legs were completed in early or late April; refer to survey reports for details.

All samples that were collected for analysis have been analyzed, and *in situ* sensor measurements have been calibrated and processed. Both types of data are used in reporting results and all are summarized in accompanying Appendices A to G.

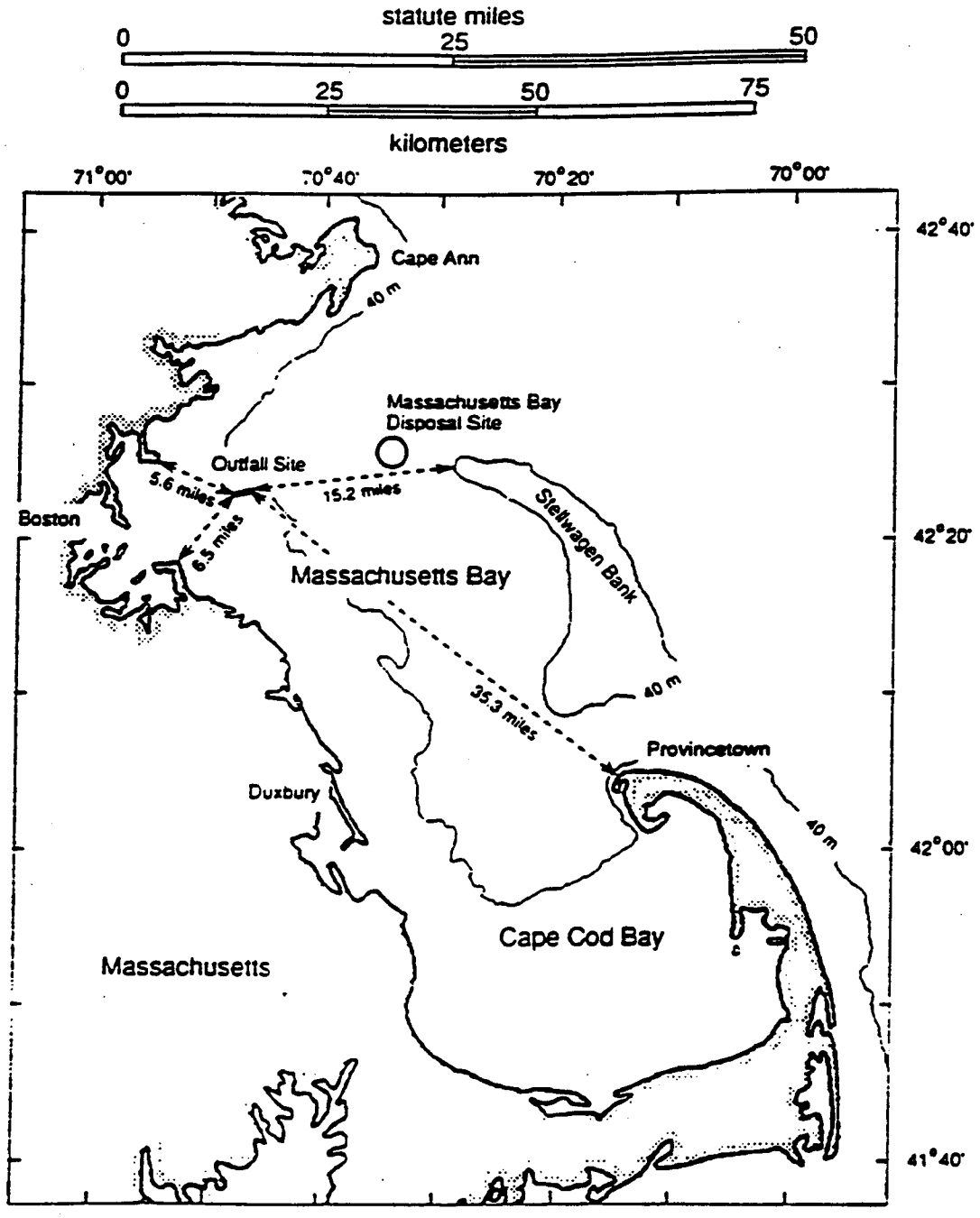



**Figure 1-1 Massachusetts and Cape Cod Bays**

| | S | M | T | W | T | F | S | | S | M | T | W | T | F | S | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 | | | | | 1 | 2 | 3 | 4 | J |
| J | 5 | 6 | 7 | 8 | 9 | 10 | 11 | | 5 | 6 | n1 | n2 | 9 | 10 | 11 | U |
| A | 12 | 13 | 14 | 15 | 16 | 17 | 18 | | 12 | 13 | 14 | 15 | 16 | 17 | 18 | L |
| N | 19 | 20 | 21 | 22 | 23 | 24 | 25 | | 19 | 20 | 21 | 22 | 23 | 24 | 25 | |
| | 26 | 27 | 28 | 29 | 30 | 31 | 1 | | 26 | 27 | n1 | n2 | 30 | 31 | 1 | |
| F | 2 | 3 | 4 | 5 | 6 | 7 | 8 | | 2 | 3 | 4 | 5 | 6 | 7 | 8 | A |
| E | 9 | 10 | 11 | 12 | 13 | 14 | 15 | | 9 | 10 | n1 | n2 | 13 | 14 | 15 | U |
| B | 16 | 17 | 18 | 19 | 20 | 21 | 22 | | 16 | 17 | 18 | 19 | 20 | 21 | 22 | G |
| | 23 | 24 | 25 | 26 | 27 | n1 | n2 | | 23 | 24 | 25 | 26 | 27 | n1 | n2 | |
| M | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 30 | 31 | 1 | 2 | 3 | 4 | 5 | S |
| A | 8 | 9 | 10 | 11 | 12 | n1 | n2 | | 6 | 7 | 8 | n1 | n2 | 11 | 12 | E |
| R | 15 | 16 | 17 | 18 | 19 | 20 | 21 | | 13 | 14 | 15 | 16 | 17 | 18 | 19 | P |
| | 22 | 23 | 24 | 25 | 26 | 27 | 28 | | 20 | 21 | 22 | 23 | 24 | 25 | 26 | |
| | 29 | 30 | 31 | 1 | 2 | 3 | 4 | | 27 | 28 | n1 | n2 | 1 | 2 | 3 | |
| A | 5 | 6 | 7 | 8 | 9 | n1 | n2 | | 4 | 5 | 6 | 7 | 8 | 9 | 10 | O |
| P | 12 | 13 | 14 | 15 | 16 | 17 | 18 | | 11 | 12 | 13 | 14 | 15 | 16 | n1 | C |
| R | 19 | 20 | 21 | 22 | 23 | 24 | 25 | | n2 | 19 | 20 | 21 | 22 | 23 | 24 | T |
| | 26 | 27 | n1 | n2 | 30 | 1 | 2 | | 25 | 26 | 27 | 28 | 29 | 30 | 31 | |
| M | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | 1 | 2 | n1 | n2 | 5 | 6 | 7 | N |
| A | 10 | 11 | 12 | 13 | 14 | 15 | 16 | | 8 | 9 | 10 | 11 | 12 | 13 | 14 | O |
| Y | 17 | 18 | n1 | n2 | 21 | 22 | 23 | | 15 | 16 | 17 | 18 | 19 | 20 | 21 | V |
| | 24 | 25 | 26 | 27 | 28 | 29 | 30 | | 22 | 23 | 24 | 25 | 26 | 27 | 28 | |
| | 31 | 1 | 2 | 3 | 4 | 5 | 6 | | 29 | 30 | n1 | n2 | 3 | 4 | 5 | D |
| J | 7 | 8 | 9 | 10 | 11 | 12 | 13 | | 6 | 7 | 8 | 9 | 10 | 11 | 12 | E |
| U | 14 | 15 | 16 | 17 | 18 | 19 | 20 | | 13 | 14 | 15 | 16 | 17 | 18 | 19 | C |
| N | 21 | 22 | 23 | 24 | 25 | n1 | n2 | | 20 | 21 | 22 | 23 | 24 | 25 | 26 | |
| | 28 | 29 | 30 | | | | | | 27 | 28 | 29 | 30 | 31 | | | |

Legend: Nearfield nutrient/hydrography survey

Biology/productivity and farfield nutrient/hydrography survey

**Figure 1-2** **Planned Schedule of Water Quality Surveys for Calendar Year 1992. This report provides data from the actual surveys conducted from April through mid-August. The late March survey was cancelled.**

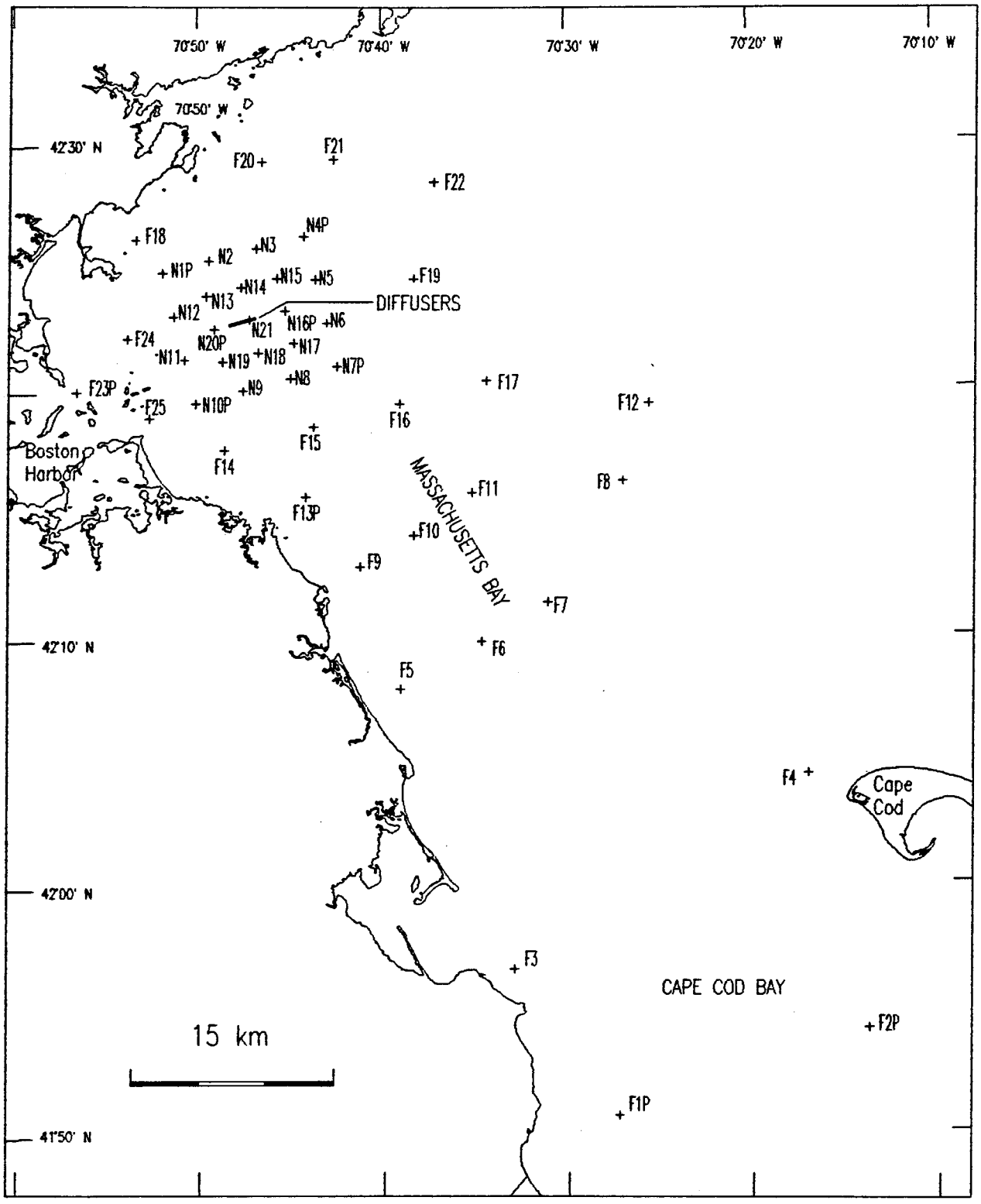



**Figure 1-3 Water Quality Sampling Stations in Massachusetts and Cape Cod Bays. Station Codes — F: Farfield, N: Nearfield, P: Biology/Productivity**

# 2.0 METHODS

Sampling equipment and procedures, sample handling and custody, sample processing and analysis, and instrument performance specifications and data quality objectives are discussed in the Quality Assurance Project Plan (Shea *et al.*, 1992) and are detailed in survey reports submitted to the MWRA. A general overview follows here.

## 2.1 Field Procedures

### 2.1.1 Hydrographic Stations

Combined surveys consisted of a farfield survey followed by a nearfield survey. During the farfield portion of a combined survey and the first day of any nearfield survey, continuous vertical hydrographic profiles of the water were performed and discrete water samples were collected at approximately five depths. During the second day of the nearfield survey, continuous tow-yo hydrographic profiles were performed and discrete water samples were collected at some locations for instrument calibration and archival. Samples for water-column metabolism, and phytoplankton and zooplankton taxonomy were collected at the biology/productivity ("Bioproductivity") stations. Sample processing and analysis was performed both onboard the vessel and in laboratories on shore.

Positioning for surveys was accomplished using a Northstar Model 800 Loran/GPS system with an absolute accuracy of 30-100 m. Depth measurements were collected with a JRC JFV-120 dual frequency color video echosounder. Transducers for this system were mounted on a swiveling boom assembly which was lowered into place upon arriving on station. Note that the depth sounder was not operational during the mid-July survey and readings from the ship's echosounder were manually entered in the log. The navigation system and depth sounder were interfaced to the BOSS navigation display and logging system. With this system, the Massachusetts Bay coastline, station locations, and the vessel track were all displayed on a color CRT. This system was also used to display and record bottom bathymetry and hydrographic data during profiling operations. Calibration checks of the Loran/GPS system were performed generally at dockside and at the B-buoy near the future outfall site.

During sampling operations, the BOSS computer displayed vessel position in relation to the target sampling location. All vertical profiles were started within 300 m of the station position. Sampling was usually finished while the ship was within a 300-m radius of the station, but in some cases where there was a high rate of drift, sampling was conducted at $>300$ m from the position. Hardcopies of the vessel position during sampling were printed after samples were collected.

### 2.1.2 BOSS Sampling System and Procedures

During the combined survey in April, for the farfield portion and the first day of the nearfield portion, vertical hydrographic profiles were obtained using a SeaBird SBE-9 CTD and SeaBird SBE-13 dissolved oxygen sensor mounted in a General Oceanics Model 1015 rosette. The CTD system was interfaced to a SeaTech transmissometer (for beam attenuation), Chelsea Instruments Aquatracka III fluorometer (for chlorophyll *a*), Biospherical Irradiance sensor (starting in June), and SeaBird SBE-13 dissolved oxygen sensor. The CTD system measures depth, temperature, conductivity, oxygen-sensor current, and oxygen-sensor temperature. Salinity, density, and dissolved oxygen concentrations were calculated from these measurements. Ambient skylight levels were measured simultaneously using a Biospherical deck cell. At the completion of a cast, a color plot of the hydrographic profile data was produced and the profile data were recorded on computer hard disc. The data were backed up on floppy discs at regular intervals.

On the downcast, a hydrographic profile was obtained from near surface to within 5 m of the bottom for salinity, temperature, dissolved oxygen, beam transmittance, chlorophyll *a,* and depth. These data were graphically displayed in real time on the color CRT monitor and were used by the chief scientist to identify the chlorophyll maximum and to determine the depths for water sampling on the upcast.

From April to June, irradiance measurements were obtained with a Licor Spherical Quantum underwater irradiance sensor. The irradiance sensor was lowered by hand and values recorded from an analog deck box at 1-m intervals for the first 10 m and thereafter at 5-m intervals until roughly the 1% light level was reached. Variation in ambient light levels during profiling was measured simultaneously by a Licor deck reference cell. Due to equipment breakage, it was necessary to use a variety of meters and irradiance sensors across the April to June period. Data have been post-cruise calibrated to ensure accurate readings.

The Biospherical Irradiance Sensor measurements began in June. Due to equipment problems there are no continuous profile data for irradiance for nearfield stations sampled on 6/25/92; neither are there dissolved oxygen data for that day. Also due to equipment hardware interface problems there are no continuous profile data for irradiance on the mid-July survey (see Appendix B).

Discrete water samples were collected with a General Oceanics Model 1015 rosette system equipped with 5- and 10-L GO-FLO (or Niskin) bottles. Samples for phytoplankton, dissolved inorganic nutrients, particulate and dissolved organic nutrients, chlorophyll, TSS, and DO were taken from these sample bottles. Bottles were lowered through the water column in an open position. On the upcast of a vertical profile, a bottle was electronically closed at each of five depths (bottom, intermediate bottom, mid-depth or chlorophyll maximum, intermediate surface, and surface) using the rosette deck unit. At stations where the bottom depth was about 20 m or less, only four depths were sampled. Discrete water-bottle sampling events were electronically flagged in the BOSS data file using an "event mark" so that the precise vessel position and the concurrent *in situ* water-column parameters (salinity, temperature, turbidity, dissolved oxygen, chlorophyll *a,* and depth) are linked with each sample.

During the first day of the nearfield portion of the June combined survey and each nearfield survey, water samples were collected for nutrients by pumping water to the surface through the BOSS pump and profiling tube with teflon manifold. The CTD was left at a depth for about 1-2 min before sampling for a given depth. Calibration samples (dissolved oxygen and chlorophyll) from the surface were also obtained at selected stations using a Niskin sampler. Surface samples (~800-1000 mL), archived for phytoplankton taxonomy, were also collected (using a Niskin sampler or a bucket) at the biology/productivity stations. Water samples for dissolved nutrients and chlorophyll *a* were filtered between sampling periods enroute to the next station.

During the second day of the nearfield surveys, hydrographic data (depth, temperature, conductivity, oxygen, beam attenuation, and chlorophyll fluorescence) were obtained, generally using the mini-BOSS equipped with an Ocean Sensors CTD, SeaBird SBE-13 dissolved oxygen sensor, SeaTech transmissometer, and Chelsea fluorometer. The towfish was used to obtain continuous tow-yo profiles from near surface to about 5 m off bottom along the nearfield tracklines. Approximately six tow-yo profiles were performed between each nearfield station. A vertical profile routinely was obtained at the middle of the nearfield, station N21.

### 2.1.3 Sampling for Nutrients, Chlorophyll, and Total Suspended Solids

Samples for dissolved nutrients, chlorophyll, and total suspended solids (TSS) were filtered onboard with a syringe-filter system. A sample of about 60 to 75 mL for dissolved inorganic nutrients was filtered through precombusted glass-fiber filters directly into 125-mL polyethylene bottles and preserved with chloroform. For dissolved organic carbon (DOC) about 60-75 mL of similarly filtered sample was placed directly into precleaned amber-glass bottles and then frozen. A 20-mL sample for dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) analysis was filtered through the precombusted glass-fiber filter into a precleaned, capped test tube. The samples were fixed with buffered potassium persulfate solution and digested at 100°C in the field (Lambert and Oviatt, 1986).

Material retained on a precombusted glass-fiber filter from a 10-mL sample was used for chlorophyll *a* analysis. This small volume technique was developed by the Marine Ecosystems Research Laboratory and has been used in highly successful field and mesocosm studies for more than a decade. Filters were carefully folded, placed in aluminum foil, and frozen. Duplicate samples were taken and analyzed for chlorophyll at each sampling depth.

For combined particulate carbon and nitrogen analysis, about 50 mL of sample were passed through a precombusted glass-fiber filter; the filter was carefully folded and frozen. For TSS, about 100 mL of water was filtered through preweighed 0.4-$\mu$m Nucleopore filters. The filters were placed in labeled petri dishes and frozen. All samples frozen on the ship remained frozen until analysis. All filtered sample volumes were recorded in a laboratory notebook.

### 2.1.4 Metabolism Measurements

Metabolism was measured using the methods described in Lambert and Oviatt (1986). Phytoplankton production and respiration were measured by the light-dark bottle oxygen technique (Strickland and Parsons, 1972). Light and dark bottles were incubated in a photosynthetron using a modification of the methodology of Lewis and Smith (1983). Eighteen 300-mL biological oxygen demand (BOD) bottles were filled with water from a given depth (surface and mid-depth) at each of the biological/productivity stations. Up to 12 samples were incubated to simulate an irradiance gradient with light levels ranging from about 20 to 2000$\mu$E/m$^2$/sec. Light levels within the incubator were created by covering individual

bottles with appropriate neutral density screening. For standardization, the light levels were fixed across stations and surveys. Three dark BOD bottles were placed in the photosynthetron to simulate zero irradiance. Three other BOD bottles were fixed (Lambert and Oviatt, 1986) immediately and represent both *in situ* DO concentrations, as well as initial values for the incubations. After about six hours (actual time was recorded), the remaining fifteen bottles from a given sampling location were fixed. The temperature of the incubator was maintained at ambient surface water temperature by a flowing seawater system. For the chlorophyll maximum samples, a separate compartment of the incubator was cooled to near *in situ* conditions; this required some strategic ordering of stations to match stations pairs and depths to temperature in the two compartments of the incubator.

In June, additional sampling was done to estimate bottom water dark respiration estimates. Taken at Bioproductivity stations, these samples were filled from the Niskin bottle at an intermediate depth between the bottom bottle and the one at the subsurface chlorophyll maximum. Three initials were fixed immediately. Three other bottles were put in a refrigerated incubator in the dark and maintained near *in situ* temperatures for a period of about 6 hours, when they were fixed.

### 2.1.5 Phytoplankton and Zooplankton Sampling

Seawater was collected in Niskin or GO-FLO bottles at five depths over the water column at each of the ten biological/productivity stations. An 800-mL subsample was collected from the Niskin bottle and was immediately preserved in 1 % (final concentration) Utermohl's solution after Guillard (1973). Utermohl's solution is a mild iodine based preservative that does not destroy or greatly distort most delicate athecate dinoflagellates and microflagellates. Once collected and preserved, samples were labelled and stored in borosilicate glass jars. Two samples, one from the surface and one from the chlorophyll maximum, were analyzed for phytoplankton abundance and species composition at each Bioproductivity station. The remaining samples, including those gathered from the surface during nearfield surveys, were archived at the University of Massachusetts-Dartmouth.

In June, sampling also was conducted to identify and quantify rarer species of large dinoflagellates. Briefly, about 2 L of whole seawater was passed through a 20-$\mu$ mesh. Retained material was rinsed from the mesh and then preserved as other whole-water samples.

Net zooplankton were collected with a 0.5-m diameter 102-$\mu$m mesh net equipped with a flowmeter. Vertical oblique tows were made at each of the ten Bioproductivity stations. Tows were made over about the upper 30 m (or less, at shallow stations). Observation that the flowmeter was turning at the end of a tow ensured that the net was not clogged. Aboard ship, samples were rinsed from the net into glass jars and immediately preserved in 5-10% formalin:seawater solution.

## 2.2 Laboratory Procedures

### 2.2.1 Nutrients and Carbon Analyses

Methods for nutrient analysis followed those described by Lambert and Oviatt (1986). Briefly, dissolved inorganic nutrient concentrations were determined on samples that had been passed through a 0.4-$\mu$m Nucleopore membrane filter. The concentrations of ammonia, nitrate, nitrite, silicate, and phosphate were measured colorimetrically on a Technicon II Autoanalyzer. This instrument simply automates standard manual techniques for the analysis of nutrients. The analysis of ammonia is based on the technique of Solorzano (1969) in which absorbance of an indophenol blue complex is measured at 630 nm. Nitrite was measured by the method of Bendschneider and Robinson (1952). Nitrate and nitrite was measured by reducing all nitrate in the sample to nitrite and analyzing for nitrite as above. The concentration of nitrate was obtained by difference. The reduction of nitrate was accomplished with a cadmium column (Morris and Riley, 1963). The analysis of phosphate was based on the molybdate blue procedure of Murphy and Riley (1962). The colorimetric analysis of silicate was based on that of Brewer and Riley (1966).

Methods for particulate carbon and nitrogen followed those described by Lambert and Oviatt (1986). Particulate matter collected on a glass-fiber filter was ignited at high temperature (1050°C) in a Carlo Erba Model 1106 CHN elemental analyzer. The combustion releases total carbon and nitrogen in the sample in gaseous form. These products were quantified by the analyzer using a gas chromatography column and a thermal conductivity detector.

The concentrations of dissolved organic nitrogen were determined by the difference between total dissolved nitrogen and total dissolved inorganic nitrogen. Concentrations of dissolved organic phosphorus

were determined in the same manner. The procedures by which the concentrations of dissolved inorganic nitrogen and phosphorus are obtained were described above. The concentrations of total dissolved nitrogen and phosphorus were determined using the method of Valderama (1981). This wet-chemistry technique utilizes persulphate to oxidize organic nitrogen and phosphorus to nitrate and phosphate. The concentrations of the latter were then determined colorimetrically on a Technicon Autoanalyzer, as described above.

Dissolved organic carbon was determined by persulphate digestion (Lambert and Oviatt, 1986) using an O.I. Model 700 TOC Analyzer. Some doubt concerning the accuracy of this method exists, and recent work suggests that the higher concentrations obtained by high temperature combustion more nearly reflect true levels of DOC in nature (Sugimura and Suzuki, 1988). The analysis used here has been intercalibrated with an Ionics high temperature combustion instrument; results for both fresh and salt water agreed to within 6%. In addition a recent comparison of methods revealed no difference between concentrations obtained by wet oxidation with persulphate and high temperature combustion (J.I. Hedges, pers. comm.).

### 2.2.2 Chlorophyll *a* and Phaeophytin

Methods were as described by Lambert and Oviatt (1986). The concentrations of chlorophyll *a* and phaeophytin was determined fluorometrically using a Turner fluorometer by the method of Yentsch and Menzel (1963) as modified by Lorenzen (1966).

### 2.2.3 Total Suspended Solids

Methods were as described in Lambert and Oviatt (1986). Briefly, the weight of material suspended in seawater was determined by filtering an appropriate volume (up to 1 liter) through a pre-weighed 0.4-$\mu$m Nucleopore membrane filter. The filter was rinsed with deionized water to remove salt, dried to constant weight at 60°C and reweighed. All weighings were performed on a Cahn electrobalance with removal of static charges on filters and sample prior to weighing.

### 2.2.4 Dissolved Oxygen

Dissolved oxygen was measured in water samples using the method of Oudot *et al.* (1988), which uses a potentiometric endpoint. A Radiometer ABU91-21/TIM90-1 autotitrator was used with a Ag/AgCl combination electrode to perform all titrations. Titrations were performed within 24 h of sample collection.

### 2.2.5 Phytoplankton Taxonomy: Identification and Counts

At the laboratory, raw seawater samples were prepared for analysis by concentrating the sample via gravitational settling. Samples were placed in 40 cm tall glass settling chambers (graduated cylinders) that were scrubbed clean before each sample was processed. The initial volume of each sample was recorded to the nearest 0.5 mL and the sample was allowed to stand undisturbed in the covered settling chamber for a period of one week. After the one week settling period had passed, the settling chamber was uncovered and the upper 700-750 mL of seawater was siphoned out of the settling chamber with a pipette attached to a 0.5 cm hose. Occasional examination of the supernatant fluid that had been siphoned off was done to ensure that no cells had inadvertently been removed from the settling chamber. The fluid remaining in the settling chamber (containing the settled out phytoplankton) was then gently mixed and transferred to a 250-mL jar. This concentrated (by a factor of approximately 10:1) plankton sample was the aliquot that was examined microscopically.

Enumeration of phytoplankton cells was done using a 1-mL subsample placed in a 1-mL Sedgwick-Rafter cell. Phytoplankton cells were observed, counted, and identified to lowest possible taxa at 200X magnification. However, 400X was used when needed to identify small cells or to discern important taxonomic features. A Whipple-grid disk placed in one ocular lens of the microscope allowed partitioning of the Sedgwick-Rafter chamber into areas of known volume (0.000195 mL per Whipple grid). A minimum of 200 cells and a maximum of 400 cells were counted for each sample. When 200 cells were counted in less than 200 Whipple grids, counting was continued until 200 Whipple grids were examined. Examining a relatively large subsample (200 Whipple grids) increases the probability of observing relatively rare cells, while counting between 200-400 cells per sample allows estimates of total phytoplankton abundance that have a precision of $\pm 10\%$ (for 400 cells counted) to $\pm 20\%$ (for 200 cells counted) of the mean (Anonymous, 1978).

The following is a sample calculation of determining total phytoplankton abundance using the above described method:

$$\frac{\#\ \text{cells}}{\text{liter}} = \frac{\#\ \text{cells counted}}{\#\ \text{grids} * \text{vol/grid}} * \frac{1000\ \text{mL}}{1\ \text{L}} * \frac{V_s}{V_o}$$

where:

$V_s$ = Volume of settled sample (typically 50-100 mL)
$V_o$ = Volume original sample minus volume of preservative (usually 800 mL)
Vol/grid = 0.000195 mL per Whipple grid (@200X)

Therefore, if 410 cells were counted in 200 Whipple grids (@ 200X) and the initial seawater sample was 800 mL settled to a volume of 80 mL, the density of phytoplankton in the water sample would be

$$\frac{\#\ \text{cells}}{\text{liter}} = \frac{410\ \text{cells}}{200\ \text{grids} * 0.000195\ \text{mL/grid}} * \frac{1000\ \text{mL}}{1\ \text{L}} * \frac{80\ \text{mL}}{800\ \text{mL}}$$

$$\frac{\#\ \text{cells}}{\text{liter}} = 1.051 * 10^6\ \text{cells per liter}$$

For the large dinoflagellate (screened) sample, the focus was on dinoflagellates and phytoflagellates, so diatoms were not counted. Calculations were similar to those for the whole seawater sample and based on the number of organisms counted in a concentrated subsample of about 1 mL multiplied by the concentration factor.

### 2.2.6 Zooplankton Taxonomy: Identification and Counts

Onshore, samples for zooplankton were transferred to 70% ethanol solutions to prevent inhalation of formalin fumes during counting. Samples were reduced to aliquots of at least 500 animals with a Folsom plankton splitter, and animals were counted under a dissecting microscope and identified to the lowest possible taxon. In most cases this was to species, and adult copepods were further characterized by sex. Copepodite nauplii of small species cannot be separated reliably to genus under a dissecting scope, so all nauplii were lumped in a single group. Concentrations of total zooplankton and all identified taxa were calculated based on the number of animals counted, divided by the volume of water filtered by the net, multiplied by the aliquot concentration factor.

## 2.3 *In Situ* Instrument Comparison and Calibration Procedures

All *in situ* BOSS instruments were calibrated by the manufacturer prior to the February cruise. For chlorophyll and dissolved oxygen sensors, additional field calibration was performed by measuring these parameters in selected water samples using traditional laboratory methods (see above). For each cruise, discrete samples were collected in bottles from the biology/productivity stations (primarily) to provide a basis for post-calibrating the *in situ* sensors.

Calibration for chlorophyll and oxygen were done on a cruise by cruise basis. The replicate chlorophyll values that were measured from the discrete water samples were compared to the 20-s time-averaged *in situ* measurements that bracketed the opening and closing of the hydrocast bottle used to collect each sample. A regression of the paired values was made to provide a means of extrapolating sensor data throughout the survey, as described in Appendix A.

A similar calibration method was used for dissolved oxygen, comparing the potentiometric endpoint titration values against the *in situ* sensor (Appendix A). For the May nearfield survey, the calibration samples for dissolved oxygen were lost and no titrations were available. To calibrate the sensor for that survey we used the regression from the previous (late April) survey, which was very similar to that for the following survey in June (see Appendix A). As a caution, we note that the routine sampling scheme did not always provide bottle samples that coincided with the lowest or highest readings by the sensors. Thus, the extrapolations for dissolved oxygen or chlorophyll are extended beyond the data to provide "calibrated" values.

## 2.4 Data Management and Processing

Samples were given unique sample/event identification numbers and/or sample-specific descriptions. These numbers were used to track data through the laboratories, to report the data and load it into the database developed specifically for the MWRA water quality monitoring program, and to link the laboratory data with the field data. All data from the *in situ* sensors and the BOSS navigation system were stored in electronic format. Sensor data associated with each bottle collection were extracted from the full time course of the electronic database, loaded into the MWRA database, and then used in data

analysis, such as plots of nutrients vs. salinity. These "discrete bottle" data are provided in Appendix A. The full electronic database was used to provide high-resolution analyses, graphical display of vertical downcasts, and display of the oscillating towed data. These profile and time-series contour sections are provided in the Appendices or as Figures in the body of the report.

### 2.5 Graphical Modeling and Statistical Analyses

Both high-resolution *in situ* sensor data and data from measurements on discrete water samples were used for data analyses presented in this report. In general, the sources of the data are identified in figure legends and references are made to the appropriate Appendix.

Besides the statistical modeling done to calibrate instruments (see above), a sequence of two models was used to fit data derived from metabolism incubations, as follows.

The first model fit 4 parameters, including both a respiration and photoinhibition term and followed Platt *et al.* (1980). The model to predict net production is

$$P_B = P_{SB} (1 - e^{-a}) e^{-b} - R_B,$$

where $a = \alpha I/P_{SB}$, and $b = BI/P_{SB}$.

$P_B$ = net production (chlorophyll-normalized) and

$P_{SB}$ = theoretical maximum *gross* production (chlorophyll-normalized) without photoinhibition

$\alpha$ = initial slope of the rise in net production with light increasing from zero irradiance [units of ($\mu$g $O_2$/$\mu$g Chl/hr)/($\mu$E/m$^2$/sec)], calculated from I (light irradiance level, $\mu$E/m$^2$/sec) and $P_{SB}$.

$R_B$ = chlorophyll-normalized respiration (units of $\mu$g $O_2$/$\mu$g Chl/hr), fit by the model.

The maximum achievable gross (g) production may be calculated from this as

$$Pg_{max} = P_{SB} (\alpha/(\alpha + B) (B/\alpha + B))^{B/\alpha}$$

and the achievable maximum net (n) production is

$$Pn_{max} = Pg_{max} - R_B.$$

For the second model, a hyperbolic tangent function (Platt and Jassby, 1976), three parameters were fit to predict net production and no photoinhibition term is included.

Here, $P_B = P_{max} * \text{Tanh} (\alpha I/P_{max}) - R_B$

and Pg is defined as $P_{max} * \text{Tanh} (\alpha I/P_{max})$.

In this model, when R is included, the $P_{max}$ estimated is gross production.

The parameters in each model were fit simultaneously for each incubation series that measured paired $P_B$ and irradiance, by least squares using the NLIN procedure in SAS (1985). Fitting was accomplished by the secant method where parameters were estimated if, within 50 iterations, the model converged on a suitable simultaneous fit (SAS, 1985). If the 4 parameter model was not fit, the hyperbolic model was attempted; if it was not fit, the data in Appendix E so indicate. Note that bottle measurements of dark respiration were not used in this fitting procedure; rather, $R_B$ was derived from fitting from the P-I data. In general, however, it was clear that respiration was low and difficult to measure directly or to fit by the model. Note, importantly, that in both model cases, the $P_{max}$ of interest is net production, so from the model parameters, $Pn_{max}$ can be calculated as $Pg_{max}$ - R, or roughly read directly from the chlorophyll-normalized P-I curves.

T-tests of statistical significance of dark bottle oxygen concentrations (n = 3) compared to initial concentrations (n = 3) were conducted. These are presented along with model-fit parameters in Appendix E.

# 3.0 EARLY APRIL 1992
# COMBINED FARFIELD AND NEARFIELD SURVEY (#3) RESULTS

## 3.1 Farfield Survey (#3)

### 3.1.1 Horizontal Distribution of Water Properties

In early April, the range in near surface water temperature was small throughout Massachusetts and Cape Cod Bays (hereafter, "the Bays"), roughly $\leq 4.0$ to $\geq 5.4$°C (Figure 3-1). Cape Cod stations had coolest temperatures. In general, coastal stations in Massachusetts Bay had highest temperatures ($>5$°C) and other Massachusetts Bay stations were mostly 4-5°C. Some of the "pattern" in Figure 3-1 may be a function of daily weather changes and a consequence of the day/time of sampling during the cruise rather than a reflection of actual regional differences. For example, the few days prior to the first survey day (April 7) had relatively cool air temperatures, yet April 8 (survey day 2) and April 10 (survey day 3) were unseasonably warm days ($+8$ and $+10$°C above the norm, R. Lautzenheiser, NE Climatic Service). Some stations sampled in late afternoon on these days, (F14 and F09 on April 8; and F21, F22 on April 10) had highest recorded temperatures and a vertical thermal structure suggesting rapid surface warming (see Appendix B).

Salinity in surfacemost waters also had a small range ($\leq 31.3$ to $\geq 32.2$ PSU) throughout the Bays (Figure 3-2). This parameter is not sensitive to daily air temperature like water temperature; thus, salinity distribution may provide a better picture of regional surface-water trends. In general, coastal waters were fresher all along the coast from Boston to Cape Cod Bay. A tongue of fresher water from the Northeast, crossing the outer edge of the nearfield was suggested. Highest salinity ($>32.2$) was seen offshore (F08, F12) at deep stations, which were also the coldest ($<3.8$°C) and therefore had the highest density (Figure 3-3).

Beam attenuation in surface water was high off Boston Harbor and was relatively high also in Cape Cod Bay as well as offshore where salinity was also high ($\sim 32$ PSU) (Figure 3-4). Beam attenuation was distinctly low from the Northeast corner of the nearfield northward.

Surface fluorescence (Figure 3-5) was high off Boston harbor, high offshore over the southern portion of Stellwagen Basin especially (FO8) where salinity was high. Fluorescence graded southward to lower values in Cape Cod Bay, but was extremely low throughout most of northern Massachusetts Bay—including the same area with distinctly low beam attenuation.

With the exception of two samples (N10P and N04P), nitrogen was essentially depleted from near-surface waters throughout the Bays. Elevated DIN and $PO_4$ concentrations was apparent at the edge of Boston Harbor (Figures 3-6 through 3-9); but both DIN and $PO_4$ were reduced quickly outside the Harbor (see F24, F25, N10P).

Surface silicate concentrations (Figure 3-10) suggested a decrease from north to south down the axis of the Bays. Surface silicate values were low throughout Cape Cod Bay. Offshore, deeper stations tended to have higher silicate concentrations. Other than Cape Cod Bay, surface silicate concentrations were much higher than they had been in March.

### 3.1.2 Water Properties Along Selected Vertical Sections

A review of vertical profile plots for each station (Appendix B) showed that most cases had only subtle vertical structure and a strong seasonal thermocline was not yet established; the water column was still generally well-mixed physically. A few stations had some surface-warming evident (as discussed above) and a few also had a salinity increase with depth (e.g. F22), so the physical profiles were not featureless everywhere.

To display some of the vertical features, we generated section contour plots of T, S, $\sigma_T$, fluorescence, beam attenuation, dissolved inorganic nitrogen, and silicate for four transects across Massachusetts Bay (Figure 3-11). Additional plots are given in Appendix C, but a selection are shown as Figure 3-12 through 3-16.

Patterns at all four transects suggested inshore surface warming, with gradation to cooler waters offshore and at depth. Deep water below 60 m was about 3.4°C or less and water at about 20-30 m usually was 3.8°C except the section from F07 to F12 (Marshfield Transect), where the 3.8°C isobar shoaled towards

the surface. The warmest inshore water was at the exit of Boston Harbor, where the isopleths seemed to extend out through the middle of the nearfield (N20P-N16P).

In terms of salinity, inshore stations generally were fresher at the surface and graded offshore in a manner similar to temperature (Figure 3-13). The exception to this pattern was the Northern Transect, which had fresher water to ~20 m depth offshore. Below about 20-30 m, salinity was everywhere about 32 PSU or greater, with the least vertical salinity or density stratification noticed in the southernmost (Marshfield) Transect. In general, most Cape Cod Bay Stations, further south, had little salinity or temperature stratification (see Appendix B).

Fluorescence across the transects (Figure 3-14) usually suggested higher chlorophyll below the surface. At many stations, highest values were as deep as about 35 m, peaking at about 4.5 $\mu$g/L. To a degree, the deeper the water column, the deeper was found the subsurface chlorophyll maxima. A lens of low surface values appeared to extend from the Northern Transect, across the eastern half of the Boston-Nearfield transect and to the middle of the Cohasset Transect. Finally, the strong temperature/salinity extrusion from Boston Harbor was accompanied by a gradient in chlorophyll (F23P to F24).

DIN also showed a striking difference in concentration between F23P and F24 (Figure 3-15). Other than the Boston Harbor exit, DIN was $< 1$ $\mu$M from the surface to at least 20 m and deeper than this in most cases. Station F22, which had lower salinity at the surface appeared to have higher DIN and bottom waters of the Northern Transect had higher DIN than those at corresponding depths across the other transects.

The pattern of silicate concentrations (Figure 3-16) differed from DIN in several ways. Surface waters had quite a bit of silicate, as did bottom waters. In most cases, inshore coastal stations had the least silicate, and isopleths shoaled outward, reflecting the fact that there was less silicate at the surface compared to depth at these stations. The exception was the Northern Transect and Station F20, where inshore silicate did not seem depleted relative to the offshore.

### 3.1.3 Analysis of Water Types

High resolution data from all vertical profiles have been used in scatter plots (Figure 3-17 a,b,c,) to begin to get an overall picture of the character of water masses in different regions. Here, all stations are plotted together. Refer to Appendix C for plots of each geographic station grouping. There was a very small range of temperature, top to bottom of most profile stations throughout the Bays (Figure 3-17a). Coastal stations had warmest surface values, as noted, and these situations were accompanied by lowest salinities ($\sim$31 PSU). Cape Cod Bay and the Northern Transect stations may have had marginally lower temperature for a given salinity, but deepest waters everywhere had similar T-S characteristics, implying relative uniformity of bottom water.

The coastal stations as a group tended to have higher beam attenuation at lower salinities. In contrast, characteristic of the deeper waters of the offshore, Northern Transect, and eastern side of the nearfield was an increase in the range of beam attenuation at higher salinity.

In Figure 3-17b, it is evident that beam attenuation and fluorescence were related. Different regions apparently had slightly different beam attenuation-fluorescence relationships; however. For example, Cape Cod Bay stations had relatively higher beam attenuation at low chlorophyll fluorescence compared to all other regions. Offshore, there were some deep readings where beam attenuation was high, but unrelated to the linear relation to chlorophyll in that group, suggesting perhaps that bottom inorganic suspended loads were encountered occasionally.

In general, chlorophyll was highest at intermediate depths. However, low as well as high values were seen at any depth (Figure 3-17c). Peak fluorescence occurred anywhere from 10-20 m (Cape Cod Bay) to as deep as 30-50 m (Northern Transect, nearfield, offshore), usually associated with intermediate $\sigma_T$ values (Figure 3-17b). In contrast to this distribution stood the coastal group, where high values were seen near the surface and the range at any depth from about 2 to 20 m was similar ($\sim$0.5 to $>5$ $\mu$g $L^{-1}$).

There was no strong relation between chlorophyll and dissolved oxygen values in general across the Bays (Figure 3-17c). The electronic DO sensor data suggests supersaturation was the rule rather than the exception. The sensor data show a wider range of concentration ($\sim$9 to almost 14 mg $L^{-1}$, excluding

a likely poor profile at F03 that suggested lower values) than the titrated values (range for Bioproductivity Stations was ~10 to almost 12 mg $L^{-1}$), and the extrapolation thus should be viewed with some caution (see Appendix A). However, both data suggest the bulk of values were higher than saturation (~10 to 10.4 mg $O_2$ $L^{-1}$ for salinity and temperature in the range of 31 to 32 PSU and 4 to 5°C).

To assess geochemical variations among the water types grouped by region (Figure 3-18), we examined the nutrient distribution. Nutrients were collected in bottles at all stations and here are examined vs. each other and vs. physical parameters associated with the position of each bottle as it was closed (see Appendix A).

To begin, plots of N vs. P (Figure 3-19a) show that most of the samples had low DIN ($\leq 2$ $\mu$M) and P04 ($\leq 0.5$ $\mu$M). The pattern suggests that nitrogen was more limiting, since the N/P ratio of this main block of points was about 4:1 or less and it appears that $PO_4$ was usually present when DIN or $NO_3$ was virtually depleted.

Some deeper waters of the Northern Transect and offshore region had relatively high $NO_3$, $NH_4$, and $PO_4$. These, as well as a few coastal and nearfield samples had much enriched N compared to P, and for coastal and nearfield samples this enrichment primarily was as $NH_4$ (compare DIN and $NO_3$ vs. $PO_4$, Figure 3-19).

The patterns for N vs. $SiO_4$ were rather similar to $PO_4$ (Figure 3-19b). For the most part, $NO_3$ and DIN seemed depleted while $SiO_4$ was still present. $SiO_4$ was generally most strongly depleted in Cape Cod Bay, where both DIN and $SiO_4$ were very low. As for phosphate, there were a few samples for each region, except Cape Cod Bay, than had higher DIN relative to $SiO_4$, and this again was usually due to $NH_4$ rather than $NO_3$.

Examination of nutrients relative to salinity or $\sigma_T$ (Figures 3-20 to 3-25) revealed features that in part were apparent from vertical section plots across transects, previously discussed. For DIN, higher values were seen at low salinity (select inshore coastal stations, including F23P) and at high salinity (deep water stations in Massachusetts Bay). As had been seen in earlier months, these two ascending "arms" of higher DIN are connected by very low DIN at intermediate salinities and $\sigma_T$. For $NH_4$ (Figure 3-21), the deep water/high salinity samples are less enriched than the edge of Boston Harbor.

For $PO_4$, the "enrichment" at high and low salinity is less pronounced, but does appear as a small curvature in the plots vs. salinity or $\sigma_T$ (Figure 3-22). A couple of samples had very high $PO_4$ values; it is unknown if they are accurate values or contaminated during sampling or analysis.

Silicate (Figure 3-23) shows a strikingly different pattern relative to salinity, and greater separation among geographic stations groups independent of depth. For example, Cape Cod Bay stood out as low, the Northern Transect as high, and the nearfield as intermediate, with respect to silicate as a function of salinity or $\sigma_T$, with this difference especially pronounced at low to intermediate salinity (or $\sigma_T$). Excepting one sample, there was little tendency for coastal stations to be enriched with silicate, in contrast to N and P.

As earlier in the year (Kelly *et al.*, 1992), highest combined nitrogen was seen at the northern Boston Harbor exit (Station F23P), where DIN was about 7-9 $\mu$M, PON was about 9-11 $\mu$M and DON was about 8-10 $\mu$M (Appendix A). High PON values ($\sim$7-9 $\mu$M) were also seen at the surface of N10P, the southwest corner of the nearfield, and at depth ($\sim$25 m) at N16P, N20P, N07P, usually corresponding with high chlorophyll. These latter points are evident in Figures 3-24 and 3-25 at salinities surrounding 32 PSU.

Total nitrogen ranged from about 29 $\mu$M (F23P) to about 14-15 $\mu$M (Figure 3-25). There was not a strong pattern of total N with salinity or $\sigma_T$, partly because of high PON (chlorophyll) at depth mentioned above. But also, coastal stations at the southern exit of Boston Harbor (F25) and F13P did not show particularly high PON, or TDN, even though they had slightly lower salinity. Cape Cod Bay stations were low to intermediate in Total N values, with higher values at F02P compared to F01P. F02P had generally higher chlorophyll than F01P. Note that Total N for most stations had minimal DIN (Figures 3-20) and was mostly particulate or dissolved organic in form. Even at F23P, DIN was only about 1/4-1/3 of Total N.

In summary, do these physical, chemical, and biological variables throughout the Bays allow distinctive characterization by region? In general, each region did have a particular distinct quality, in its mix of surface parameter values as summarized in Table 3-1. Differences in vertical features however were also a large part of what made a region distinctive. One of the most striking features was the low salinity, low beam attenuation, and chlorophyll across the surface of the Northern Transect, extending over a good

portion of northern Massachusetts Bay, including some of the nearfield. Here, a very deep subsurface chlorophyll maximum, perhaps sinking cells, was detected often.

A second striking feature was the low surface silicate in Cape Cod Bay relative to the rest of the area. A final feature of note was the lower salinity and often higher temperature along the coast. Only F23P showed much DIN enrichment, but surface chlorophyll was relatively high in the entire coastal region outside of, and south from, Boston Harbor.

### 3.1.4 Distribution of Chlorophyll and Phytoplankton

*In situ* fluorescence (Figure 3-17c) indicated that chlorophyll concentrations might be about 0-6 $\mu g\ L^{-1}$ from 0 to 20 m depth, with a tendency for all but the coastal regions to have higher values below the surface. At some deeper water stations, including those in the nearfield, a deep chlorophyll maximum $\geq 6\mu g\ L^{-1}$ was noted below 20 m. These patterns were also seen in the extracted chlorophyll samples (Figure 3-26); this of course was not surprising, because the relation between *in situ* and extracted values was strong and used to calibrate *in situ* values (Appendix A). Highest chlorophyll $>3.5\mu g\ L^{-1}$ was documented at F23P and F25 (surface and deeper) and N04P, N07P, N16P (deep only) along the eastern side of the nearfield.

As shown in Figure 3-27, there was a strong linear correlation between extracted chlorophyll and phytoplankton cells counts, with a ratio of about 1 x $10^6$ cells per $\mu g$ of chlorophyll suggested. Relative to the nearfield, Cape Cod Bay samples appeared to have more cells per unit of chlorophyll. Highest cell counts were recorded in the sample at depth ($\sim$25m) from Station N07P, where total counts were over 9 x $10^6$ cells $L^{-1}$. Total cell counts at the subsurface sample approached or exceeded $10^6$ in all cases. Counts were usually not as high at the surface sample, but were only less than $10^6$ for the surface at a group of stations in the nearfield (N20P, N16P, N04P). Stations N16P and N04P, to the eastern (deeper) side of the nearfield joined N07P in having high counts at depth: 6.7 and 4.9 x $10^6$ at about 25 and 38 m, respectively. Station F23P had high counts at surface and depth (10 m), *both* being $>$ 5 x $10^6$ cells $L^{-1}$.

That a strong relation between counts and chlorophyll was apparent suggested 1) that the *in situ* fluorometry could in this case be roughly converted to cell counts, but also 2) that samples must have had

biological similarity. Figure 3-28 begins to suggest such similarity, showing that diatoms, dinoflagellates, and microflagellates were a small quantitative fraction of the cell counts.

Indeed, the most striking result was the numerical dominance of *Phaeocystis pouchetii* (Table 3-2) at each station and each depth. This species is a mucilage-producing Prymnesiophyte, in this case present primarily in colonies (although individual cells were counted because colonies were not fully intact in the samples). It is known as a nuisance species, can clog fine nets, and has been implicated in coastal perturbations in Europe and elsewhere; it has been noted in the Bays since the early 1900's. During our survey, this single species nearly always accounted for over 80% and often over 90% of the individuals counted in a sample. (See Figure 3-28)

Usually, *Phaeocystis* was more abundant at the subsurface sampling depth. Numbers above $10^6$ cells $L^{-1}$ were observed at all stations except N20P, N07 (surface and depth), N16P (surface only) and N04P (surface only). Highest counts ($>6 \times 10^6$) were made from samples at depth at stations N07P and N16P. High counts ($>3 \times 10^6$) were also recorded from depth at stations F23P, N04P, N10P, and F02P (Rep 2) and also the surface of F23P. For comparison, during the February-March cruises in which diatom blooms were detected, the highest cell counts were about $2 \times 10^6$ cells $L^{-1}$.

From a phytoplankton community perspective, the dominance by *Phaeocystis* at the time of sampling in April seemed acute: there were relatively few taxa in general throughout the region, substantially fewer than noted during the previous two months (Kelly *et al.*, 1992). To some degree, it appeared that where *Phaeocystis* was present in highest numbers, lesser taxa were encountered (see Appendix F). Table 3-2 shows that for the surface of most stations the other taxa on the list of top five numerical dominants included microflagellates and cryptomonads. Additionally, diatoms characteristic of the winter-spring bloom (*Chaetoceros debilis* and a small *Chaetoceros* spp.) were still among dominants even though numbers were reduced from counts in February and March. With the high *Phaeocystis* dominance, these other taxa were small contributors to total counts. For example, microflagellates, uniformly constituted less than 5% of the total number in samples.

There was strong similarity in taxa between surface and deep samples at most stations. Figures 3-29 to 3-32 show several station examples of the difference in abundance, by all taxa seen, as a function of the depth of the sample (full listings are given in Appendix F). As noted above, higher total numbers and

numbers of many dominant species were found often in the subsurface (deep) sample (e.g. N04P), but there were only a few cases where dominants (other than *Phaeocystis*) were found at one depth and not another.

The only minor variation of the dominants list occurred at station F23P, at the edge of Boston Harbor. Two diatoms, *Skeletonema costatum* and *Thalassiosira nordenskioldii* were among the dominants, although their abundances were not particularly high (Table 3-2). These species were part of the dominant assemblage of diatoms that were found at many stations, and at higher concentrations, earlier in the year (Kelly *et al.*, 1992).

At one Cape Cod Bay Station, a full replication of the hydrocast sampling was conducted after completion of the first cast sampling. The ship was repositioned as normally done in occupying a station. This effort was to provide initial assessment on the variability in results expected at a given sampling station. The effort was not to assess the repeatability of a given parameter's method, but the entire variance associated with repeated sampling and analysis at a "station" (the ~300 m-radius target navigational position occupied for each cast or tow) in a short period of time. Each cast was treated as unique; since the bottle positions are set for a cast based on observed profiles, the bottle positions varied slightly between the two replicate casts (see below). Results for phytoplankton between replicates 1 and 2 at station F02P were similar (Figure 3-30a and b) in both taxa and counts by taxa. Comparing the total cell abundance across replicates, the results (in $10^6$ cells $L^{-1}$) were:

| | Surface sample (bottle depth) | Deep sample (bottle depth) |
|---|---|---|
| Replicate cast #1 | 2.49 (~2 m) | 2.98 (~13 m) |
| Replicate cast #2 | 2.82 (~1.5 m) | 3.32 (~10 m) |
| Mean (std dev) | 2.655 (0.23) | 3.15 (0.24) |

Expressed as a coefficient of variation (CV), the two sample variability was about ±8% for the mean of total counts at each depth. Expressed a percentage, total counts for the first replicate were 88 to 90% of the second replicate.

### 3.1.5 Distribution of Zooplankton

The total numbers of zooplankton varied from 1,929 (F23P) to 11,631 (F13P) individuals $m^{-3}$ at the ten Bioproductivity Stations in April. The mean (std dev) of 11 samples, including a replicate tow at station F02P, was 6,252 (2,975). Average abundances were much reduced (roughly 1/3) compared to those measured in the two previous months (Kelly *et al.*, 1992).

Where total numbers were lower ($<5{,}000$ $m^{-3}$) (F23P, N01P, N04P, N07P), copepod nauplii were less abundant and were a smaller fraction ($\sim 10\%$ or less) of the total (Figure 3-33). In the case of N04P and N07P, perhaps the net sampling did not fully capture organisms at the very deep chlorophyll max and the zooplankton numbers may reflect the low surface phytoplankton values throughout the top 20 m or so.

In general, as in previous months, *Oithona similis* and *Paracalanus parvus*, small (<1 mm in length) copepods, were the either the top taxa in numbers, or among the top, at all stations with the exception of N01P, where the most abundance zooplankter was *Oikiopleura dioica* (e.g. category "other" in Figure 3-33). Full listing of taxa are given in Appendix G.

Station F23P was distinctly different from others, not only with respect to zooplankton numbers (low) but for taxa as well. As two examples, the large copepod, *Calanus finmarchicus*, was especially low in abundance at F23P compared to all other stations, and a smaller species *Microsetella norvegica* was a major organism (18% of total numbers), whereas it was only ever present at two other stations (where only 1 individual was counted). Taxonomically, the Cape Cod Bay stations were quite similar to each other. F13P and N10P were fairly similar. Based on numbers and taxa, the "neighboring" and very similar couplets of N07P/N04P and N20P/N16P defined the main zooplankton community present in the nearfield region.

Replicate tow samples at station F2P were analyzed as part of the effort to characterize sampling effects on results (see Section 3.1.4). Total numbers were 6,456 and 8,193 individuals $m^{-3}$ for replicates 1 and 2, respectively. Expressed a percentage of the second, the first zooplankton sample replicate was thus about 79%, compared to about 88-90% for total phytoplankton cells (above). The principal difference

in total zooplankton counts was due to variation in the numbers of copepod nauplii; in general, the taxa and their relative abundances across the two replicates were very similar (Figure 3-33).

### 3.1.6 Whole-Water Metabolism Incubations

Data generated from 6-hr light bottle incubations consistently showed that net production rates rose sharply as a function of increasing irradiance and in many cases, that rates were inhibited at intensities above ~1000-1500 $\mu E\ m^{-2}\ sec^{-1}$ (Appendix E). In general, $P_{max}$ appeared to be reached at irradiance from about 200 to 500 $\mu E\ m^{-2}\ sec^{-1}$.

It was clear that where chlorophyll was high (>2 $\mu gL^{-1}$), the data were reasonably well modeled (Appendix E). Where chlorophyll was low (<2 $\mu gL^{-1}$), with the exception of Cape Cod Bay Stations, the model fits were less satisfactory. All modeling is presented in Appendix E, but two station examples which were well fit are given in Figure 3-34.

In general, peak *net* production rates ($P_{max}$) at a station were usually in the range of 15 to 40 $\mu g\ O_2 (\mu g\ chl^{-1})\ hr^{-1}$ (see Figure 3-34). There were several cases where chlorophyll was low (N04P, N07P surface) and no net production was calculated at any light level; rather, net respiration was suggested and no P-I pattern was apparent. Curiously, these cases had low zooplankton numbers. In contrast, Cape Cod Bay Stations (F01P, F02P) had low chlorophyll but an extremely high $P_{max}$ (~80-170 $\mu g\ O_2\ (\mu g\ chl^{-1})\ hr^{-1}$) in 3 out of 4 cases (Appendix E). The Cape Cod Bay Stations were quite distinctive in this regard. It was noted previously that the cells/chlorophyll ratio at stations was rather high and the high normalized $P_{max}$ appear to be related to this. It cannot be determined from the data but, given that it was primarily *Phaeocystis* everywhere, there may have been something different about the physiology or population status of *Phaeocystis* in Cape Cod Bay compared to most of the rest of the Bays.

Looking at net production on a volumetric basis (as $\mu gO_2\ L^{-1}\ hr^{-1}$), $P_{max}$ appeared to be in the range of about 15 to 195, excepting the few cases where net respiration was suggested (especially N04P, N07P). It was noted the Cape Cod Bay Stations, although showing high chlorophyll - normalized production rates, had relatively low volumetric production rates.

F23P, at the edge of the Harbor and with high chlorophyll, had high $P_{max}$ rates ($\sim 150$ $\mu g$ $O_2 L^{-1}$ $hr^{-1}$) and light levels in the surface meters were high enough even early in the day (Appendix B) to support maximum production. The other location that had especially high volumetric rates was N07P, the deep sample from about 26 m, which had highest recorded chlorophyll (by extracted method). From Figure 3-34, one can see that $P_{max}$ occurred at about 200 $\mu Em^{-2}$ $sec^{-1}$. Measured irradiance at 13:07 EST, near daily maximum, at 25 m was about 3.5 $\mu Em^{-2}$ $sec^{-1}$; using the light data (Appendix B), it is suggested that $P_{max}$ have been supported at mid-day to a depth of about 10-15 m. On April 8 (the date of P-I incubations) maximum chlorophyll appeared to occur below this depth, and mostly at or below the 1% light level, which was below a sharp pycnocline (Figure 3-35). On April 12, this station was revisited, and the pycnocline, as well as the chlorophyll maximum, was even deeper ($>30$ m). Although the *potential* for high net growth existed for this water (as shown by the P-I data), it may be reasoned that the population was not particularly photosynthetically-active, for lack of light at the depth it was found.

With respect to dark respiration it was again difficult to statistically detect differences between initials and finals (Appendix E), although significant respiration was seen at F13P and N16P (surface) and N7P (surface and deep). Finally, respiration nonetheless was reasonably modeled in many cases as part of the P-I modeling (Appendix E) and the irradiance level at which net production because zero is suggested from some plots.

## 3.2 Nearfield Survey (#3)

### 3.2.1 Distribution of Water Properties from Vertical Profiling

The data for all nearfield vertical profile sampling are given in Appendix A (bottle measurements), and Appendix B (vertical downcast profiles). Summary plots of several parameters from vertical downcasts are shown in Figure 3-36. Temperature and salinity had small ranges and there was only subtle vertical density stratification in most cases. Beam attenuation was strongly related to chlorophyll fluorescence. Chlorophyll (as noted previously) was usually higher at depth (higher $\sigma_T$ values), an exception being N10P, the southeast corner of the nearfield, where higher ($>3 \mu L^{-1}$) chlorophyll was noted throughout the water column including the surface.

Figure 3-37 shows the chlorophyll maximum at each station, along with the station sampling track for reference. On this day (April 12) the maximum was at depth in most, if not all cases, (see Figure 3-36c) and, excepting the value $>3.6$ $\mu g$ $L^{-1}$ at N10P (southwest corner), highest chlorophyll occurred throughout the eastern side of the nearfield.

With respect to nutrients ($\sim 130$ samples analyzed) only about 15% of the DIN concentrations were greater than 1 $\mu$M (Figure 3-38), yet most samples below 30 m were in this group. These are primarily from the deeper stations on the eastern side of the nearfield, just below or within the layer of high subsurface chlorophyll.

Phosphate had a narrow range, mostly from about 0.2 to 0.5 $\mu$M; values above this were from samples taken at greater 20-30 m. In contrast, silicate roughly ranged from about 7 to slightly over 10 $\mu$M, without a strong depth tendency, an exception being N10P again - where values less than 6 $\mu$M were characteristically seen above 10-15 m depth.

### 3.2.2 Distribution of Water Properties from Towing

A three-dimensional perspective of the nearfield is provided from the towed instrument sampling day (April 14). The entire outer box was towed (N10P - N04P, N04P - N07P, N07P - N10P, and N10P - N01P) and two legs of the inner box were also sampled (N13 - N15 and N17 - N19). Data from these "tow-yos" (the instrument was oscillated from surface to near bottom continuously along the track) were contoured and examples are provided in a series of plots in Figure 3-39 and 3-40 for $\sigma_T$ and chlorophyll. The temperature series is given in Appendix D.

Several patterns are revealed from these high spatial resolution data. First, examine the series of four East-West transects that are lined up to give a view to the North through the nearfield (Figures 3-39a and 3-40a). $\sigma_T$ vertical structure generally appears only across the western half of the nearfield (the right, in all sections). A distinct structure was apparent from N10P towards N09, with lighter water inshore and shoaling out to the surface moving offshore. This feature carried very high chlorophyll. Otherwise, chlorophyll ($>1 \mu g L^{-1}$) was generally found from the N13-15 transect southward, at depths below about 20 m, generally shoaling to greater depths offshore.

Second, examine the variability from the perspective of viewing the field from offshore looking towards Boston Harbor. Unfortunately, the instrument was not properly working from N10P TO N11, so the extent of a high chlorophyll/low density feature at N10P at this time can not be resolved, but chlorophyll $>1$ $\mu g$ $L^{-1}$ was noted north of N11 (Figure 3-40b) at slightly lower $\sigma_T$ values. The $\sigma_T$ picture along the outer eastern tracks showed a weak pycnocline shoaling from $>40$ m to lesser depths. High chlorophyll was not seen at depth at N04P where this pycnocline was deepest, but was seen from N05 to N07P from $\sim 25$ to 40 m. Whether this feature suggests the movement of a lighter water from the North along this track can only be speculated.

### 3.2.3 Analysis of Small-Scale Variability

Timewise, we already noted the deepening of the pycnocline and subsurface chlorophyll layer at N07P between sampling on April 8 and April 12 (Figure 3-35). Some temporal variation undoubtedly could be found by examining other "P" stations visited several times during the early April cruise.

With respect to spatial variability, clearly the nearfield had different "regions" of it's own: the southwest corner and the eastern part of the field were distinctive.

The array of stations and tracks provided a good resolution of the "regional" nearfield distinctions, which were well apparent and distinctive against the lesser "noise" of time and space variability that are apparent when one dissects each cast, bottle, or section track in its finest detail. With respect to this, it was interesting also to note that, often $\sigma_T$, chlorophyll, temperature and other parameters (probably including DIN) seemed to follow bathymetric changes. For example, $\sigma_T$ vertical structure seemed a bit related to a 25 m ridge from stations N14 to N18 to N08 (Figure 3-39a). Additionally, the shoaling of $\sigma_T$ and high chlorophyll in the southwestern corner appears coincident with a bathymetric feature rising from about 25 m to 17 m just east of N10P (Figure 3-39a, 3-40a).

### 3.2.4 Water Types, as Related to Nutrients, Fluorescence, and Dissolved Oxygen

As seen in earlier months, the nearfield appears to be a mixing zone, where water from shallow inshore and water from the north become involved with waters in this $\sim 100$ $km^2$ area. Chlorophyll, temperature, salinity, and nutrients are among key variables that help define water masses and mixing

within this area. The range of dissolved oxygen was not large (Figure 3-36c), did not appear strongly related to chlorophyll, but also was not examined in great detail in this analysis.

**Table 3-1. Analysis of surface water types in early April 1992.**

| Water Type | | Characteristics by Parameter | | | | |
|---|---|---|---|---|---|---|
| **Classification** | **Geographic Descriptor** | **T (°C)** | **S (PSU)** | **Beam Attenuation ($m^{-1}$)** | **Fluorescence ($\mu g\ L^{-1}$)** | **Nutrients** |
| Coastal | Most of nearshore western Mass. Bay (~less than 30m) | >5 | Mostly <31.5 | ~1.5 - 2.4 | ~2 - 4 | Some higher N, medium Si |
| Northern Transect | Transect along northern entrance to Mass. Bay, (F20-F22) surface water | >5 | ~31.4 - 31.6 | <0.6 | <1 | low N, high Si |
| Nearfield | Within nearfield sampling grid | 4.4 - 5 | ~31.4 - 31.7 | <0.6 - 1.8 | <1 - 4 | Mostly low N, medium to high Si |
| Offshore | Mainstem Mass. Bay (~ greater than 40m) | 3.8 - 4.6 | ~31.5 - 32.2 | 0.6 - 1.6 | <1 - 2.5 | low N, high Si |
| Cape Cod | All Cape Cod Bay stations | 4.0 - 4.2 | 31.7 - 32 | ~1.6 | <1 - 2 | low N, low Si |

**Table 3-2. Top 5 dominant phytoplankton taxa in near surface samples collected in early April 1992.**

| Species | Coastal Stations | | Nearfield Stations | | | | | | Cape Cod Bay Stations | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F23P | F13P | N01P | N04P | N07P | N10P | N16P | N20P | F01P | F02P Rep 1 | F02P Rep 2 |
| Phaeocystis pouchetii | (1) 4.373 | (1) 1.979 | (1) 1.099 | (1) 0.295 | (1) 0.997 | (1) 2.423 | (1) 0.787 | (1) 0.519 | (1) 1.344 | (1) 2.32 | (1) 2.633 |
| Chaetoceros debilis | | (5) 0.049 | | | | (3) 0.103 | | | (2) 0.097 | | |
| Chaetoceros spp. $<10\ \mu m$* | (3) 0.135 | (3) 0.071 | | | | | | | (3) 0.085 | (2) 0.042 | |
| Cryptomonads | (2) 0.174 | (2) 0.076 | | (3) 0.015 | | (2) 0.118 | (3) 0.014 | (3) 0.012 | (4) 0.068 | (3) 0.036 | (2) 0.087 |
| Detonula confervacea | | | | | | (5) 0.074 | | | (5) 0.055 | | |
| Microflagellates | | (4) 0.060 | (2) 0.053 | (2) 0.027 | | (4) 0.089 | (2) 0.022 | (2) 0.041 | | (3) 0.036 | |
| Skeletonema costatum | (4) 0.116 | | | | | | | | | | |
| Thalassiosira nordenskioldii | (5) 0.087 | | | | | | | | | | |

( ): rank; listed are species only where >4 individuals were counted.
Number: millions of cells $L^{-1}$
*May be C. socialis

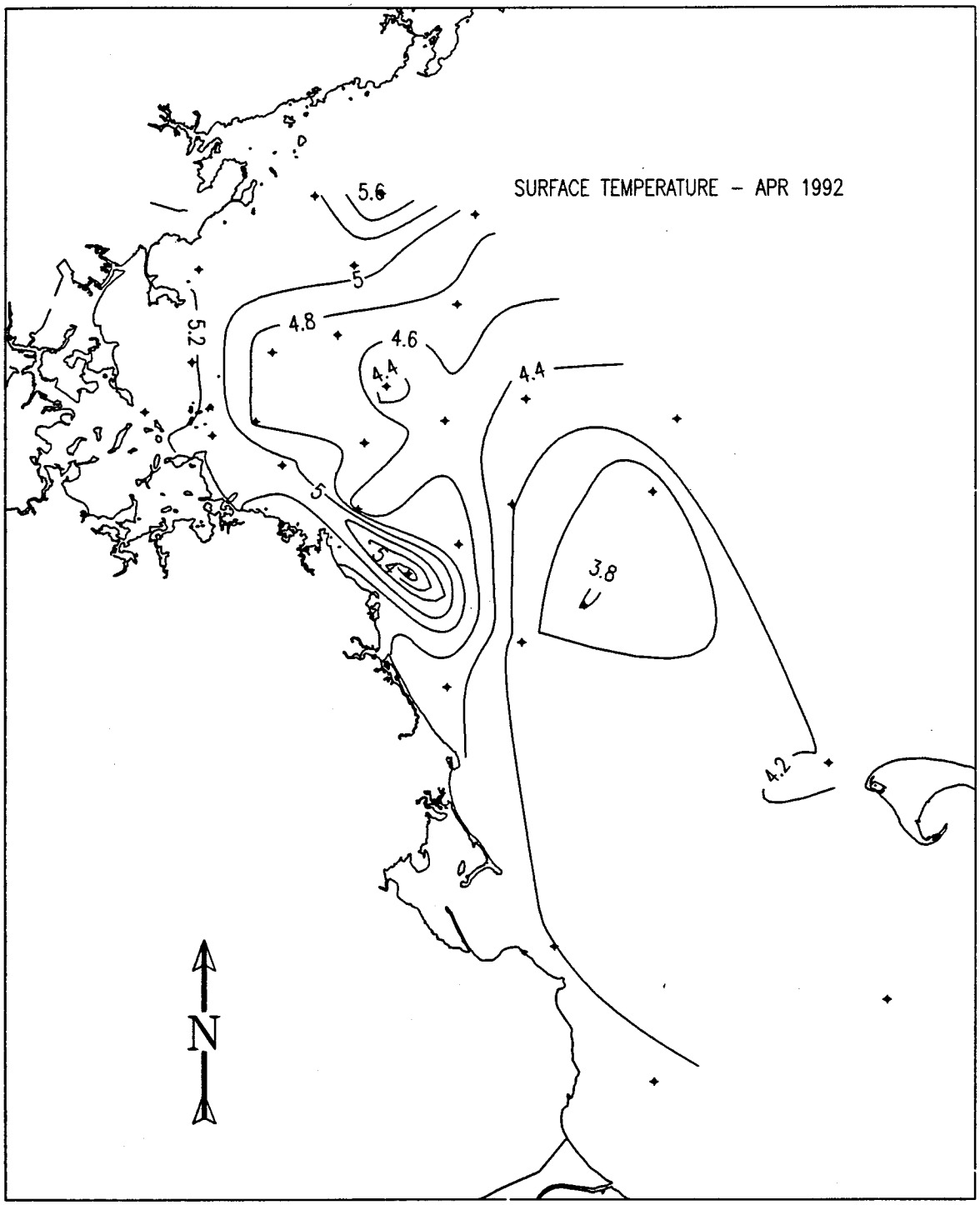



**Figure 3-1** **Surface temperature (°C) in the region in April 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.2°C.**

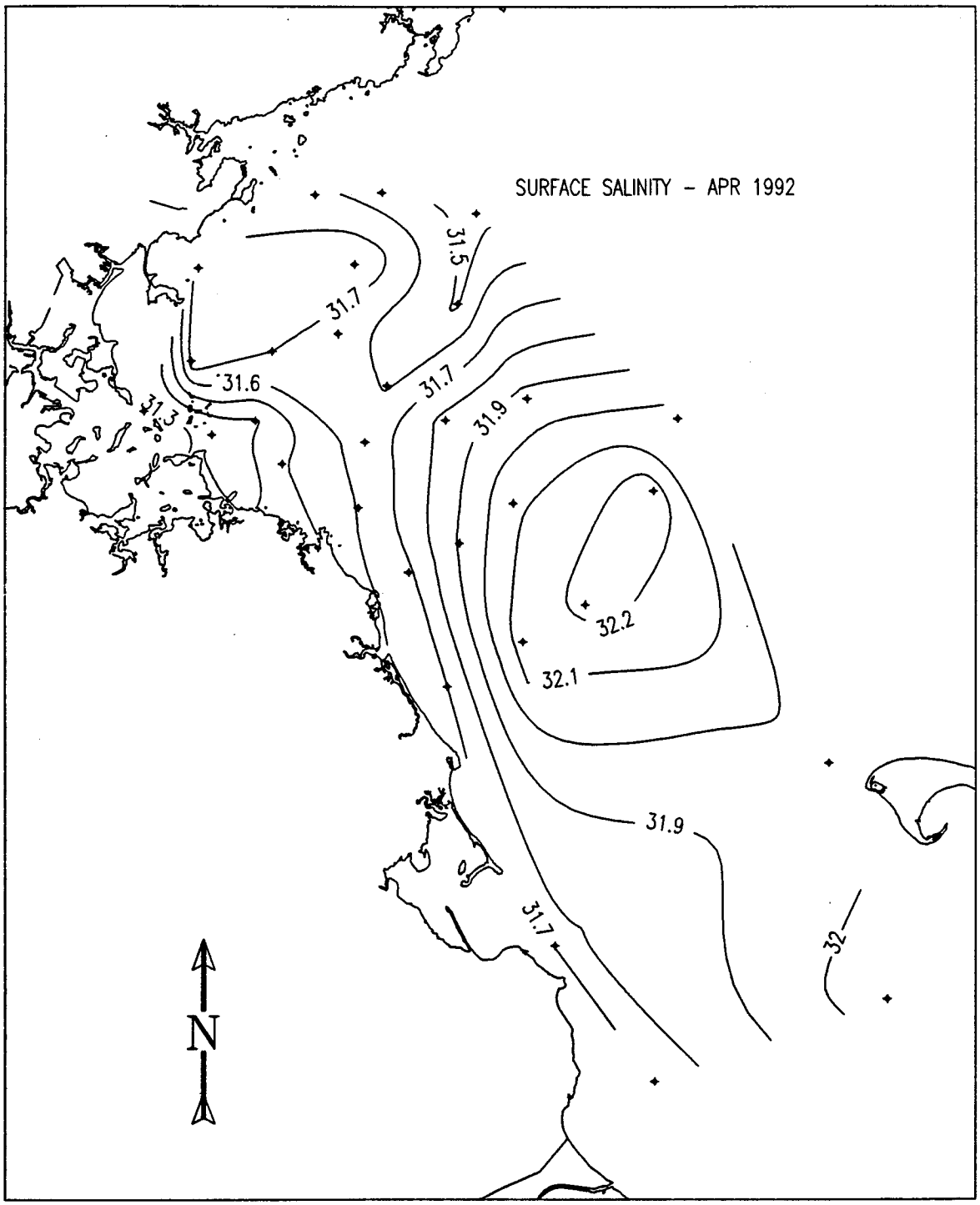



**Figure 3-2 Surface salinity (PSU) in the region in April 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.1 PSU.**

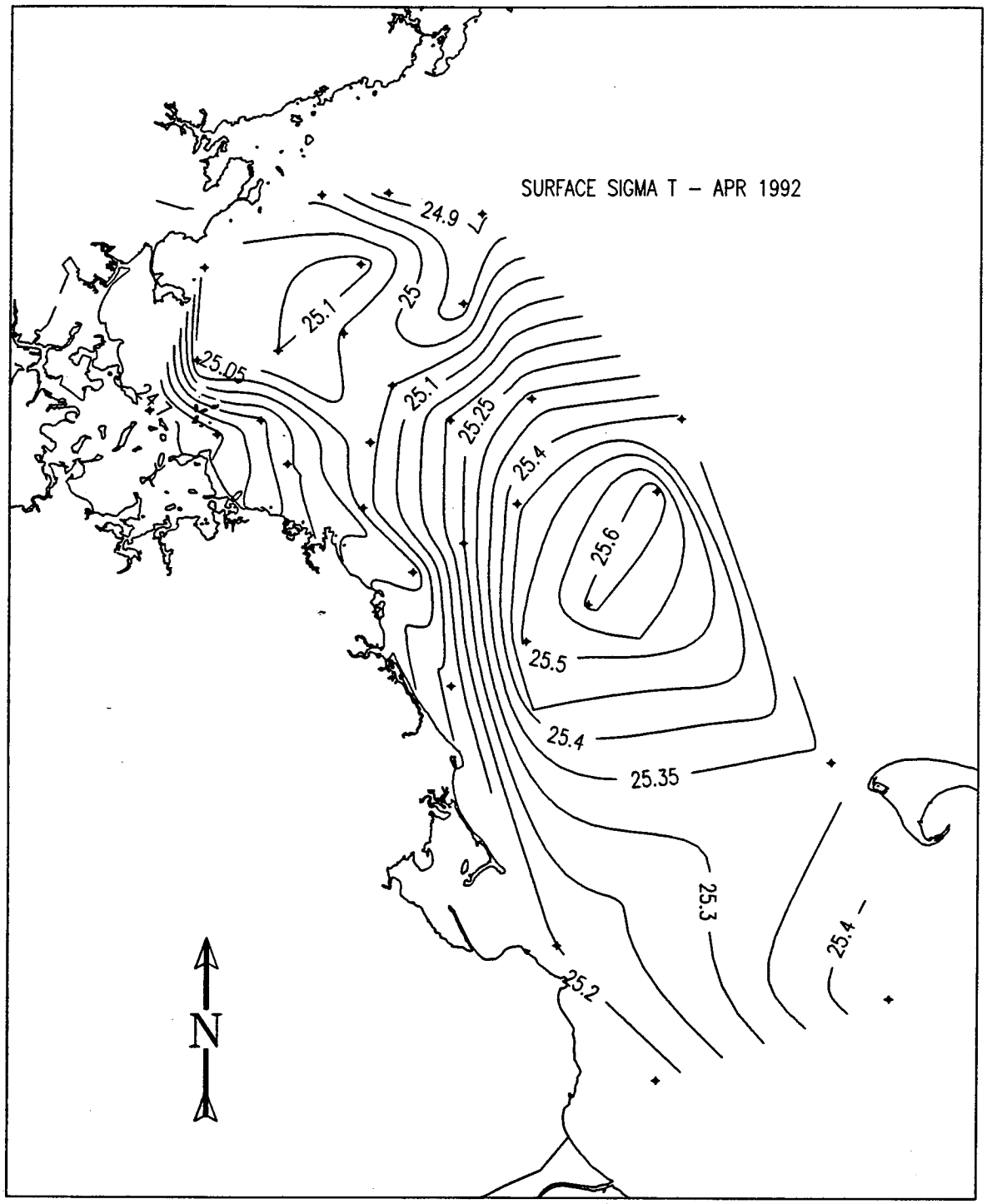



**Figure 3-3** **Surface $\sigma_T$ in the region in April 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.05 units.**

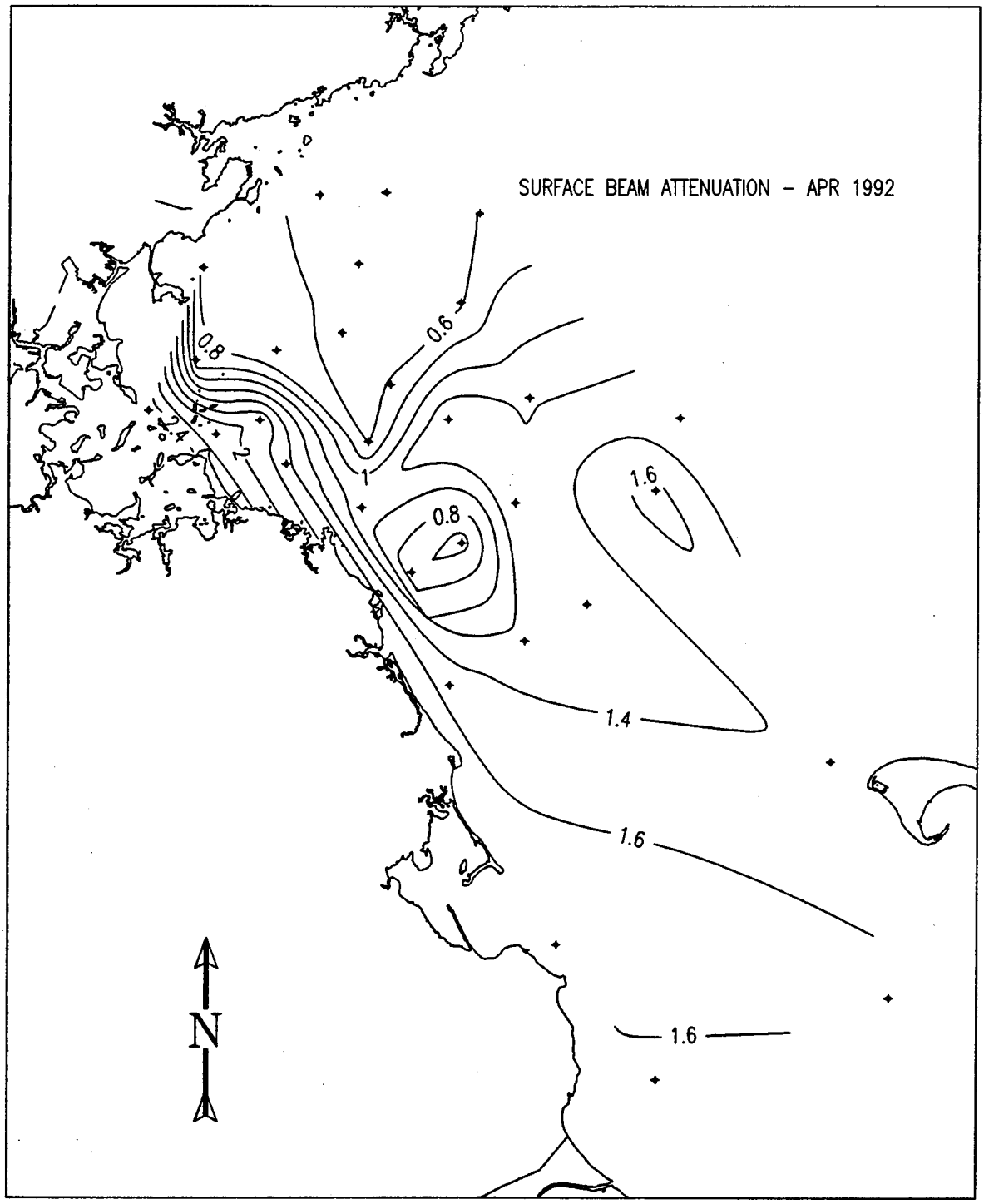



**Figure 3-4** **Surface beam attenuation ($m^{-1}$) in the region in April 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.2 $m^{-1}$.**

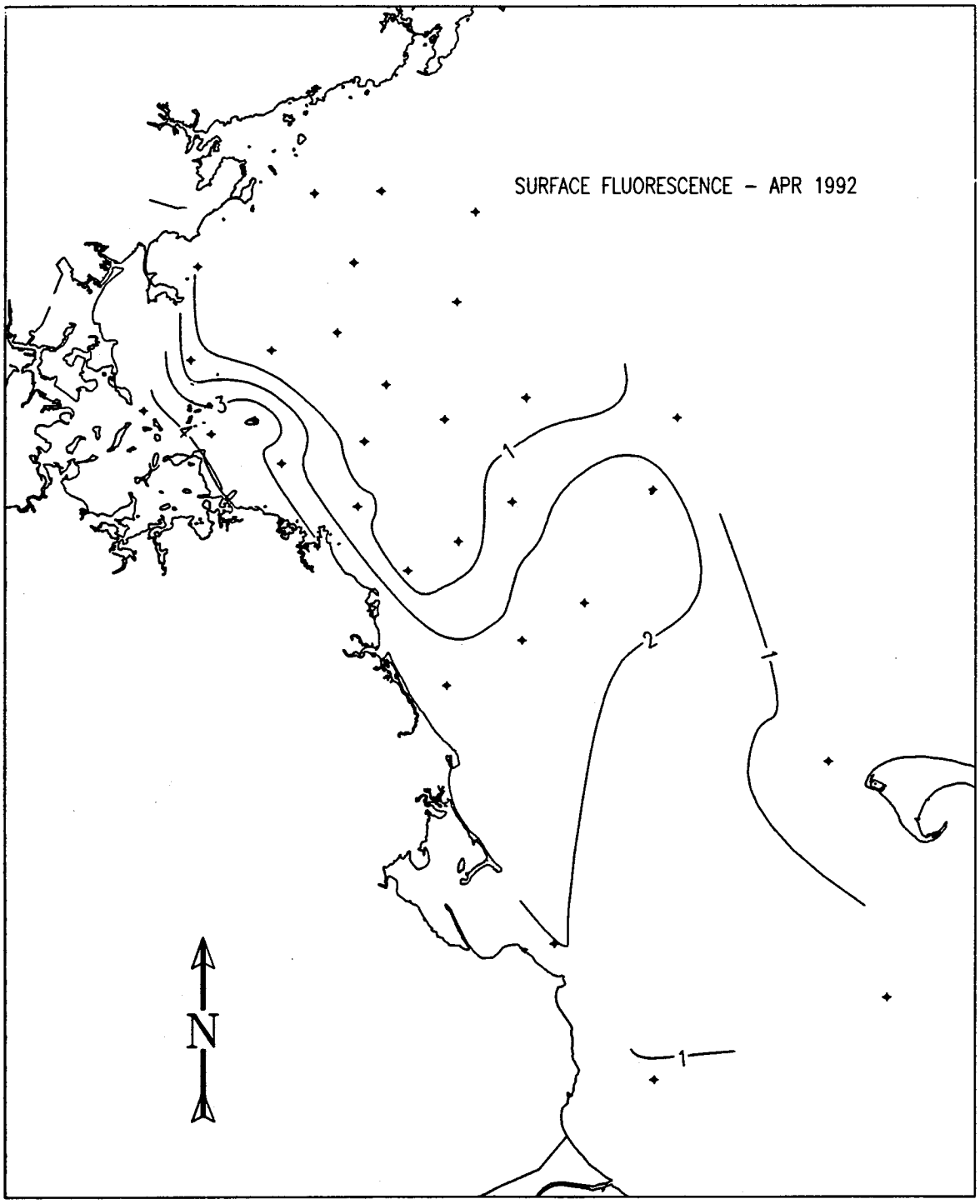



**Figure 3-5** Surface *in situ* fluorescence (as $\mu$g Chl $L^{-1}$) in the region in April 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 $\mu$g $L^{-1}$.

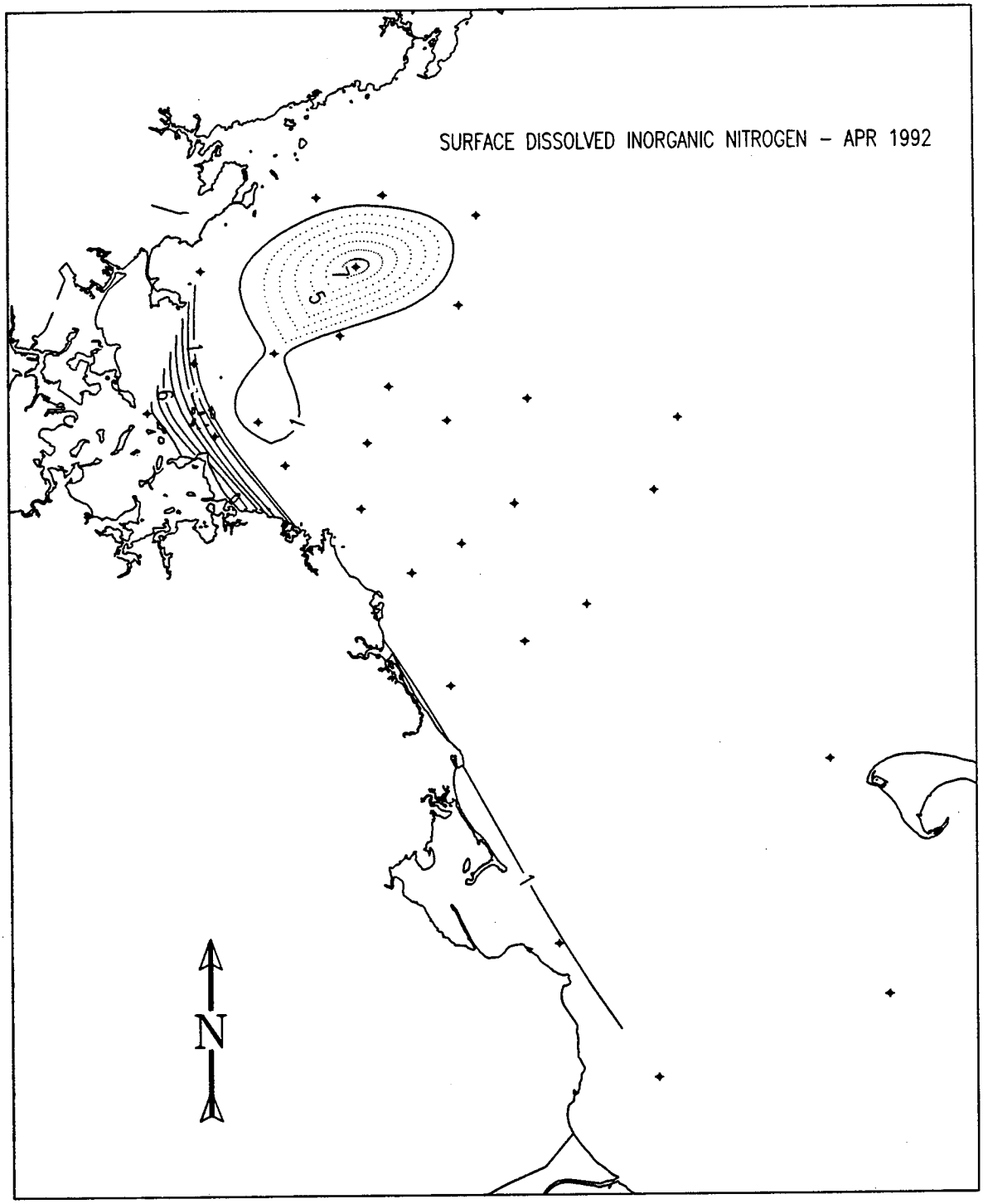



**Figure 3-6** **Surface dissolved inorganic nitrogen (DIN, μM) in the region in April 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 μM.**

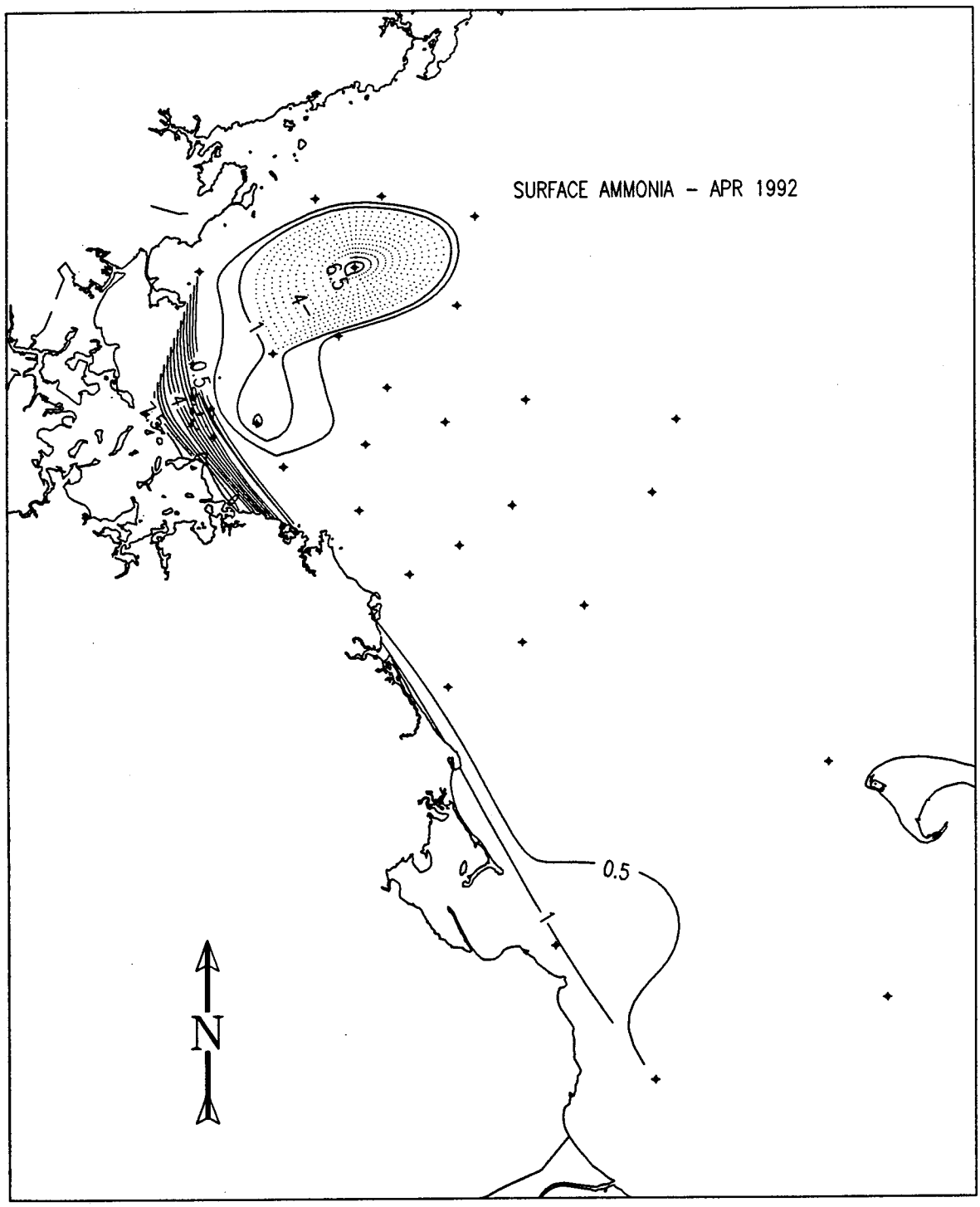



**Figure 3-7** **Surface ammonia ($\mu$M) in the region in April 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.5 $\mu$M.**

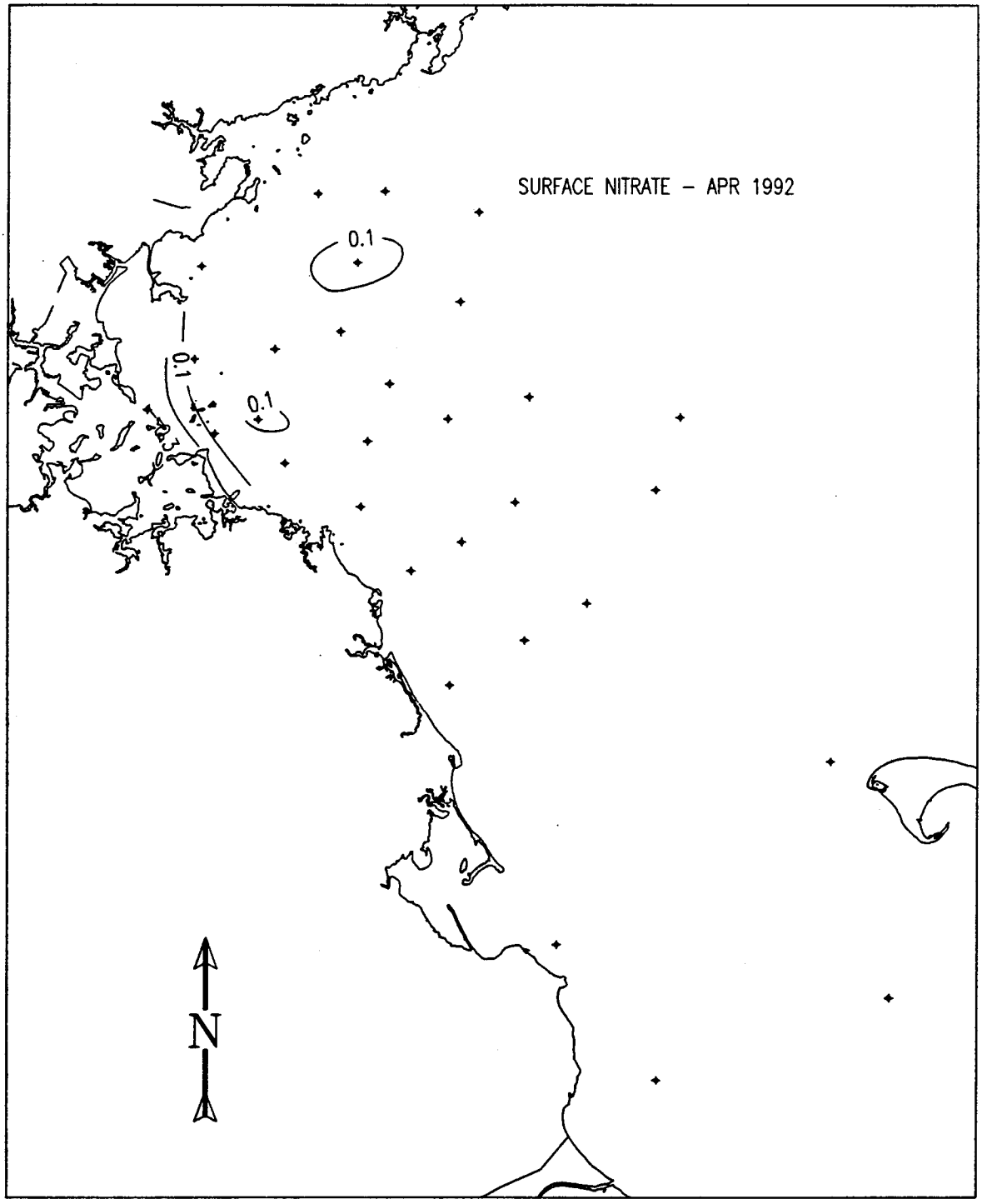



**Figure 3-8** **Surface nitrate ($\mu$M) in the region in April 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.1 $\mu$M.**

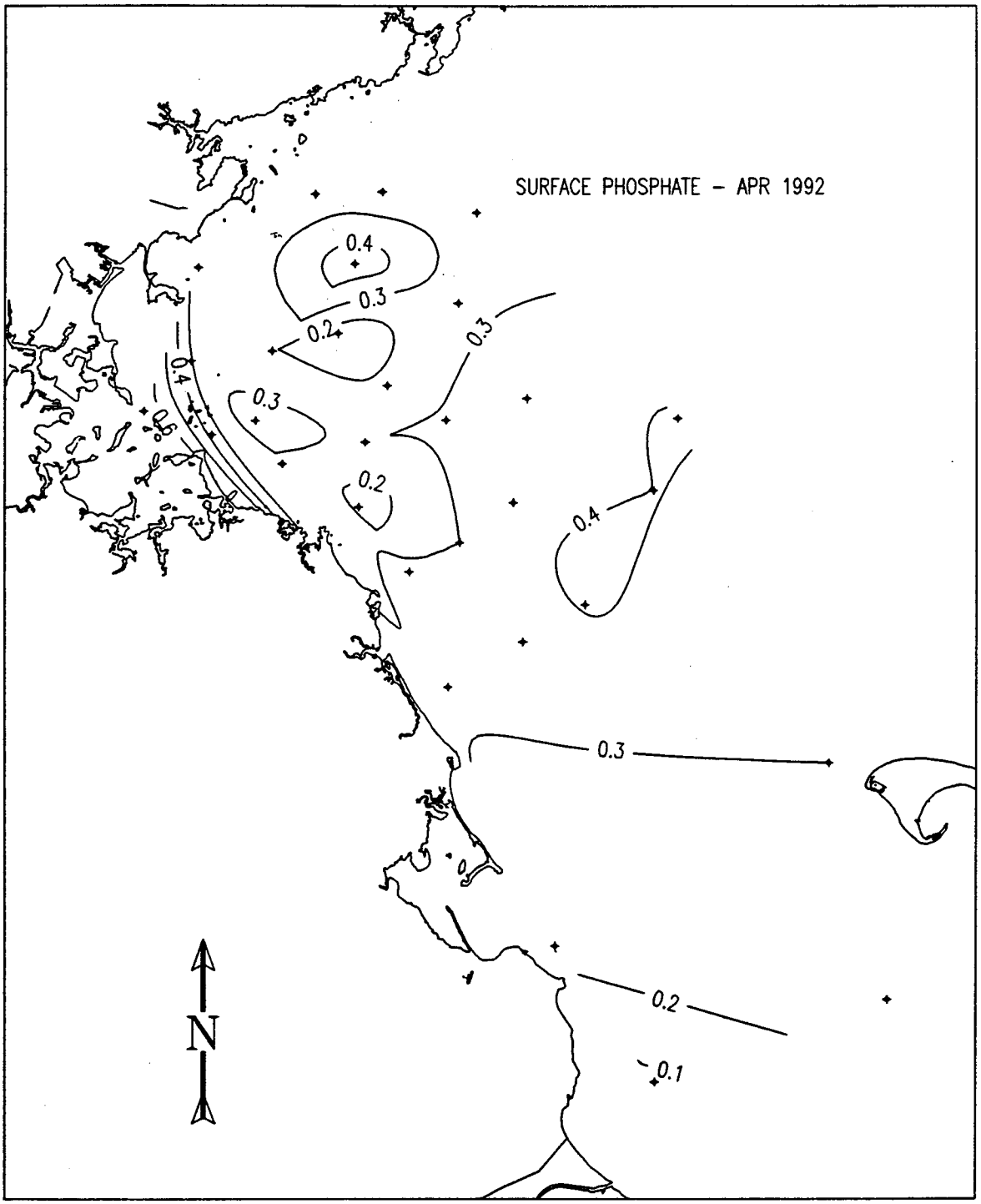



**Figure 3-9** **Surface phosphate ($\mu$M) in the region in April 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.1 $\mu$M.**

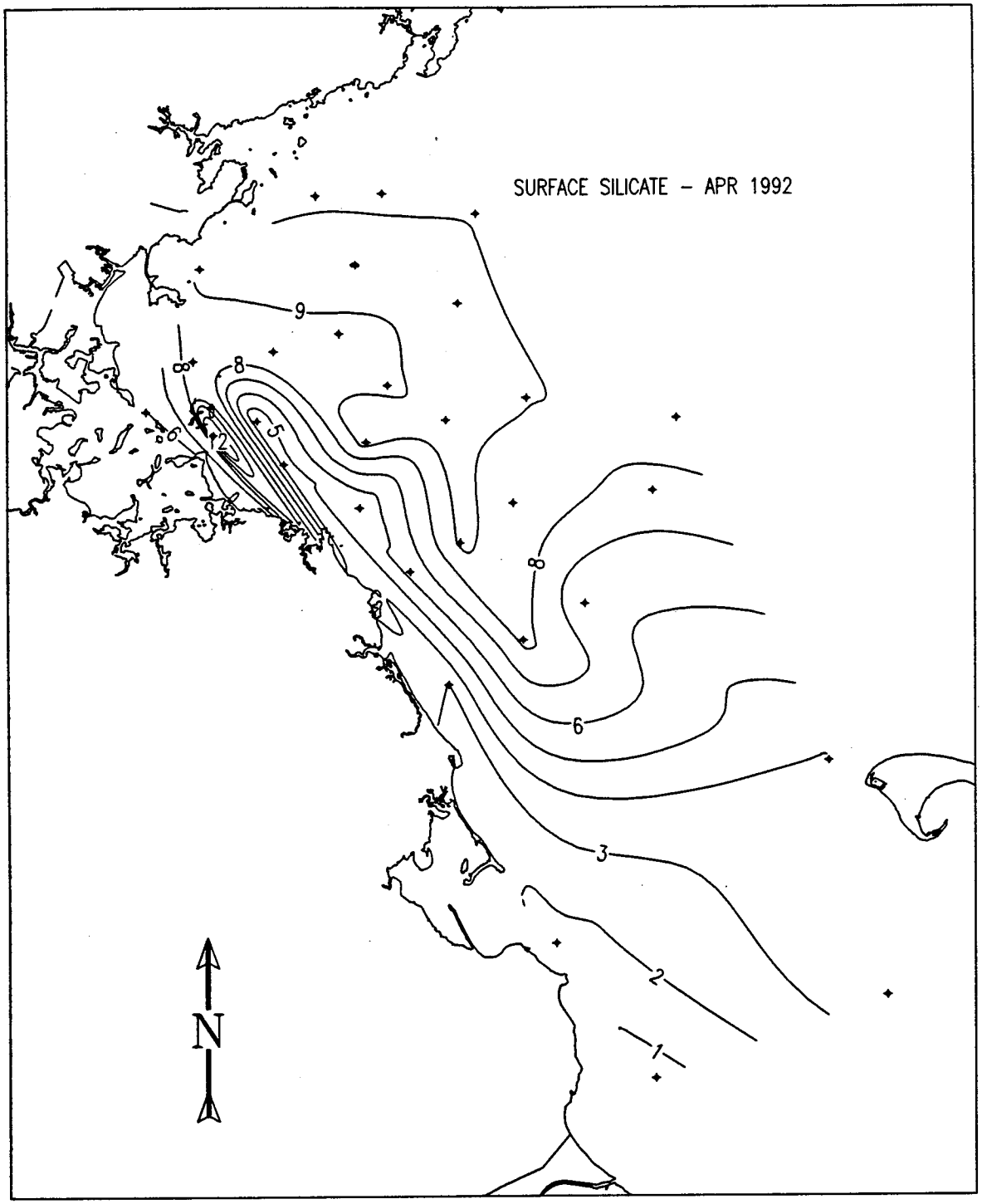



**Figure 3-10 Surface silicate ($\mu$M) in the region in April 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 $\mu$M.**

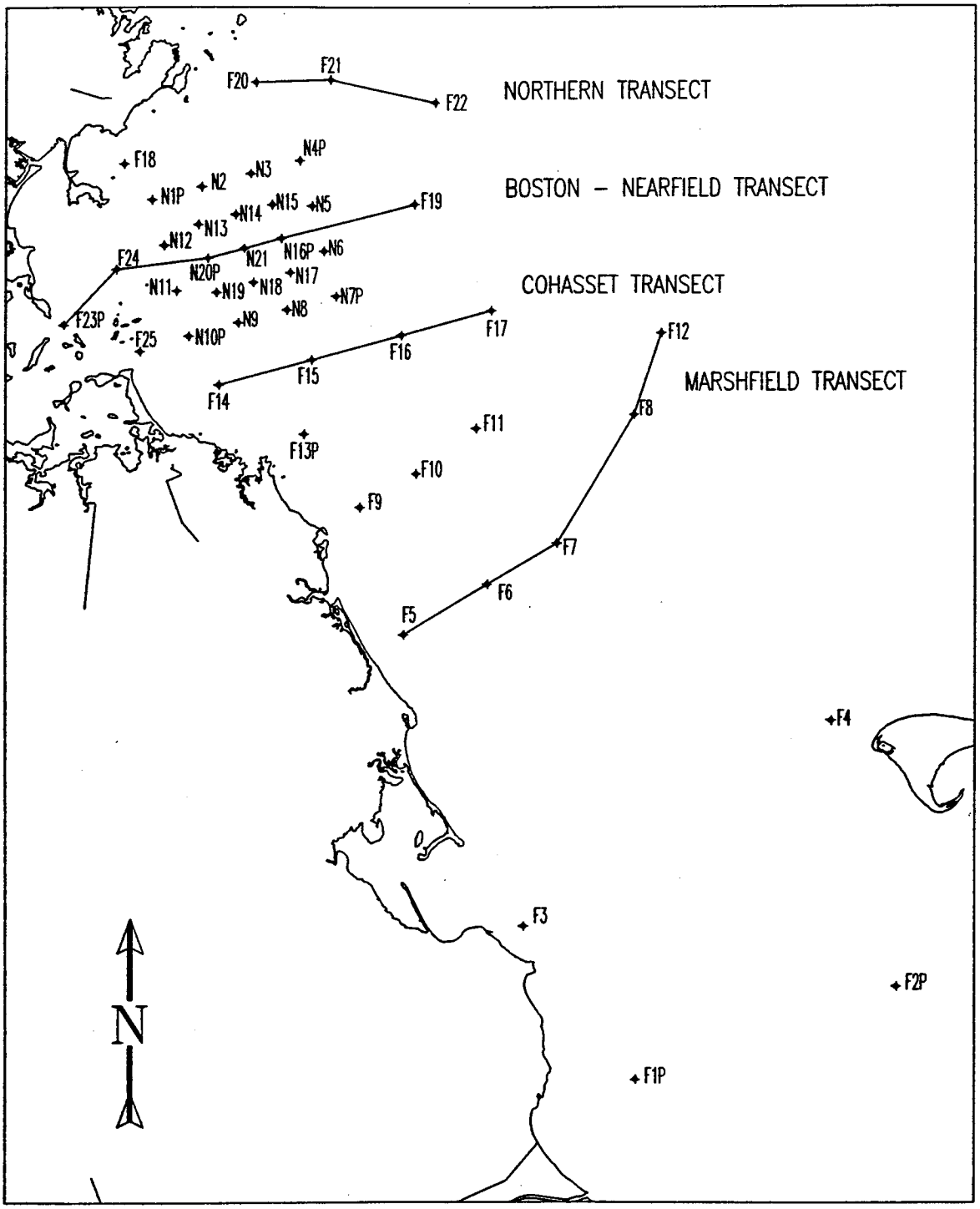



**Figure 3-11** **Map showing position of four standard transects for which vertical contour plots were produced in the following Figures 3-12 through 3-16 and Figures 6-11 through 6-15.**

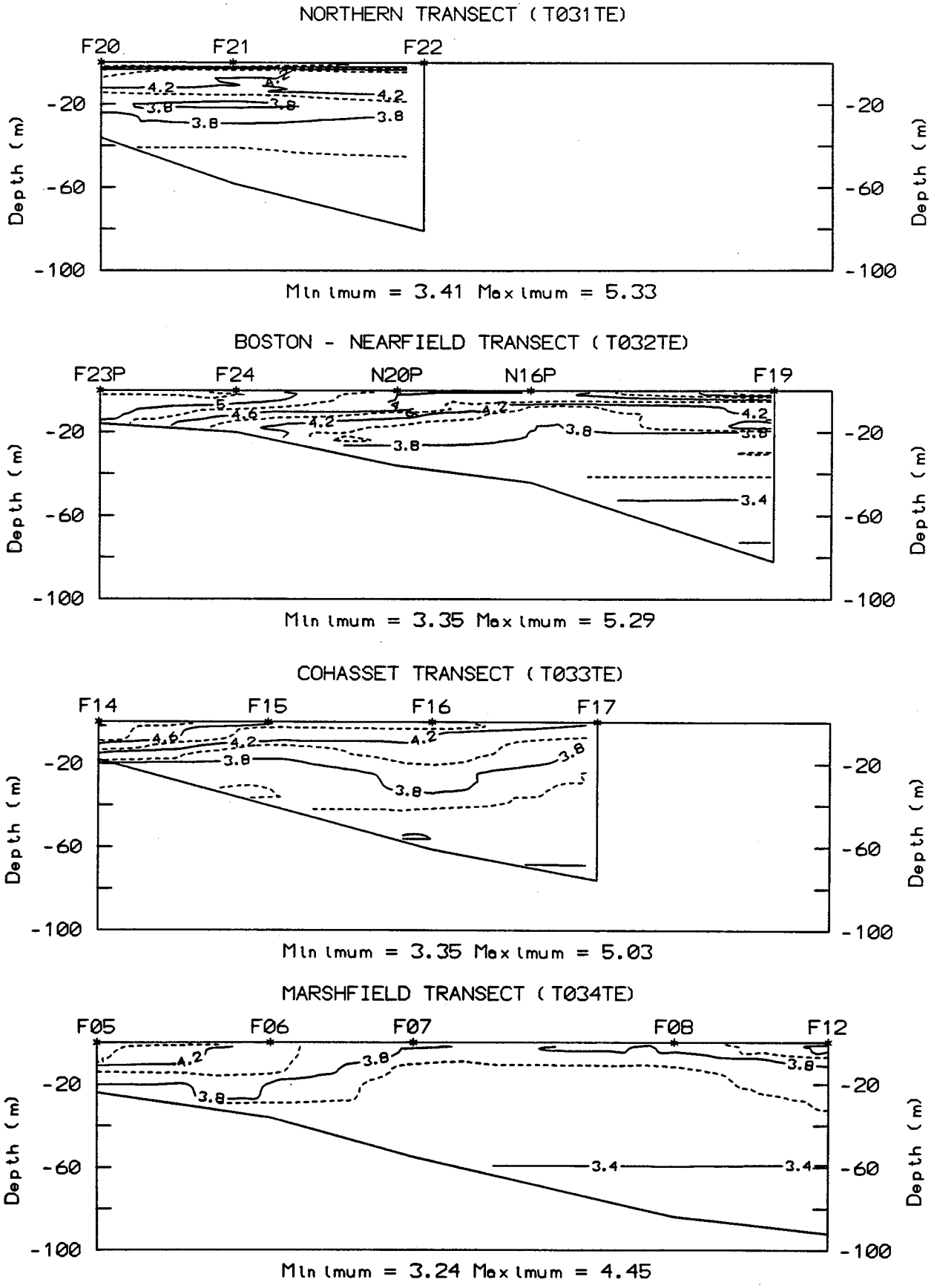



**Figure 3-12 Vertical section contours of temperature in April for standard transects (see Figure 3-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 0.2°C.**

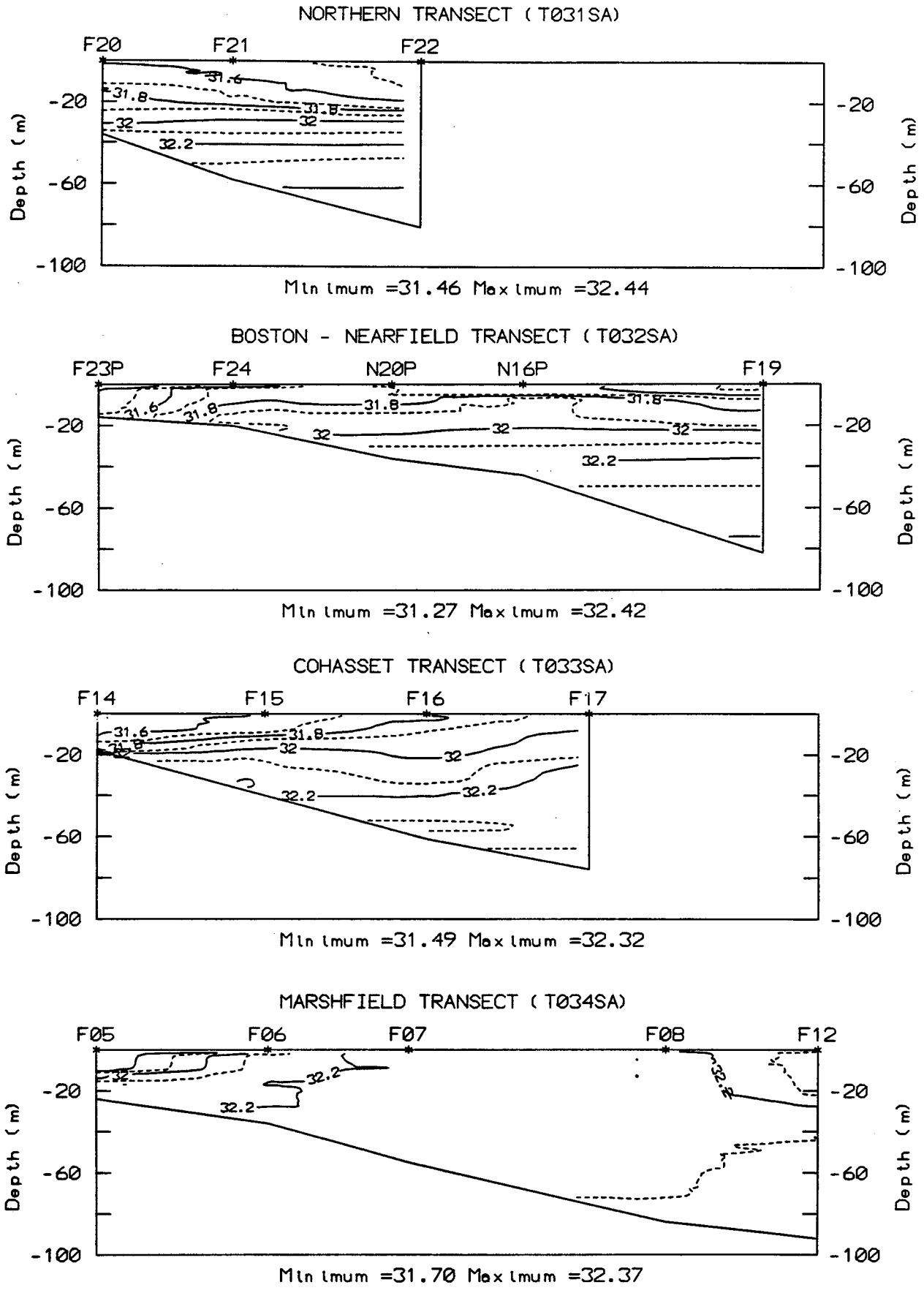



**Figure 3-13 Vertical section contours of salinity in April for standard transects (see Figure 3-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 0.1 PSU.**

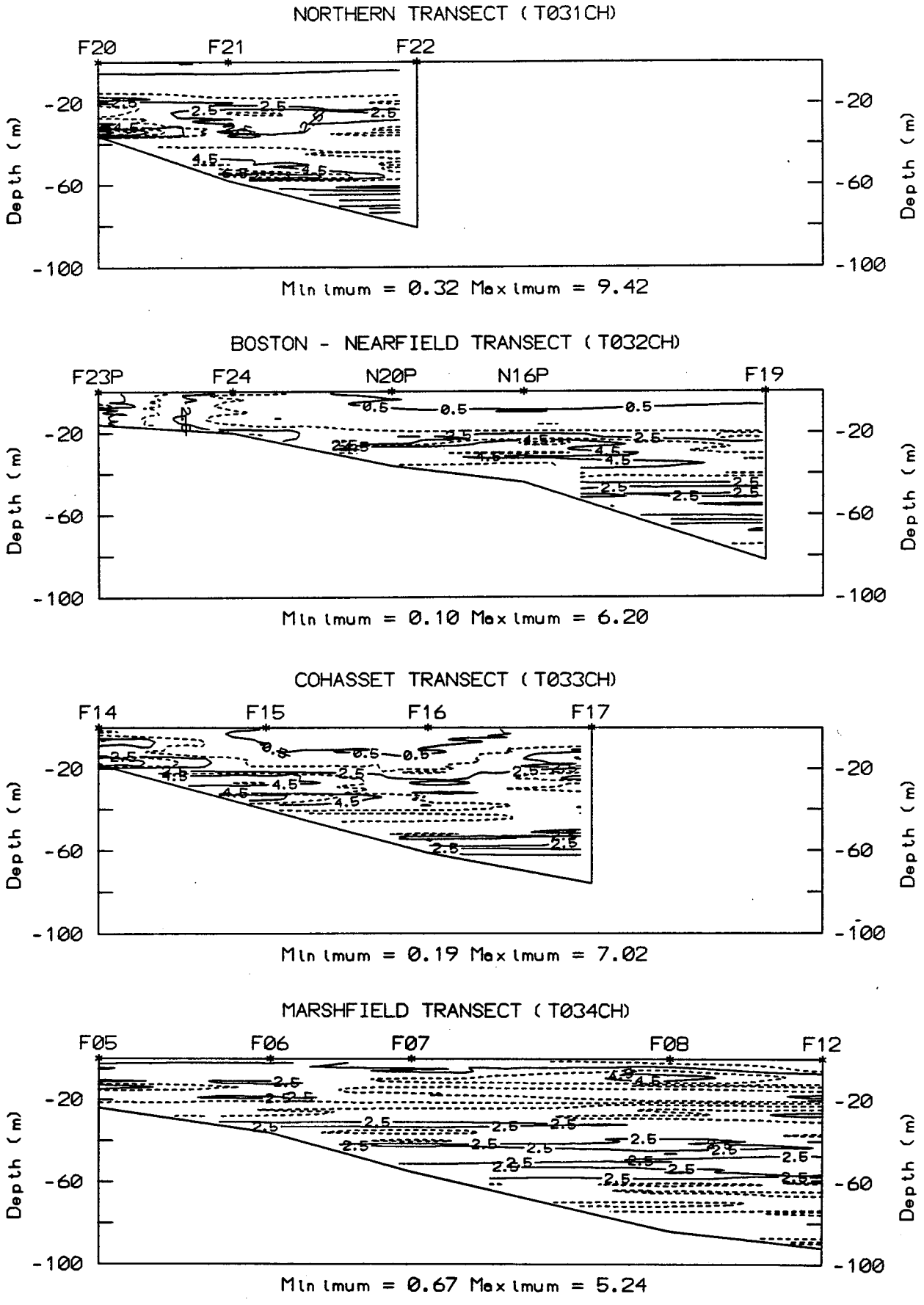



**Figure 3-14.** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) in April for standard transects (see Figure 3-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 1 $\mu$g $L^{-1}$.**

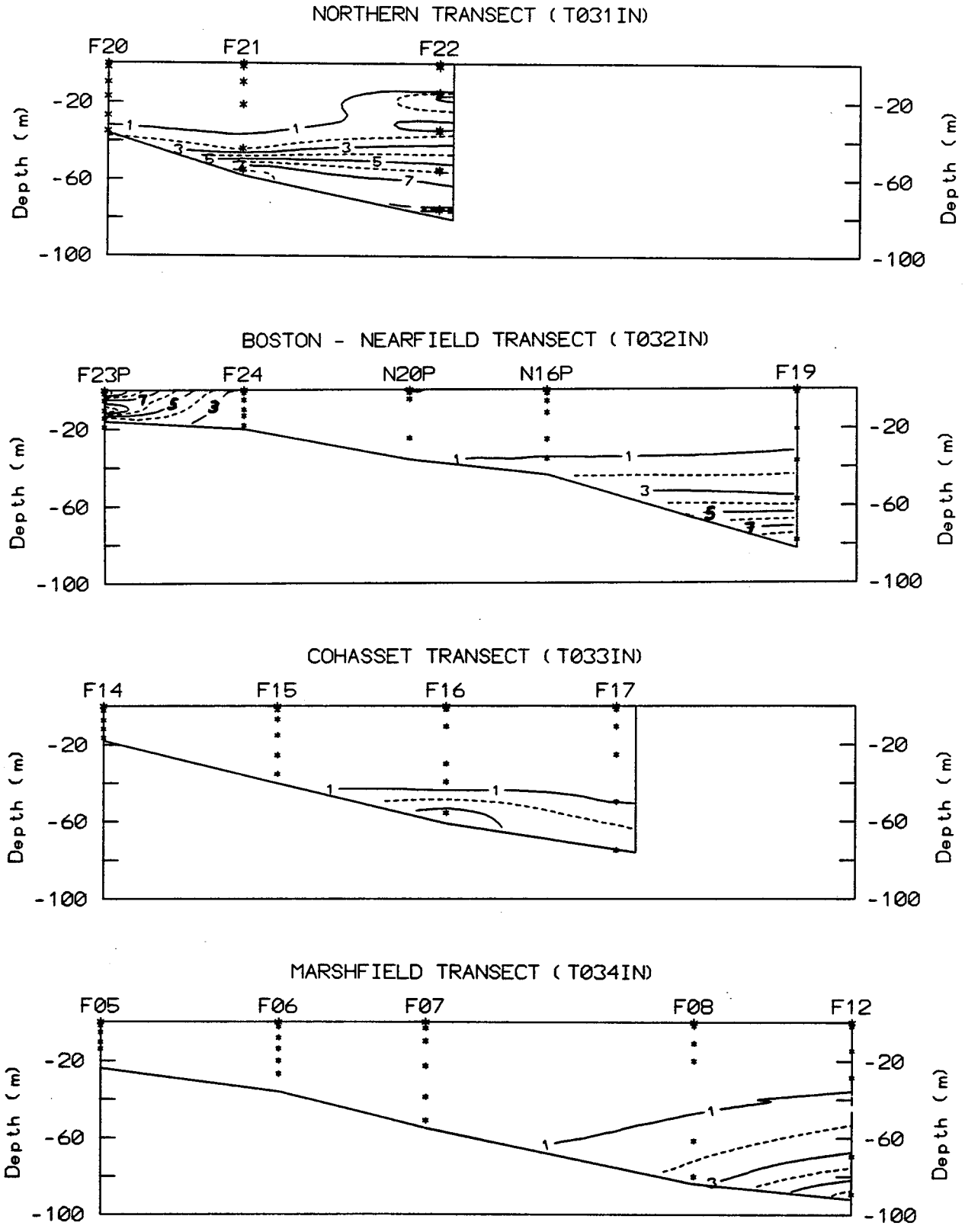



**Figure 3-15 Vertical section contours of dissolved inorganic nitrogen ($\mu$M) in April for standard transects (see Figure 3-11). The data used to produce contours are from discrete bottle samples as given in Appendix A. The contour interval is 1$\mu$M.**

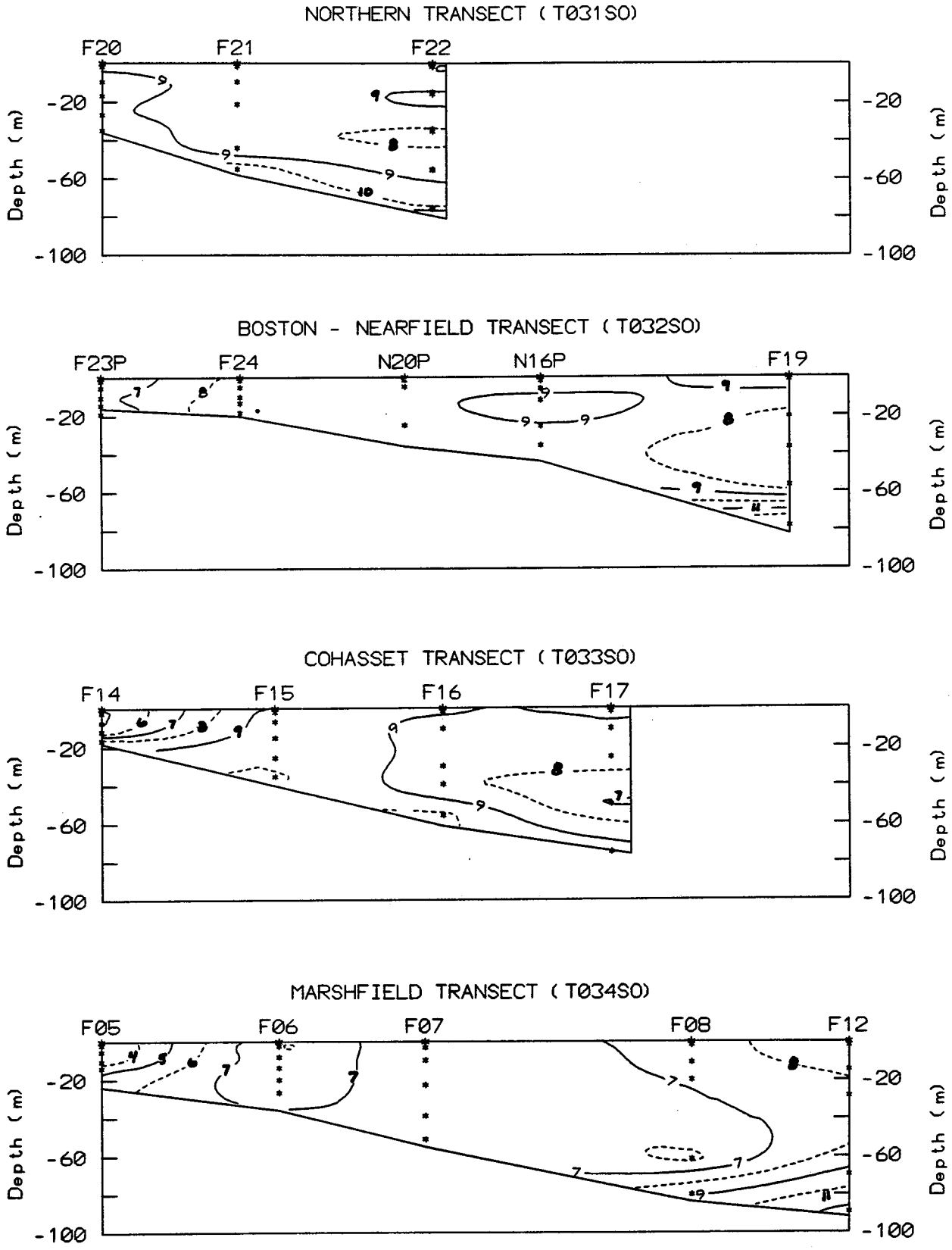



**Figure 3-16** Vertical section contours silicate ($\mu$M) in April for standard transects (see Figure 3-11). The data used to produce contours are from discrete bottle samples as given in Appendix A. The contour interval is 1$\mu$M.

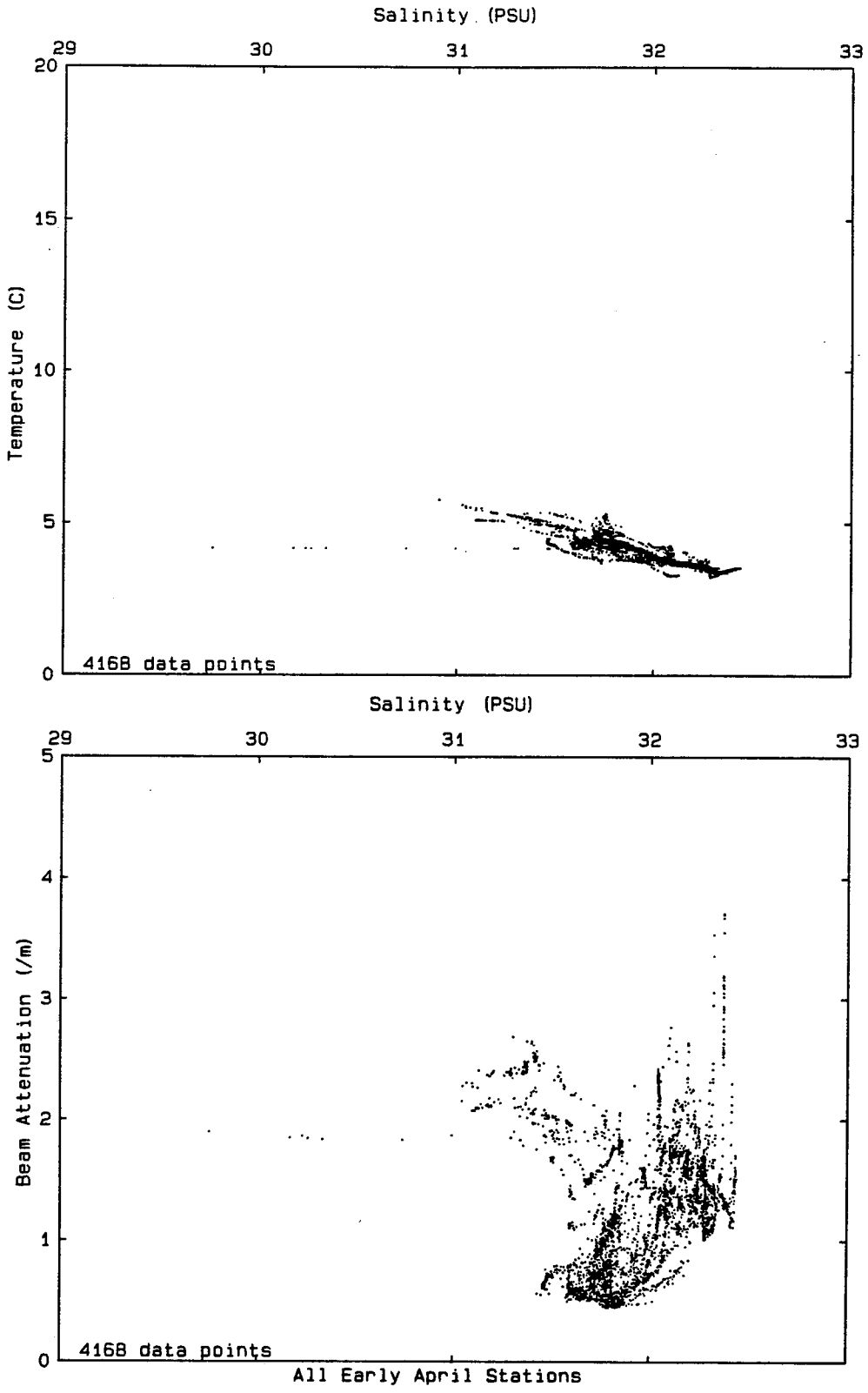



**Figure 3-17a** **Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in April 1992. Individual station cast plots that were used to produce this composite are in Appendix C.**

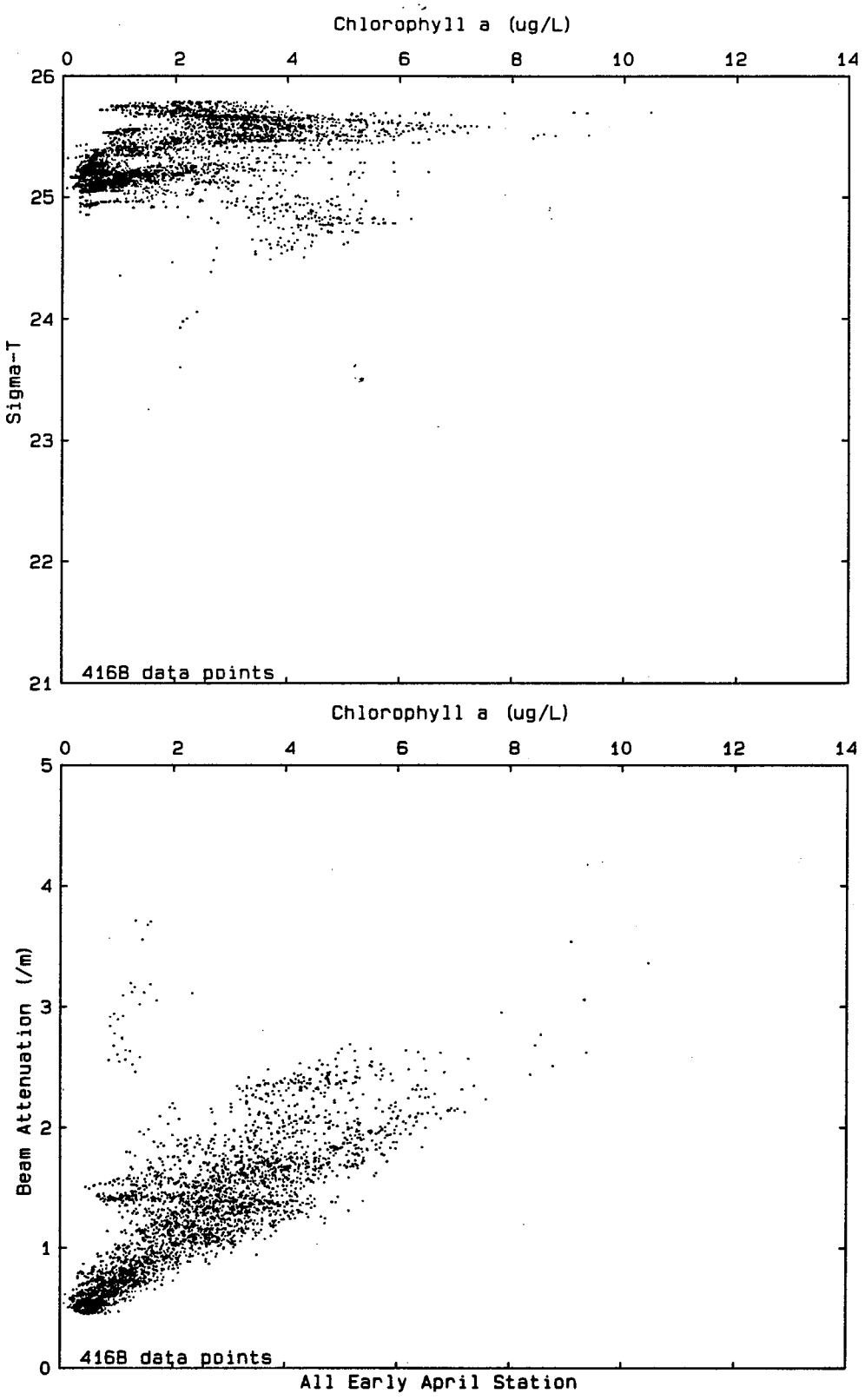



**Figure 3-17b** **Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in April 1992. Individual station cast plots that were used to produce this composite are in Appendix C. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

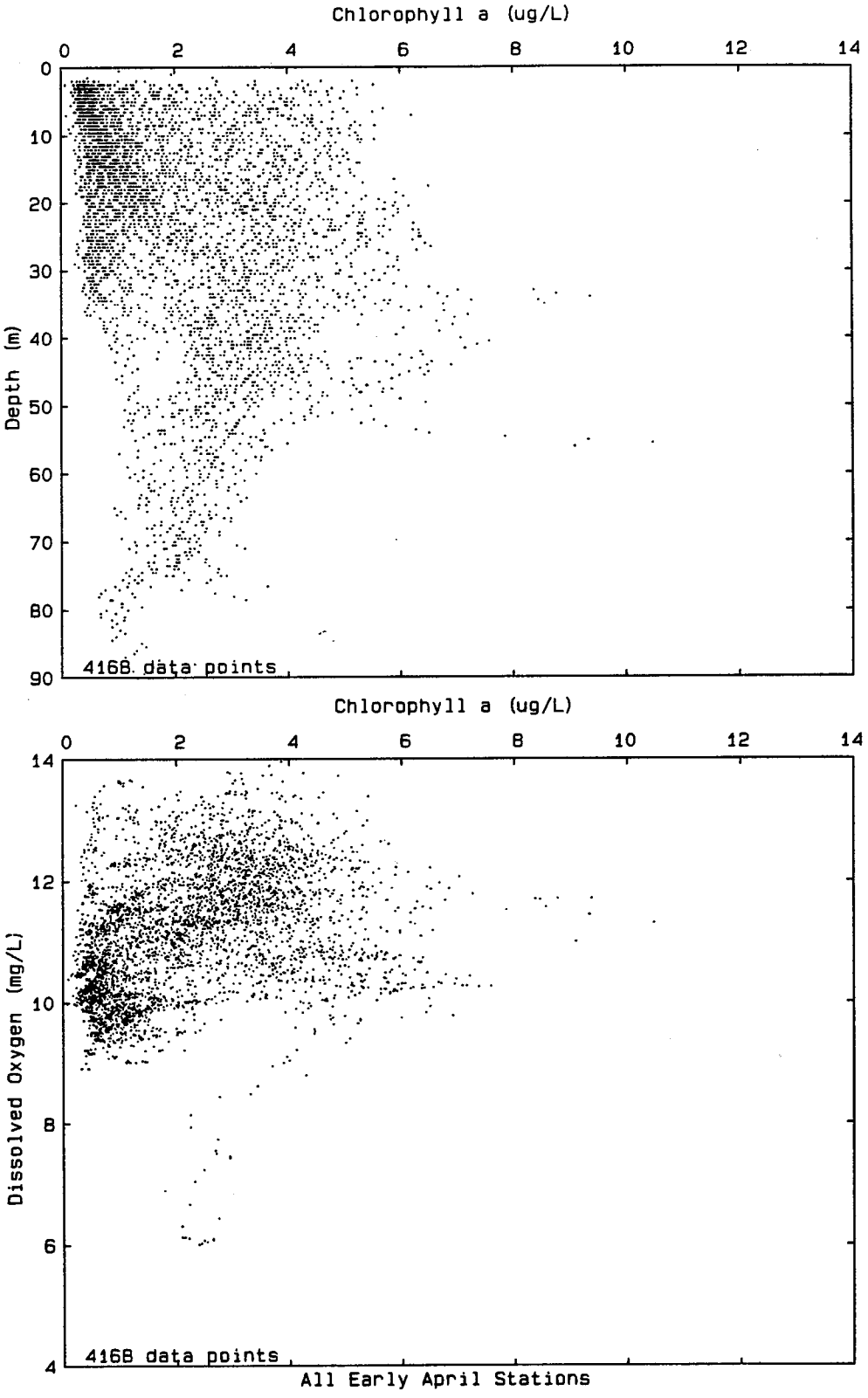



**Figure 3-17c** **Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in April 1992. Individual station cast plots that were used to produce this composite are in Appendix C. Note that chlorophyll and dissolved oxygen concentrations are post-calibrated values estimated from fluorescence and DO sensor readings (see Appendix A).**

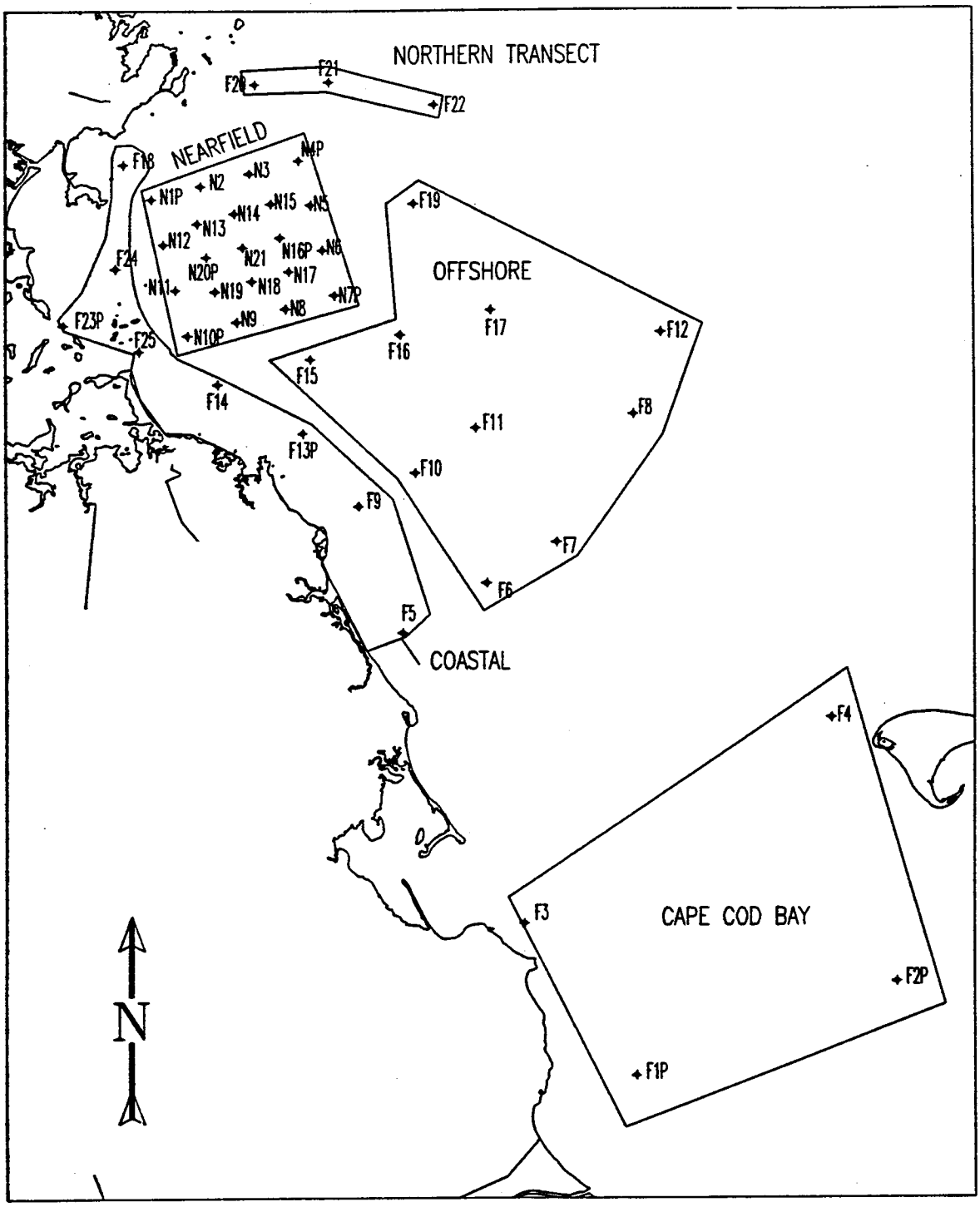



**Figure 3-18** **Map to show station groups designated in Figures 3-19 through 3-25, 6-18 through 6-26, 6-37, and 10-3 through 10-6. Massachusetts Bay was separated into 4 groups based on water depth and geographic position.**

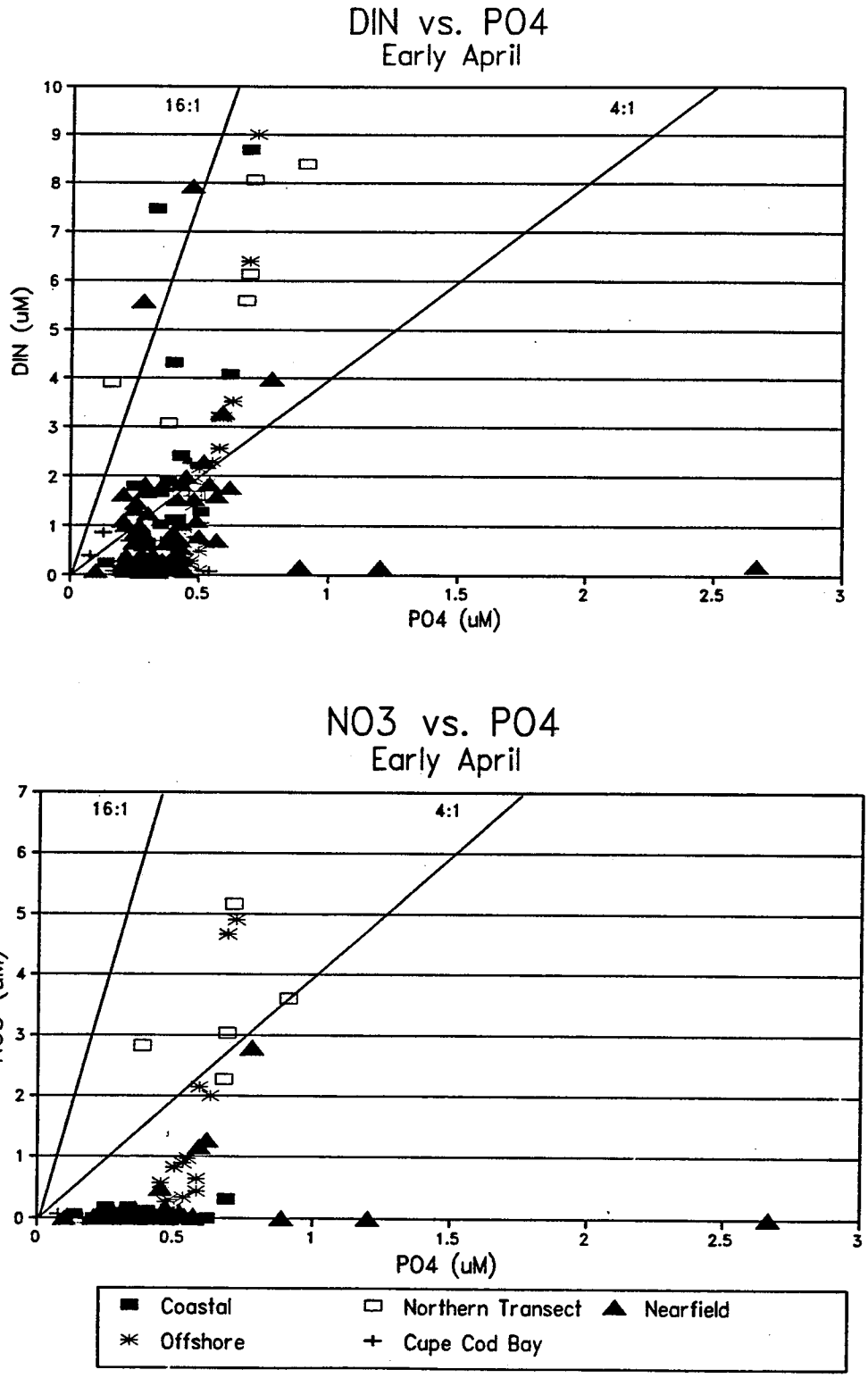



**Figure 3-19a** **Scatter plots of nitrogen forms vs. phosphate during April 1992. All stations and depths are included, and data are given in Appendix A. Lines show constant proportions of nitrogen relative to phosphorous across a range of N:P ratios.**

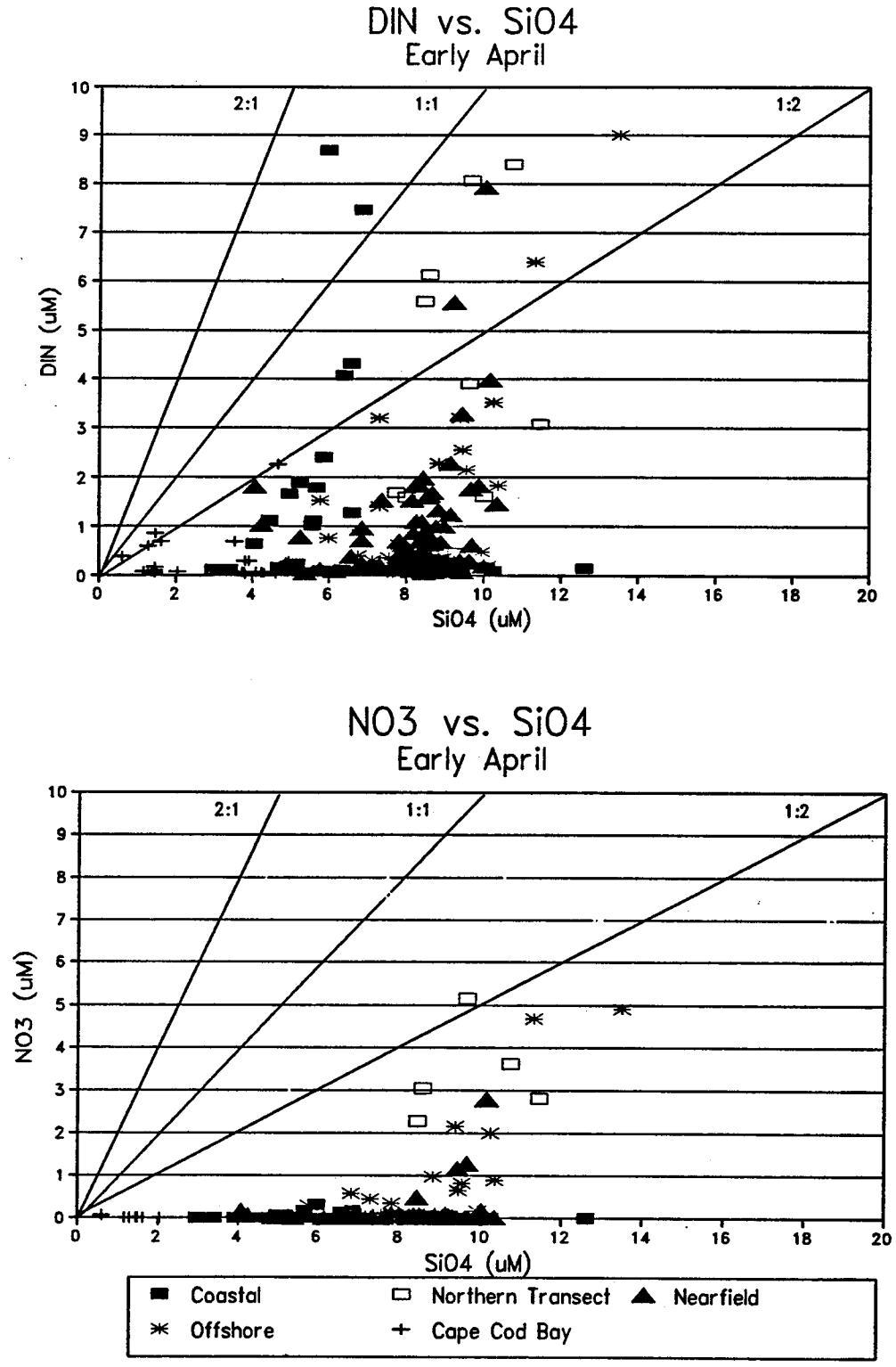



**Figure 3-19b** **Scatter plots of nitrogen vs. silicate during April 1992. All stations and depths are included, and data are given in Appendix A. Lines show constant proportions of nitrogen relative to silicate across a range of N:Si ratios.**

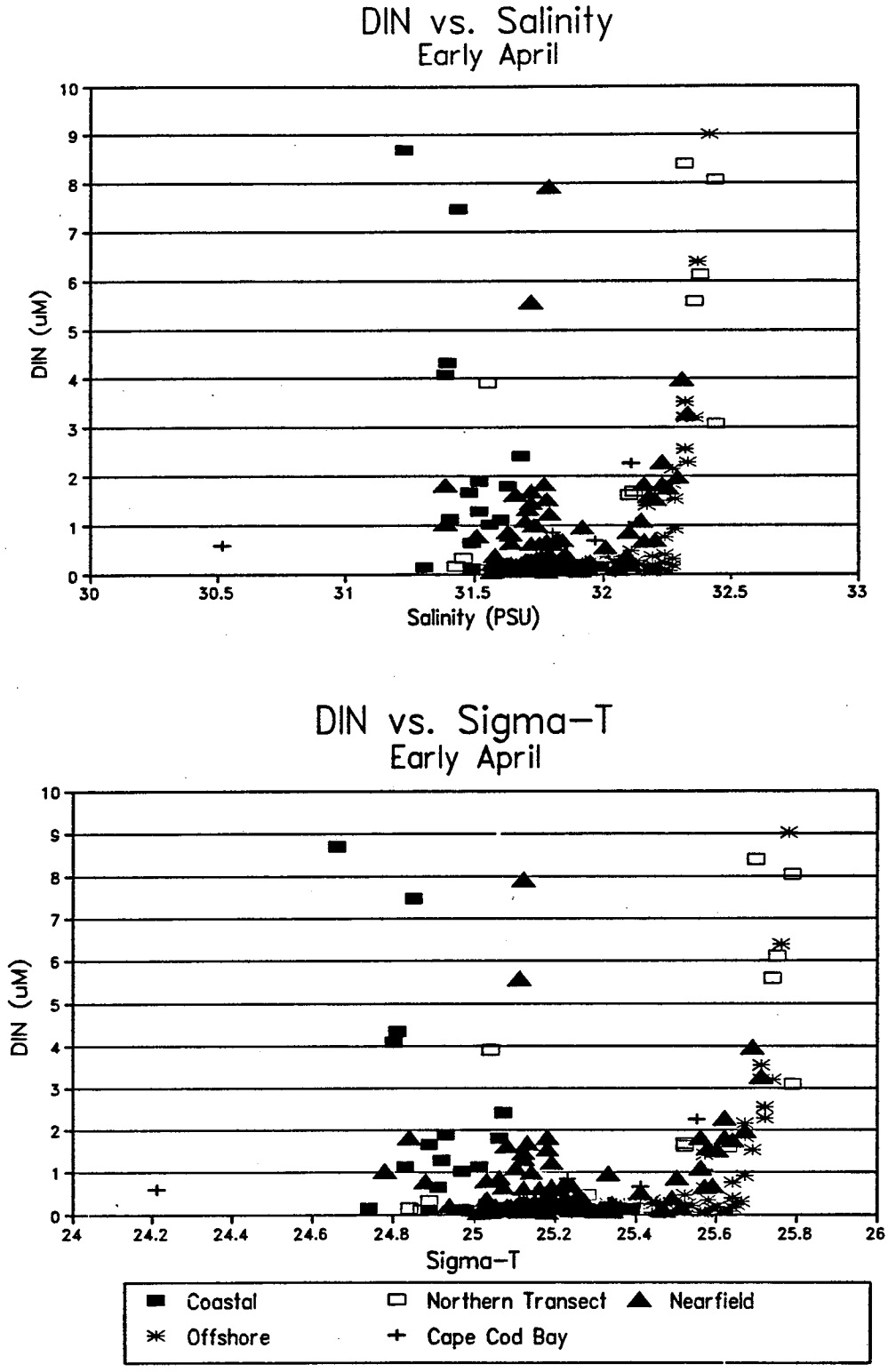



**Figure 3-20 Dissolved inorganic nitrogen vs. salinity and $\sigma_T$ in April 1992. All stations and depths are included, and data are given in Appendix A.**

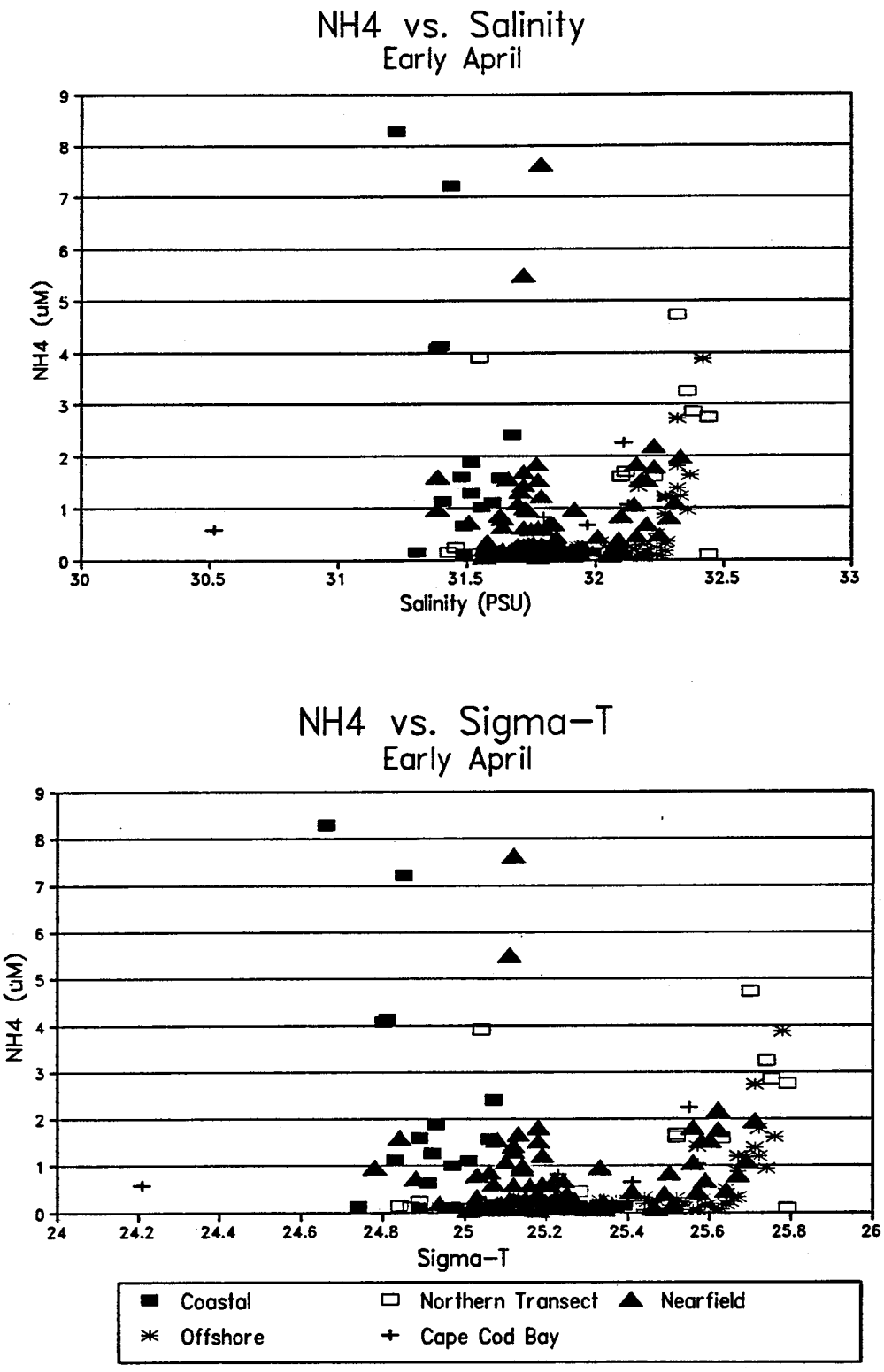



**Figure 3-21 Ammonia vs. salinity and $\sigma_T$ in April 1992. All stations and depths are included, and data are given in Appendix A.**

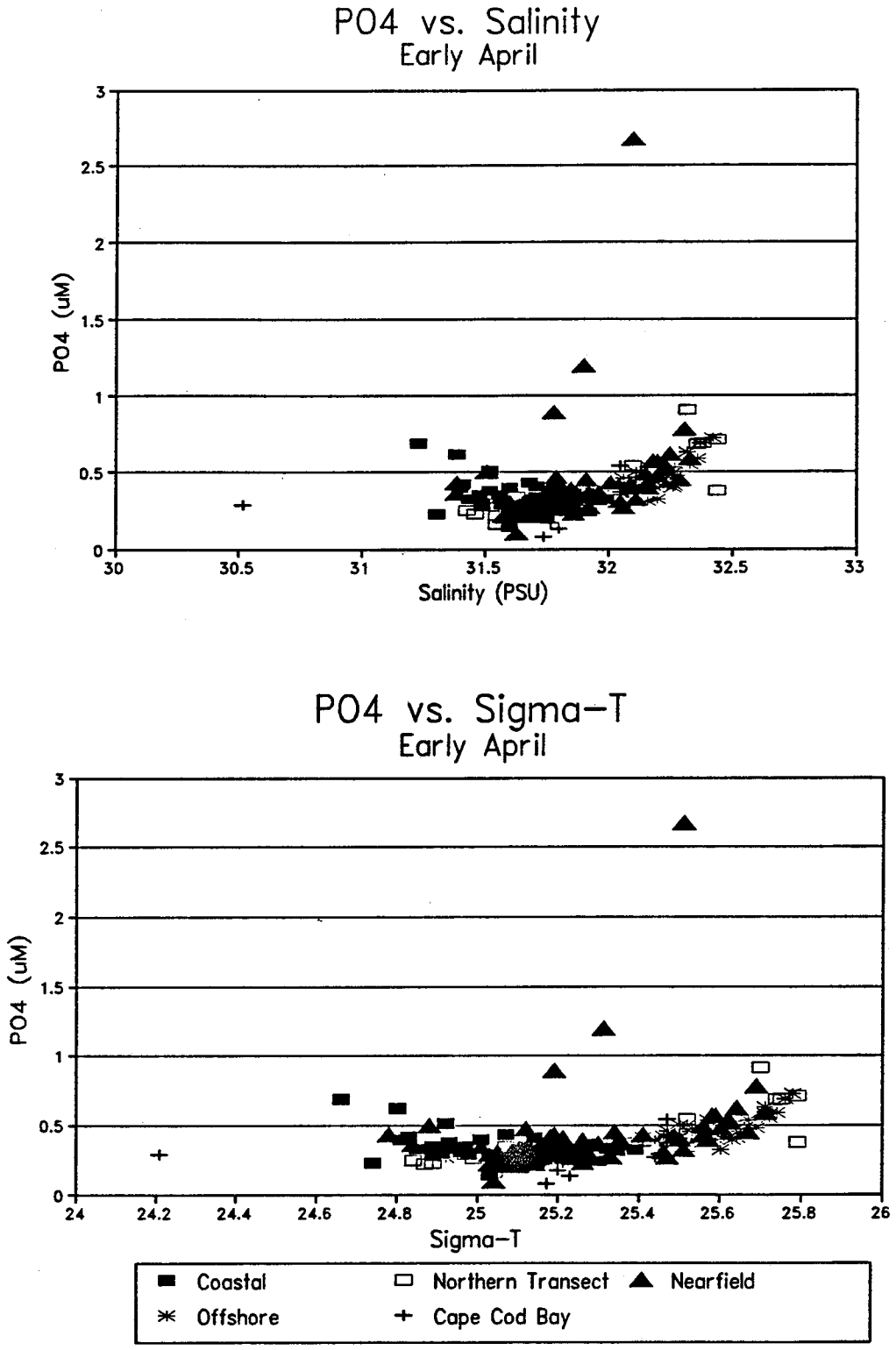



**Figure 3-22 Phosphate vs. salinity and $\sigma_T$ in April 1992. All stations and depths are included, and data are given in Appendix A.**

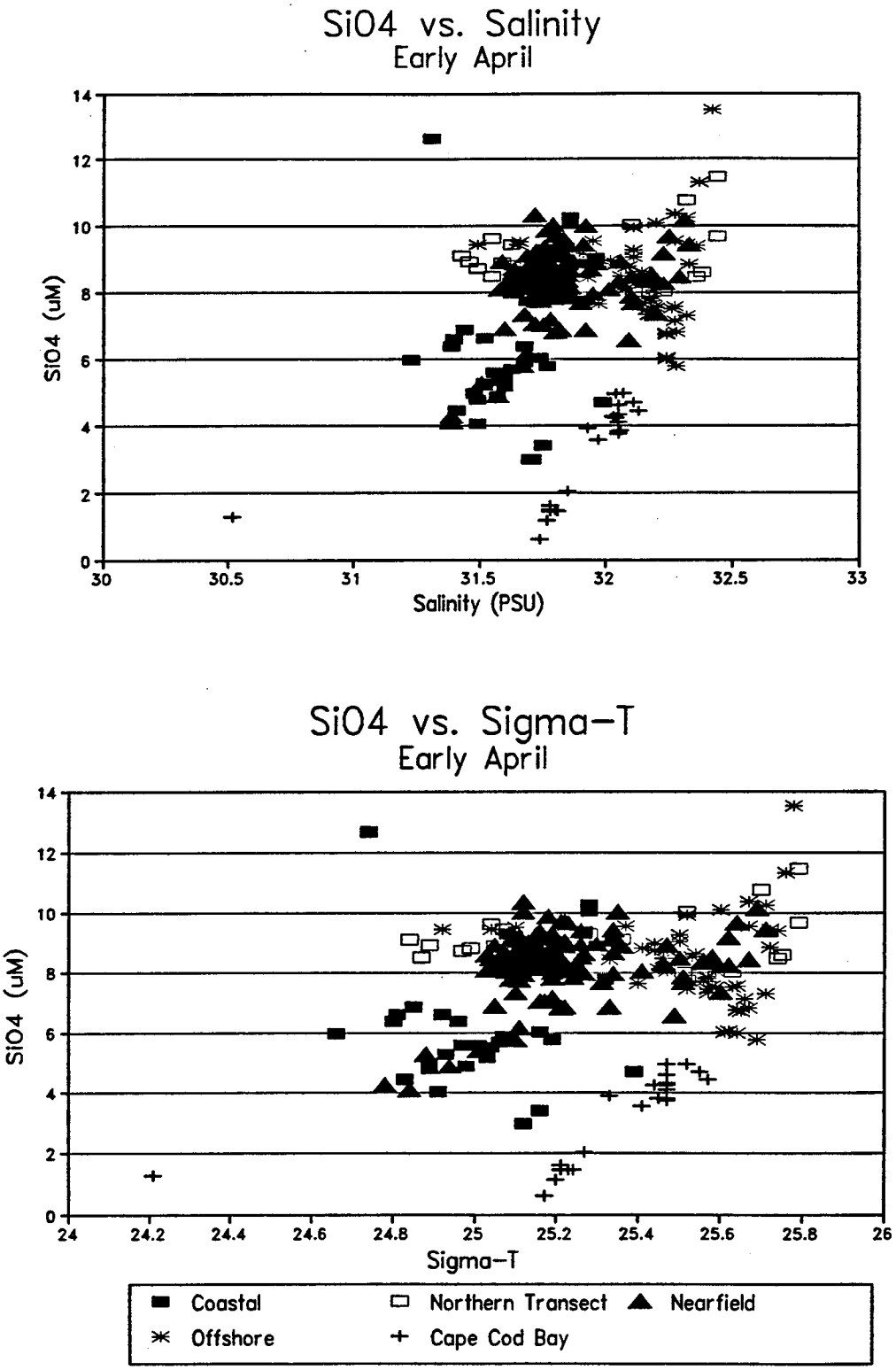



**Figure 3-23 Silicate vs. salinity and $\sigma_T$ in April 1992. All stations and depths are included, and data are given in Appendix A.**

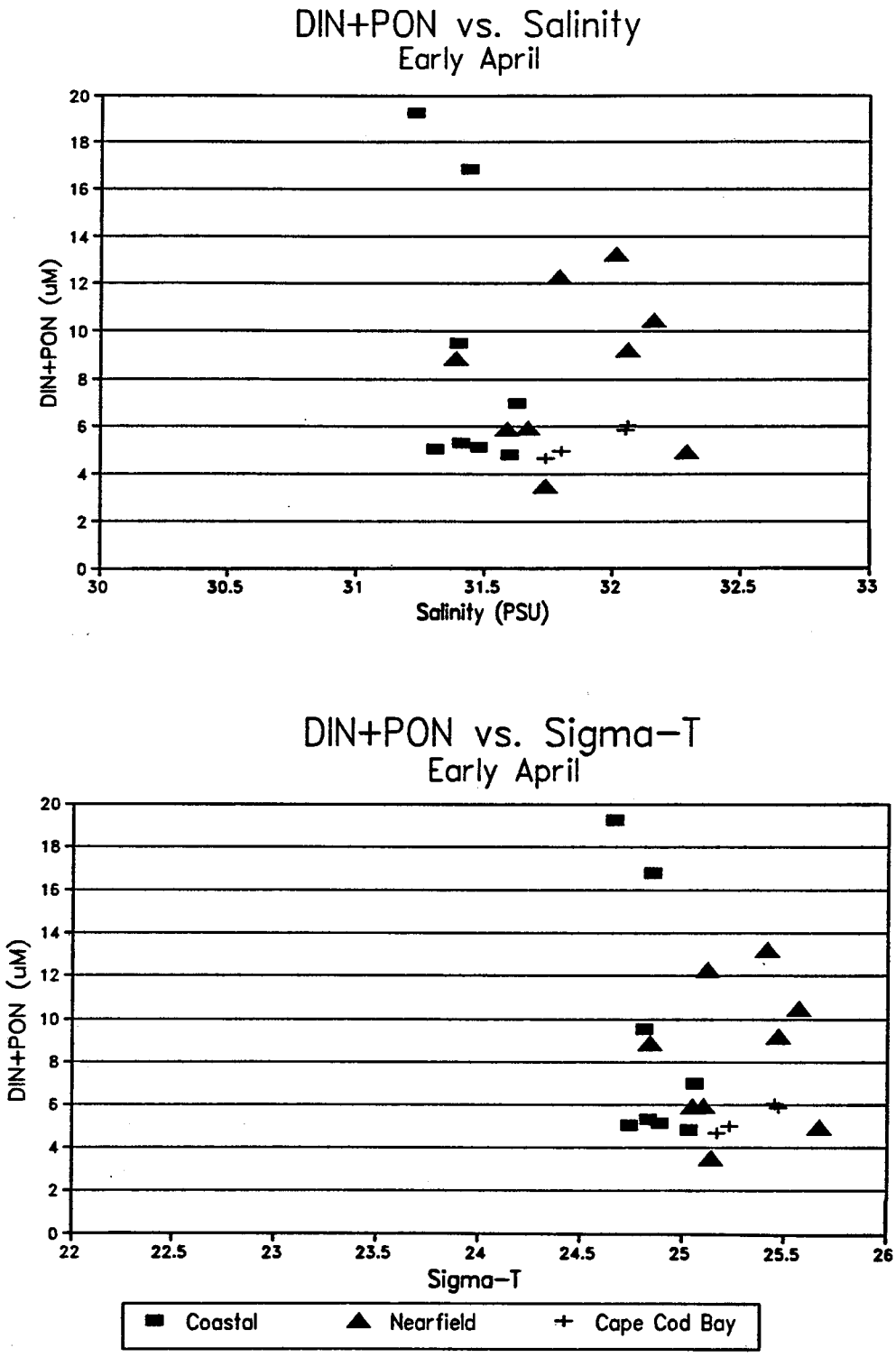



**Figure 3-24** **The sum of dissolved inorganic nitrogen and particulate organic nitrogen vs. salinity and $\sigma_T$ in April 1992. Data are from Bioproductivity stations and special station F25 and are given in Appendix A. The station groups are coded as given in Figure 3-18; there are no Bioproductivity stations in the Offshore or Northern Transect groups. PON concentrations were not available for several samples (see Appendix A).**

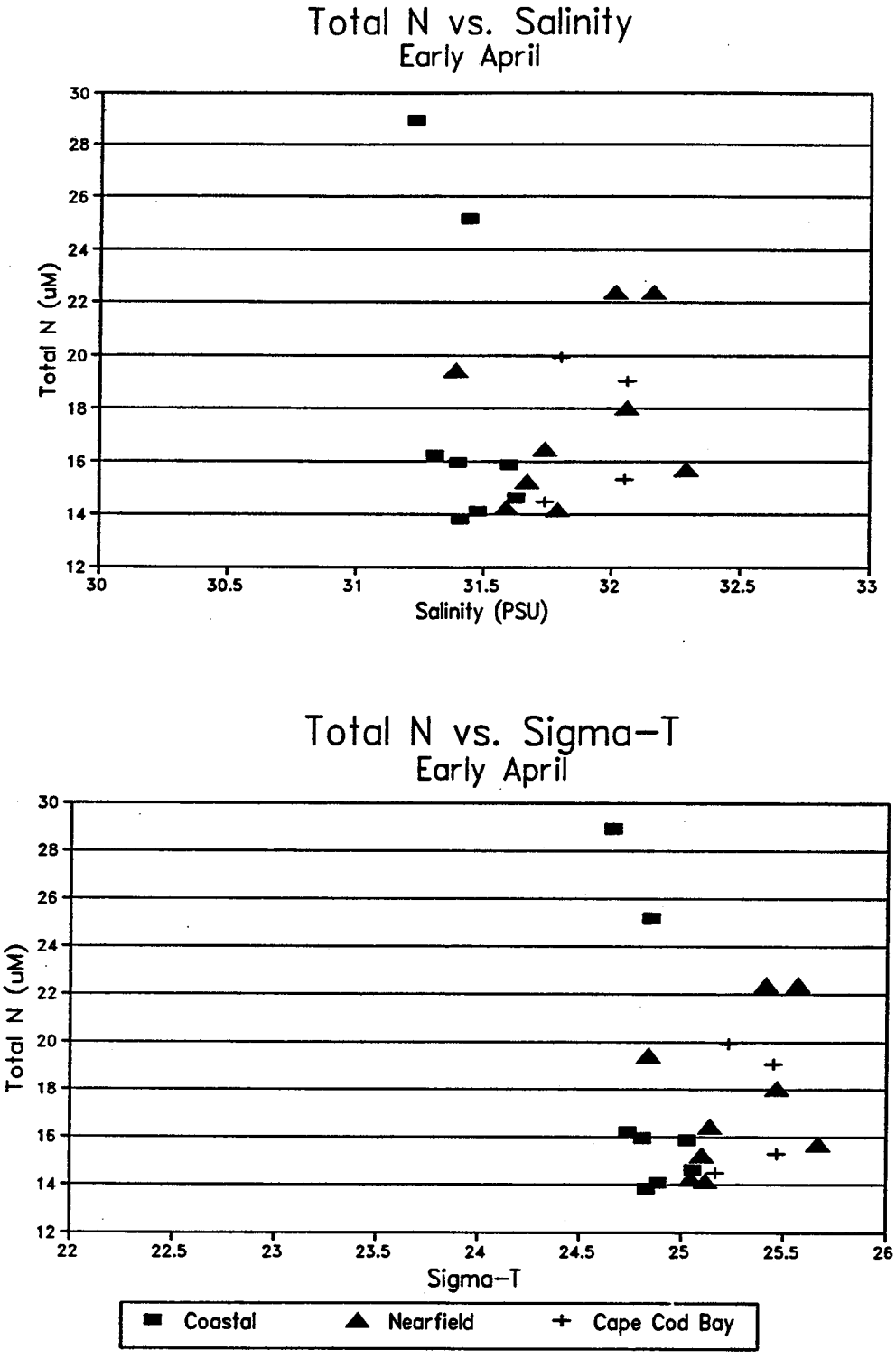



**Figure 3-25** **The sum of total dissolved nitrogen and particulate organic nitrogen (=total nitrogen) vs. salinity and $\sigma_T$ in April 1992. Data are from Bioproductivity stations and special station F25 and are given in Appendix A. Groups are the same Figure 3-18. PON, and thus total nitrogen, concentrations were not available for several samples (see Appendix A).**

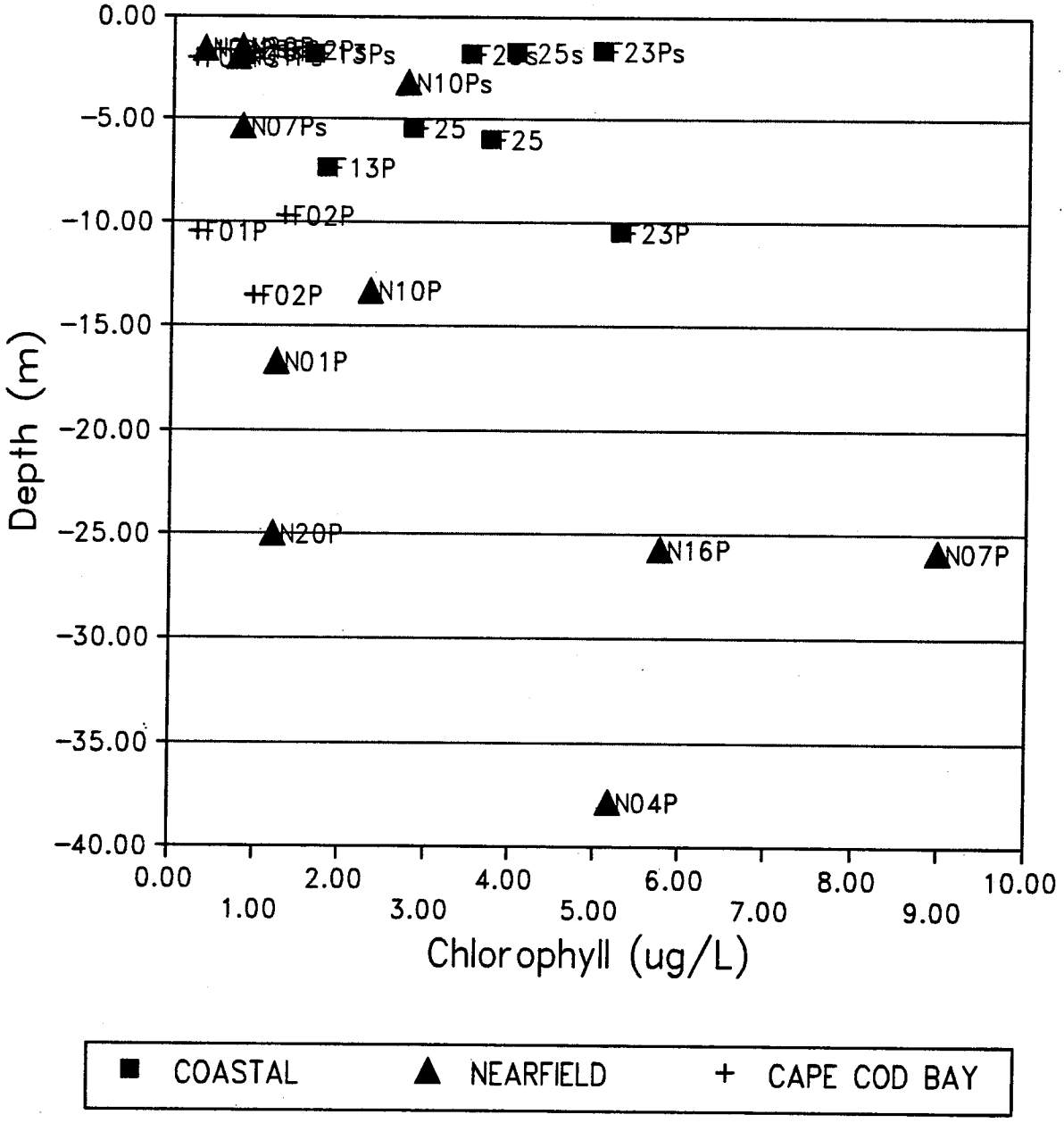



**Figure 3-26 Surface and deeper chlorophyll at BioProductivity stations and special station F25 as a function of depth in April 1992.**

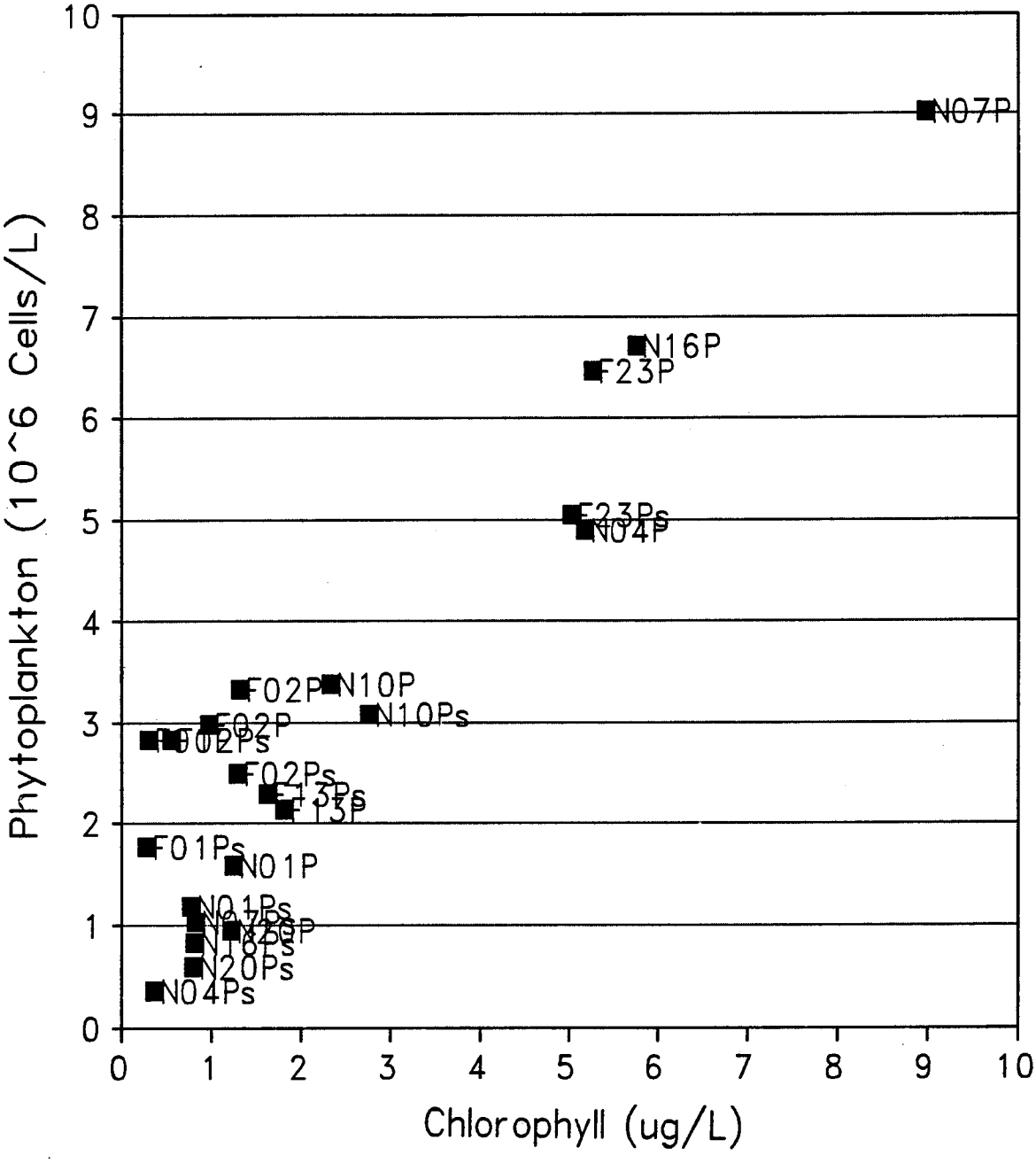



**Figure 3-27 Total phytoplankton abundance vs. extracted chlorophyll at BioProductivity stations in April 1992. Data are given in Appendices A and F.**

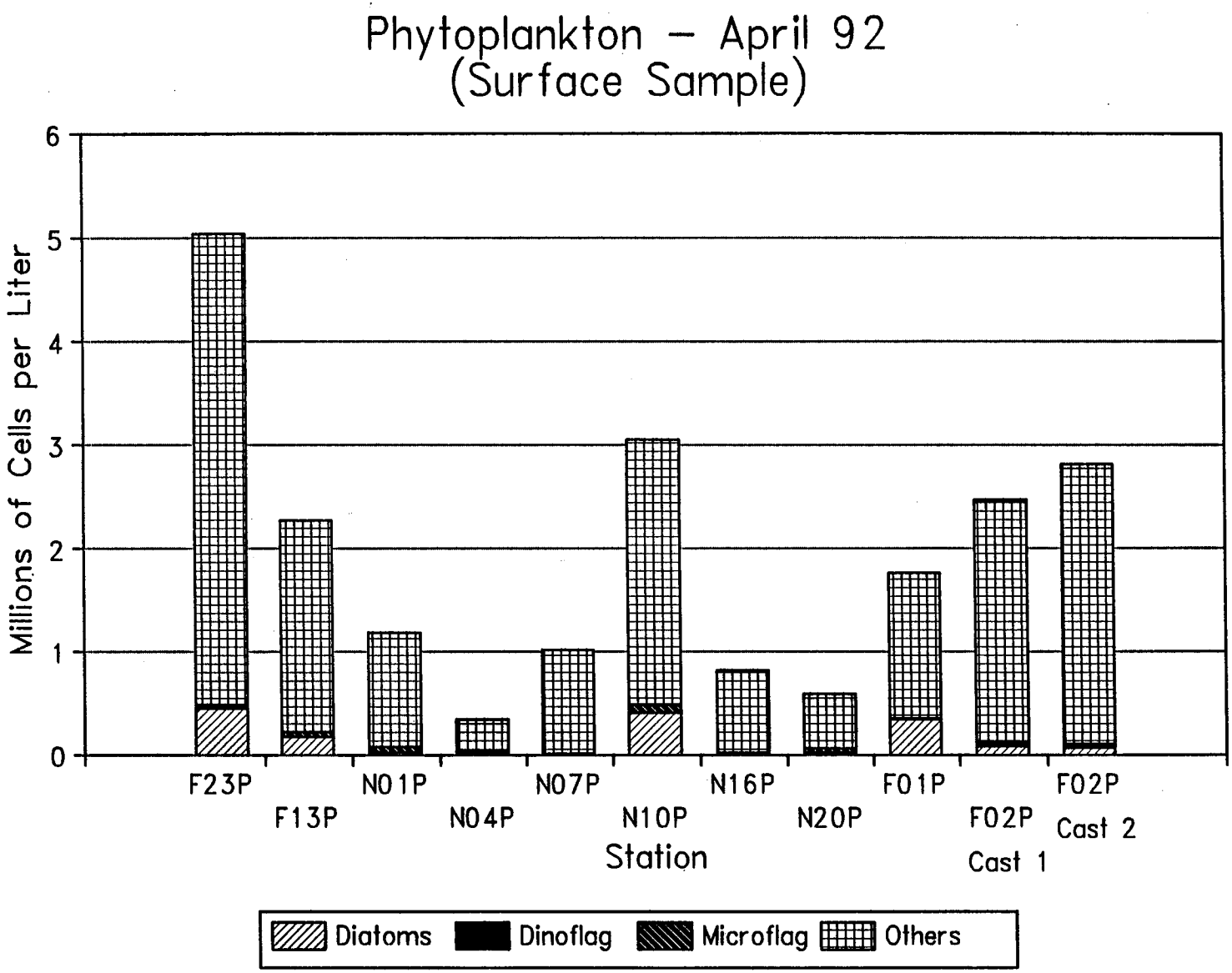



**Figure 3-28** **Total phytoplankton abundance, by taxonomic groups, at Bioproductivity stations in April 1992. Data are given in Appendix F.**

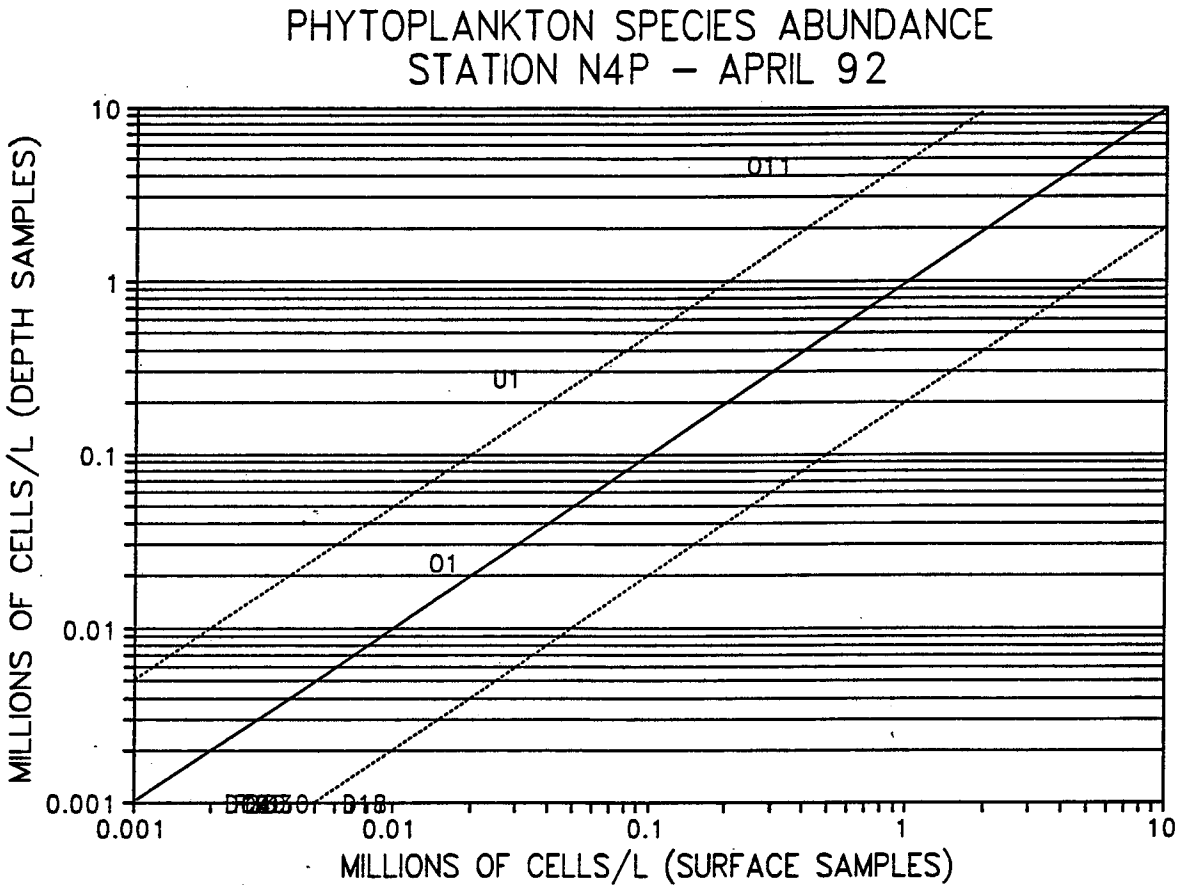



**Figure 3-29 Comparison of phytoplankton taxonomic composition of surface and deeper samples at station N4P in April 1992. Full species codes are given in Appendix F, but the alphabetical prefix indicates the following: D= diatom, F= dinoflagellate, U= microflagellates, O= other. Solid line shows 1:1 relationship, dotted lines show 1:5 and 5:1 isopleths.**

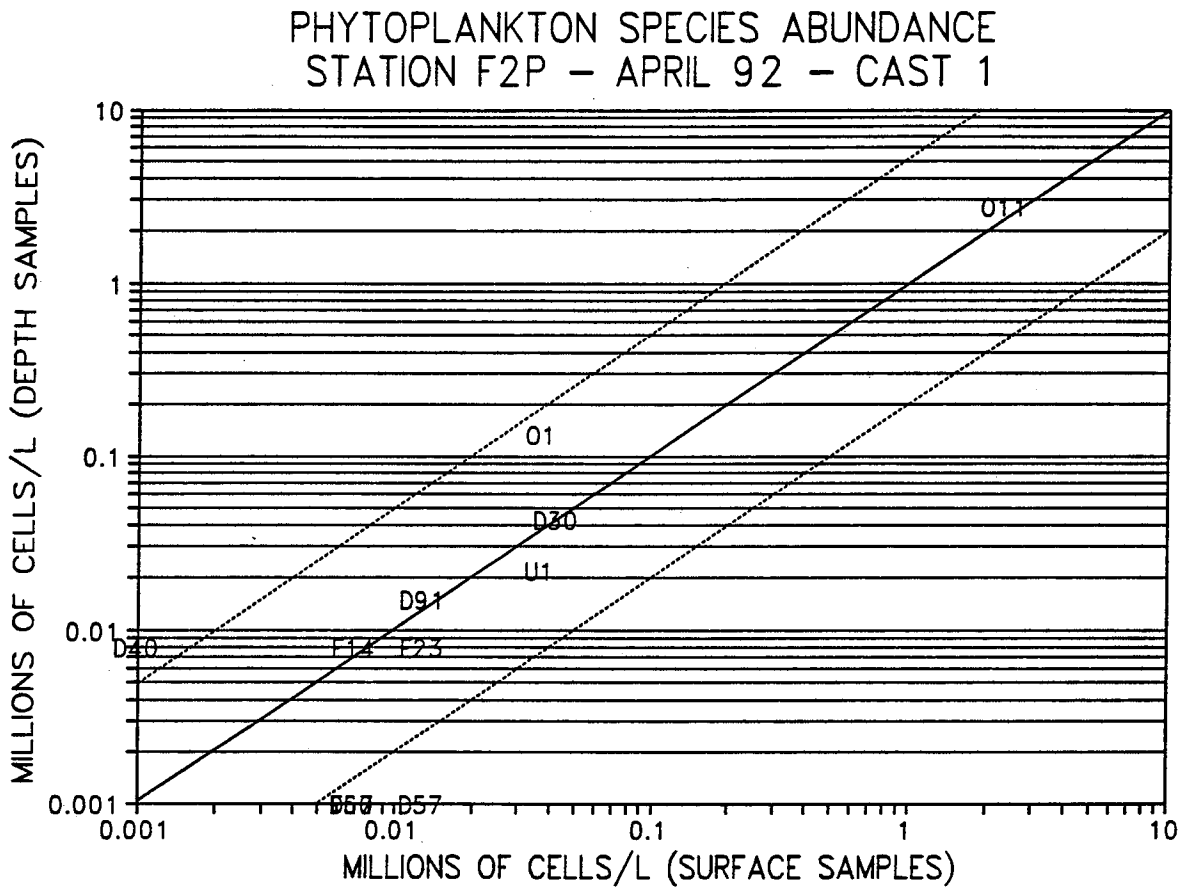



**Figure 3-30a** **Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F2P in April 1992 on cast 1. Species codes are given in Appendix F.**

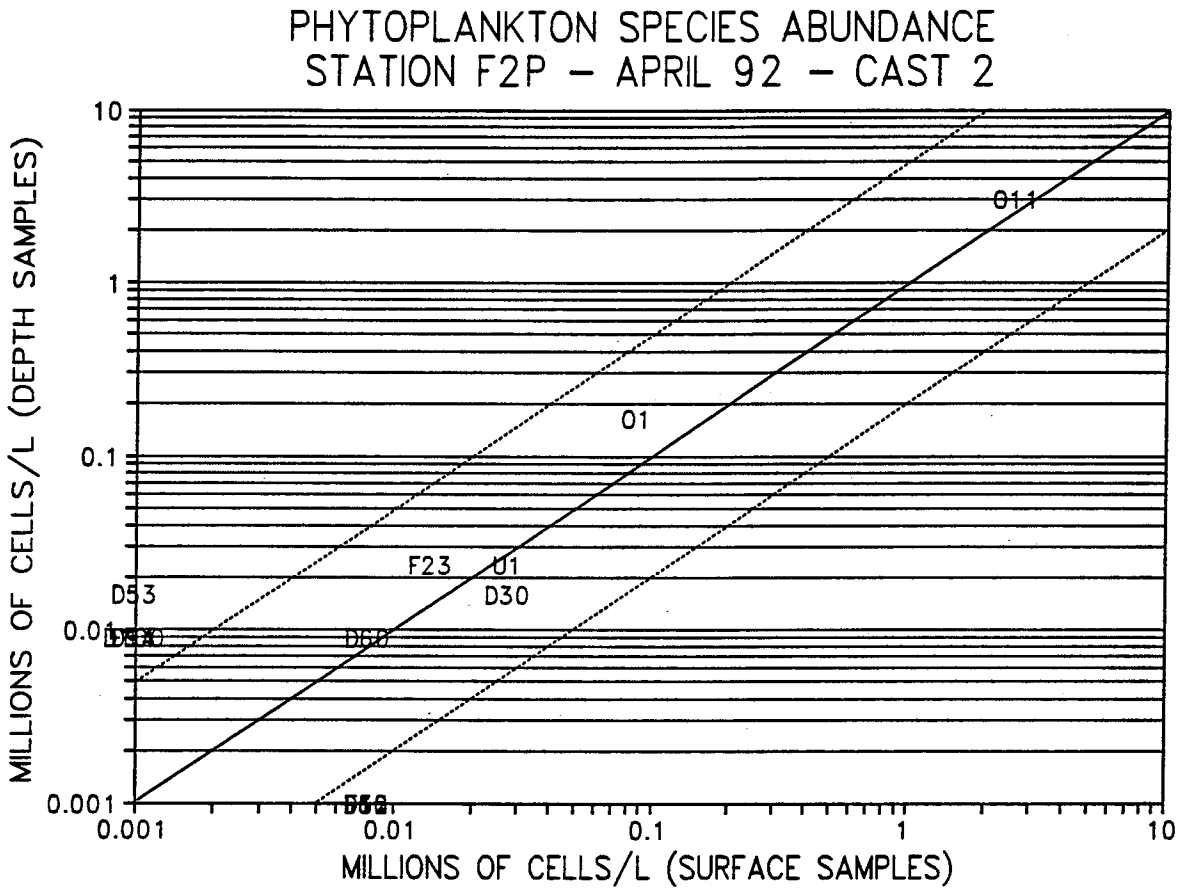



**Figure 3-30b** **Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F2P in April 1992 on cast 2. Species codes are given in Appendix F.**

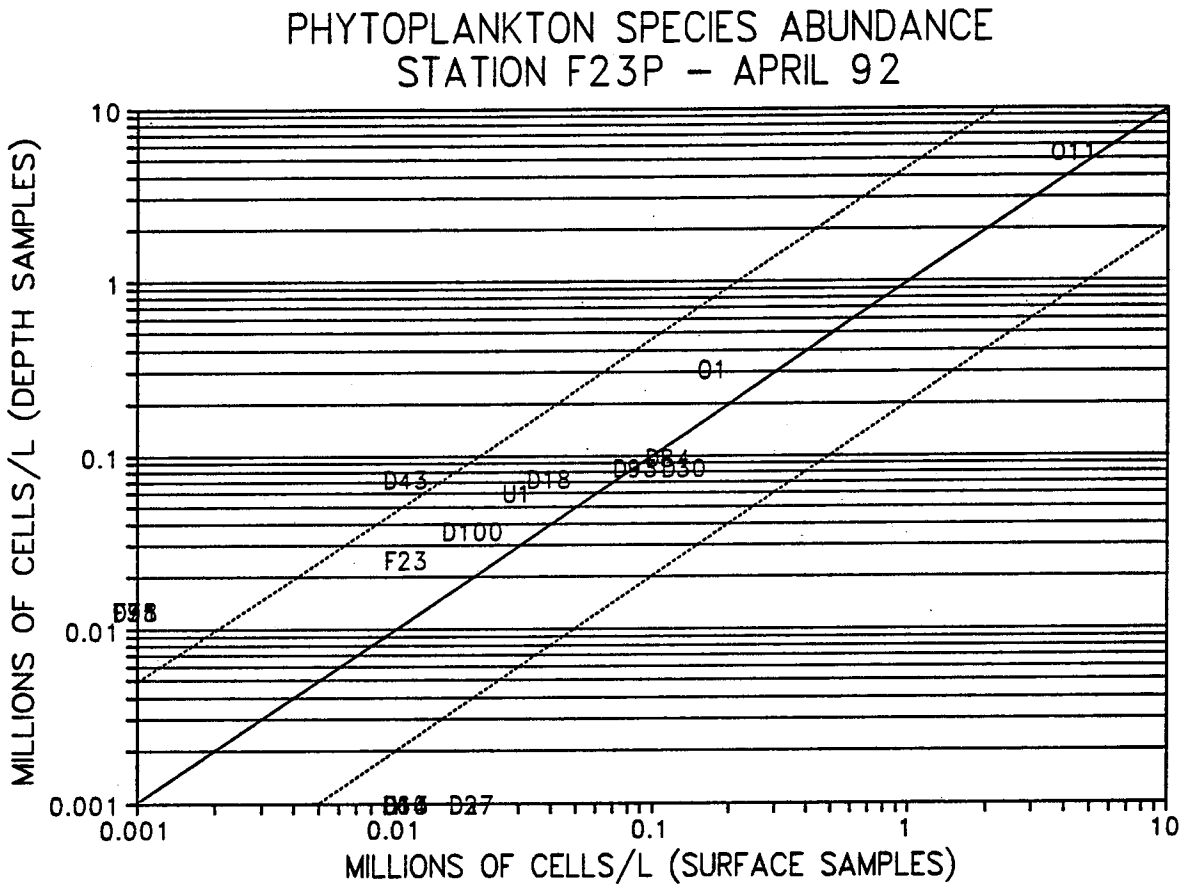



**Figure 3-31 Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F23P in April 1992. Species codes are given in Appendix F.**

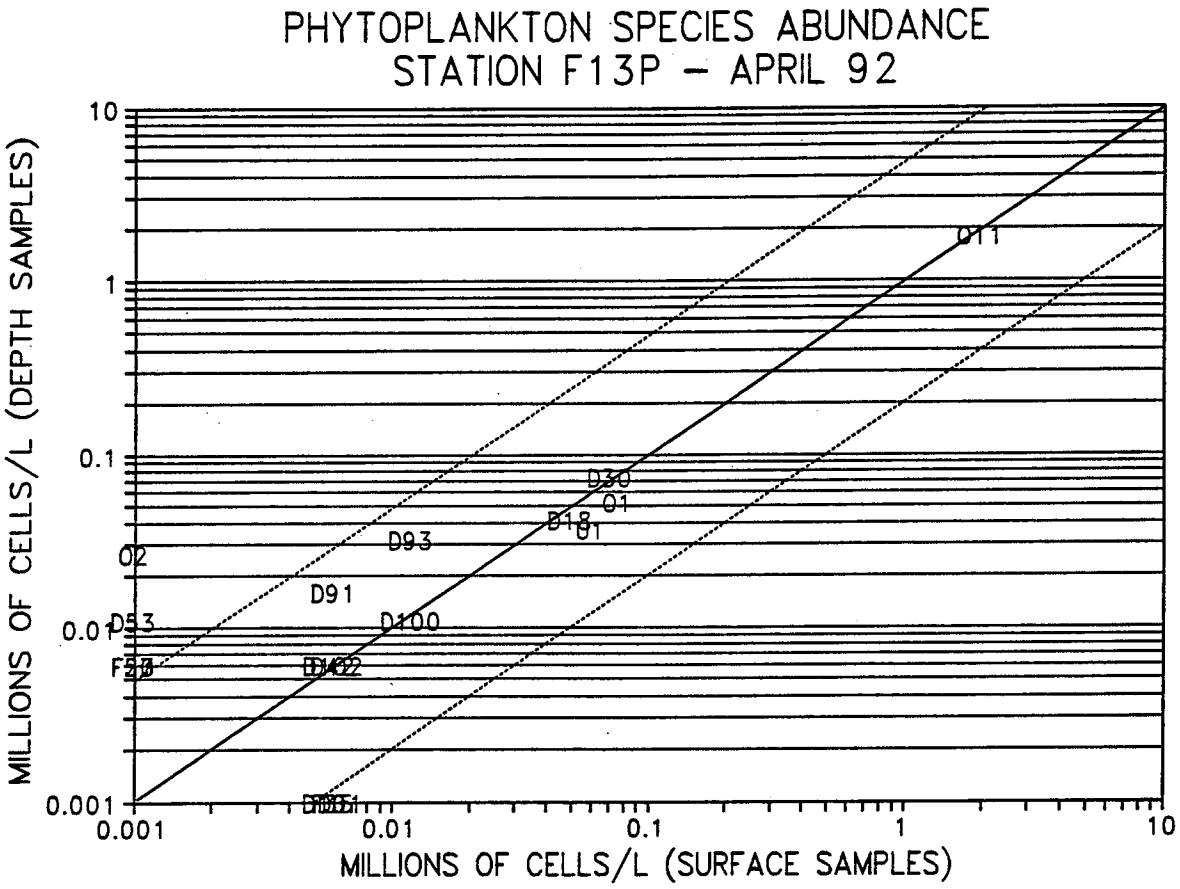



**Figure 3-32 Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F13P in April 1992. Species codes are given in Appendix F.**

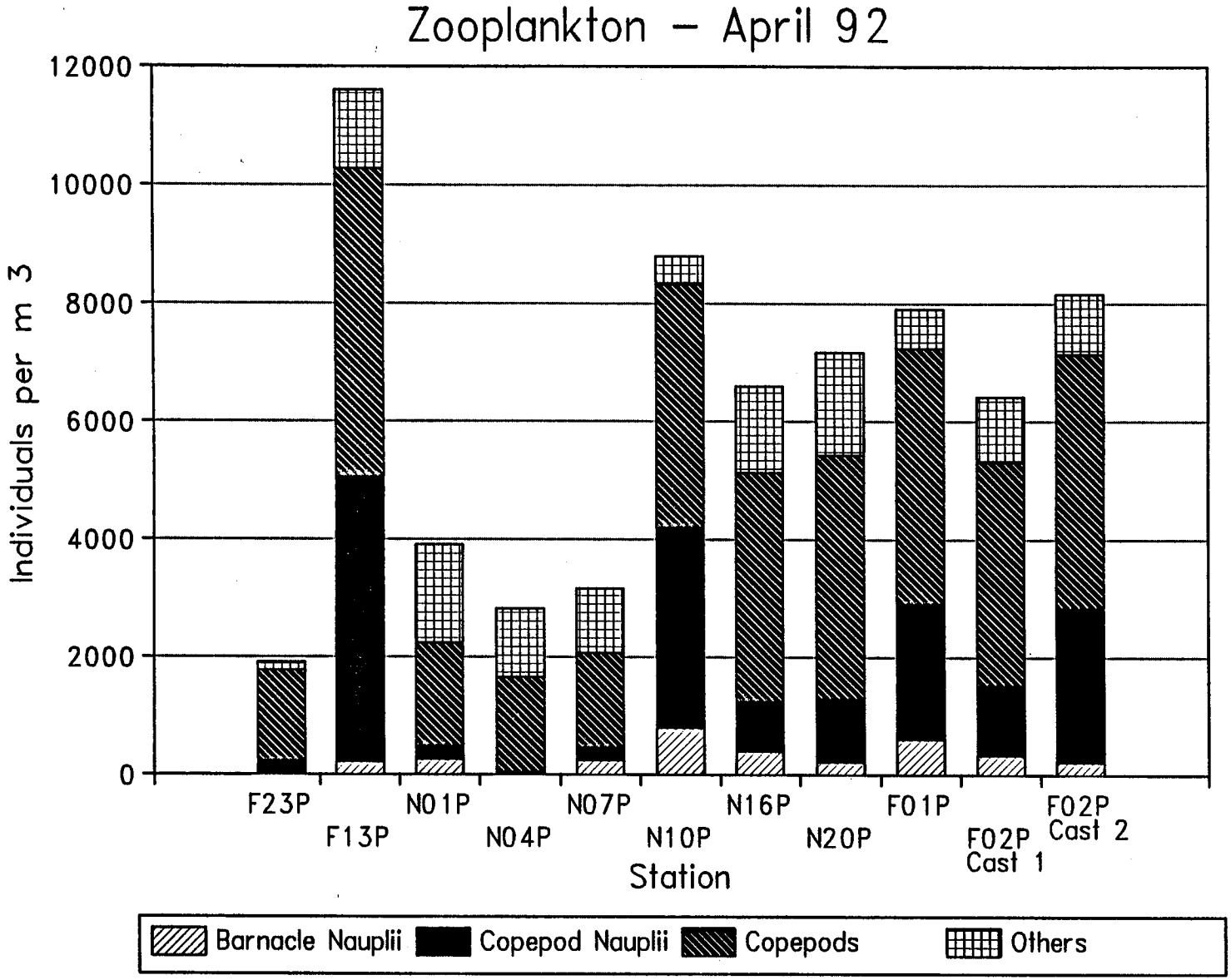



**Figure 3-33 Zooplankton abundance, by groups, at BioProductivity stations in April 1992. Data are given in Appendix G.**

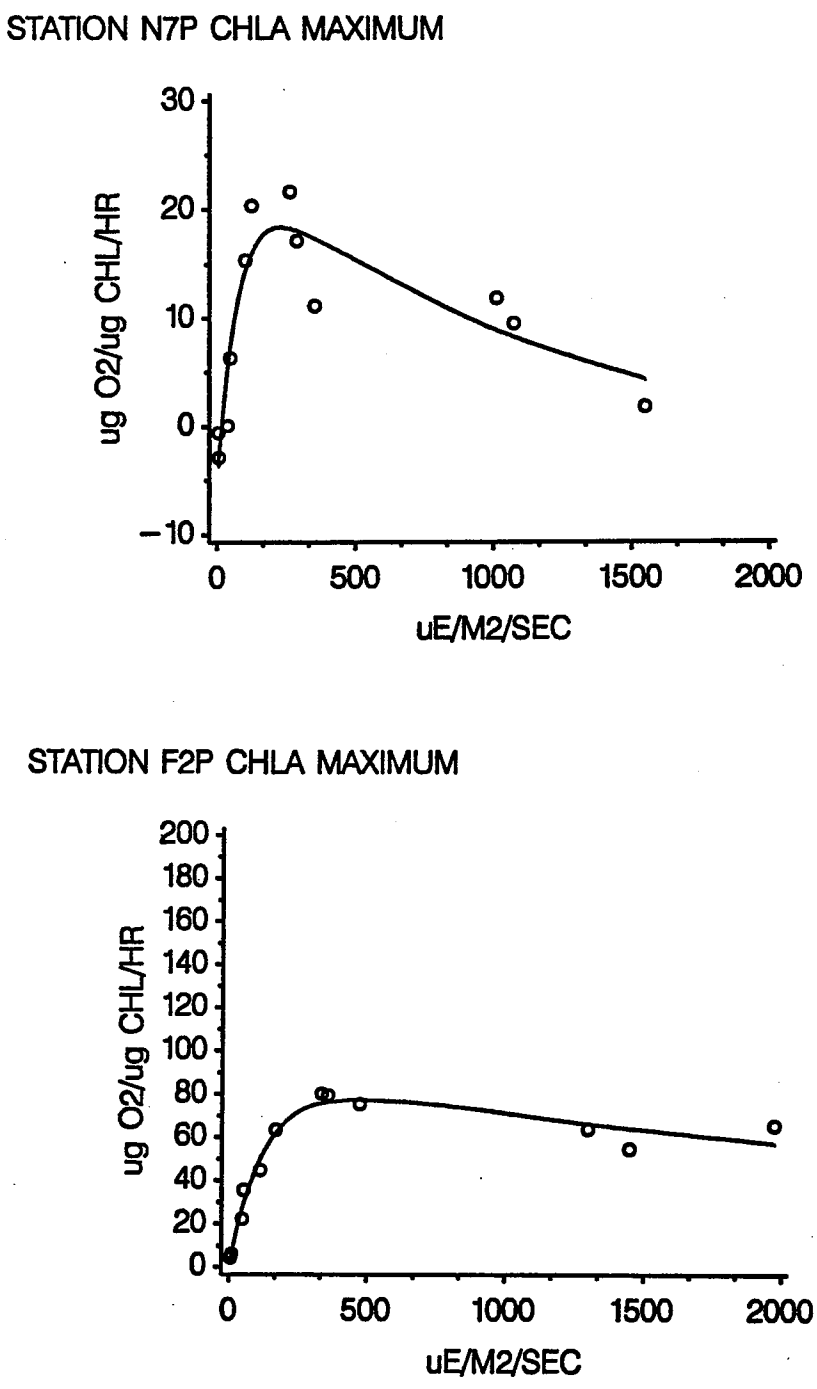



**Figure 3-34 Selected net production (P) vs. irradiance (I) curves in April 1992. Data are chlorophyll-normalized rates see Appendix E.**

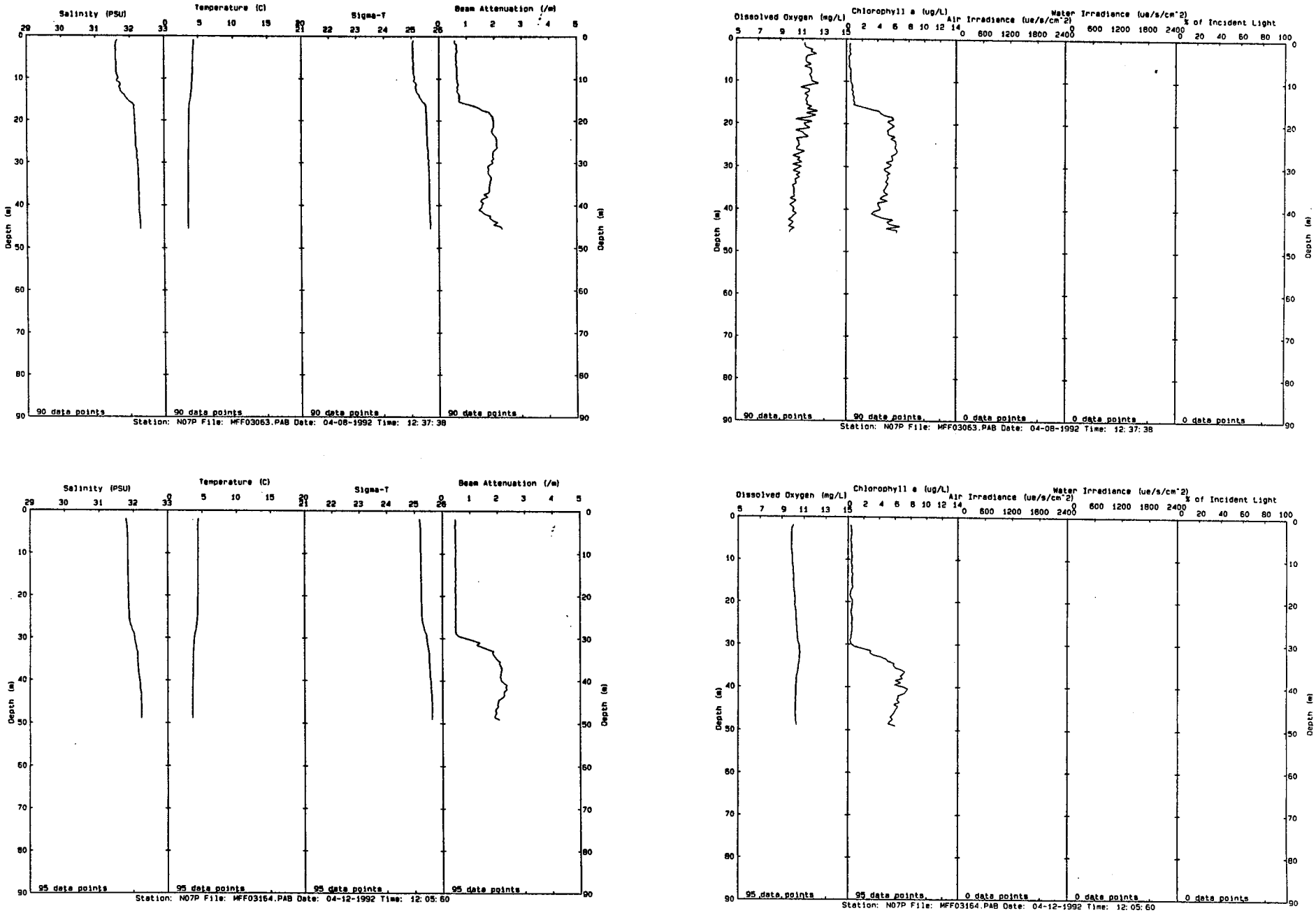



**Figure 3-35 Profiles at Station N07P on April 8 (top) and April 12 (bottom).**

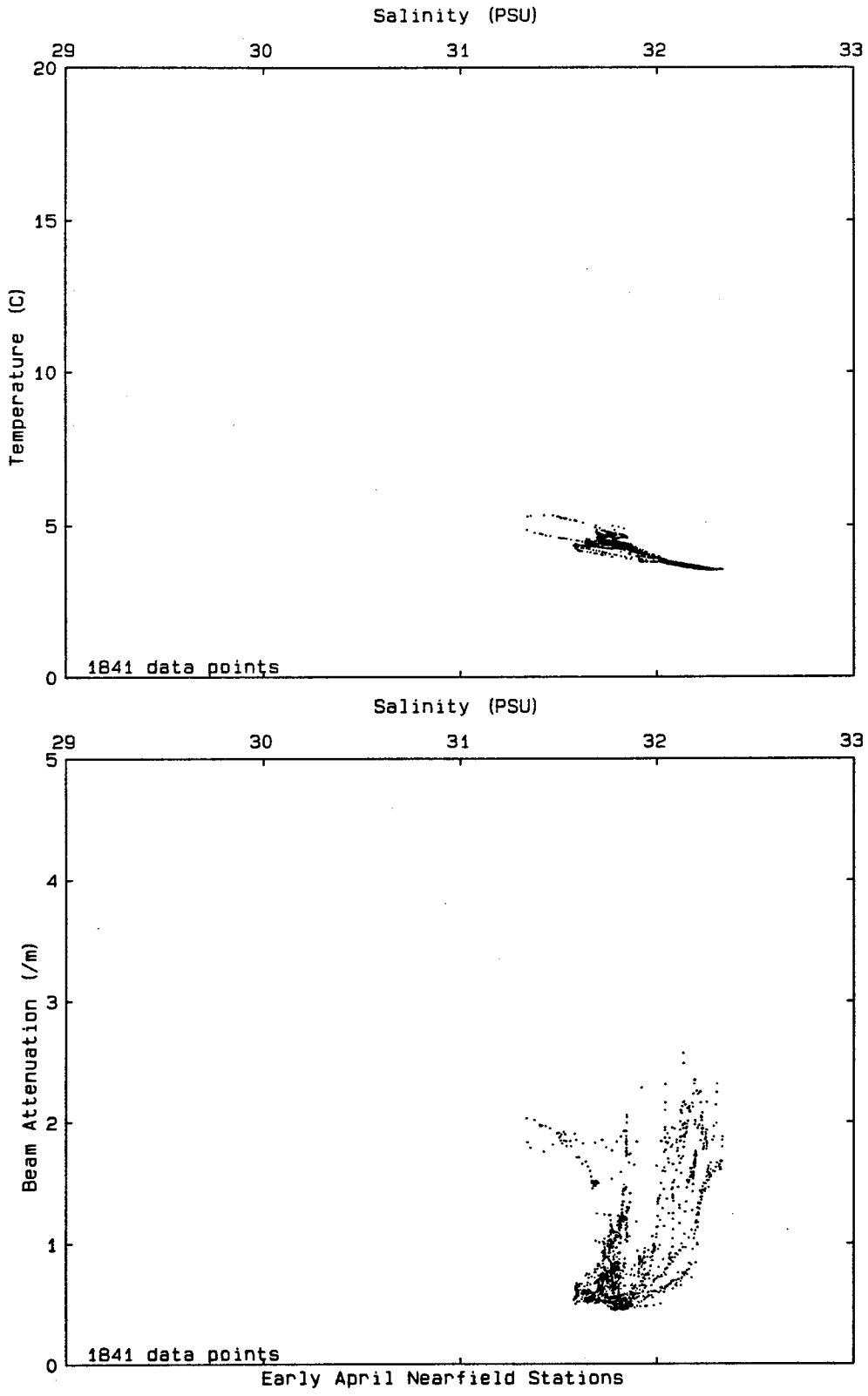



**Figure 3-36a Scatter plots for nearfield stations only in April 1992. Compare to Figure 3-17a.**

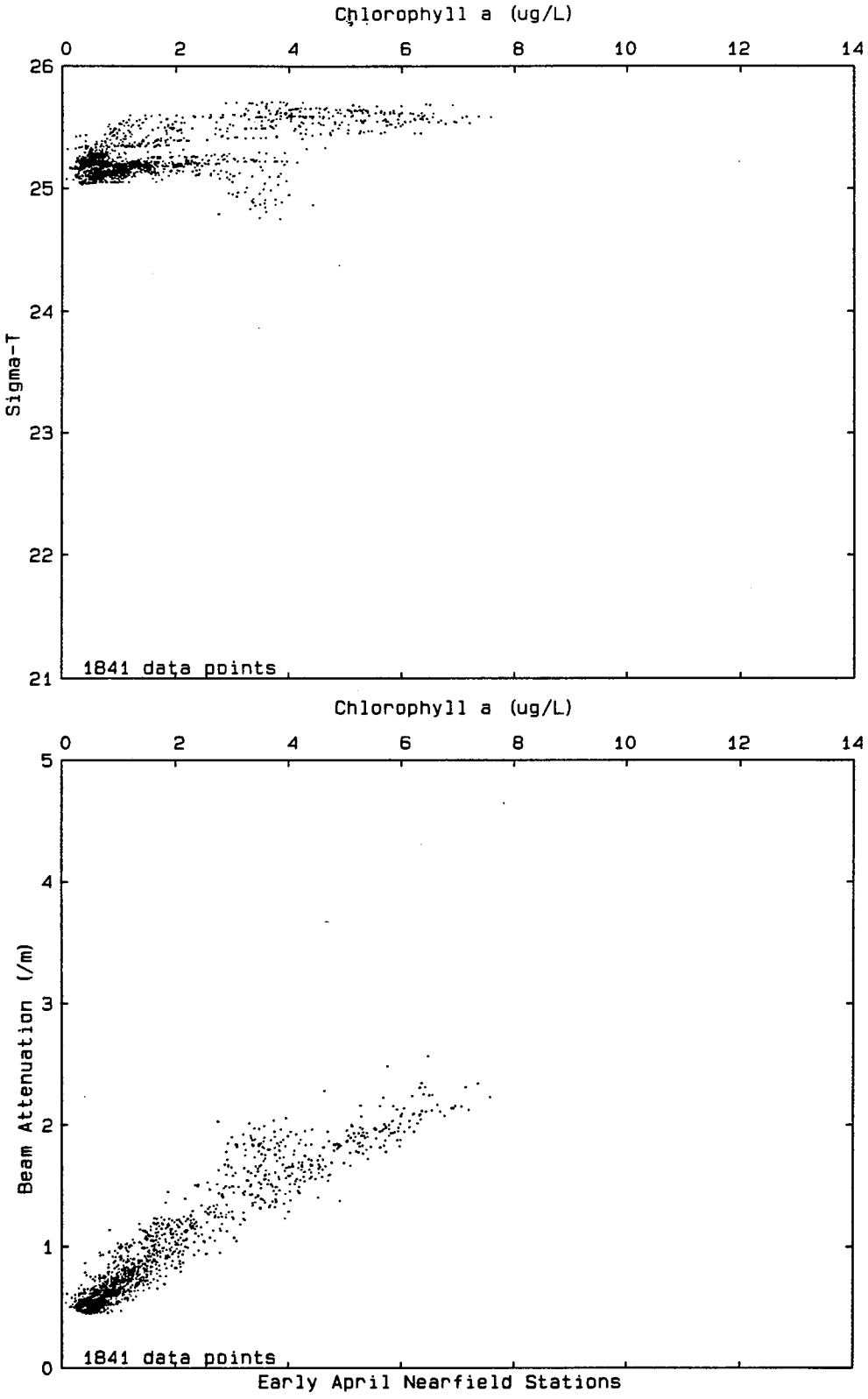



**Figure 3-36b** **Scatter plots for nearfield stations only in April 1992. Compare to Figure 3-17b. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

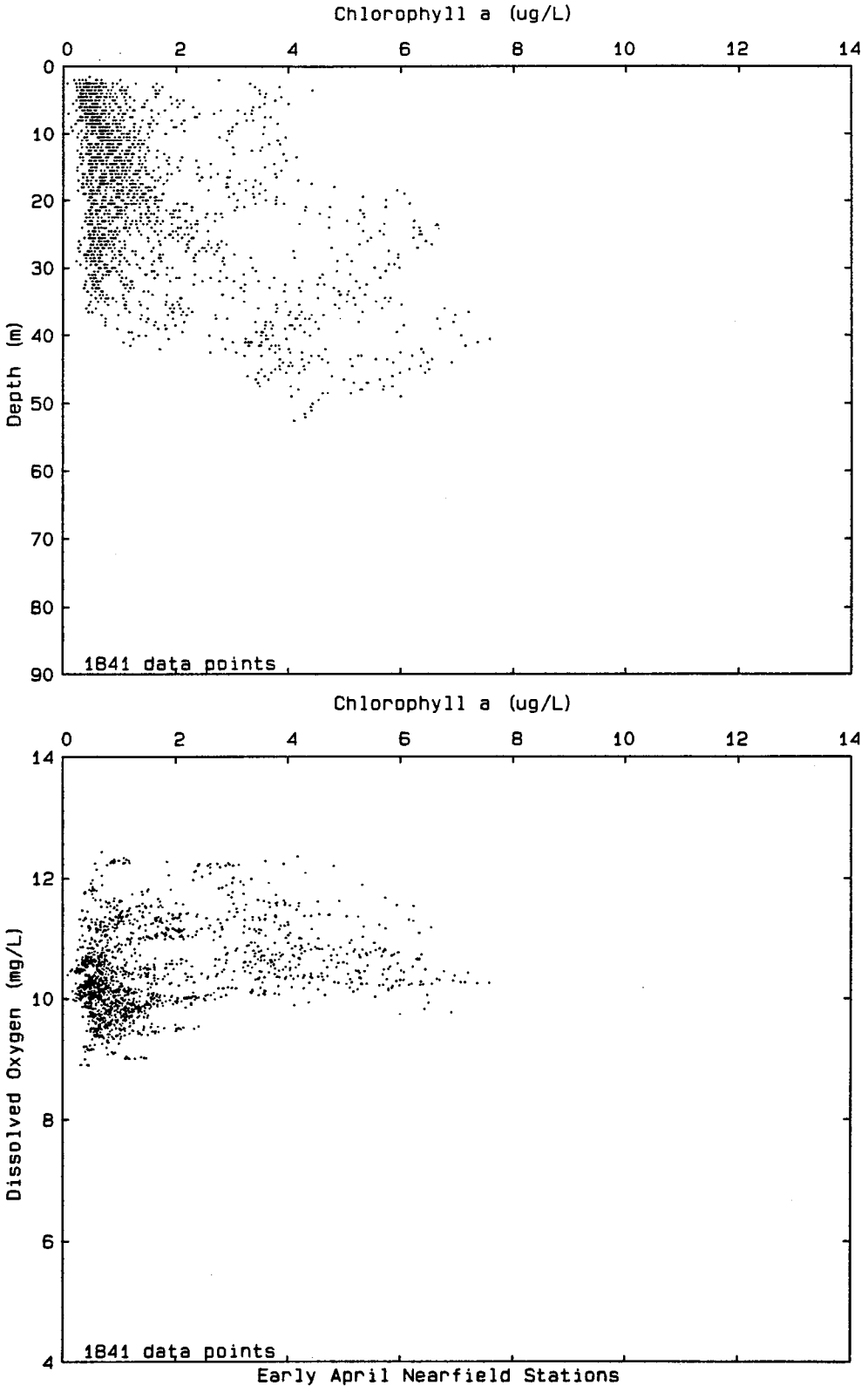



**Figure 3-36c** **Scatter plots for nearfield stations only in April 1992. Compare to Figure 3-17c. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

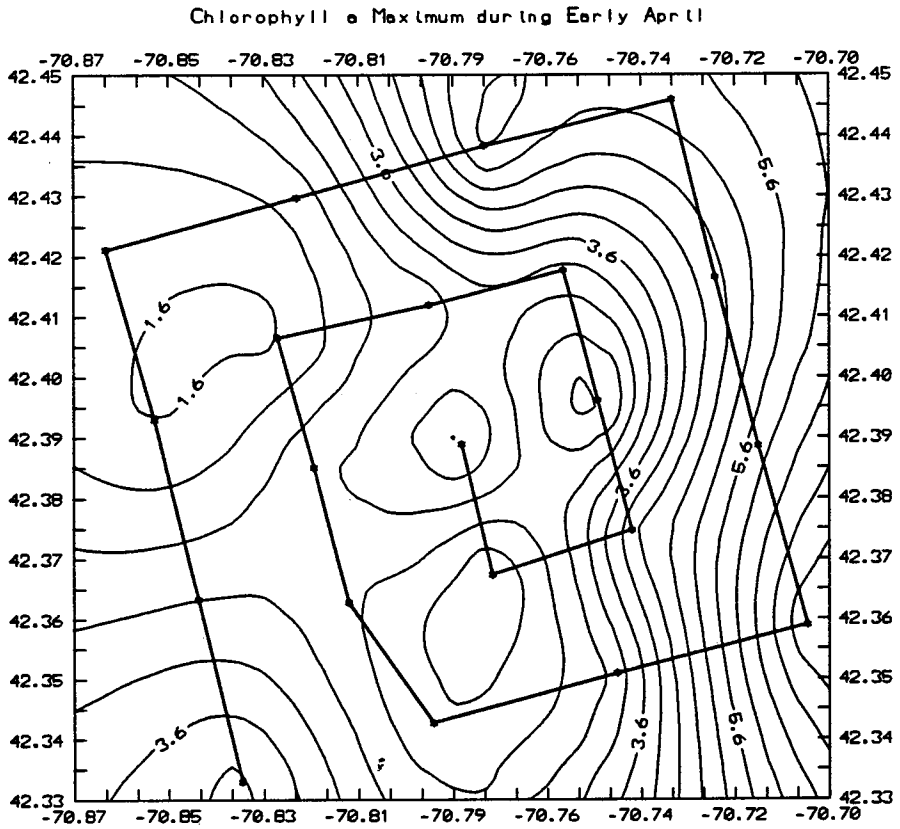



**Figure 3-37** **Chlorophyll maximum at each nearfield station from vertical profile day (Appendix B). Track shows sampling, starting at southwest corner of nearfield. Chlorophyll maximum may not be at the same depth at different stations. The contour interval is 0.4 $\mu g\ L^{-1}$.**

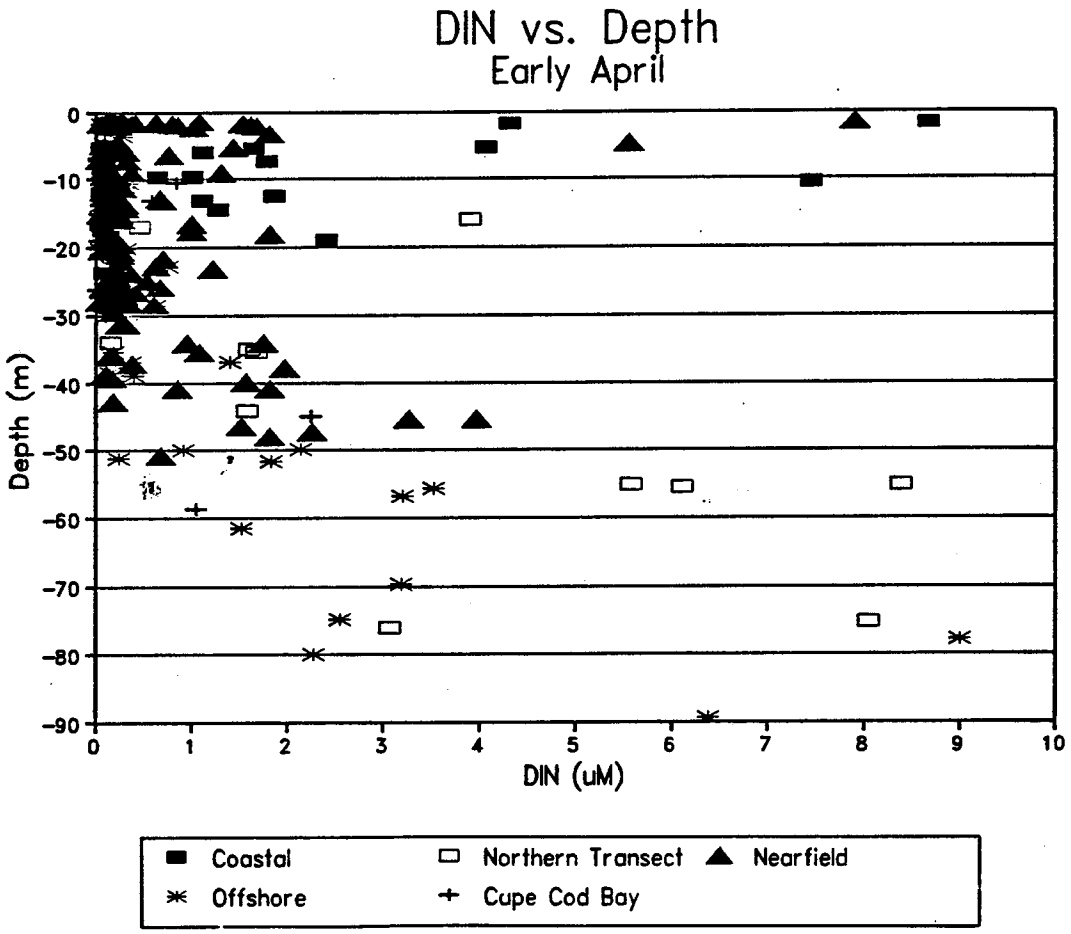



**Figure 3-38 DIN vs. Depth in April 1992.**

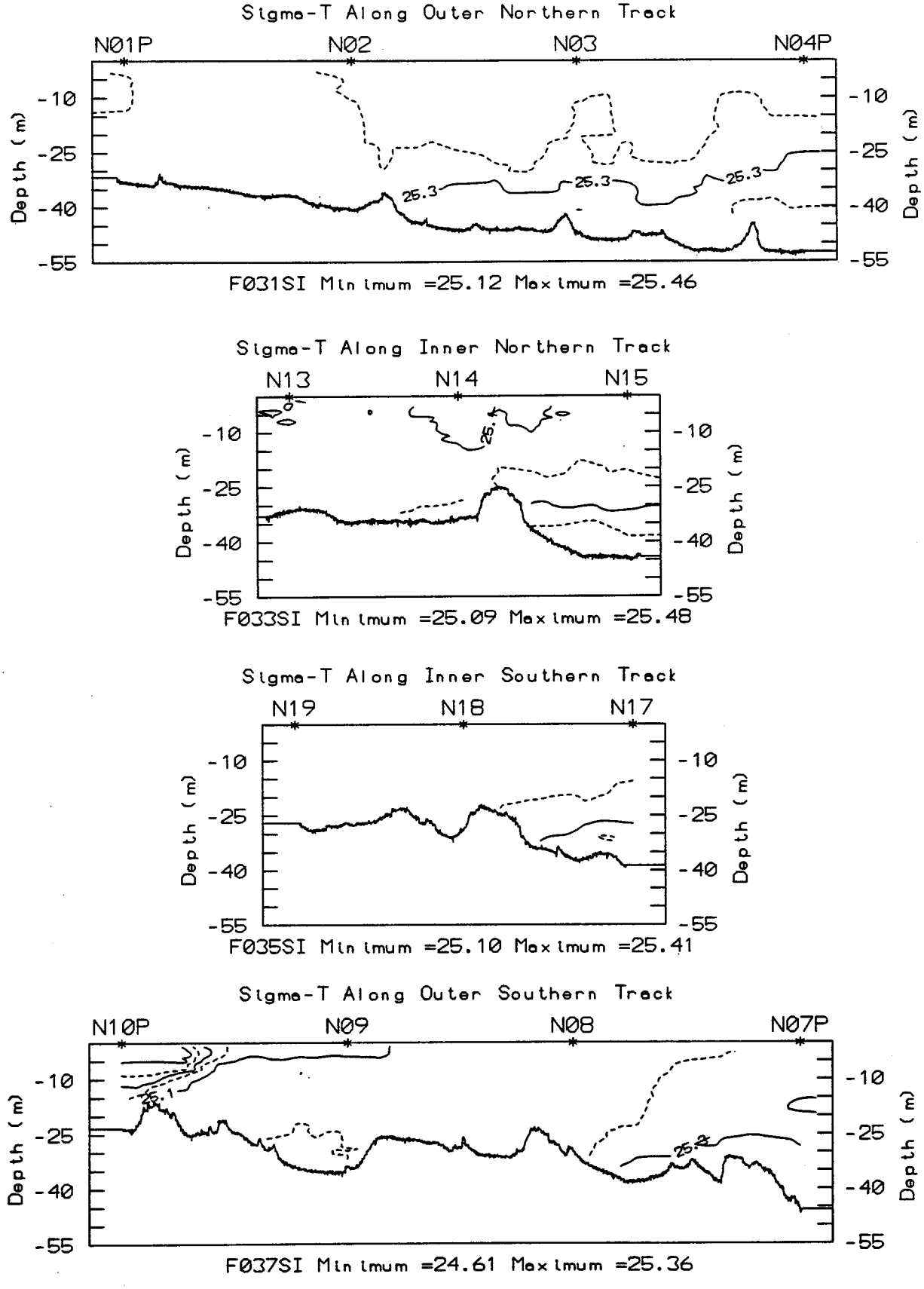
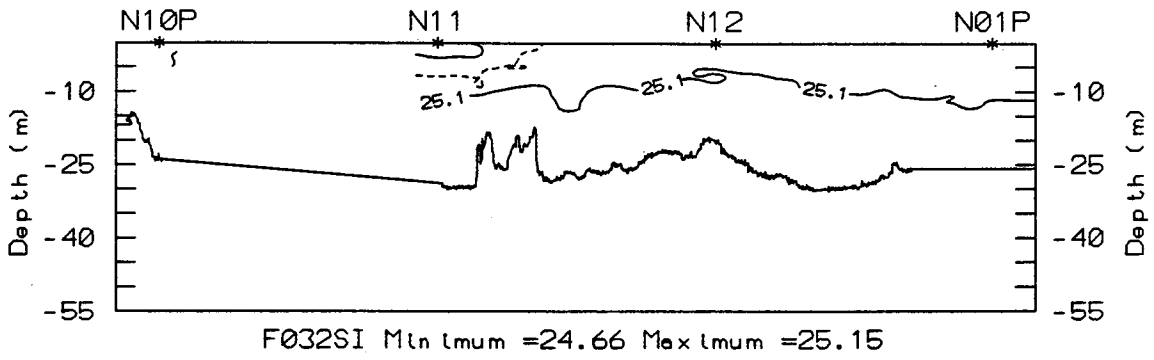



**Figure 3-39a** **Vertical section contours of $\sigma_T$ generated for tow-yos in April 1992. The view is towards the North. The contour interval is 0.1 $\sigma_T$.**




No data were collected along Inner Western Track and Inner Eastern Track.

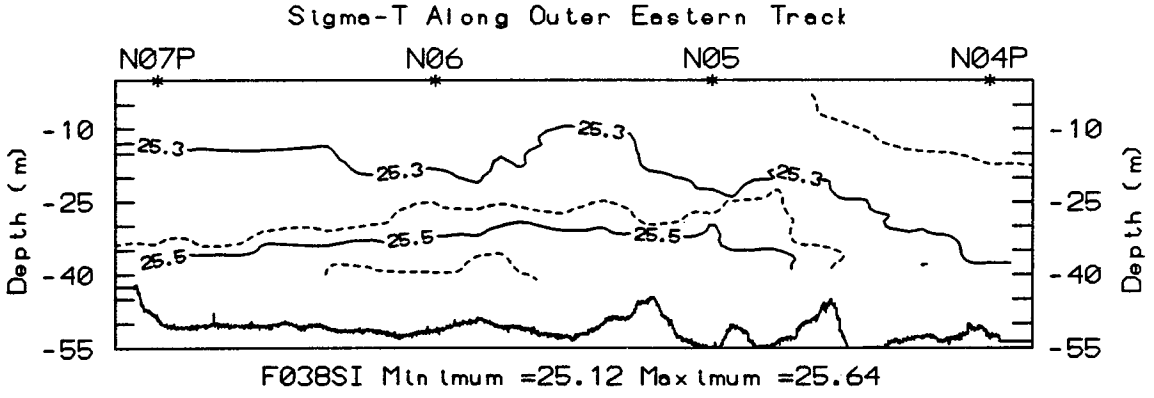



**Figure 3-39b** **Vertical section contours of $\sigma_T$ generated for tow-yos in April 1992. The view is towards Boston Harbor.**

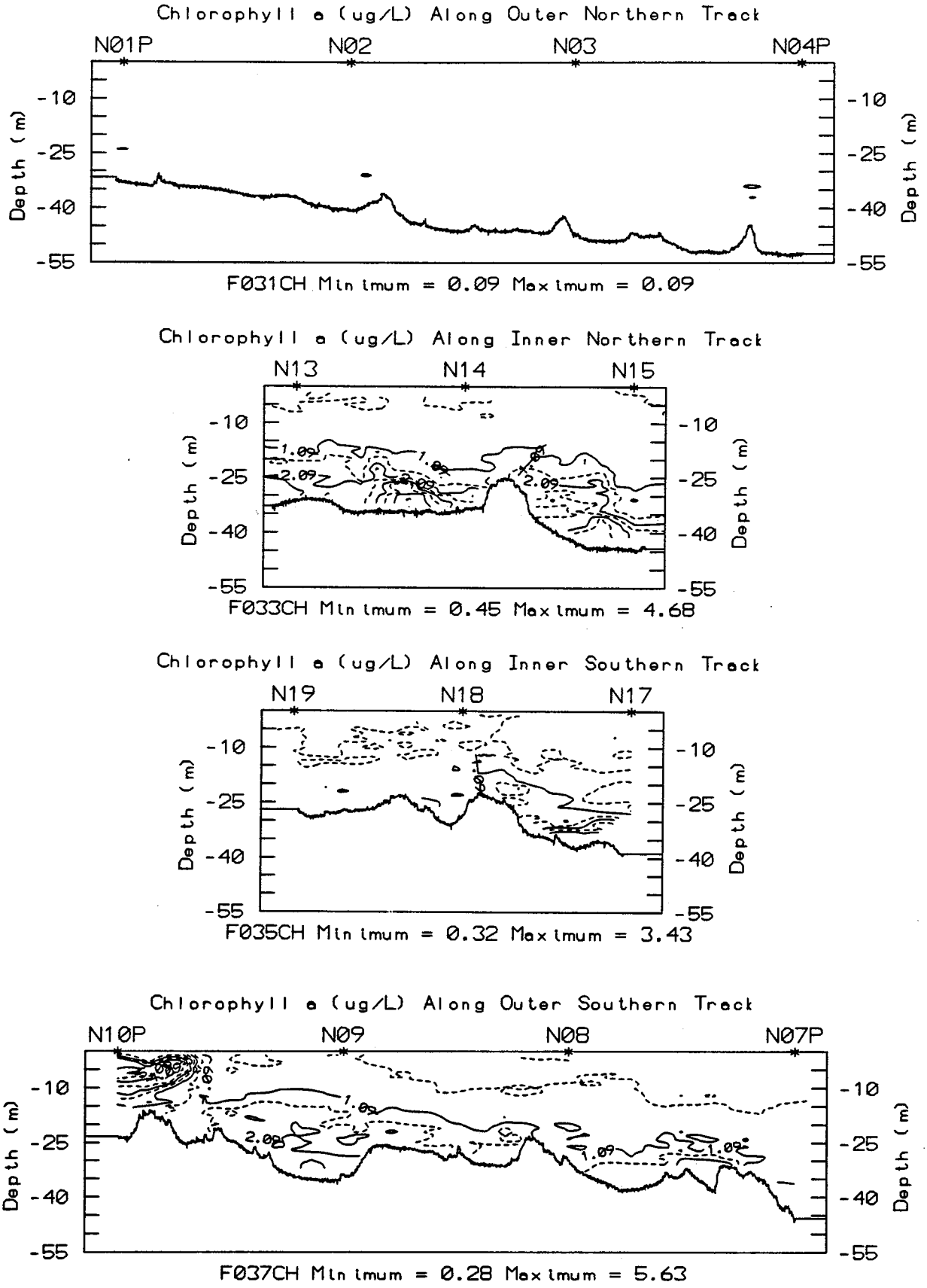
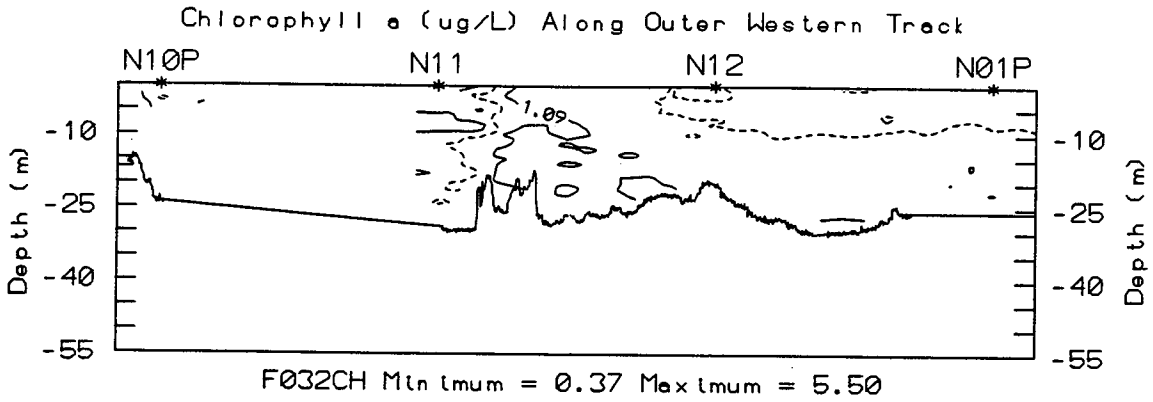



**Figure 3-40a** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in April 1992. The view is towards the North. The contour interval is 0.5 $\mu$g $L^{-1}$.**




No data were collected along Inner Western Track and Inner Eastern Track.

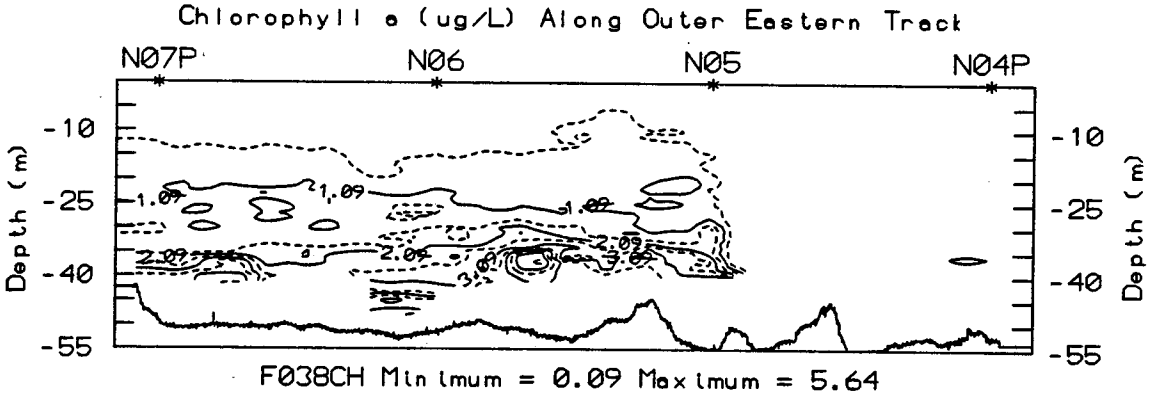



**Figure 3-40b** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in April 1992. The view is towards the Boston Harbor.**

# 4.0 LATE APRIL NEARFIELD SURVEY (#4) RESULTS

## 4.1 Distribution of Water Properties from Vertical Profiling

Data from the vertical profiling day (April 29) are given in Appendix A (upcast bottle measurements) and Appendix B (downcast vertical profiles). Surface temperatures had increased slightly since the previous survey about two weeks prior. Surface temperatures were near 6°C and most of the water column was above 4.5°C; only the deepest water >40 to 50 m was colder than 4°C. The associated range in salinity was from about 30-31 PSU at the surface and >32 PSU in the deepest water (Figure 4-1a). Due to a warmer and fresher surface, the seasonal pycnocline had become stronger, in most cases, since early April (see Appendix B for plots).

Beam attenuation varied little throughout the field and chlorophyll was low, only exceeding 1 $\mu g\ L^{-1}$ in a few profiles (Figure 4-1b). The few higher chlorophyll readings were mostly found below 30 m (Figure 4-1c). Figure 4-2 illustrates that this deeper chlorophyll was seen at eastern stations, including N06 and N7P.

Nutrient concentrations (Figures 4-3 and 4-4) were generally lower in the surface 20-40 m, and increased below this. This was most evident for $NO_3$ and $PO_4$. $PO_4$ and $SiO_4$ were, even at the surface, still not depleted, whereas $NO_3$ was. $NH_4$ was mostly well less than 1 $\mu$M. Thus, N/P ratios were generally quite low, as were N/Si ratios. A few $NH_4$ and $SiO_4$ were higher in the surface waters; in the case of either nutrient, these instances were a small fraction of the total samples analyzed and patterns with stations were not striking.

## 4.2 Distribution of Water Properties from Towing

On the towing day (April 30), the full inner box (4 legs) and two legs of the outer box were completed (N01P-N04 and N07P-N10P). These data (see also Appendix D) provide for 4 sections viewed from the South (e.g., Figure 4-5a) and 2 viewed from the East (e.g., Figure 4-5b).
With respect to $\sigma_T$ (Figure 4-5), the formation of vertical density layers and a broad pycnocline (in most cases) from ~10 to 25 m was illustrated. In Figure 4-5a, one can see a distinction between the eastern

and western surface water masses at about the center of each transect, where the pycnocline emerged to the surface, most sharply seen at N18. Indeed, as towing occurred, a surface accumulation of debris, usually indicative of a front between two water masses, was observed visually. Another feature of interest was the parcel of lighter water around N10P. Temperature of this parcel was much higher than the rest of the field, above 7°C and closer to the Harbor which was ~9-10°C around this time. We observed at N21 (at about mid-day) a surface plume of water discharged from drilling operations and headed west, observable from some distance. It is unknown the extent to which this may have created some of the apparently frontal conditions and surface lenses of warmer water seen in these transects.

With respect to biology, as indicated by chlorophyll, these surface thermal and density gradients varying in the horizontal, seemed to have little influence on the field, mostly depleted of DIN and with low chlorophyll. With one area exception (see below) the highest chlorophyll detected was again at depth. Towing may not have been deep enough to capture the deep surface chlorophyll maximum above 1 $\mu g\ L^{-1}$ that had been seen at depth the previous day; however, the outer east track was not towed, only N07P, and relatively high chlorophyll was suggested at depth there.

The physical feature that was not transparent to biology was the warmer, fresher, lighter water at the southwestern corner of the nearfield (N10P), which had been seen in a number of previous surveys. Chlorophyll in this parcel exceeded 3 $\mu g\ L^{-1}$ (Figure 4-6a).

### 4.3 Analysis of Small-Scale Variability

The preceding sections emphasized some of the spatial variability, horizontally and vertically, through the region. As in previous months, we noted strong inshore-offshore distinctions. But one of the most striking results on variability relates to time.

On day 1 of the survey, the first station occupied was N10P (0751 EST) and little chlorophyll (Figure 4-2), nor much of a density gradient, was seen (Figure 4-7). These results contrast with the towing day data (Figures 4-5 and 4-6) where sharp stratification and the highest chlorophyll fluorescence of the two-day cruise were noted. For the tow day, N10P was occupied at about 1800 h. On the first day, high tide was about 0839 h and low tide ~1443 h, so N10P was visited very near full flood, when

water would have been pushed into the Harbor. In contrast, the towing day visited the location a few hours after dead low, and most likely sampled some of the ebb water coming out of the Harbor.

We believe the results of this survey (and others in this report) illustrate the sensitivity of the southwest corner of the nearfield in particular, with respect to water quality, to small-scale water motion associated with tidal dynamics.

### 4.4 Water Types, as Related to Nutrients, Fluorescence, and Dissolved Oxygen

Most of the nearfield was low in dissolved inorganic nitrogen and although vertical and horizontal water mass features were suggested, phyto-plankton biomass (as fluorescence) did not appear to vary strongly with physical variations. The exceptions included: some deep chlorophyll, presumably a continued accumulation of sinking cells that was initiated in early April (see Section 3), and an intrusion of inshore water into the nearfield on day 2. Unfortunately nutrients were not sampled at that time. In general, dissolved oxygen (as measured by sensor, Figure 4-1) showed a fairly small range of values, for the most part near saturation.

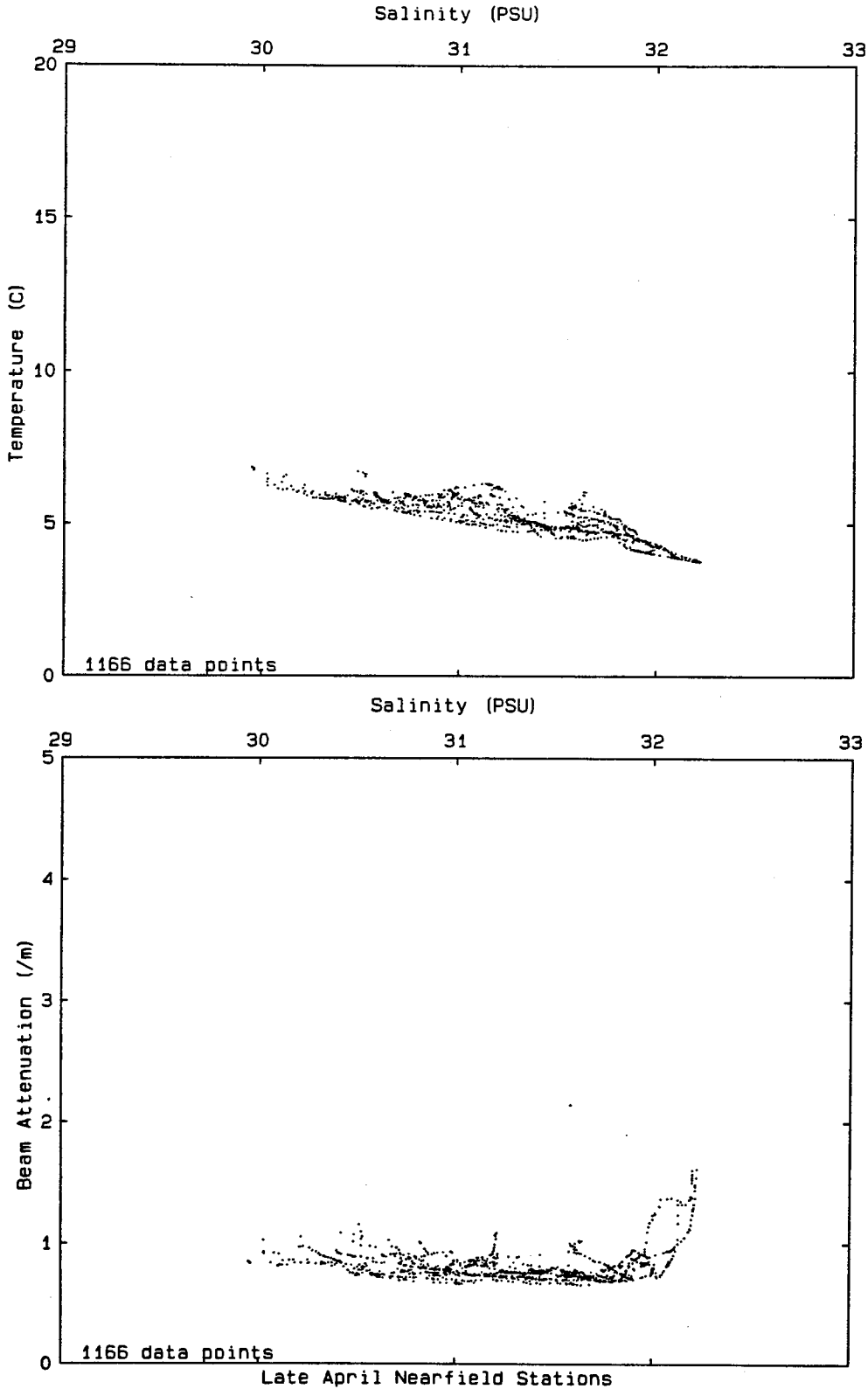



**Figure 4-1a** Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in late April 1992. Individual station casts that were used to produce this composite are in Appendix B.

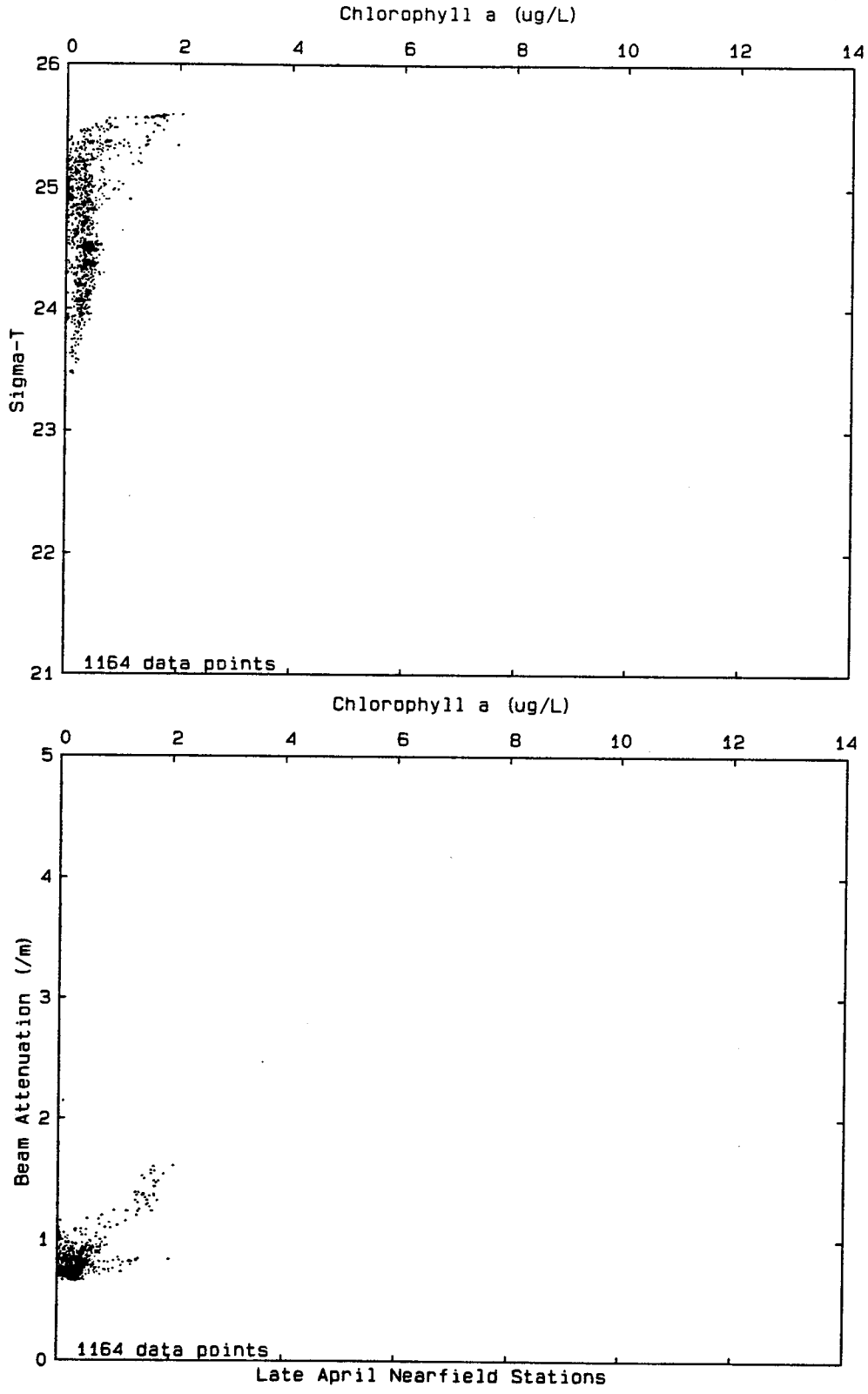



**Figure 4-1b** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in late April 1992. Individual station casts that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

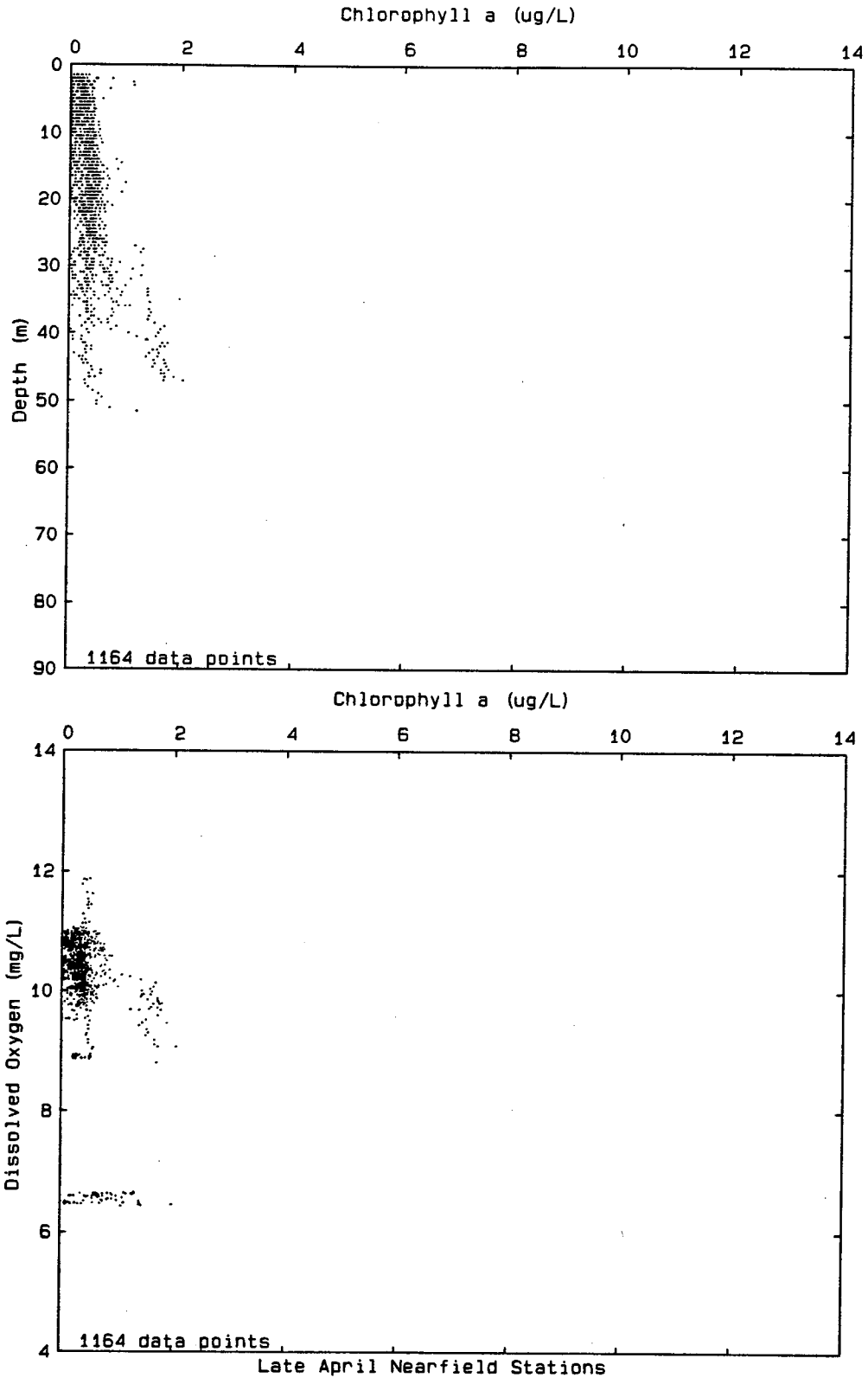



**Figure 4-1c** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in late April 1992. Individual station casts that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

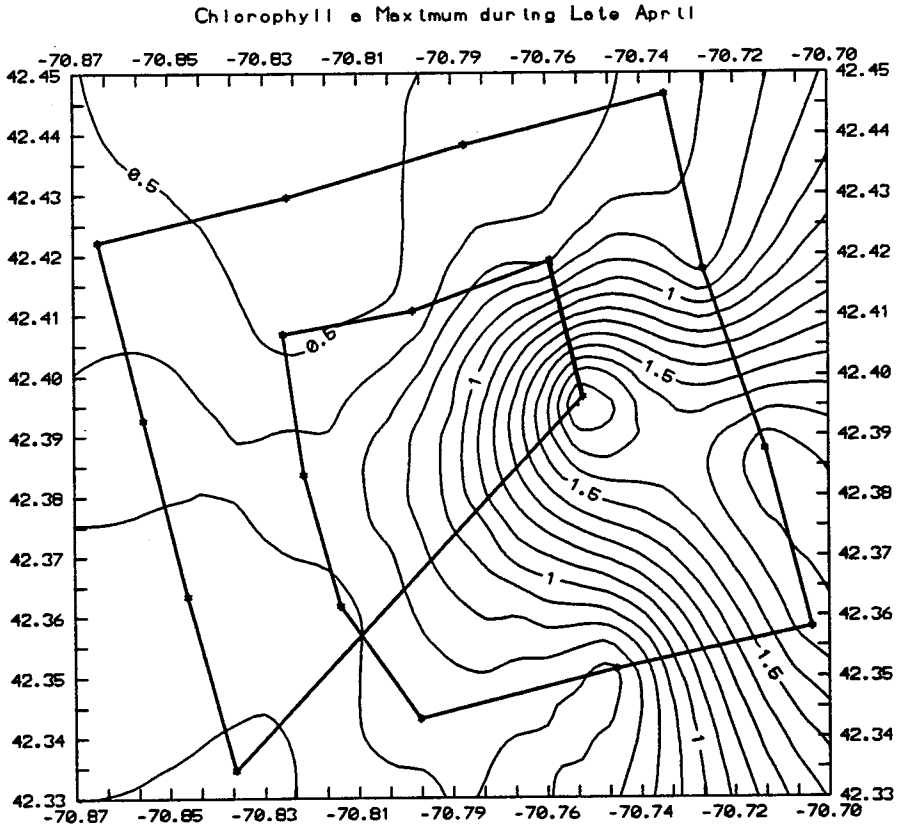
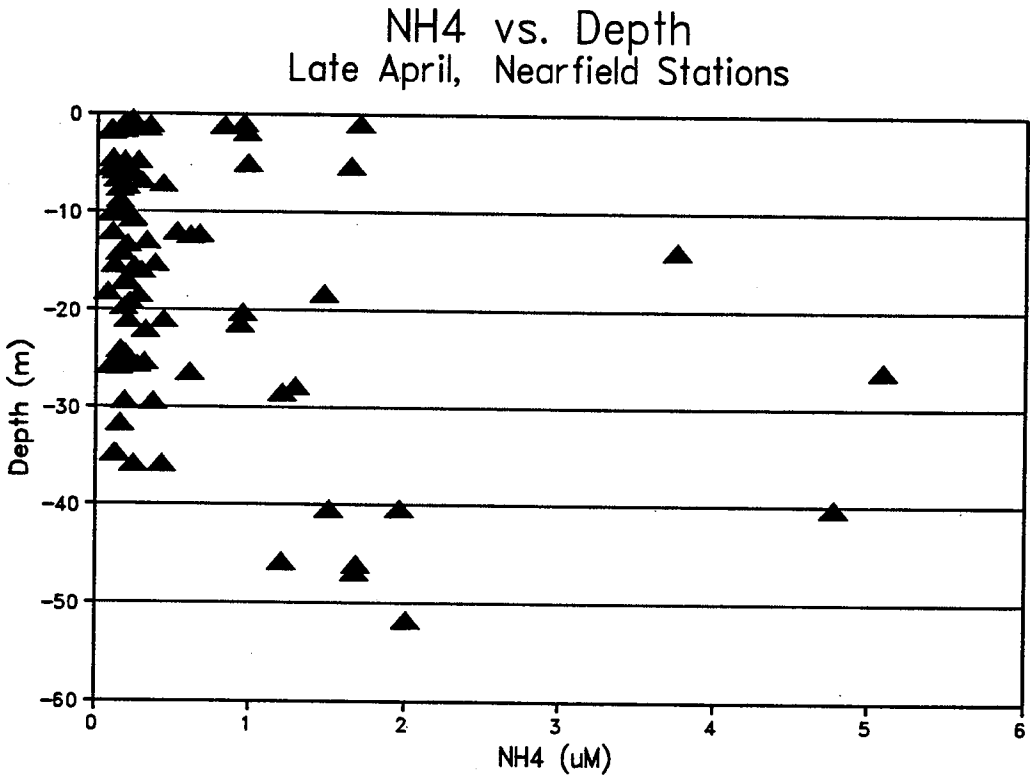



**Figure 4-2** **Chlorophyll maximum at each nearfield station from vertical profile day (Appendix B). Track shows sampling, starting at southwest corner of nearfield and proceeding clockwise to spiral into the middle of the field. Not all 21 stations were sampled. Chlorophyll maximum may not be at the same depth at different stations.**



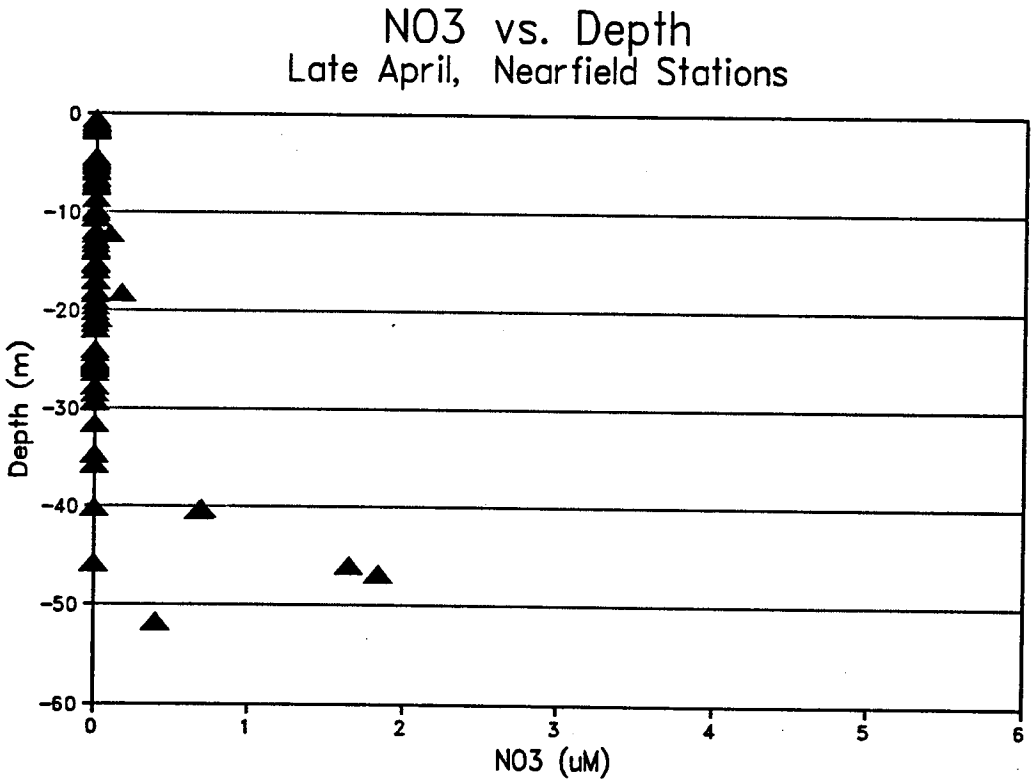




**Figure 4-3 $NH_4$ and $NO_3$ vs. depth in late April 1992.**

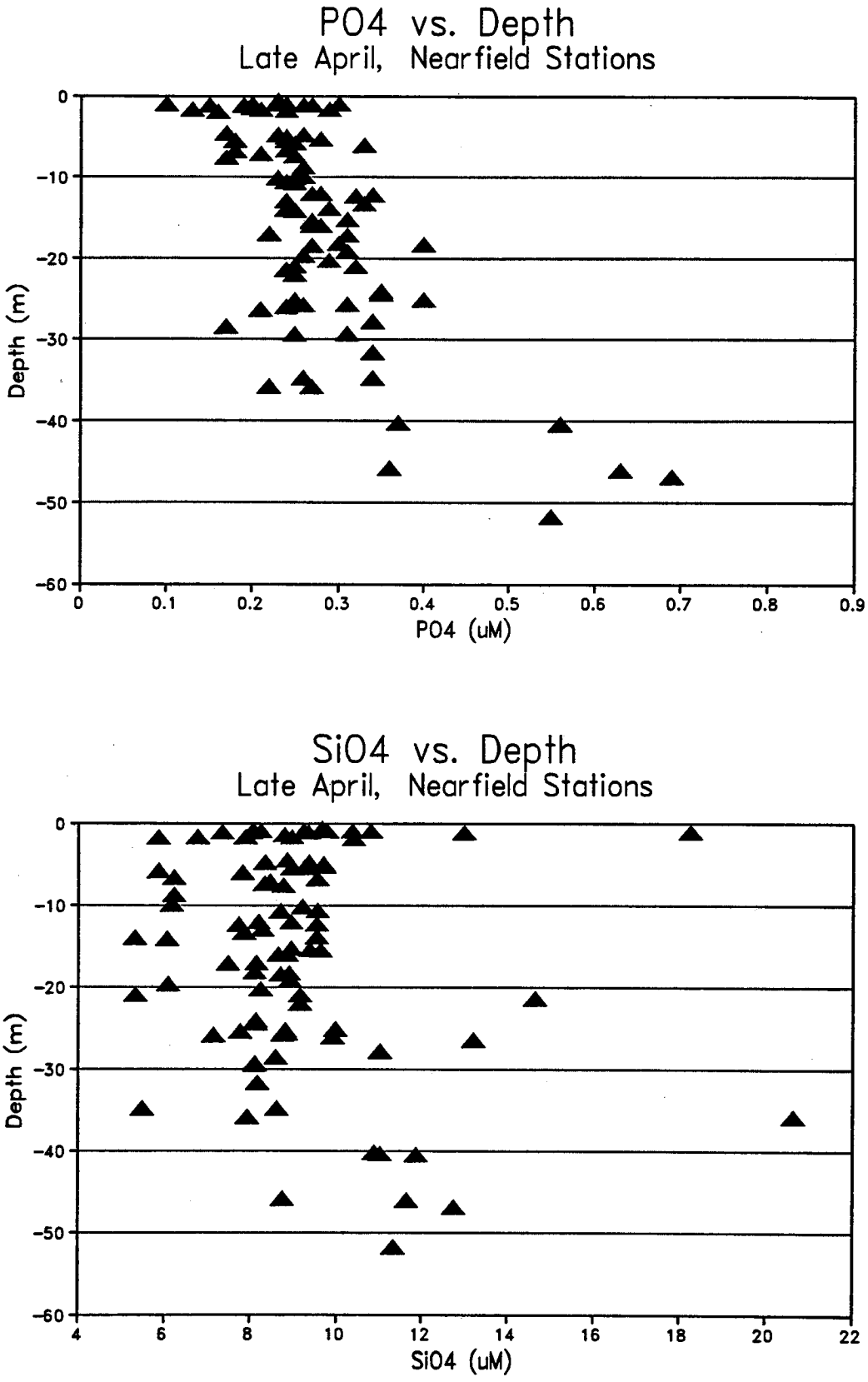



**Figure 4-4 $PO_4$ and $SiO_4$ vs. depth in late April 1992.**

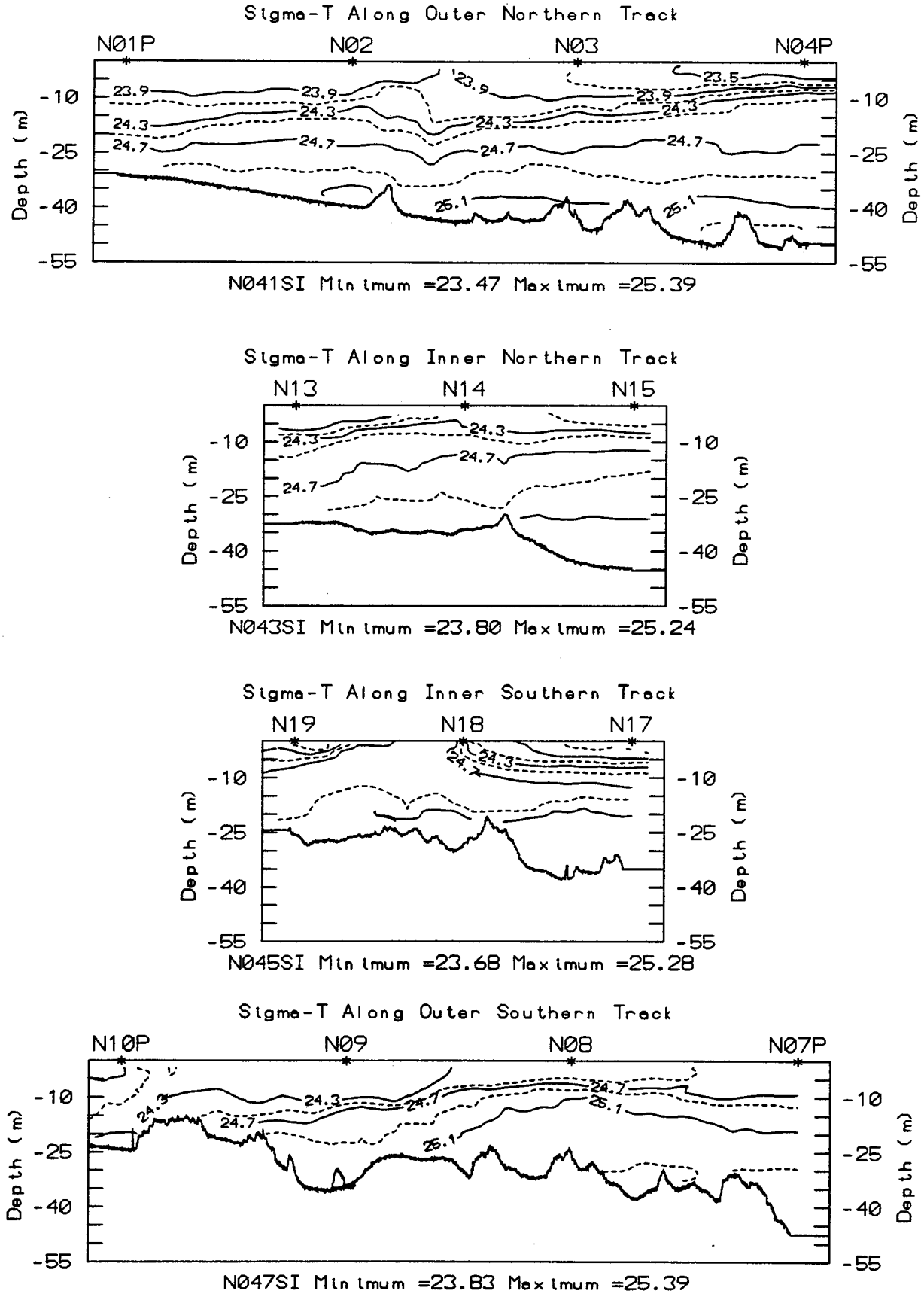



**Figure 4-5a** **Vertical section contours of $\sigma_T$ generated for tow-yos in late April 1992. The view is towards the North. The contour interval is 0.2 $\sigma_T$.**

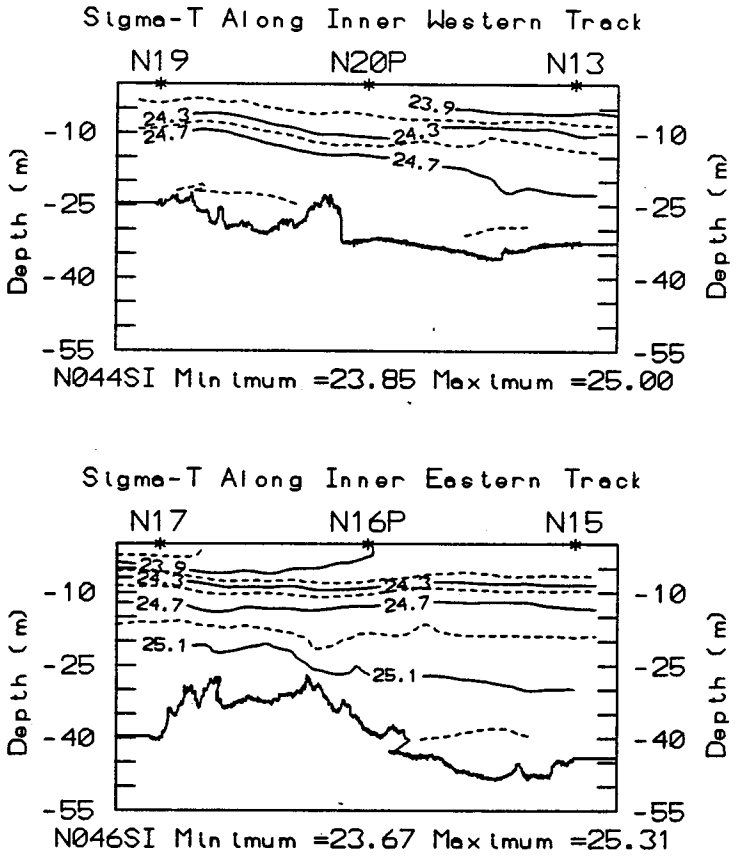



**Figure 4-5b Vertical section contours of $\sigma_T$ generated for tow-yos in late April 1992. The view is towards Boston Harbor.**

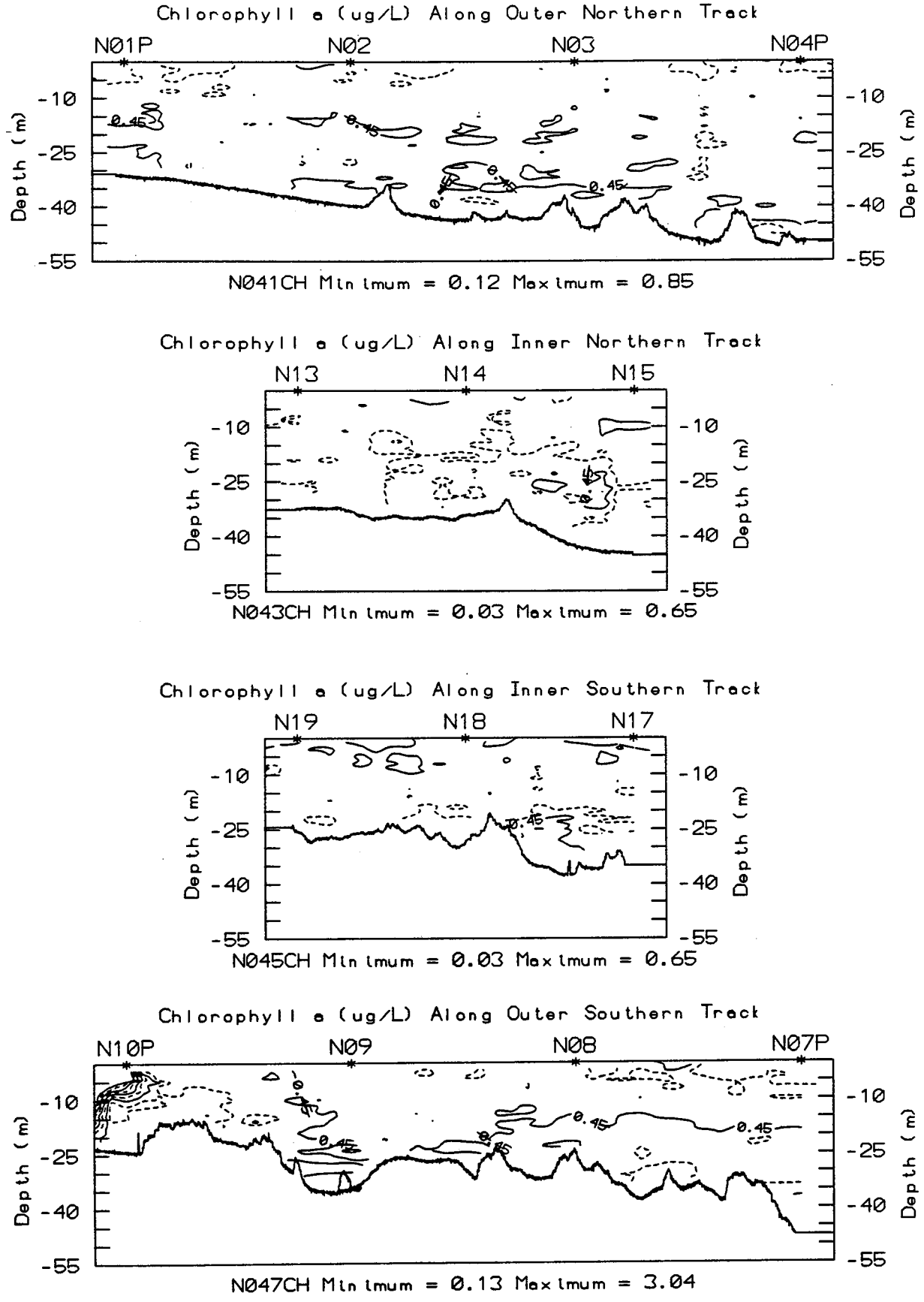



**Figure 4-6a** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in late April 1992. The view is towards the North. The contour interval is 0.2 $\mu$g $L^{-1}$.**

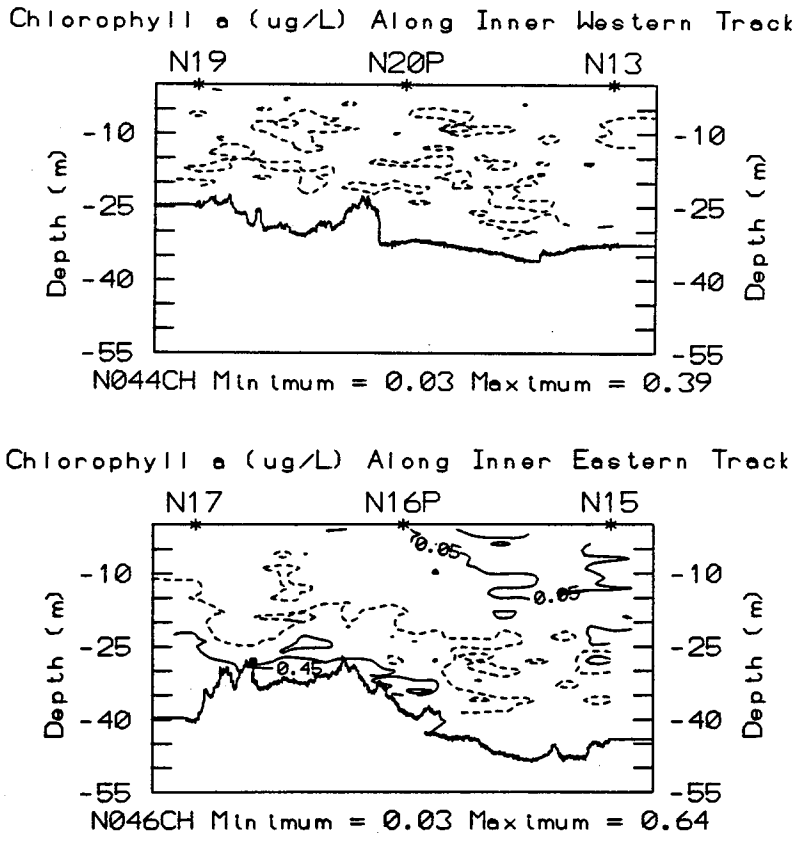



**Figure 4-6b** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in late April 1992. The view is towards Boston Harbor.**

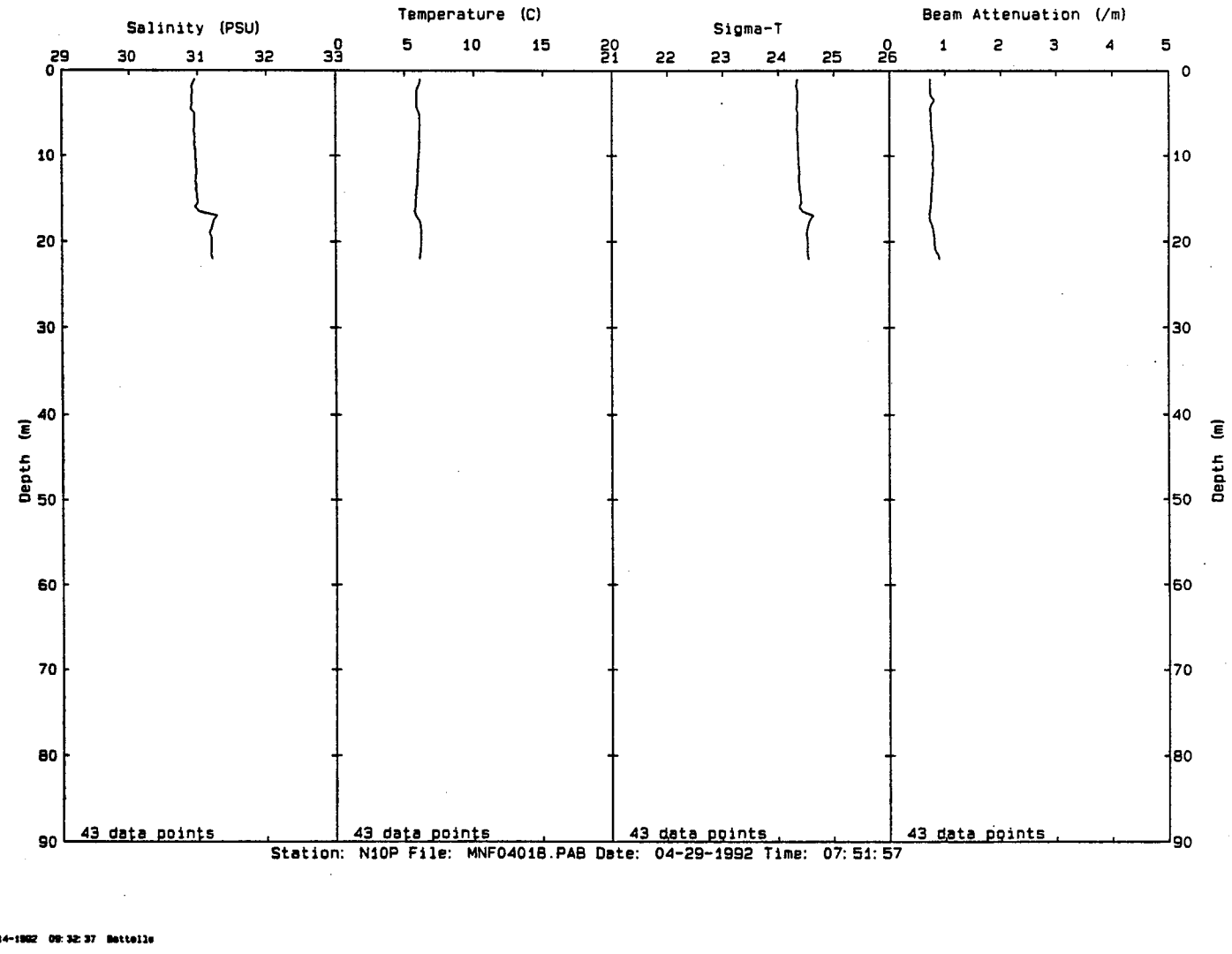



Figure 4-7 **Vertical profiles from downcast on the vertical profiling day in late April 1992 for station N10P.**

# 5.0 MAY 1992 NEARFIELD SURVEY (#5) RESULTS

## 5.1 Distribution of Water Properties from Vertical Profiling

In mid-May, the vertical structure of the seasonal pycnocline was more pronounced (see Appendix B), with many stations showing a distinct upper layer of warmer, fresher water in the upper 10-15 m. This was underlain by a pycnocline, anywhere from about 5 to 20 m thick, in which conditions gradually or sharply changed to a more constant deeper layer that was colder ($\leq$ 5°C) and saltier ($\sim$32 PSU). Some stations, such as N10P, had a near bottom pycnocline (gradient) but not an underlying cold bottom layer since they were not deep ($<$25 m). Compared to April the temperature-salinity range had broadened (Figure 5-1a), with surface temperatures near 10° and salinities 30 PSU or less.

Beam attenuation and chlorophyll fluorescence were uniformly low (Figure 5-1b). Deep subsurface chlorophyll was not longer detected and highest levels (still less than 1 $\mu$g $L^{-1}$, Figure 5-2) were in the surface 10-15 m (Figure 5-1c). The range for dissolved oxygen was apparently a bit lower than previous months, but in a narrow range nonetheless (Figure 5-1c).

Higher bottom-water nutrients ($NH_4$ and $NO_3$ especially) were noted at Station N10P (Figure 5-3). Other than that station, $NH_4$ in the surface 20 m was generally less than 1 $\mu$M and mostly below 0.5 $\mu$M. A similar pattern was apparent from $NO_3$, although an occasional value of $\sim$1 $\mu$M was seen in the surface 20 m in mid-water of a few other stations. $PO_4$ was less uniformly and strongly depleted at the surface (Figure 5-4). In the case of most nutrients (especially $NO_3$, $PO_4$ and $SiO_4$), higher values tended to be found below the pycnocline, especially along the outer eastern track (N04P - N07P). In general then, the upper layer of lighter, warmer surface after above the pycnocline was nutrient poor and accordingly had little chlorophyll.

## 5.2 Distribution of Water Properties from Towing

On day 2 (May 20) towing was completed on all four legs of both the inner box (the sequence was N19 - N13 - N15 - N17 - N19) and the outer box (the sequence was N10P - N07P - N04P - N01P - N10P).

Thus, four sections for each of the northward-looking and westward-looking views of the nearfield are presented in Figures 5-5 and 5-6.

In general, water below 20-30 m was colder than 6°C, this depth being shallower at the northern edge of the nearfield than the southern, especially in the southeastern corner (see Appendix D).

The broad pycnocline from about 10-20 or even 30 m is well illustrated by the sections in Figure 5-5. The relative uniformity of the field can be seen. One can also see that a bottom water layer is distinct along the outer northern (N01P - N04P) and outer eastern (N07P - N04P) tracks, but not so elsewhere, except in the bathymetric valley starting around N16P and N14, deepening offshore towards N15 and the northeastern corner. At this time the center region of the nearfield had a bottom water physical gradient but only a small distinct bottom water layer. We noted that at N10P at the start of the outer box towing, which was near high tide, the pycnocline (Figure 5-5a) was different from the end of the survey (near low tide). In comparison, the 23.2 $\sigma_T$ surface was above 10 m in the former and below at the latter. This would be consistent with the concept of tidal oscillation, with water ebb and flow between this point and towards the entrance of Boston Harbor creating variability in physical parameters.

It was noted on the towing day that chlorophyll was low and the only place much of a feature appeared was around the southwestern (N10P - N09 - N11) region. Generally higher chlorophyll was observed at N10P at the last sampling (near low tide), on the leg from N01P to N10P (Figure 5-6b) rather than the leg from N10P to N07P (Figure 5-6a).

### 5.3 Analysis of Small-Scale Variability

The region was fairly uniform with broad trends as a function of water depth the dominant variation, rather than station-by-station individual variability.

Once again, depending on the time of sampling the southwestern corner (N10P) of the nearfield differed slightly from the rest of the nearfield. Biology seemed responsive to this variation and slightly higher nutrients seen at N10P (day 1) may influence slightly higher patches of fluorescence seen at this location.

## 5.4 Water Types, as Related to Nutrients, Fluorescence, and Dissolved Oxygen

Dominant variations in water quality including nutrients and fluorescence, which were very minor, appeared to occur in the vertical distinction, rather than horizontal distinction of water masses. The only exception to this may be the conditions and variability implied at the inshore corner near Boston Harbor.

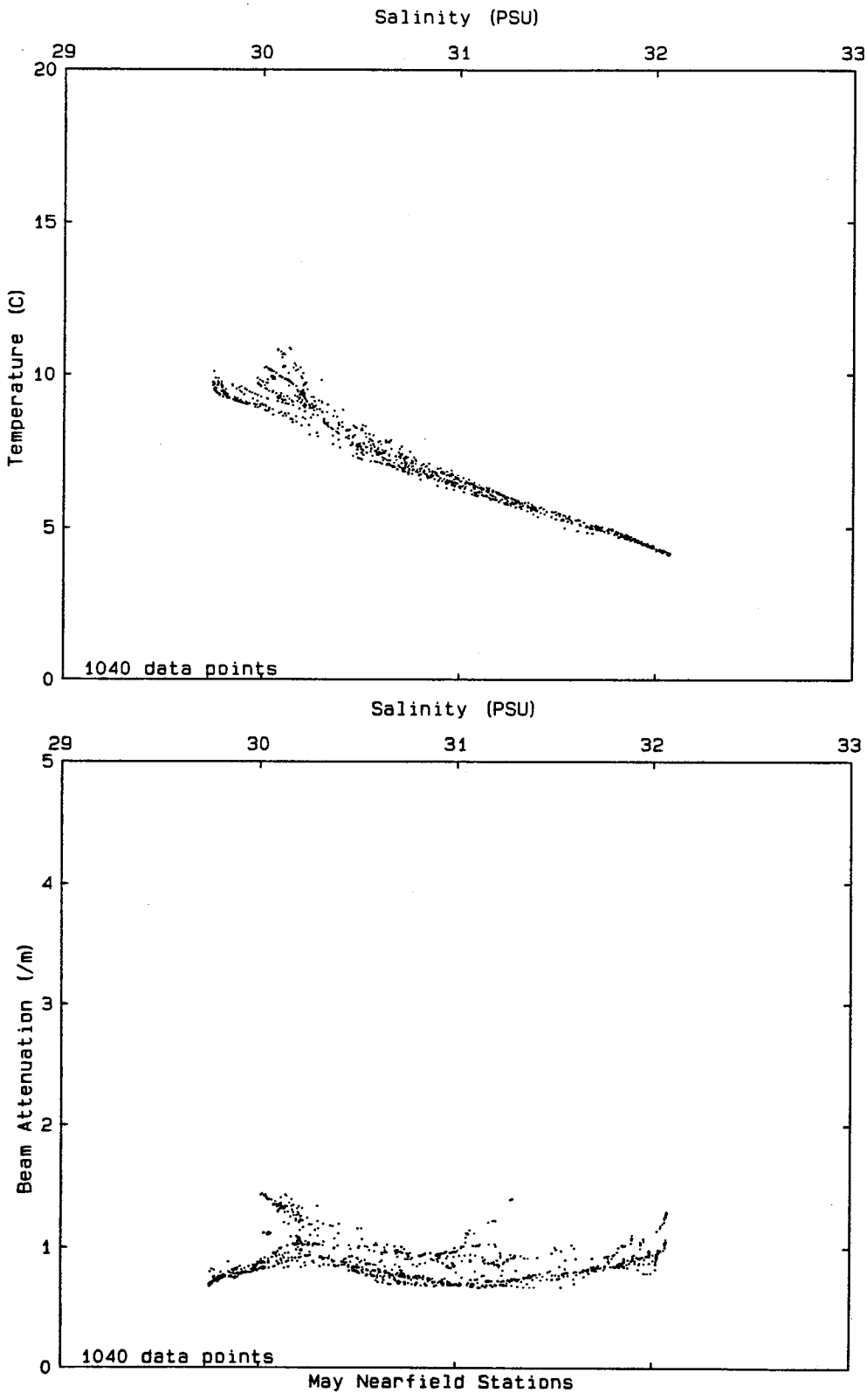



**Figure 5-1a** Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in May 1992. Individual station casts that were used to produce this composite are in Appendix B.

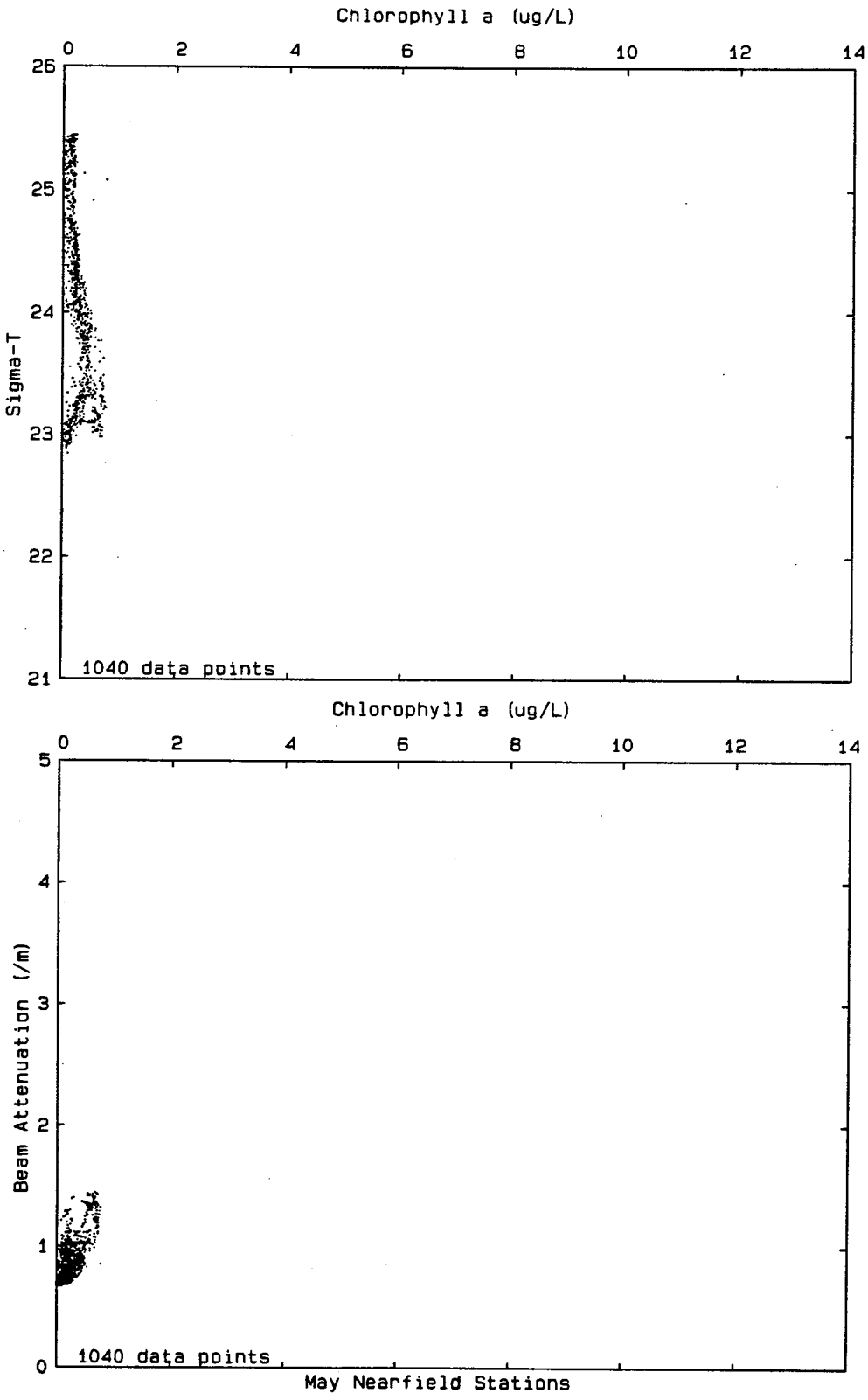



**Figure 5-1b Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in May 1992. Individual station casts that were used to produce this composite are in Appendix B.**

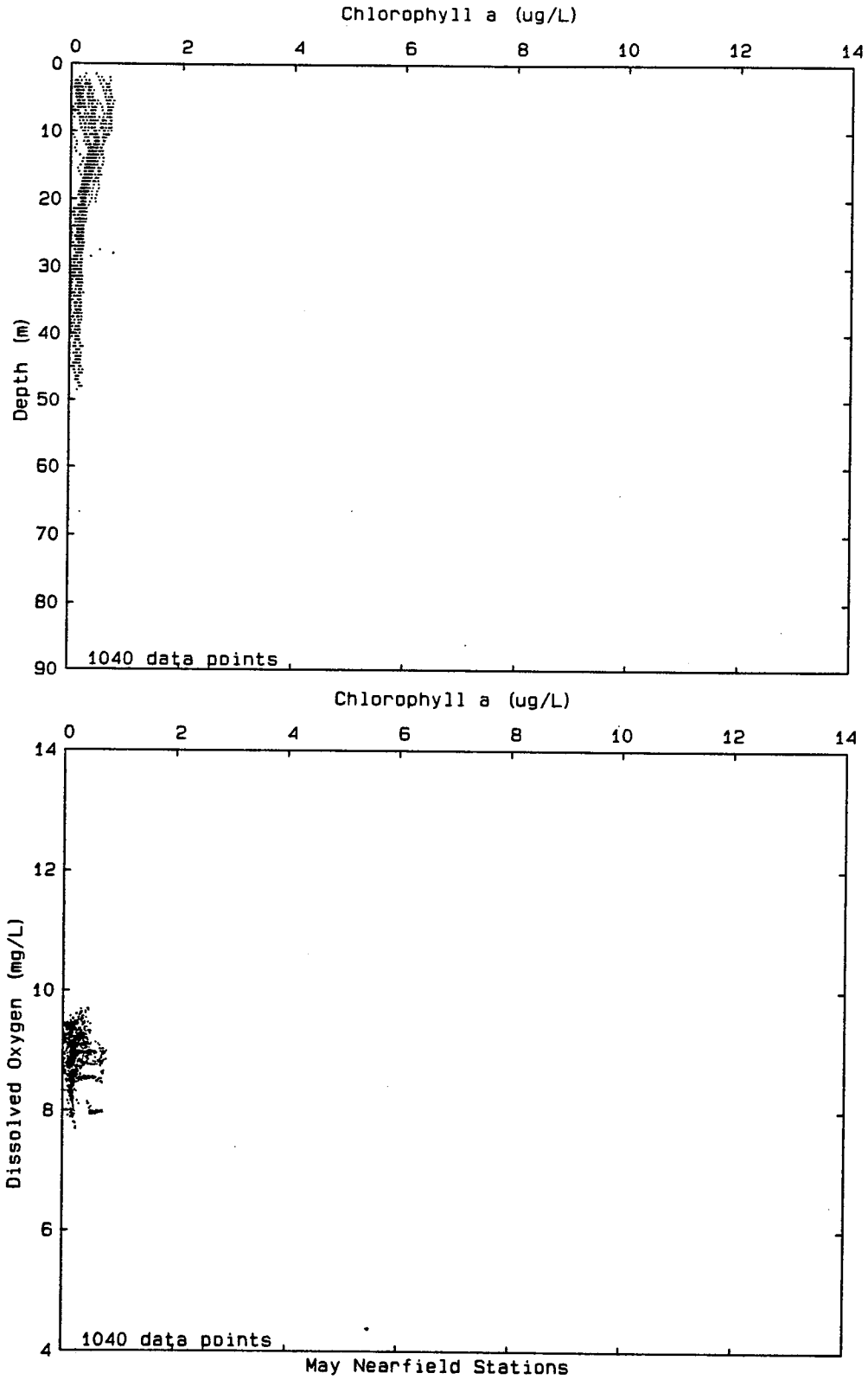



**Figure 5-1c Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in May 1992. Individual station casts that were used to produce this composite are in Appendix B.**

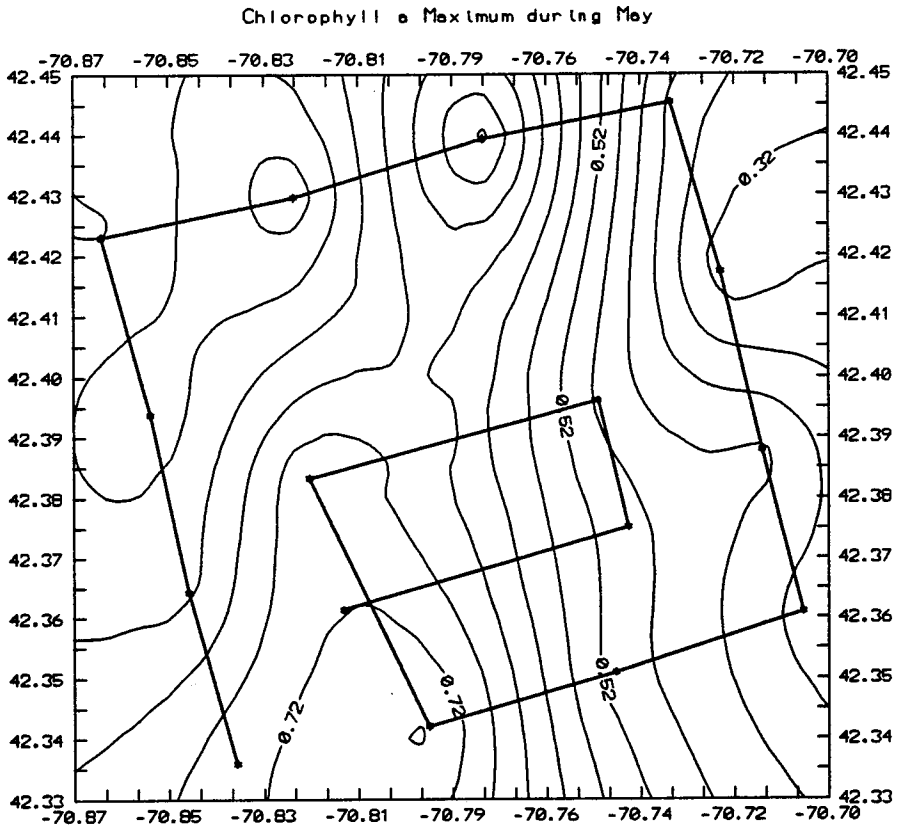
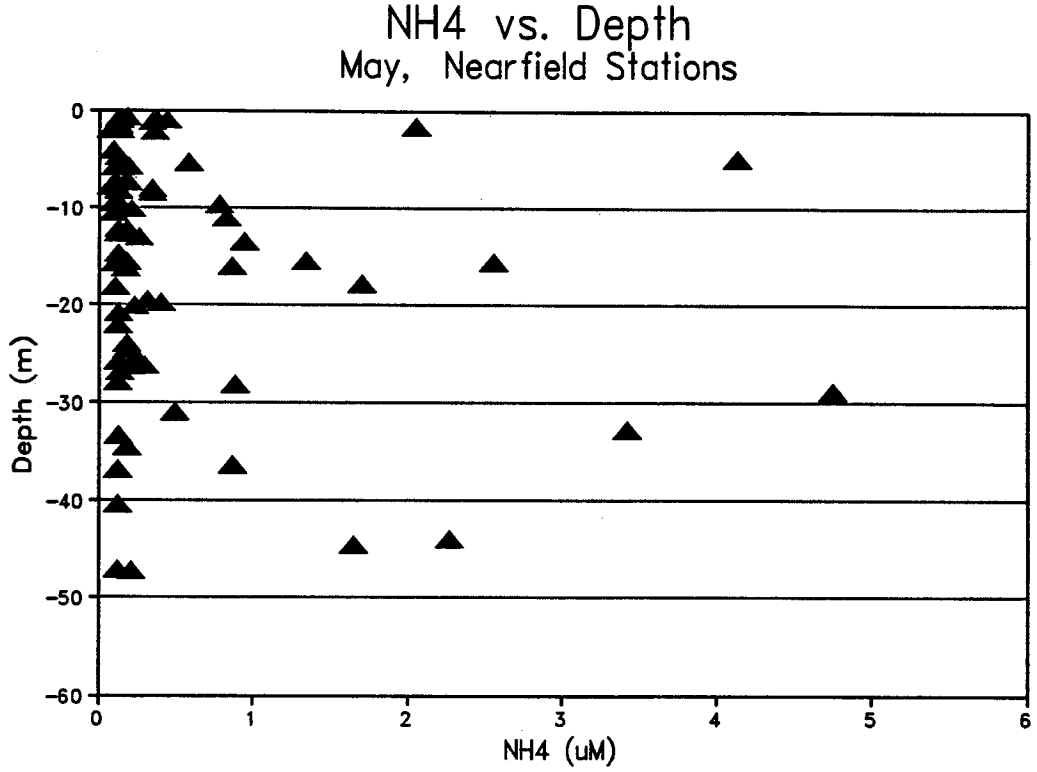



**Figure 5-2** **Chlorophyll maximum at each nearfield station from vertical profile day (Appendix B). Track shows sampling, starting at southwest corner of nearfield and proceeding clockwise to spiral into the middle of the field. Not all 21 stations were sampled. Chlorophyll maximum may not be at the same depth at different stations.**



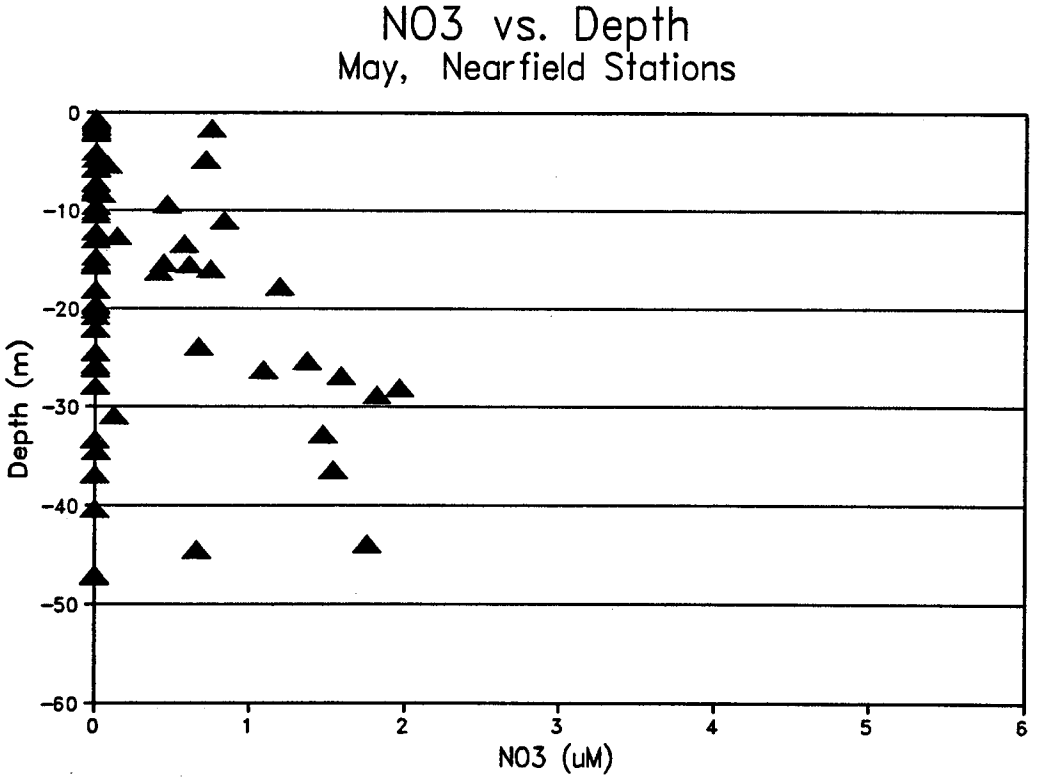
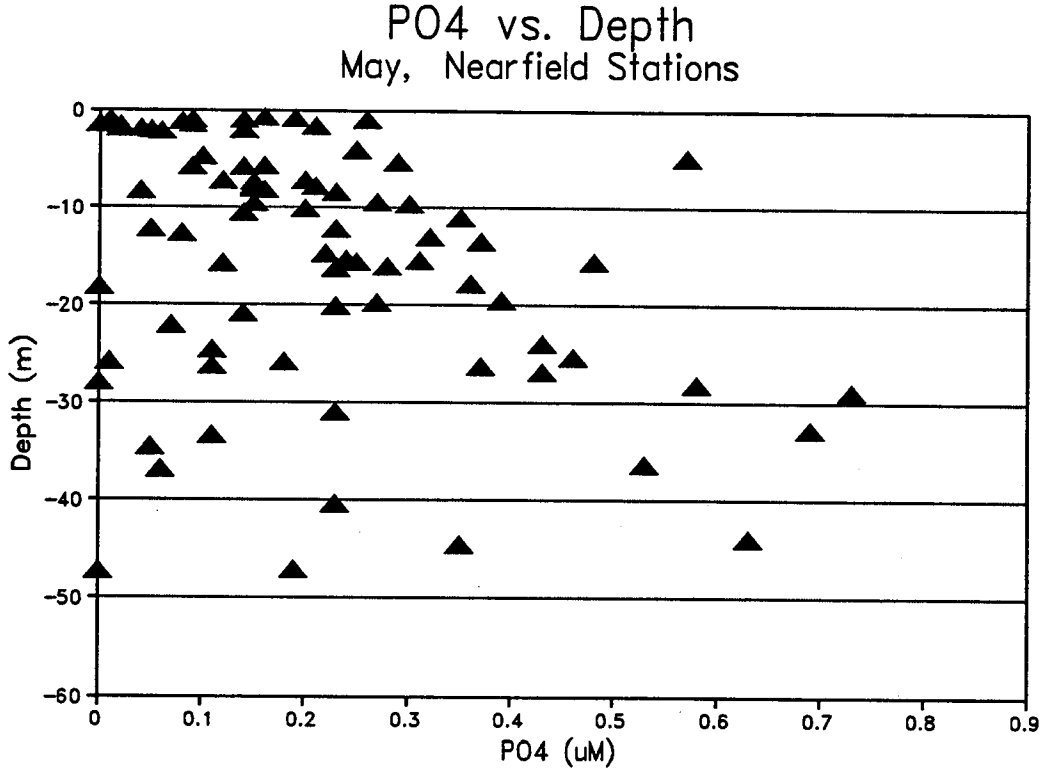




**Figure 5-3 $NH_4$ and $NO_3$ vs. depth in May 1992.**



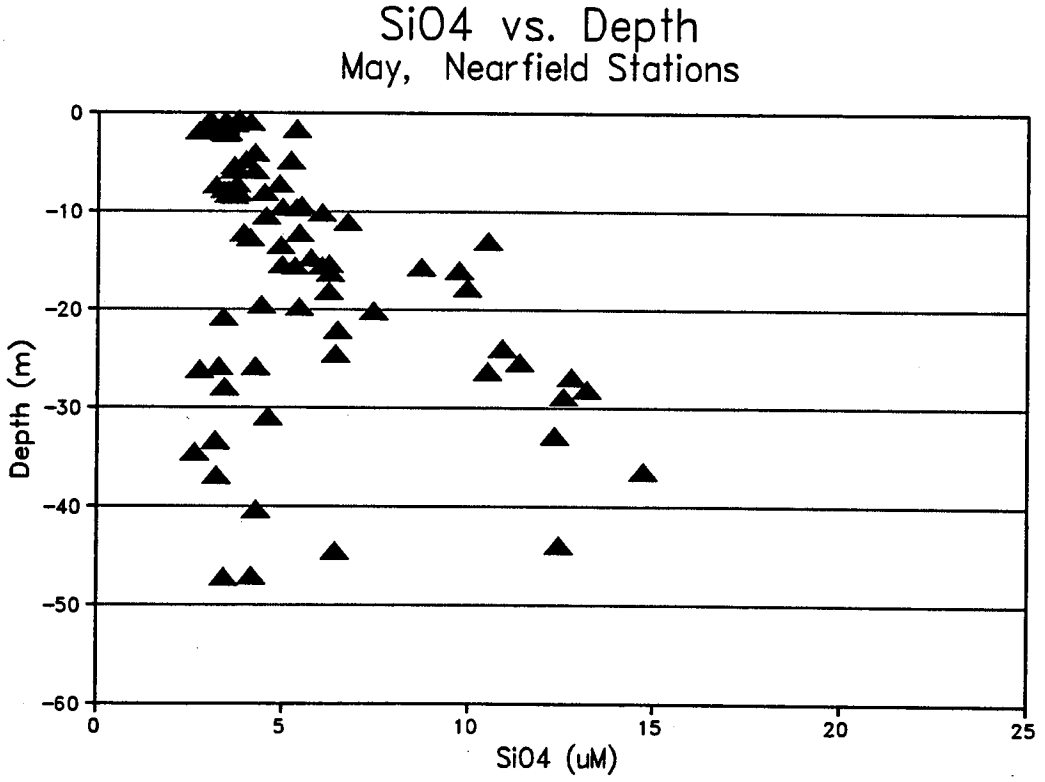




**Figure 5-4 $PO_4$ and $SiO_4$ vs. depth in May 1992.**

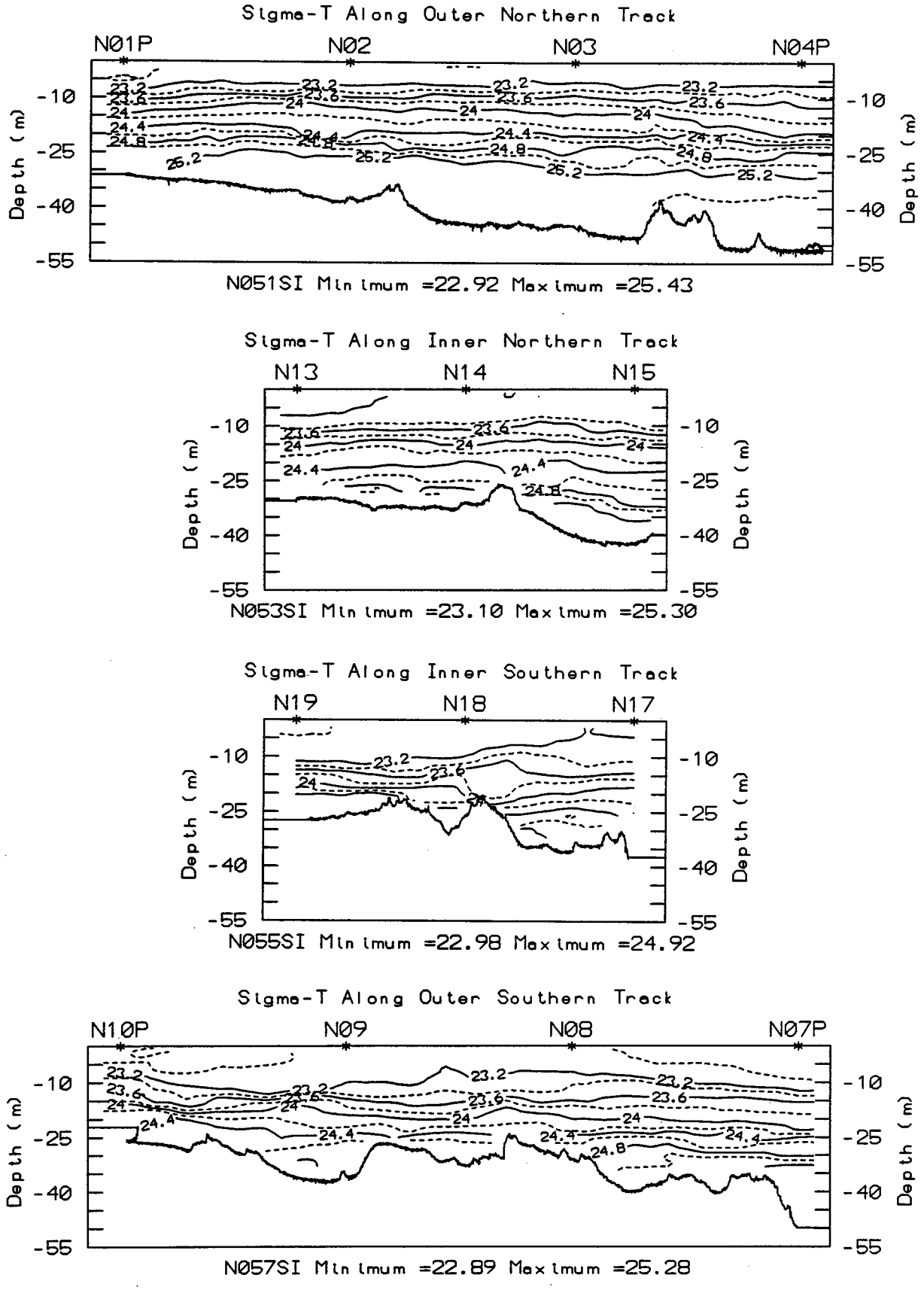



**Figure 5-5a** **Vertical section contours of $\sigma_T$ generated for tow-yos in May 1992. The view is towards the North. The contour interval is 0.2 $\sigma_T$.**

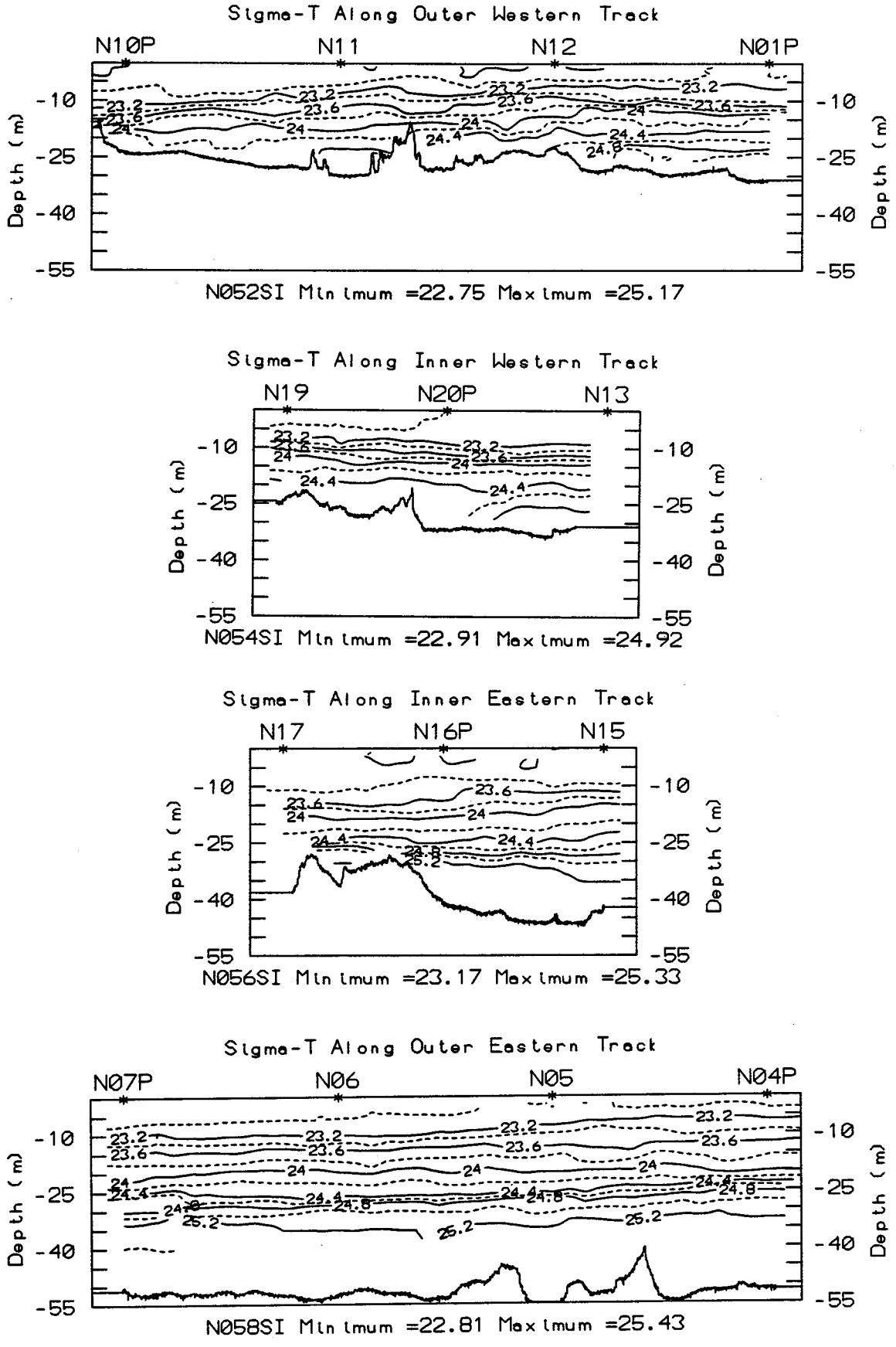



**Figure 5-5b Vertical section contours of $\sigma_T$ generated for tow-yos in May 1992. The view is towards Boston Harbor.**

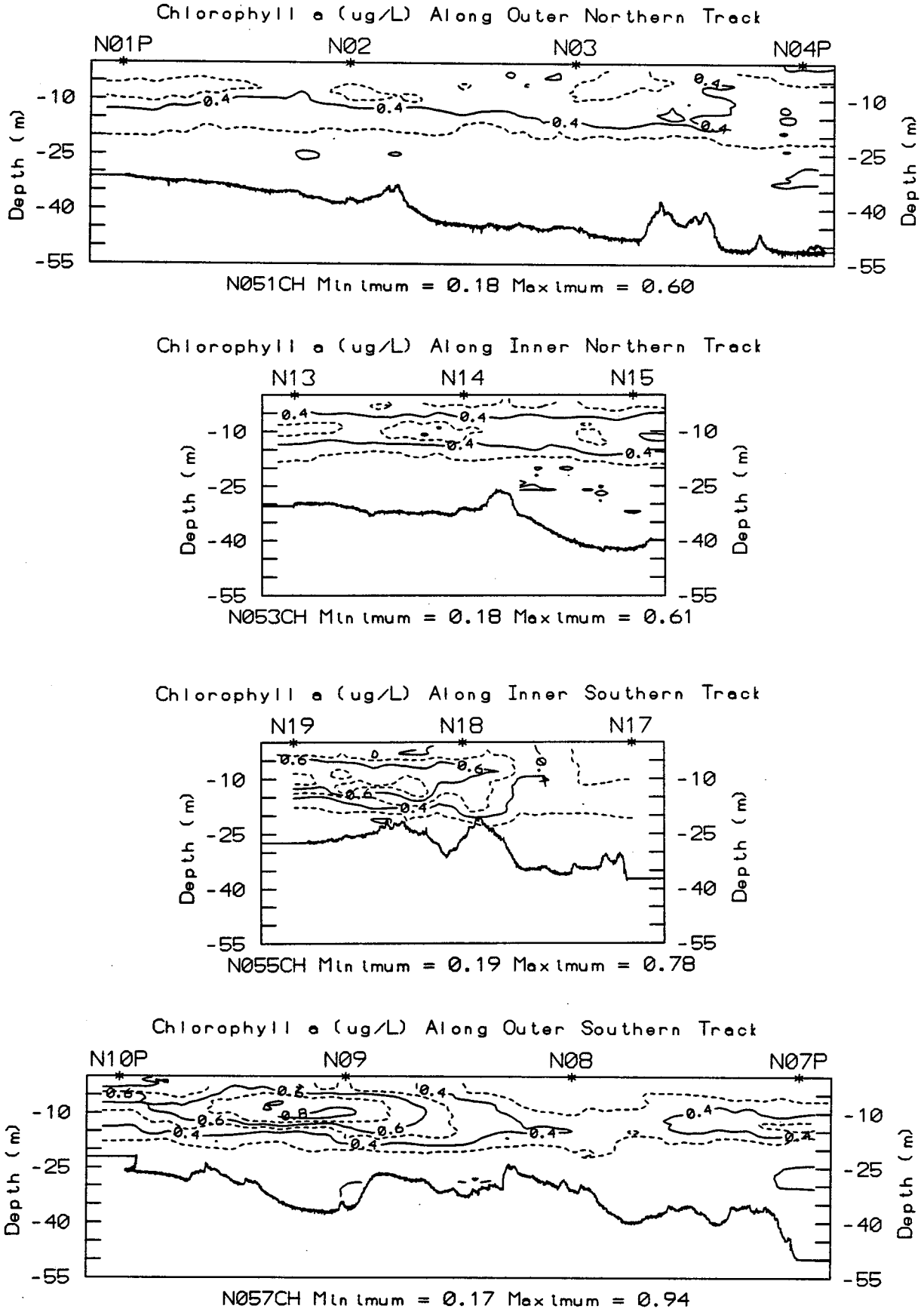



**Figure 5-6a** **Vertical section contours of Fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in May 1992. The view is towards the North. The contour interval is 0.1 $\mu$g $L^{-1}$.**

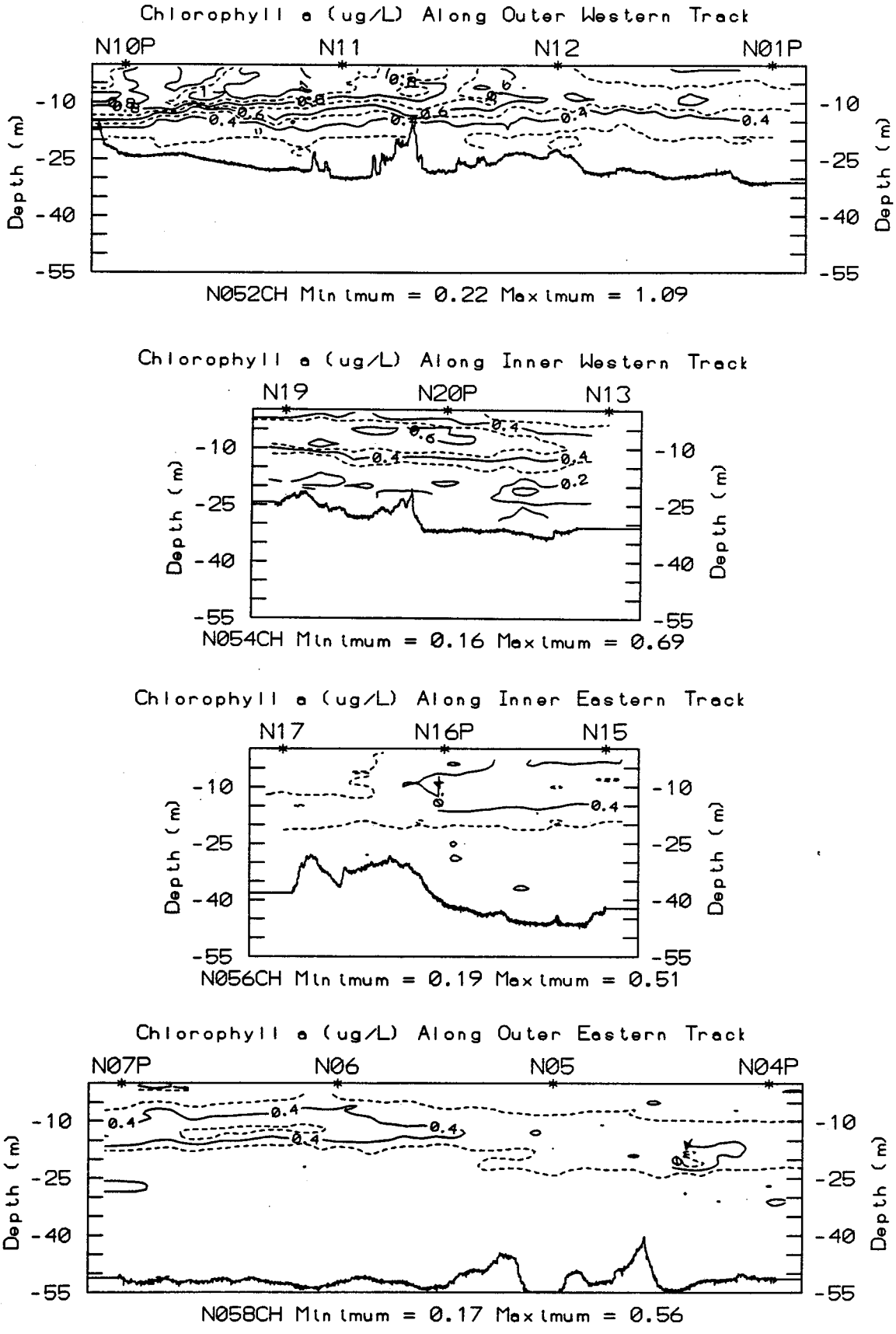



**Figure 5-6b Vertical section contours of Fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in May 1992. The view is towards Boston Harbor.**

# 6.0 JUNE 1992 COMBINED FARFIELD (#4) AND NEARFIELD SURVEY (#6) RESULTS

## 6.1 Farfield Survey (#4)

### 6.1.1 Horizontal Distribution of Water Properties

During the June survey, a thermal division of the two Bays, based on surface measurements, was suggested (Figure 6-1). From the Marshfield transect southward, excepting the shallow station outside Plymouth Bay, the surface temperature was above 15° C. Northward, surface temperatures were from about $<10$ to $>14.5$°C, generally grading from cooler inshore along both the North and South Shores to warmer surface water offshore. It is possible that this distinction is partially a function of sampling and climate variability. The three days prior to the first survey day (June 22) were relatively warm and the Cape Cod Bay area was sampled on that day. That day itself was unseasonably cool, starting a relatively cool period that continued for the remainder of the survey.

Surface salinity showed small Bay to Bay distinction also (Figure 6-2). Most of Cape Cod Bay (Marshfield Southward) was $<30.8$ PSU. With the exception of the edge of Boston Harbor, most of Massachusetts Bay was $>30.8$ PSU.

Because there were similar geographic patterns of temperature and salinity, surface $\sigma_T$ also suggested a sharp distinction between the Bays (Figure 6-3) at the surface.

With respect to surface water beam attenuation and chlorophyll fluorescence (Figures 6-4, 6-5) the coastal areas around Boston and Plymouth were elevated, with values of fluorescence $>4$ to 6 $\mu g\ L^{-1}$ (as chlorophyll) indicated close to Boston. Most of the surfacee water at stations in Cape Cod Bay and the northeastern transect in Massachusetts Bay had low in beam attenuation and fluorescence ($<1\ \mu g\ L^{-1}$).

With respect to nutrients (Figures 6-6 to 6-10) there were a couple of interesting features. DIN was generally below 1 $\mu$M. The notable exception was N07P (dashed contour lines in Figure 6-6), where 3 bottle samples taken at $\sim$2, 7, and 14 m all had high $NH_4$, $NO_3$, $PO_4$ and $SiO_4$. It is difficult to know if these are true values or whether this set of samples had been contaminated. Station F02P in Cape Cod

Bay had among the highest surface $NH_4$ and $NO_3$ values observed at the surface in the Bays. A nutrient gradient towards shore was not distinct around Boston Harbor, even though surface $NO_3$ suggested a slight enrichment.

The most distinctive regional pattern among the nutrients in the near surface water was shown by silicate. There was suggested a slight enrichment at F23P, but the entire selection of stations in Cape Cod Bay had elevated silicate, particularly F03, F01P, and F02P. Thus, the horizontal pattern of silicate was, in part, coincident with the thermal, salinity, and density distributions, further distinguishing the two Bays.

### 6.1.2 Water Properties Along Selected Vertical Sections

Most of the Bays' stations had developed a sharp thermally-driven pycnocline by the June survey and this was apparent from vertical profiles (Appendix B). The contoured sections from our standard transects (Figure 6-11 and 6-12) illustrate this. Generally bottom waters less than 20 m were still cooler than 6°C, grading to 4°C at about 60 m. The sharp thermocline and pycnocline (See Appendix C) was generally from 5-20 m; in shallow coastal waters the pycnocline was at the bottom. The surface distinction noted between Massachusetts and Cape Cod Bays is evident in Figures 6-11 and 6-12, where the Marshfield transect (especially F06 to F07) had a surface lens of much warmer ($>16$°C), fresher ($<31$ PSU) and lighter ($\sigma_T$ $<23$) water. Note the thermocline was a bit broader and extended deeper at this location compared to other transects (Figure 6-11).

With respect to chlorophyll fluorescence and nutrients (Figures 6-13 to 6-15) there were some interesting vertical and geographic patterns. Low fluorescence was characteristic of surface and deep subsurface waters. Maxima ($>3$ $\mu g\ L^{-1}$) were generally seen within, or near the base of, the pycnocline. Inshore, near Boston and just south off Cohasset, the highest values were seen but for each transect there was a deep chlorophyll "tongue" extending out from shore, especially at about 20 m. Near Boston F23P there were high values at the surface, whereas off Cohasset ~Stations F15 and F16) the very high maxima ($\sim 10$ $\mu g\ L^{-1}$) were at $\sim 15$ to 20 m.

DIN and $SiO_4$ showed depleted surface waters. Concentrations increased with depth, sharply so at the level of the pycnocline and generally just below the chlorophyll maximum. Highest surface DIN and $SiO_4$ were just outside Boston Harbor (F24-F23P).

It was interesting that the warmer lens of water at the surface across the Marshfield transect did not have any obvious corresponding difference in chlorophyll or nutrients. Finally, it was noted that DIN was highest at the very bottom water across the Northern Transect (F21 and F22), as well as the deepest water measured in Stellwagen Basin (F19, F12).

As a final vertical feature it was interesting to note a deep subpycnocline oxygen maximum. This is illustrated for Station F2P in Cape Cod Bay (Figure 6-16) where a replicate cast showed nearly the exact same feature (Appendix B). This deep oxygen maximum, clearly associated with a deep chlorophyll maximum, was usually noted as the rule, rather than the exception for the survey.

### 6.1.3 Analysis of Water Types

High-resolution *in situ* data show the range of salinity was slightly less than in May (~30.5 to 32 PSU) but the range in temperature had now become pronounced. Several deep water (offshore or Northern Transect Stations) had small salinity variation over depth and temperature (5-10°C); otherwise, the T-S relations (Figure 6-17a) were fairly similar across our standard geographic grouping of stations (Cape Cod Bay, Coastal, offshore, nearfield, and Northern Transect Groups).

High beam attenuation at lower salinities was noted at coastal and nearfield stations and increases in beam attenuation at the bottom of deepwater (high salinity) profiles was also noted. The former generally was related to increases in chlorophyll whereas the latter was not (Figure 6-17b).

It is apparent from Figures 6-17b and 6-17c that very high chlorophyll peaks were found around 20 m and thus at greater $\sigma_T$ values. The exception to this was the coastal stations which as a group, more characteristically had their highest chlorophyll (up to 6 $\mu g\ L^{-1}$) within the surface 10 m or so (see Appendix C). Below 30 m, chlorophyll fell sharply everywhere.

With respect to nutrients (Figure 6-18 through 6-25), one principal Bays-wide distinction was by depth, rather than region. Where nutrients were high (depth) all increased together. Distinctions on a geographic basis related to silicate, which was especially high in Cape Cod Bay without an associated high $NO_3$ or DIN concentration (Figure 6-19). Secondly, the nearfield had lower $NO_3$ and DIN than the offshore or Northern Transect for equal $SiO_4$ in samples below the pycnocline.

From the plots, it is apparent that phosphate was still available where $NO_3$ and $NH_4$ were depleted. In general, N limitation is still implied, but it is also interesting that the increase of N and P parallel a 16:1 ratio expected from decomposition of marine planktonic organic matter.

As shown in Figures 6-20 to 6-22 the occasional higher N or P concentration in nearsurface, lower salinity water usually was noted in nearfield or coastal samples. The increase with salinity $>31.5$ is related to depth. Actually, $PO_4$, rather than N, seemed to have a stronger signature, as elevated values at lower salinity (compared to intermediate salinity) in coastal and nearfield samples. Silicate generally was like N, excepting the higher values throughout the salinity range that were characteristic of Cape Cod Bay samples (Figure 6-23).

PON was relatively high in many samples, such that most concentrations of DIN + PON were $>3$ $\mu$M even though DIN was virtually depleted (Figure 6-24). A slight concentration drop in DIN + PON with intermediate salinity levels was suggested by the set of coastal and nearfield stations, but the highest DIN + PON values were seen at depth in Cape Cod Bay. A roughly similar pattern was apparent for Total N [TN = (Includes DIN + DON) + PON]. As discussed below, the Cape Cod Bay chlorophyll maximum samples (n = 3 samples at higher salinity) had high PON associated with a high cell count of a dinoflagellate species and very high chlorophyll ($>6$ $\mu g\ L^{-1}$). Another high Total N sample ($>16$ $\mu$M) at high salinity was at N20P, a mid-depth maximum of high chlorophyll ($\sim 3.9$ $\mu g\ L^{-1}$). The data point in Figure 6-25 at high salinity, with Total N near 14 $\mu$M, was the surface anomaly at N04P shown in Figures 6-6 to 6-10, and the N was DIN not PON. Excluding these five samples with higher TN at high salinity, one would have a stronger overall relation of Total N with salinity. Nevertheless these data may serve to illustrate the ability of plankton to concentrate N and obscure patterns expected from simple physical mixing and dilution of dissolved forms.

Finally, we note that concentrations of Total N in general were lower at this time than seen in previous months at these stations (Section 3 and Kelly *et al.*, 1992).

Summarizing, the primary water type distinctions were in the vertical dimension, with a strong pycnocline established. However, Cape Cod and Massachusetts Bays had different surface water characteristics and silicate was high in Cape Cod Bay. The influence of shallowness and coastal nutrient sources was also evidenced in chlorophyll, beam attenuation, and nutrients, to some extent.

### 6.1.4 Distribution of Chlorophyll and Phytoplankton

Discrete bottle sampling for chlorophyll, directly measured by extraction at all the Bioproductivity Stations, well captured the major peaks in chlorophyll as shown by fluorescence profile readings (cf. Figure 6-17c and Figure 6-26). Coastal stations (F23P, F25, F13P) and one nearfield station (N10P) had high values ($>3$ $\mu g$ $L^{-1}$) in the upper 10-12 m. The deeper and more intense peaks in Cape Cod Bay (F01P, F02P) underlay very low surface values. In most of the nearfield deeper samples had slightly higher concentrations than the surface samples, excepting N20P which had high chlorophyll at 12 m. The relation between chlorophyll and total phytoplankton counts in the discrete samples was fairly strong, although the deep chlorophyll maximum in Cape Cod Bay (F01P, F02P) was anomalous in having exceptionally high chlorophyll for the cell counts (Figure 6-27). This difference is most likely real, attributable to the dominant presence of a larger-size phytoplankton species, with lots of chlorophyll packed into fewer but large cells.

Most of the stations exhibited a mixed microflagellate-diatom or mixed microflagellate-diatom-dinoflagellate community of phytoplankton (Figure 6-28).

Dominant taxa are indicated in Tables 6-2 and 6-3 for surface and deep samples, respectively. Besides microflagellates, and cryptomonads, the top dominants included one or more diatoms (especially *Chaetoceros socialis, C. debilis, C. compressus*, a small *Chaetoceros* sp. ($<10$ $\mu m$) that may be *C. socialis, Skeletonema costatum*, and *Cerataulina pelagica* (surface only), with a few others being more occasional). For dinoflagellates, *Heterocapsa triquetra* was noted among top dominants around Boston Harbor at F23P and the surface of N10P. At stations in Cape Cod Bay, the dinoflagellate *Ceratium longipes* was the overwhelmingly dominant organism at the subsurface chlorophyll maximum ($\sim 18$ to 22 m), even though it was rare in the surface sample at those stations (F01P, F02P). This species is morphologically very similar to *Ceratium tripos*, implicated in the major anoxic event on the N.Y. Bight in 1976 (Falkowski *et al.*, 1980), and in this case the numbers indicated a major bloom event within Cape Cod Bay.

In terms of vertical distribution, subsurface and surface cell counts were often similar; subsurface counts were as often less than, as they were greater than, surface counts. In terms of taxonomic composition, especially dominants (Tables 6-2 and 6-3), results were quite similar for surface and deep samples at a

given station (Figures 6-29 to 6-32). But there were two interesting exceptions, the first being *Ceratium longipes* at depth as described above. The second was the presence of the diatom *Cerataulina pelagica*, among the top dominants (sometimes the most dominant), but only in surface samples (throughout the region, including all stations except the stations most near Boston Harbor — F13P, F23P, and N10P). *C. pelagica*, though not in the top 5, was present at these remaining three stations, always slightly more so at the surface than at depth (Appendix F). Five of the six samples at these three stations had relatively high numbers of another diatom, *Skeletonema costatum*; in virtually all cases where *Skeletonema* was among the dominants, *Cerataulina* was not (Tables 6-2 and 6-3).

Highest cell numbers were observed at the same trio of inshore stations (F23P, F13P, N10P) most proximal to Boston Harbor and its outflow; cell abundance exceeded $2 \times 10^6$. Nowhere else were counts as high, and only at N01P, N16P and N20P did they exceed $10^6$ cells $L^{-1}$ (Figure 6-28). Highest counts at F23P at the edge of the Harbor were composed of a diverse taxa, whereas F13P and N10P had very high diatom fractions.

Once again, replicate sampling was conducted at station F02P. Results showed a very similar community, considering relative numerical ranking of taxa, and confirmed the strong difference between surface and subsurface samples (Figure 6-30 a,b). With respect to total counts, the results (in $10^6$ cells $L^{-1}$) were:

| | Surface sample (bottle depth) | Deep sample (bottle depth) |
|---|---|---|
| Replicate cast #1 | 0.48 (~1.7 m) | 0.54 (~22 m) |
| Replicate cast #2 | 0.52 (~1.6 m) | 0.60 (~22 m) |
| Mean (std dev) | 0.50 (0.03) | 0.57 (0.04) |

Expressed as a coefficient of variation (CV), the two sample variability was about ±6-7% for the mean of total counts at each depth. Expressed a percentage, total counts for the first replicate were 90 to 92% of the second replicate.

With the exception of *Ceratium* at depth in Cape Cod Bay and *Heterocapsa* near Boston Harbor, individual large dinoflagellate species or genera were $< 10^5$ and for the most part $< 10^3$ cells $L^{-1}$ as measured by the screened technique (Tables 6-4 and 6-5). The new method for quantitatively estimating large dinoflagellates resulted in counts in general that were in the $10^3$ range or less, with *Ceratium* again being the exception. The bloom of *Ceratium* documented in the whole water sampling was confirmed at the subsurface of F01P and F02P (both replicates), where counts showed numbers around the $10^5$ level and higher at F02P, both being results comparable to the whole water samples. In contrast, *Heterocapsa* counts in the screened sample were at least 1 to 2 orders of magnitude lower than the whole water sample; the size and shape of these cells may cause them mostly to pass through the 20 $\mu$m mesh and could explain this difference in estimates by the two methods.

Thus, the target species of this screened method, bloom exceptions noted, were numerically minor components of the community; note that nevertheless they have relatively large cell volumes and in the case of *Ceratium* in Cape Cod Bay contributed to the high mid-depth PON concentration.

With respect to vertical patterns, only two stations (F23P and N07P) had higher total dinoflagellate numbers in the surface sample than in the sample from depth. Thus, in most cases, the large cell dinoflagellate community tended to be present in greater numbers around a subsurface chlorophyll maximum. This pattern was most acute for Cape Cod Bay, the contributing species being *Ceratium longipes*, but other species but others followed this pattern too (*C. fusus, C. lineatum, C. tripos, Dinophysis norvegica*, and *Protoperidinium claudicans*, among others). For F23P, a diverse assemblage of species, including *Heterocapsa*, had higher numbers at the surface, but there seemed as much a general increase in numbers as there was a sharp taxonomic bias. At N07P many species again contributed to the generally higher numbers at the surface but two of the pronounced surface "enrichments" were of *Ceratium longipes* and *Dinophysis norvegica*. Note that this surface sample had anomalously high inorganic nutrients (e.g. Figure 6-8 and Appendix A).

In the screened sample, some non-dinoflagellates were also counted, and those detected include silicoflagellates (*Distephanus, Eutreptia, Ebria*), an autotrophic ciliate (*Mesodinium*), and freshwater chlorophytes (*Scenedesmus, Pediastrum*). As a group these were all rare ($< 100$ cells $L^{-1}$) and not seen in Cape Cod Bay, except *Distephanus*. The distribution of the freshwater species *Scenedesmus* was interesting. Highest counts were at F23P, an outflow point from the Harbor, a principal source of

freshwater to western Massachusetts Bay. This is strictly a freshwater species and must have some limited survival time in seawater; only cells with internal cellular structure intact (i.e., not decomposed) were counted. *Scenedesmus* was only present at N10P surface, F13P deep (1 cell) and N20P (1 cell). *Pediastrum* was only detected at F23P and N10P. Interestingly, of the Bioproductivity sampling stations, N10P and F13P are most in the path to receive, on some timeframe, less saline water output from the Harbor. Results here are indeed scant; but whether these freshwater cells have potential as short-lived biological tracers, or as residence time indicators of water in or flowing out of the Harbor, is intriguing and could be investigated.

Replicate station (F02P) sampling results again showed a very similar community, considering relative numerical ranking of taxa, and confirmed the strong difference between surface and subsurface samples (Tables 6-4 and 6-5). With respect to total counts, the results (in $10^6$ cells $L^{-1}$) were:

| | Surface sample (bottle depth) | Deep sample (bottle depth) |
|---|---|---|
| Replicate cast #1 | 0.0065 (~1.7 m) | 0.1327 (~22 m) |
| Replicate cast #2 | 0.0060 (~1.6 m) | 0.1686 (~22 m) |
| Mean (std dev) | 0.0063 (0.0004) | 0.1507 (0.0254) |

Expressed as a coefficient of variation (CV), the two sample variability was about ±6-17% for the mean of total counts at each depth. Expressed a percentage, total counts for the first replicate were 79-108% of the second replicate.

### 6.1.5 Distribution of Zooplankton

Very high abundances of zooplankton were recorded. The number of individuals per cubic meter sampled in June at each of the ten Bioproductivity stations exceeded the highest numbers observed anywhere in the region during the peak of the February-March 1992 winter-spring bloom (Kelly *et al.*, 1992) and were higher than abundances at the April sampling by an order of magnitude. Counts ranged from just over 30,000 (F01P and F02P in Cape Cod Bay) to almost 90,000 (N20P near the center of the nearfield) individuals $m^{-3}$. Much of the nearfield had high numbers (Figure 6-33). The outer northeastern edge (N04P) and stations inshore of the nearfield (F23P and F13P) had intermediate numbers

(40,000 - 50,000 $m^{-3}$). Overall, the distribution suggests a regional difference in zooplankton abundance, i.e. the sampled Massachusetts Bay region vs. the sampled Cape Cod Bay regions.

There were approximately equivalent fractions of copepods (adults and copepidites) and nauplii in most Massachusetts Bay samples. Copepod nauplii were proportionally low only at N04P, but in Cape Cod Bay they were also low.

Taxonomically, the copepod *Oithona similis* again was abundant (as in previous months). Generally, this was the most abundant taxa at all stations. The distinctive exception to this was F23P, the Harbor edge, where *Acartia tonsa* was very abundant ($>10,000$ $m^{-3}$) and the dominant taxa. *Paracalanus parvus* was once again also one of the dominants at a number of stations, notably contributing to high total number at N20P.

With respect to sampling variability, the total counts from replicate tows 1 and 2 at Station F02P were 32,555 and 30,372 individuals $m^{-3}$, respectively, the first value being 107% of the second. With respect to taxa, the overwhelming numerical dominance by *Oithona similis* was indicated in both tows, and the remainder of species present and their relative abundances were very similar (Appendix G).

### 6.1.6 Whole-Water Metabolism Incubations

P-I incubations again showed a strong light response and the majority could be modeled reasonably with either a four parameter model with a photoinhibition term, or a three parameter model lacking a photoinhibition term (Appendix E). Surface incubations were performed near *in situ* surface temperatures $\sim$16-17°C in Cape Cod Bay, and $\sim$10-12°C elsewhere. Chlorophyll maximum incubations were performed also near *in situ* temperature which was around 6°C, except for F23P, N10P, and F23P which had similar temperatures at surface and chlorophyll maximum sampling depths.

We noted, again, as in April, that in general the highly variable P-I data with poor fit or lack of model fit occurred mostly in cases where chlorophyll or cell counts were low. The latter case is demonstrated in Figure 6-34, where F02P had relatively low cell counts, quite a bit of scatter, and in spite of high chlorophyll (due to *Ceratium*), low chlorophyll-normalized net production rates. Another extreme is

**Table 6-2. Top 5 dominant phytoplankton taxa in near the chlorophyll maximum in samples collected in June 1992.**

| Species | Coastal Stations | | Nearfield Stations | | | | | | Cape Cod Bay Stations | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F23P | F13P | N01P | N04P | N07P | N10P | N16P | N20P | F01P | F02P Rep 1 | F02P Rep 2 |
| Microflagellates | (1) 1.154 | (2) 0.502 | (2) 0.214 | (1) 0.137 | (1) 0.200 | (1) 0.834 | (4) 0.198 | (4) 0.091 | (1) 0.302 | (1) 0.178 | (1) 0.262 |
| Cryptomonads | (2) 0.385 | | | (2) 0.107 | (3) 0.071 | (3) 0.235 | | | (2) 0.117 | (3) 0.071 | (2) 0.087 |
| Chaetoceros sp. <10 μm* | (5) 0.108 | (4) 0.173 | (3) 0.151 | | | (4) 0.187 | (2) 0.261 | (3) 0.098 | (3) 0.080 | (4) 0.029 | (4) 0.028 |
| Chaetoceros socialis | (4) 0.130 | | (1) 0.260 | (3) 0.045 | | | (2) 0.315 | (5) 0.081 | | | |
| Leptocylindrus danicus | | (5) 0.151 | | | | | | | (4) 0.076 | (2) 0.073 | (3) 0.054 |
| Cerataulina pelagica | | | (4) 0.147 | (5) 0.012 | (2) 0.083 | | (1) 0.423 | (1) 0.243 | (5) 0.015 | (5) 0.023 | (5) 0.023 |
| Ceratium longipes | | | | | | | | | | | |
| Dinophysis norvegica | | | | | | | | | | | |
| Amphidinium sp. | | | | | | | | | | | |
| Skeletonema costatum | | (1) 0.540 | | | | (2) 0.299 | | | | | |
| Nitzschia spp. | | (3) 0.243 | | | | | | | | | |
| Heterocapsa triquetra | (3) 0.187 | | | | | (5) 0.096 | | (5) 0.081 | | | |
| Nitzschia (cf.) delicatissime | | | (5) 0.130 | | | | | | | | |
| Chaetoceros debilis | | | | | | | (5) 0.144 | | | | |
| Rhizoselenia delicatula | | | | | (4) 0.065 | | | (2) 0.105 | | | |
| Chaetoceros compressus | | | | (4) 0.024 | | | | | | | |
| Cyanophyceae | | | | | (5) 0.050 | | | | | | |
| Chaetoceros spp. >10μm | | | | | | | | | | | |

( ): rank
Number: millions of cells $L^{-1}$
*May be C. socialis

**Table 6-3. Top 5 dominant phytoplankton taxa near the chlorophyll maximum in samples collected in June 1992.**

| | Coastal Stations | | Nearfield Stations | | | | | | Cape Cod Bay Stations | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F23P | F13P | N01P | N04P | N07P | N10P | N16P | N20P | F01P | F02P Rep 1 | F02P Rep 2 |
| Microflagellates | (1) 1.103 | (2) 1.032 | (3) 0.140 | (1) 0.197 | (1) 0.277 | (1) 0.811 | (3) 0.106 | (2) 0.185 | (2) 0.133 | (2) 0.110 | (2) 0.130 |
| Cryptomonads | (2) 0.409 | (4) 0.186 | (5) 0.053 | (3) 0.081 | (3) 0.026 | (3) 0.228 | (5) 0.067 | (4) 0.078 | (3) 0.044 | (3) 0.027 | (3) 0.060 |
| Chaetoceros sp. <10 μm* | (5) 0.077 | (5) 0.177 | (1) 0.734 | (4) 0.017 | (3) 0.026 | (5) 0.120 | (4) 0.101 | (1) 0.346 | | (5) 0.019 | |
| Chaetoceros socialis | | | (2) 0.386 | | | | | (3) 0.139 | | | (4) 0.036 |
| Leptocylindrus danicus | | | | | | | | | | | (5) 0.029 |
| Cerataulina pelagica | | | | | | | | | | | |
| Ceratium longipes | | | | | | | | | (1) 0.144 | (1) 0.199 | (1) 0.200 |
| Dinophysis norvegica | | | | | | | | | (5) 0.031 | | |
| Amphidinium sp. | | | | | | | | | (4) 0.035 | | |
| Skeletonema costatum | (3) 0.143 | (1) 1.367 | | | (2) 0.099 | (2) 0.332 | | (5) 0.074 | | (4) 0.021 | |
| Nitzschia spp. | | (3) 0.325 | | | | | | (5) 0.074 | | | |
| Heterocapsa triquetra | (4) 0.082 | | | | | | | | | | |
| Nitzschia (cf.) delicatissime | | | | | (5) 0.024 | (4) 0.031 | | | | | |
| Chaetoceros debilis | | | (4) 0.076 | | | | (2) 0.114 | | | | |
| Rhizoselenia delicatula | | | | | | | | | | | |
| Chaetoceros compressus | | | | (2) 0.159 | | | (1) 0.218 | | | | |
| Cyanophyceae | | | | | | | | | | | |
| Chaetoceros spp. >10μm | | | | (5) 0.015 | | | | | | | |

(): rank
Number: millions of cells $L^{-1}$
*May be C. socialis

**Table 6-4. All identified phytoplankton taxa in near surface screened (20 $\mu$m ) samples collected in June 1992.**

| SPECIES | F23P | F13P | N01P | N04P | N07P | N10P | N16P | N20P | F01P | F02P | F02P-2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ALEXANDRIUM TAMARENSE | | | | | | | | 4 | | | |
| AMPHIDINIUM SPP. | | | | | 5 | | | | | | |
| CERATIUM FUSUS | 5 | 45 | 57 | 128 | 160 | 3 | 28 | 22 | 190 | 125 | 149 |
| CERATIUM LINEATUM | 2 | 15 | 20 | 3 | 38 | 8 | 30 | 58 | 3 | 8 | 2 |
| CERATIUM LONGIPES | 51 | 716 | 1616 | 512 | 2392 | 178 | 937 | 1131 | 305 | 390 | 303 |
| CERATIUM TRIPOS | | 10 | 9 | 132 | 68 | 3 | 6 | 16 | 120 | 83 | 66 |
| DINOPHYSIS ACUMINATA | 20 | | 3 | 9 | | | 52 | 52 | | 3 | |
| DINOPHYSIS NORVEGICA | 257 | 215 | 451 | 17 | 553 | 208 | 50 | 16 | 38 | 18 | 18 |
| DINOPHYSIS OVUM | 41 | 40 | 54 | 8 | 48 | 28 | 36 | 14 | | 3 | 3 |
| DIPLOPSALIS (CF) LENTICULA | | | | | | 3 | | | | | |
| DISSODINIUM ASYMMETRICUM | | 5 | | | | | | | | | |
| DISSODINUM SPP. | 2 | | | | | | 6 | 8 | | | |
| DISTEPHANUS SPECULUM | 11 | 8 | 5 | | 10 | 8 | 2 | | 3 | 8 | 2 |
| EBRIA TRIPARTITIA | 11 | 3 | | | 3 | 3 | | 2 | | | |
| EUTREPTIA SPP. | | 3 | | | | | | 2 | | | |
| GLENODINIUM ROTUNDUM | 2 | | | | | | | | | | |
| GONYAULAX DIACANTHA | 2 | | | | | | | | | | |
| GONYAULAX SPINIFERA | | | | | | | | | | | 3 |
| GYMNODINIUM SPP. | 5 | | | | 5 | 3 | | | | | |
| GYRODINIUM SPIRALE | 23 | 13 | 3 | 2 | 55 | 30 | 4 | 6 | | | |
| GYRODINIUM SPP. | | | | 2 | | | | | | | |
| HETEROCAPSA TRIQUETRA | 1138 | 78 | 98 | 35 | 30 | 318 | 1213 | 436 | | | |
| MESODINIUM RUBRUM | 9 | 8 | 3 | 9 | 20 | 15 | 16 | 34 | | | |
| PEDIASTRUM SPP. | 3 | | | | | 3 | | | | | |
| PROROCENTRUM MICANS | 68 | 25 | 72 | 12 | 48 | 33 | 34 | 80 | | 13 | 14 |
| PROTOPERIDINIUM BIPES | 14 | 13 | 18 | | 30 | 15 | 32 | 24 | | | |
| PROTOPERIDINIUM BREVIPES | | | | | | | | | | | |
| PROTOPERIDINIUM CLAUDICANS | 21 | 33 | 15 | | 13 | 25 | 6 | 34 | 8 | 3 | 2 |
| PROTOPERIDINIUM DEPRESSUM | 3 | 3 | 62 | 2 | 28 | 15 | 34 | 22 | | 3 | 2 |
| PROTOPERIDINIUM LEONIS | | 23 | | | | | | | | | |
| PROTOPERIDINIUM PELLUCIDUM | 5 | 50 | 11 | | 18 | 30 | 10 | 8 | | | 5 |
| PROTOPERIDINIUM SPP. | 189 | 138 | 98 | 36 | 133 | 188 | 72 | 142 | 10 | | 11 |
| PROTOPERIDINIUM STEINII | | | | | | | | | | | 5 |
| PROTOPERIDINIUM ACICULIFERA | | 18 | | | | | | | | | |
| SCENEDESMUS SPP. | 69 | | | | | 13 | | | | | |
| SCRIPPSIELLA TROCHOIDEA | 60 | 3 | 54 | 5 | 8 | 160 | 40 | 72 | | | |

**Values are cells $L^{-1}$.**

**Table 6-5. All identified phytoplankton taxa near the chlorophyll maximum in screened (20 μm) samples collected in June 1992.**

| SPECIES | F23P | F13P | N01P | N04P | N07P | N10P | N16P | N20P | F01P | F02P | F02P-2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ALEXANDRIUM TAMARENSE | | 3 | | | | | | | | | |
| AMPHIDINIUM SPP. | 2 | | | | | | | | | | |
| CERATIUM FUSUS | 2 | 33 | | 20 | 2 | 35 | 57 | 80 | 1321 | 286 | 551 |
| CERATIUM LINEATUM | 10 | 2 | | | | 3 | 15 | 5 | 991 | 4294 | 3083 |
| CERATIUM LONGIPES | 66 | 526 | 2042 | 1671 | 62 | 753 | 4057 | 2942 | 86657 | 113799 | 158118 |
| CERATIUM TRIPOS | 2 | 9 | 4 | | | 13 | | | 1101 | 1002 | 551 |
| DINOPHYSIS ACUMINATA | 30 | | | | | | 6 | 13 | 110 | | |
| DINOPHYSIS NORVEGICA | 102 | 626 | 292 | 33 | 44 | 1607 | 2676 | 721 | 12442 | 6298 | 3083 |
| DINOPHYSIS OVUM | 16 | 65 | 8 | 8 | 82 | 108 | 30 | 45 | | 286 | |
| DINOPHYSIS SPP. | 4 | | | 2 | | | | | | | |
| DIPLOPSALIS (CF) LENTICULA | | | | | | | | | | | |
| DISSODINIUM ASYMMETRICUM | | | | | | | | | | | |
| DISSODINUM SPP. | | | | | | | | 3 | | | |
| DISTEPHANUS SPECULUM | 34 | 2 | 20 | | 4 | 13 | 12 | 13 | 220 | 716 | 330 |
| EBRIA TRIPARTITIA | 12 | 2 | | | 2 | | 3 | 3 | | | |
| EUTREPTIA SPP. | | | | | | | | 16 | | | |
| GLENODINIUM ROTUNDUM | | | | | | 3 | | | | | |
| GONYAULAX DIACANTHA | | | | | | | | | | | |
| GONYAULAX SPINIFERA | | 2 | | | | 3 | | | | | |
| GYMNODINIUM SPP. | | | | | | 3 | | | | | |
| GYRODINIUM SPIRALE | 2 | 39 | 4 | | 24 | 50 | | 8 | | 286 | |
| GYRODINIUM SPP. | | | | | | | | | | | |
| HETEROCAPSA TRIQUETRA | 332 | 26 | 16 | | 22 | 163 | 36 | 419 | | | |
| MESODINIUM RUBRUM | 46 | 11 | 52 | 8 | 2 | 5 | 33 | 83 | | | |
| PEDIASTRUM SPP. | 4 | | | | | | | | | | |
| PROROCENTRUM MICANS | 32 | 24 | 20 | 15 | 2 | 108 | 45 | 21 | | | |
| PROTOPERIDINIUM BIPES | 2 | 21 | 4 | | 6 | 20 | 3 | 5 | | | |
| PROTOPERIDINIUM BREVIPES | | | | | 2 | | | | | | |
| PROTOPERIDINIUM CLAUDICANS | 12 | 72 | 20 | 9 | 32 | 73 | 21 | 19 | 2973 | 5439 | 2312 |
| PROTOPERIDINIUM DEPRESSUM | | 36 | 164 | 134 | 30 | 58 | 123 | 112 | 771 | 286 | 110 |
| PROTOPERIDINIUM LEONIS | | 45 | | | | | | | | | |
| PROTOPERIDINIUM PELLUCIDUM | | 38 | 40 | 2 | 38 | 35 | 3 | 29 | 110 | 143 | |
| PROTOPERIDINIUM SPP. | 88 | 45 | 144 | 42 | 54 | 345 | 108 | 155 | | 143 | 661 |
| PROTOPERIDINIUM STEINII | | | | | | | | | | | |
| PROTOPERIDINIUM ACICULIFERA | | | | | 2 | | | | | | |
| SCENEDESMUS SPP. | 36 | 2 | | | | | | 3 | | | |
| SCRIPPSIELLA TROCHOIDEA | 14 | | 8 | 3 | | 10 | | 16 | | | |

**Values are cells $L^{-1}$.**

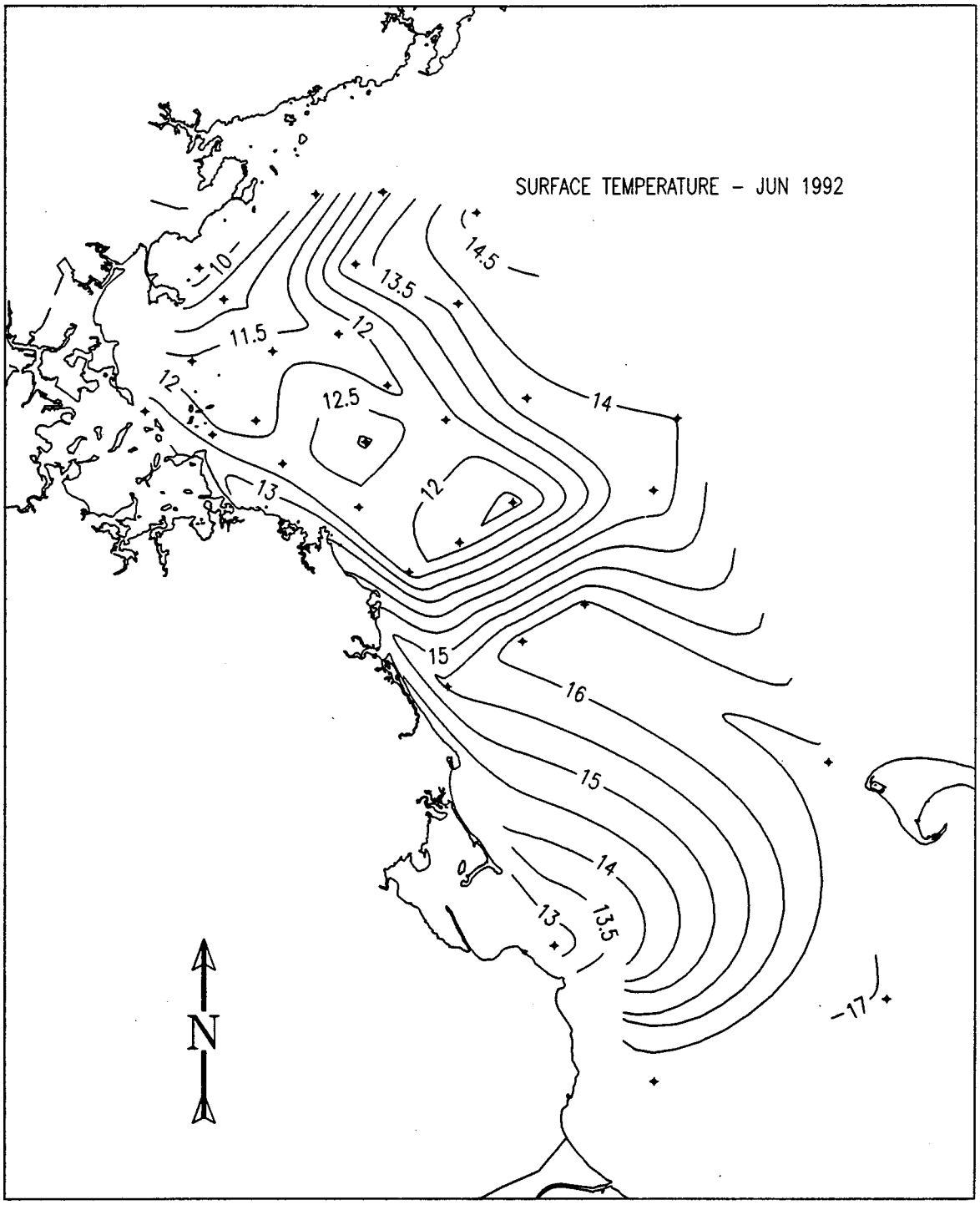



**Figure 6-1** **Surface temperature (°C) in the region in June 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.5°C.**

given in the Figure; the case of F23P showed relatively high chlorophyll-normalized rates and a good model fit with slight inhibition.

Data generally suggested $P_{max}$ occurred above ~200 $\mu$E $m^{-2}$ $sec^{-1}$. This irradiance level was seen at considerable depth at most stations considering the ambient light profiles shown in Appendix B, usually 5 m or so, sometimes greater than 10 m around mid-day (e.g. F02P).

Based on the P-I and extinction curves, in most cases, the depth of a deep chlorophyll maximum was located at a depth where probably only strong mid-day sunlight would have been strong enough to provide light at levels to sustain $P_{max}$.

Finally, we noted that highest volumetric net production rates for $P_{max}$ were recorded at F23P and N10P (see Appendix E). Here rates exceeded 0.2 mg $O_2$ $L^{-1}$ $hr^{-1}$ for surface samples.

Dark respiration rate measurements, in addition to being measured at surface and chlorophyll maximum depths, were also performed for bottle depths in bottom water below the chlorophyll maximum sample. These dark bottles were incubated separately from the P-I bottles in a BOD refrigerator set near their *in situ* collection temperature. All light-dark bottle dissolved oxygen values for these incubations are given in Appendix E. Only in two cases did either bottom water or chlorophyll maximum samples have a significant respiration suggested. The temperature was still low ($\leq$6°C) at those depths. Indeed, the surface samples (~5 to 10°C higher), more often had significant dark respiration rates.

## 6.2 Nearfield Survey (#6)

### 6.2.1 Distribution of Water Properties from Vertical Profiling

Scatter plots of high-resolution data (Figure 6-35) for nearfield stations showed a restricted range of salinity and about a 10°C range in temperature, the latter being largely responsible for the seasonal pycnocline. Highest beam attenuation was at lower salinity, in part relating to high chlorophyll. Surface chlorophyll at several stations was relatively high, though the highest values were at two mid-depth samples (Figure 6-36), both at about 20-30 m ($\sigma_T$ = 25) at different stations.

As discussed earlier, nutrients were high at the surface of one nearfield station (N07P), and occasional values were ~0.5 to 2 $\mu$M (similar to more inshore coastal stations), but the surface was generally depleted. Especially at the deeper nearfield stations, DIN increased sharply below about 10-15 m (Figure 6-37).

### 6.2.2 Distribution of Water Properties from Towing

Contoured data from the towing day (June 26) include a complete set of four tracks shown in the view to the North (Figure 6-38a). The entire inner box was towed first (clockwise starting at N13), followed by the outer Northern, then outer Southern tracks.

The sharp and shallow pycnocline from about 5-15 m is readily apparent. The eastern side of the field appeared to have a surface lens, notable by the shoaling of the $\sigma_T$ = 23.4 contour towards the surface approximately down the center of the nearfield as shown in each track. A shoaling of this density from N15 to N17 is also apparent (Figure 6-38b). Examining the temperature sections (Appendix D), it is apparent that this was a surface lens (5-10 m deep) of warmer water (>13°C). The surface of center of the nearfield (running N-S) was slightly cooler and lighter than waters east or west.

Based on chlorophyll fluorescence (Figures 6-39 a,b), there was a mid-depth distinction in eastern and western water masses associated with the above thermal and density features. Chlorophyll was highest (up to 10-13 $\mu$g $L^{-1}$) at the base of, or often just *below*, the pycnocline in the uppermost bottom water. But this feature did not occur much east of N03, N14, N18, N08 down the center of the nearfield, or at all in the track from N15-N17.

To the inshore side, while chlorophyll throughout the thin mid-depth layer (~5 m thick) was at least 2.5 $\mu$g $L^{-1}$, there were obvious patches of intense concentration of phytoplankton biomass on scales much smaller than the distance between stations (several kilometers apart).

### 6.2.3 Analysis of Small-Scale Variability

The towing data above illustrate some of the spatial biological patchiness possible in the nearfield. With the correct spacing of vertical stations, one could either miss the intense patches almost entirely or hit

each one, in either case gaining a picture of the field as much more uniform than the towing transects suggest.

In addition to spatial variation, the data may also serve to illustrate some fine scale temporal variability. Note in Figure 6-36, that a mid-water patch of high chlorophyll ($>10$ $\mu g$ $L^{-1}$) was seen at two stations. Following the track line the two peaks were seen about 10 hrs apart. It is possible that the features were one and the same, but it had moved southward several kilometers. It may, in contrast, be that both these were separate patches, both moving southward. Note that on the following day the northern outer track (Figure 6-39a) was sampled in the early afternoon, but no intense peak was seen. A peak on this day was seen between N20P and N13 (Figure 3-39b) along with a second more southerly peak ($>10$ $\mu g$ $L^{-1}$) at the outer southern track between N09 and N08, interrupted by chlorophyll around 7 $\mu g$ $L^{-1}$ at the inner southern track.

If these twin peaks were indeed separate and both moved southward over a day then general drift of bottom water (near the base of the pycnocline) on the order of 1-3 km per day might be implied. This is highly speculative with the data at hand, but by employing drogues at the time of high resolution tow-yo sampling one could most likely fully resolve patch movements and temporal dynamics.

### 6.2.4 Water Types, as Related to Nutrients, Fluorescence, and Dissolved Oxygen

Even on the vertical profiling day (Figure 6-36) maximum chlorophyll throughout the eastern part of the field was not high, suggesting that an inshore/offshore distinction across the nearfield was a strong feature at this sampling, nor was it on the towing day. We have not analyzed the nutrient or oxygen-sensor data to see if any patterns with mid-water chlorophyll are apparent. Noticing the gentle undulations of the pycnocline across the tracks suggests there may be some subtle physical dynamics along the pycnocline as it meets bottom waters. Such features might be useful to investigate in search of linkage to biological patch dynamics.

**Table 6-1. Analysis of surface water types in June 19192.**

| Water Type | | Characteristics by Parameter | | | | |
|---|---|---|---|---|---|---|
| **Classification** | **Geographic Descriptor** | **T (°C)** | **S (PSU)** | **Beam Attenuation ($m^{-1}$)** | **Fluorescence ($\mu g\ L^{-1}$)** | **Nutrients** |
| Coastal | Most of nearshore western Mass. Bay (~less than 30m) | 12.5 - 15.5 | <30.8 - 31.0 | ~1 - 2.8 | 2 - 7 | low N, low Si |
| Northern Transect | Transect along northern entrance to Mass. Bay, (F20-F22) surface water | 11 - 14.5 | 31.2 - 31.4 | <1 | <1 | low N, low Si |
| Nearfield | Within nearfield sampling grid | ~11 - 13 | ~31.0 - 31.2 | <1.2 - 2.4 | ~1 - 3 | low N, low Si (one exception) |
| Offshore | Mainstem Mass. Bay (~ greater than 40m) | 12 - 14 | ~30.6 - 31.2 | <1 - 1.4 | ~1 | low N, low Si |
| Cape Cod | All Cape Cod Bay stations | 13 - 17 | <30.8 - 31.0 | <1 - 1.4 | <1 - 2 | low N, medium Si |

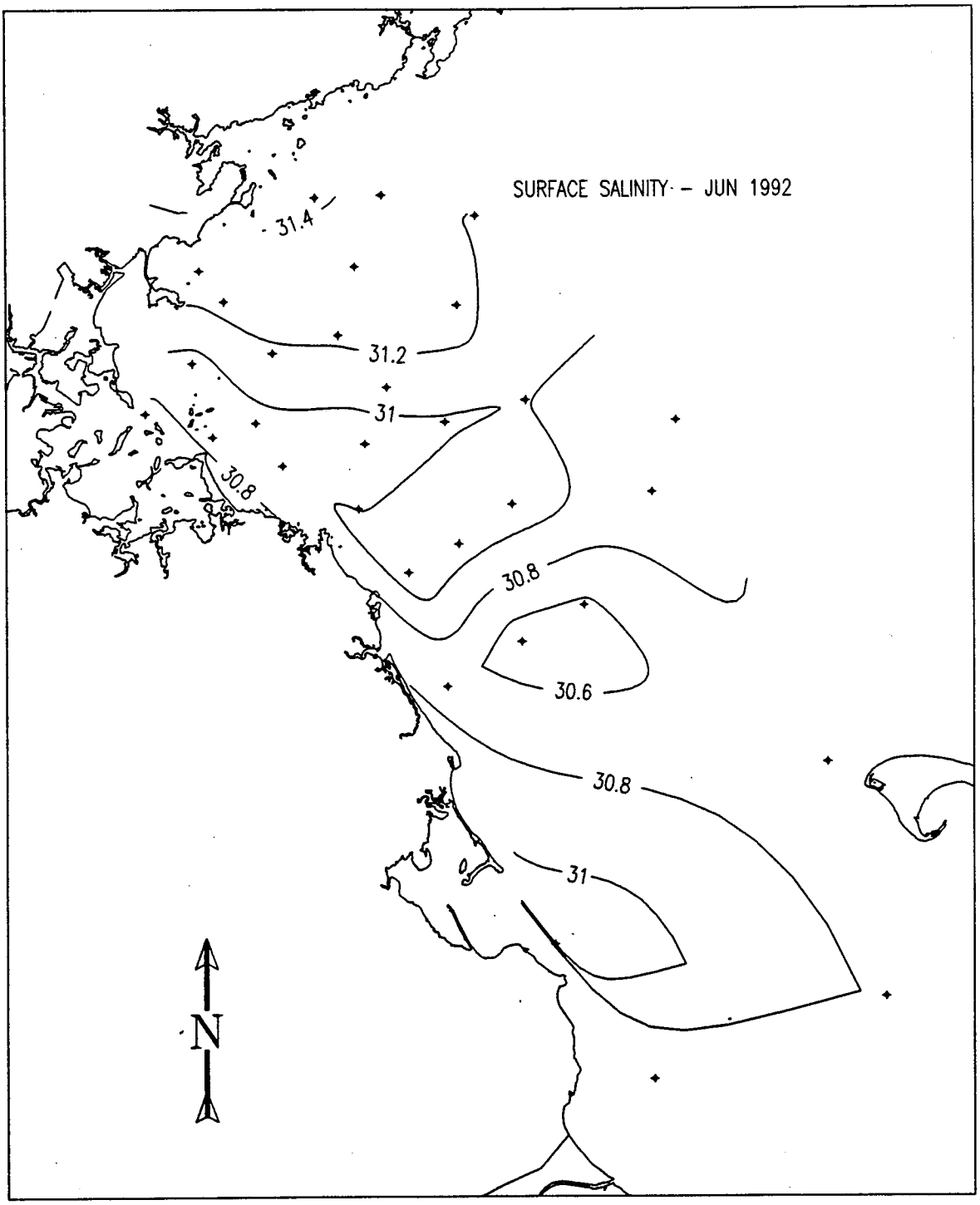



**Figure 6-2** **Surface salinity (PSU) in the region in June 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.2 PSU.**

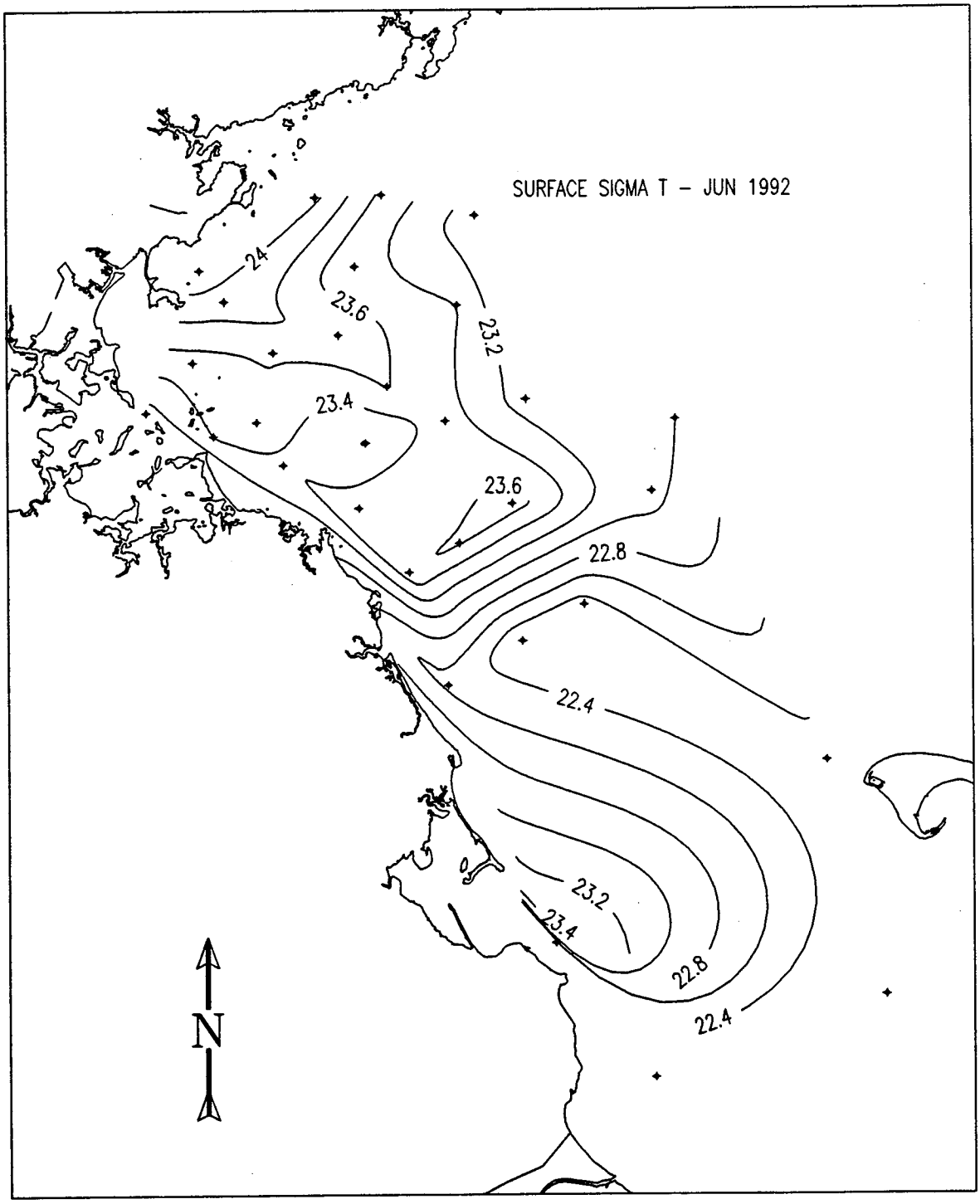



**Figure 6-3** Surface $\sigma_T$ in the region in June 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.2 units.

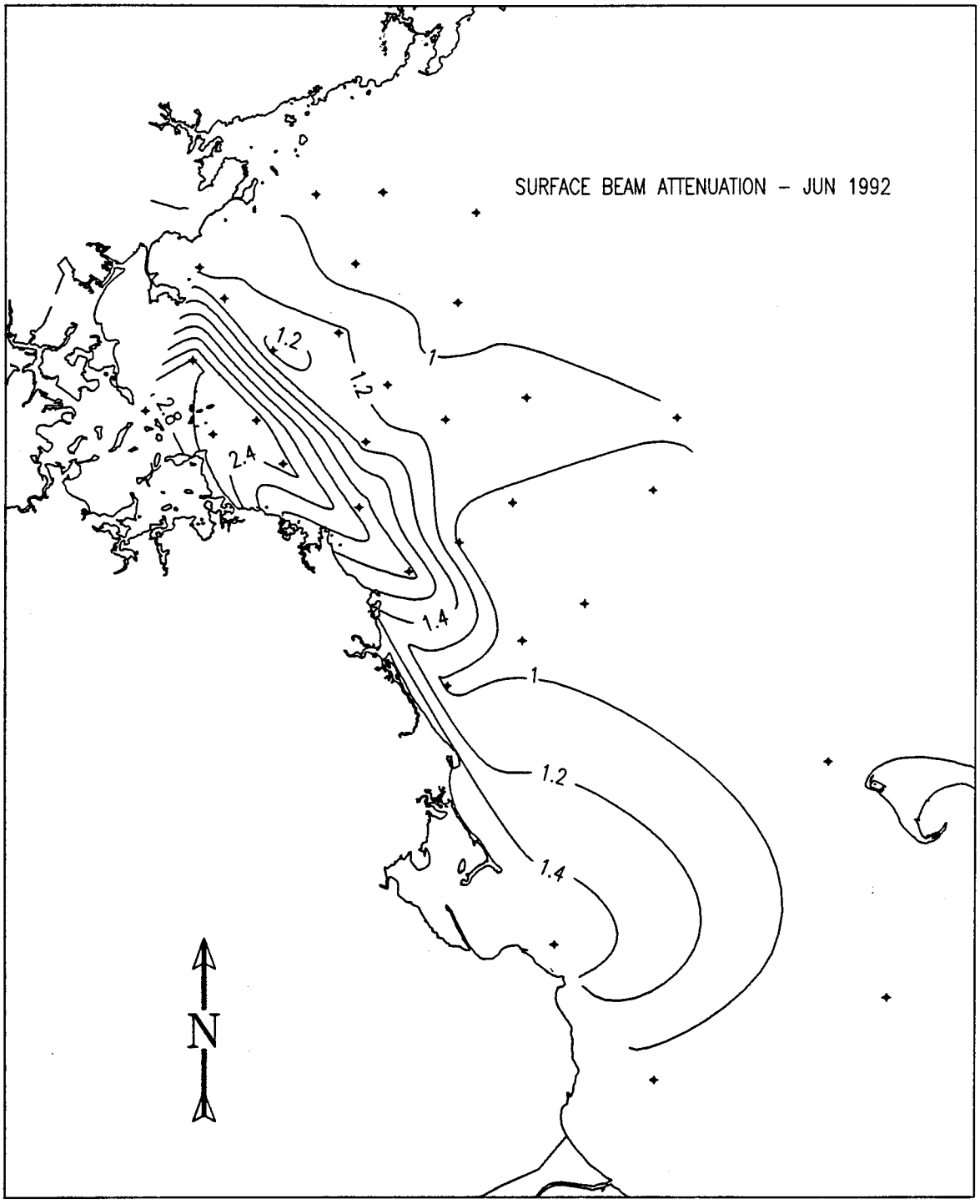



**Figure 6-4** **Surface beam attenuation ($m^{-1}$) in the region in June 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.2 $m^{-1}$.**

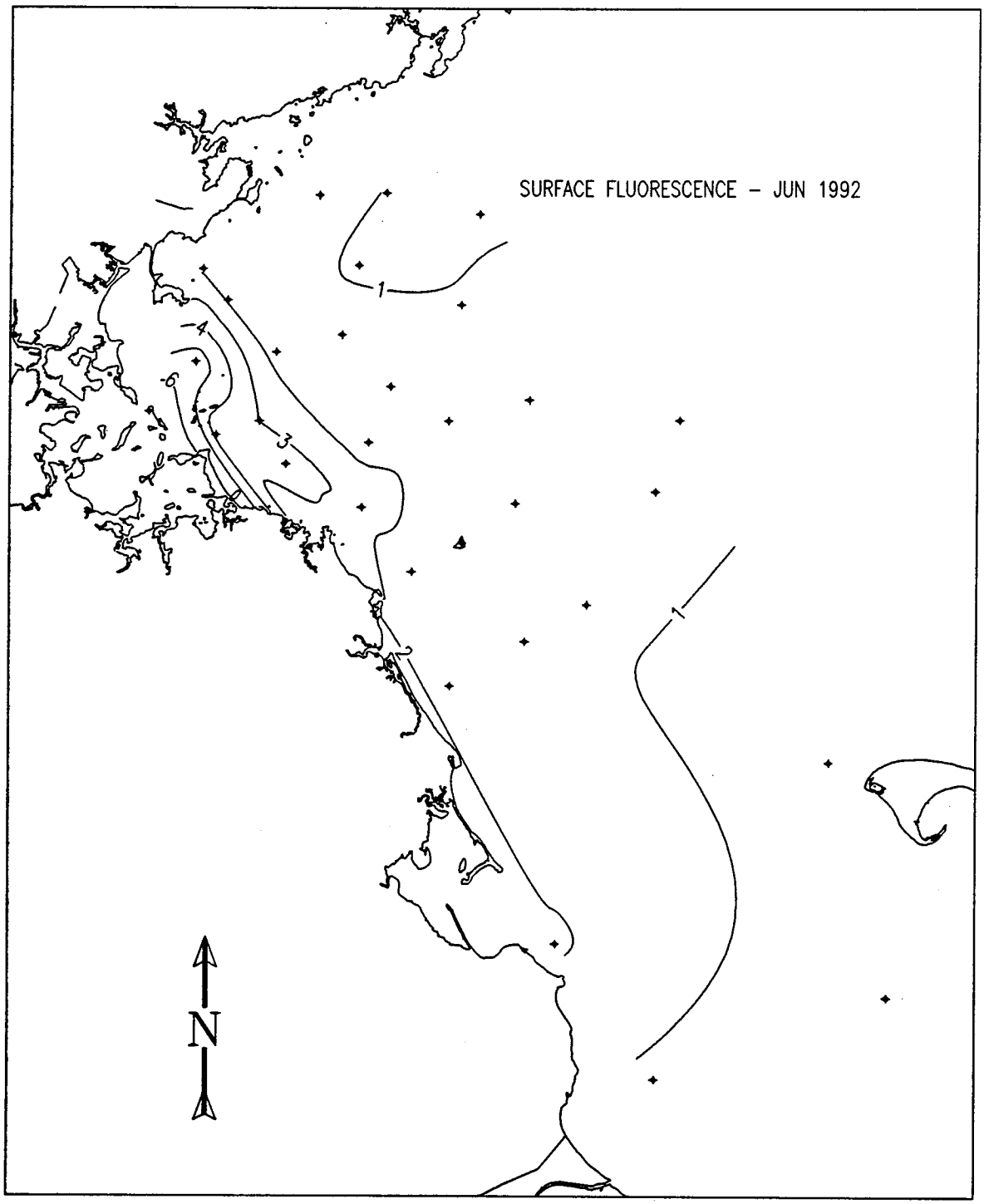



**Figure 6-5** **Surface *in situ* fluorescence (as $\mu$g Chl $L^{-1}$) in the region in June 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 $\mu$g $L^{-1}$.**

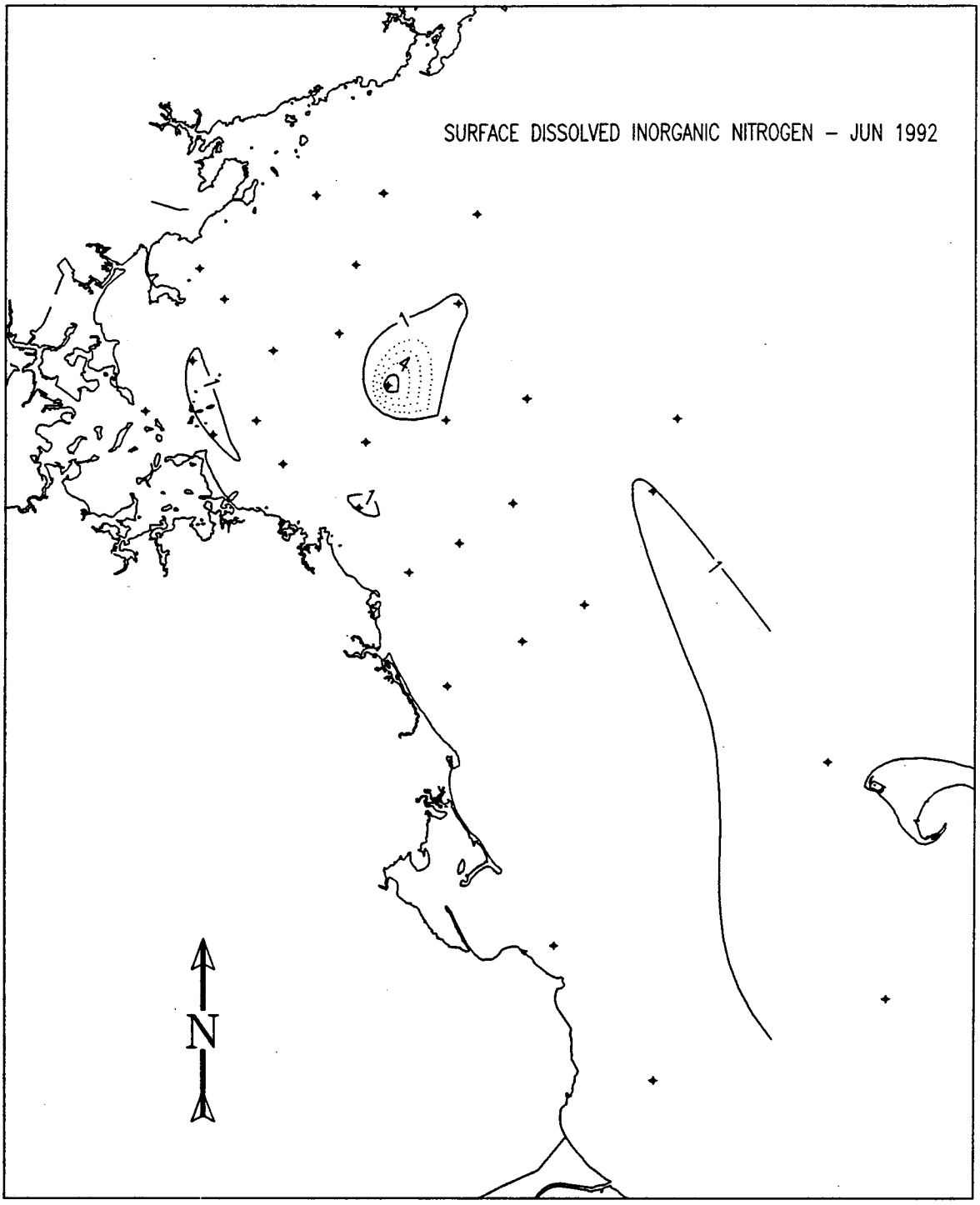



**Figure 6-6** **Surface dissolved inorganic nitrogen (DIN, μM) in the region in June 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 μM.**

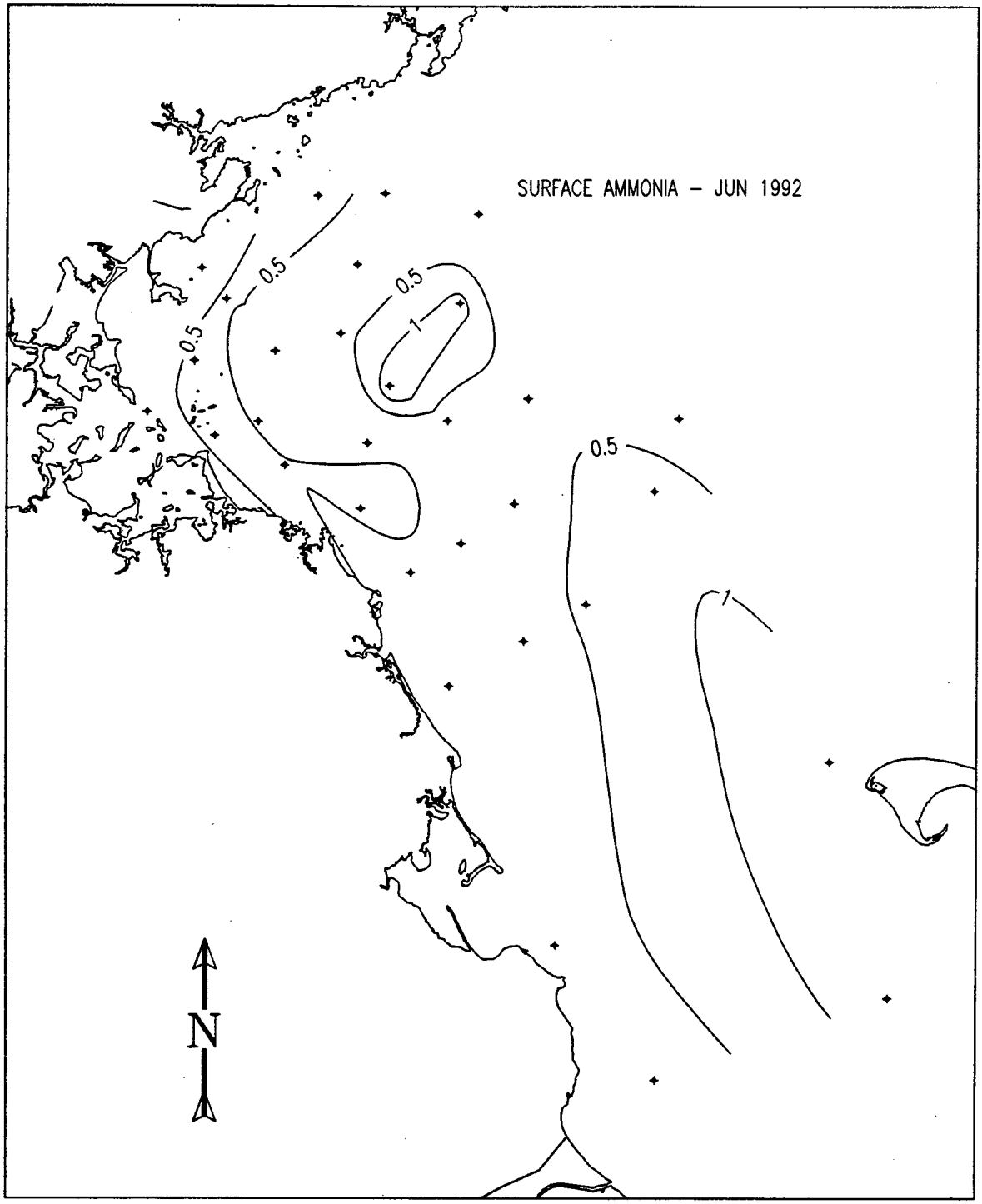



**Figure 6-7** **Surface ammonia ($\mu$M) in the region in June 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.5 $\mu$M.**

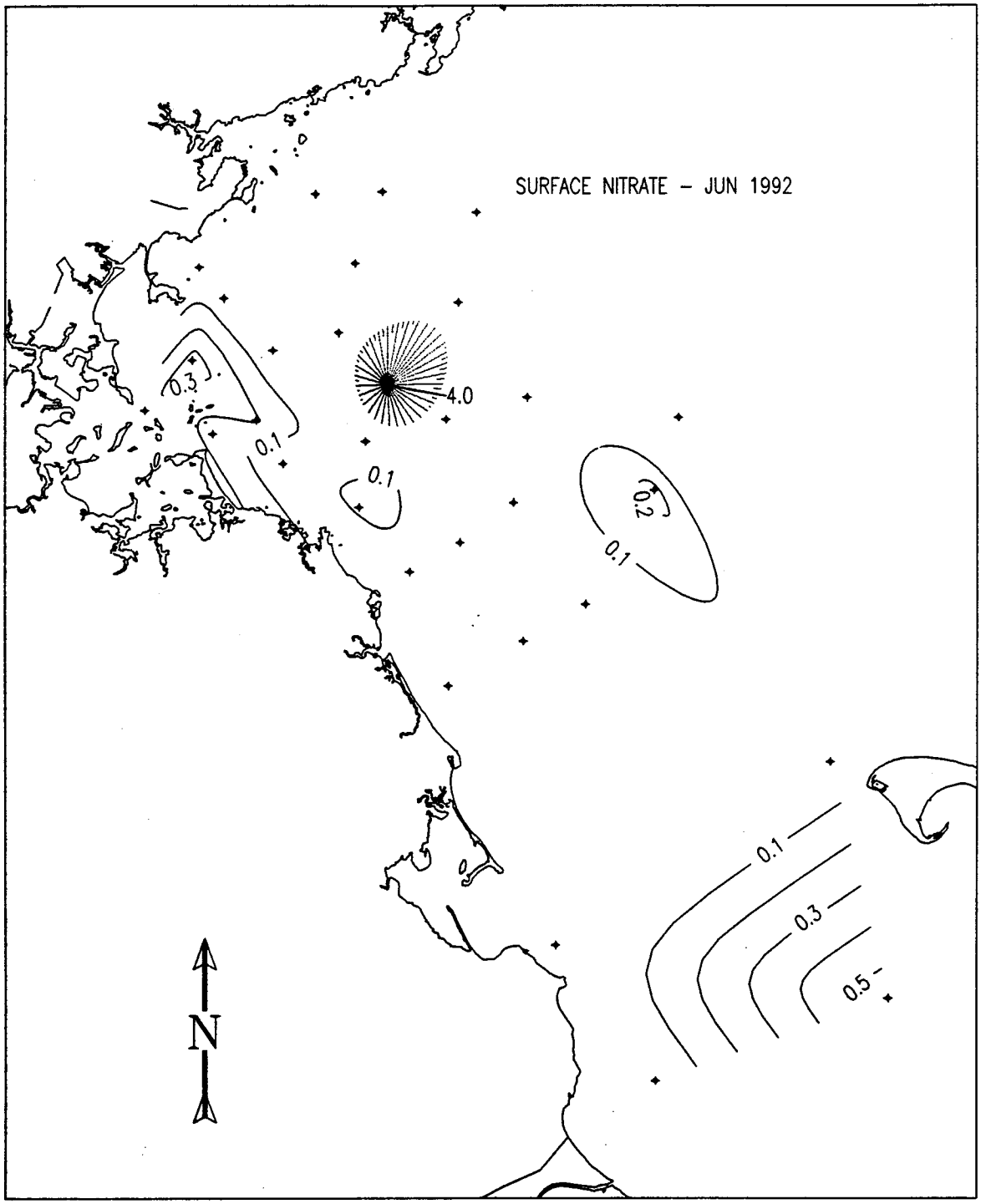



**Figure 6-8** Surface nitrate ($\mu$M) in the region in June 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.1 $\mu$M.

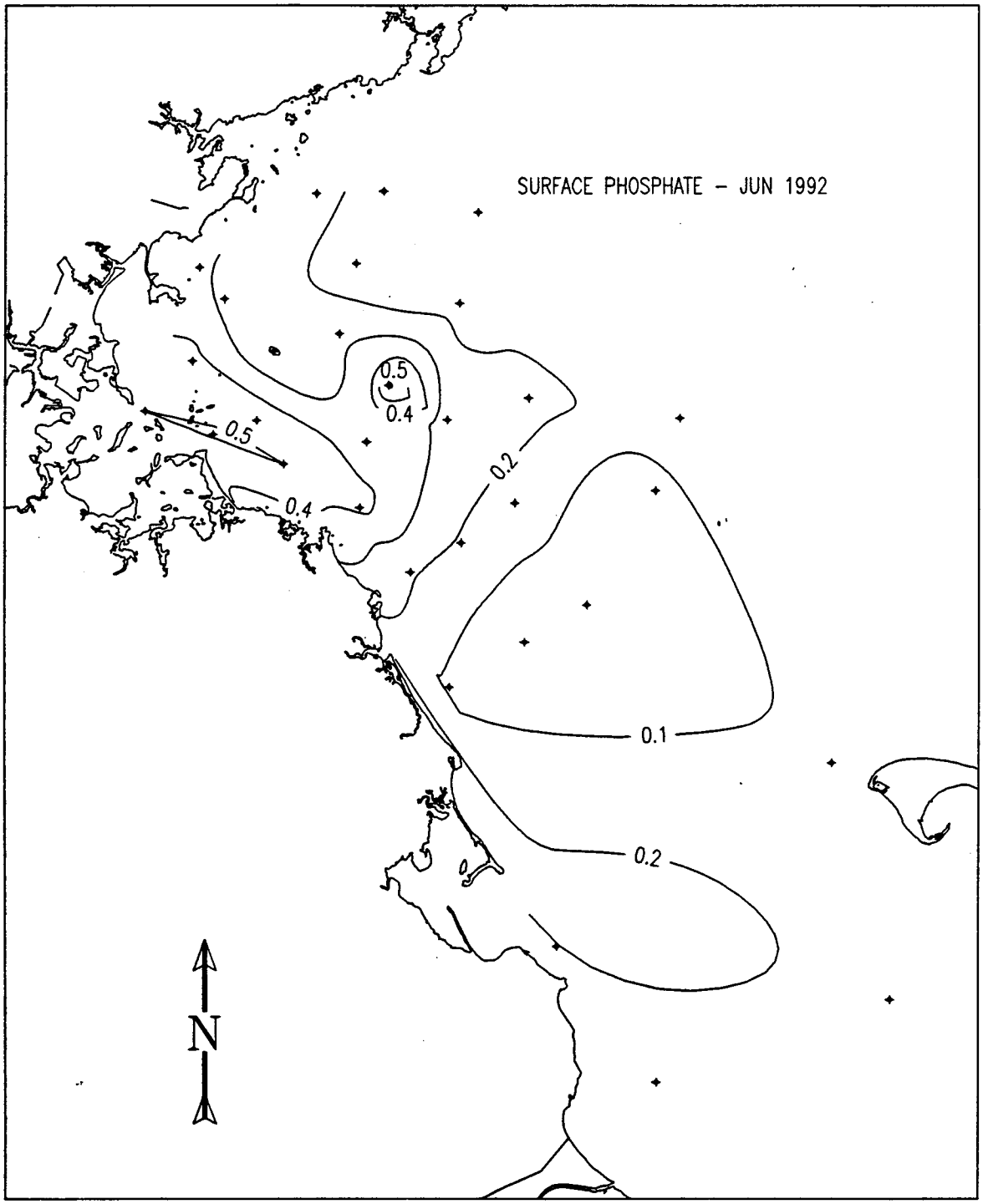



**Figure 6-9** **Surface phosphate ($\mu$M) in the region in June 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.1 $\mu$M.**

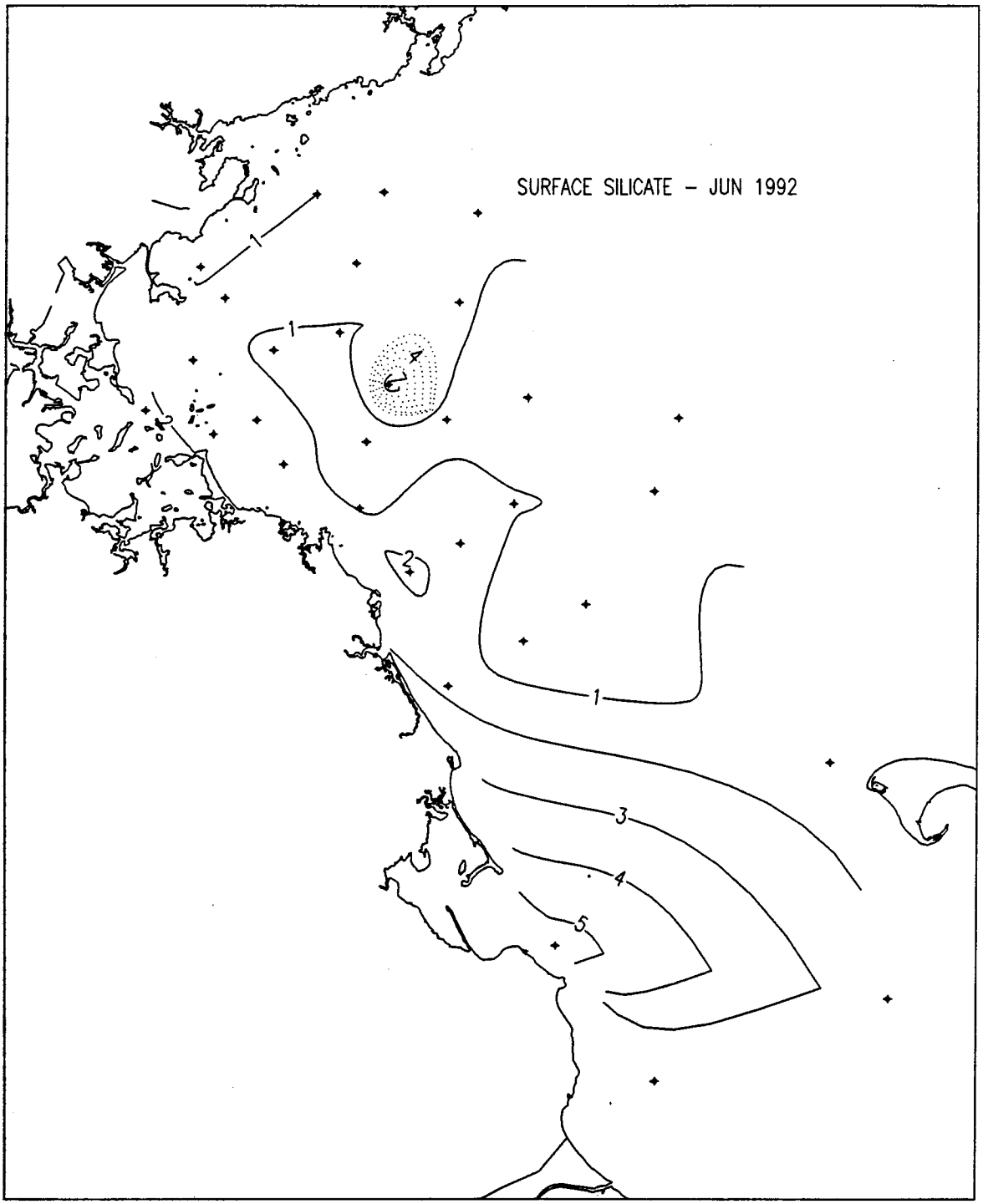



**Figure 6-10** Surface silicate ($\mu$M) in the region in June 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 $\mu$M.

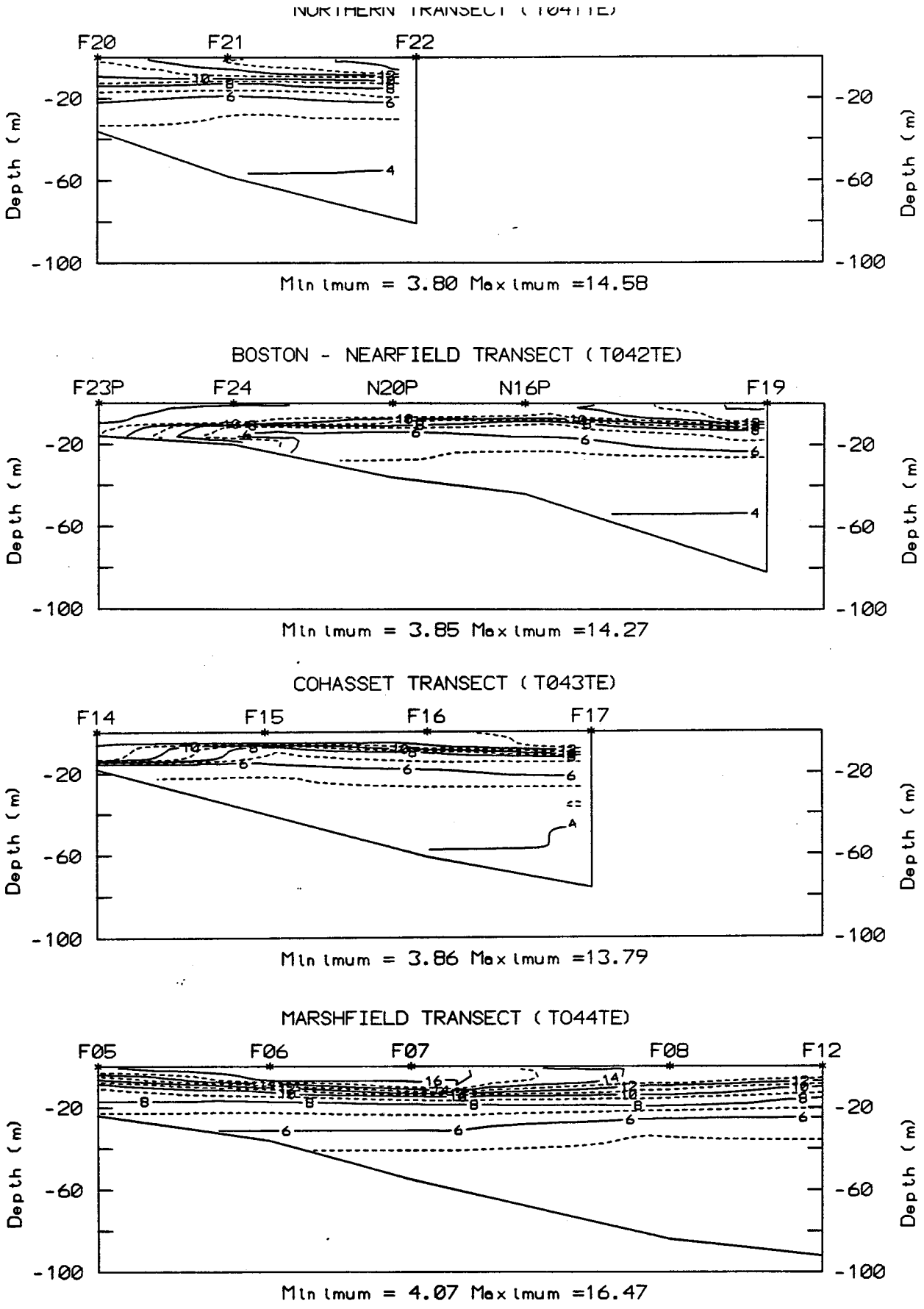



**Figure 6-11 Vertical section contours of temperature in June for standard transects (see Figure 3-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 2°C.**

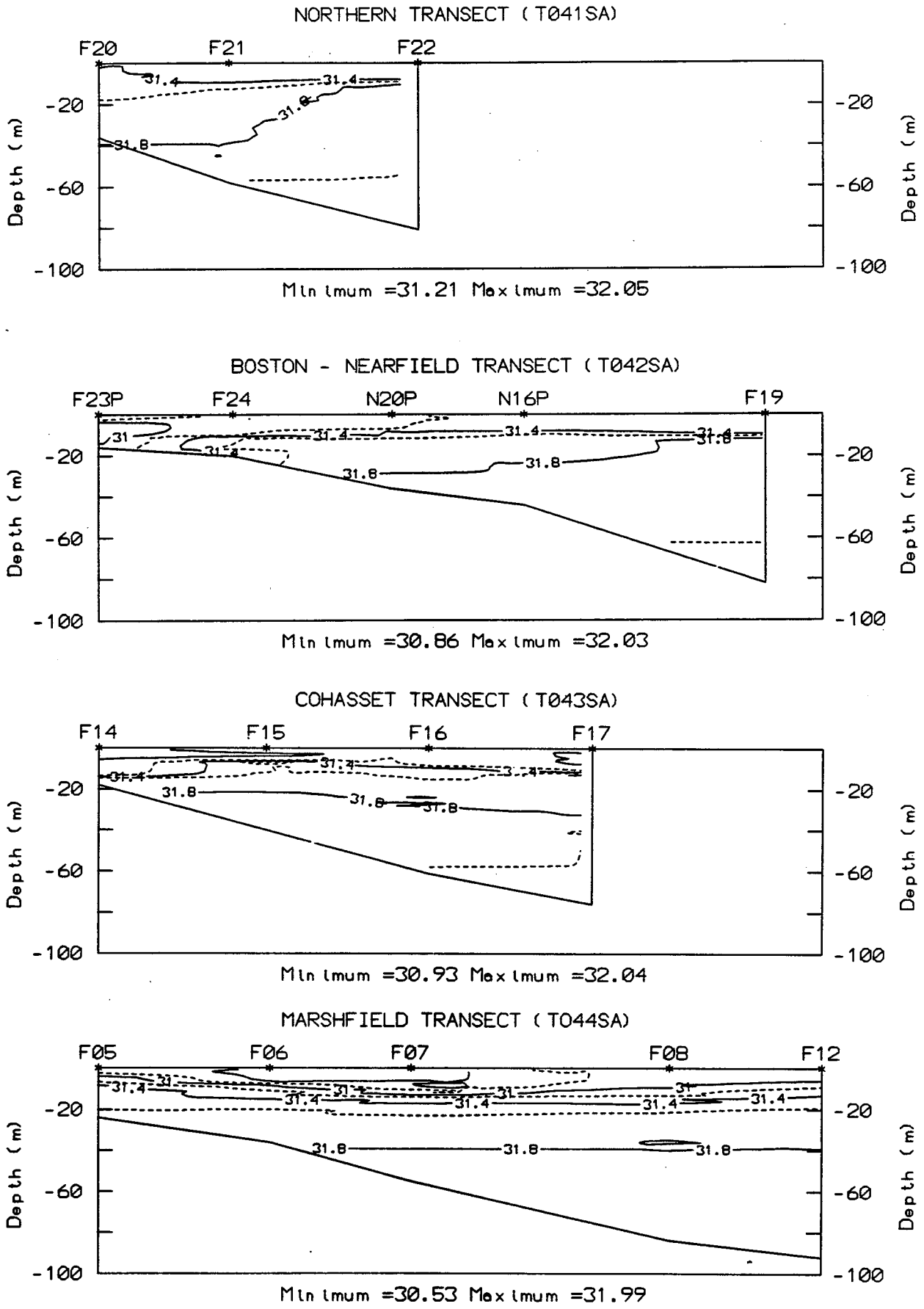



**Figure 6-12 Vertical section contours of salinity in June for standard transects (see Figure 3-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 0.2 PSU.**

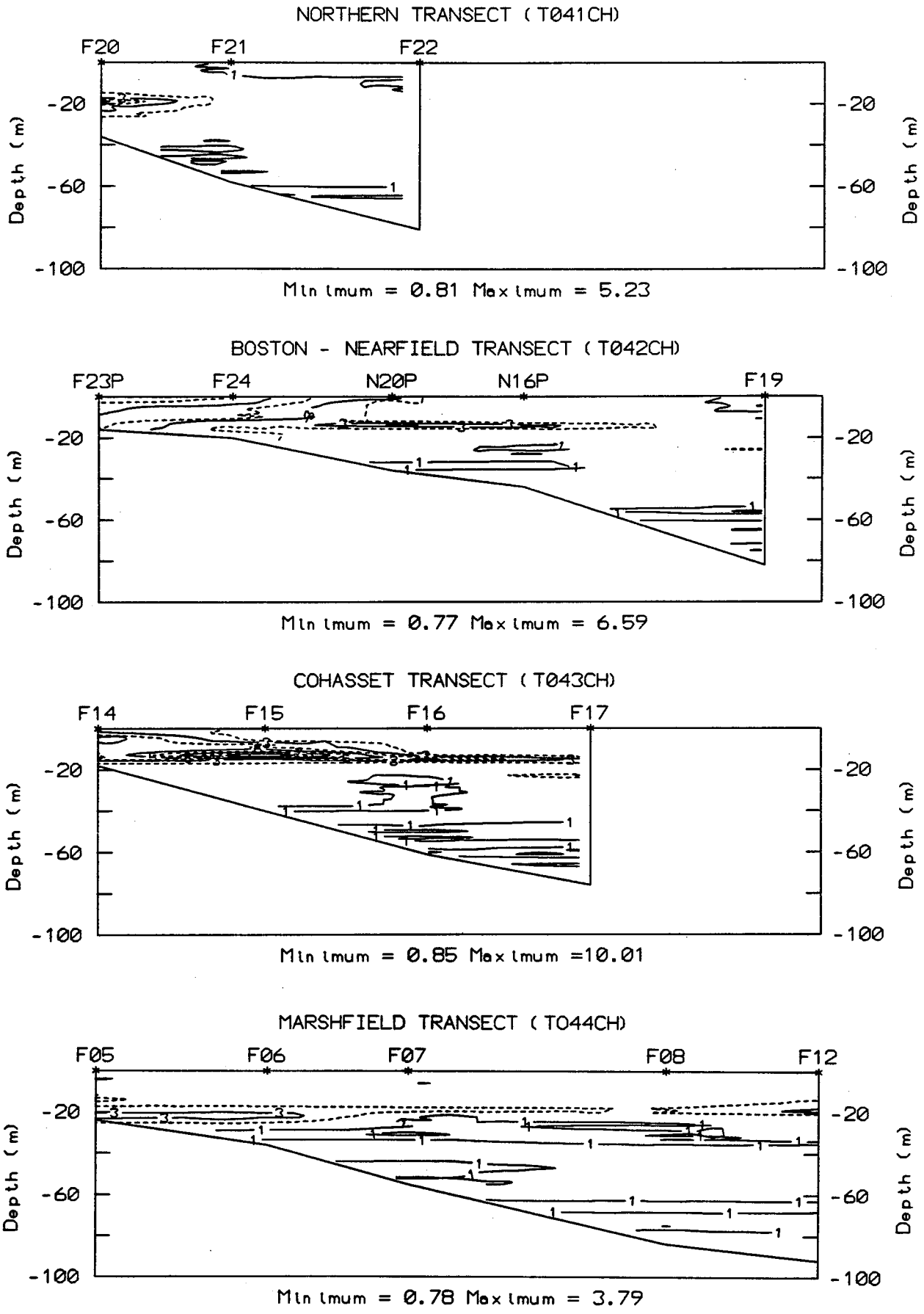



**Figure 6-13** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) in June for standard transects (see Figure 3-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 1 $\mu$g $L^{-1}$.**

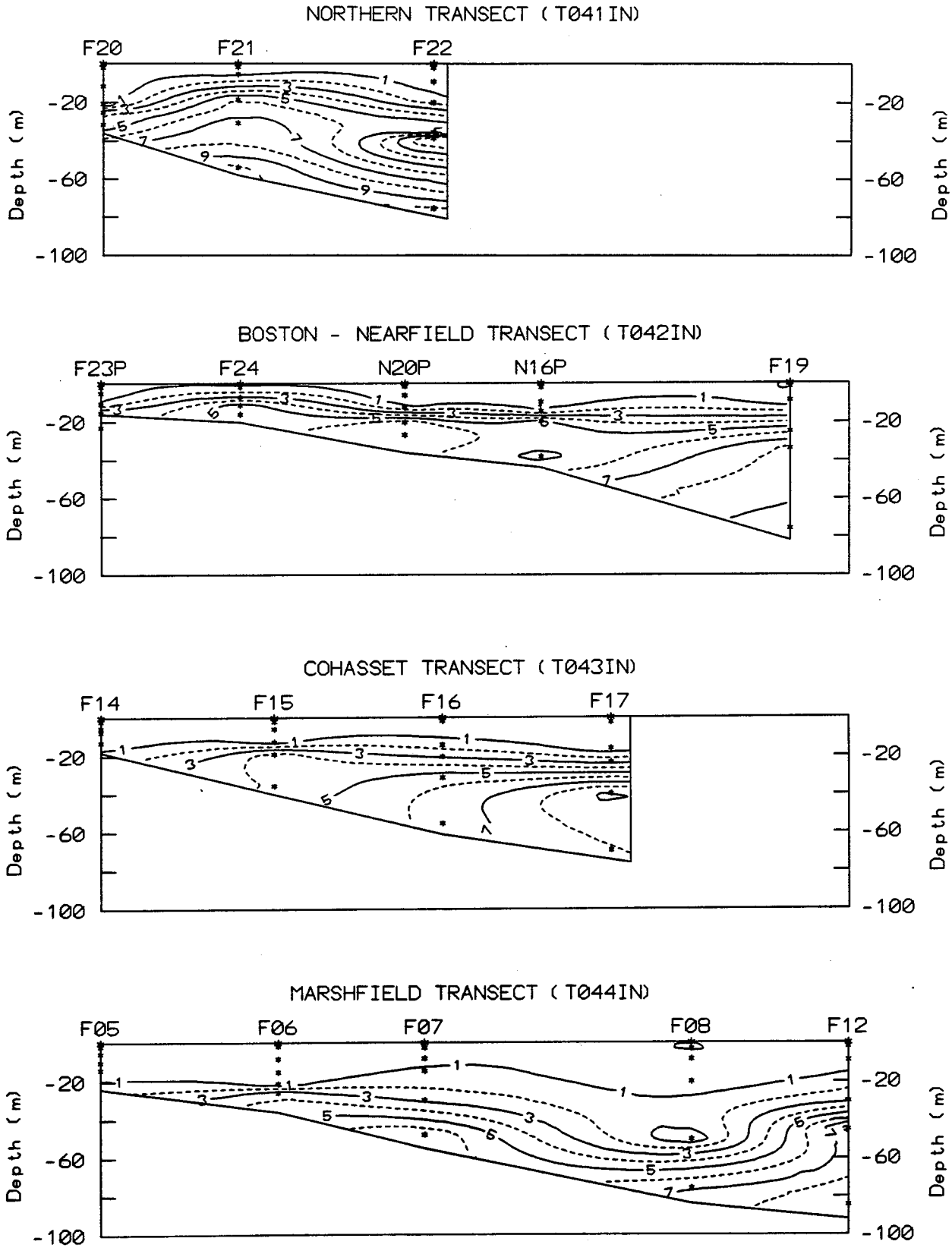



**Figure 6-14 Vertical section contours of dissolved inorganic nitrogen (DIN, $\mu$M) in June for standard transects (see Figure 3-11). The data used to produce contours are from discrete bottle samples as given in Appendix A. The contour interval is 1 $\mu$M.**

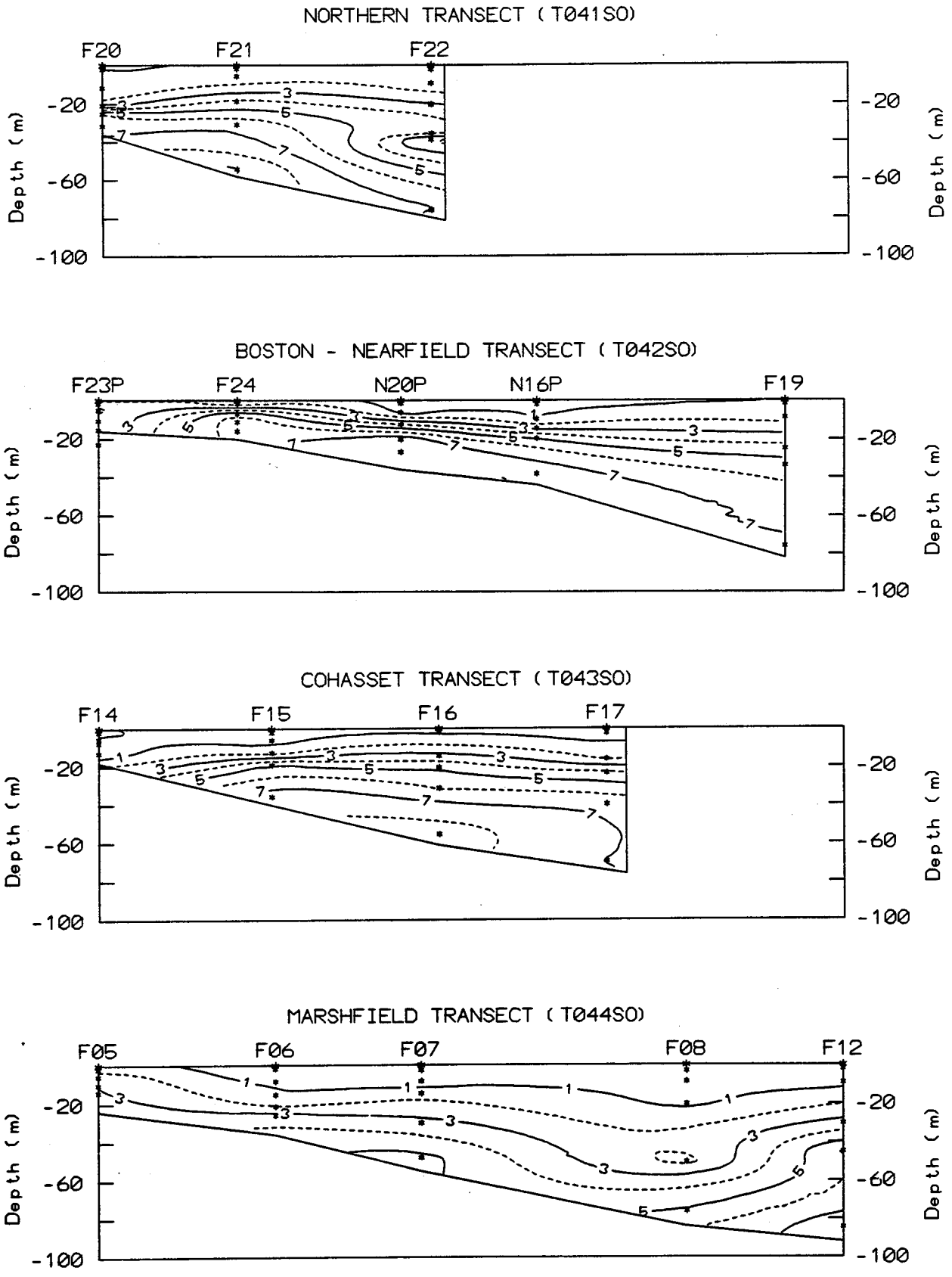



**Figure 6-15 Vertical section contours of silicate ($\mu$M) in June for standard transects (see Figure 3-11). The data used to produce contours are from discrete bottle samples as given in Appendix A. The contour interval is 1 $\mu$M.**

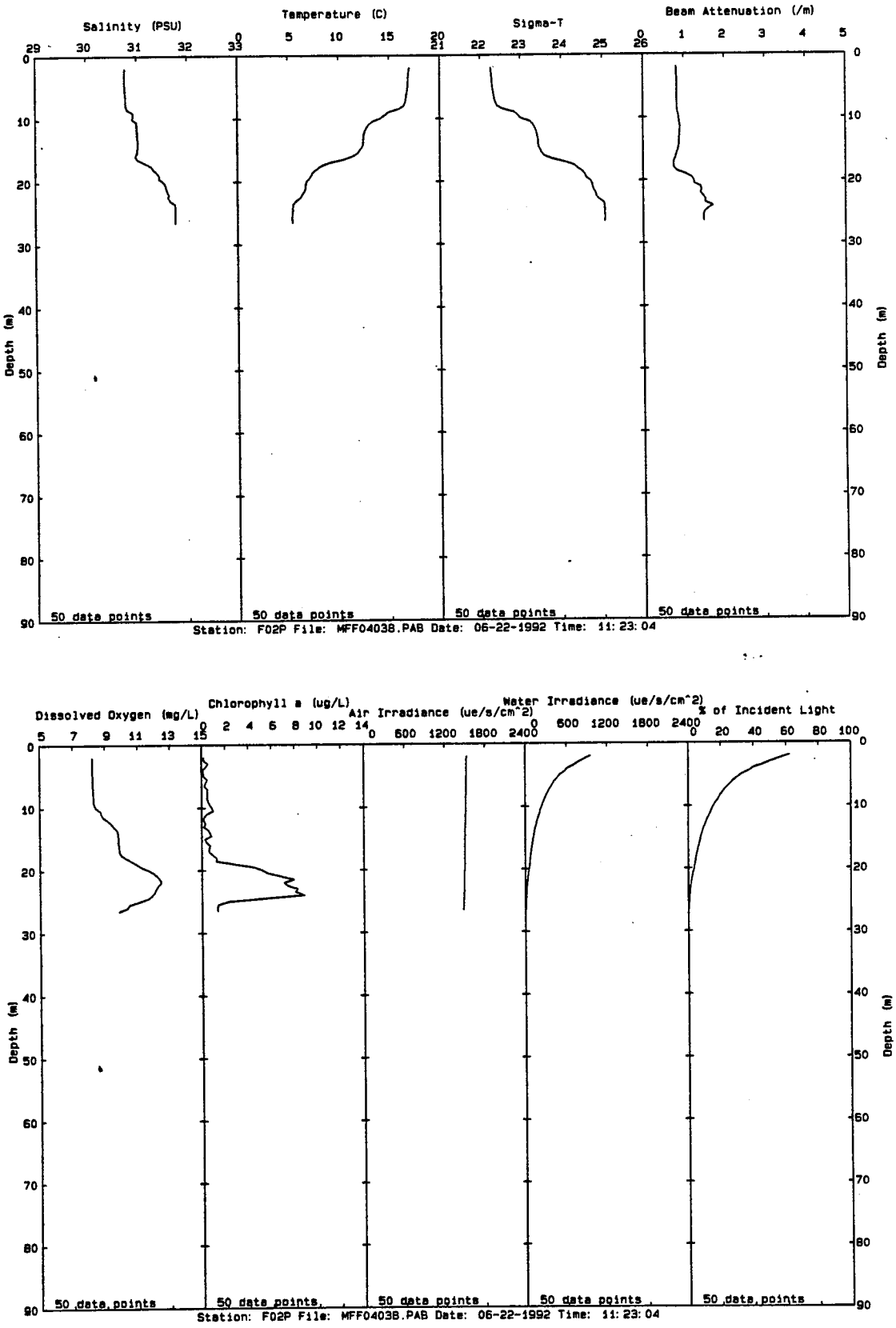



**Figure 6-16 Vertical profile plots of data acquired by *in situ* sensor package during downcasts at all station F02P in June 1992. Note the high subsurface chlorophyll, with an assocaited dissolved oxygen maximum near 20 m in the upper bottom water.**

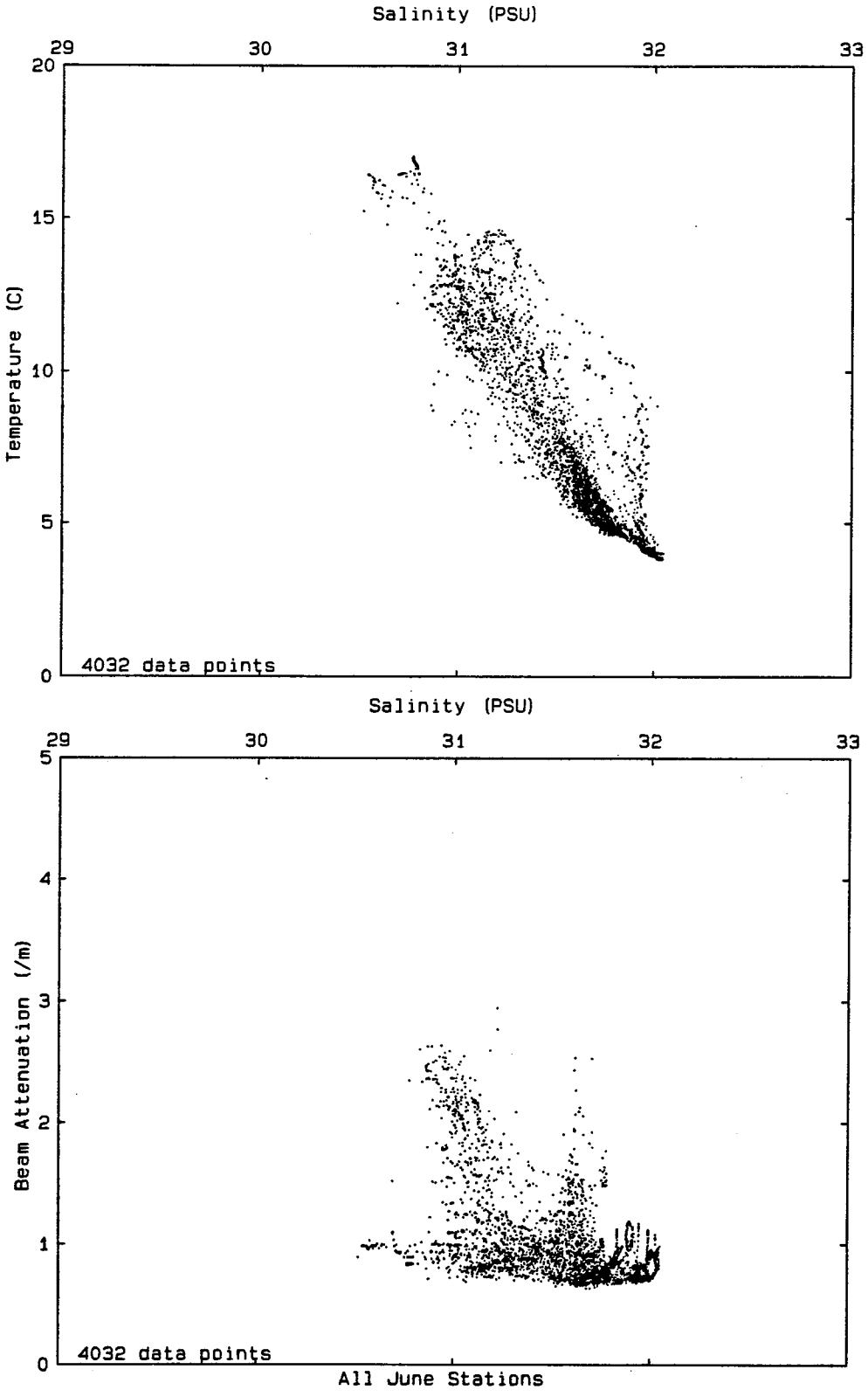



**Figure 6-17a** **Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in June 1992. Individual station cast plots that were used to produce this composite are in Appendix B.**

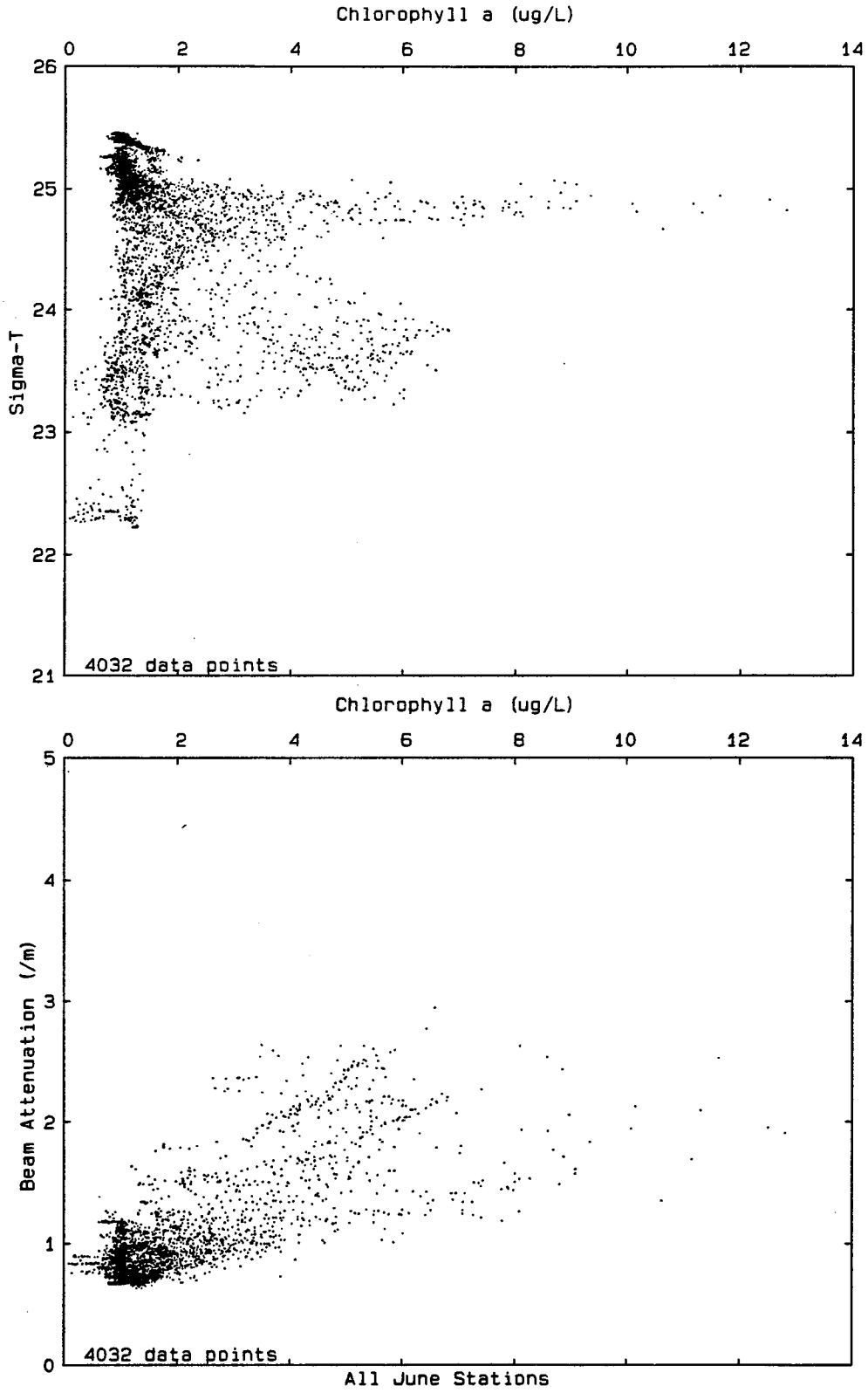



**Figure 6-17b** **Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in June 1992. Individual station cast plots that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

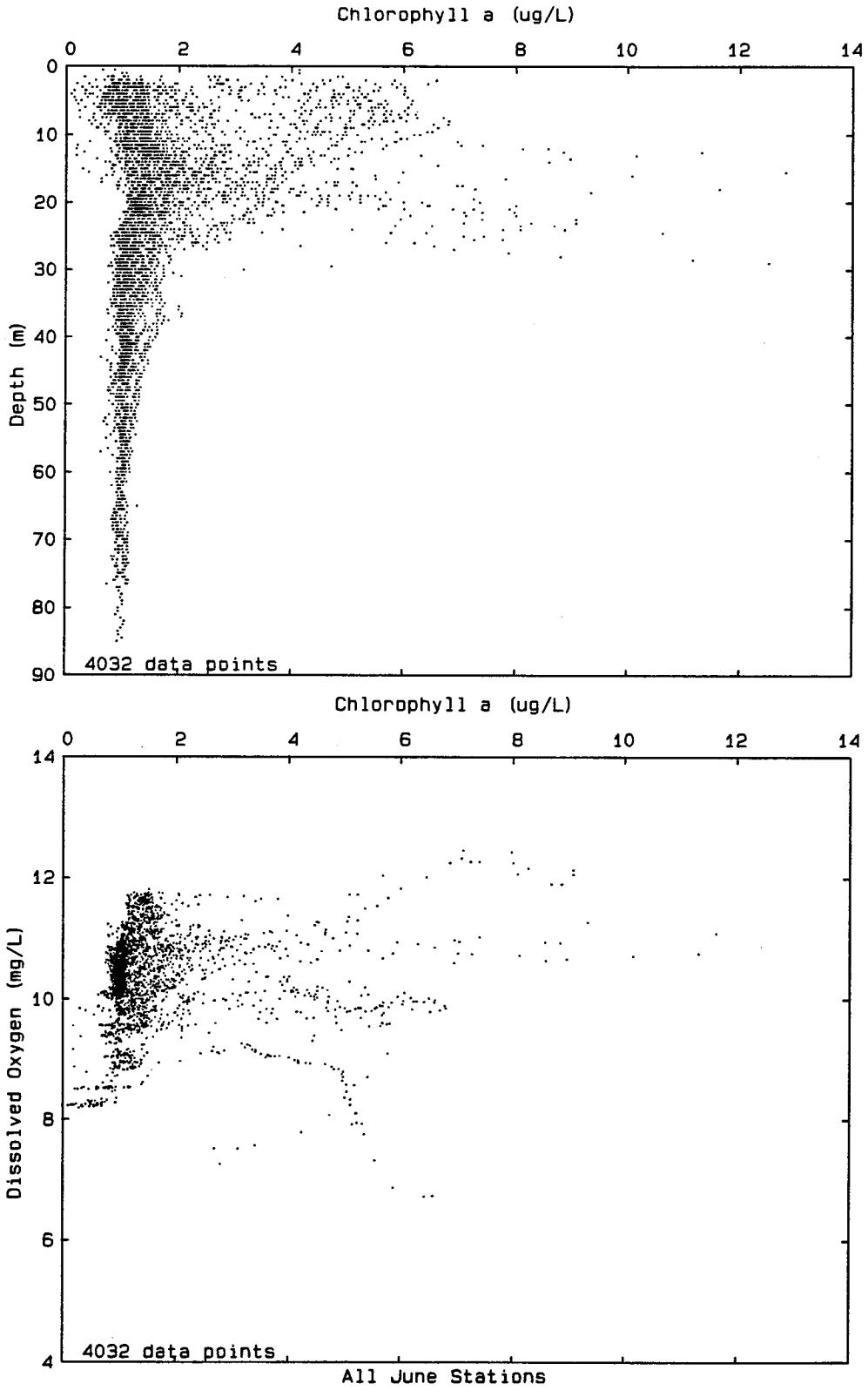



**Figure 6-17c** **Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in June 1992. Individual station cast plots that were used to produce this composite are in Appendix C. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

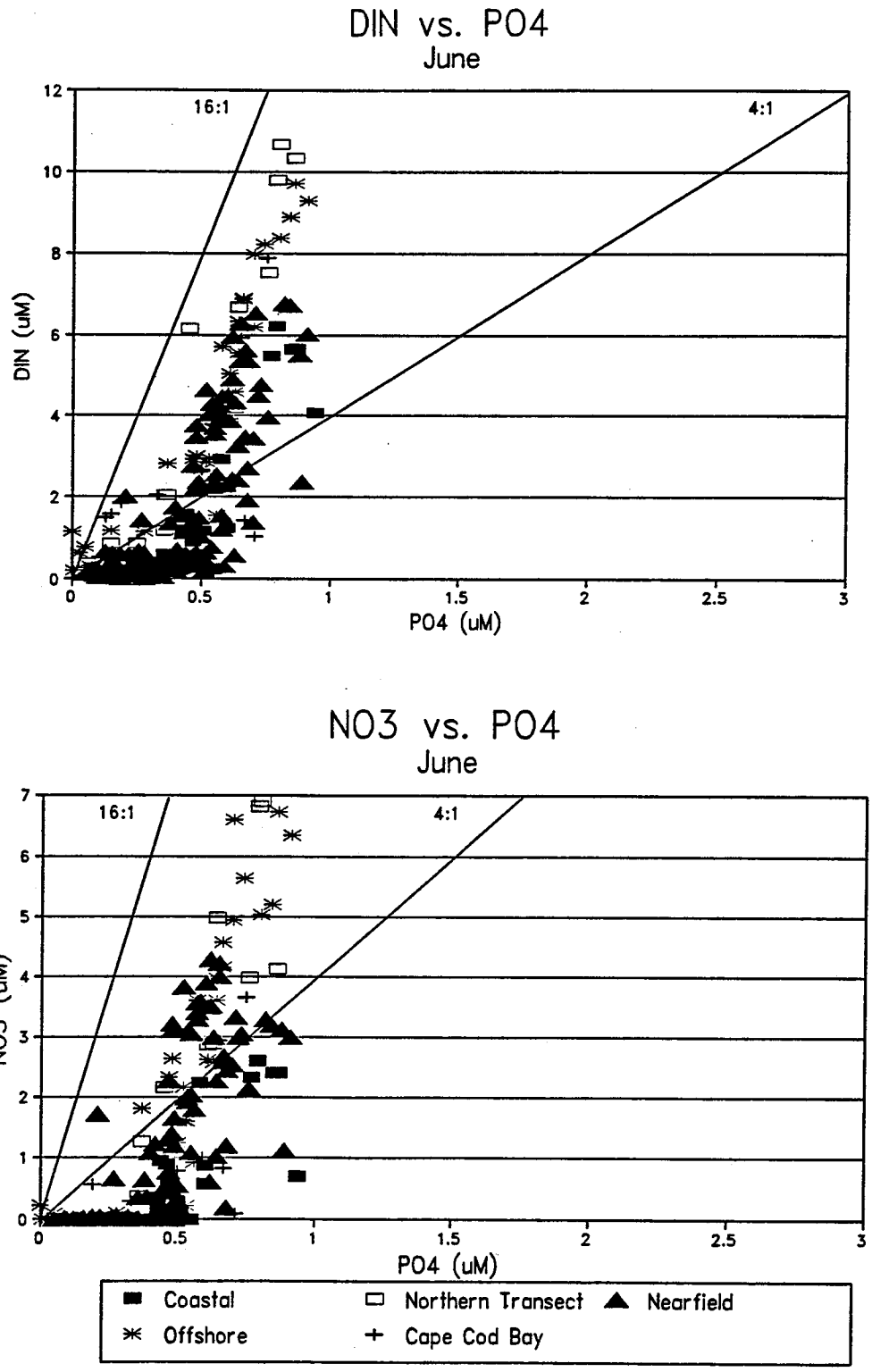



**Figure 6-18** **Scatter plots of nitrogen forms vs. phosphate during June 1992. All stations and depths are included, and data are given in Appendix A. Lines show constant proportions of nitrogen relative to phosphorous at two different N:P ratios. Station groups are defined in Figure 3-18.**

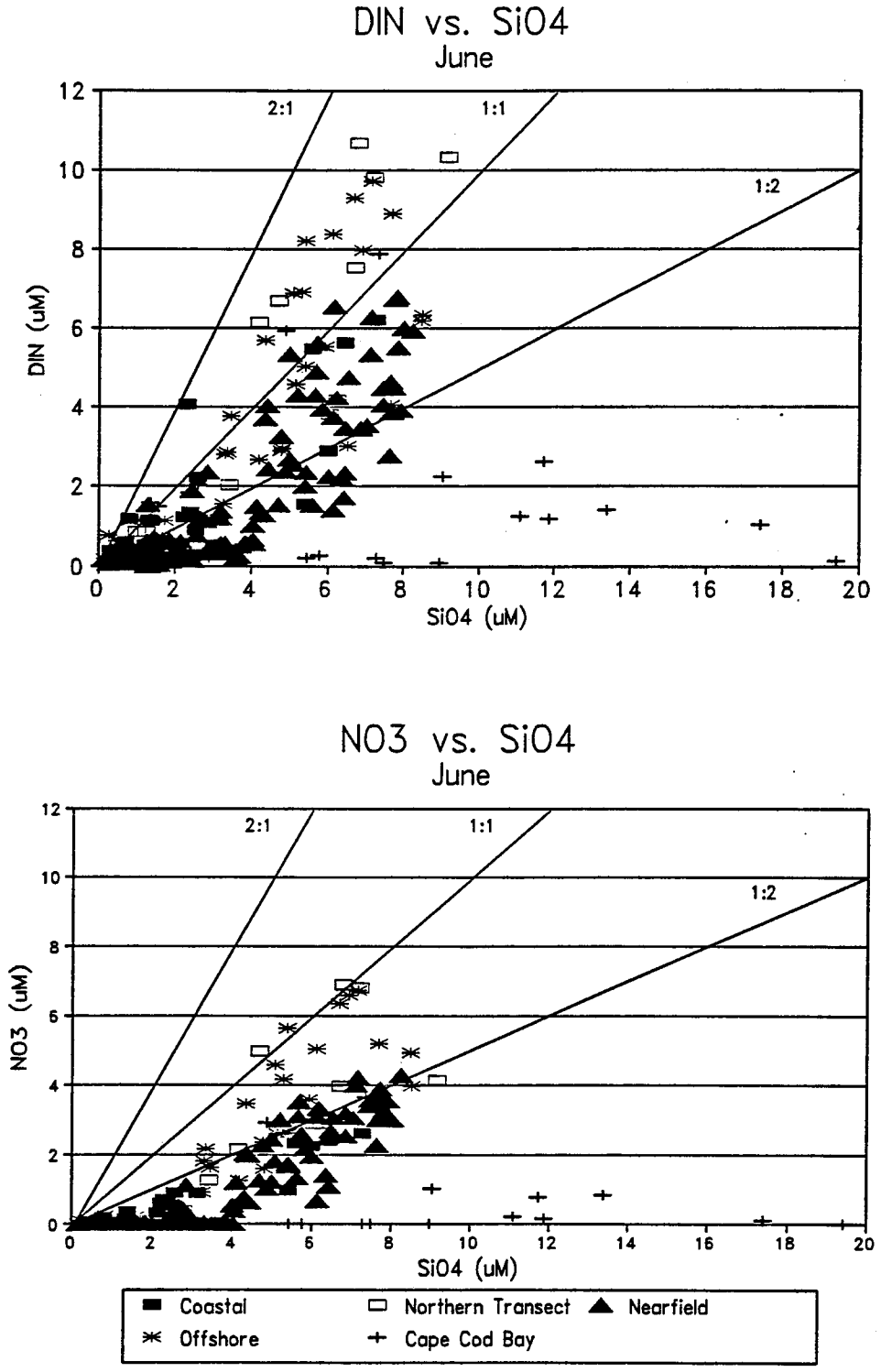



**Figure 6-19 Scatter plots of nitrogen vs. silicate during June 1992. All stations and depths are included, and data are given in Appendix A. Lines show constant proportions of nitrogen relative to silicate across a range of N:Si ratios.**

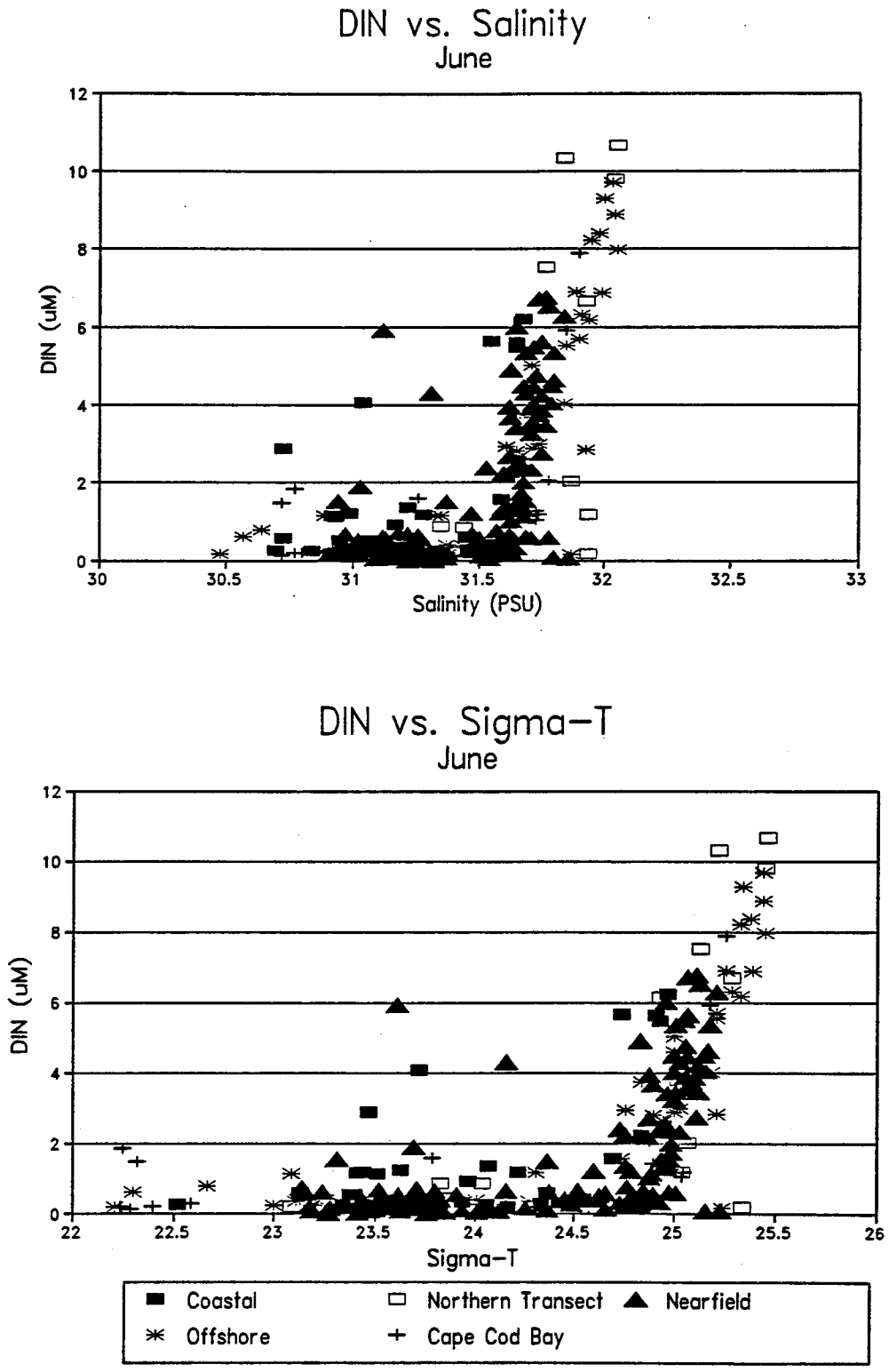



**Figure 6-20 Dissolved inorganic nitrogen vs. salinity and $\sigma_T$ in June 1992. All stations and depths are included, and data are given in Appendix A.**

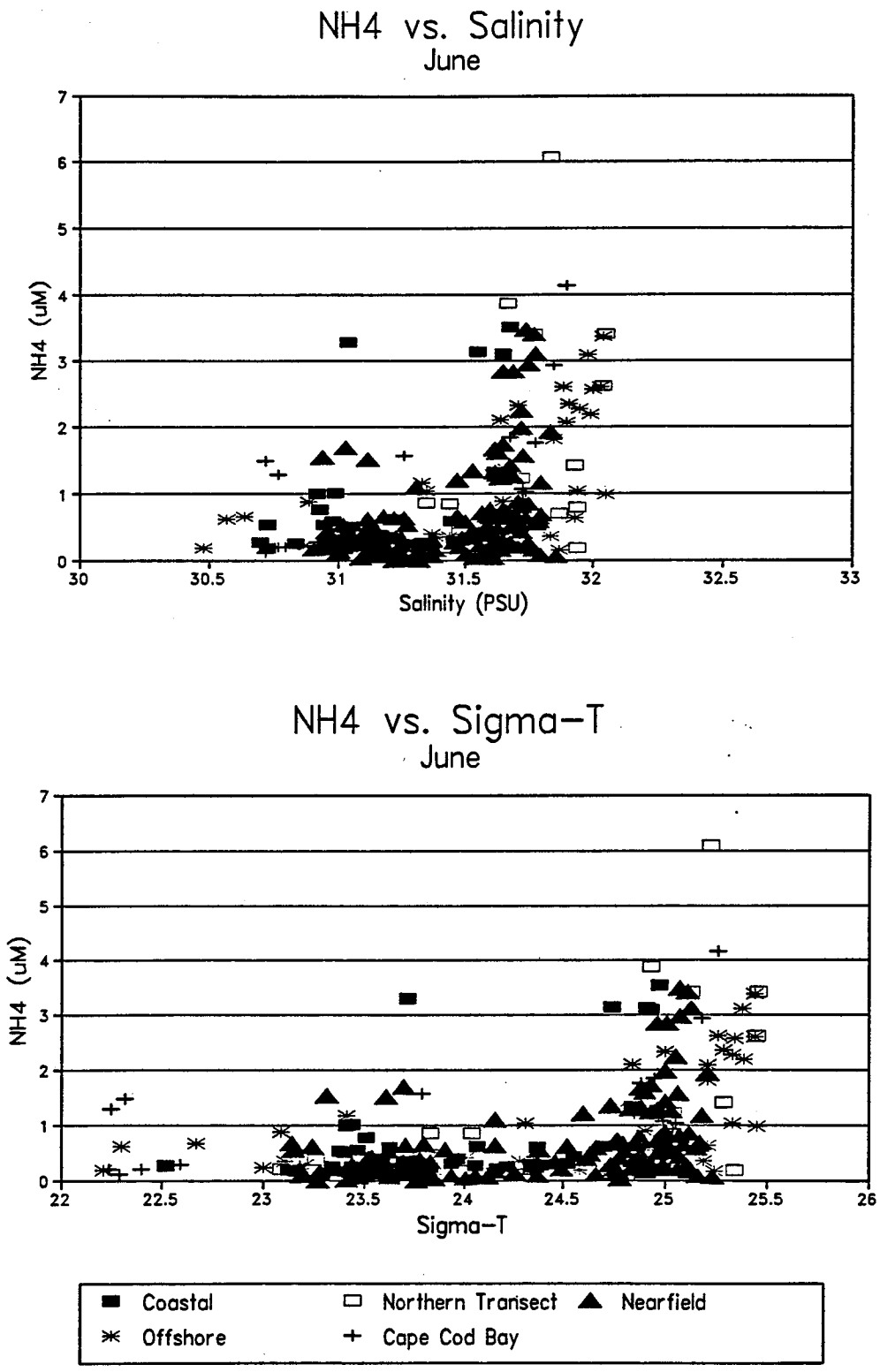



**Figure 6-21 Ammonia vs. salinity and $\sigma_T$ in June 1992. All stations and depths are included, and data are given in Appendix A.**

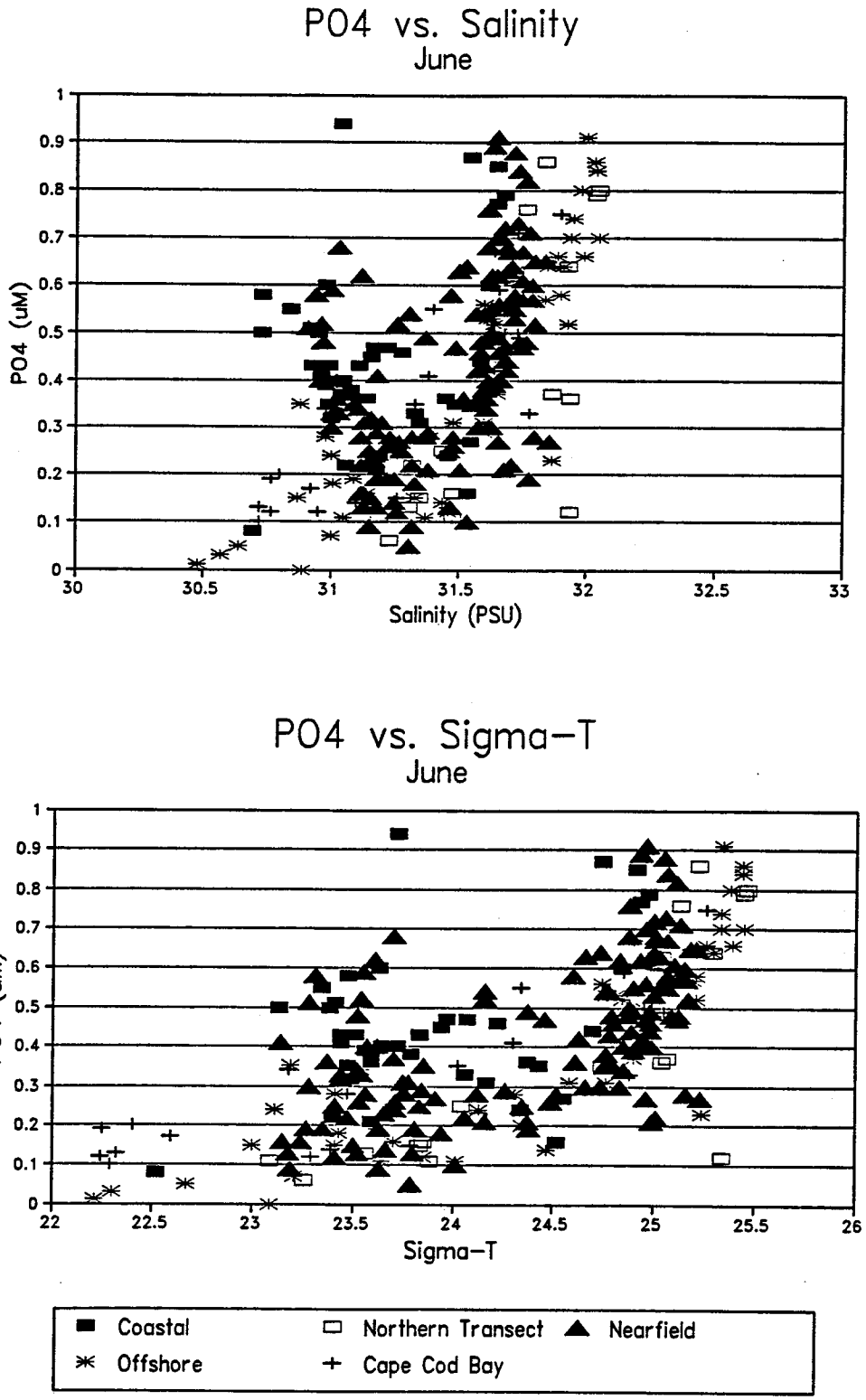



**Figure 6-22 Phosphate vs. salinity and $\sigma_T$ in June 1992. All stations and depths are included, and data are given in Appendix A.**

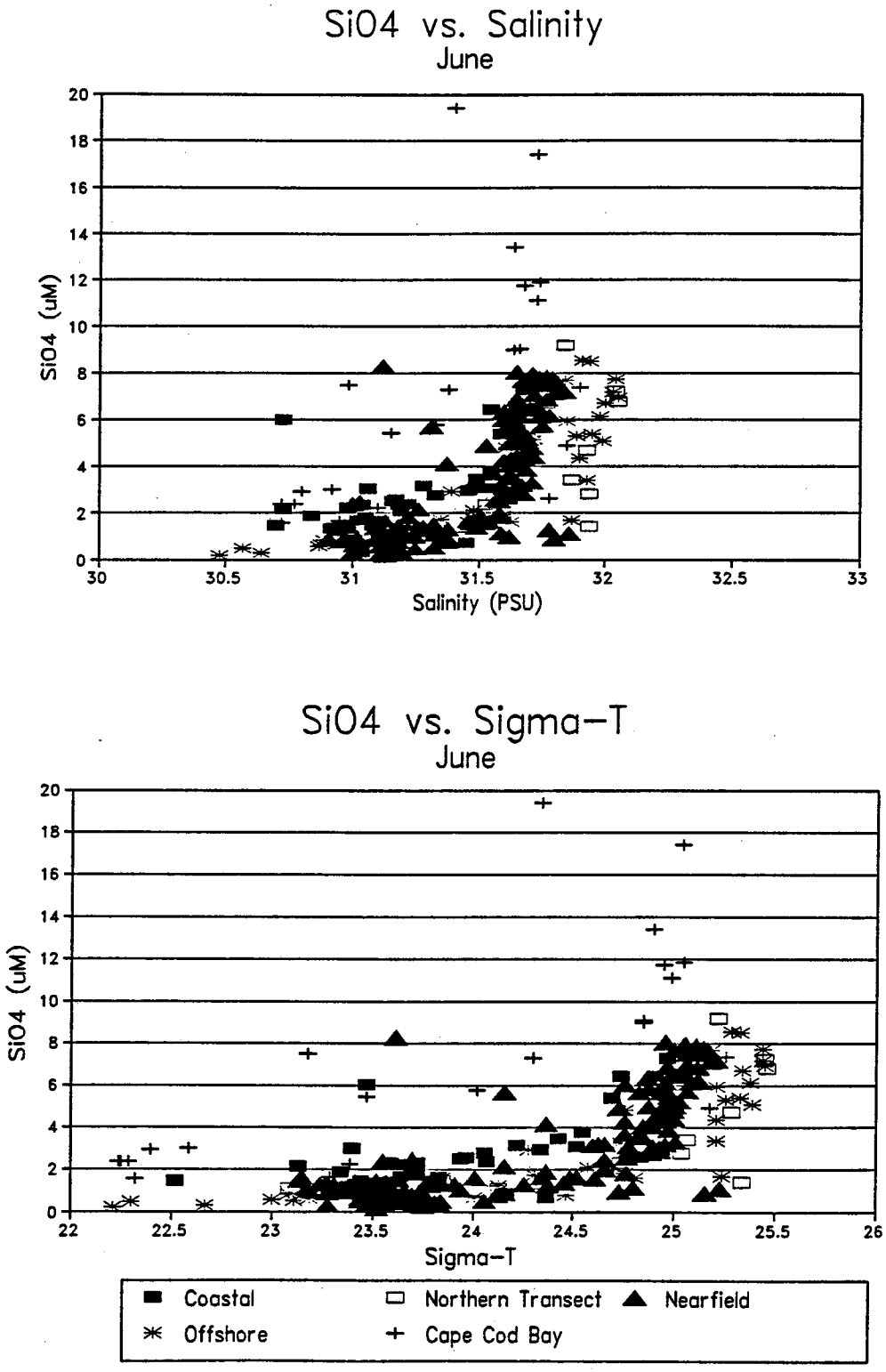



**Figure 6-23 Silicate vs. salinity and $\sigma_T$ in June 1992. All stations and depths are included, and data are given in Appendix A.**

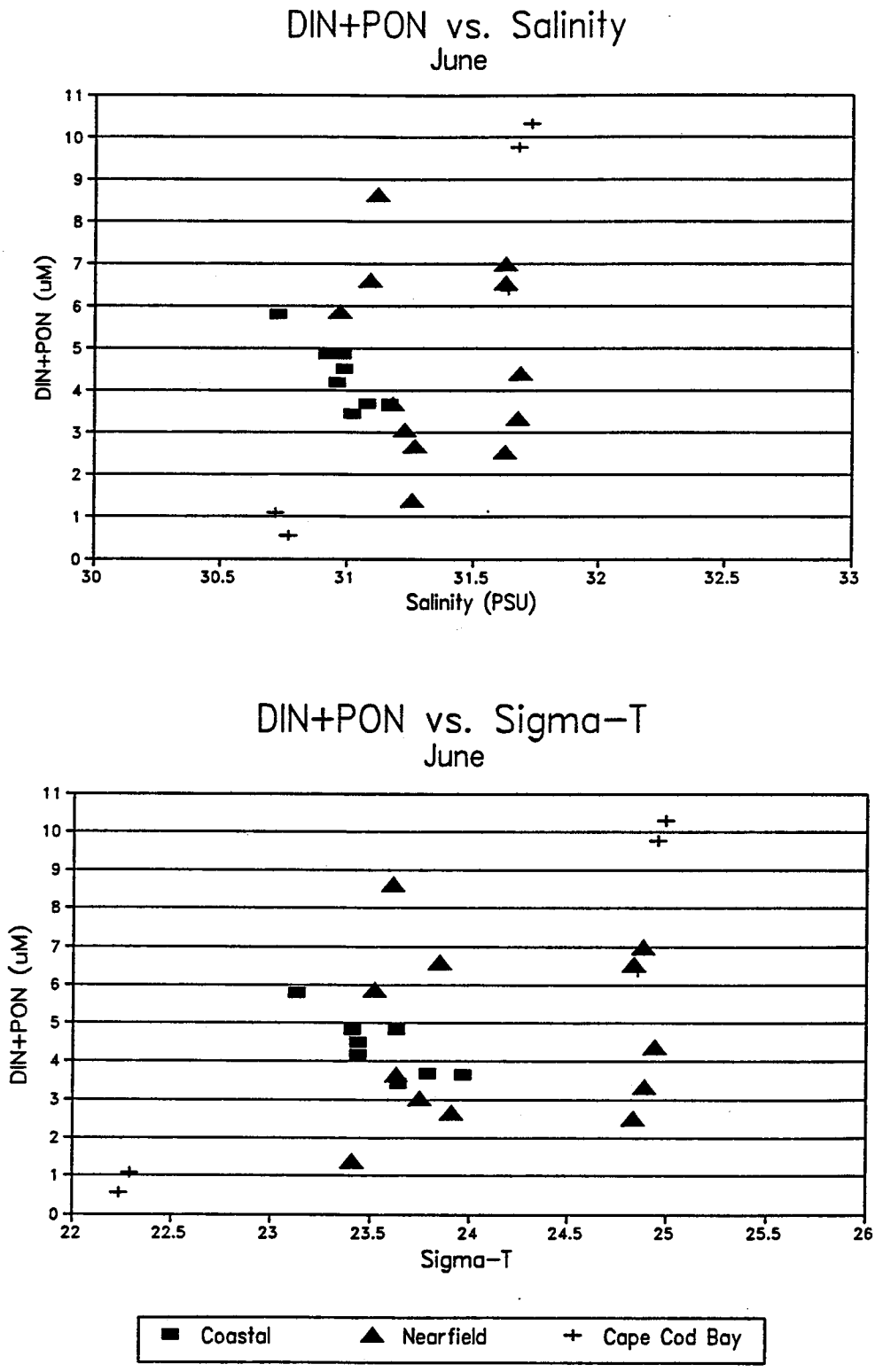



**Figure 6-24** **The sum of dissolved inorganic nitrogen and particulate organic nitrogen vs. salinity and $\sigma_T$ in June 1992. Data are from BioProductivity stations and special station F25 and are given in Appendix A. The station groups are coded as given in Figure 3-18; there are no BioProductivity stations in the Offshore or Northern Transect groups. PON concentrations were not available for one sample (see Appendix A).**

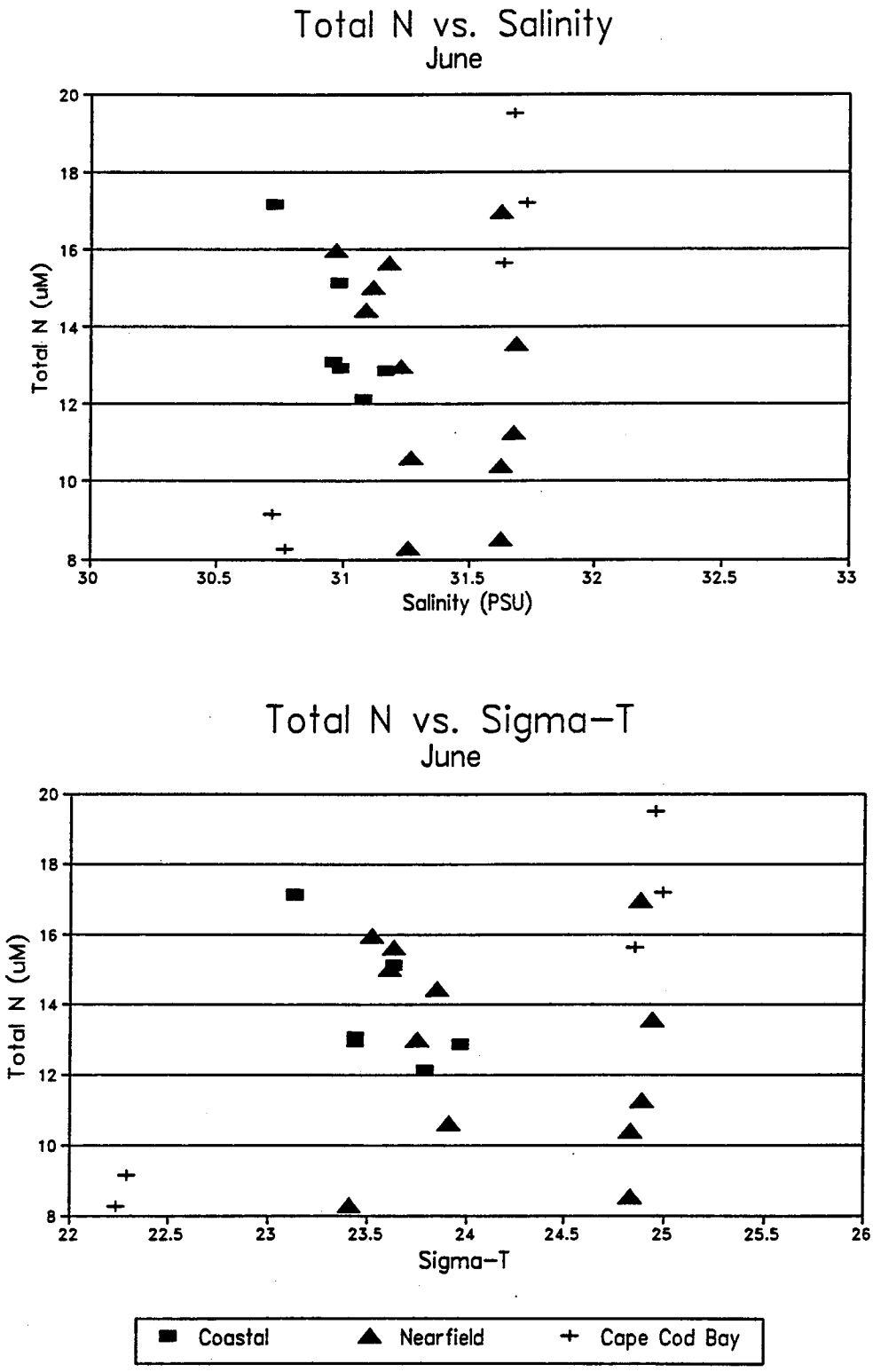



**Figure 6-25** **The sum of total dissolved nitrogen and particulate organic nitrogen (=total nitrogen) vs. salinity and $\sigma_T$ in June 1992. Data are from BioProductivity stations and special station F25 and are given in Appendix A. Groups are the same as Figure 6-24. PON, and thus total nitrogen, concentrations were not available for one sample (see Appendix A).**

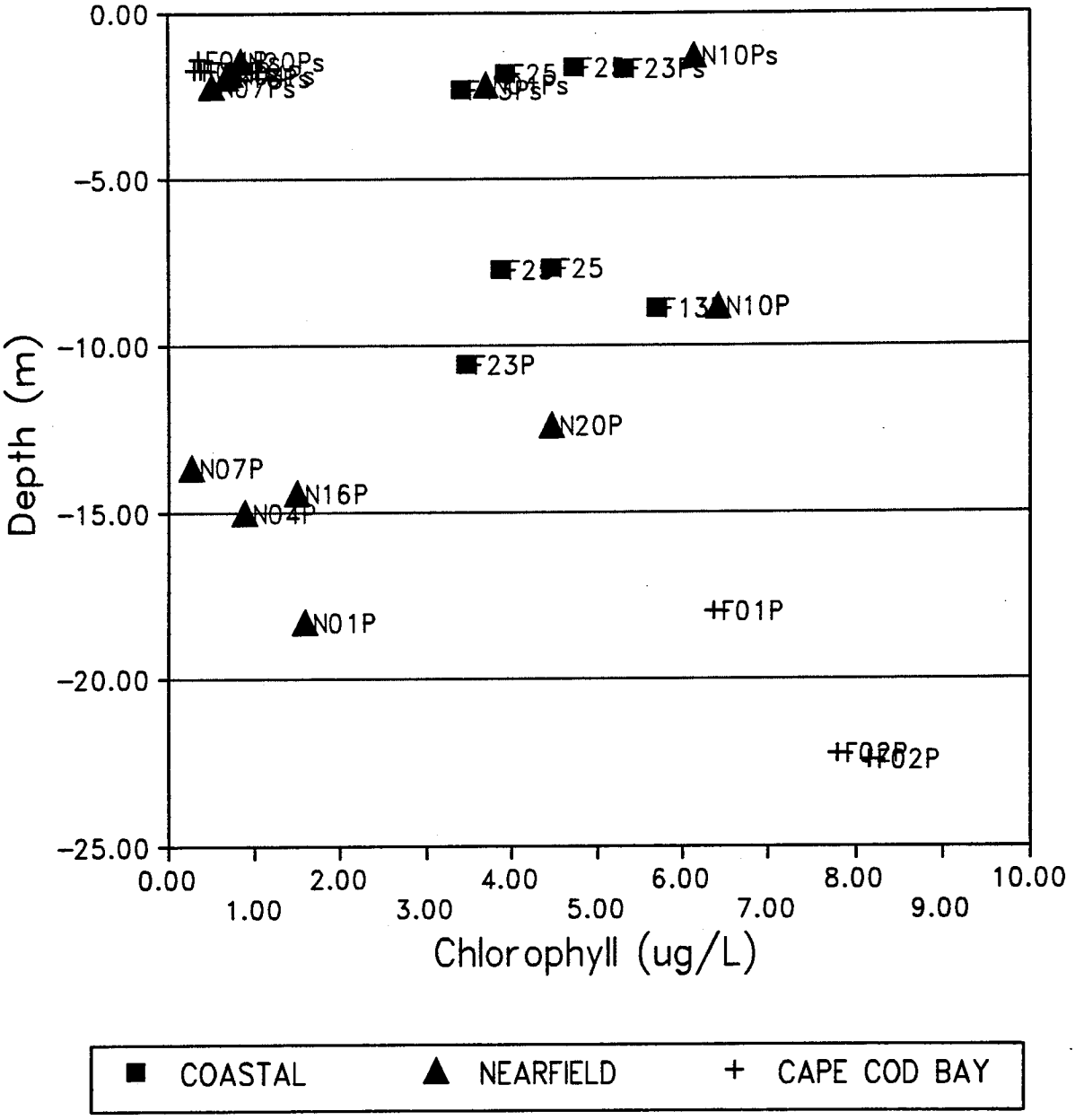



**Figure 6-26 Surface and deeper chlorophyll at BioProductivity stations and special station F25 as a function of depth in June 1992.**

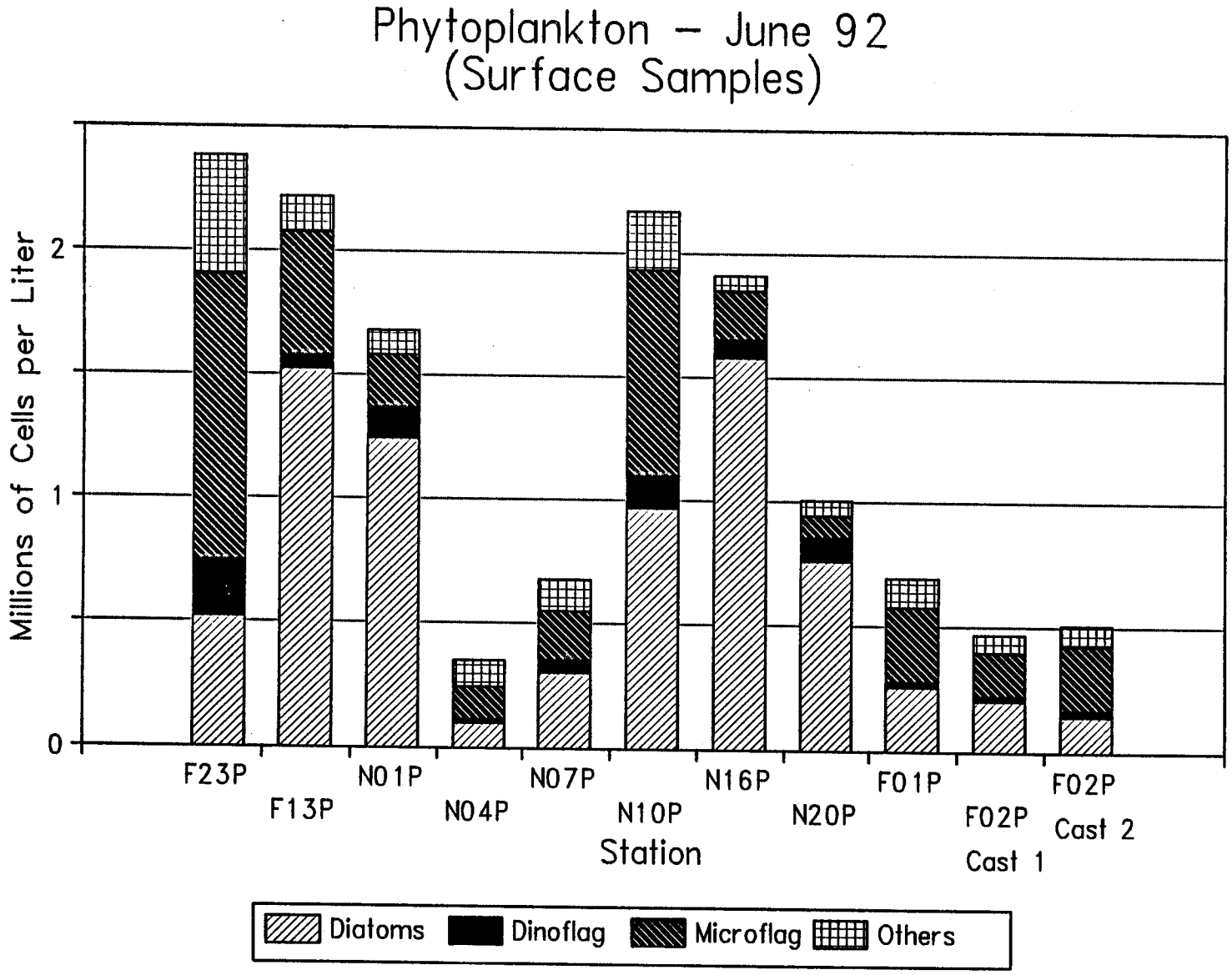



**Figure 6-28** **Total phytoplankton abundance, by taxonomic groups, at BioProductivity stations in June 1992. Data are given in Appendix F.**

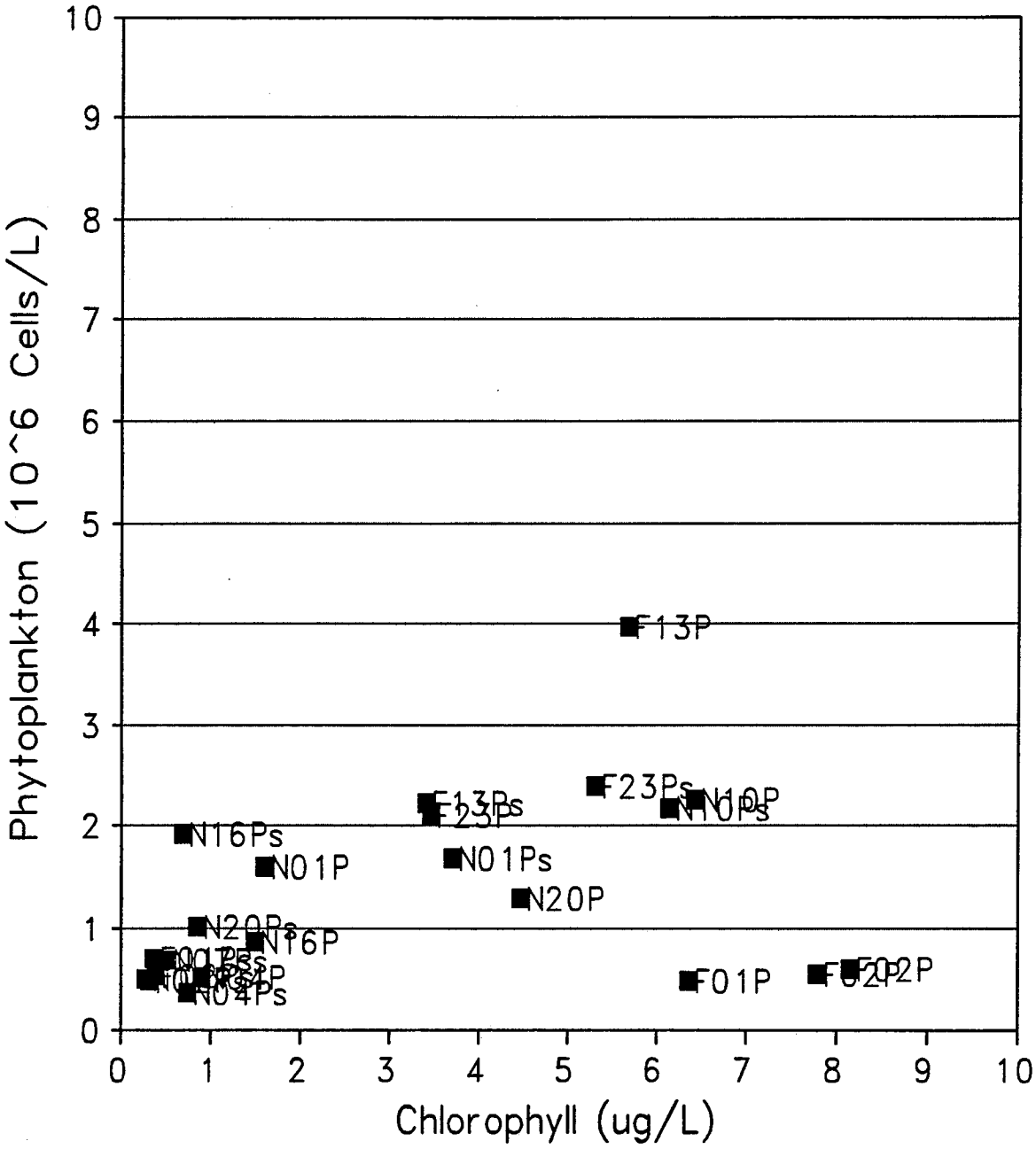



**Figure 6-27 Total phytoplankton abundance vs. extracted chlorophyll at BioProductivity stations in June 1992. Data are given in Appendices A and F.**

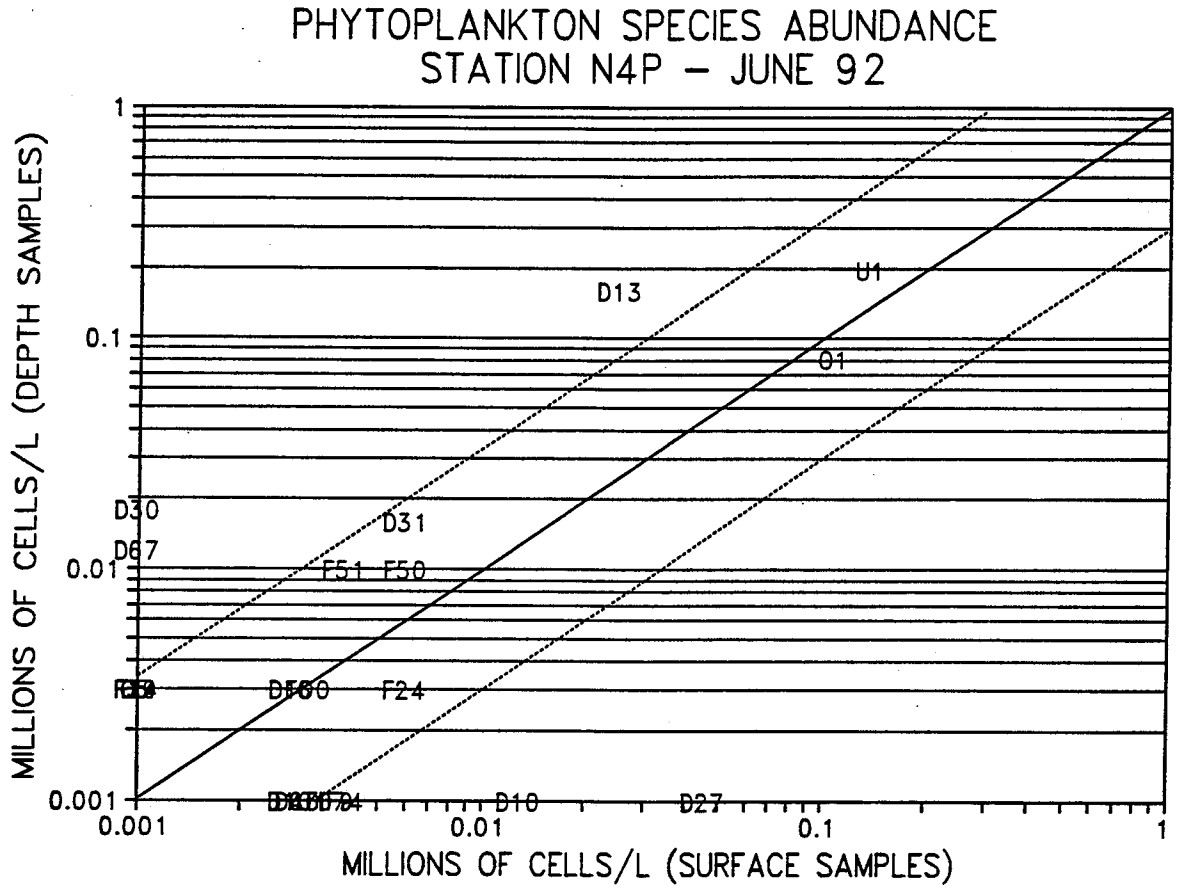



**Figure 6-29** **Comparison of phytoplankton taxonomic composition of surface and deeper samples at station N4P in June 1992. Full species codes are given in Appendix F, but the alphabetical prefix indicates the following: D= diatom, F= dinoflagellate, U= microflagellates, O= other. Solid line shows 1:1 relationship, dotted lines show 1:5 and 5:1 isopleths. Note that 0.001 has been added to all values to enable log-log plotting for samples present in one sample, but not the other (indicated by a value of 0.001).**

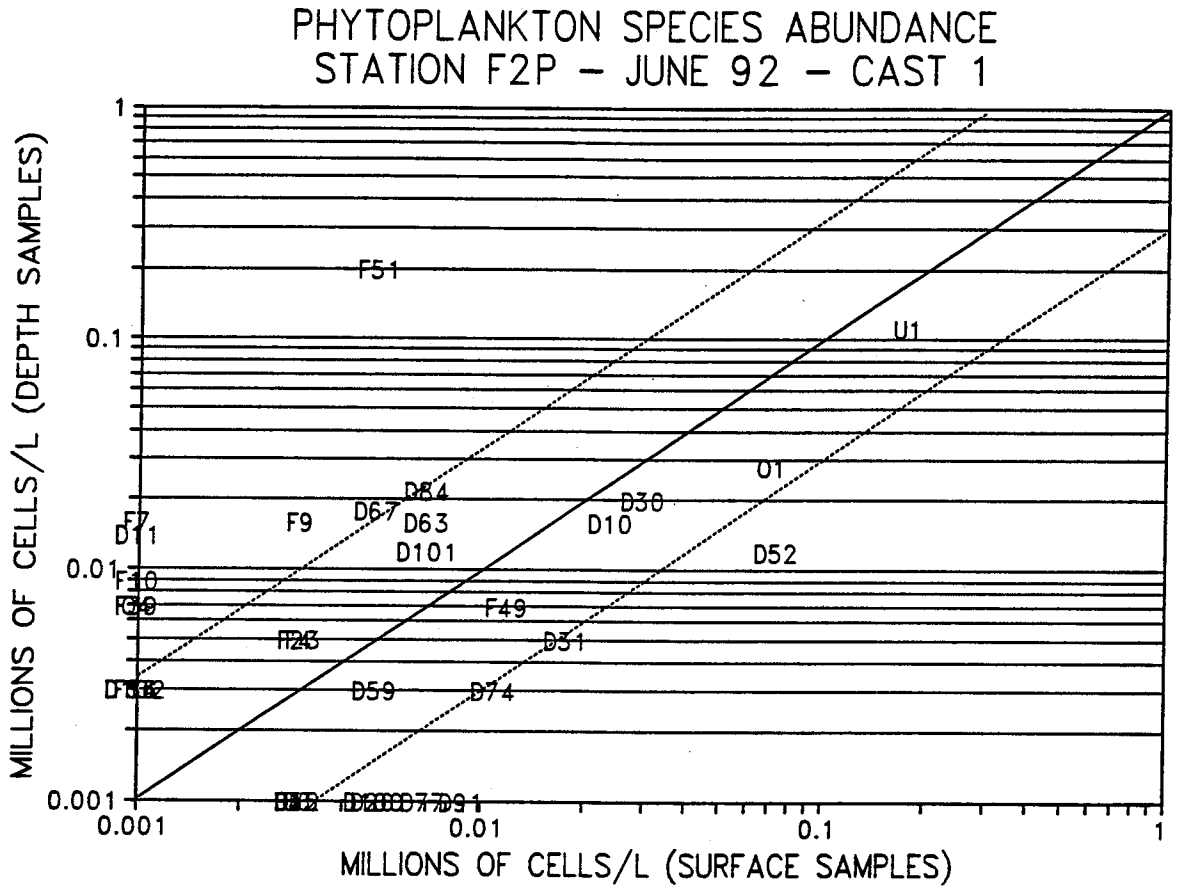



**Figure 6-30a** **Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F2P in June 1992 on cast 1. Species codes are given in Appendix F. Note that 0.001 has been added to all values to enable log-log plotting for samples present in one sample, but not the other (indicated by a value of 0.001).**

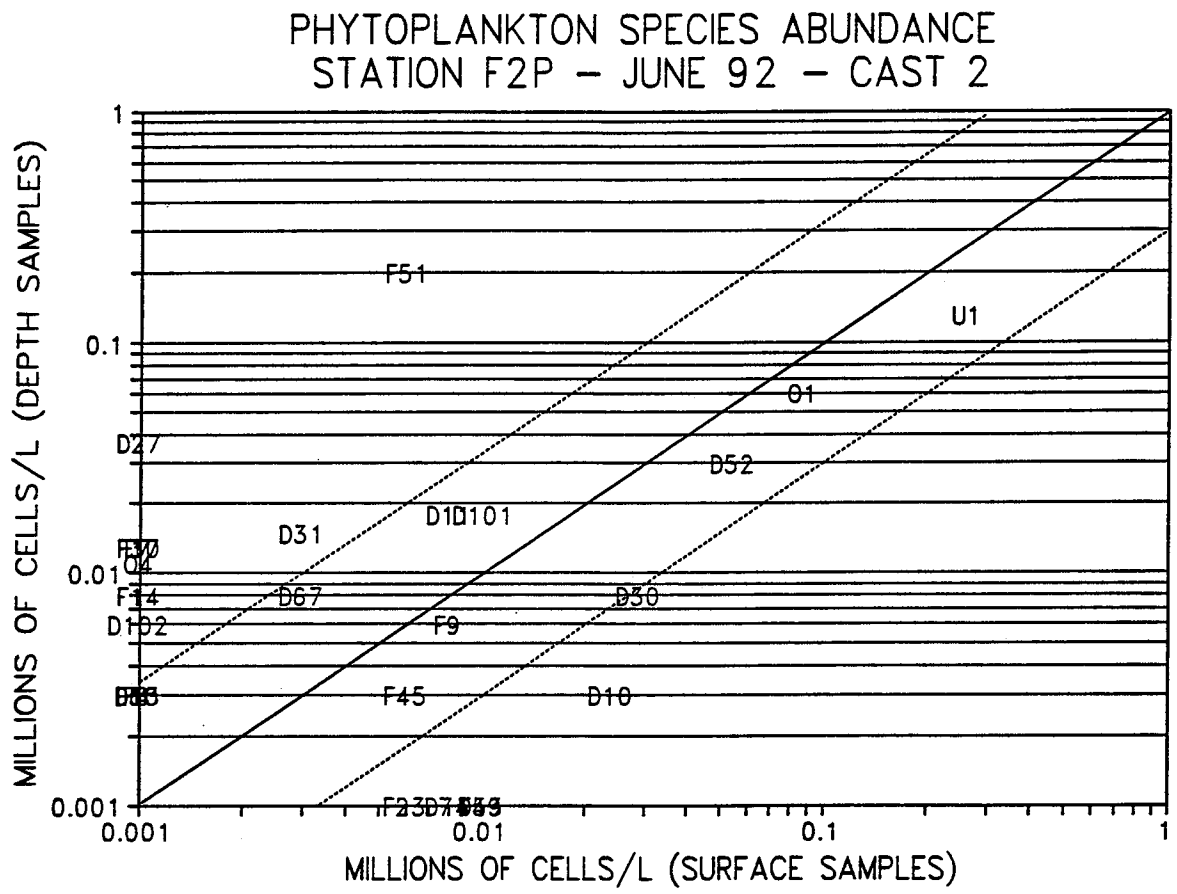



**Figure 6-30b** **Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F2P in June 1992 on cast 2. Species codes are given in Appendix F. Note that 0.001 has been added to all values to enable log-log plotting for samples present in one sample, but not the other (indicated by a value of 0.001).**

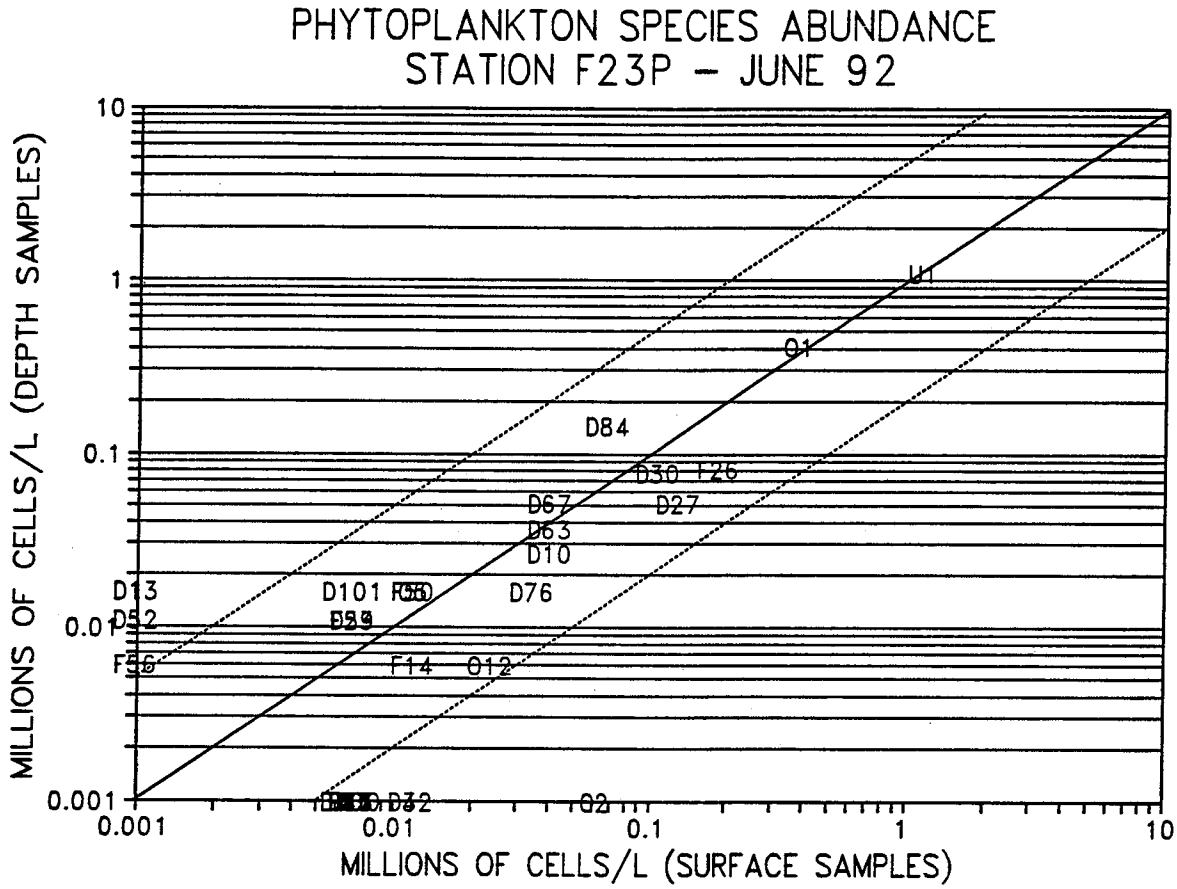



**Figure 6-31** **Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F23P in June 1992. Species codes are given in Appendix F. Note that 0.001 has been added to all values to enable log-log plotting for samples present in one sample, but not the other (indicated by a value of 0.001).**

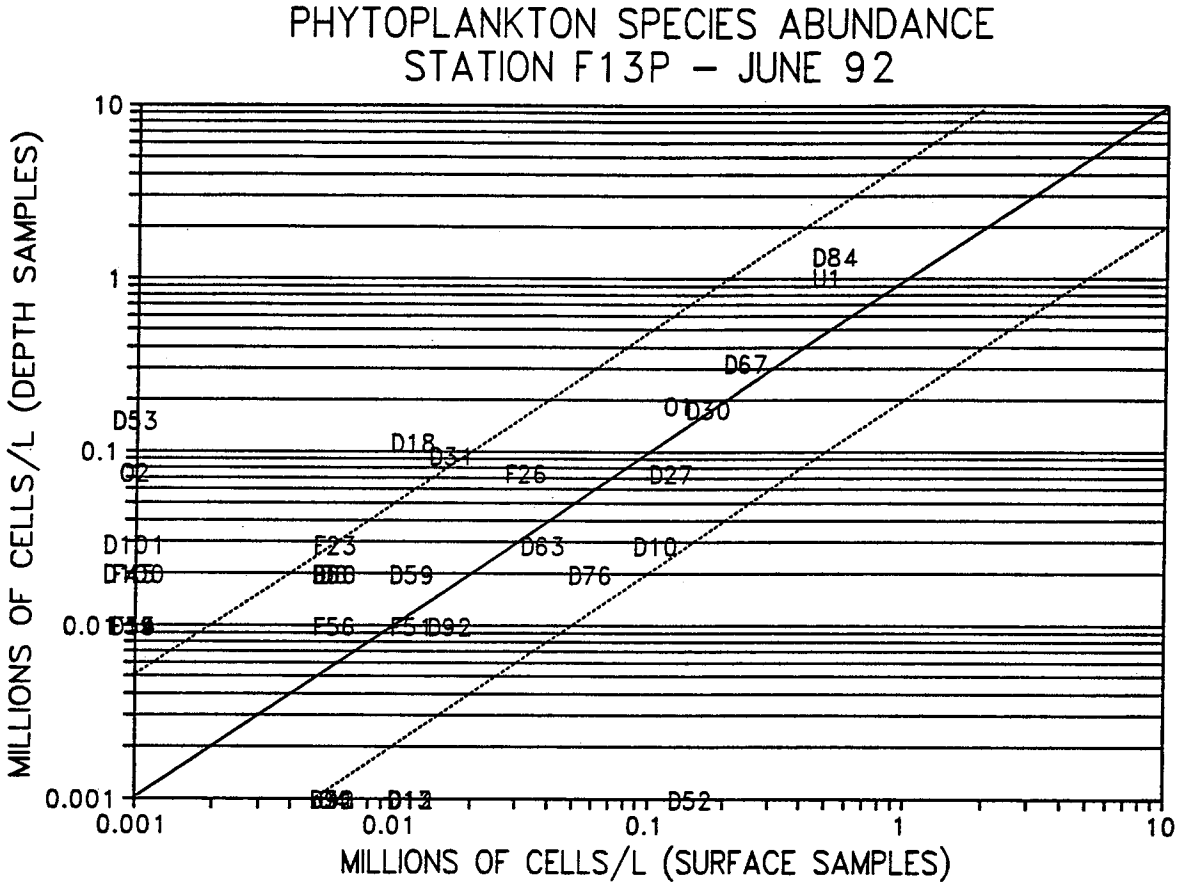



**Figure 6-32** **Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F13P in June 1992. Species codes are given in Appendix F. Note that 0.001 has been added to all values to enable log-log plotting for samples present in one sample, but not the other (indicated by a value of 0.001).**

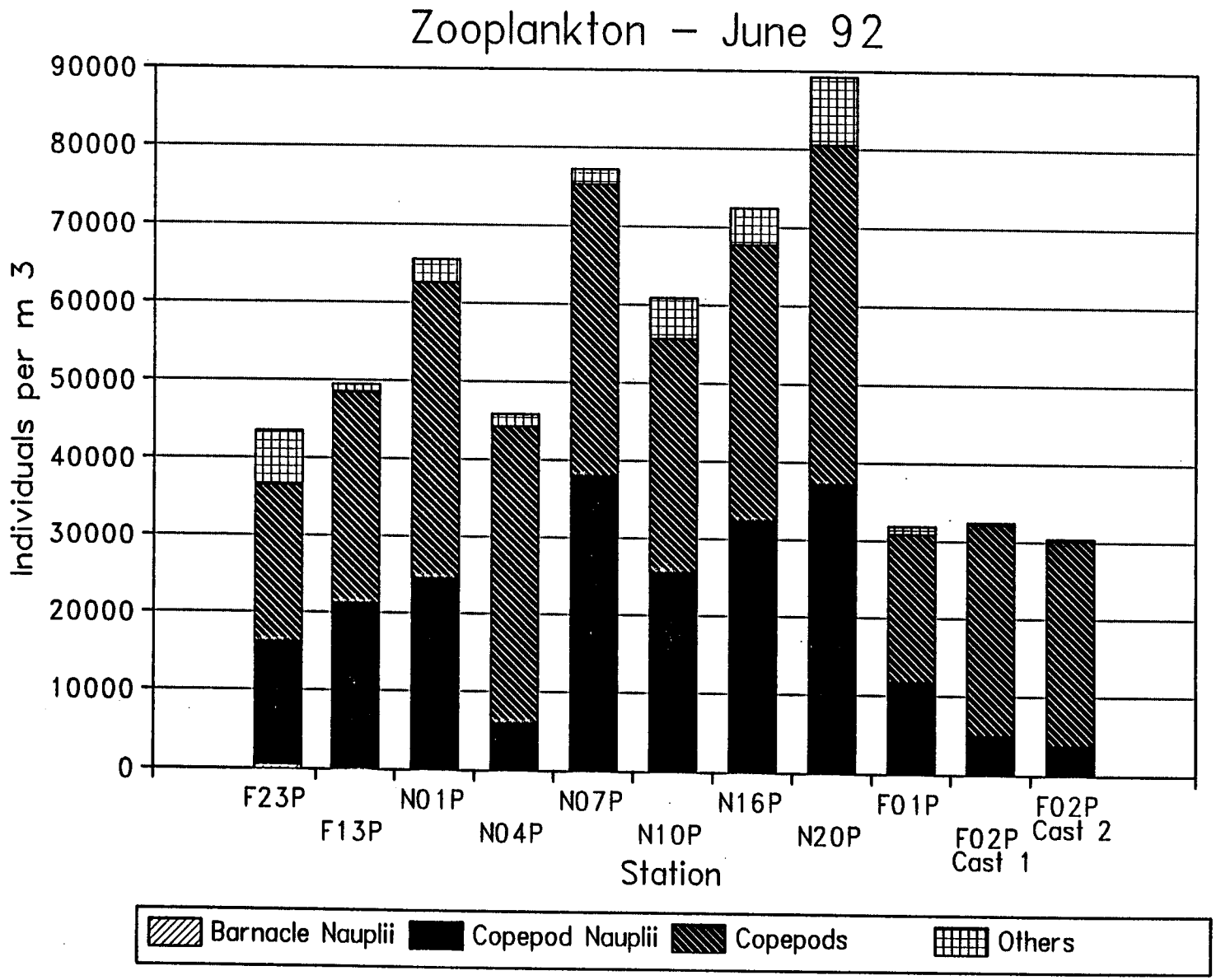
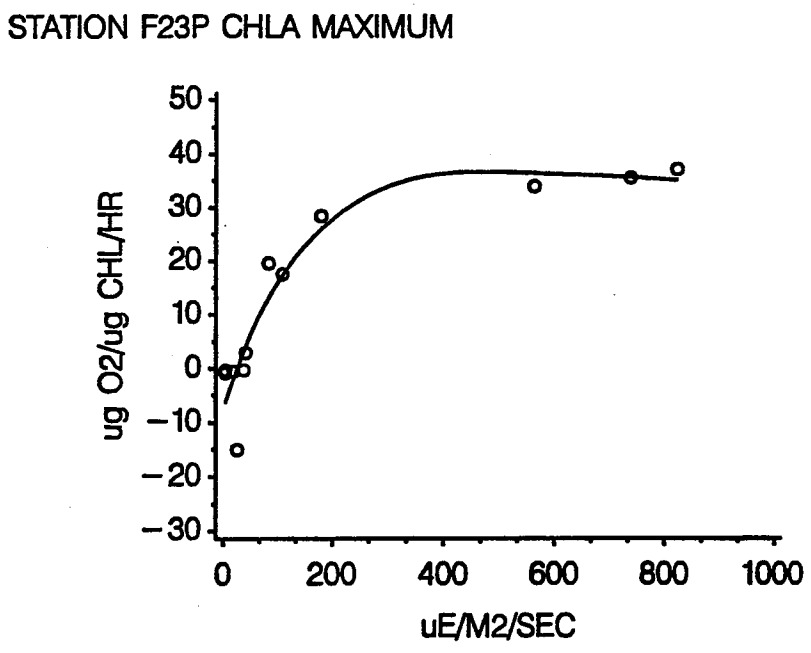



**Figure 6-33 Zooplankton abundance, by groups, at BioProductivity stations in June 1992. Data are given in Appendix G.**



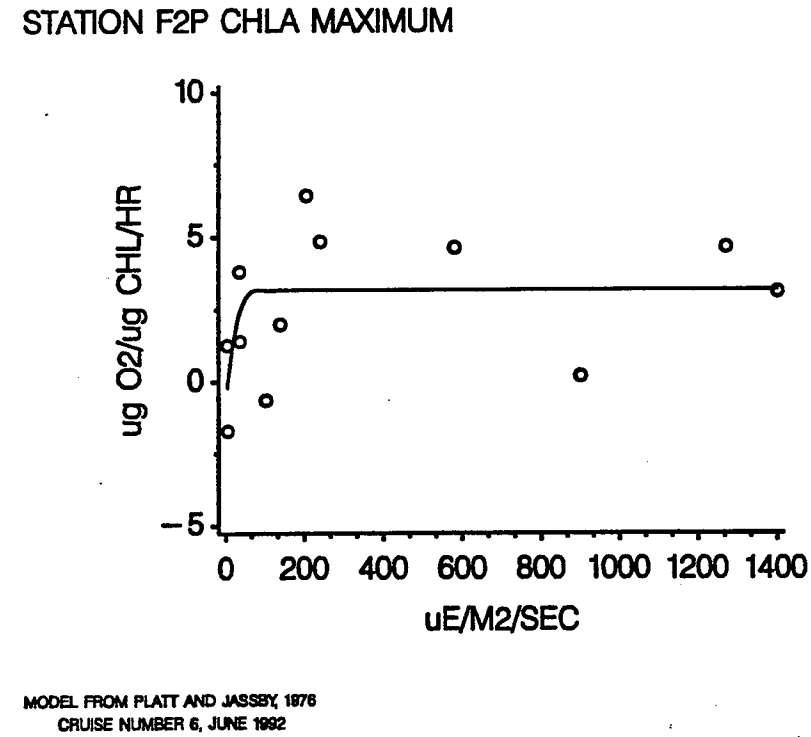




**Figure 6-34 Selected net production (P) vs. irradiance (I) curves in June 1992. Data are chlorophyll-normalized rates, see Appendix E.**

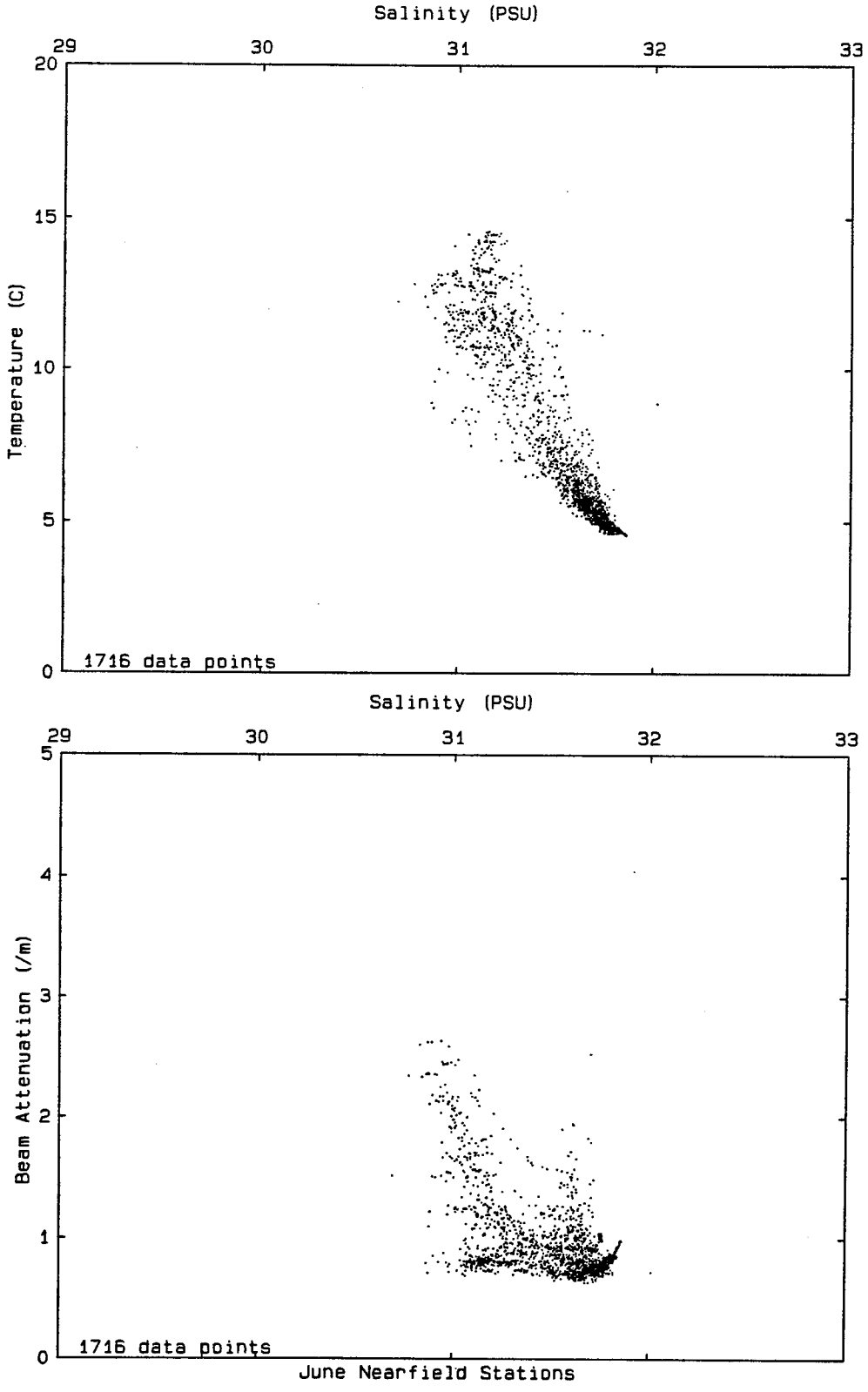



**Figure 6-35a Scatter plots for nearfield stations only in June 1992. Compare to Figure 6-17a.**

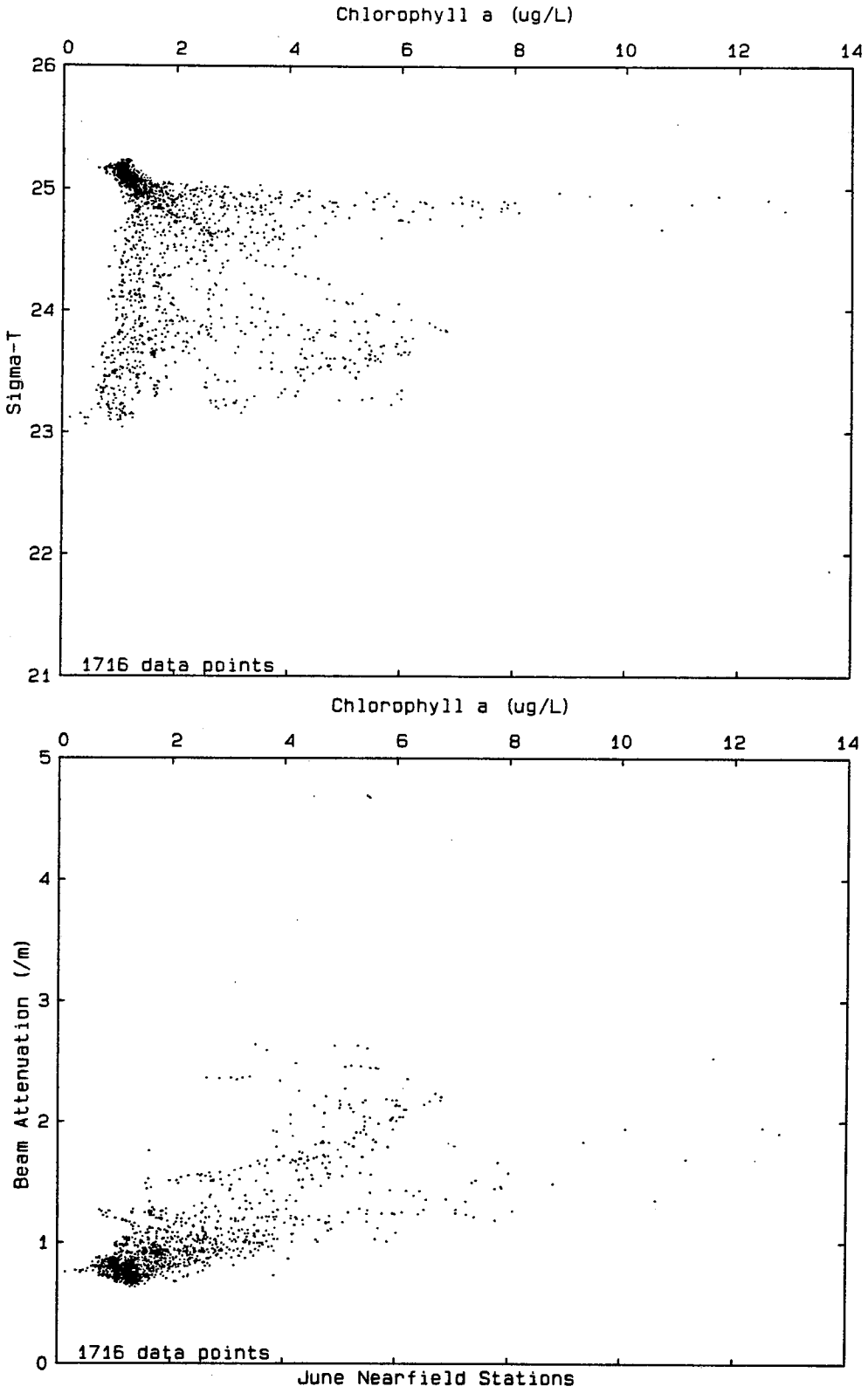



**Figure 6-35b** **Scatter plots for nearfield stations only in June 1992. Compare to Figure 6-17b. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

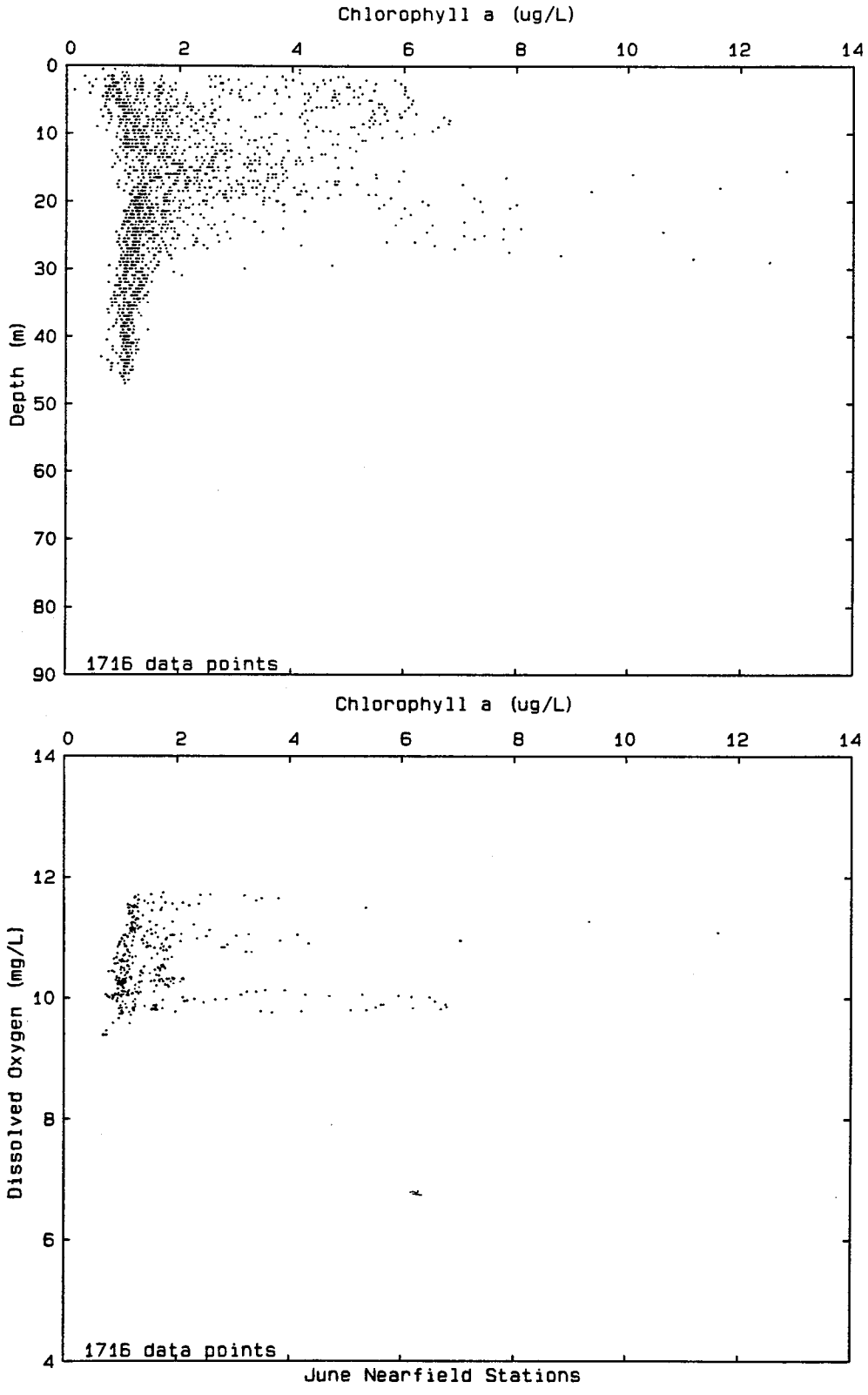



**Figure 6-35c** **Scatter plots for nearfield stations only in June 1992. Compare to Figure 6-17c. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

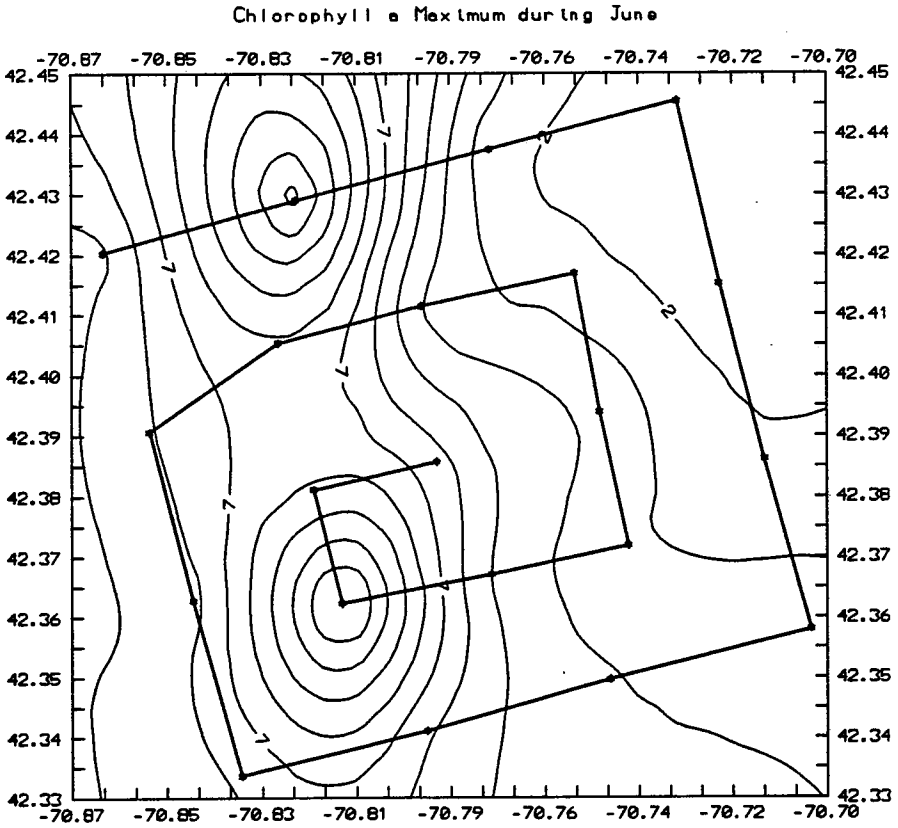



**Figure 6-36 Chlorophyll maximum at each nearfield station from vertical profile day (Appendix B). Track shows sampling, starting at southwest corner of nearfield. Chlorophyll maximum may not be at the same depth at different stations.**

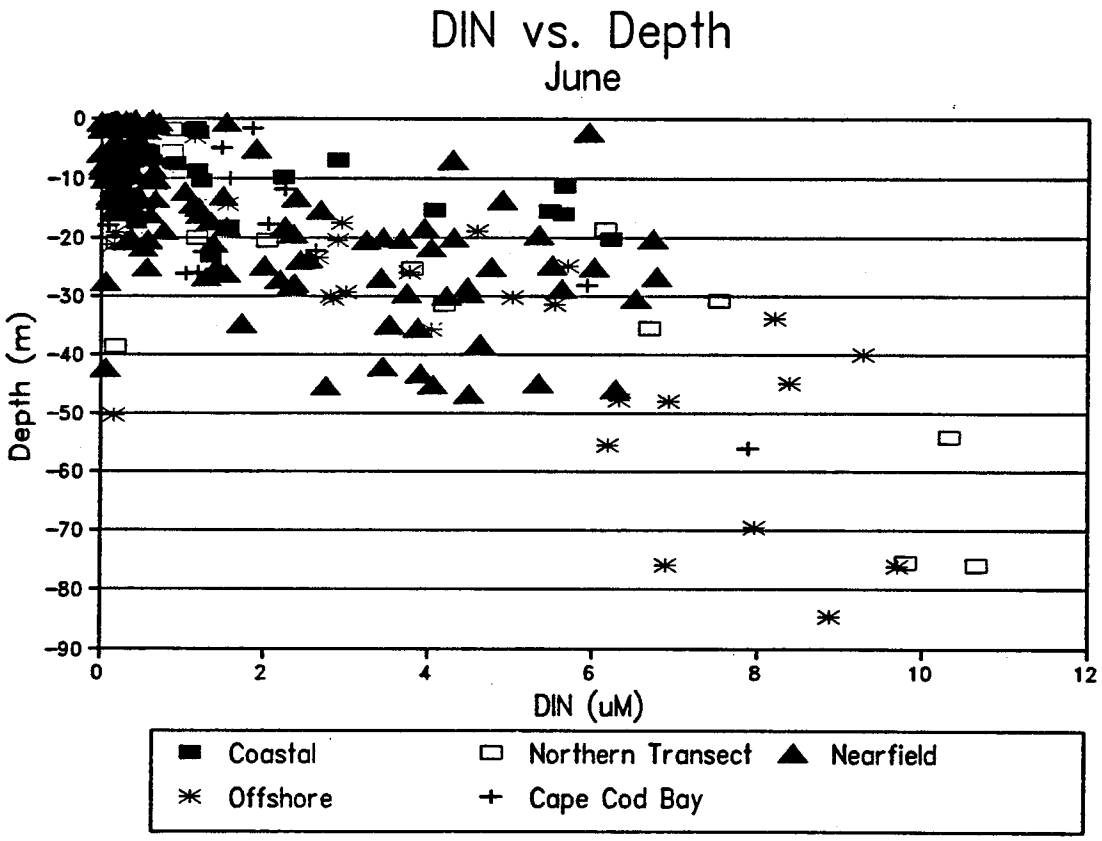



**Figure 6-37 DIN vs. Depth in June 1992.**

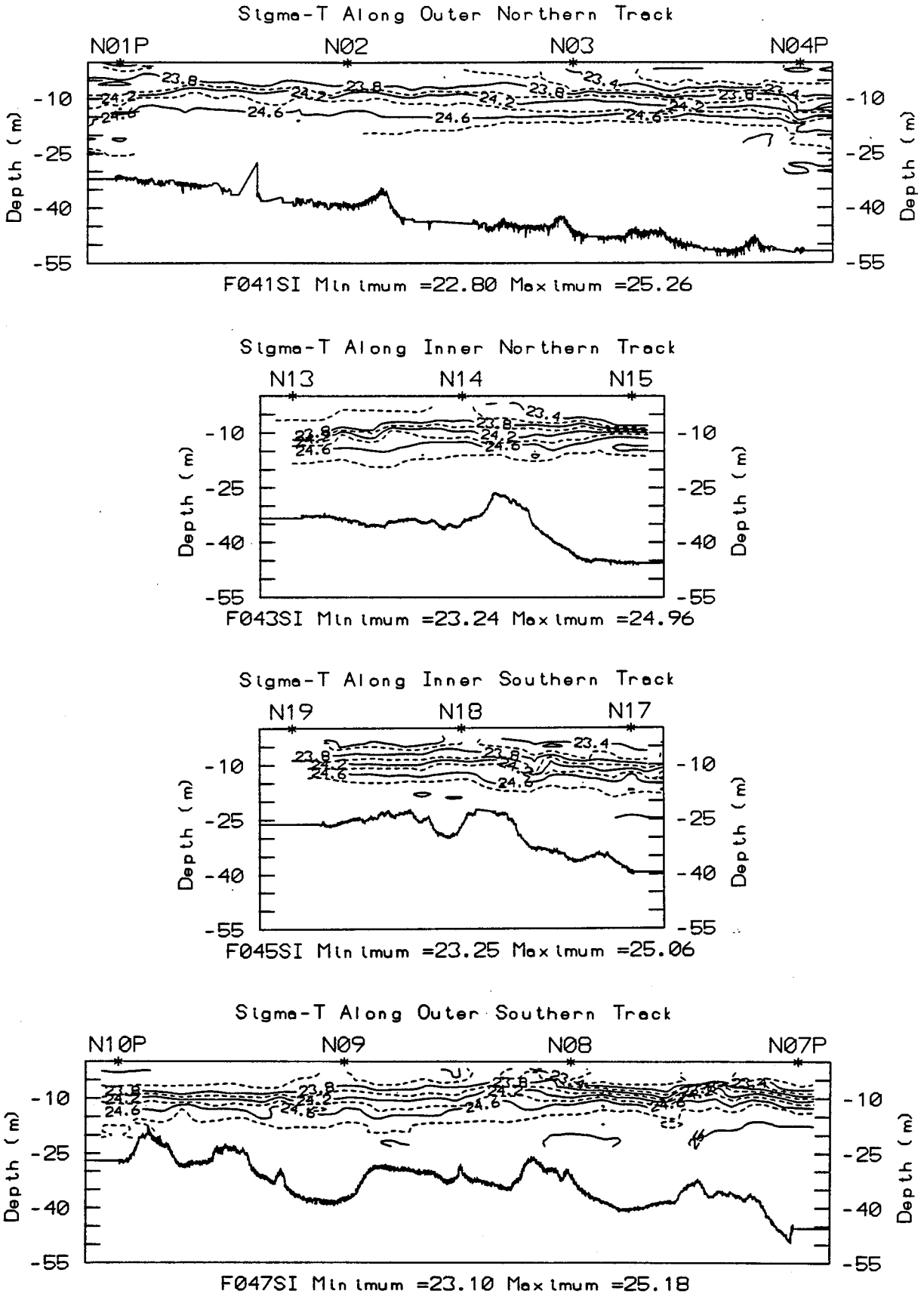



**Figure 6-38a** **Vertical section contours of $\sigma_T$ generated for tow-yos in June 1992. The view is towards the North. The contour interval is 0.2 $\sigma_T$.**

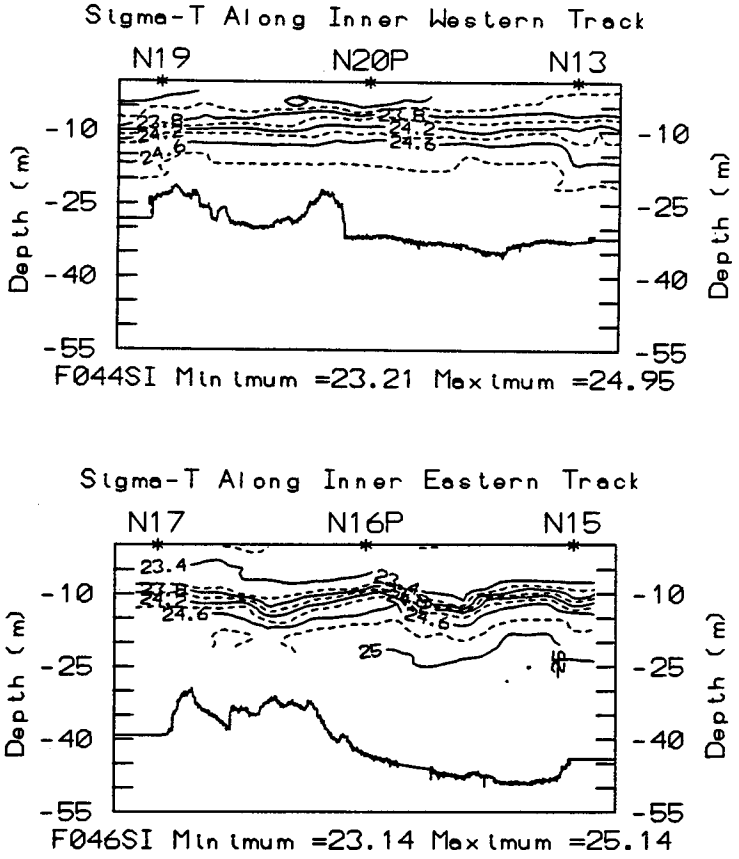



**Figure 6-38b** **Vertical section contours of $\sigma_T$ generated for tow-yos in June 1992. The view is towards Boston Harbor.**

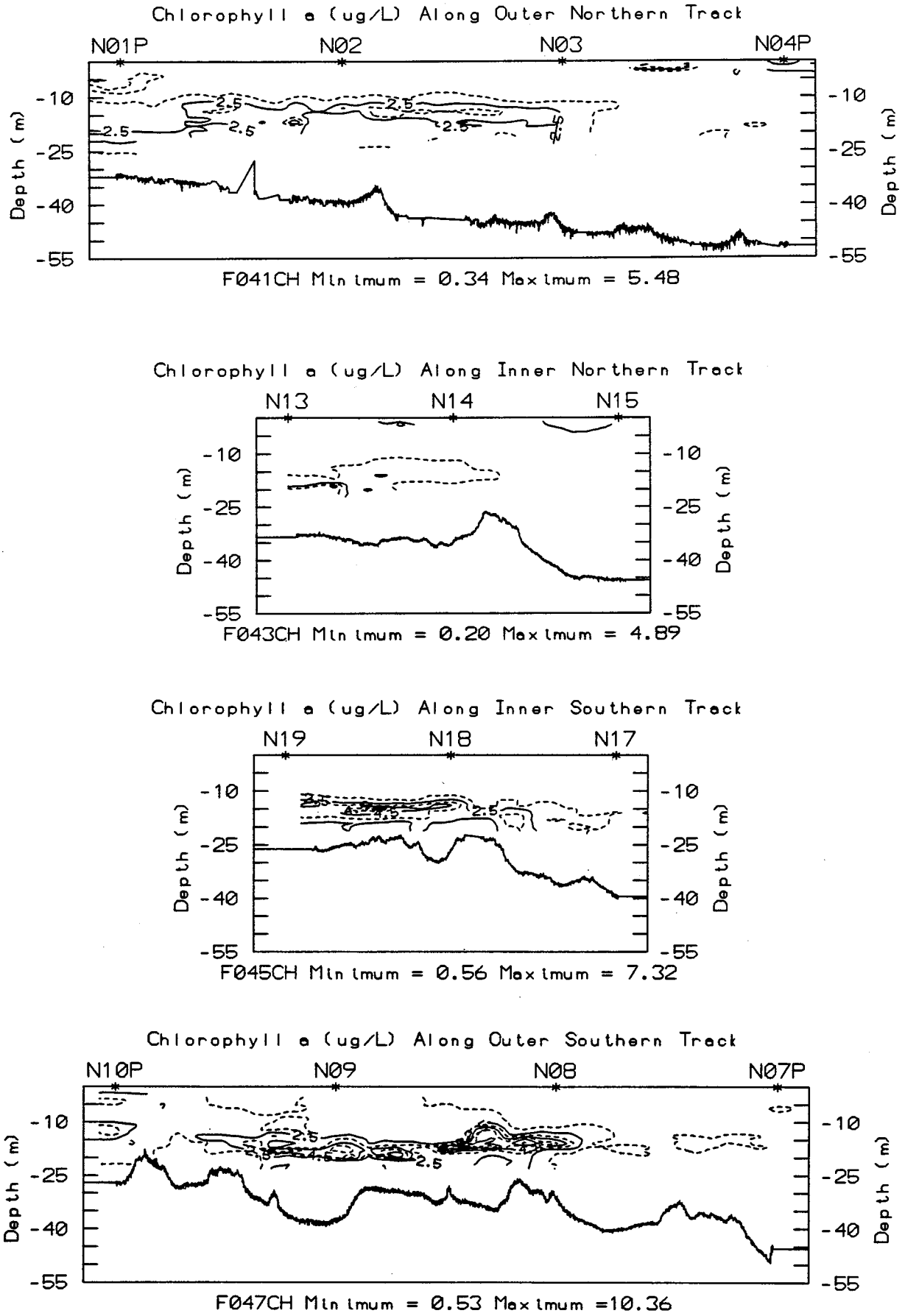



**Figure 6-39a** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in June 1992. The view is towards the North. The contour interval is 1 $\mu$g $L^{-1}$.**

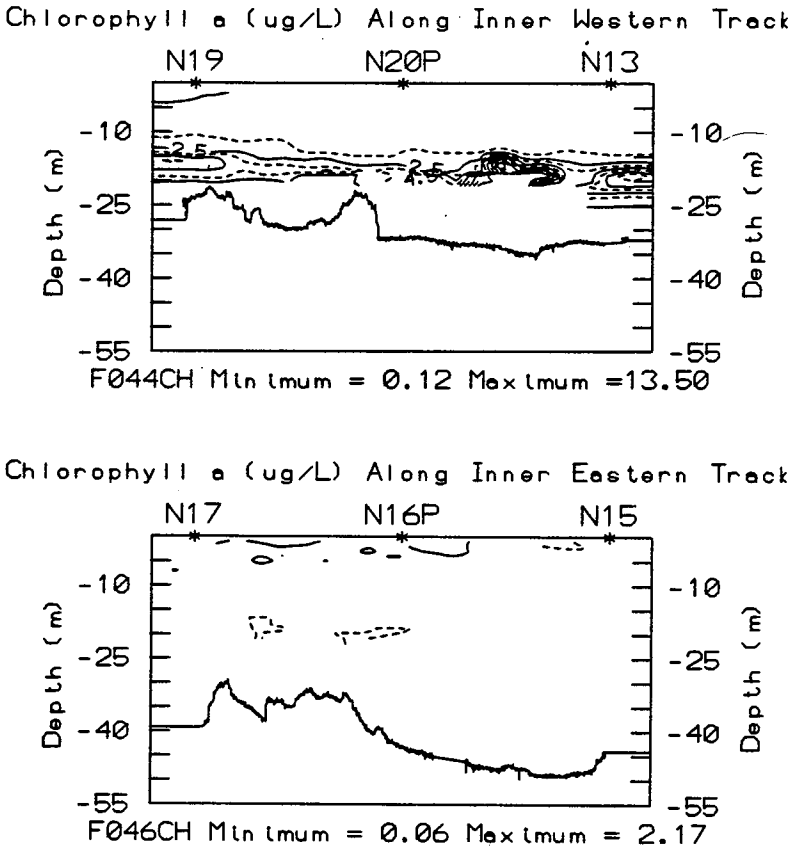



**Figure 6-39b** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in June 1992. The view is towards the Boston Harbor.**

# 7.0 MID-JULY 1992 NEARFIELD SURVEY (#7) RESULTS

## 7.1 Distribution of Water Properties from Vertical Profiling

At the mid-July sampling of the nearfield, the temperature was from $<5$ to $>15°C$ and salinity mostly within a 1 PSU range ($\sim 30.75$ to $\sim 31.75$) as shown in Figure 7-1a. Highest beam attenuation was at intermediate salinity and strongly correlated with chlorophyll fluorescence (Figure 7-1b). Generally, the highest chlorophyll occurred from about 5-15 m (Figure 7-1c).

Examination of the individual station profiles (Appendix B) reveals that the sharpness of the pycnocline varied slightly across the stations. For example, NO1P had a 5 m surface layer and a broad pycnocline from 5 to about 20 m. In contrast, N10P was weakly stratified and N16P had a sharp pycnocline from 10 to 20 m, with distinct surface and bottom waters. Along with this physical variation, it was apparent that the chlorophyll maximum was sometimes at the surface, sometimes within the pycnocline, and sometimes below it, depending on the station. Oxygen often mimicked the chlorophyll profile, with a mid-depth maximum near (sometimes below) the chlorophyll maximum and then decreasing into the bottom water layers.

Figure 7-2 gives a picture for the horizontal gradient across the field, with highest chlorophyll seen across the whole southwestern corner almost from N01P to N07P. Although the corner (N10P) and western track was sampled near low tide, N09 and N20P (both high in chlorophyll were sampled very near high tide. The suggestion might be that tidal dynamics are influencing the region, but if so it perhaps not by a simple seiching of water in and out, rather, perhaps some net inshore release of water (surface) to the nearfield may be suggested (but see towing discussion below).

With respect to nutrients, $NO_3$ was generally low in the surface 10 m, increasing sharply below this (Figure 7-3). $PO_4$ for the field looked almost like a general increase with depth (Figure 7-4), as did SiO4. A few $NH_4$ samples showed slightly enrichment as the surface ($\sim 0.5$ to $1.0\ \mu M$). These enriched samples included the surface samples at stations NO9, N10P, N11, N19, and N20 - all stations with higher chlorophyll.

## 7.2 Distribution of Water Properties from Towing

For the towing day (July 16), the inner box was towed first, clockwise (N19 - N13 - N15 - N17 - N18), followed by the outer box, also clockwise (N11 - N01P - N07P - N10P). As seen the day before, there was some variability in the sharpness of the pycnocline. The broad trend was a more distinct gradient between surface and bottom waters to the east and to the southeast, especially visible along the outer southern track (Figure 7-5). The interesting aspect of the data that was the chlorophyll fluorescence seemed to map rather strongly with the presence of a more diffuse and/or crenulated pycnocline. High chlorophyll was seen at N10P, along much of the outer western track (the most inshore edge) with a continuous patch (with peaks about 3 $\mu g\ L^{-1}$) stretching out from shore to the inner western track. In general, this subsurface chlorophyll feature was found within the pycnocline itself. Note that in the mid-field itself (e.g. around N14 and N18), some smaller, seemingly more isolated particles of chlorophyll ($>3$ and $<4\ \mu g\ L^{-1}$) were suggested.

## 7.3 Analysis of Small-Scale Variability

Probably more impressive than very small spatial-scale variability, although some of this was evident as physical and biological complexity and heterogeneity at many shallower stations, was the general trend of graded chemical, physical, biological conditions from the southwestern corner towards the northeastern corner. With respect to short-term temporal change, the vertical stratification generally was very similar between the two days of nearfield sampling, perhaps implying little influence of forces send as winds, tides, or offshore water intrusions at this particular time. Examining the climate records showed that the two days of sampling were very calm, and with very low average winds (Lautzenheiser, N.E. Climatic Service)

## 7.4 Water Types, as Related to Nutrients, Fluorescence, and Dissolved Oxygen

Inshore, higher nutrients could be seen and chlorophyll there was nearer the surface. Coupled with this horizontal gradient was a sharp vertical gradient, especially offshore. Offshore the distinction between surface and bottom waters was most apparent for many parameters. Profiles (Appendix B) suggested

lowest dissolved oxygen levels were associated with the offshore deeper waters >30 m and warm upper waters with lower % saturation thus in the bottom waters. Even, so, the dissolved oxygen levels were all above 8 mg $L^{-1}$ (Figure 7-1c).

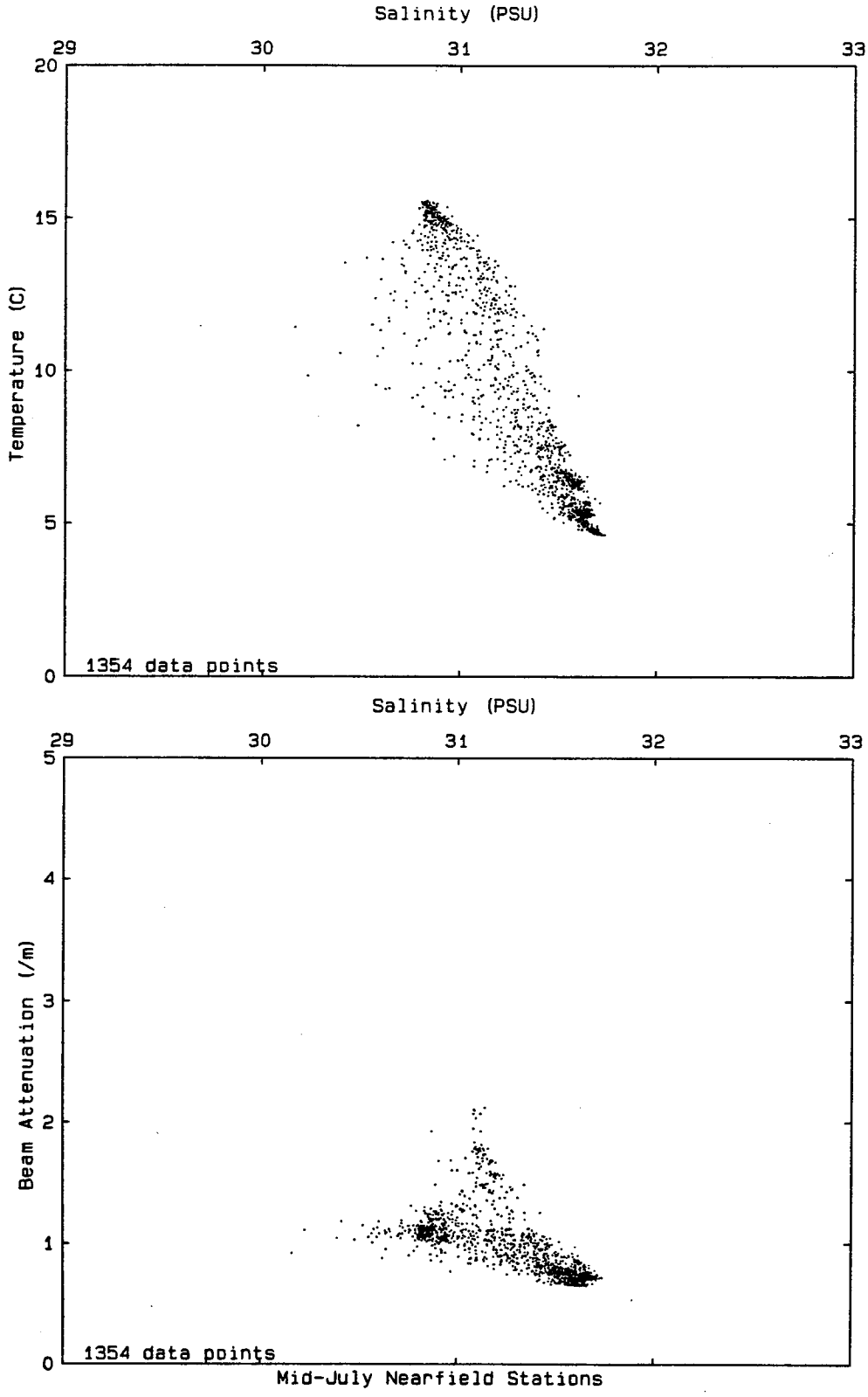



**Figure 7-1a Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in mid-July 1992. Individual station casts that were used to produce this composite are in Appendix B.**

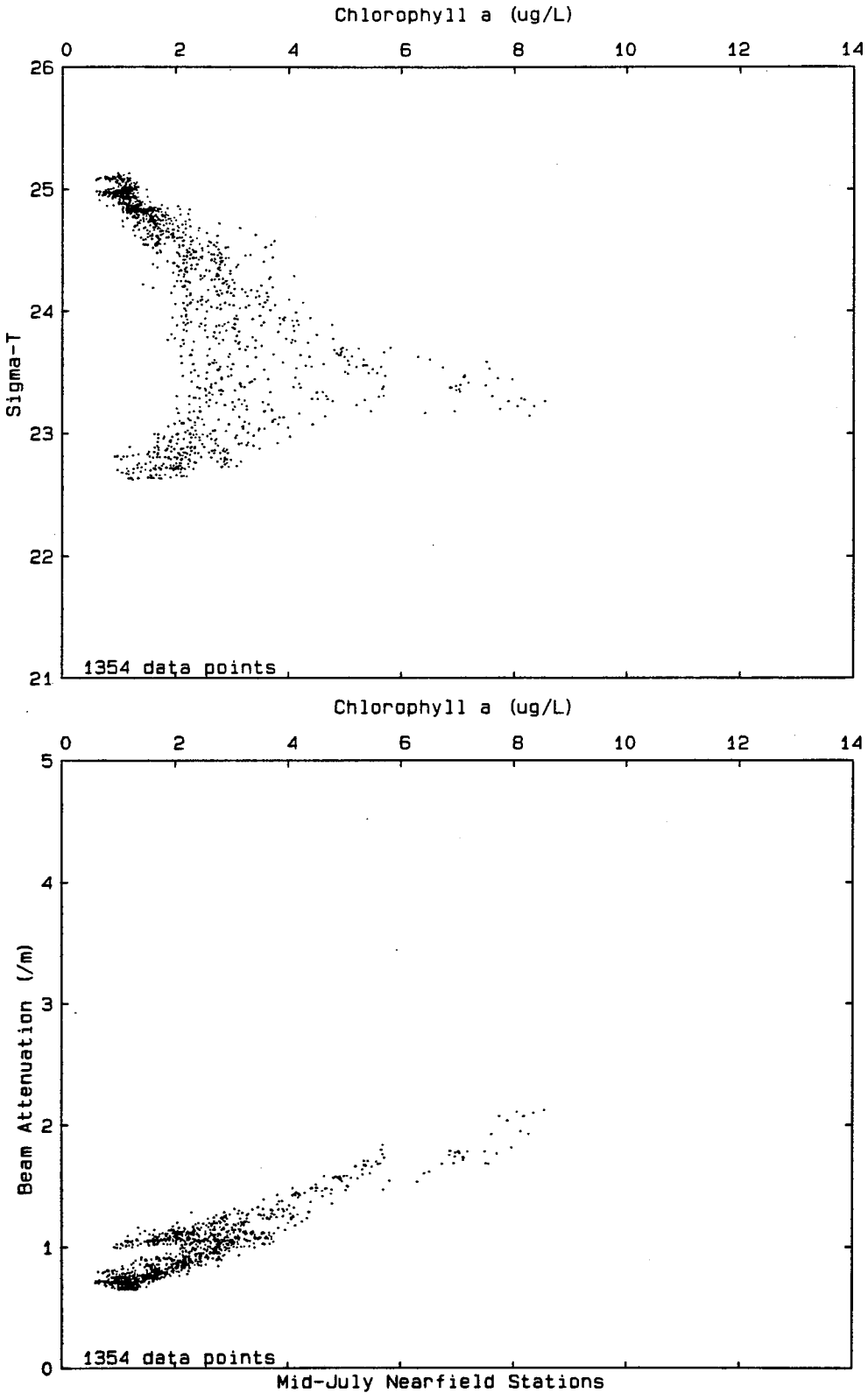



**Figure 7-1b** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in mid-July 1992. Individual station casts that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

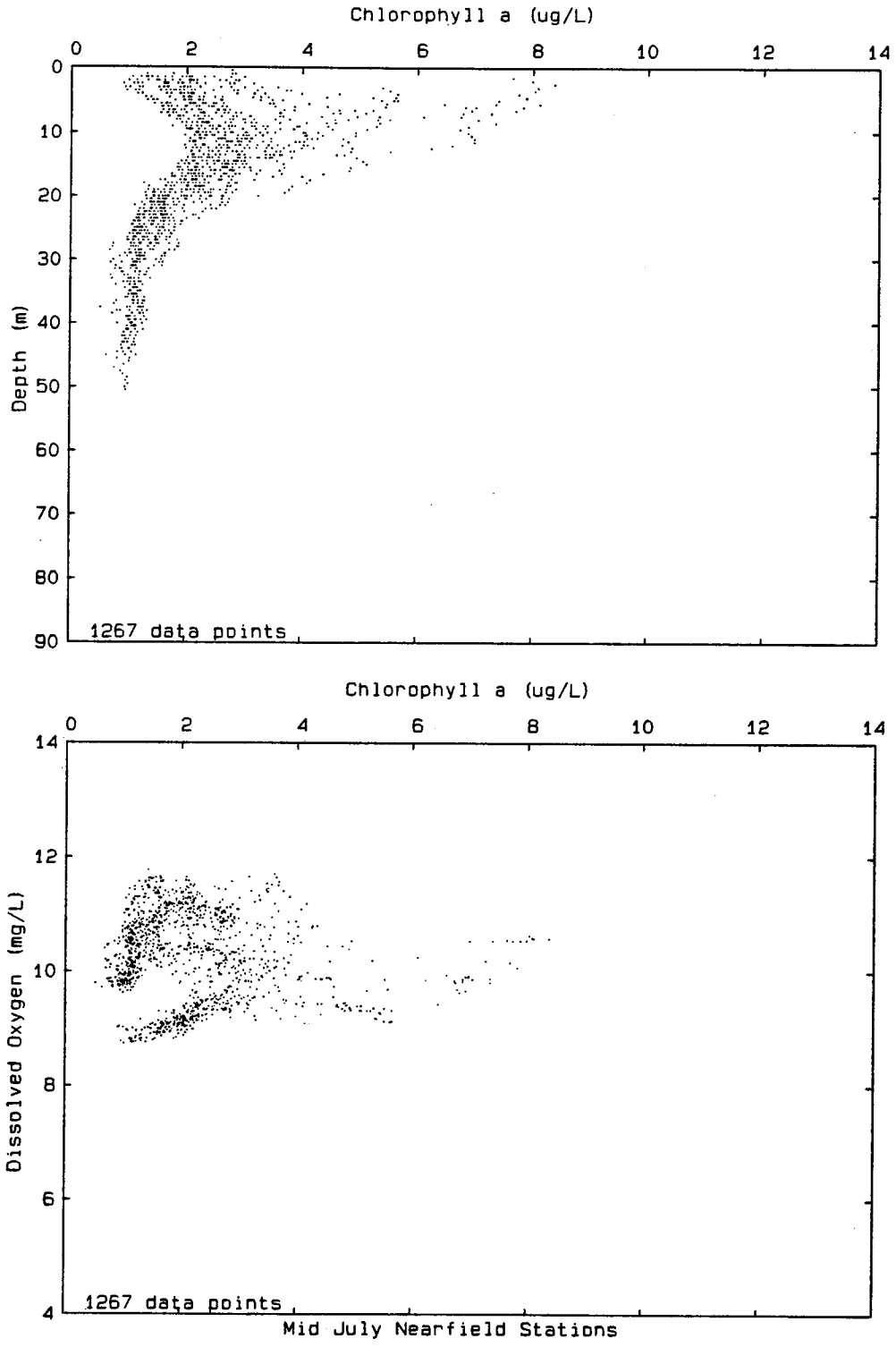



**Figure 7-1c** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in mid-July 1992. Individual station casts that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

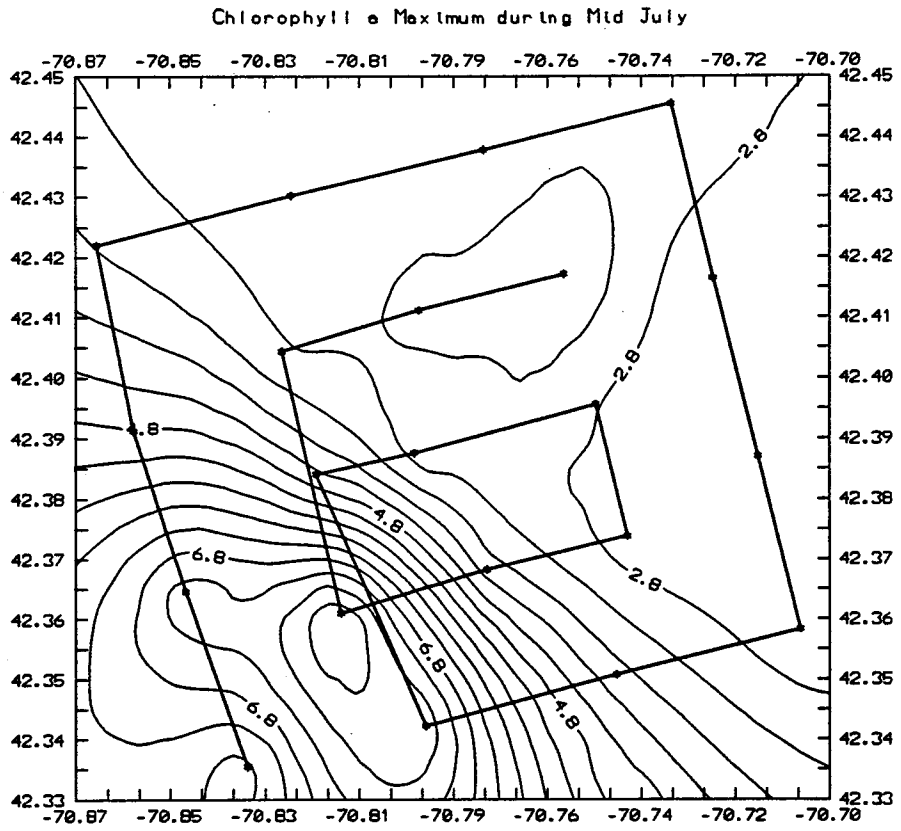



**Figure 7-2** **Chlorophyll maximum at each nearfield station from vertical profile day (Appendix B). Track shows sampling, starting at southwest corner of nearfield and proceeding clockwise to spiral into the middle of the field. Chlorophyll maximum may not be at the same depth at different stations.**

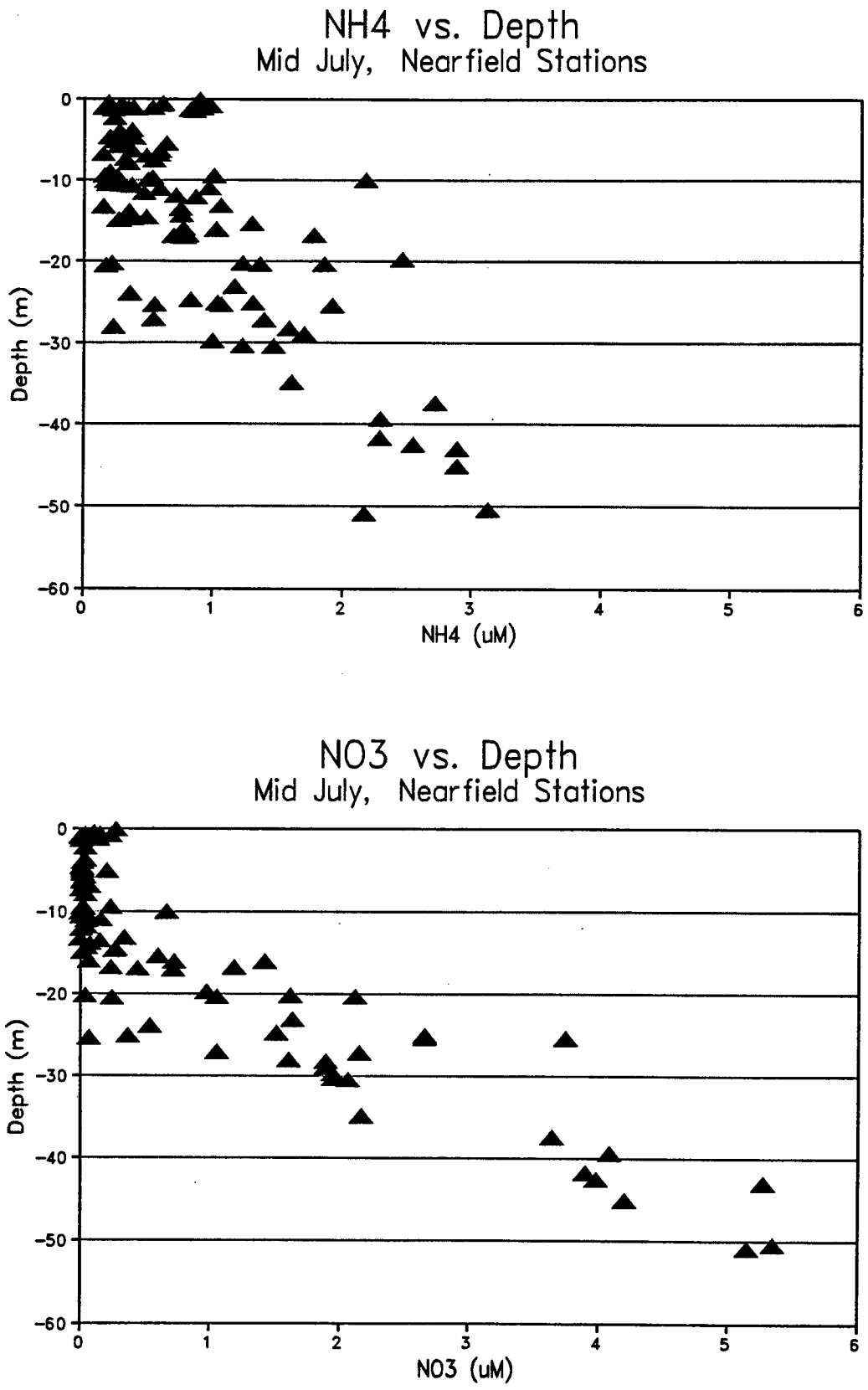



**Figure 7-3 $NH_4$ and $NO_3$ vs. depth in mid-July 1992.**

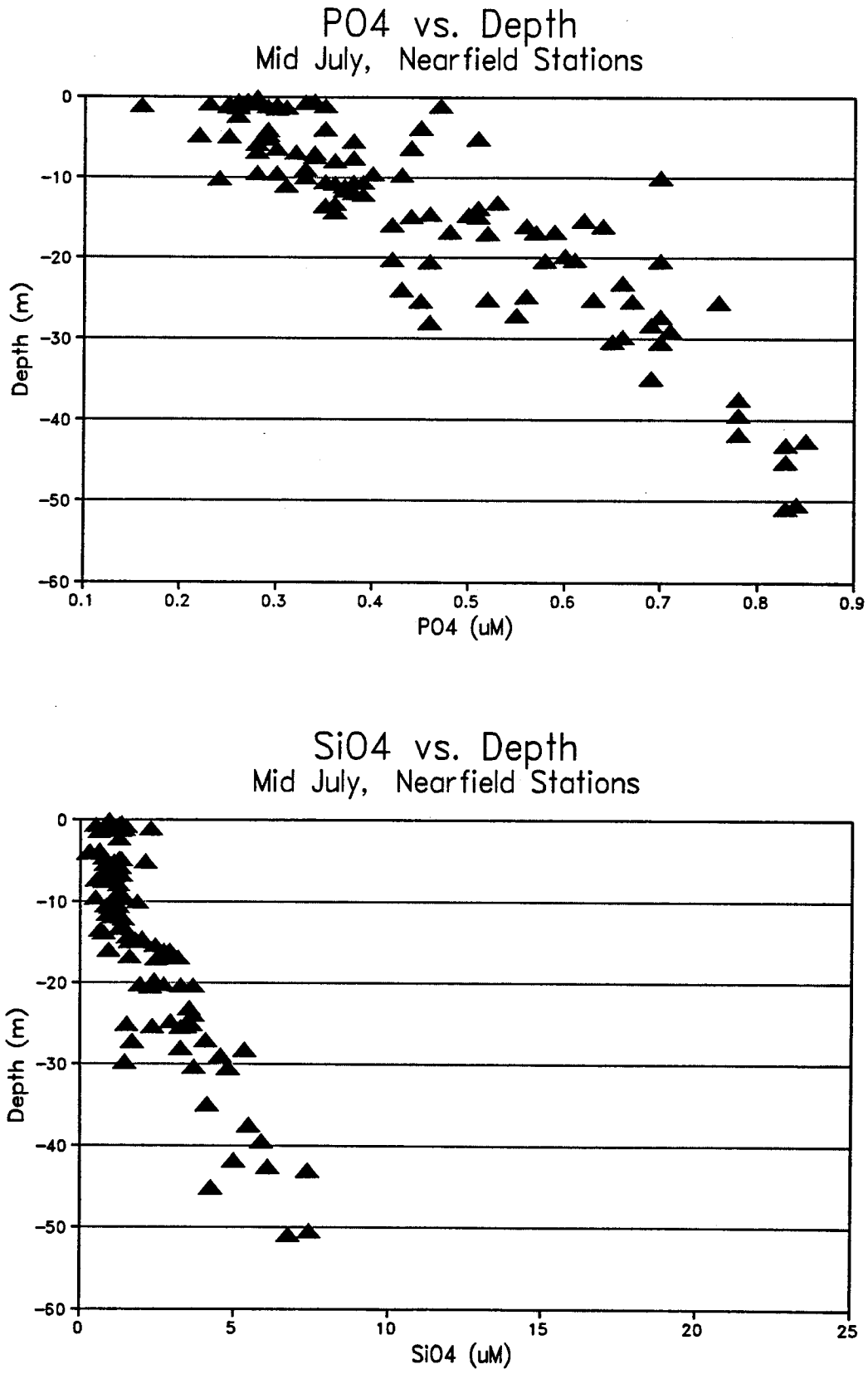



**Figure 7-4 $PO_4$ and $SiO_4$ vs. depth in mid-July 1992.**

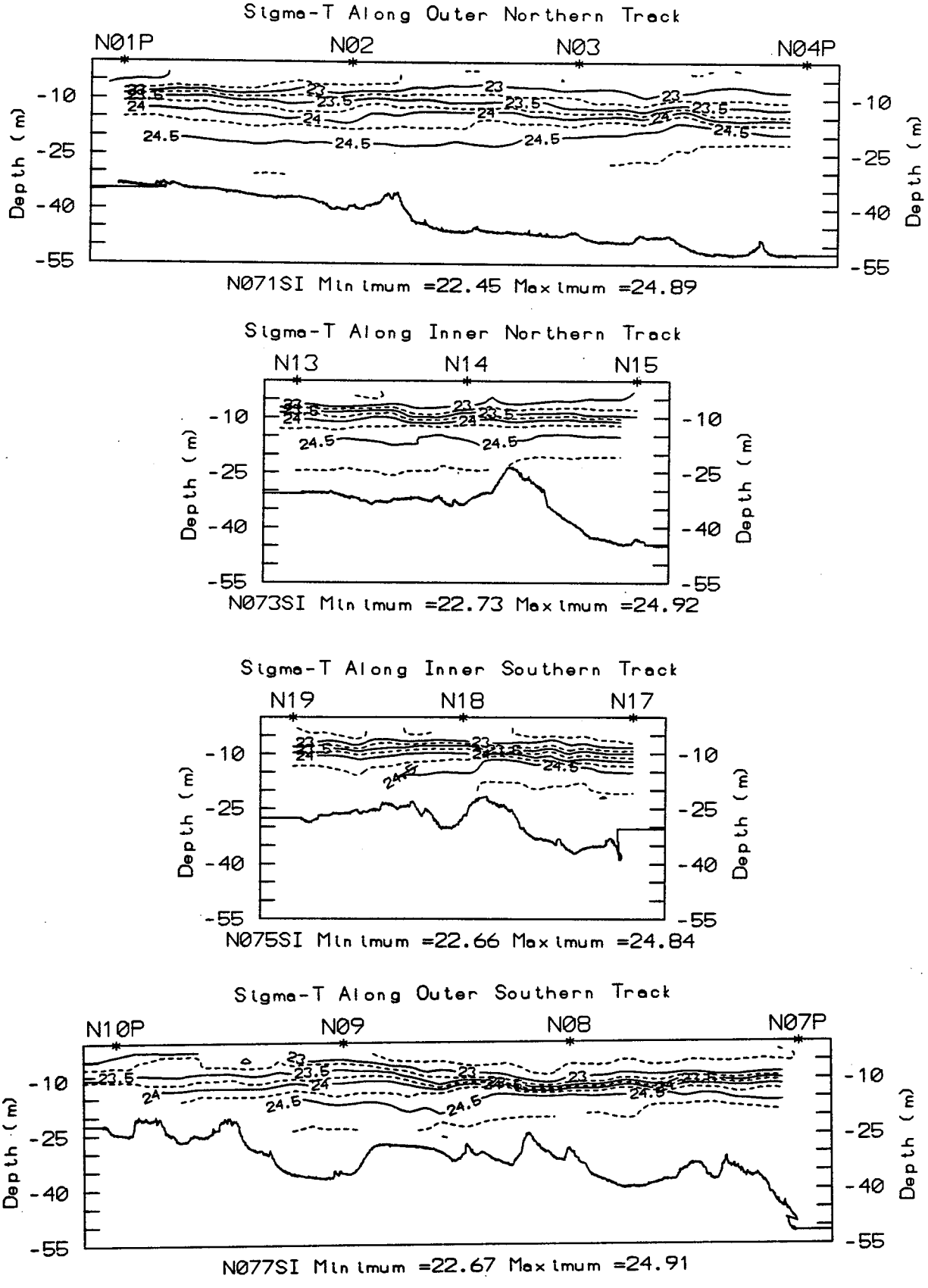



**Figure 7-5a** **Vertical section contours of $\sigma_T$ generated for tow-yos in mid-July 1992. The view is towards the North. The contour interval is 0.25 $\sigma_T$.**

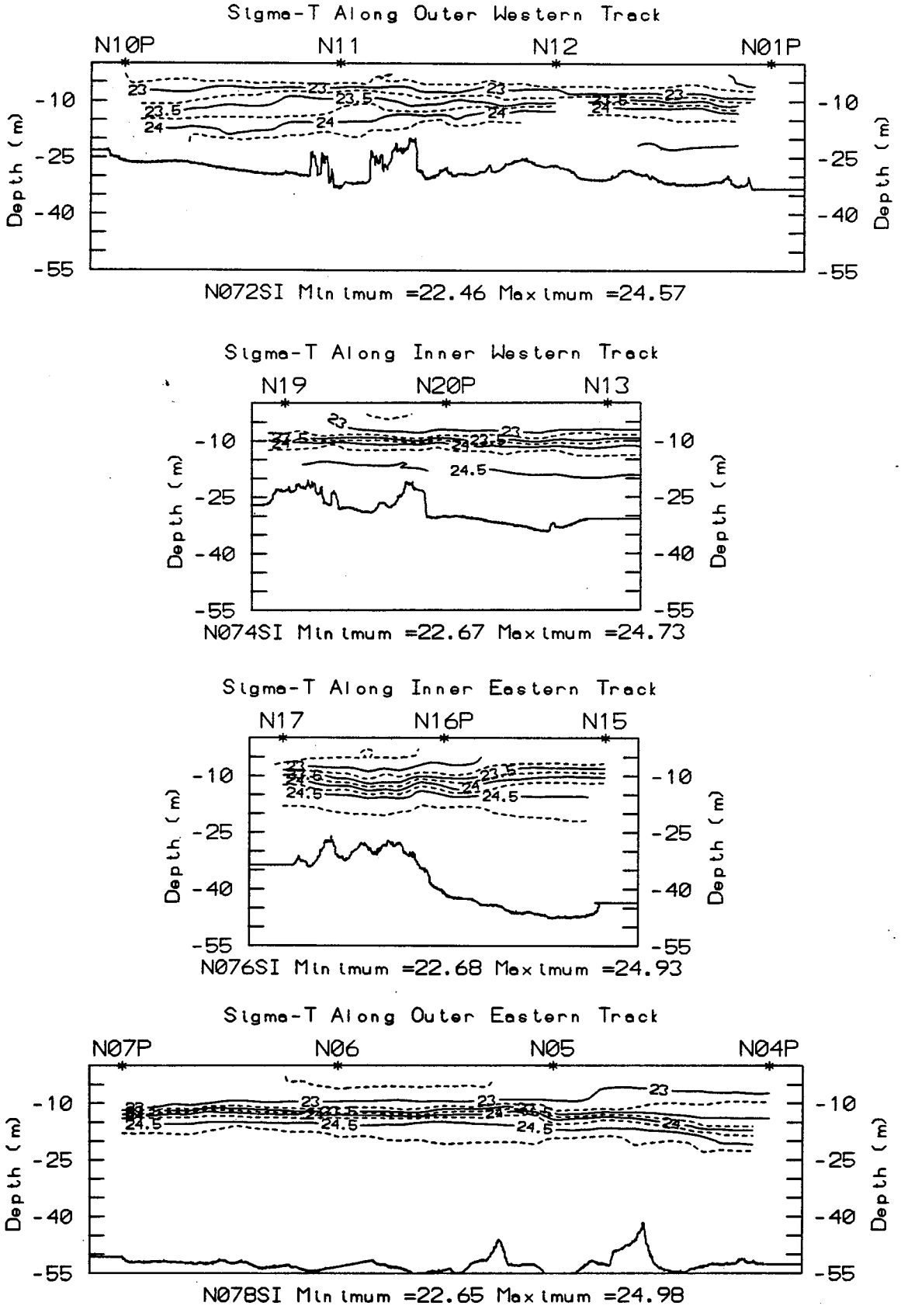



**Figure 7-5b Vertical section contours of $\sigma_T$ generated for tow-yos in mid-July 1992. The view is towards Boston Harbor.**

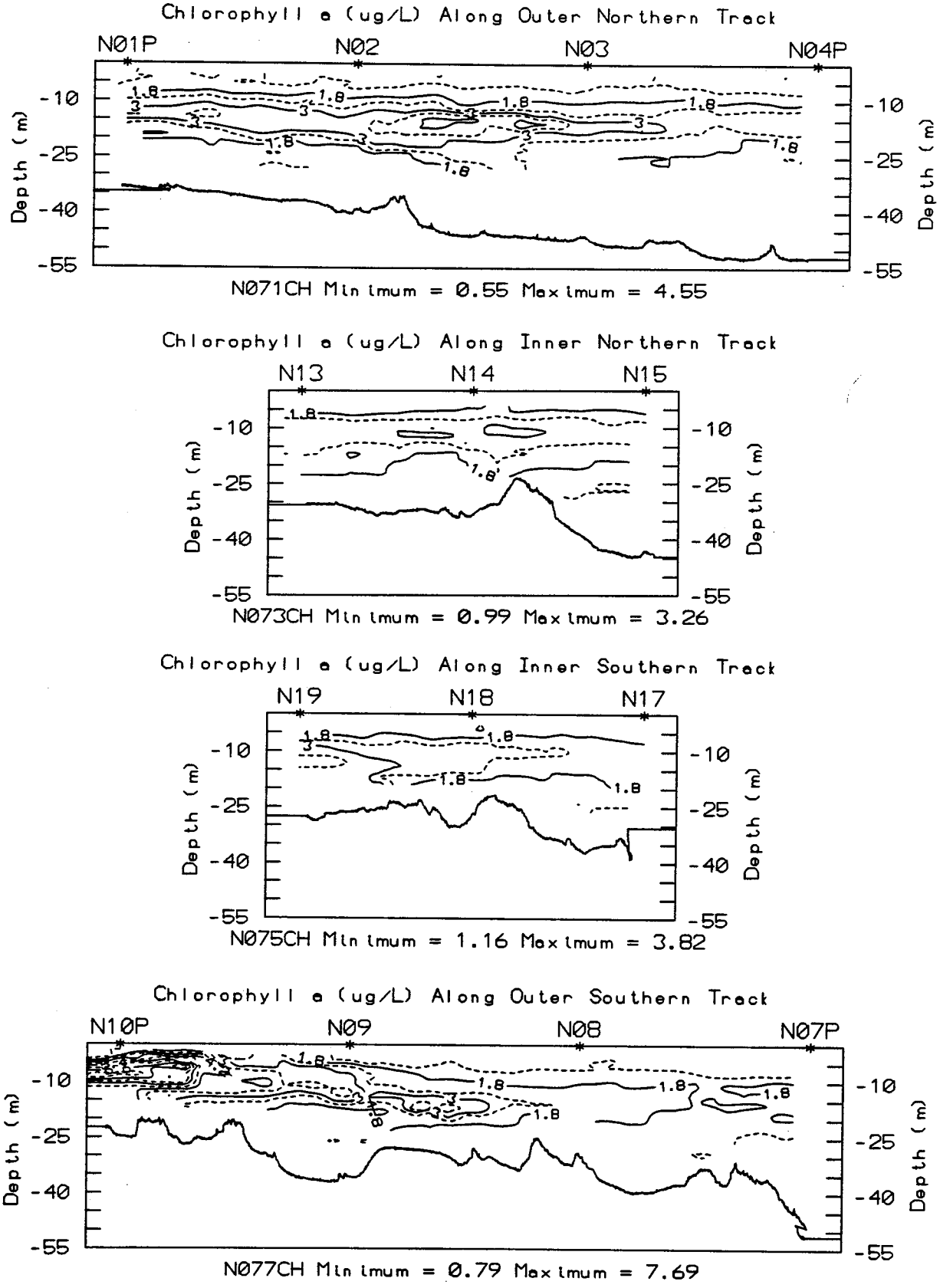



**Figure 7-6a** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in mid-July 1992. The view is towards the North. The contour interval is 0.6 $\mu$g $L^{-1}$.**

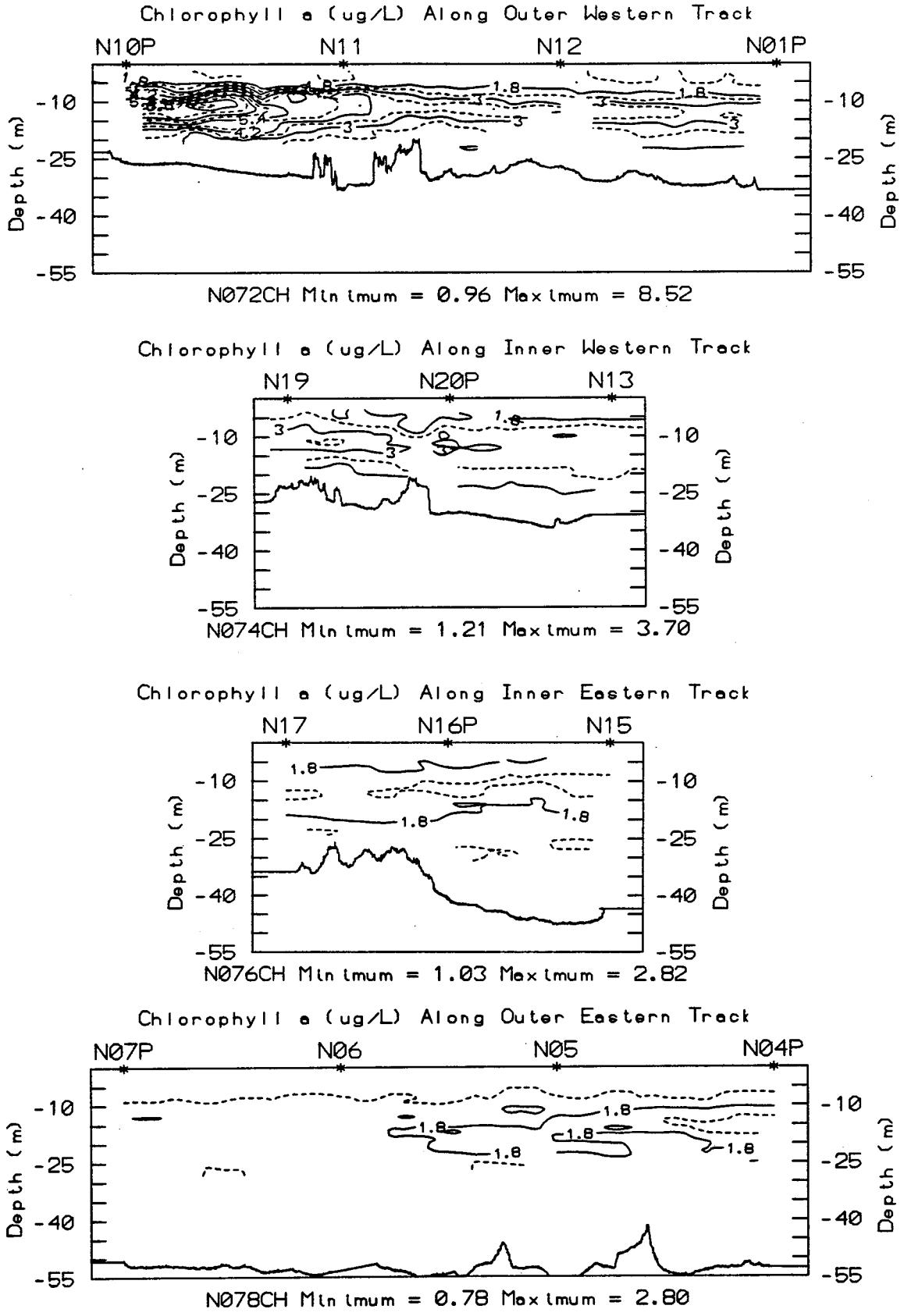



**Figure 7-6b** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in mid-July 1992. The view is towards Boston Harbor.**

# 8.0 LATE JULY NEARFIELD SURVEY (#8) RESULTS

## 8.1 Distribution of Water Properties from Vertical Profiling

Compared to the mid-July survey (July 15, 16), the late July survey only two weeks later (29th, 30th) had surface temperatures higher by a couple degrees (Figure 8-1a). It was interesting to note that surface temperatures were lowest along the inshore string of stations (N10P to N01P) ($\sim$16.1-17.5°C), whereas the field east of this was mostly 18°C.

Salinity, compared to two weeks earlier, had a slightly narrower range. Deepest bottom waters were still similar with respect to T and S, but the surface water salinity was slightly more saline, all surface samples from stations were in a narrow range from 30.92-30.99 (Appendix A).

The pycnocline tended to be shallowest inshore, where some stations had no distinct surface layer. In contrast, Station N07P offshore had a very well-defined 10 m surface layer and a relatively sharp pycnocline to 20 m (Appendix B). Intermediate depth stations, e.g. N16P, had a complex thermocline, and three distinct density layers (0-8 m , 10-16 m, and $>$28 m) Appendix B.

Once again beam attenuation had some of the highest values at low salinity, and there was a positive correlation between beam attenuation and chlorophyll fluorescence (Figure 8-1b). Chlorophyll maxima were found at two density surfaces ($\sim\sigma_T$ = 23 and $\sigma_T$ = 24.7). In Figure 8-1c, one can see that these surfaces were at about 5-10 m and near 20 m depth across the full set of stations.

Dissolved oxygen concentrations ranged from $>$8 to $>$12 mg $O_2$ $L^{-1}$. In general, dissolved oxygen was lowest in the warmer surface waters, highest at mid-depth (usually within the pycnocline and near the subsurface chlorophyll maximum, and intermediate in the colder subpycnocline waters (Appendix B).

We sampled the southwest corner of the nearfield (N10P) near full high tide on the vertical profiling day (Figure 8-2). Chlorophyll at the surface was near 1.8 $\mu$g $L^{-1}$ at that time, and higher chlorophyll values were seen running diagonally (NW to SE) across most of the field (Figure 8-2).

With respect to nutrients and their depth distribution, $NH_4$ and $NO_3$ concentrations were fairly similar to results from the surveys two weeks before. A few stations had detectable levels in the 0-15 m layers. The few $NH_4$ samples above 1 $\mu$M in the surface 0-15 m were at N10P, N11, and N12 along the inshore track and higher $NO_3$ values were associated with these (see Appendix A). One difference between the two surveys in July was that more values of $NH_4$ and $NO_3$ below 30 m depth were $<1$ $\mu$M in the late July sampling. This could suggest some vertical mixing or water mass movements at some stations during this period, as also suggested by some of the complex physical profiles already mentioned.

$PO_4$ was distinctly different from two weeks prior. Concentrations from $\sim 0$ to 0.9 $\mu$M were measured. The entire range was distributed more or less evenly at every depth level, so no depth pattern was apparent.

$SiO_4$ showed the same strong relationship with depth that had been seen two weeks earlier, but the upper water column ($\sim$0-20 m) had a generally increased concentration at this survey. We noted that the greater increase in near-surface $SiO_4$ appeared across most of the southwestern corner of the field, extending to the middle (N21P). At this part of the field, over the two weeks, $SiO_4$ usually increased by more than 1 $\mu$M and often several $\mu$M. Bottom water $SiO_4$, between these surveys, was essentially constant.

### 8.2 Distribution of Water Properties from Towing

Towing clearly confirmed the surface temperature patterns seen the day before. Temperature along the inshore track was cooler by a couple of degrees from the offshore track. The thermocline was deepest offshore. However, there was much variation suggested in the structure of the thermocline across the field and a smooth gradient from inshore to offshore was not apparent. Many of the oscillating tow-yo tracks yielded a pattern of an undulating thermocline and virtual surfacing of the thermocline at some locations (near the mid-field). Similar comments could be made regarding the contour patterns of $\sigma_T$ (Figure 8-5).

Examining Figure 8-6, the trend of higher chlorophyll to the inshore side of the field was apparent. Interestingly, the chlorophyll maximum in the shallower stations tended to be nearer the surface and in

the upper pycnocline, whereas offshore it tended to be at the lower base of the pycnocline. At many stations in the western-to-middle section of the field (North to South), a double chlorophyll maximum was seen (e.g. N02, N20P, N09). This double maximum feature ($\sim$8 m, then 15-20 m) was also apparent in a number of vertical profiles from the day before. Small-to-intermediate size patches of chlorophyll $>2$ $\mu g\ L^{-1}$ were seen throughout most of the field, excepting the most eastern track. The track with the greatest number of intense patches seemed to be the southernmost track (N07P-N10P). On the eastern half of this, the patches were centered below 10 m, whereas on the western half the chlorophyll was at about 5 m. In general, on this track the waviness and patchiness of the chlorophyll contours (Figure 8-6b) seemed to be, in part, a reflection of the same physical irregularities seen in the $\sigma_T$ (Figure 8-5b).

## 8.3 Analysis of Small-Scale Variability

The N07P-N10P section just described again demonstrated the tidal-related variability at N10P. Both on the vertical profiling day and at first occupation of the towing day (Figure 8-6b, outer western track), N10P was visited near high tide. Then, chlorophyll was less than 2 $\mu g\ L^{-1}$, temperature cooler, and density higher. Yet at the end of the day's towing from N07P to N10P, the station was visited near low tide and higher chlorophyll, higher temperature, and lighter water were observed (e.g. Figure 8-5, 8-6). At this time, a similar mass of water from N10P to N09 was suggested, each station appearing to have a localized patch of chlorophyll at about 5 m depth.

With regard to spatial variability, some of the pycnocline variability has been noted already. In general, the features noted for most parameters, both horizontal and vertical, were quite consistent across the field and noted in about the same location over time.

## 8.4 Water Types, as Related to Nutrients, Fluorescence, and Dissolved Oxygen

There was some distinction between inshore and offshore waters with respect to the depth of the pycnocline, surface water temperature, depth and intensity of the chlorophyll maximum, and, to a small extent, surface nitrogen. With respect to N-S patterns, there was a bit of bias to higher chlorophyll being

detected further offshore to the south. The temperature/$\sigma_T$ structure suggested two slightly different water masses may have been interacting near the center of the field, angled from about N02 to the North, to N13, and then to N18, to N09-N08 at the South. The presence of these presumed different water masses, if there occurred some mixing of their waters, may have created some of the anomalies noted in nutrients relative to the previous survey.

Curiously, the inshore (and especially SE corner) surface section of the field had a relatively large increase in $SiO_4$ since the previous survey. If the tidal dynamic notion of outflow from the Harbor into surface waters here is valid, a suggestion would be that silicate was being infused into the field with, or remineralized within, this water. More detailed geochemical analyses of these data might resolve this speculation. Moreover, analysis of the plankton community in the chlorophyll maximum at $\sim$8 to 10 m versus that at $\sim$20 m would probably have provided some additional water mass discrimination potential.

The range in dissolved oxygen (Figure 8-1c) was slightly larger than, but still very similar to, the previous survey.

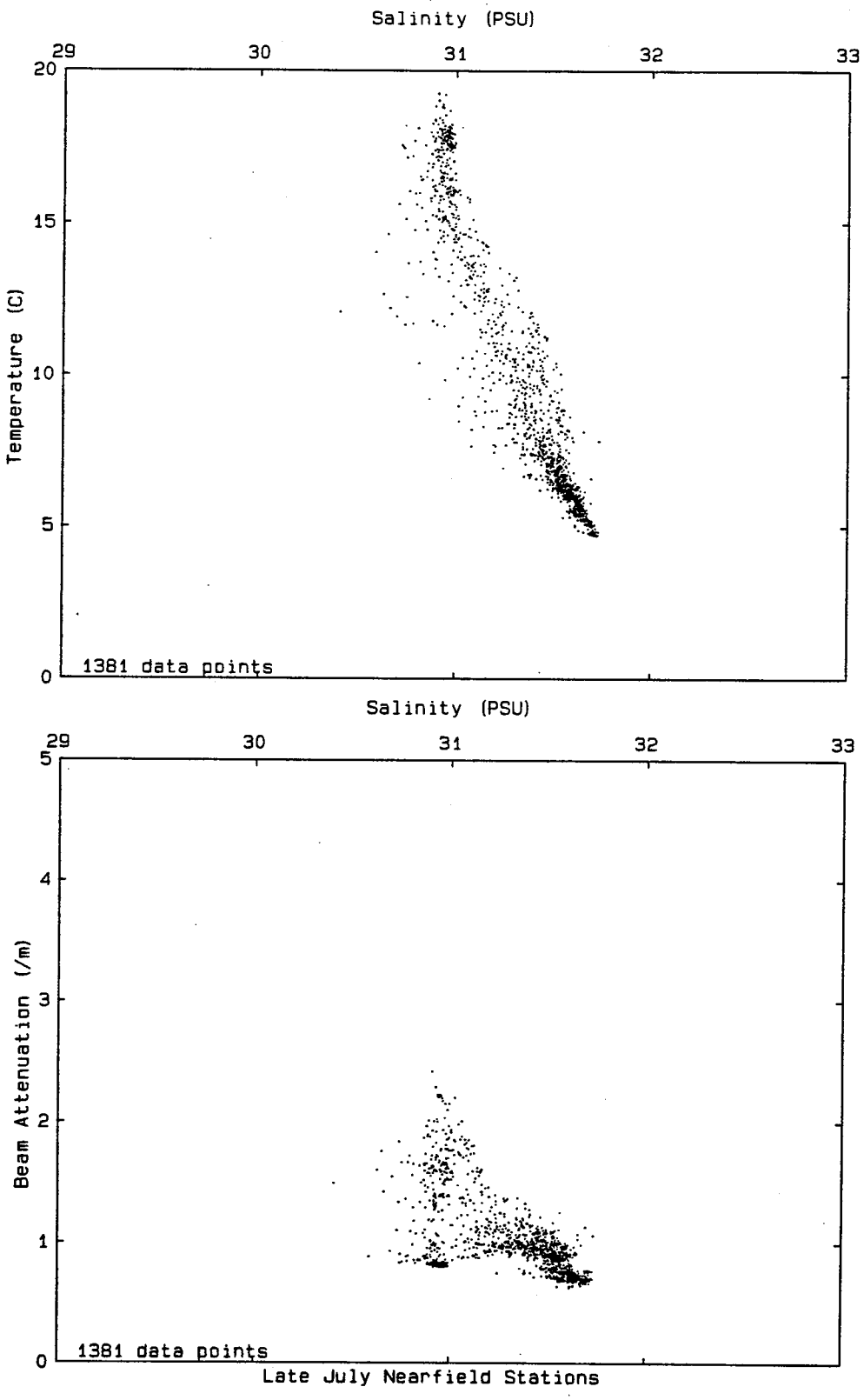



**Figure 8-1a** Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in late July 1992. Individual station casts that were used to produce this composite are in Appendix B.

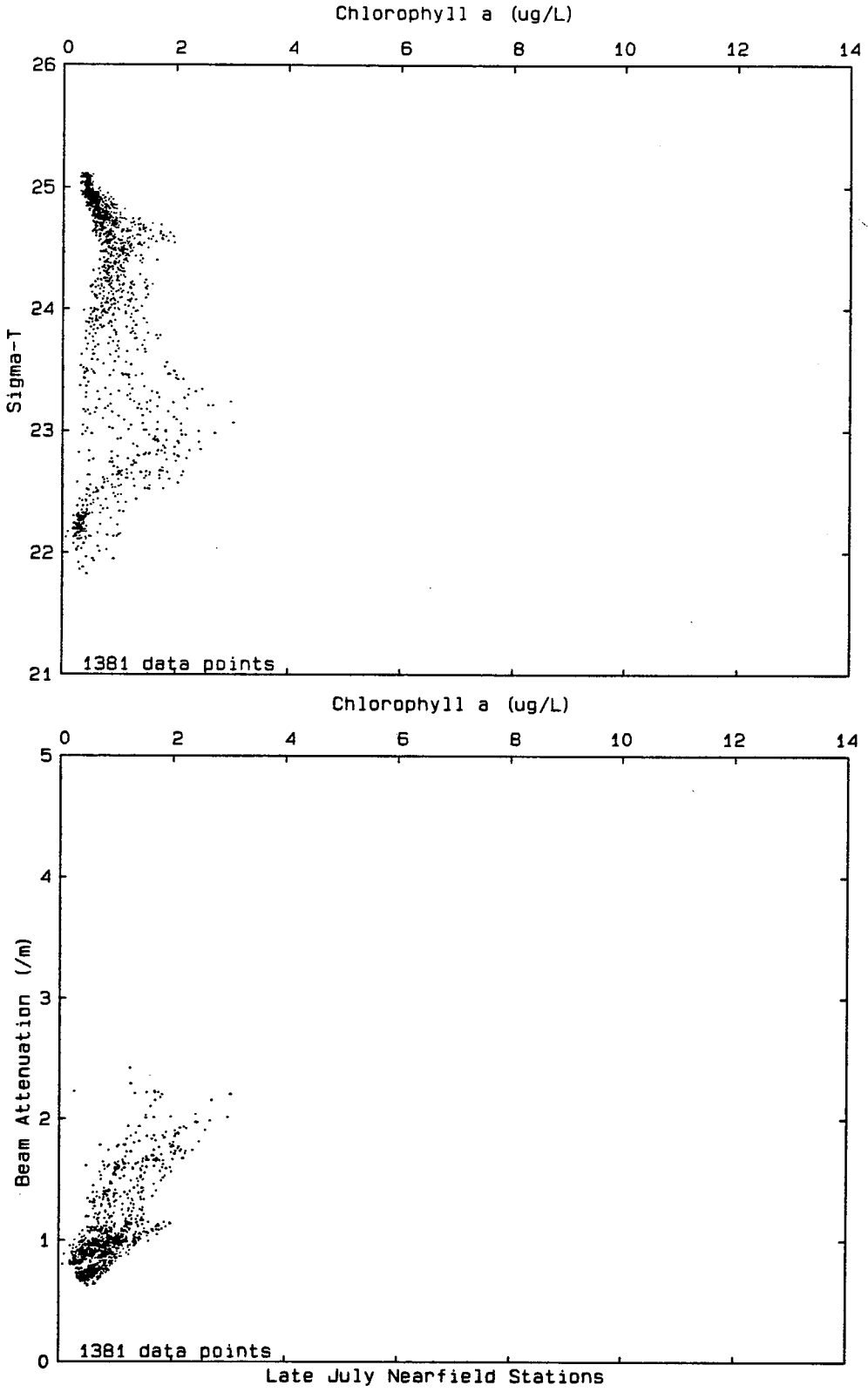



**Figure 8-1b** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in late July 1992. Individual station casts that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

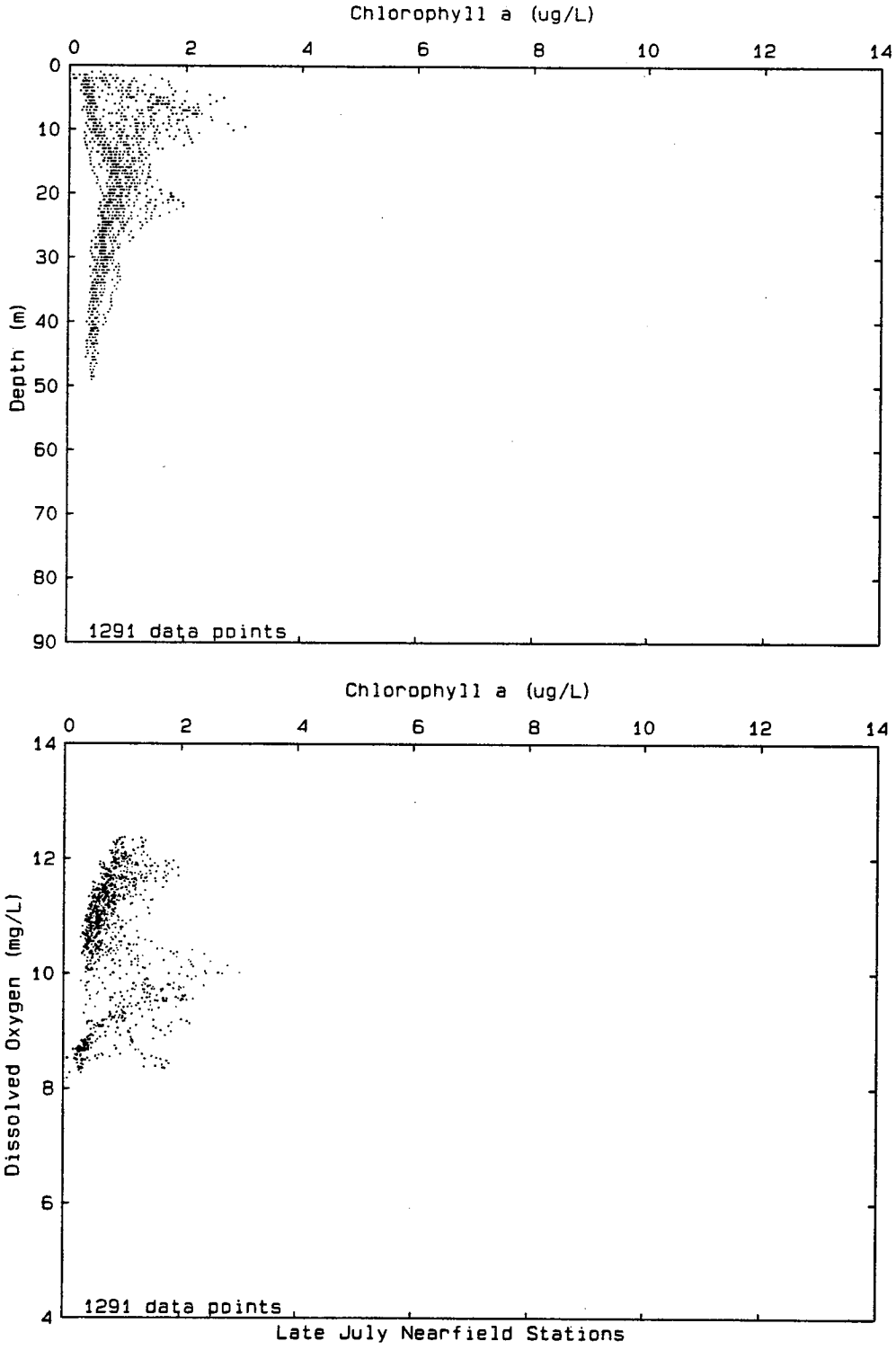



**Figure 8-1c** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in late July 1992. Individual station casts that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

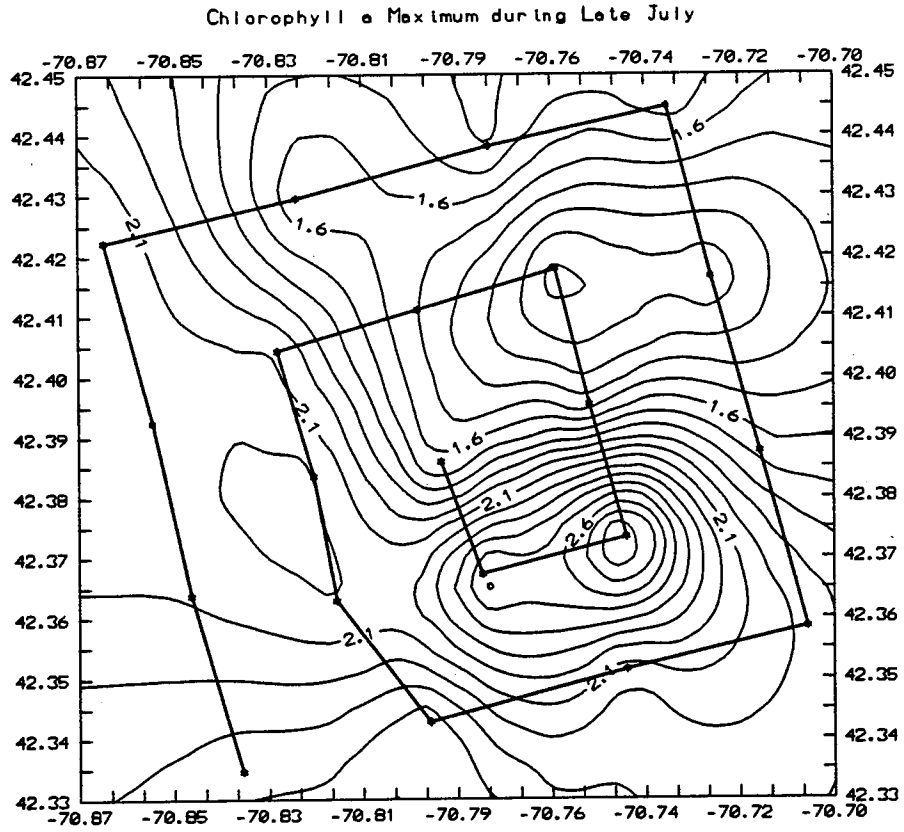
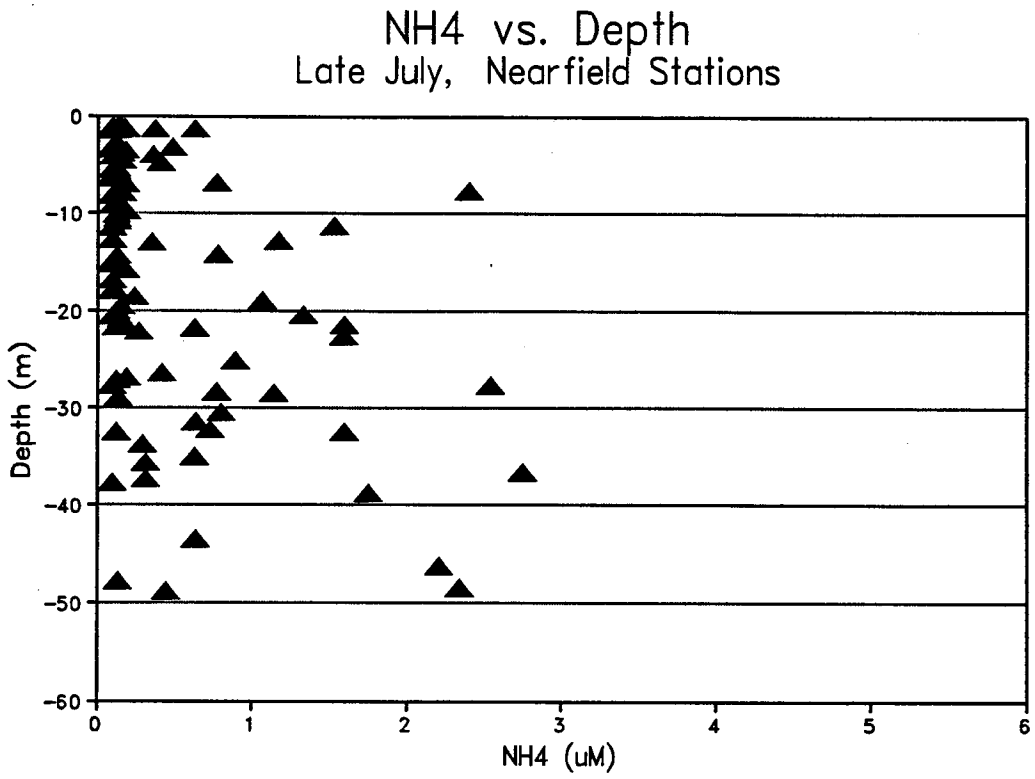



**Figure 8-2** **Chlorophyll maximum at each nearfield station from vertical profile day (Appendix B). Track shows sampling, starting at southwest corner of nearfield and proceeding clockwise to spiral into the middle of the field. Chlorophyll maximum may not be at the same depth at different stations.**



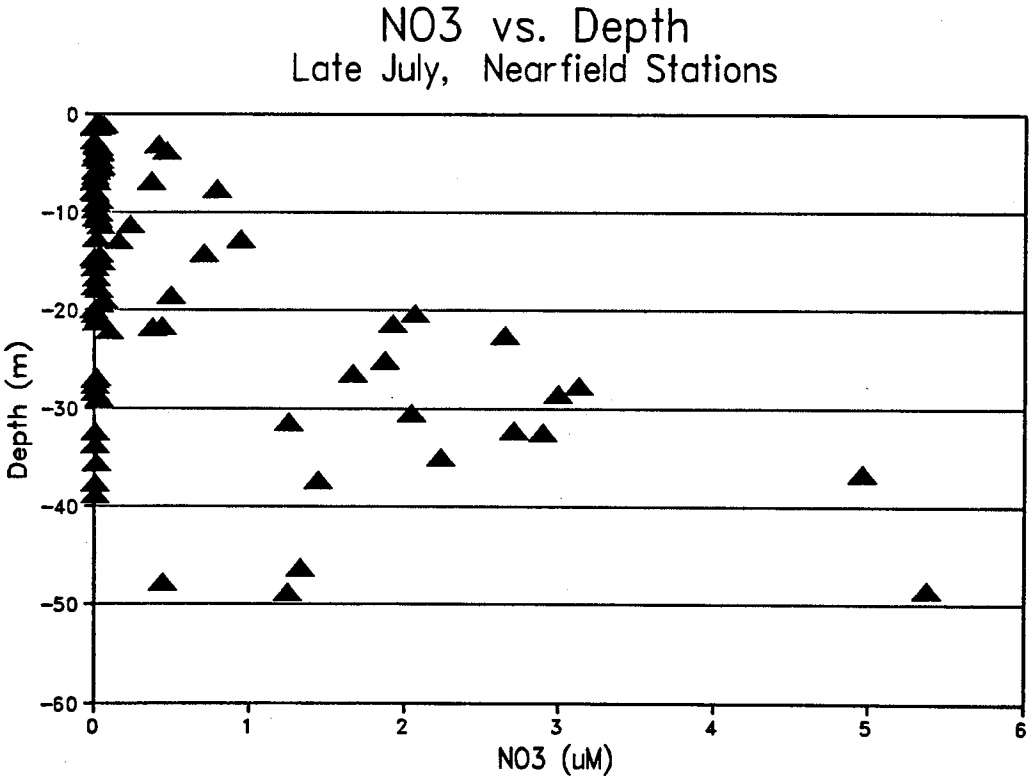
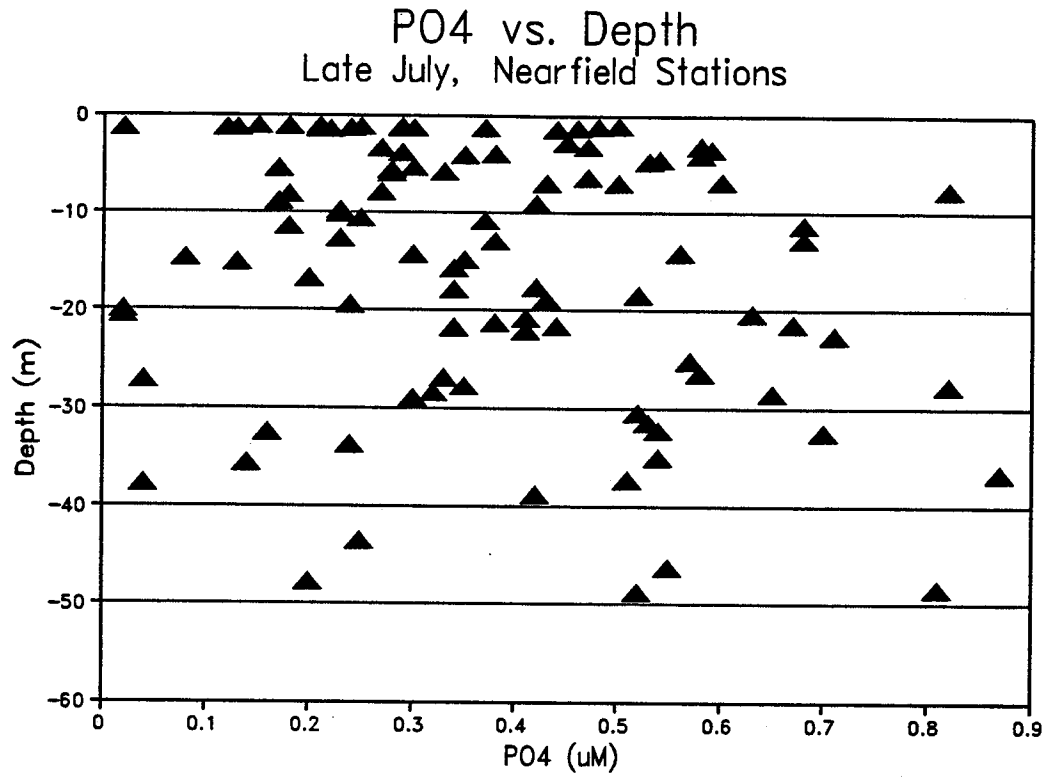




**Figure 8-3 $NH_4$ and $NO_3$ vs. depth in late July 1992.**



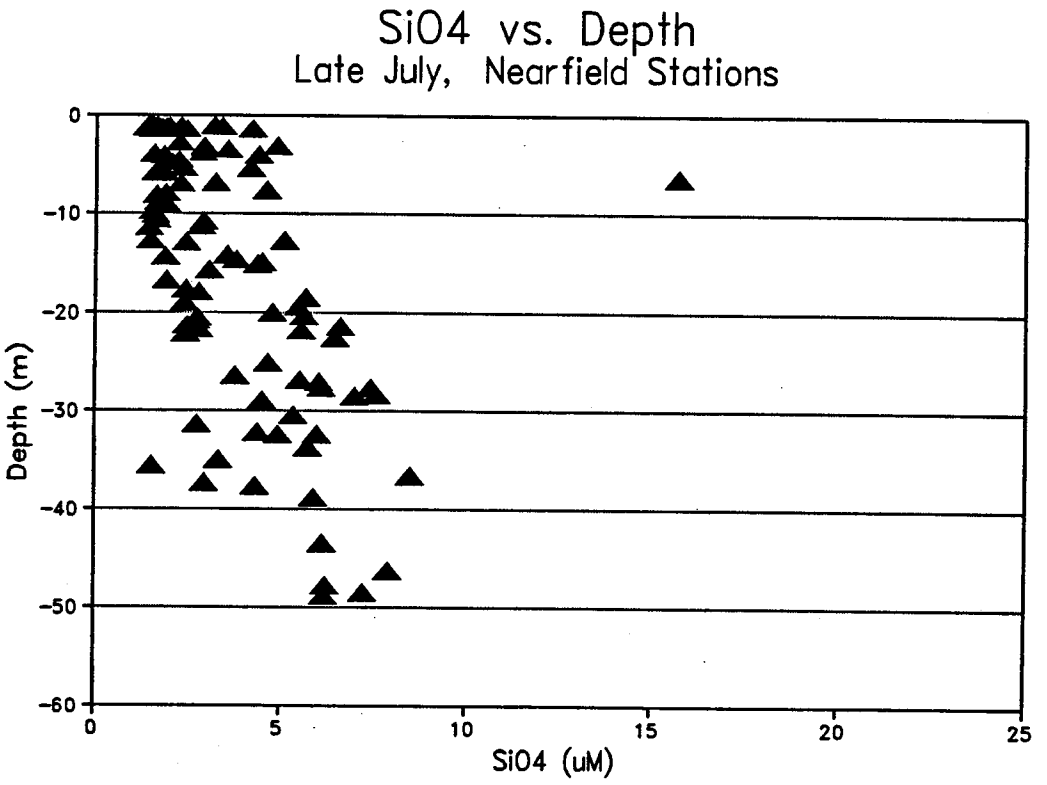




**Figure 8-4 $PO_4$ and $SiO_4$ vs. depth in late July 1992.**

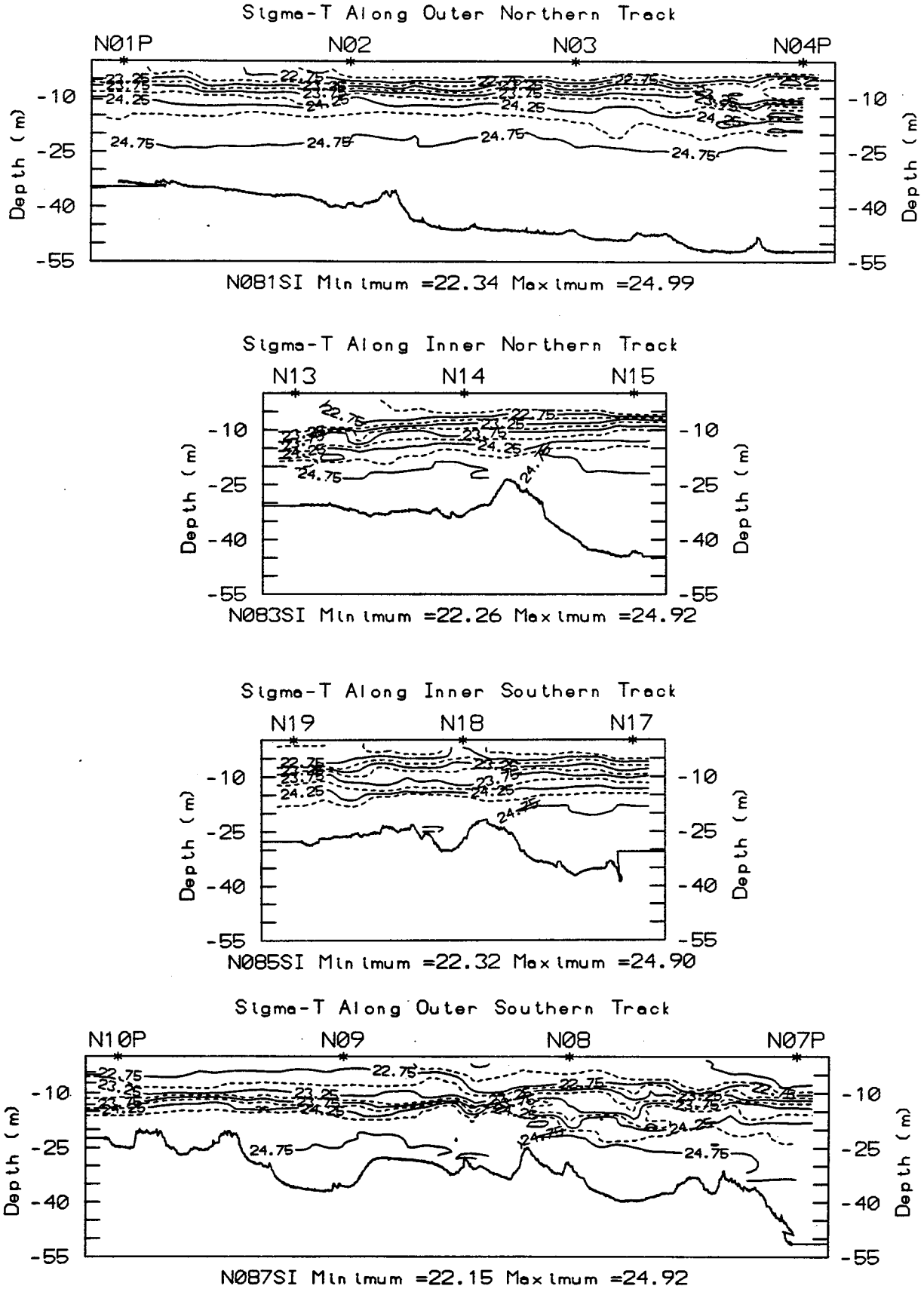



**Figure 8-5a Vertical section contours of $\sigma_T$ generated for tow-yos in late July 1992. The view is towards the North.**

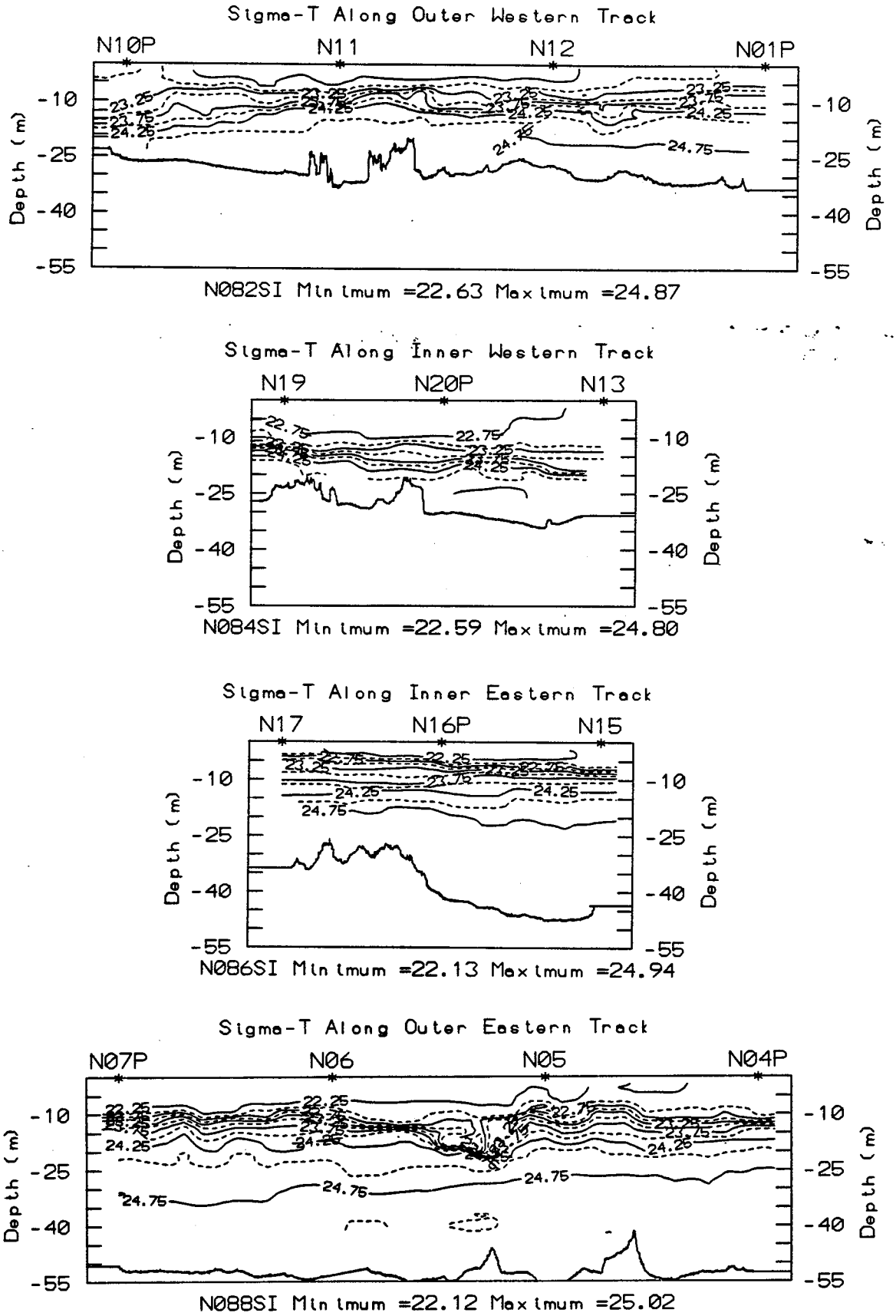



**Figure 8-5b** **Vertical section contours of $\sigma_T$ generated for tow-yos in late July 1992. The view is towards Boston Harbor. The contour interval is 0.25 $\sigma_T$.**

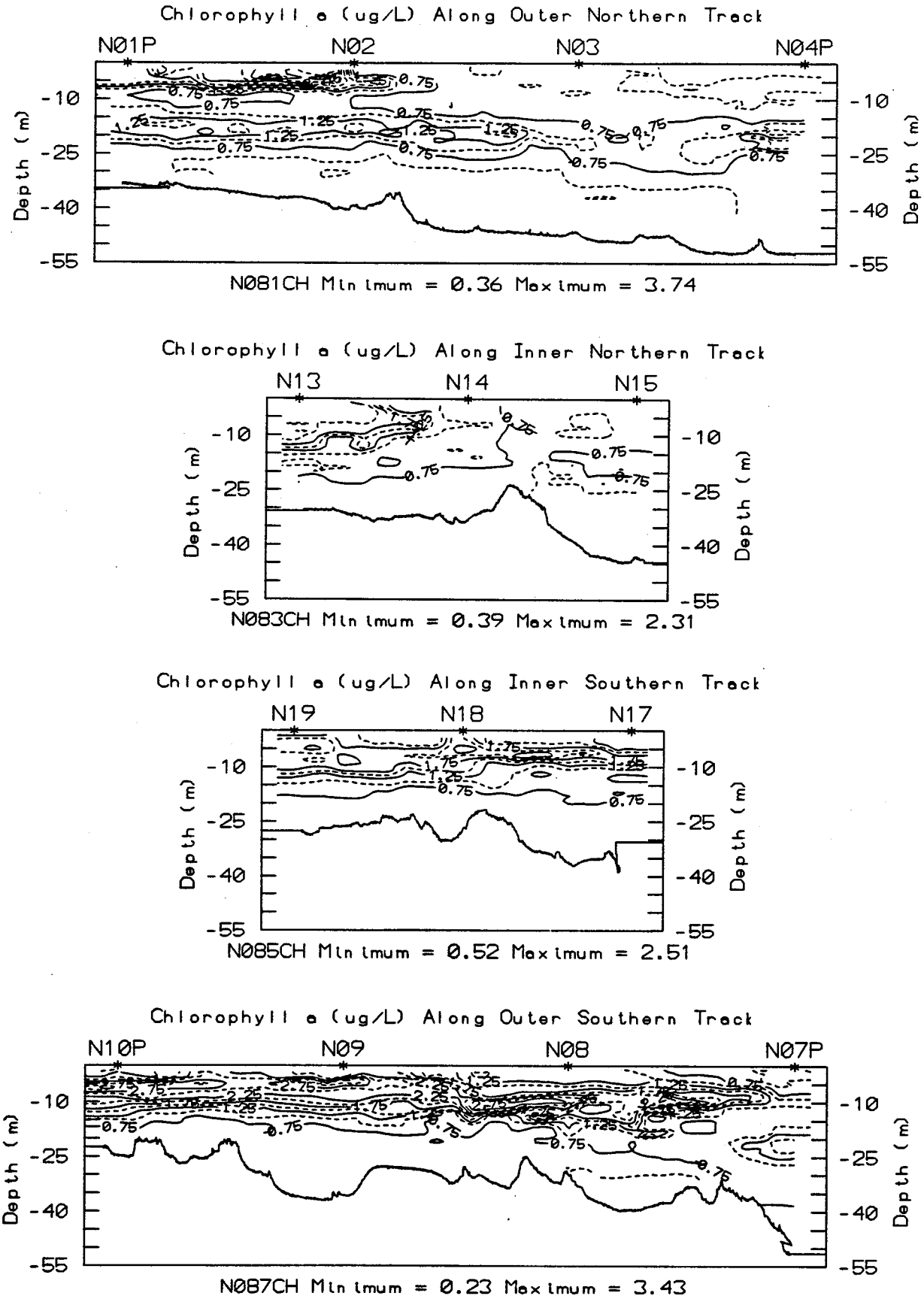



**Figure 8-6a** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in late July 1992. The view is towards the North. The contour interval is 0.25 $\mu$g $L^{-1}$.**

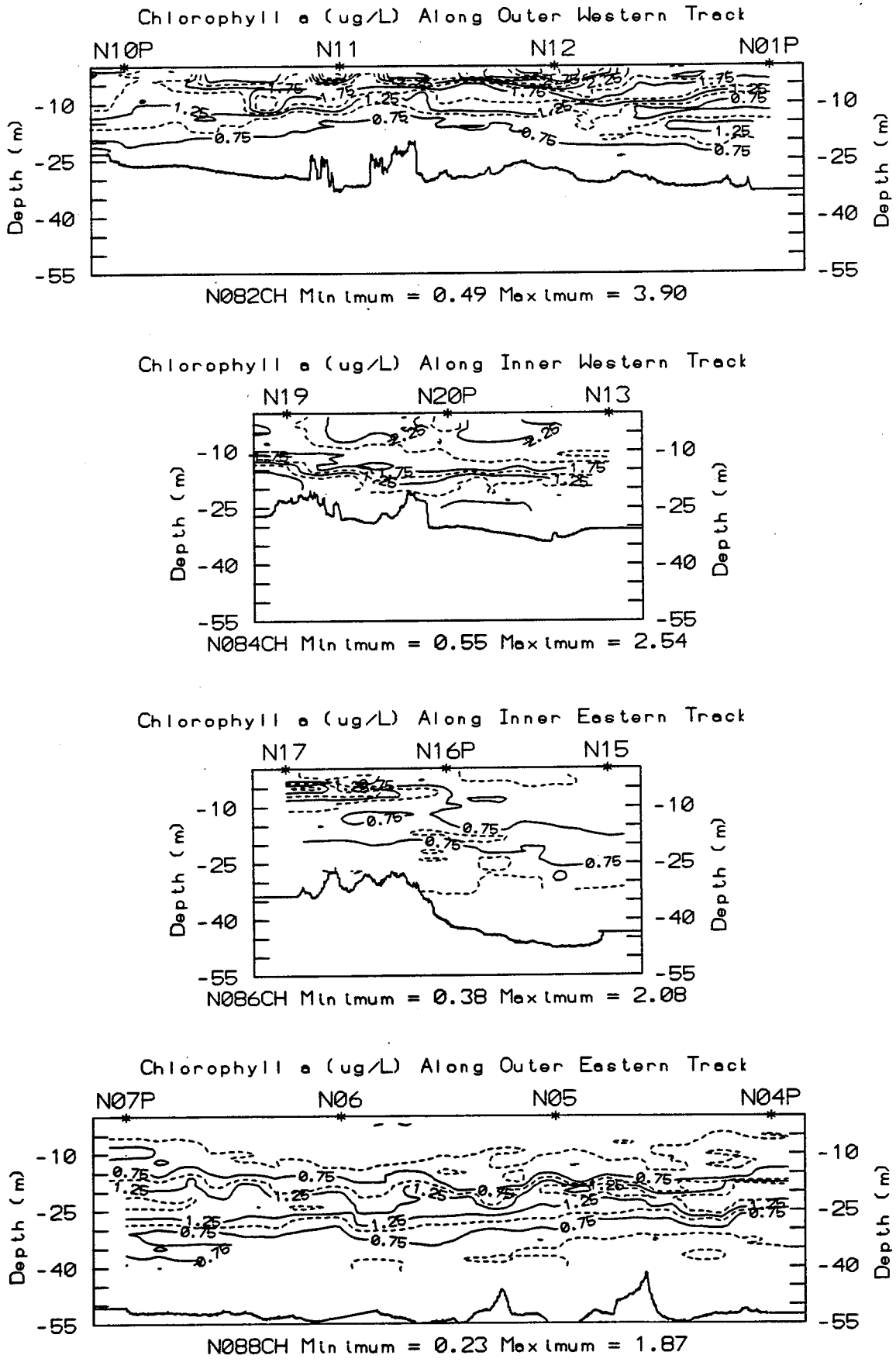



**Figure 8-6b Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in late July 1992. The view is towards Boston Harbor.**

# 9.0 MID-AUGUST 1992 NEARFIELD SURVEY (3) RESULTS

## 9.1 Distribution of Water Properties from Vertical Profiling

The surface temperatures recorded across the nearfield actually decreased up to several °C in the approximately two weeks since the late July survey. Maximum temperatures were slightly above 16°C (Figure 9-1), the previous survey pattern of higher temperatures offshore was not repeated, and the range in surface temperatures was only about 1°C. The range in salinity was again narrow, with surface values about 31 PSU or greater and deepest water (5-6°C) about 31.75 PSU-both water layers had shifted to slightly high salinity from July. Beam attenuation showed a familiar pattern with salinity and chlorophyll (Figure 9-1).

Chlorophyll $>4$ $\mu g\ L^{-1}$ was seen within the top 10 m, yet a deeper chlorophyll maximum (15-20 m), with values of 2-4 $\mu g\ L^{-1}$ was again characteristic of stations in deeper water offshore.

Highest chlorophyll was clearly located along the western inshore side of the field (Figure 9-2). Most of this western side of the field was sampled near an ebbing tide, and some stations near low tide, so the high chlorophyll probably indicates the Harbor influence.

Once again, inshore shallow stations often did not have a well defined surface layer; rather, the whole water column was a gradual density gradient. Offshore, a well defined pycnocline with distinct surface and bottom layers was characteristic. In general, the vertical structure, looking across stations (Appendix B) was less variable than had been the case in late July and broad N-S and E-W trends were the main pattern.

With the observed stratification, it was perhaps not surprising to see nitrogen generally depleted from the surface to about 12 or 15 m (Figure 9-3). $NO_3$ in particular showed a very strong pattern of increase below this depth.

$PO_4$ had a slightly narrower range and a more distinct pattern of increase with depth than it had in late July.

$SiO_4$ was similar to late July with respect to its distribution over depth. But there was a continued trend of increase in surface concentrations (on average), such that the difference between surface and bottom concentrations was not as great as it had been a month, or even two weeks, before.

Often, a mid-depth maximum occurred for dissolved oxygen. This often coincided with a chlorophyll maximum, but this was not a consistent pattern (Figure 9-1c). In contrast to the surveys in July, the bottom water dissolved oxygen was no longer intermediate to mid-depth and surface values, but had generally decreased to be quite similar to surface water concentrations even though the difference in temperature between surface and bottom layers was about 10°C. Surface waters and mid-depths near the maximum were often super saturated, whereas the deepest waters were usually 90-100% saturated. Overall the range of dissolved oxygen across the nearfield was not large and was similar to July surveys (cf. Figures 7-1c, 8-1c, 9-1c).

## 9.2 Distribution of Water Properties from Towing

Contoured sections from the towing day revealed some strong trends (Figures 9-5, 9-6). There was a fairly smooth gradient in the thermocline and pycnocline structure from inshore to offshore. Inshore, the pycnocline tended to be a bit more dispersed, and it become sharper offshore. The depth of the top of the pycnocline gradually increased to the offshore. Similarly, the sharpness of the thermocline/pycnocline tended to be greater to the North (Figure 9-5b), and slightly deeper there in relation to the South, especially at the southwest corner. In general, the subtle broad trends were evident because they were not interrupted by a lot of local (station) variability. Note that the field was also highly similar to the day before, implying some temporal as well as spatial regularity.

With respect to chlorophyll, the regions of higher values were to the western edge and to the southern edge, but here mostly between N10P and N09 (Figure 9-6a). Those regions were sampled on ebbing tides so waters originating from further inshore may have been detected; maximum chlorophyll fluorescence was $>5\ \mu g\ L^{-1}$. Offshore, mid-water maximum were generally seen as slightly greater than $2\ \mu g\ L^{-1}$. In contrast to the inshore distribution, for which the chlorophyll maximum was at $\sim 10$ m and *within* the initial sharp pycnocline, the offshore mid-water maximum was generally near the base of the pycnocline, sometimes even appearing to be in the bottom water layer.

## 9.3 Analysis of Small-Scale Variability

The vertical structure was strong and regular throughout. Little short-term variability was noted.

## 9.4 Water Types, as Related to Nutrients, Fluorescence, and Dissolved Oxygen

The dominant features in the data across the field were edge-to-edge gradual trends in water quality parameters, with distinctly high inshore chlorophyll. Accompanying the geographic trends in vertical physical structure was a low dissolved nutrient layer at the surface and sharp increase in nutrients (especially $NO_3$), and decrease of oxygen, with depth below the base of the pycnocline.

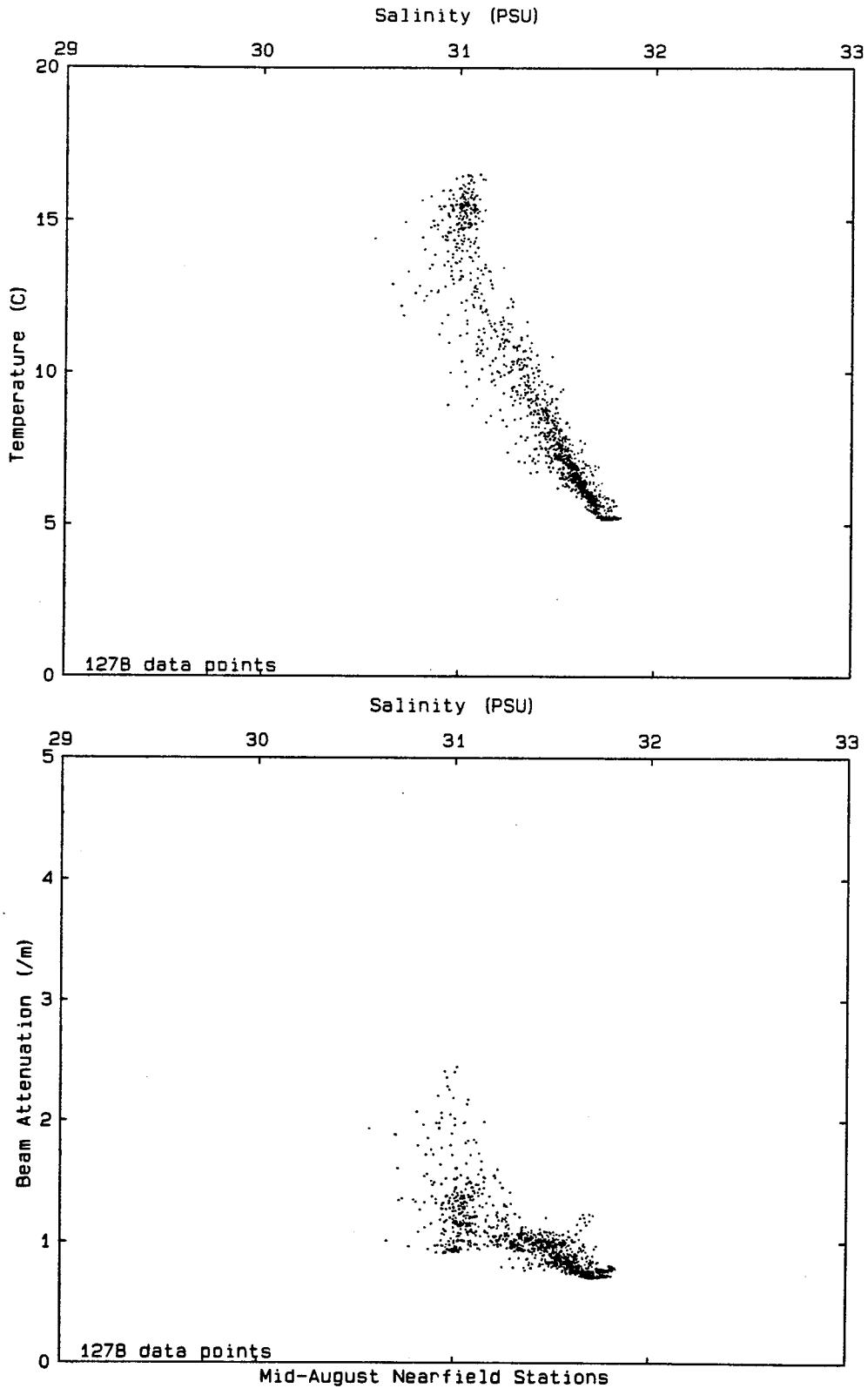



**Figure 9-1a** Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in mid-August 1992. Individual station casts that were used to produce this composite are in Appendix B.

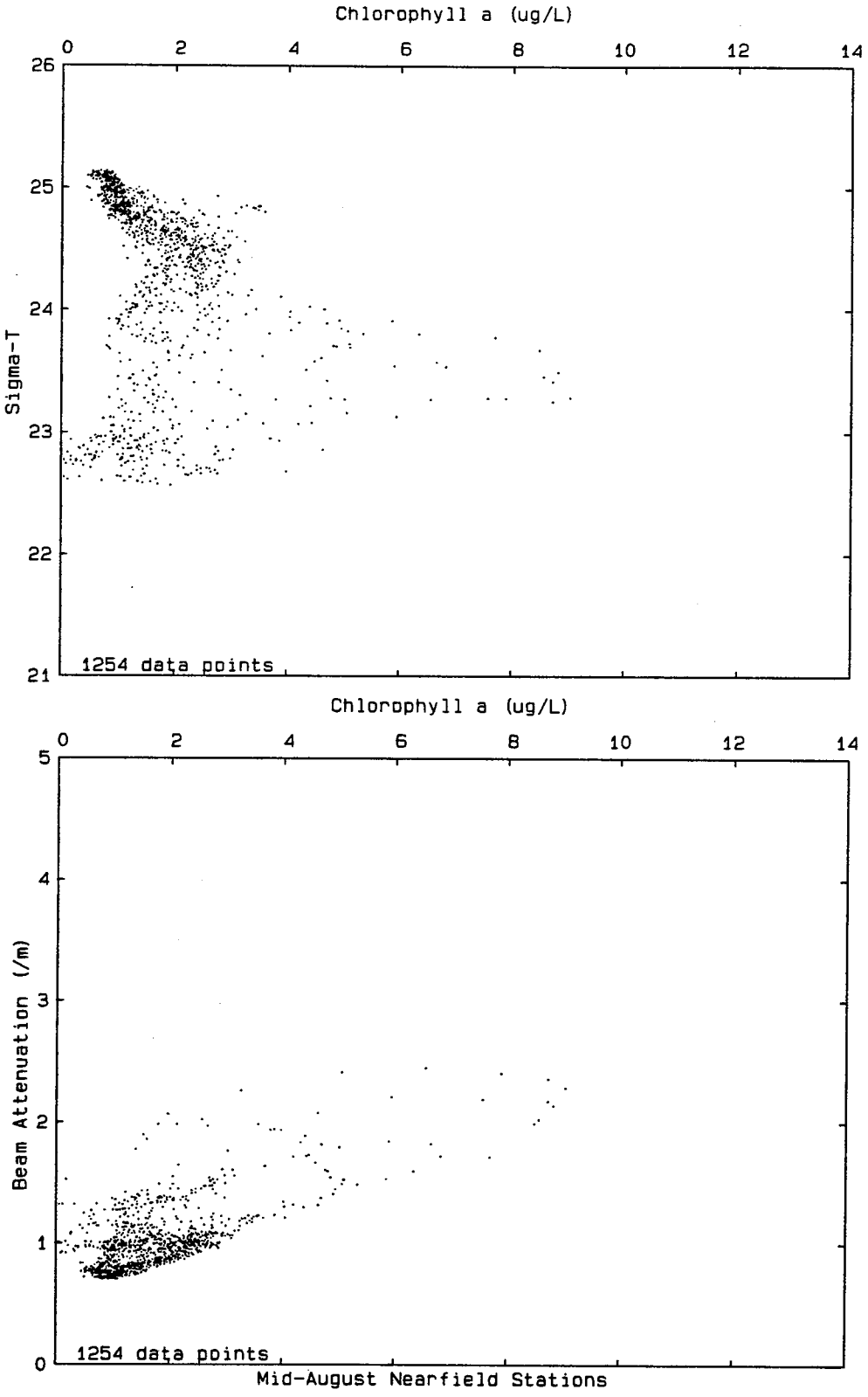



**Figure 9-1b** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in mid-August 1992. Individual station casts that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

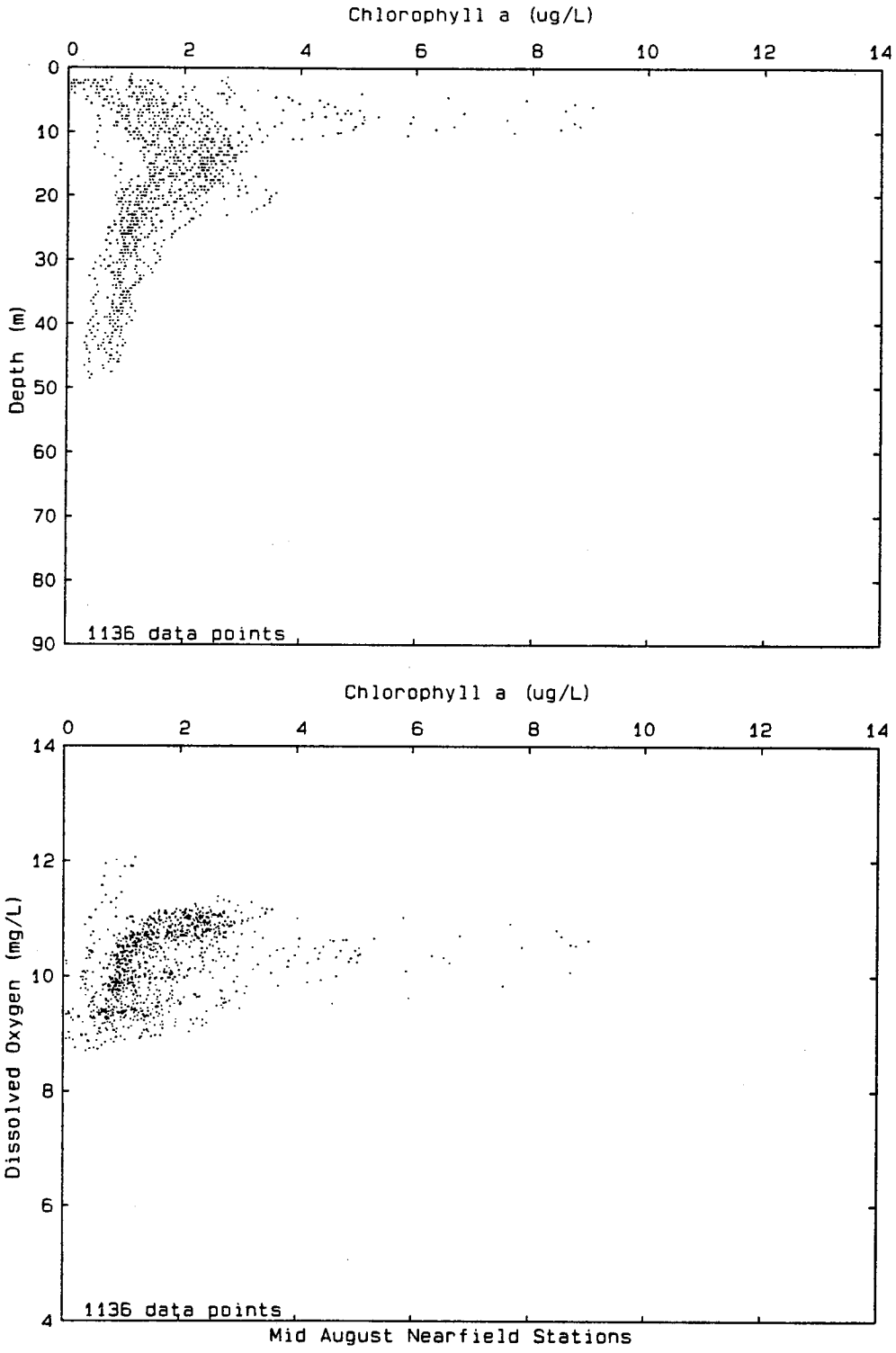



**Figure 9-1c** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in mid-August 1992. Individual station casts that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

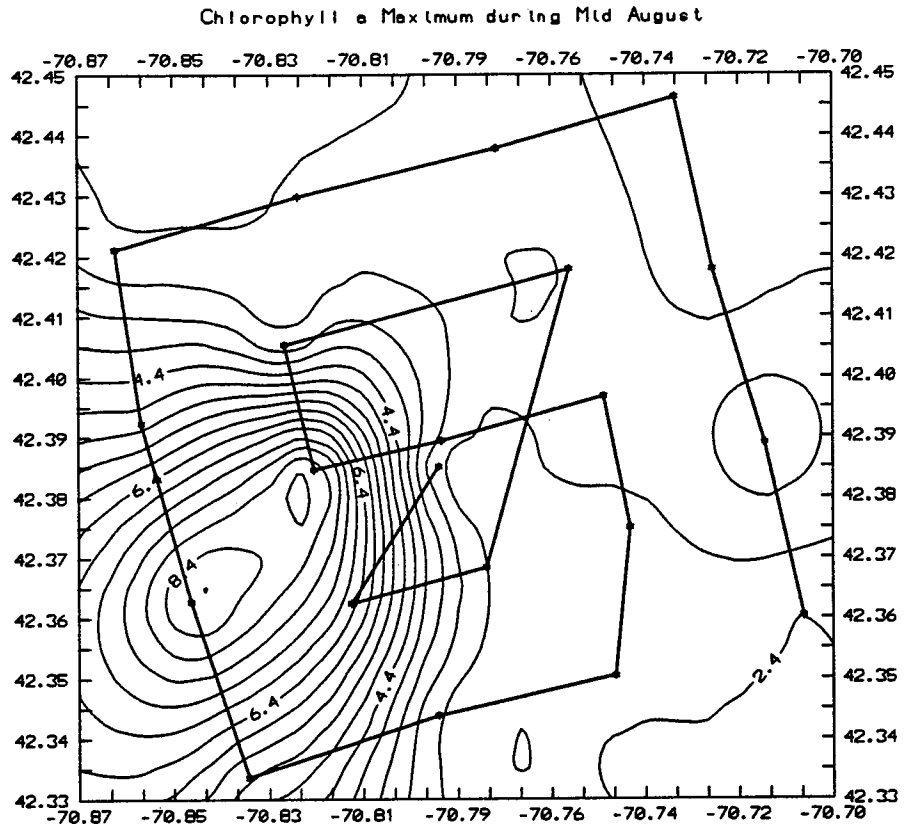
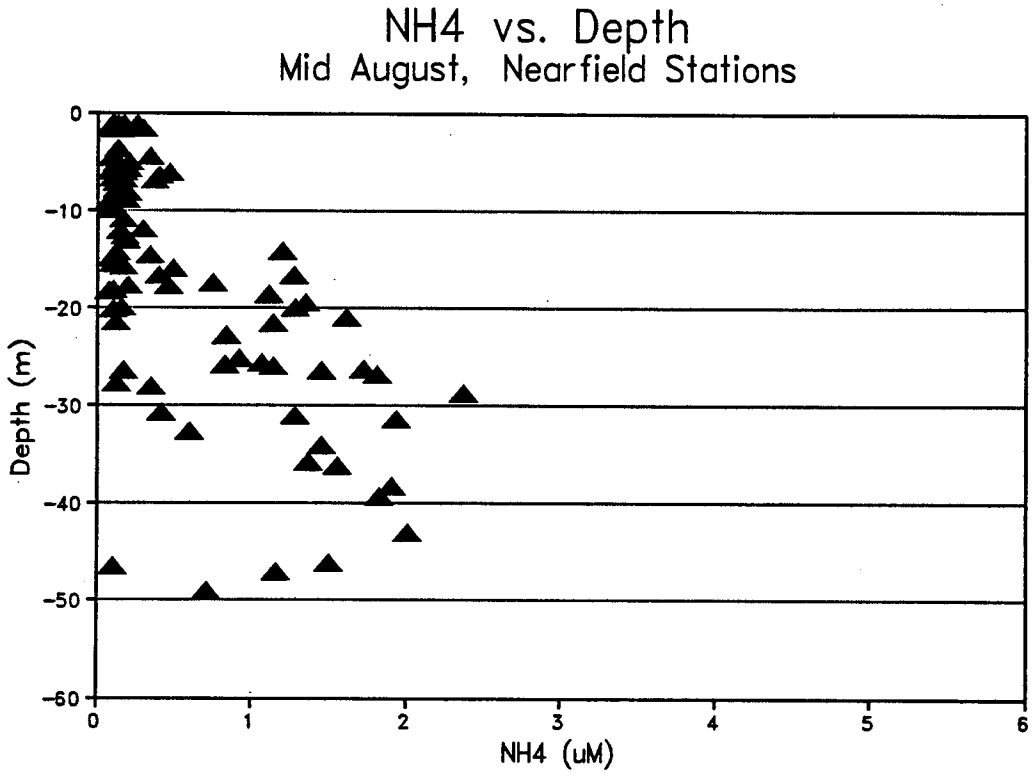



**Figure 9-2** **Chlorophyll maximum at each nearfield station from vertical profile day (Appendix B). Track shows sampling, starting at southeast corner of nearfield and proceeding counter clockwise to spiral into the middle of the field. Chlorophyll maximum may not be at the same depth at different stations.**



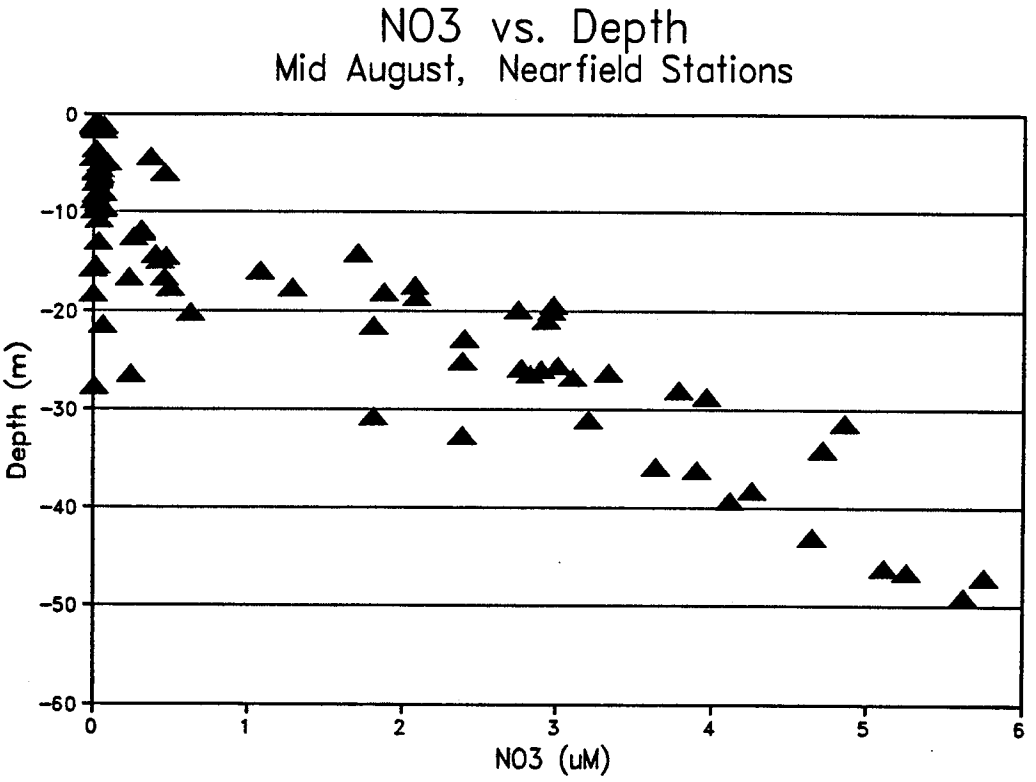
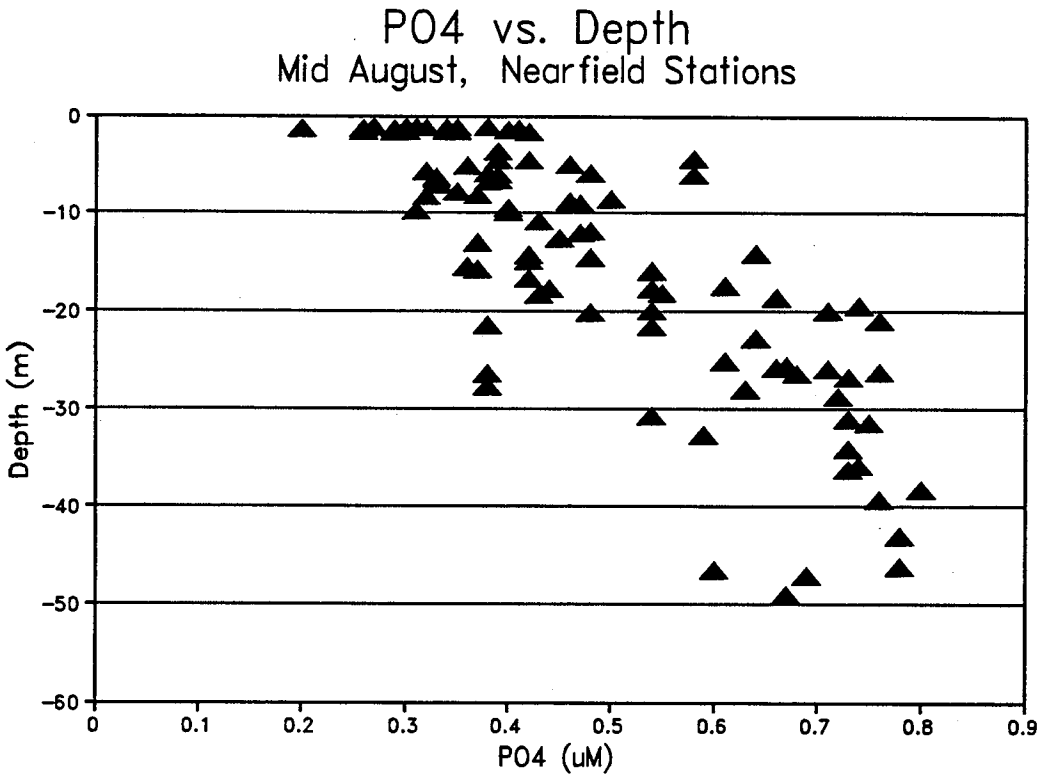




**Figure 9-3 $NH_4$ and $NO_3$ vs. depth in mid-August 1992.**



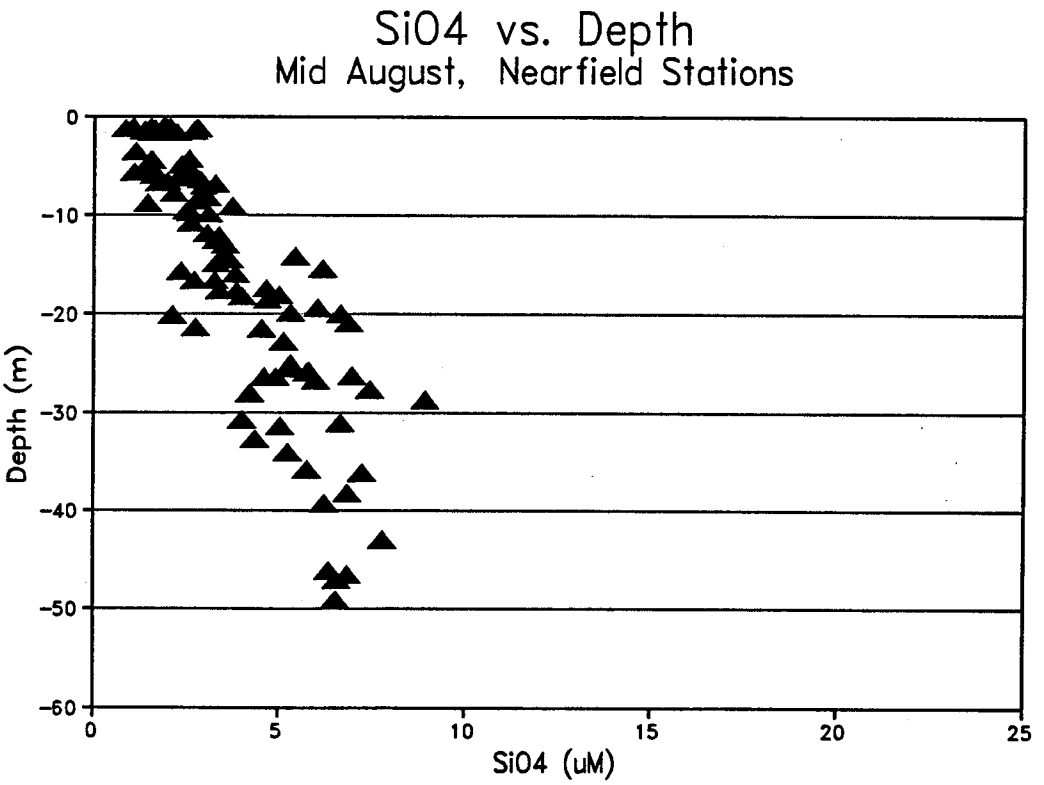




**Figure 9-4 $PO_4$ and $SiO_4$ vs. depth in mid-August 1992.**

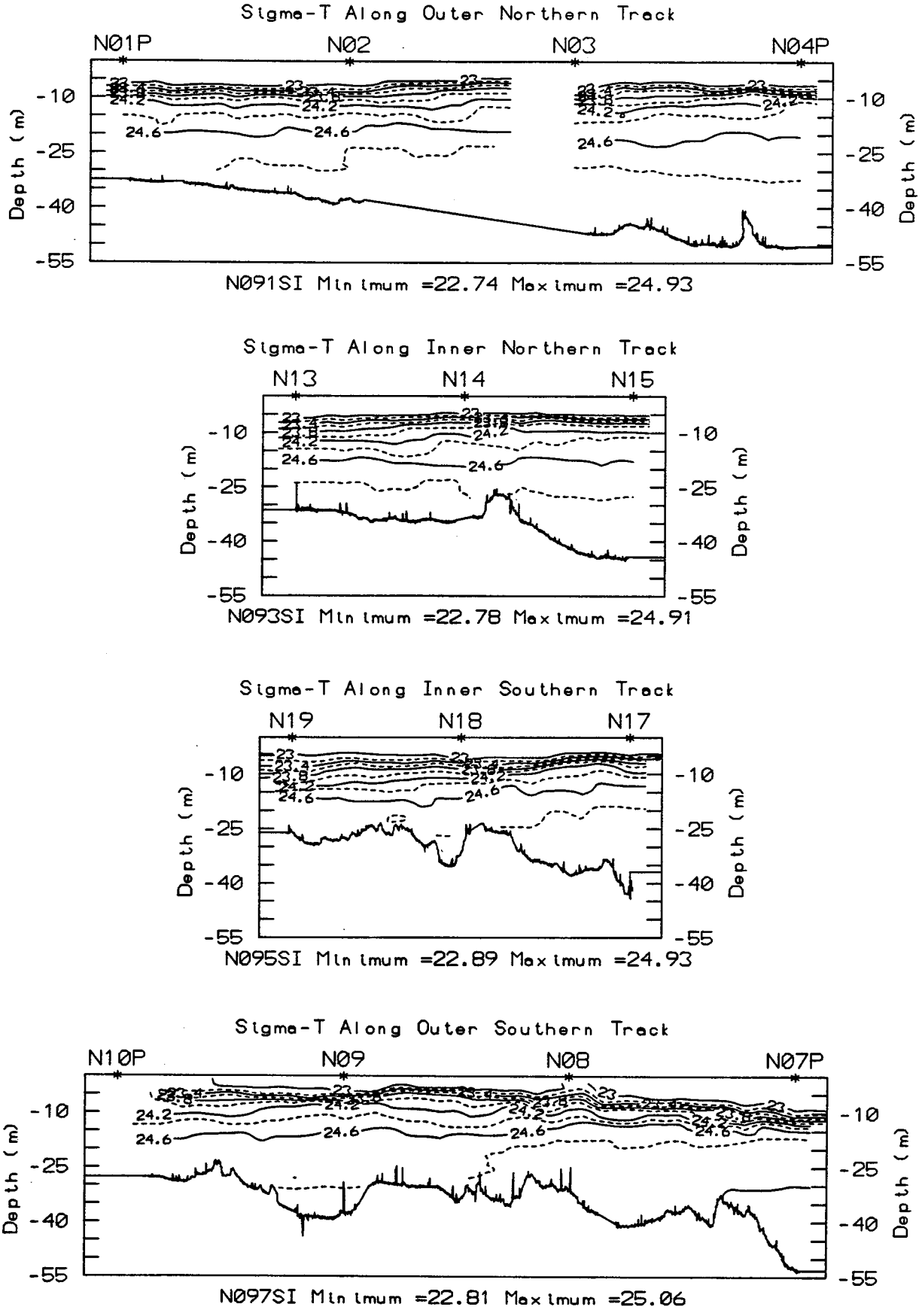



**Figure 9-5a** **Vertical section contours of $\sigma_T$ generated for tow-yos in mid-August 1992. The view is towards the North. The contour interval is 0.2 $\sigma_T$.**

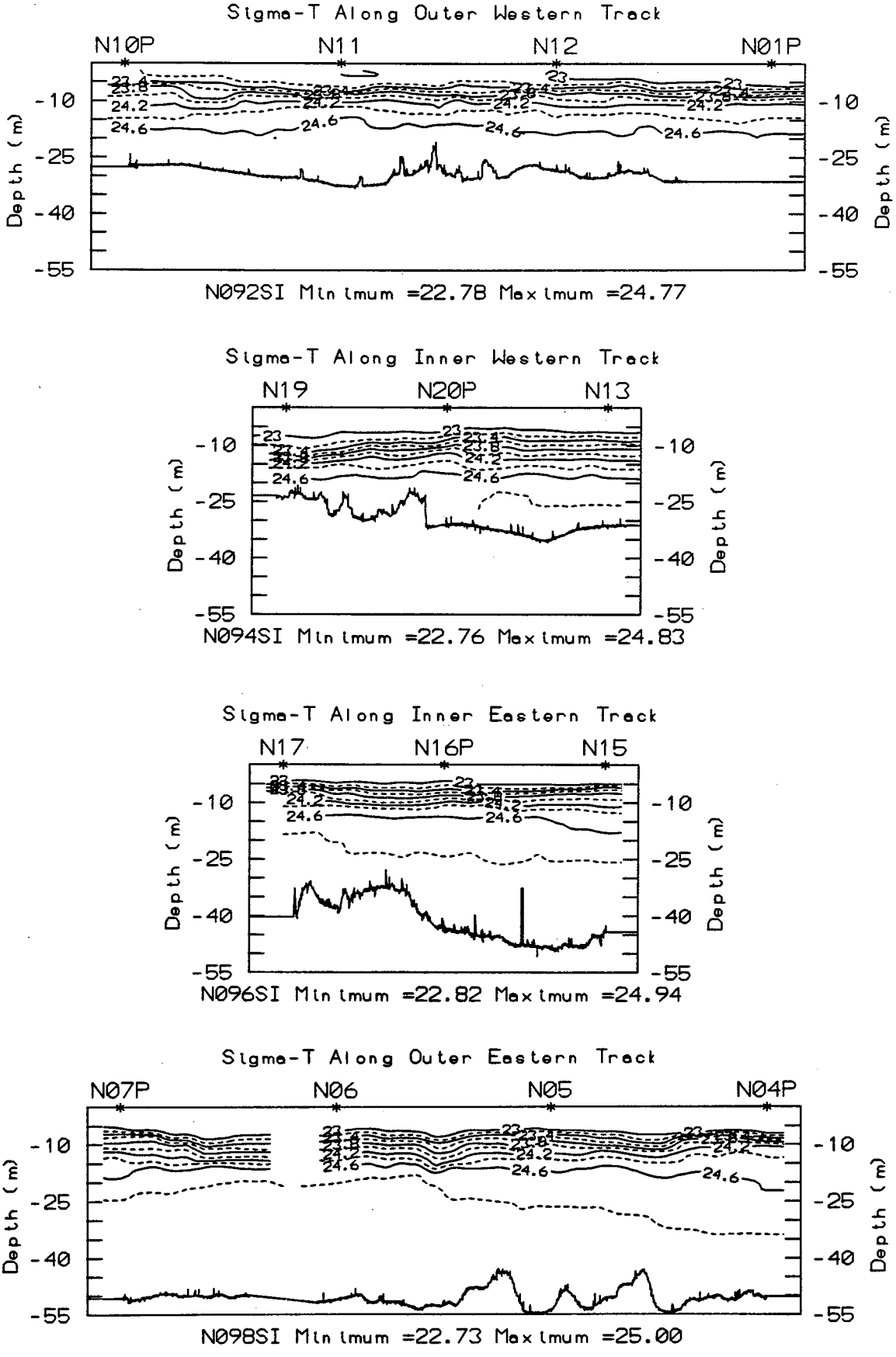



**Figure 9-5b Vertical section contours of $\sigma_T$ generated for tow-yos in mid-August 1992. The view is towards Boston Harbor.**

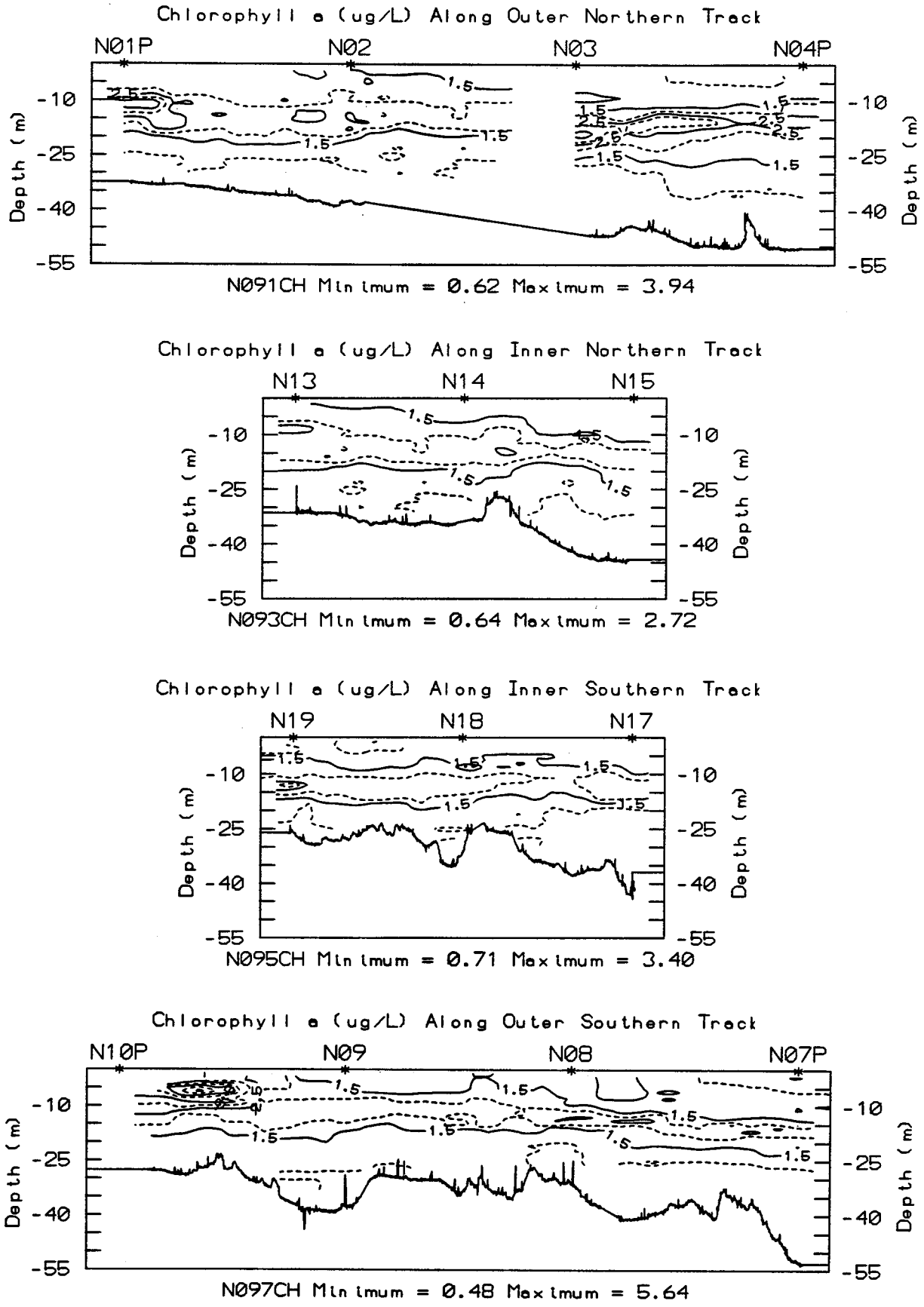



**Figure 9-6a** **Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in mid-August 1992. The view is towards the North. The contour interval is 0.5 $\mu$g $L^{-1}$.**

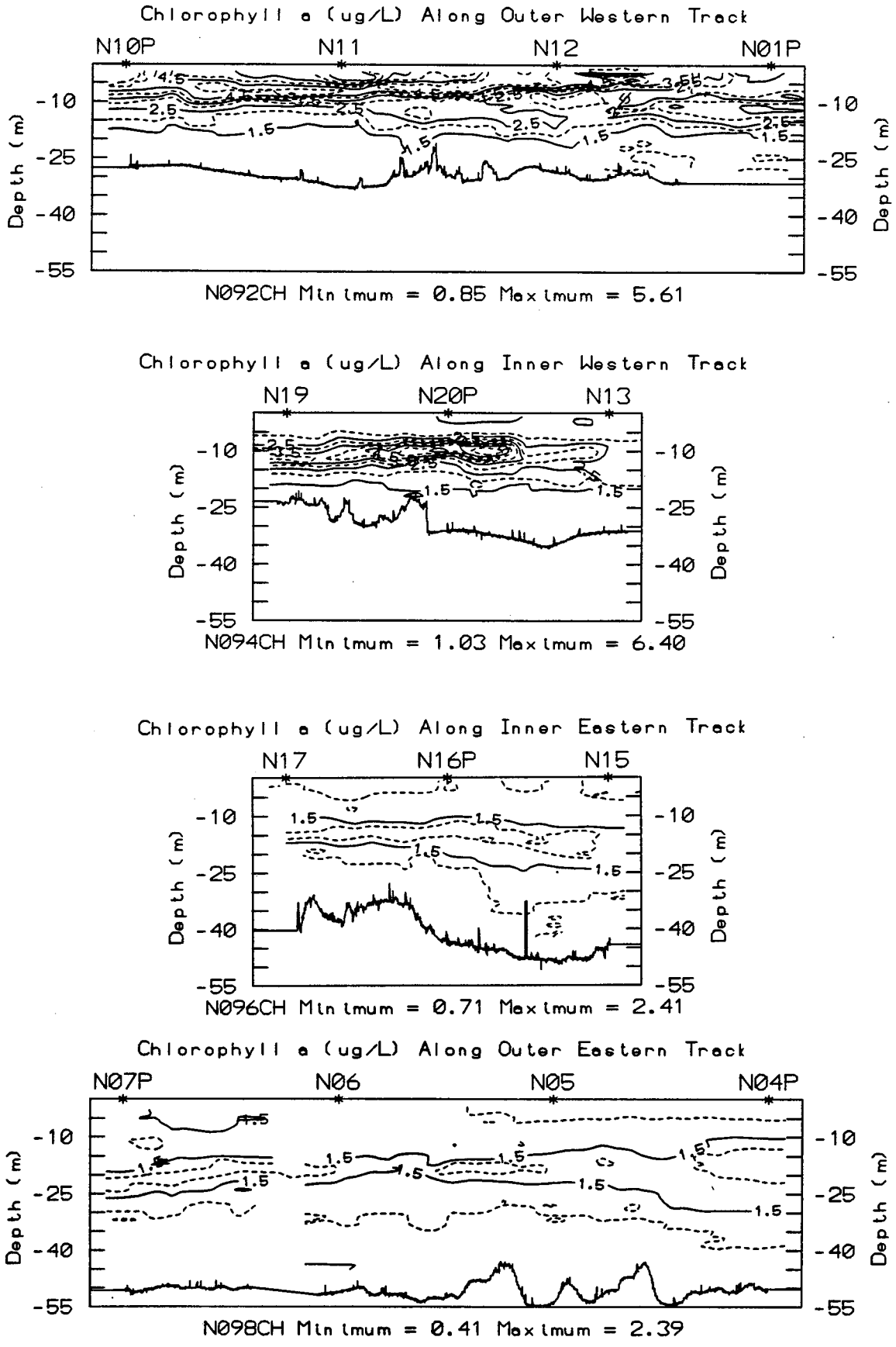



**Figure 9-6b Vertical section contours of fluorescence (as $\mu$g Chl $L^{-1}$) generated for tow-yos in mid-August 1992. The view is towards Boston Harbor.**

# 10.0 DISCUSSION

## 10.1 Water Properties (Physical and Chemical), early April to mid-August

### 10.1.1 Variability at the Regional Scale (early April and June)

Physical properties, of course, varied throughout the region as a whole in early April and June, the months when farfield surveys occurred. The major variation was in temperature in the upper water column; surface temperatures increased by about 5-10°C over this period. Deep bottom waters only increased about 0.5 to 1.5°C (Figure 10-1). The salinity range was small; in general both surface and bottom waters freshened slightly (~0.2 to 0.6 PSU) over the period (Figure 10-1). Temporally, the warming induced a progression from slight vertical stratification to a distinct layering of a warm surface layer over a cold bottom water layer. Dissolved oxygen concentrations followed the temperature change, and values in early April were ~10-14 mg $L^{-1}$, whereas they were ~8-12 mg $L^{-1}$ in June, July, and mid-August (Figure 10-1c).

Over this regional seasonal change, it was possible to distinguish different areas of the Bays with different surface water (and upper water column) characteristics in each month. With respect to this, Cape Cod Bay appeared generally cooler than most of Massachusetts Bay in early April, but was warmer in June. Additionally, the northeasternmost stations sampled in Massachusetts Bay, as well as most coastal stations, characteristically tended to be warmer than the nearfield and main body of offshore Massachusetts Bay stations. As a final note, the signature of coastal water was distinct as compared to deeper stations with respect to temperature, salinity and the shape of vertical profiles (both where strong inshore freshwater sources occur and where they do not).

Chemically, there were distinguishing features apparent as a function of station location, water depth, and salinity. Features varied a bit with the nutrient element or form considered (Figure 10-2 to 10-6). At the regional scale, one of the most distinct geochemical features involved silicate. Cape Cod Bay stood out as much depleted in silicate concentration in early April, yet substantially higher in June, compared to the rest of the station groups (Figure 10-6).

In any event, as in previous surveys, areas within the region were easily "typed".

### 10.1.2 Variability in the Nearfield

In the nearfield, the progression of seasonal warming through the full time period and the change in T-S patterns was readily apparent (Figure 10-1). The most rapid temperature change occurred from late April to June, although between early April and June a substantial "freshening" ($\geq$1 PSU) came and went.

Spatially, across the nearfield, the physical influence of inshore water was often seen extending at the surface to as far as the middle of the field. The eastern side of the field was less dynamic and apparently less subject to tidally-induced physical variability. At various times, it appeared that offshore and inshore fronts were meeting in the middle of the nearfield. In general, the image of the nearfield as a highly variable and a mixing zone for offshore and inshore waters seems supported, as hypothesized in previous reporting (Kelly *et al.*, 1992).

The nearfield nutrient concentrations could be characterized as a subset of Massachusetts Bay conditions (Figures 10-2 to 10-6). Geochemically, the image of the nearfield as a mixing zone in the horizontal and in the vertical dimensions was supported. Occasionally, a very high degree of spatial variability in nutrients was noted (e.g., late July, Section 8). Also occasionally a high nutrient concentration in a sample (or several samples of a station) were distinctly different from the remainder of the field, (e.g., April and June, Sections 3 and 6).

### 10.1.3 Coherence of Nearfield and Farfield Station Properties

The nearfield and *proximal* farfield stations in Massachusetts were usually physically and geochemically similar. In sharp contrast, the nearfield and the Cape Cod Bay stations appeared to be rather different with respect to thermal properties—including surface values of temperature, vertical structure, and seasonal progression—and also with respect to some nutrient concentrations and nutrient ratios. From these data, it is valid to consider that the nearfield region in Massachusetts Bay and Cape Cod Bay may be functionally distinct regions at periods of the year.

### 10.1.4 Comparison to Previous Studies

Virtually the entire period covered by this report was unseasonably cool compared to historical records (R.E. Lautzenheiser, N.E. Climatic Service). Undoubtedly, this could affect such things as the pacing of surface warming and development of the pycnocline. We noted that in comparison to data of 1990-1991 (Geyer *et al.*, 1992), the peak surface water temperatures in summer of 1992 were not as high. In general, parameter ranges were similar to those of Townsend *et al.* (1990). It was interesting to note that surface and vertical section plots of temperature for July 24-25, 1990 (Geyer *et al.*, 1992) showed a warm Cape Cod Bay surface, as distinct from most of Massachusetts Bay and similar to our pattern seen for June (Figure 6-1). Moreover, high silicate related to $NO_3$ in Cape Cod Bay, as seen in our June survey was also documented by Geyer *et al.* (1992) on their July 25-27, 1990 survey.

## 10.2 Water-Column/Nutrient Dynamics, early April to mid-August

### 10.2.1 Vertical Structure and Development of Stratification

Over the period April to June, nutrient distributions were related to development of stratification. Thus, from mostly low or depleted surface waters (0-30 m), underlain by some increasing concentrations (April), the distribution shifted upward to have higher concentrations starting within or just below the pycnocline ($\sim$10-30 m) in June (e.g., Figures 10-2, 10-4). This pattern occurred rather region-wide. Regional differences were only strikingly apparent with respect to silicate, as noted.

The nearfield data set also includes cruises in late April and May as well as in July and August (Figure 10-7 through 10-11). Throughout occasional values of DIN in the 1-5 $\mu$M range were seen in the surface 10 m, often near the Boston Harbor side of the field. What is evident though in this set is the progressive organization to a strong two-layered system—about 10-20 m of low nutrient surface water with a gradient below about 20 m and a 7 to 8 $\mu$M increase over the next 30 m. This bottom water DIN gradient thus was about +0.25 $\mu$M per meter starting at about 20 m.

Note that the geochemical progression may be disrupted (late July, Figure 10-10). Perhaps in this case, the disruption was associated with some physical events (see Section 8) although independent or

concomitant biological events cannot be ruled out. Nevertheless, the system was again reorganized shortly afterwards to resemble the conditions the month before (Figures 10-11 vs. Figure 10-9).

### 10.2.2 Inshore-Offshore Gradients, Including Boston Harbor Mouth

There were again nutrient gradients evident from the edge of Boston Harbor but they appeared to be much sharper (i.e. over a shorter distance) than earlier in the year. Gradients were not evident as a conservative mixing diagram with salinity akin to the results of February (Kelly *et al.*, 1992) But Station F23P had highest PON, DIN + PON and TDN concentrations ($\sim$9-11 $\mu$M, 17-19 $\mu$M, and 25-29 $\mu$M, respectively) in April.

In June, a nitrogen-salinity gradient from the Harbor was perhaps less evident, as DIN, PON, or DIN + PON when looking across all Bioproductivity stations (Figure 6-25). Even so, F23P still had highest Total N ($\sim$17 $\mu$M).

From the many nearfield surveys, it seemed apparent that chlorophyll-laden water often was intruding into the surface of the nearfield and the intrusion was related to tidal ebb flow. It seems that much of the nitrogen export from the Harbor during the whole period was in phytoplankton PON, not in dissolved forms, and this was intermittently carried offshore in surface lenses.

### 10.2.3 Influence of Water from Northern Rivers

Often, the surface layer of the northeast corner or the entire outer track of the nearfield was slightly different with respect to parameters, including T, S, fluorescence and nutrients. For example, the pycnocline sometimes tilted to its deepest point at N04P. In general, it is believed that the nearfield often had water entering from the north and in cases where we had Northern Transect data, the progression of physical or other data north to the nearfield supported this view of surface water mass relationships.

### 10.2.4 Special Features/Anomalous Stations

The regional thermal and geochemical distinction within the Bays has already been noted above.

### 10.2.5 Comparison to Previous Studies

The pattern of seasonal nutrient depletion in the surface and buildup in bottom waters has been reported by Townsend *et al.* (1990), summarized by Kelly (1991), and also by Geyer *et al.* (1992). The vertical patterns in concentrations were similar to the recent previous studies.

## 10.3 Biology in Relation to Water Properties and Nutrient Dynamics, early April and June

### 10.3.1 Phytoplankton-Zooplankton Relationships

In Figures 10-12 and 10-13, we compared total zooplankton counts from a tow at each station to the averaged values of surface and chlorophyll maximum samples for chlorophyll and total phytoplankton cell counts. This is a first cut to look for phyto-zooplankton abundance patterns and might be improved by using integrated water column chlorophyll from fluorescence readings rather than simple averages of the two bottle samples. There may be select cases where the chlorophyll maximum sample was very deep (e.g., N04P in April) and the net tow may not have fully sampled this feature.

In both April and June, the resulting pattern from the data, as used, tended with minor exceptions to suggest less numbers of zooplankton at higher chlorophyll or plankton counts. Interestingly, F23P, the edge of the Harbor, routinely seemed to have relatively low zooplankton counts for the chlorophyll present. Whether this is related, i.e. a lack of grazing pressure allowing for high standing stock of the prey item (phytoplankton), cannot be determined from the data.

Especially striking in the graphs is the order of magnitude increase in zooplankton numbers between April and June. The April period was dominated floristically by *Phaeocystis*, but great pains were taken to sort and count zooplankton from the mucous produced by sample preservation with *Phaeocystis* in it. Thus, the lower counts in April do not reflect miscounting because of difficulties with the preserved sample matrix.

Across the entire field in June, in contrast, the increased numbers of zooplankton indicated great Bay-wide abundance. In this case, zooplankton counts were lowest in Cape Cod Bay (F01P, F02P [2 replicate casts]), where a *Ceratium* bloom was pronounced.

### 10.3.2 Plankton Species and Water Properties

The two surveys of this reporting period for which plankton were identified and counted, early April and June, were different biologically. Moreover, the pattern of species relative to water properties was different across the surveys. In April, one dominant phytoplankton species occurred everywhere, in spite of some physical and geochemical differences apparent throughout the region. In contrast, in June the stations in Cape Cod Bay were distinct from all those in Massachusetts Bay, and there were some concomitant physical and chemical distinctions by Bay.

Elaborating for early April, for example, there were observed variations in

- temperature — differences at the surface and in vertical profiles among groups of stations (e.g., coastal, nearfield, offshore, etc.)
- nutrients — an elevated DIN concentration at the edge of the Harbor, with a very sharp distance gradient, and a relative depletion of silicate in Cape Cod Bay.

Yet *Phaeocystis pouchettii* was overwhelmingly dominant. Sometimes counts (and chlorophyll) at a given station were highest at the surface, sometimes at quite some depth. In some instances when DIN was high phytoplankton were high (F23P), but in others phytoplankton were low (N04P, surface). Conversely, DIN was low in several cases where counts were very high (N07P, N16P, and N04P at depth). The data thus do not give a clear picture as to a DIN—cell count or DIN—chlorophyll relationship (Figure 10-14). In contrast, there was a strong positive relationship between counts and Total N (Figure 10-16).

These data suggest two results of interest. First, higher cell counts and plankton biomass appear related to higher Total N, but note that a substantial fraction of the Total N at this time was PON, presumably mostly of the phytoplankton itself. Secondly, given the uniform distribution and dominance of *Phaeocystis*, these data support a notion that variations in Total N and in physical conditions, over the range of conditions and at this particular time, did not produce plankton species shifts. Related to this

latter point, it was interesting that silicate was distinctly low in Cape Cod Bay. This biogeochemical variation, across Bays, was not at this time accompanied by a different phytoplankton community or dominant taxa, nor did there seem an unusual cell count in Cape Cod Bay relative to DIN or Total N.

Elaborating further for June, some principal physical and chemical variations were broad geographic ones that discriminated the two Bays, for example, on the basis of

- temperature — higher near surface thermal regimes (and lower density) in Cape Cod Bay relative to Massachusetts Bay
- nutrients — only a slight Harbor-related elevation of most dissolved inorganic forms (N, P, Si), but much higher silicate in most of Cape Cod Bay.

A clear biological difference accompanied the Bay-to-Bay trends. Interestingly, the biological differences were not striking for near surface samples of phytoplankton (Tables 6-2 and 6-4), although it was noted that Massachusetts Bay usually had more taxa among stations and routinely more taxa of large dinoflagellates at each station. More striking, however was the difference at the subsurface chlorophyll maximum sample, where *Ceratium* was pronounced at both Cape Cod Bay stations; presumably related to this dominance, less dinoflagellate taxa were seen in Cape Cod Bay (Table 6-5).

As in April, there was no obvious relation between total cell counts, *Ceratium* counts, or chlorophyll and DIN (e.g. Figure 10-15). The *Ceratium* counts were highest at F02P ($> 10^5$ $L^{-1}$), which had higher DIN than F01P ($> 10^4$ cells $L^{-1}$), but highest DIN was at N07P ($\sim$5-6 $\mu$M, surface and depth). Interestingly, the surface at N07P had *Ceratium* counts in the $10^3$ range, but at depth, the counts were $< 10^2$.

The relation between total cell counts and Total N in June was not strong across the stations, as it had been in April. Cape Cod Bay stations and several nearfield samples had very high Total N (Figure 10-17), but not especially high cell counts. As mentioned previously, it is reasonable to presume that due to *Ceratium* being a relatively large organism, more chlorophyll and PON per cell would be expected.

Thus, in contrast to April, biological community differences between the two Bays were associated with their regional physical-chemical differences. Underlying mechanisms can only be speculated with the data in hand, but we noted that the major dissolved nutrient distinction was silicate, not nitrogen. Higher Si/N

ratios were present where the *Ceratium* bloom was present and this may in part be causal, since *Ceratium* would not be drawing silicate from solution like a diatom would. Compared to April, silicate increased dramatically in Cape Cod Bay. It was interesting to note that deep water station F04 in Cape Cod Bay did not show a sharp increase in silicate with depth (Figure 10-6), but instead followed the pattern of deep offshore stations in Massachusetts Bay. This may suggest there were sources of silicate within Cape Cod Bay, probably shallow-water. Likely this would be the sediments, remineralizing silicate in part deposited during the earlier intense and prolonged winter-spring diatom growth in this Bay (Kelly *et al.*, 1992).

### 10.3.3 Chlorophyll Biomass and Nutrient Distribution

Phytoplankton biomass as estimated by fluorescence, calibrated against chlorophyll determinations, showed a dynamic range from near 0 to $>12$ $\mu g\ L^{-1}$, but the vast majority of data were less than 4 $\mu g\ L^{-1}$ (Figure 10-1). The position of peaks, if present, varied as a function of survey as well as station. The composite scatter plots of all surveys identify maxima regularly aggregated at certain density surfaces (Figure 10-1b) and depths (Figure 10-1c).

The basic trend over time was that a subsurface maxima became more identifiable as the pycnocline sharpened. At shallower stations which did not develop a strong pycnocline between well-defined surface and bottom layers, chlorophyll was often high near the surface and usually more evenly distributed over depth (e.g. F23P). In general, then the vertical distribution of chlorophyll seemed regulated by the physical structure; as the physical structure helped regulate nutrient concentrations (see previous), chlorophyll and nutrients were generally related. At stations with low nitrogen supplies in the upper water column, chlorophyll was usually found at some depth; logically, this is where nutrient supplies were higher due to flux from bottom waters and/or *in situ* remineralization processes. Noting that a high degree of patchiness in chlorophyll was documented in nearfield towing exercises, some fine-scale physical-chemical processes may be implied.

It is not easy to see a direct relationship between chlorophyll and DIN using the data of the Bioproductivity stations (Figures 10-14 and 10-15). Some scatter must be attributable to time and/or space lags. For example, the high chlorophyll at N07P very deep in the water column in April may have been chlorophyll produced earlier higher in the water column and which had settled subsequently to this point. Additionally, in June, when water temperatures were higher, higher assimilation rates are possible.

DIN being *supplied* to a given location may be rapidly converted to particulate form and thus not appear in dissolved form. Whether this oft-hypothesized disjunction between *supply* and *concentration* can occur depends on the various time scales for physics and biology that are involved at a location, but in principle such phenomenon can create scatter in a data set, especially one including points across a variety of physical-biology couplings. With respect to the issue, note that one hydrocast at F02P surface in June had DIN higher than one of the deep cast samples, but the deep sample was the one with very high chlorophyll. Note also that station N07P in June had high surface and deep DIN, but consistently low chlorophyll. Some event must have created this rather anomalous nutrient condition in the middle of Massachusetts Bay, yet at the time of sampling there seemed little response in terms of chlorophyll biomass.

### 10.3.4 Metabolism and Environment

We have noted already the tendency of P-I data to be well-behaved, with respect to being fit by models, when chlorophyll biomass was higher. Further analysis might be performed to determine the limits and sensitivity of the methods with respect to metabolism; such analysis should include additional data that will be available from late August and October 1992 cruises.

Cape Cod Bay stations had distinct P-I curves in April. All four incubations (surface and chlorophyll maximum at F01P and F02P) yielded relatively high $P_{max}$ estimates (chlorophyll-normalized), much higher than the remaining Bioproductivity stations in Massachusetts Bay, both for coastal and nearfield locations. Note that the volumetric net production rates were not unusual (Appendix E). But the lower chlorophyll per cell (Figure 3-27), an influence on the normalized $P_{max}$, made the region a bit biologically distinctive, even when the region was not taxonomically different.

In June, the Cape Cod Bay samples from the deep chlorophyll maximum (*Ceratium*) had, in contrast, rather low $P_{max}$, judging from the P-I curves. Interestingly, however, a number of other stations had deep chlorophyll maximum samples with relatively low $P_{max}$ estimates. Again, the volumetric net production rates were not distinctive in Cape Cod Bay (Appendix E). Thus, at this time when the two Bays had some physical, chemical, and biological (including taxonomic) distinctions, a metabolic pattern by region was not obvious.

Across both months, many of the highest maximum volumetric net production rates were at F23P or N10P, both influenced by the Harbor outflow (Appendix E). Other high rates usually were associated with high chlorophyll.

In general, maximum production rates were predicted at light levels that were experienced through a substantial part of the surface layer above the pycnocline, but this is not where high concentrations of chlorophyll were found, except in mostly shallow and weakly mixed water columns. In June especially the chlorophyll maximum at many places was at rather low light levels, well below those associated with maximum production rates. Likely, these deep phytoplankton populations were not growing very fast. Interestingly, there were many profiles where the chlorophyll biomass maximum was in the bottom water layer and oxygen profiles by sensor readings also showed maxima, which would be an indication that net production (*system* production even) was occurring even if rates were slow.

A final note on respiration. Results were only a bit more satisfying than earlier in the year. Only a small fraction of the incubations indicated rates significant from zero (Appendix E) in either month. April was still rather cold, and most chlorophyll maximum and deeper bottom water samples in June were also in relatively cold water. In the case of surface waters in June, which were warmer, there was usually low plankton biomass; although significant rates were detected in some cases, no geographic or environmental pattern was immediately obvious.

### 10.3.5 Special Features/Anomalous Stations

Throughout the surveys, a spot here or there occasionally stood out as anomalous with respect to surrounding waters. Moreover, some broader regional distinctions have been pointed out.

Actually, one of the most interesting special features was a somewhat regular one — chlorophyll patchiness and its fine-scale variability seen in the nearfield. The biological samples suggested that, at least for the periods and stations analyzed, the communities in regions were either mostly the same dominant species, or the same (or functionally similar) complement of taxa. It is not known whether small patches, which were not targeted for taxonomic analyses, but which in many cases did appear to relate directly to physical or chemical features, had special biological character other than a higher concentration of plankton biomass.

### 10.3.6 Comparison to Previous Studies

The range of chlorophyll concentration was similar to that reported recently in the Bays, with respect to maxima, minima, general distribution over depth and over season (cf. Cura, 1990; Townsend *et al.*, 1991). An annual low in about May, and occasional bursts at mid-depth in summer, are characteristic within the historical databases.

With respect to phytoplankton species, the overall taxa lists of these surveys were expected from previous studies in the Bays and surrounding regions. The large dinoflagellate method, to our knowledge, has not been used previously to document these lesser abundance species. The whole-water samples revealed dominant features that beg a brief discussion and comparison.

First, consider *Phaeocystis* throughout the Bays in April. Its occurrence has been previously documented in the Bays (see Cura, 1990 and Smayda, 1992). It has been noted since early in the century, to levels as high as were seen here (see Smayda, 1992). The March to April period, following the winter-spring diatom succession, is a prime time for its occurrence in the Bays and other temperate coastal regions. Its consistency as part of an annual cycle is unknown; it was present in the nearfield region in 1990 studies of Townsend *et al.* (1991).

Second, consider *Ceratium longipes* in Cape Cod Bay in June. A related species of this genus (*C. tripos*) was implicated in the New York Bight anoxic event during the 1970s. The abundance recorded at the two stations rivaled the highest abundance seen in *C. tripos* in the Bight (Falkowksi *et al.*, 1980), so this was a major bloom that was detected in June. Cura (1990) noted that *Ceratium* has been known to occur in the Bays since early in the century during the late spring to summer period. Methodology may be critical to detection of this species if it is not a major bloom; note that the large dinoflagellate sampling detected the species at relatively low levels in many places.

With respect to metabolism, there is a small historical base to compare metabolism trends of these surveys. Cura (1990) summarized much of this, including about 30 individual data points for net primary production. The pattern of those data suggest July and August rates may be higher on average than April though June, but the range for each month overlaps the range for nearly all other months. The total

range of Cura's summary, about 0.1 to 5.2 gC $m^{-2}$ $day^{-1}$, was seen within the month of August for measurements of western Massachusetts Bay stations.

Our data for only April and June of 1992 suggest some higher volumetric rates nearshore, and lower volumetric rates in low-nutrient surface/low-light deep conditions characteristic of offshore stations as stratification became pronounced. Many P-I curves (Appendix E) were similar to those shown by Townsend *et al.* (1991) for the same months. Integrated water column rates have not been calculated from these data.

### 10.4 Recommendations

As suggested previously, it appeared that the station locations allowed sufficient characterization of different geographic regions.

Sampling strategies allowed description of variability in time and space at a level not before reported for many parameters in the Bays and gave strong hints as to the underlying mechanisms. Replicate casts at selected stations provided an estimate of sampling variability and revealed that some stations (e.g. F23P) were highly time-variable, whereas others in deeper waters were much less so.

Given the noted variabilities, it would be reasonable to review the objectives for sampling near Boston Harbor, at the dynamic inshore edge and within the overall patchiness of the nearfield, and in the farfield region. From this, an assessment of the sufficiency of the sampling design could follow.

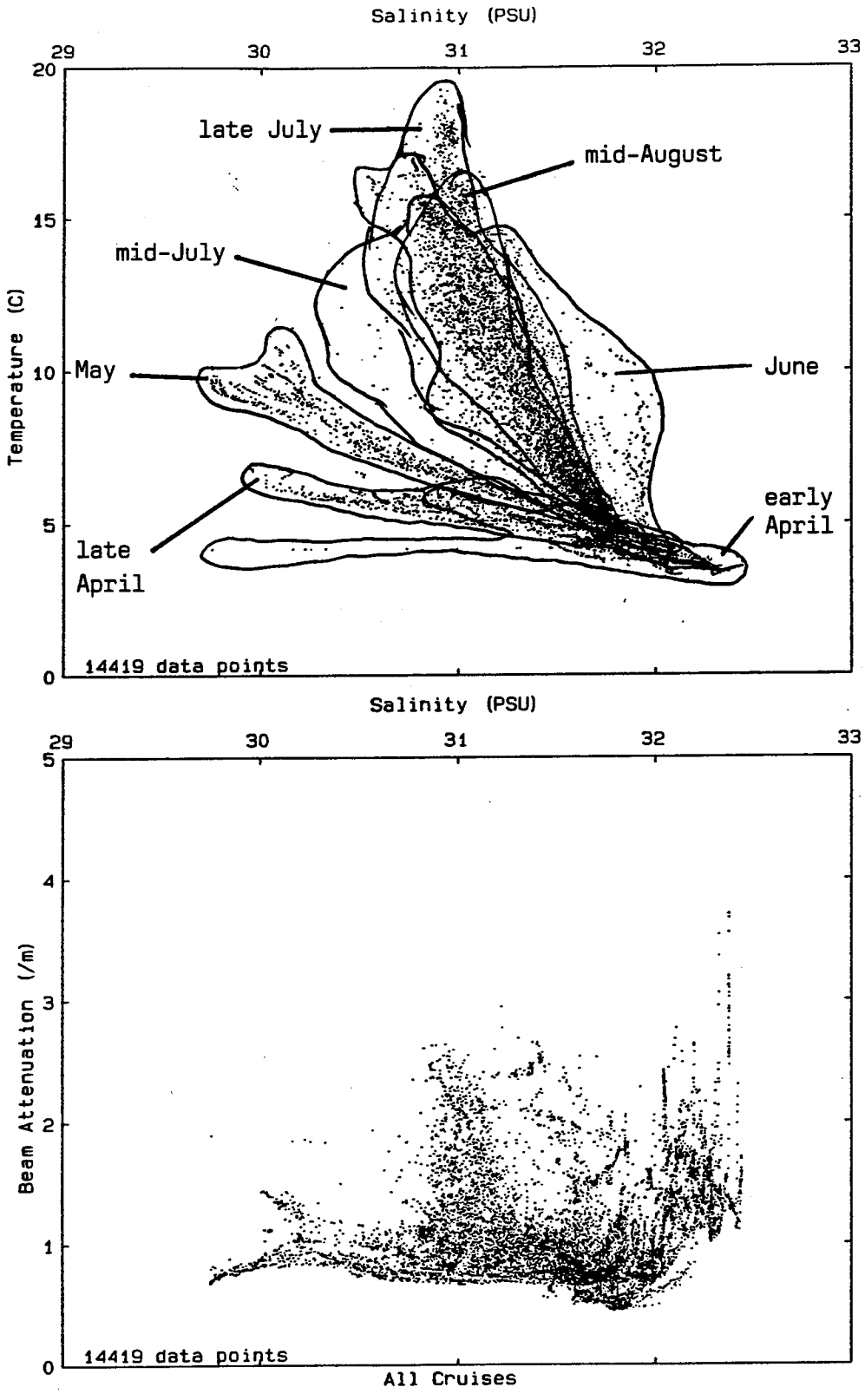



**Figure 10-1a** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all stations occupied from early April though mid-August 1992. Individual station casts that were used to produce this composite are in Appendix B. For the T-S plot, clusters of points by survey are roughly indicated.**

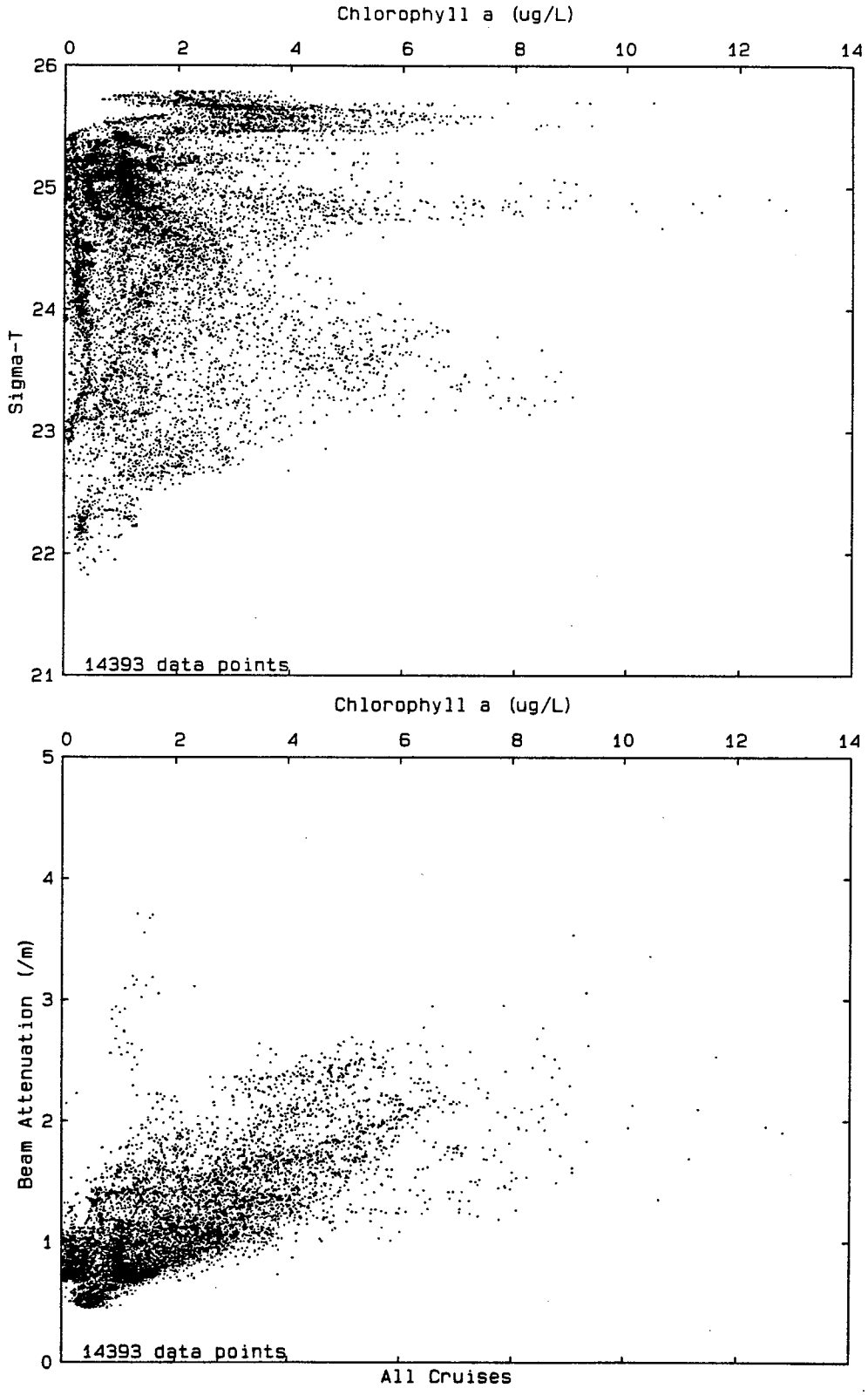



**Figure 10-1b** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all stations occupied from early April though mid-August 1992. Individual station casts that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

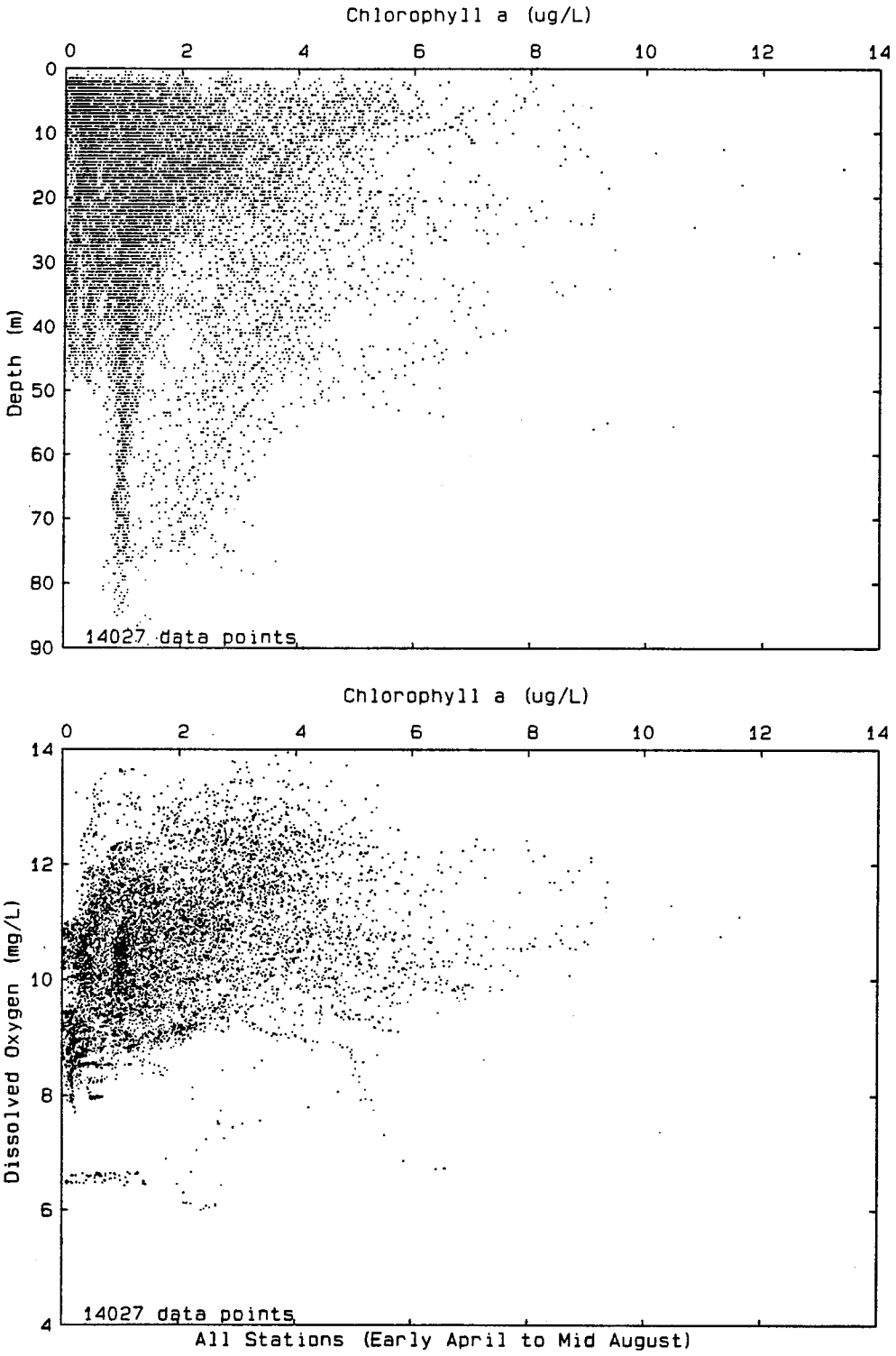



**Figure 10-1c** **Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all stations occupied from early April though mid-August 1992. Individual station casts that were used to produce this composite are in Appendix B. Note that chlorophyll concentrations are post-calibrated estimates from fluorescence readings (see Appendix A).**

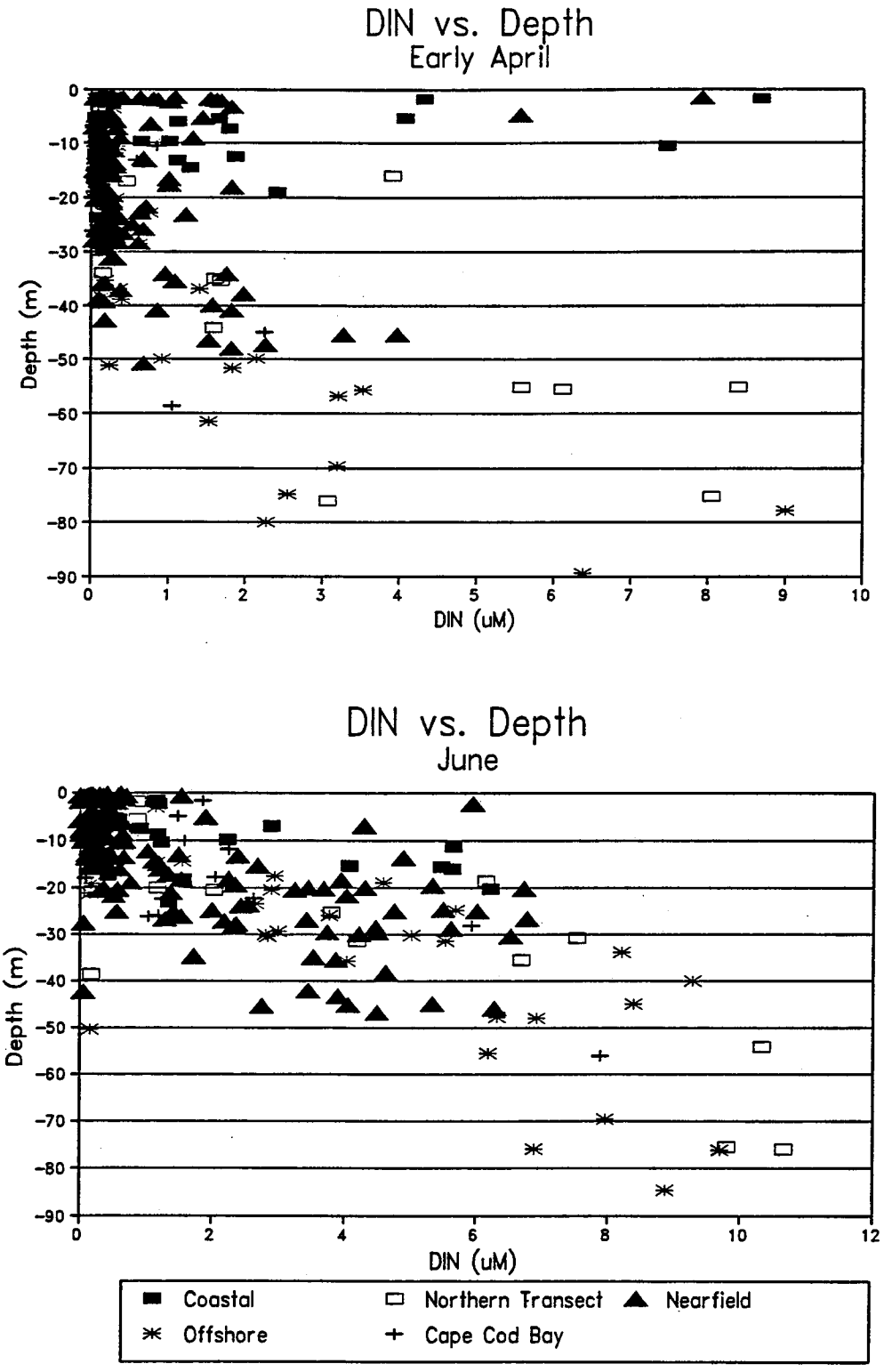



**Figure 10-2 Dissolved inorganic nitrogen vs. depth for all stations on combined survey cruises in early April and June 1992. Stations groups are as given in Figure 3-18. Data are given in Appendix A.**

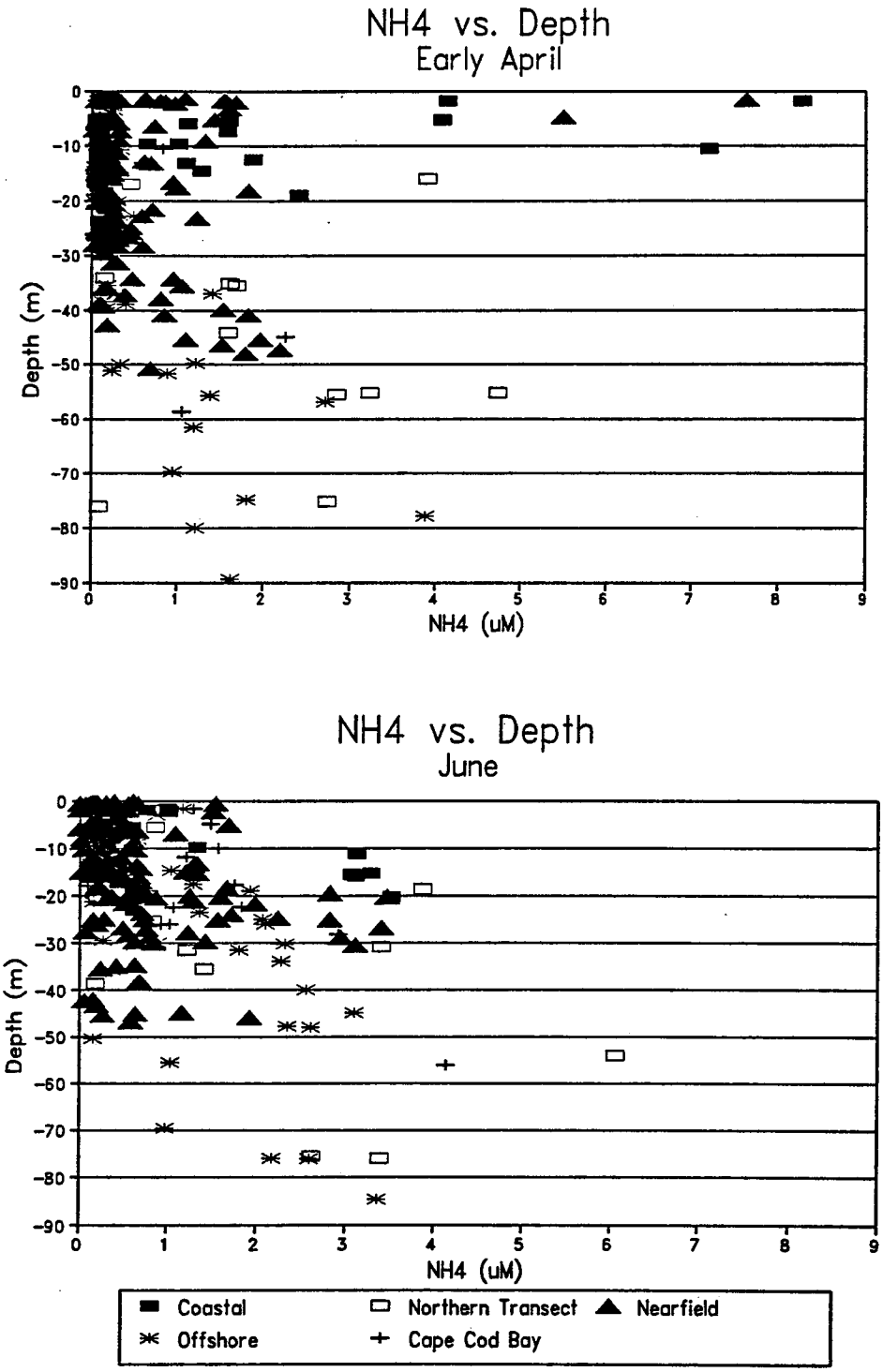



**Figure 10-3 $NH_4$ vs. depth for all stations on combined survey cruises in early April and June 1992. Stations groups are as given in Figure 3-18. Data are given in Appendix A.**

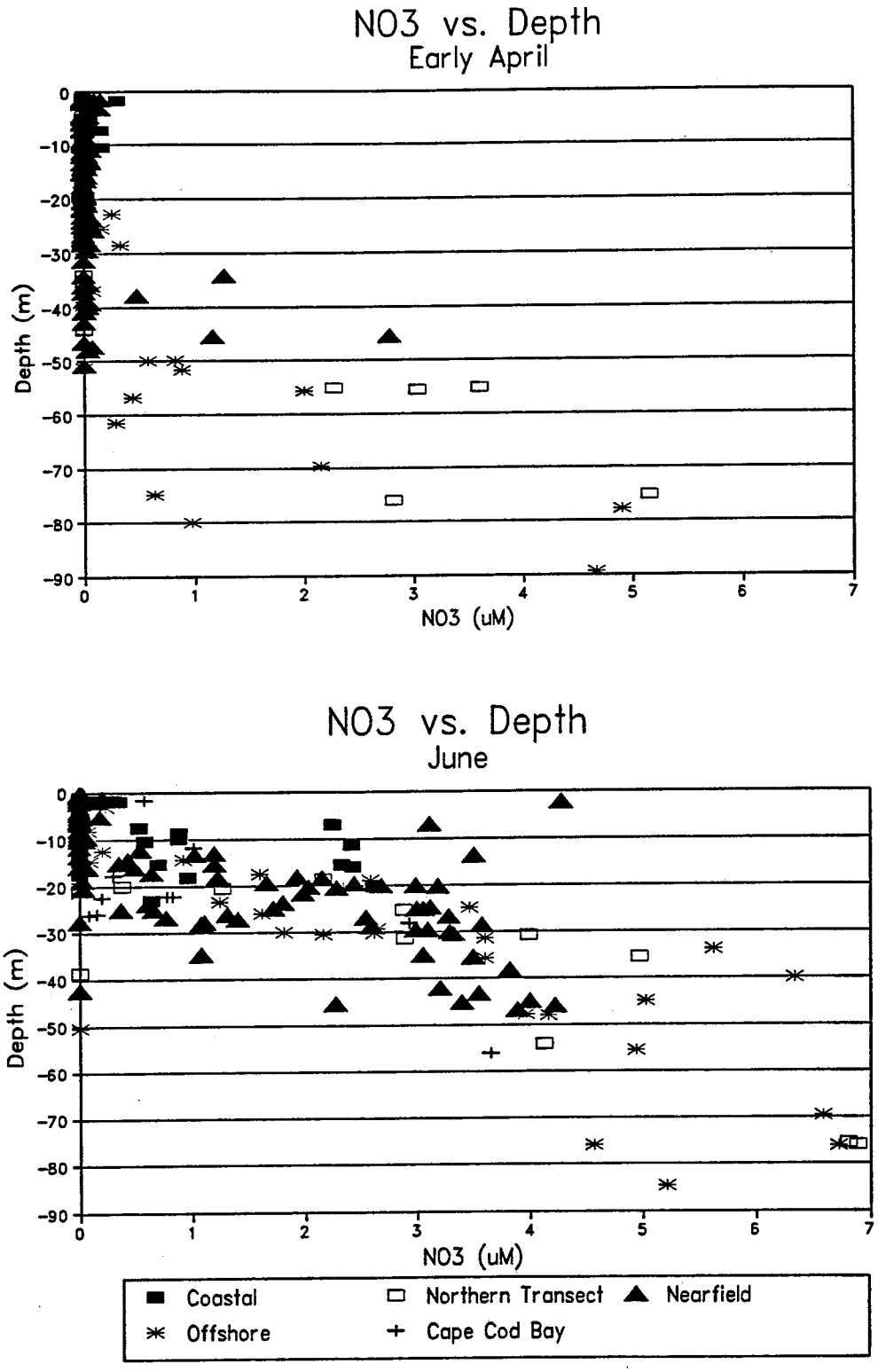



**Figure 10-4 Nitrate vs. depth for all stations on combined survey cruises in early April and June 1992. Stations groups are as given in Figure 3-18. Data are given in Appendix A.**

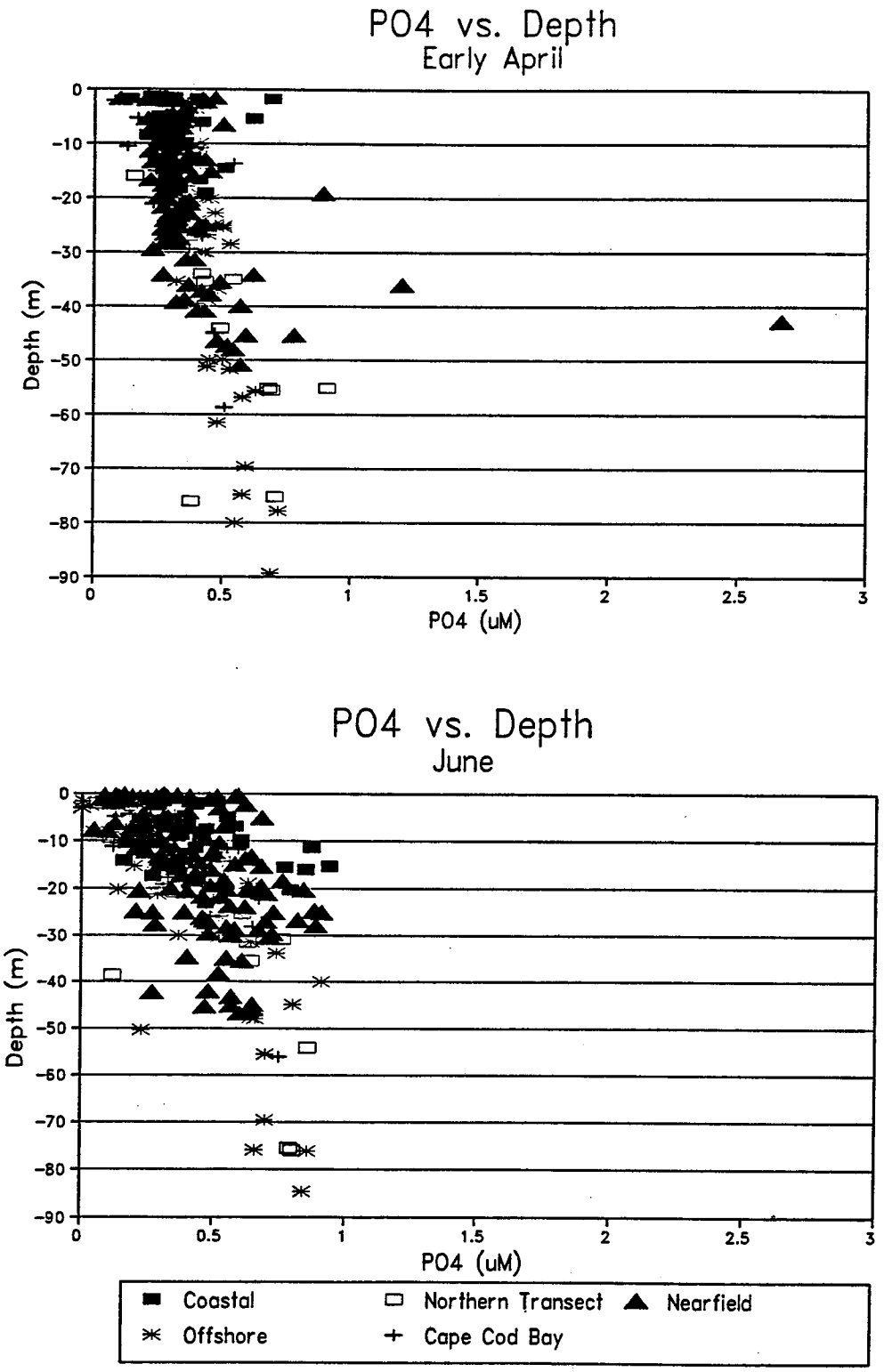



**Figure 10-5 Phosphate vs. depth for all stations on combined survey cruises in early April and June 1992. Stations groups are as given in Figure 3-18. Data are given in Appendix A.**

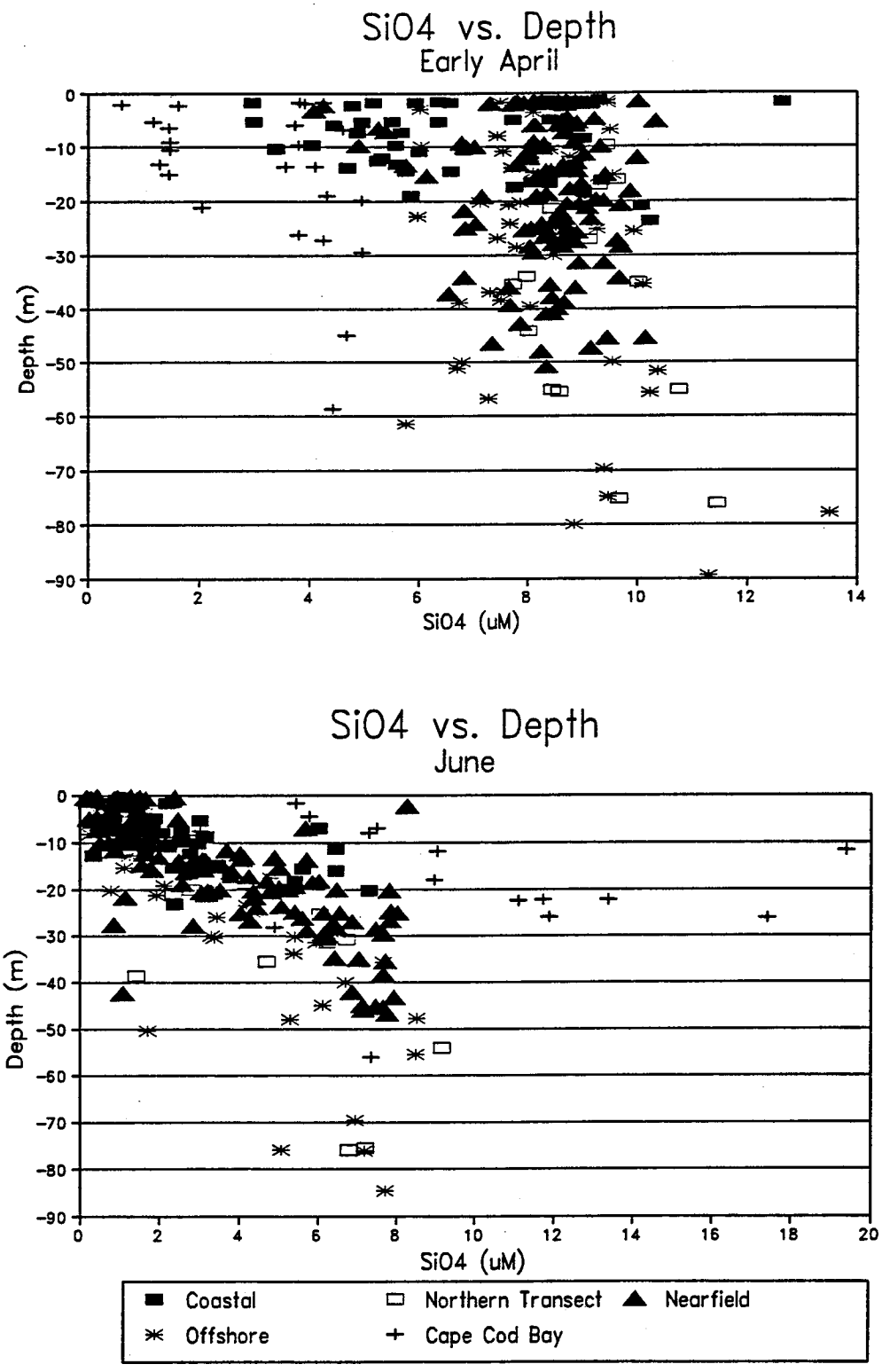



**Figure 10-6 Silicate vs. depth for all stations on combined survey cruises in early April and June 1992. Stations groups are as given in Figure 3-18. Data are given in Appendix A.**

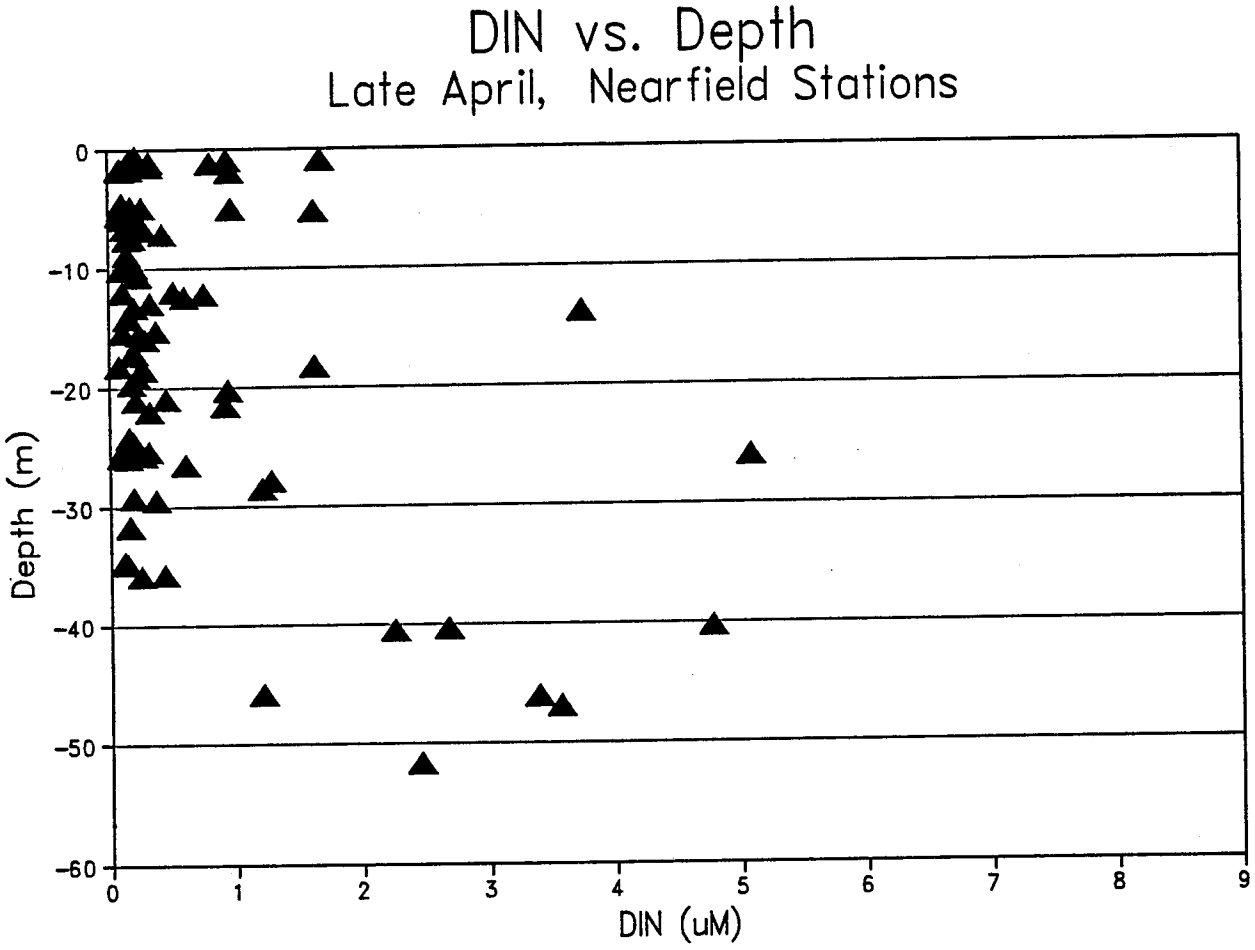



**Figure 10-7 Dissolved inorganic nitrogen vs. depth at nearfield stations in late April 1992. Data are in Appendix A.**

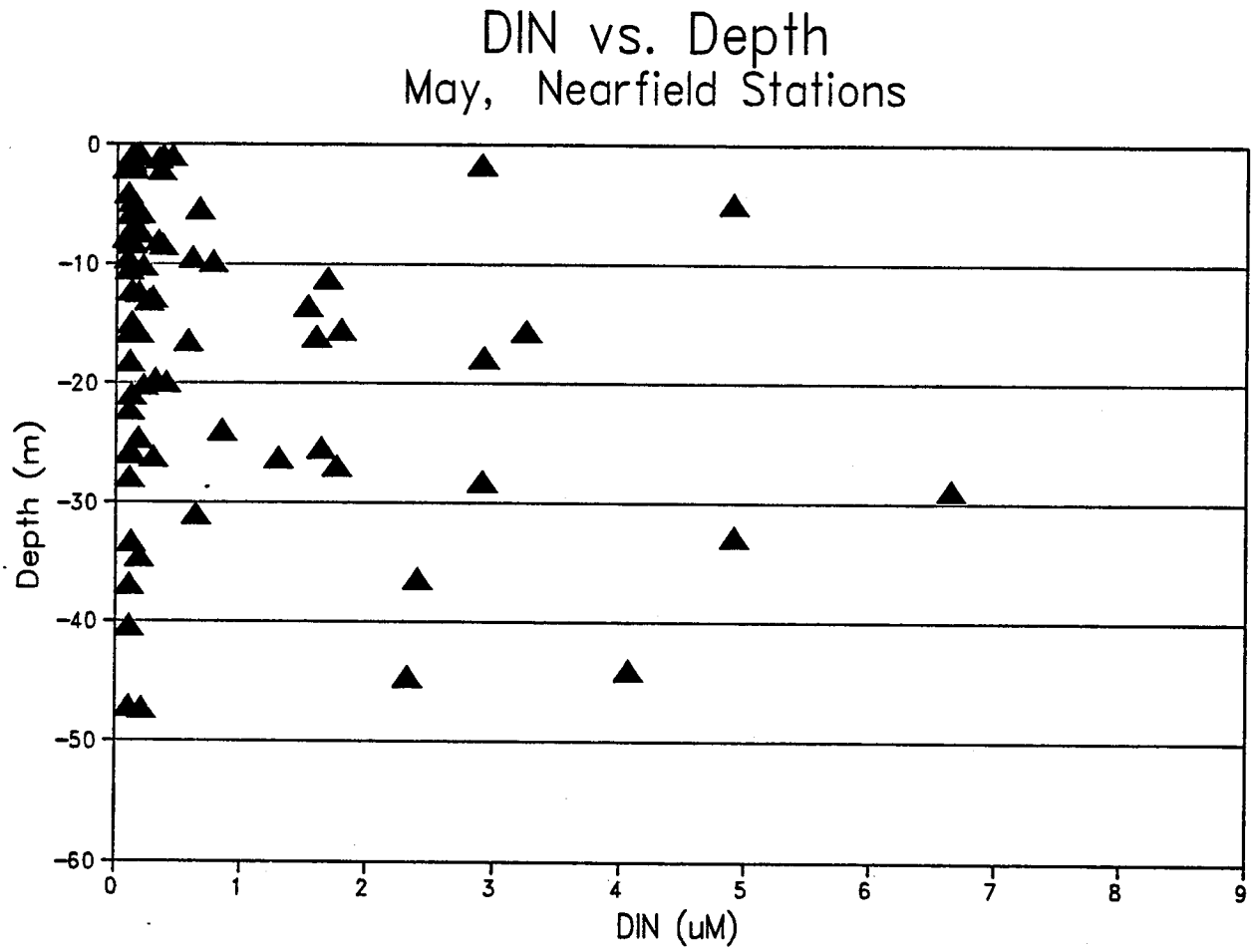



**Figure 10-8 Dissolved inorganic nitrogen vs. depth at nearfield stations in May 1992. Data are in Appendix A.**

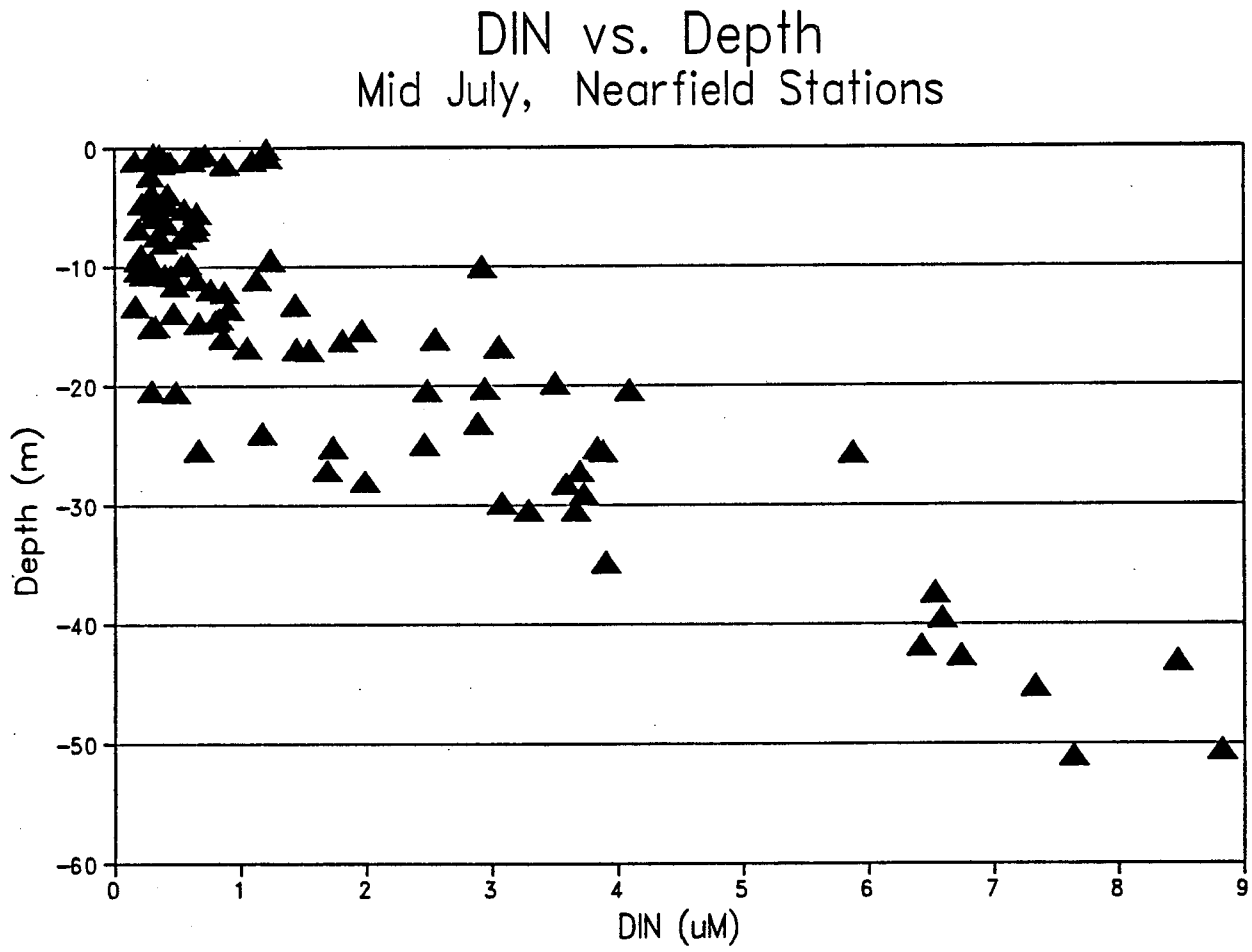



**Figure 10-9 Dissolved inorganic nitrogen vs. depth at nearfield stations in mid-July 1992. Data are in Appendix A.**

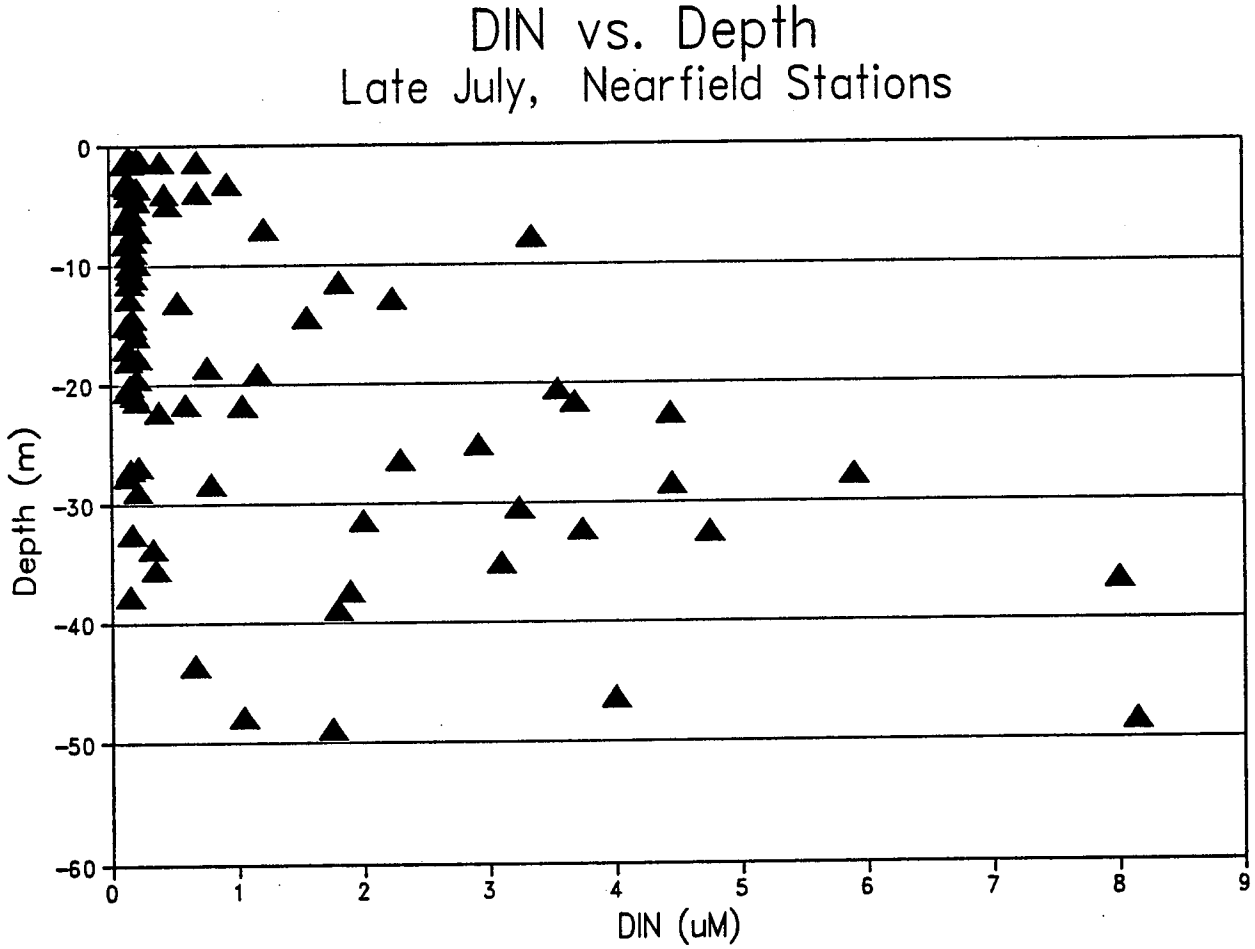



**Figure 10-10** **Dissolved inorganic nitrogen vs. depth at nearfield stations in late July 1992. Data are in Appendix A.**

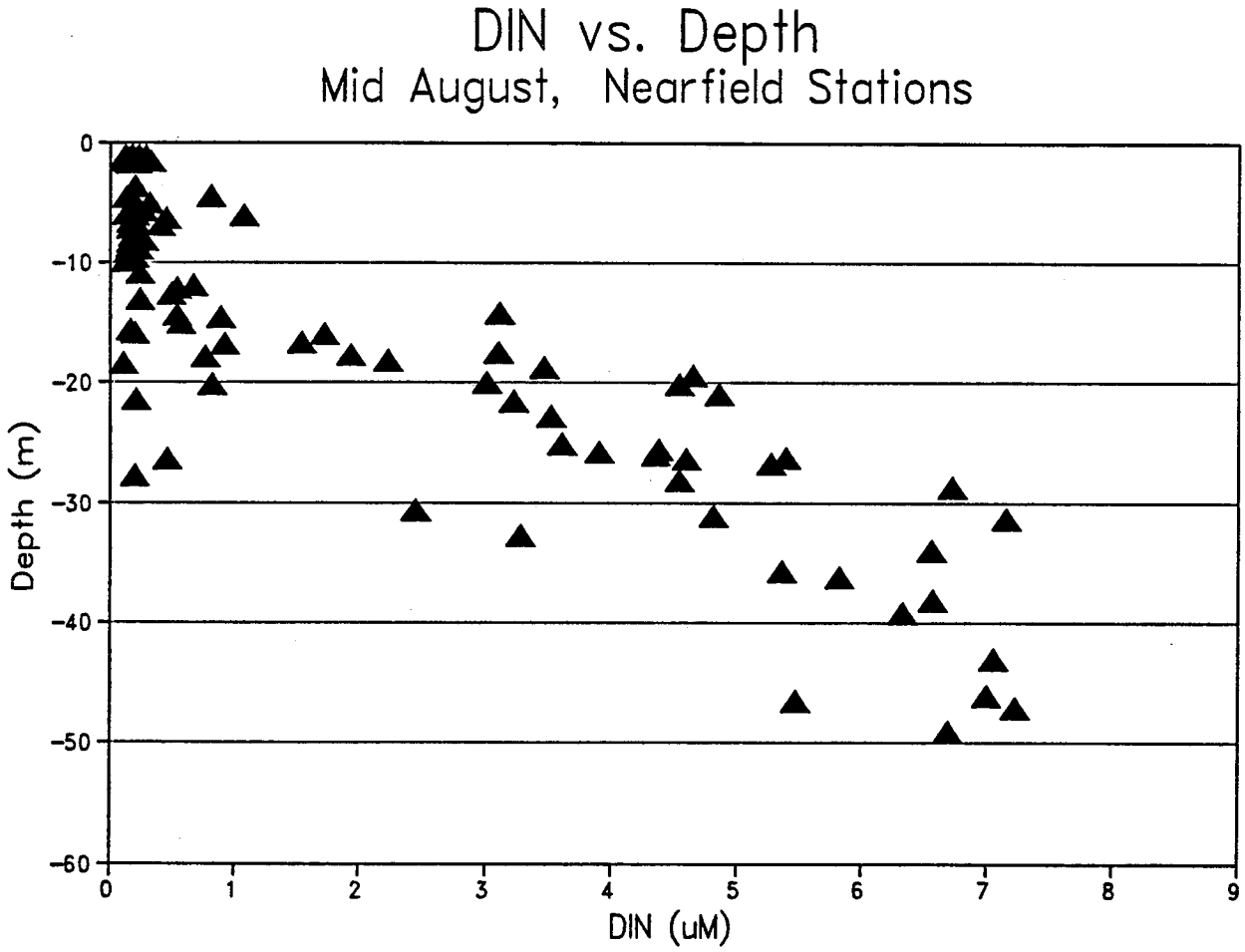



**Figure 10-11** **Dissolved inorganic nitrogen vs. depth at nearfield stations in mid-August 1992. Data are in Appendix A.**

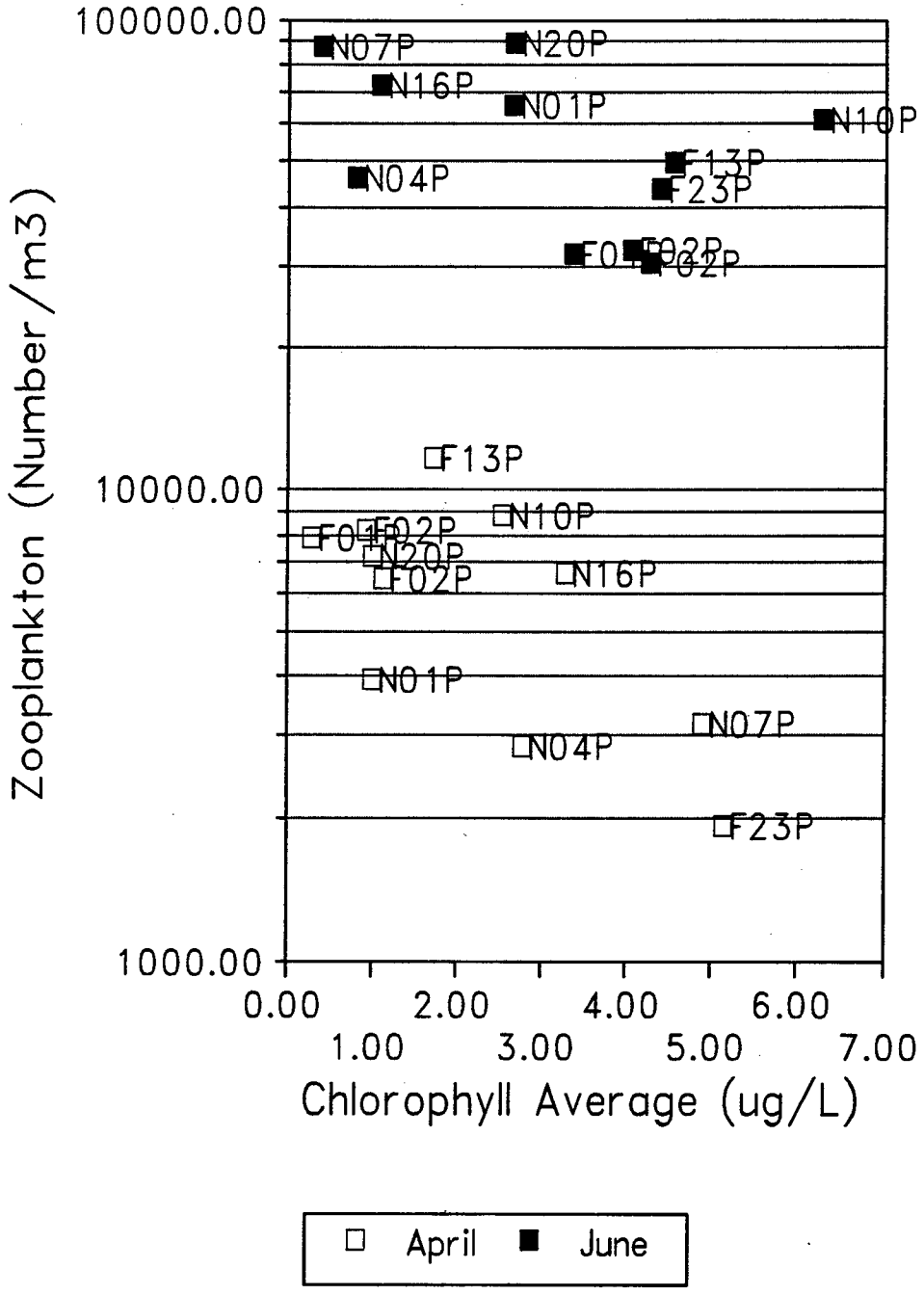



**Figure 10-12** **Zooplankton abundance vs. chlorophyll from all Bioproductivity stations in early April and June 1992. Data are in Appendices A and G.**

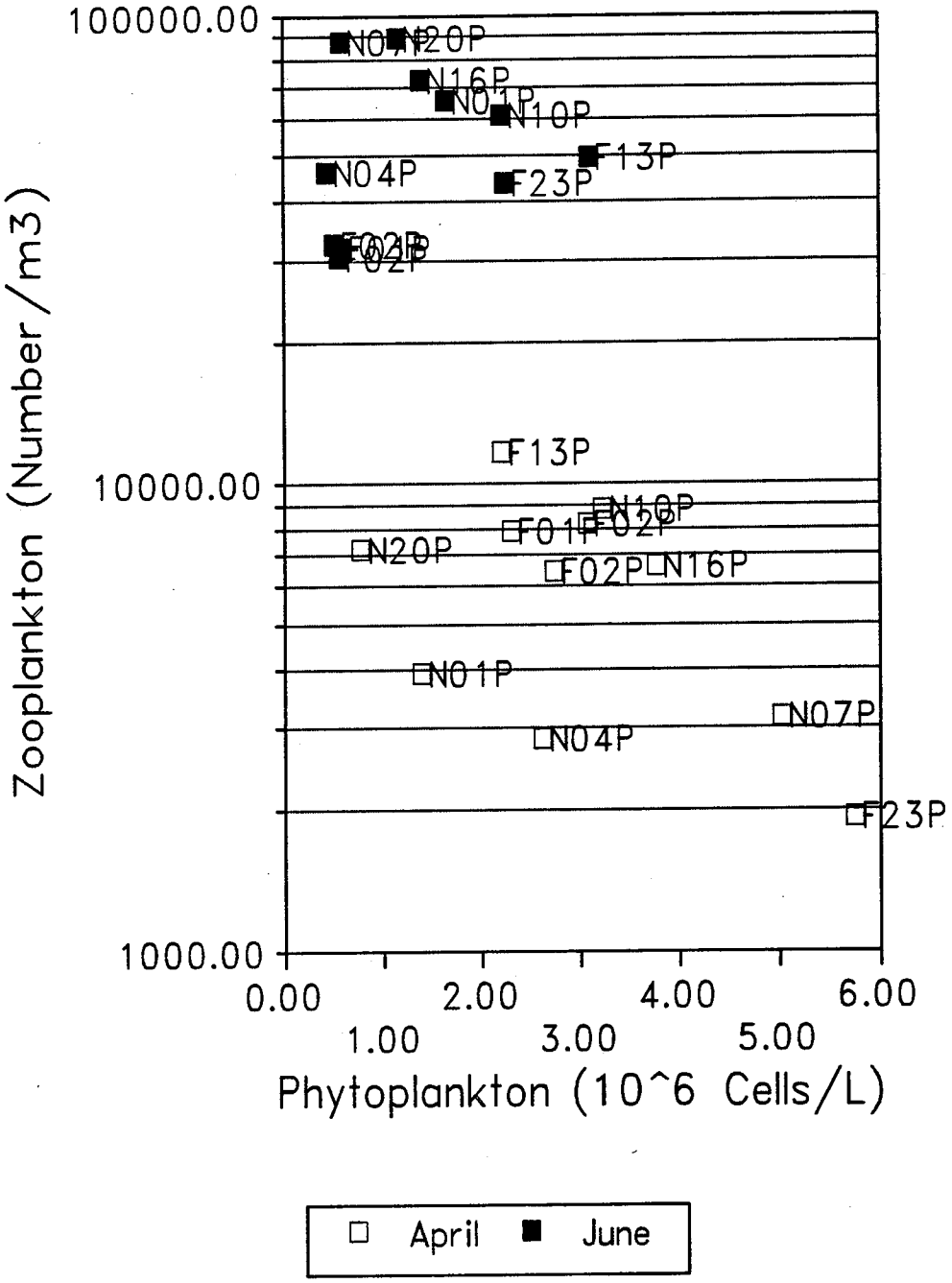



**Figure 10-13** **Zooplankton abundance vs. average phytoplankton abundance from all Bioproductivity stations in early April and June 1992. Data are in Appendices F and G. The average phytoplankton abundance is calculated as the mean of surface and chlorophyll maximum sample cell counts at a station.**

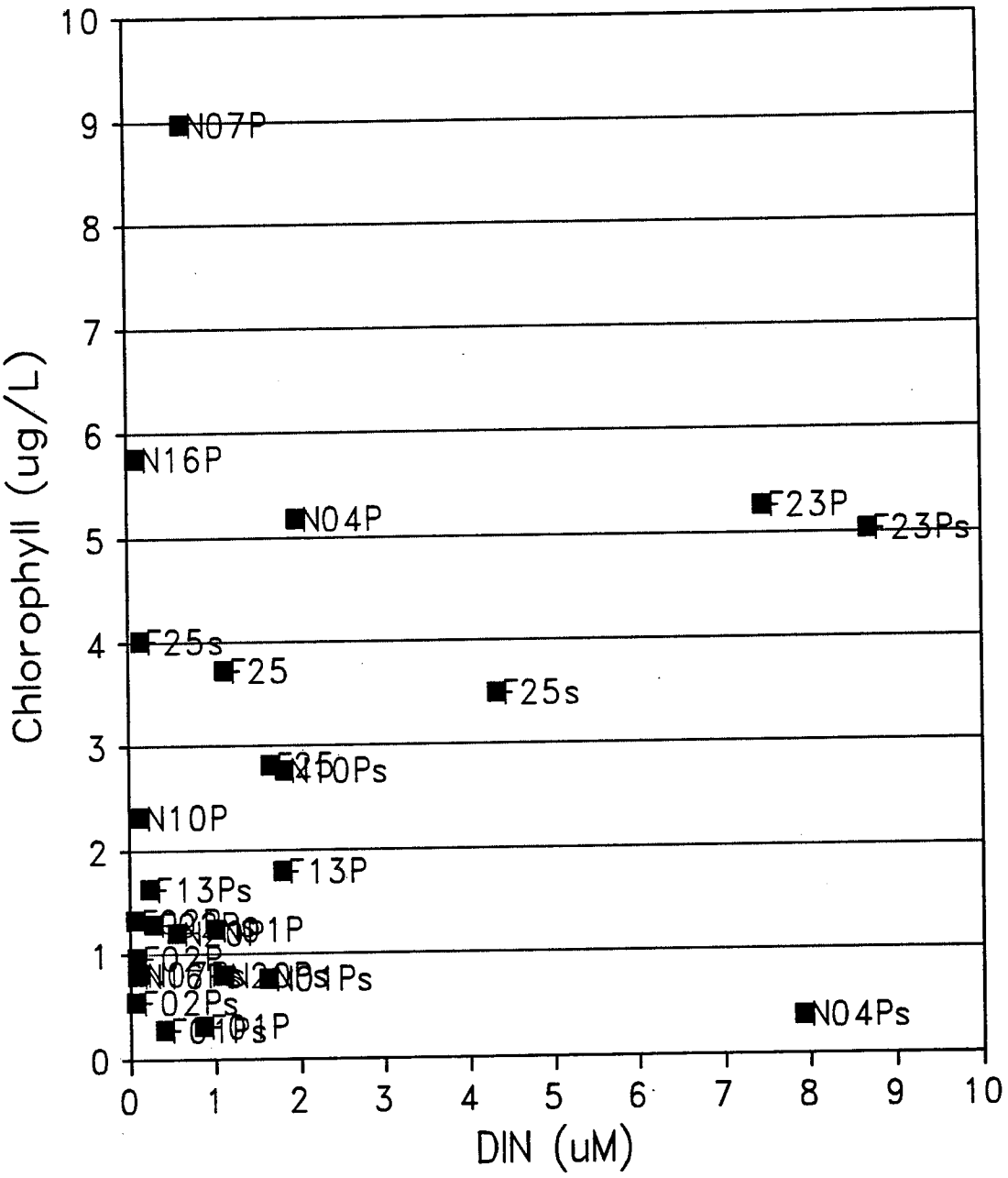



**Figure 10-14** **Chlorophyll vs. dissolved inorganic nitrogen from all Bioproductivity stations in early April 1992. Data are in Appendix A. The subscript "s" for each station identifies the surface sample.**

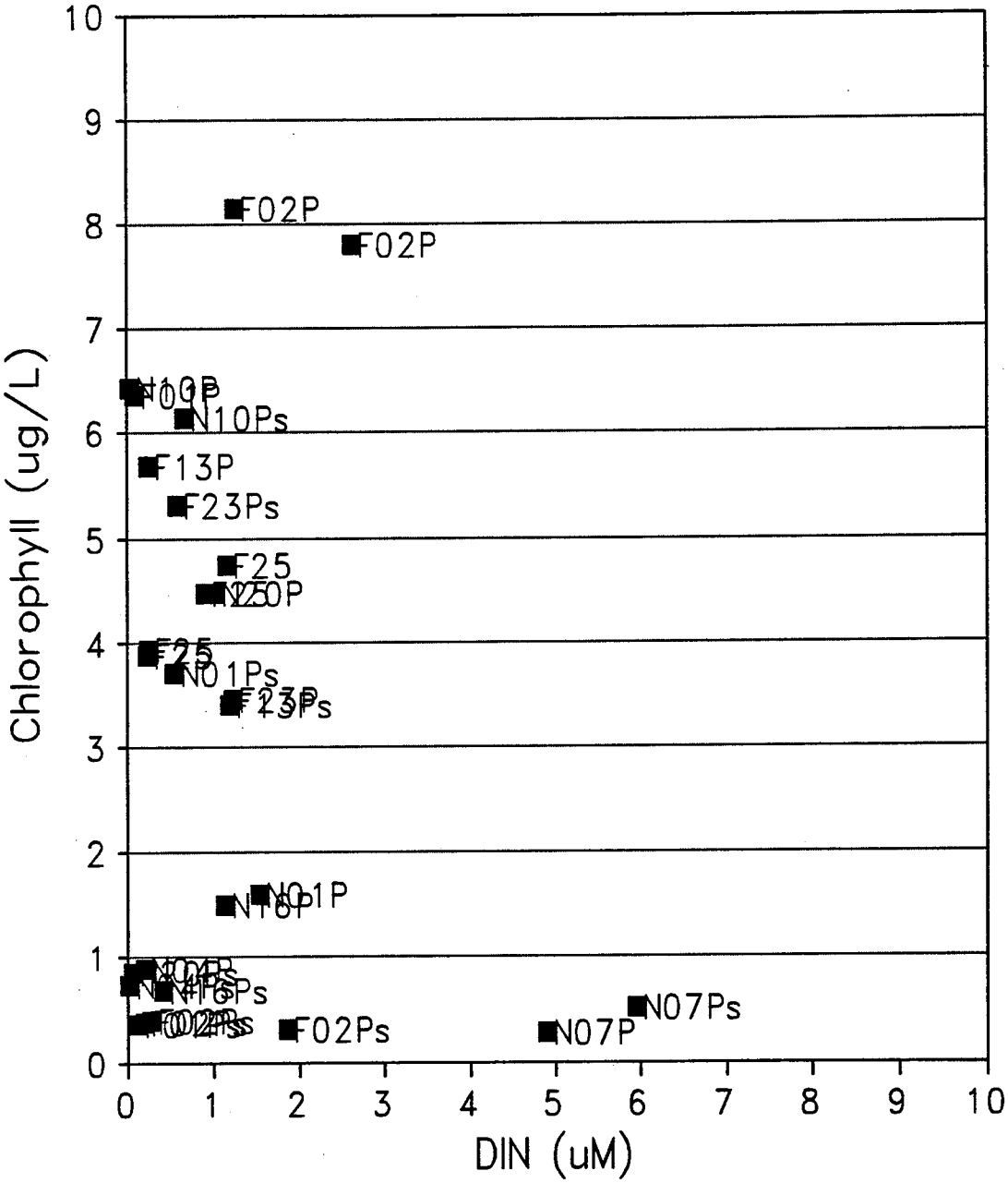



**Figure 10-15** **Chlorophyll vs. dissolved inorganic nitrogen from all Bioproductivity stations in June 1992. Data are in Appendix A. The subscript "s" for each station identifies the surface sample.**

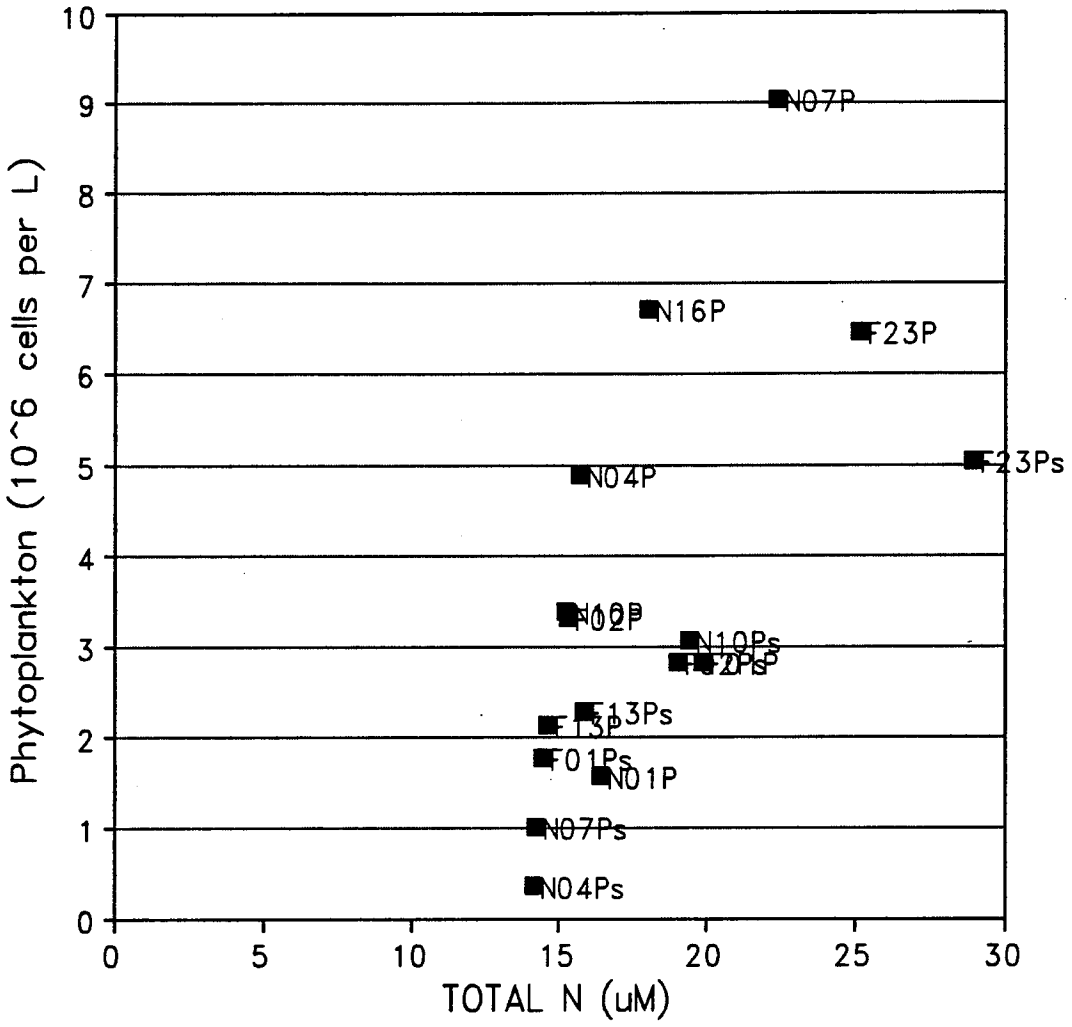



**Figure 10-16** **Total phytoplankton counts vs. total nitrogen from all Bioproductivity stations in early April 1992. Data are in Appendices A and F. The subscript "s" for each station identifies the surface sample. For several samples, PON concentrations were not available (see Appendix A) and no estimates of total N can be made.**

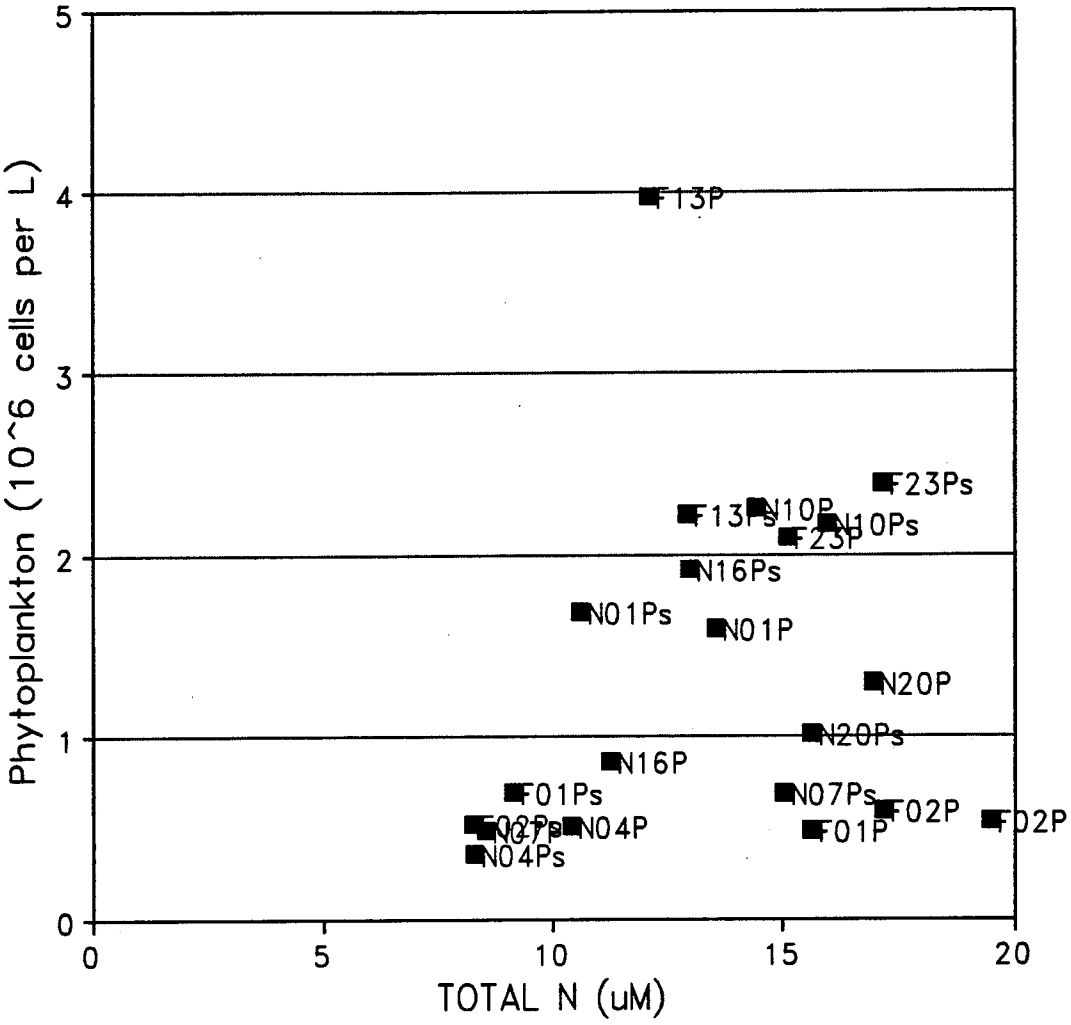



**Figure 10-17** **Total phytoplankton counts vs. total nitrogen from all Bioproductivity stations in June 1992. Data are in Appendices A and F. The subscript "s" for each station identifies the surface sample. For sample F02PS (1st cast) no PON concentration is available (see Appendix A) and no estimate of total N can be made.**

# 11.0 SUMMARY INTERPRETATION OF 1992 SPRING — SUMMER DYNAMICS

## 11.1 Farfield Scale (early April to June)

### 11.1.1 Water Properties in Space and Time

The principal physical heterogeneities in the water column of Massachusetts and Cape Cod Bays were more strongly seen in temperature than in salinity. The seasonal warming of surface waters created the normal initiation layering expected in late spring, with more sharply defined layers apparent in early summer. By June, a cold bottom water was still present throughout the Bays, except in shallow, more well-mixed coastal waters. Some spatial differences in surface temperatures were noticed, with coastal waters usually distinct from offshore, and the Massachusetts Bay region usually thermally distinct from the Cape Cod Bay region. Cape Cod seemed a bit colder on average in early April, yet warmer on average in June. Some interesting biological and chemical patterns were associated with these regional-scale distinctions.

### 11.1.2 Ecological dynamics

As season and temperature progress, biogeochemical processes usually quicken and this may be a partial explanation for the less distinct and spatially more restricted gradient of DIN from Boston Harbor compared to previous months. Nevertheless, coastal waters around the Harbor and into the nearfield normally showed substantial chlorophyll in their surface waters. Qualitatively, it appears that a large fraction of the N being dispersed from the Harbor source region at this time was packaged in planktonic organic matter; the horizontal and vertical fate of this material has not been quantified here.

Throughout the surveys and the region there was a general association between nutrients, physics, and phytoplankton. When the pycnocline was sharp and surface layers depleted of nutrients, the highest concentration of chlorophyll was relatively deep in the water column, accumulations ostensibly developing near sufficient nutrient supplies but at relatively low light levels. Other the other hand, where surface nutrient sources were available and the water somewhat mixed, chlorophyll was seen nearer the surface.

In April in particular, it is believed that some of the deep chlorophyll we detected was sinking from the water column; this was suggested by trends over the course of the combined survey in early April and the nearfield survey in late April. Further data analyses might examine this dynamic, which controls some of the annual delivery of organic matter to bottom layers.

The plankton community composition of the Bays was similar at the time of termination of the winter-spring bloom in April, as stratification strengthened and some dissolved nutrients were very low. DIN got low virtually everywhere even while phosphate was still available. For some reason, silicate in the surface, and even through the water column, had become more depleted by winter-spring bloom activity in Cape Cod Bay than in Massachusetts Bay.

Following this, two months later, a dinoflagellate bloom was in progress in Cape Cod Bay, and silicate concentrations there now well exceeded those in Massachusetts Bay. How connected were the depletion of silicate, the development of a *Ceratium* bloom, and the subsequent renewal of silicate is a matter only for speculation at this point. Physical and climatic factors, as well as biogeochemical processes, must play a role. Mechanisms aside, the interpretation must be that some of the pelagic ecological dynamics in the two Bays were not highly coupled to each other over the period in review here. Whether the pelagic production dynamics of Cape Cod Bay simply were preceding those of Massachusetts Bay as had been mildly suggested in earlier months (Kelly *et al.*, 1992) may become apparent as data from later cruises are available.

## 11.2 Nearfield Scale

### 11.2.1 Water Properties in Space and Time

The nearfield continued to be a region where inshore waters mixed with offshore waters. With occasional anomalies, nutrient and chlorophyll concentrations and vertical distributions were part of the group of parameters useful in "typing" the water at a given place.

As the season progressed, the pycnocline was generally sharper and deeper and the water layering more crisply defined in deeper waters along the north and east tracks. Overall, the data suggest a progression

into summer towards the case where physical dynamics were more strongly a function of within-field processes than they were driven by mesoscale processes like water advection from the North. With respect to this, very clear from the data was the influence of tidal dynamics in creating time and space heterogeneities to at least the middle of the nearfield. Presumably, pycnocline non-uniformities in space and time were also related to processes like internal waves and wind events. This notion of a reduced role of mesoscale events during the summer stratified period should not be overplayed however, for there were horizontal "frontal" features noticed with the surveys, origins unknown, and these appeared significant to chemical and biological features in some cases.

### 11.2.2 Ecological Dynamics

For the period of combined surveys, the nearfield was seen as a microcosm of the broader region surveyed in Massachusetts Bay, but not necessarily Cape Cod Bay. Much of the total Massachusetts Bay variability in time and space of most parameters was indeed displayed within the nearfield. The shallower western side of the field differed distinctly from the deeper eastern side and there was also some trend apparent from north to south. So, within this region one can see that ecological dynamics differ as function of physical and chemical conditions in part regulated by water depth and in part influenced by the character and outflow of inshore waters.

Data from the full sequence of nearfield surveys show marvelously rich details in patchiness of biological features as well as expected general seasonal progressions of lower nutrient surface water underlain by higher nutrient bottom water. However, the surveys also suggest that progressions can be interrupted and reestablished (cf. mid summer surveys). Indeed, the data very well show the "noise" of biological events, where chlorophyll maximum of various intensities and spatial extents within the field were observed to move within hours and days. Over the period, highest biological concentrations were seen at virtually all quadrants of the field, but they were clearly biased to the southwestern corner on average.

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The Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Charlestown, MA 02129
(617) 242-6000