Water quality monitoring in Massachusetts and Cape Cod Bays:

August - November 1992

Massachusetts Water Resources Authority

Environmental Quality Department
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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:

WATER QUALITY MONITORING IN MASSACHUSETTS BAY AND CAPE COD BAYS: AUGUST - NOVEMBER 1992

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WATER QUALITY MONITORING
IN MASSACHUSETTS AND CAPE COD BAYS: AUGUST-NOVEMBER 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, twenty-two water-quality surveys throughout Massachusetts Bay and Cape Cod Bay were conducted 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 four surveys from late August through November. Included are results of a "combined" survey in two months (late August and October). 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 two separate surveys conducted only in the nearfield in September and November. The report briefly provides background information on the water quality surveys and objectives and describes field, laboratory, and data analysis procedures. Results by survey are then 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 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 late August and October surveys. As in previous studies, the two Bays had several 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 both air and water temperatures cooled and consequently, this progression eroded the density layering of the water column that was being maintained principally by a thermal gradient. In mid-October the thermocline had broadened and deepened from late August; a less sharply stratified, but distinctly two-layer system was still evident. By early November, the water column in the nearfield was essentially vertically uniform in terms of physical properties. The Fall overturn (mixing of seasonally stratified waters) characteristic of temperate-zone aquatic ecosystems occurred between October and November 1992 in this region (about 20-50 m deep).

As in the first two reports for 1992 (Kelly *et al.* 1992, 1993), 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 strongly stratified to thoroughly mixed. There were characterizable horizontal gradients from Boston Harbor to western Massachusetts Bay. Water mass distinctions, mostly subtle, between surface waters of coastal and offshore waters were possible, as were distinctions between Cape Cod and Massachusetts Bays. For example, Cape Cod Bay (compared to Massachusetts Bay) surface waters are usually a bit warmer than western Massachusetts Bay and the nearfield region. Perhaps the most notable physical pattern discerned was the continued presence of a temperature, salinity, and turbidity (beam attenuation) gradient from near Boston Harbor to the nearfield. Advection and mixing of coastal water of obvious Boston Harbor origin with nearfield water was suggested by a variety of data. 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 "perturbations" of the density layering were observed in the center of the field. By the end of the sampling period (November), a fairly uniform nearfield was noted in terms of physical parameters.

Chemical (nutrients) variability. Nutrient concentrations were strongly a function of vertical stratification. While stratified, the surface water layer was virtually depleted in dissolved inorganic nitrogen and the nitrogen in suspended organic particles was usually higher than the dissolved forms. As stratification was broken down, a more uniform vertical distribution of nutrients resulted, as expected. As with previous monitoring surveys, there was usually a notable signal of higher nutrients and chlorophyll in waters close to Boston Harbor. The difference between Cape Cod Bay and Massachusetts Bay with respect to silicate concentrations that had been seen earlier (April, June 1992) (cf. Kelly *et al.*, 1993) was no longer pronounced.

Biological variability. There regularly was evidence for a chlorophyll gradient from Boston Harbor, with some very high chlorophyll (fluorescence readings on the western edge of the nearfield in September. In this area, the chlorophyll was often found near the surface rather than at a deeper subsurface chlorophyll maximum within a pycnocline, as was often noted at stations in deeper water and away from the Harbor.

The biological community of plankton was dominated numerically by microflagellates in late August, but there were a number of diatoms among the dominants. Dinoflagellates were relatively rare. Although the total numbers of cells often differed with depth, the species composition appeared to be more robust. Species composition was generally similar across stations excepting near the Harbor, where diatoms were slightly more prevalent. As breakdown of stratification ensued into October, the diatoms generally became a bit more dominant (numerically) and dinoflagellates were relatively rare; this is a normal, characteristic seasonal feature for many other coastal waters. Three common species — *Rhizoselenia delicatula, Leptocylindrus minimus,* and *Thalassiosira* sp. — were the principal diatoms of the Fall phytoplankton "bloom".

In general, incubation measurements suggested that metabolism (production/respiration) was, in part, a function of chlorophyll. Respiration was difficult to detect using short incubations. Where rates were significant, the waters were usually warmer (near the surface) and/or there was relatively high chlorophyll. Bottom water oxygen concentrations did not reach low (<75%) saturation levels anywhere in the Bay, including Stellwagen Basin stations.

Initial conclusions on monitoring design

The station sampling design and array of sample analyses were able 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 generally were highly repeatable when made hours apart. In contrast, the coastal stations showed considerably more short-term variability in all parameters. Results of intensive nearfield sampling revealed much fine-scale variability, especially in chlorophyll. High resolution in parts of the nearfield may be required for adequate baseline characterization because changes there occurred within a tidal cycle, as well as over periods of days. Finally, the measurements to estimate respiration should be lengthened if they are to provide actual rate estimates.

1.0 INTRODUCTION

This report is the third 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 late August and October combined nearfield-farfield surveys and from two other nearfield-only surveys in September and November 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. A brief summary of the 1992 late summer-fall 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 prepared during 1993.

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. Early April to mid-August surveys were reported by Kelly *et al.* (1993). A combined nearfield-survey was conducted as planned in late August (25-29) and also in October (13-17). Nearfield surveys were conducted as planned in early September (9-10) and early November (9-10). A planned survey in late September was not conducted because of weather.

1.4 Summary of Accomplishments during late August through November

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.

1-3

- 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 N13, N15, N17 and N19.

Most 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 H.

statute miles

0   25   50

0   25   50   75

kilometers

71°00'   70°40'   70°20'   70°00'

42°40'

Cape Ann

40 m

Massachusetts Bay
Disposal Site

Outfall Site

Boston

5.6 miles   15.2 miles

6.5 miles

Stellwagen Bank

42°20'

Massachusetts Bay

35.3 miles

40 m

Duxbury

Provincetown

40 m

42°00'

Cape Cod Bay

Massachusetts

41°40'
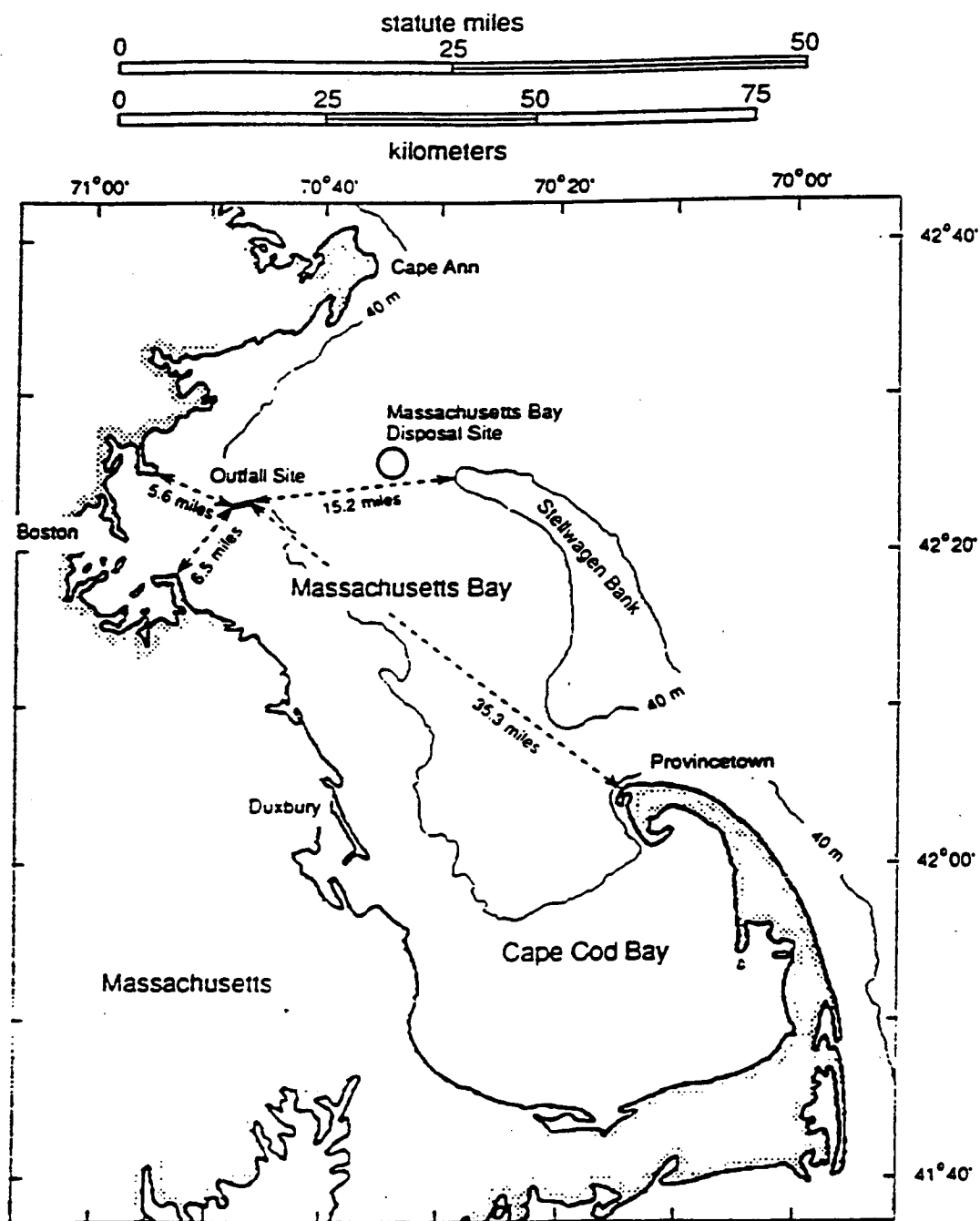
Figure 1-1. Massachusetts and Cape Cod Bays

```
         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 late August through November. The late March and late September 1992 surveys were cancelled due to foul weather.
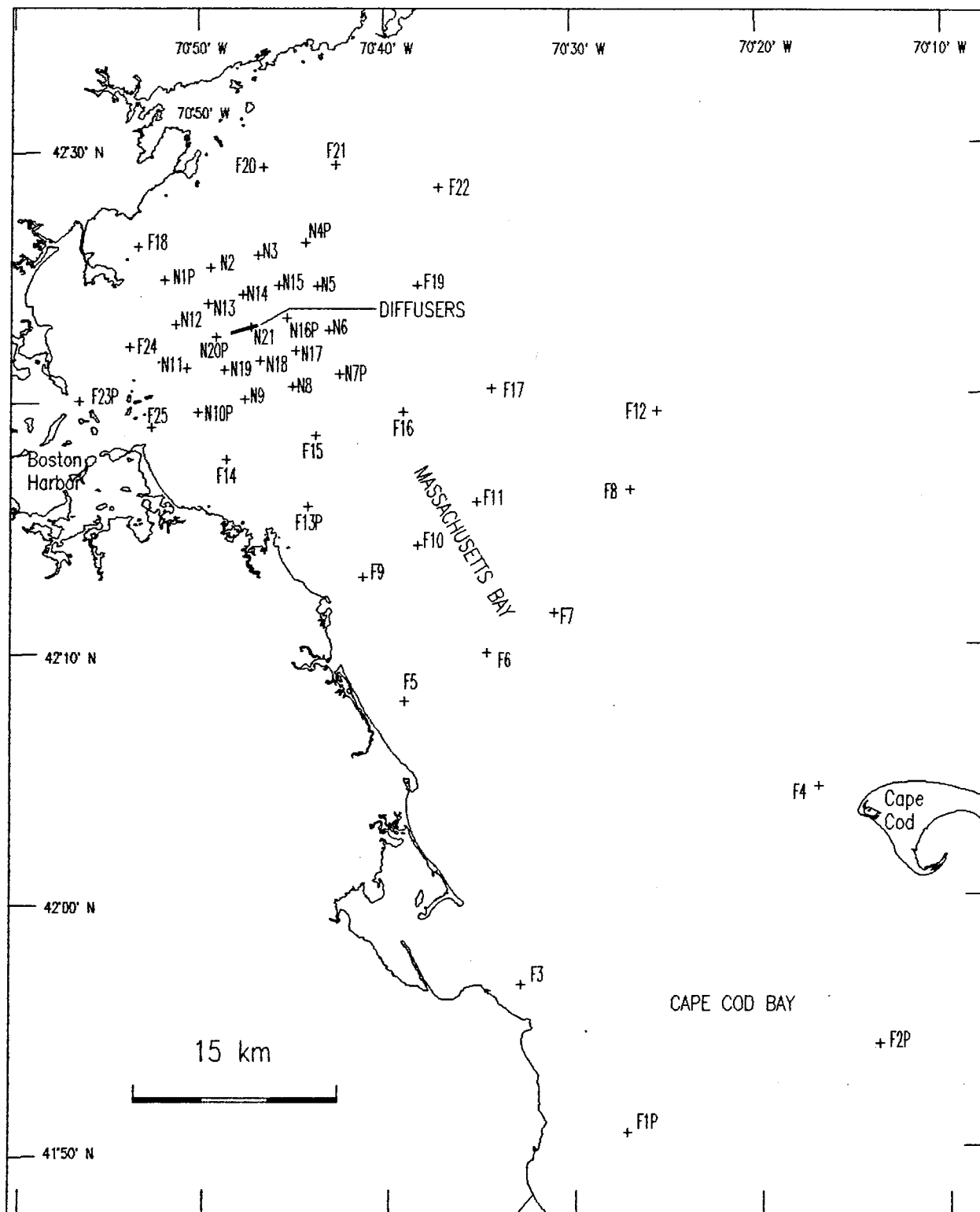
Figure 1-3. **Water quality sampling stations in Massachusetts and Cape Cod Bays.**
Station codes — F: Farfield, N: Nearfield, P: BioProductivity. The location of the
future outfall is shown by a line in the middle of the nearfield.

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. 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 each of the combined surveys, 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, 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, irradiance, 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 determine the depths for water sampling on the upcast.

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 a limited subset of stations on the combined surveys in late August and October, a replicate vertical profile and "BioProductivity" sampling (phytoplankton and zooplankton) was conducted to provide estimates of sampling variability. At stations where the bottom depth was about 20 m or less, only four depths were sampled. Discrete bottled-water sampling events were electronically flagged in the BOSS data file using

2-2

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-only surveys, water samples were collected for nutrients and chlorophyll 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 2 min before sampling for a given depth. Surface samples for dissolved oxygen (for calibration) and for phytoplankton (for archiving) were obtained at selected stations using a Niskin sampler. Oxygen samples were siphoned into 300-mL BOD bottles and fixed immediately. Phytoplankton samples (~ 800-1000 mL of whole seawater) were preserved; these were collected at the Bioproductivity stations within the nearfield. 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 using the Mini-BOSS towfish 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).

(almost 6 million L^{-1}), showed any taxa having counts $> 10^3$ (*Prorocentrum micans*). All other taxa counts were in the 10^2 range or less. Overall, it appeared that there were fewer dinoflagellate taxa in Cape Cod Bay samples, but many of the additional taxa recorded at Massachusetts Bay stations were present as only a few individuals per L — not high enough to provide valid statistical estimates.

3.1.5 Distribution of Zooplankton

The total numbers of zooplankton were very high. Station totals varied from 67,316 (F23P) to 261,075 (N01P) individuals m^{-3}. Copepod adults, copepidites, and nauplii contributed virtually all the counts at all stations (Figure 3-33). Copepod nauplii in most cases were about 1/4 of the total, but in the two cases where totals were above 150,000, copepod nauplii contributed roughly 40% of the total. There was no striking geographic pattern (Figure 3-33) and Cape Cod Bay stations were similar to many nearfield stations. Highest counts were observed where the highest chlorophyll had been recorded (N01P) and lowest counts were recorded at the edge of Boston Harbor (F23P).

As in all previous surveys, two smaller copepods, *Oithona similis* and *Paracalanus parvus*, were usually by far the top two numerically dominant taxa. The community in general was comprised of typical coastal shelf species. The copepod, *Acartia tonsa*, a species typical of summer inshore and estuarine conditions, was present at a number of stations. Not surprisingly, it was present in relatively high numbers at F23P and N10P (Boston Harbor and the southwest corner of the nearfield that typically receives Harbor water). Interestingly, this species was also present in relatively high numbers at station F01P in Cape Cod Bay. Complete species list by station are given in Appendix G.

3.1.6 Whole-Water Metabolism Incubations

Data generated from light-incubations over 4- to 6-hr periods characteristically showed that maximum rates were reached by irradiance levels in the range of 200 to 600 μE m^{-2} sec^{-1}. Note that all measured *in situ* irradiance levels and the % incident irradiance as a function of depth are provided in Appendix B vertical profiles for each station. In a number of cases, production rates seemed inhibited at high intensities (above 600 to 1000 μE m^{-2} sec^{-1}). About five cases of 20 (= 2 depths times 10 BioProductivity stations) were well fit by a model with a photoinhibition term and all of these were from chlorophyll maximum sampling depths (Appendix E). Approximately another 8 cases were well fit by

a hyperbolic model. In general, the cases that could not be fit by either model were very low nutrient, low chlorophyll situations (including F01P, F02P, N04P, and F13P).

Figure 3-34 gives two examples of reasonably well-modeled cases. In general for the well-modeled cases, maximum net production rates (P_{max}) ranged from as low as about 5 to as high as about 60 μg O_2 (μg Chl)$^{-1}$ hr^{-1}. It was noted that most of the high rates were at locations of higher nutrients and chlorophyll (i.e. stations F23P, N01P, N20P, N20P). All model-fits and chlorophyll-normalized rates, as well as volumetric production rates are given in Appendix E.

With respect to dark respiration, there were twelve cases out of 30 (= 3 depths times 10 BioProductivity stations) where t-tests showed a significantly lower (p ≤ 0.05) final dissolved oxygen concentration compared to initial concentrations. These cases included the chlorophyll maximum sample at the two Cape Cod Bay stations and at N04P. Also included were two depths at F23P (Boston Harbor), all three depths at N20P and N01P, and the surface at N10P; not surprisingly, these were cases where higher chlorophyll was observed. In the cases of N01P and N20P, where significant respiration was seen in deeper waters, the bottom water samples were at 27.7 and 25.5 m, respectively; these waters underlay rather intense chlorophyll surface blooms within the top 5 to 12 m (see previous). Calculated rates of net respiration are provided in Appendix E.

3.2 Nearfield Survey

3.2.1 Distribution of Water Properties from Vertical Profiling

The data for all nearfield vertical profile sampling are given in Appendices A (bottle measurements) and B (vertical downcast profiles). Summary plots for several parameters from vertical downcasts are shown in Figure 3-35. Parameter ranges and general distribution of chlorophyll fluorescence over depth have been presented previously. Note that higher fluorescence and beam attenuation were observed at lower salinities. Although a subsurface chlorophyll peak was routinely observed at about 20 m, a small set of stations had higher chlorophyll and this was in the top 10 m.

Figure 3-36 displays the chlorophyll maximum, independent of the depth of occurrence, at each station, along with the sampling track for reference. On this day (August 28), highest chlorophyll values were biased to the northwestern corner of the field.

Figure 3-37 shows DIN concentrations as a function of depth for all stations in late August. DIN concentrations were very low throughout the nearfield; DIN in surface waters of the coastal stations were often higher than in the nearfield and the highest concentrations were typically at water depths greater than found in the nearfield area. Only at N01P (the northwestern corner) did DIN exceed 1 μM within the top 10 m (at 8 m it was >2μM on August 28) and in general DIN only exceeded 1 μM below 15 to 20 m at offshore eastern stations.

3.2.2 Distribution of Water Properties from Towing

A three-dimensional perspective of the nearfield is provided from the towed instrument sampling day (August 29). The entire inner box was towed clockwise (N09-N20P-N13-N14-N15-N16P-N17-N18-N19-N09) followed by the outer box towed counterclockwise (N10P-N09-N08-N7P-N06-N05-N04P-N03-N02-N01P-N12-N11-N10P). 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 for sigma-T and chlorophyll fluorescence (Figures 3-38 and 3-39). A temperature series is given in Appendix D.

Several interesting features are apparent from these high-resolution data. First, consider sigma-T and the distribution of the pycnocline across the nearfield. Three features were noted. The pycnocline was more sharply defined towards the inshore and to the North (to an extent— see particularly Figure 3-38b). Secondly, not only was the change in density with depth more gradual towards the offshore, but the depth of pycnocline, particularly the bottom of it, gradually increased into more offshore deeper waters (see especially Figure 3-38a). Finally, across the center of the nearfield (along inner box tracks especially), there appeared to be some stations where the pycnocline shoaled a bit towards the surface (e.g., N19, N16P).

In terms of chlorophyll (Figure 3-39), the bias of higher chlorophyll towards the northwest corner that was apparent the day before (Figure 3-36) was again seen. High values were seen along the entire outer

western track (closest to Boston Harbor), as well as most of the outer northern track from N01P to N04P. Generally, maximum values were above 6.5 μg L^{-1} all along these tracks, and peak values were above 8 μg L^{-1}. It was noted that peak chlorophyll along the shallow inshore track was in the surface layer or near the top of the pycnocline. To a high degree the sharpness and depth of the chlorophyll maximum correlated with the sharpness and depth of the pycnocline, therefore the subsurface chlorophyll maximum was broader and deeper at the eastern side of the field.

3.2.3 Water Types and Analysis of Small-Scale Variability

As in previous surveys, the data suggest the nearfield was a mixing zone of inshore and offshore waters. At this time, surface water along some stations of the inshore edge of the nearfield seemed to be influenced by inshore water, a most notable feature being a higher chlorophyll concentration. Broad spatial trends were apparent in both physical, geochemical, and biological parameters; by and large these were rather smooth secular trends with minor local spatial anomalies.

With respect to temporal scales, we had noted in previous surveys (Kelly *et al.*, 1993) that tidal dynamics play a role in determining conditions in the inshore side of the nearfield, and the time of sampling relative to tide height may influence the water properties observed at a fixed station location. This was again apparent from our data for this survey. Station N10P was visited twice on the towing day. The first occupation (shown in Figures 3-38a and 3-39a as the outer southern track) was near high tide, the second visit (completion of towing, the outer western track from N01P to N10P in Figures 3-38b and 3-39b) was near low tide. A difference in properties at these two visits was apparent, with a deeper pycnocline (deeper surface water layer) and higher surface chlorophyll levels being associated with the low tide sampling, or when tidal ebb waters from the Harbor would be dispersed into the Bay.

TABLE 3-1. ANALYSIS OF SURFACE WATER TYPES

Water Type		Characteristics by Parameter				
Classification	Geographic Descriptor	T (°C)	S (PSU)	Beam Attenuation (m^{-1})	Fluorescence (μg L^{-1})	Nutrients
Coastal	Most of nearshore western Mass. Bay (~less than 30m)	~17 - 19.8	30.4 - 31	~1 - 2.7	<2 - 8	Low
Northern Transect	Transect along northern entrance to Mass. Bay, (F20-F22) surface water	18.8 - 19.7	30.7 - 30.9	~1 - 1.4	<1 - 2.4	Low
Nearfield	Within nearfield sampling grid	16.7 - 19.8	~30.7 - 30.9	~1 - 3.0	<1 - 9.5	Low
Offshore	Mainstem Mass. Bay (~ greater than 40m)	17.2 - 19	~30.8 - 31	<1 - 1.4	≤1	Low
Cape Cod	All Cape Cod Bay stations	17.1 - 19.1	30.8 - 30.9	~1 - 1.2	<1 - 2	Low

Table 3-2. Top 5 dominant phytoplankton taxa in near surface samples collected in late August 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) 1.208	(1) 1.101	(1) 1.900	(1) 1.000	(1) 1.649	(1) 1.412	(1) 1.461	(1) 0.446	(1) 1.912	(1) 1.311	(1) 1.367
Cryptomonads	(3) 0.298	(2) 0.109	(3) 0.798	(2) 0.216	(3) 0.107	(3) 0.393	(3) 0.110	(5) 0.197	(2) 0.196	(2) 0.147	(2) 0.191
Chaetoceros sp. <10 μm*	(5) 0.175	(3) 0.016	(5) 0.342	(3) 0.029			(4) 0.032		(3) 0.034		
Chaetoceros socialis											
Leptocylindrus danicus	(3) 0.298					(5) 0.184		(3) 0.286			
Leptocylindrus minimus					(4) 0.048			(4) 0.207			
Unidentified naked Dinoflagellate											
Rhizoselenia fragilissima					(5) 0.036						
Cylindrotheca closterium			(4) 0.405			(4) 0.201					
Skeletonema costatum											
Cerataulina pelagic									(4) 0.028		
Heterocapsa triquetra											
Ebria tripartitia				(4) 0.023							
Unidentified Centiales											
Rhizoselenia delicatula	(2) 0.517		(2) 1.304		(2) 0.482	(2) 0.770	(2) 0.156	(2) 0.338			
Chaetoceros compressus										(4) 0.019	
Cyanophyceae											
Rhizoselenia alata									(4) 0.028	(3) 0.054	(3) 0.043

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

Table 3-3. Top 5 dominant phytoplankton taxa near the chlorophyll maximum collected in late August 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) 1.090	(1) 1.468	(2) 0.909	(1) 1.052	(1) 1.857	(1) 1.353	(1) 1.582	(1) 0.890	(1) 2.259	(1) 1.558	(1) 1.452
Cryptomonads	(4) 0.230	(2) 0.224	(4) 0.186	(2) 0.167	(2) 0.260	(2) 0.130	(2) 0.291	(5) 0.187	(2) 0.610	(2) 0.299	(2) 0.439
Chaetoceros sp. <10 μm*											
Chaetoceros socialis									(3) 0.196		
Leptocylindrus danicus	(3) 0.237						(3) 0.539				
Leptocylindrus minimus											
Unidentified naked Dinoflagellate		(3) 0.026					(3) 0.028		(5) 0.051	(4) 0.024	(4) 0.040
Rhizoselenia fragilissima											
Cylindrotheca closterium			(3) 0.196			(5) 0.038		(4) 0.201			
Skeletonema costatum					(4) 0.042					(4) 0.024	
Cerataulina pelagica			(5) 0.156								
Heterocapsa triquetra											
Ebria tripartitia				(3) 0.028					(5) 0.051		
Unidentified Centrales	(5) 0.190										
Rhizoselenia delicatula	(2) 0.372		(1) 2.161			(3) 0.071		(2) 0.711	(4) 0.065		
Chaetoceros compressus											
Cyanophyceae											(3) 0.080
Rhizoselenia alata										(3) 0.029	

(): rank; taxa are included if >4 individuals were counted
Number: millions of cells L^{-1}
*May be C. socialis

Table 3-4. All identified taxa in near surface screened (20 um) samples collected in late August 1992.

SPECIES	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P	F02P-2
CERATIUM FUSUS		5	8	2	15	9	12		14	17	18
CERATIUM LINEATUM	2					18		2		2	2
CERATIUM LONGIPES	2	6	6	2	9	5	3		8	9	9
CERATIUM SPP.				3							
CERATIUM TRIPOS					2		2		2	12	5
DICTYOCHA SPECULUM											
DINOPHYSIS ACUMINATA	20	2	8			2		3			
DINOPHYSIS NORVEGICA		2	8		3					5	
DINOPHYSIS OVUM						2					
DINOPHYSIS SPP.											
DISSODINIUM SPP.			9								
DISTEPHANUS SPECULUM						3					
EUGLENOIDS											
EUTREPTIA/EUTREPTIELLA SPP.				5							
GLENODINIUM ROTUNDUM			3								
GYMNODINIUM SPP.		5	6					3			
GYRODINIUM SPIRALE		2	2	2							
HETEROCAPSA TRIQUETRA	5		5	3							
HETEROSIGMA AKASHIWO	5	8	5	2				11			
MESODINIUM RUBRUM		5		9	2						
OBLEA SPP.			18					11			
PEDIASTRUM			2					8			
PROROCENTRUM MICANS	167	38	1156	144	84	134	11	281	6	20	18
PROROCENTRUM MINIMUM	5	3	17	15		2		33			
PROROCENTRUM TRIESTINUM			2					8			
PROTOPERIDINIUM (CF) BREVIPES	11										
PROTOPERIDINIUM CLAUDICANS	2		3		2						
PROTOPERIDINIUM CONICUM								2			2
PROTOPERIDINIUM DEPRESSUM						3					
PROTOPERIDINIUM PELLUCIDUM					2	6				2	
PROTOPERIDINIUM PENTAGONUM		3	5								
PROTOPERIDINIUM SPP.	78	3	167	12	14	95	9	27	5	5	5
PROTOPERIDINIUM STEINII			6								
PROTOPERIDINIUM TROCHOIDIUM			2								
PROTOPERIDINIUM MARIELEBOUR											
PROTOPERIDINIUM MINUSCULLUM			5			2		6			
SCENEDESMUS SPP.			2						2		
SCRIPPSIELLA TROCHOIDEA										2	

Values are cells/L

Table 3-5. All identified taxa near the chlorophyll maximum in screened (20 um) samples collected in late August 1992.

SPECIES	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P	F02P-2
CERATIUM LINEATUM	3	5	17	5	3	2	2		5	11	3
CERATIUM LONGIPES		122	8	156	95	15	146	72	317	60	30
CERATIUM SPP.											
CERATIUM TRIPOS		2		14					21	8	11
DICTYOCHA SPECULUM	6	57	2	6	11		2	9			
DINOPHYSIS ACUMINATA	6	8	3		2				2		
DINOPHYSIS NORVEGICA	5	17	6	3	2		3	9	18	11	
DINOPHYSIS OVUM	3				2	2					
DINOPHYSIS SPP.											
DISSODINUM SPP.											
DISTEPHANUS SPECULUM						6				2	2
EUGLENOIDS											
EUTREPTIA/EUTRIPTIELLA SPP.					2			2			
GLENODINIUM ROTUNDUM											
GYMNODINIUM SPP.	5		3	2							2
GYRODINIUM SPIRALE	5		5	2	2			2			2
HETEROCAPSA TRIQUETRA	5							3	2		
HETEROSIGMA AKASHIWO	9	3	3	3	3			2	5		
MESODINIUM RUBRUM	3	2	3	2	3	2		9			
OBLEA SPP.					3						
PEDIASTRUM											
PEDIASTRUM SPP. COLONY	2										
PROROCENTRUM MICANS	311	30	32	50	26	11	14	41	6	15	14
PROROCENTRUM MINIMUM	5		2	14				23		2	
PROROCENTRUM TRIESTINUM	2										
PROTOPERIDINIUM (CF) BREVIPES	20										
PROTOPERIDINIUM CLAUDICANS		3	3	2			2			2	
PROTOPERIDINIUM CONICUM											
PROTOPERIDINIUM DEPRESSUM	5	3	5	2			3	12	8	21	
PROTOPERIDINIUM PELLUCIDUM		6									
PROTOPERIDINIUM PENTAGONUM		11	5	2	29		6	2			
PROTOPERIDINIUM SPP.	105	59	57	53	87	2	32	26	5	23	9
PROTOPERIDINIUM STEINII											
PROTOPERIDINIUM TROCHOIDIUM											
PROTOPERIDIUM MARIELEBOURAE					11						
PROTOPERIDIUM MINUSCULLUM	5										
SCENEDESMUS SPP.											
SCRIPPSIELLA TROCHOIDEA											

Value are cells/L
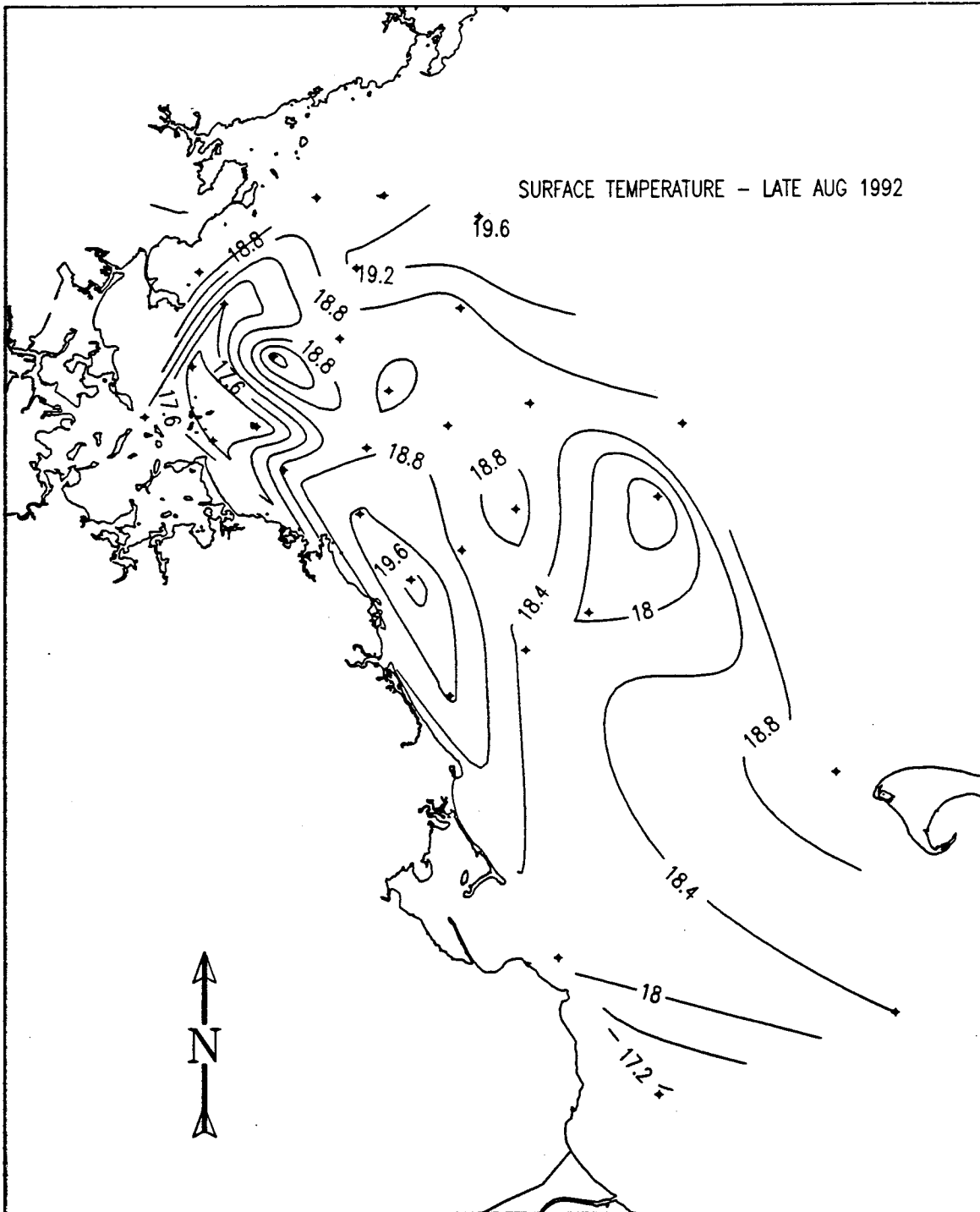
Figure 3-1   Surface temperature (°C) in the region in late August 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.4°C.
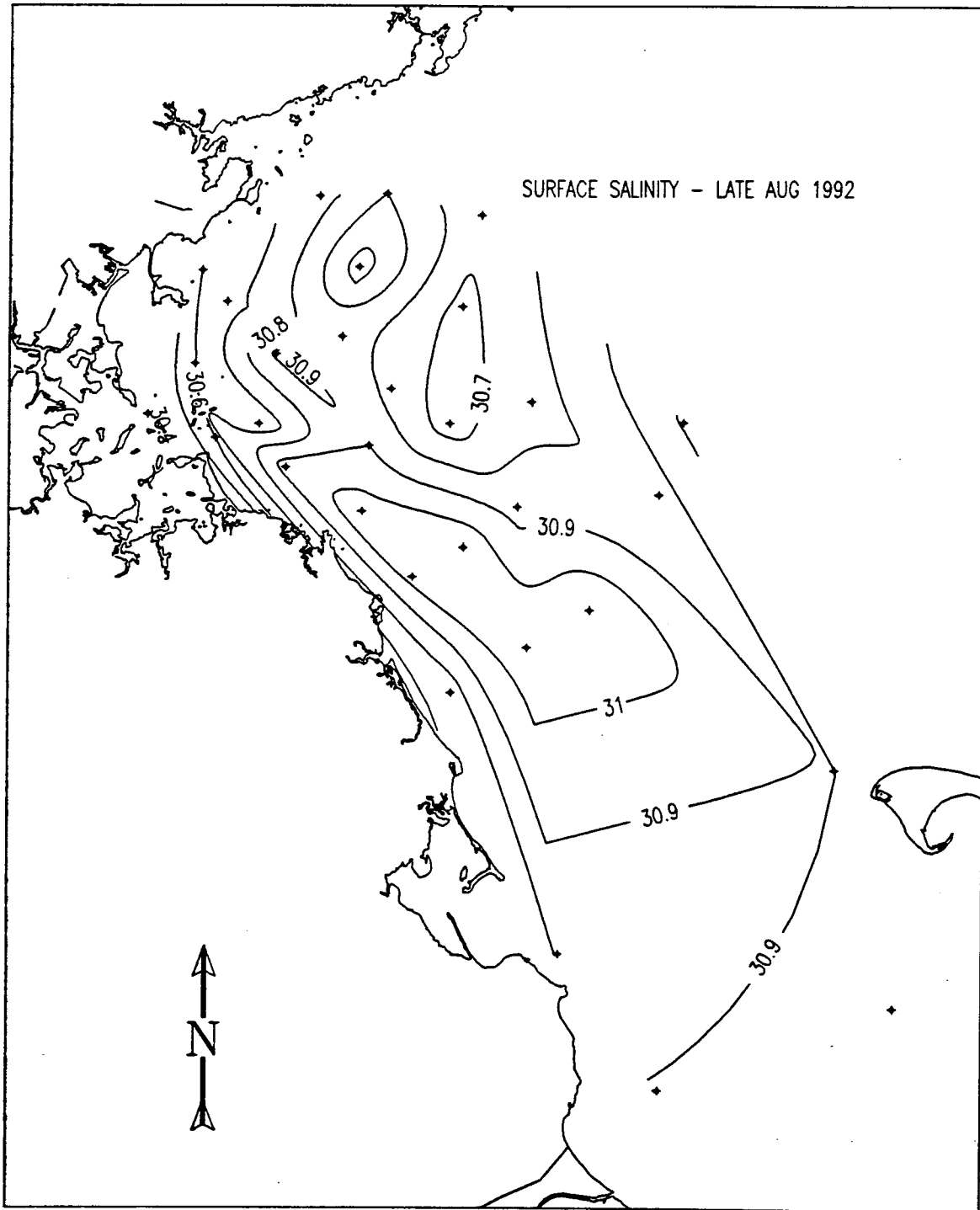
Figure 3-2 Surface salinity (PSU) in the region in late August 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.1 PSU.

SURFACE SIGMA T – LATE AUG 1992
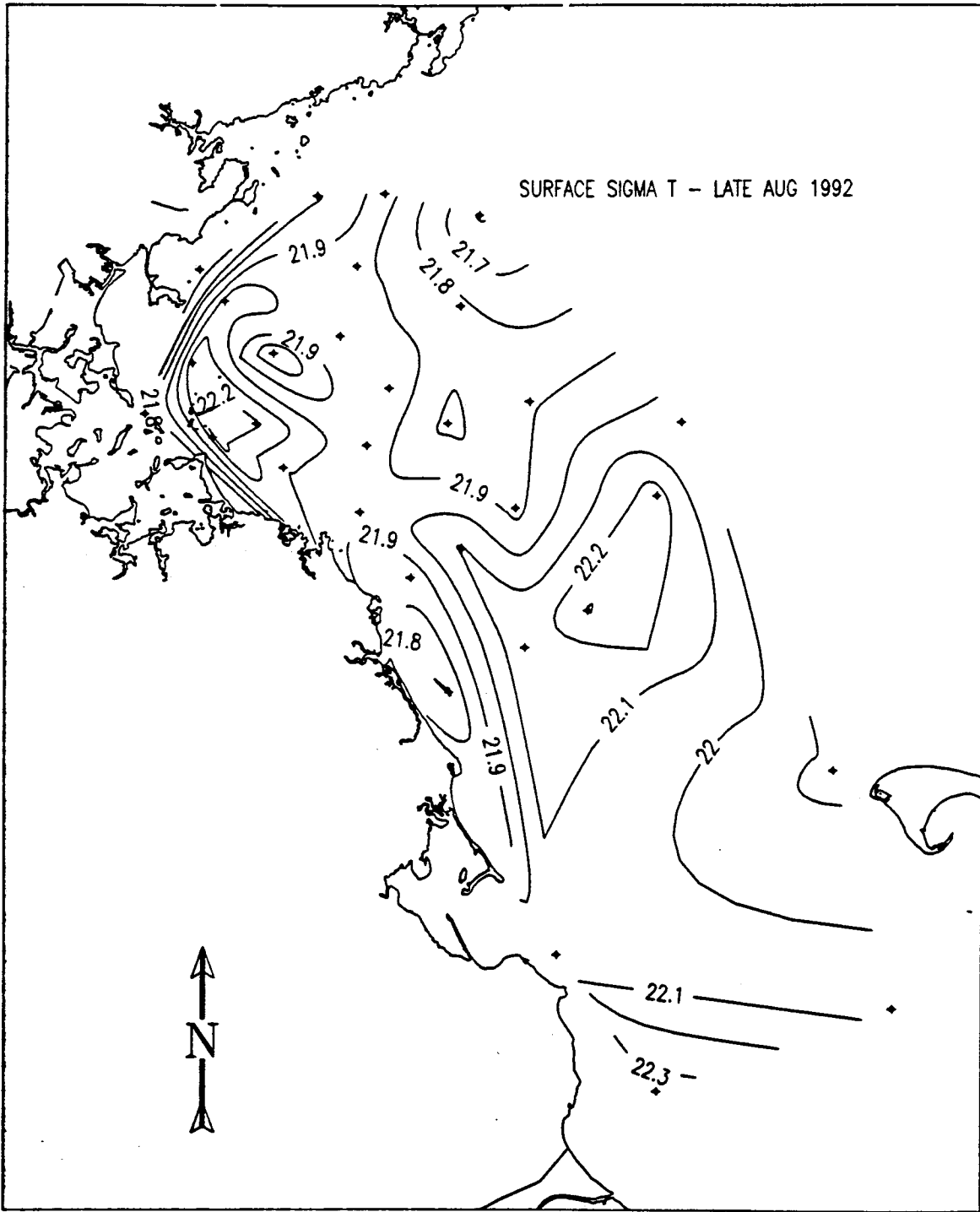
Figure 3-3   Surface σ_T in the region in late August 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.1 units.
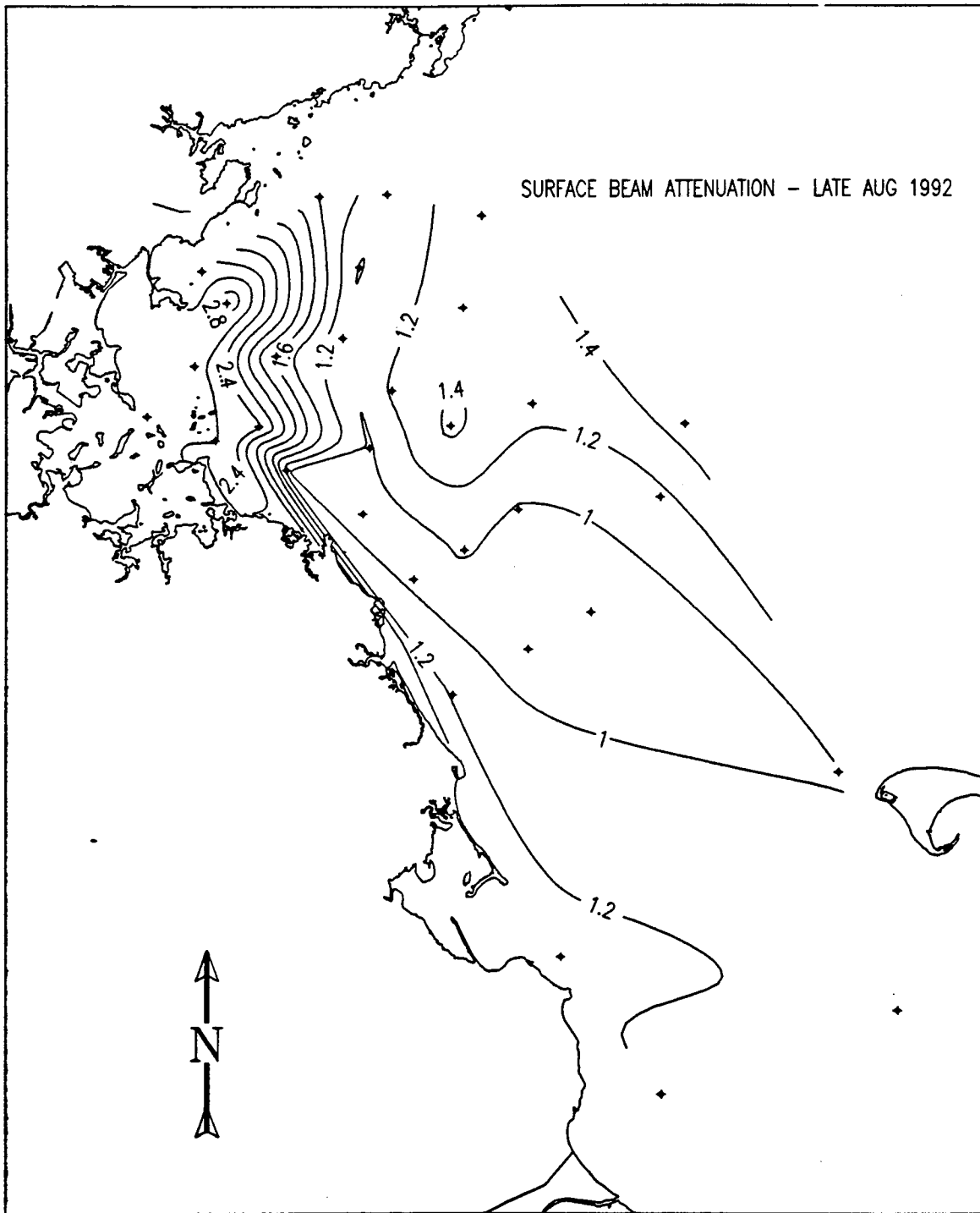
Figure 3-4   Surface beam attenuation (m⁻¹) in the region in late August 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.2 m⁻¹.
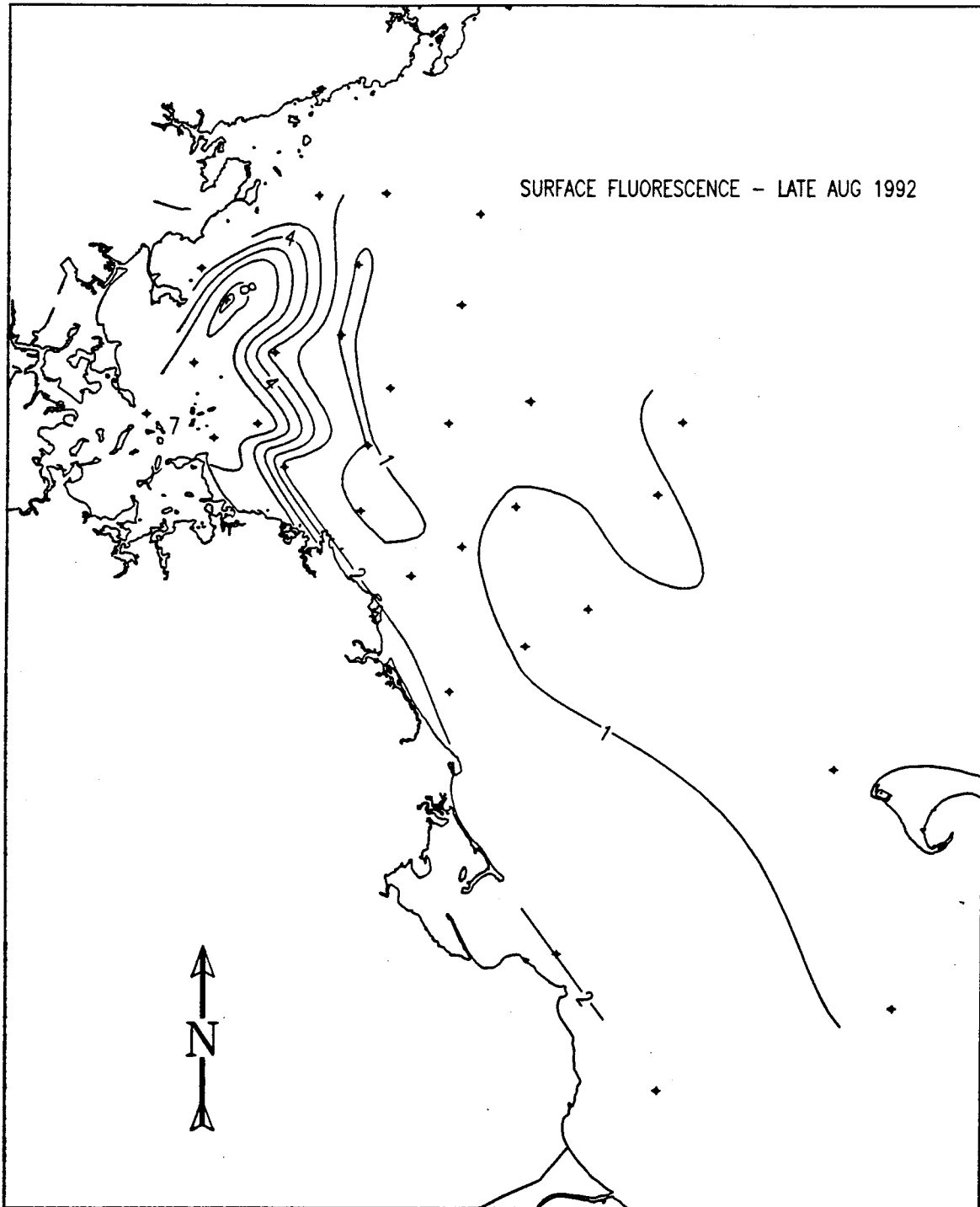
Figure 3-5 Surface *in situ* fluorescence (as μg Chl L^{-1}) in the region in late August 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 μg L^{-1}.
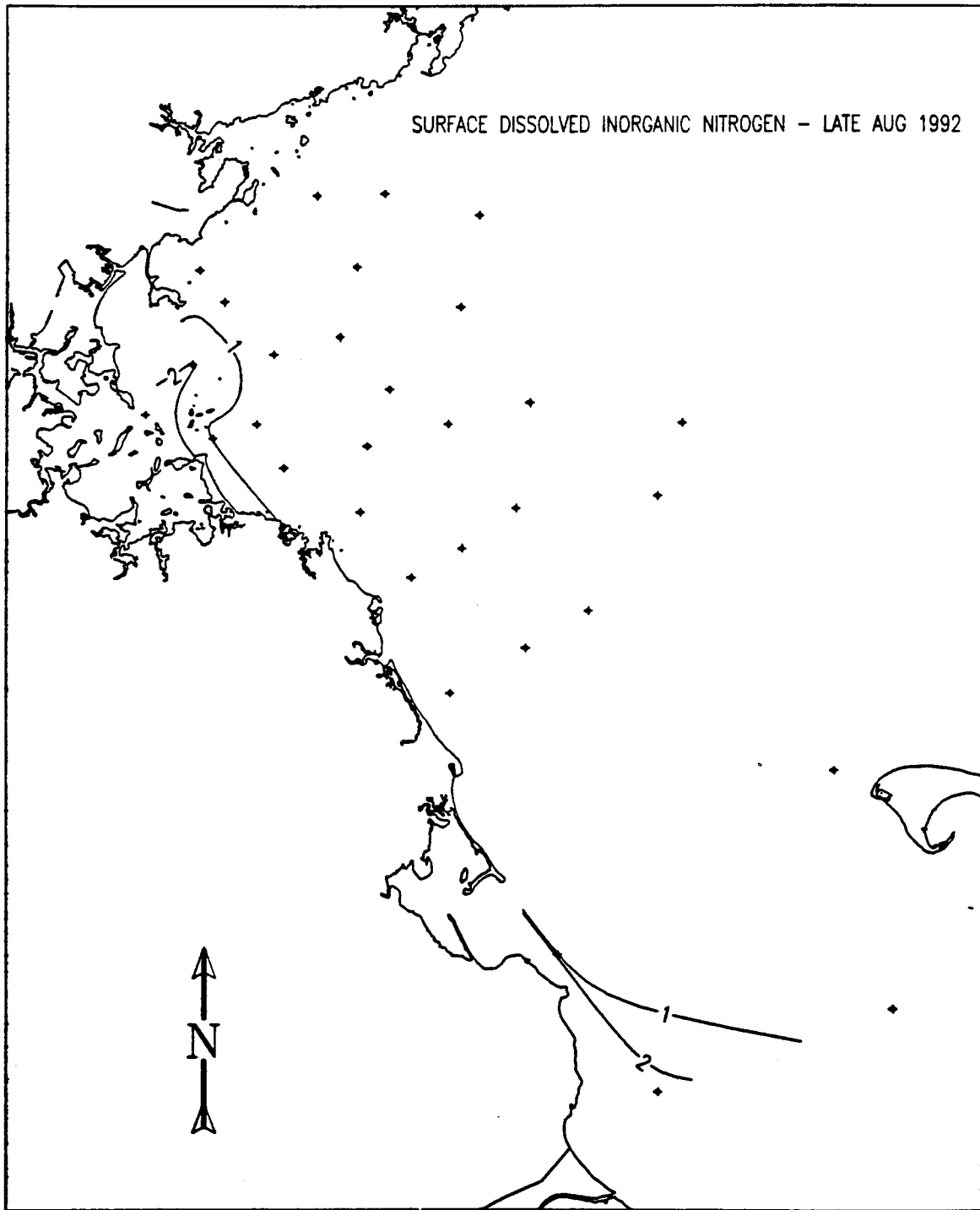
Figure 3-6   Surface dissolved inorganic nitrogen (DIN, μM) in the region in late August 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 μM.
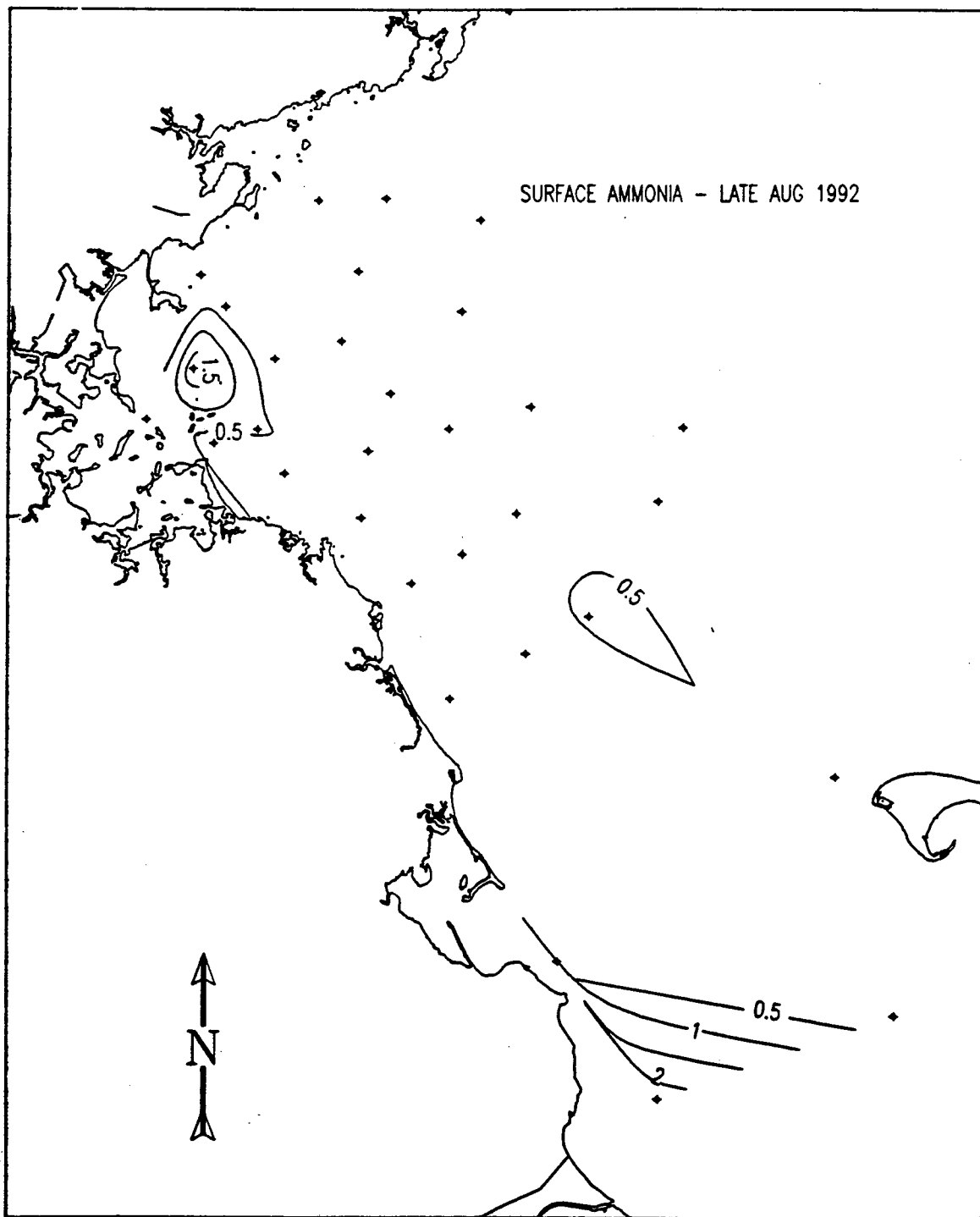
Figure 3-7   Surface ammonia (µM) in the region in late August 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.5 µM.

SURFACE NITRATE – LATE AUG 1992
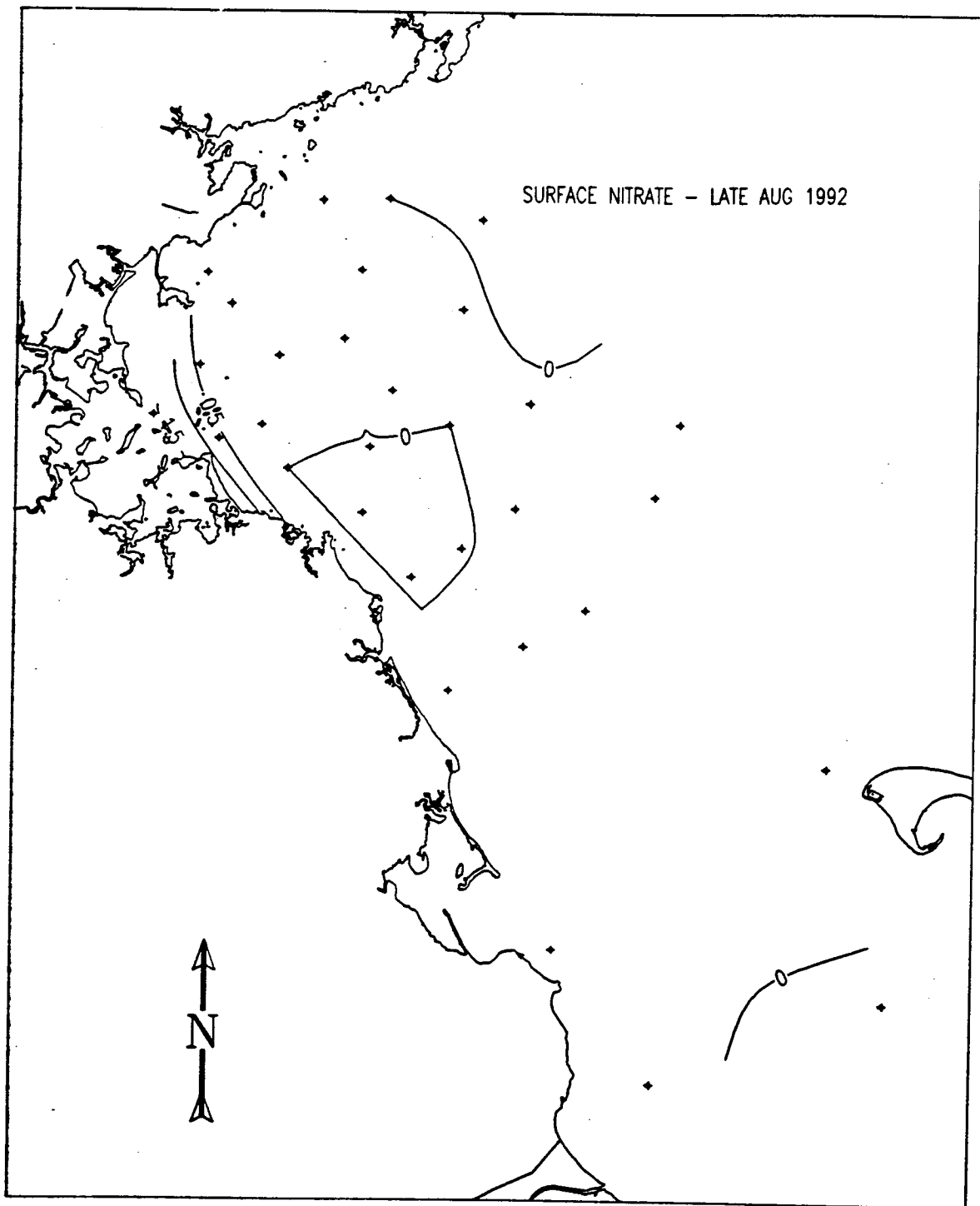
Figure 3-8 Surface nitrate (μM) in the region in late August 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.5 μM.
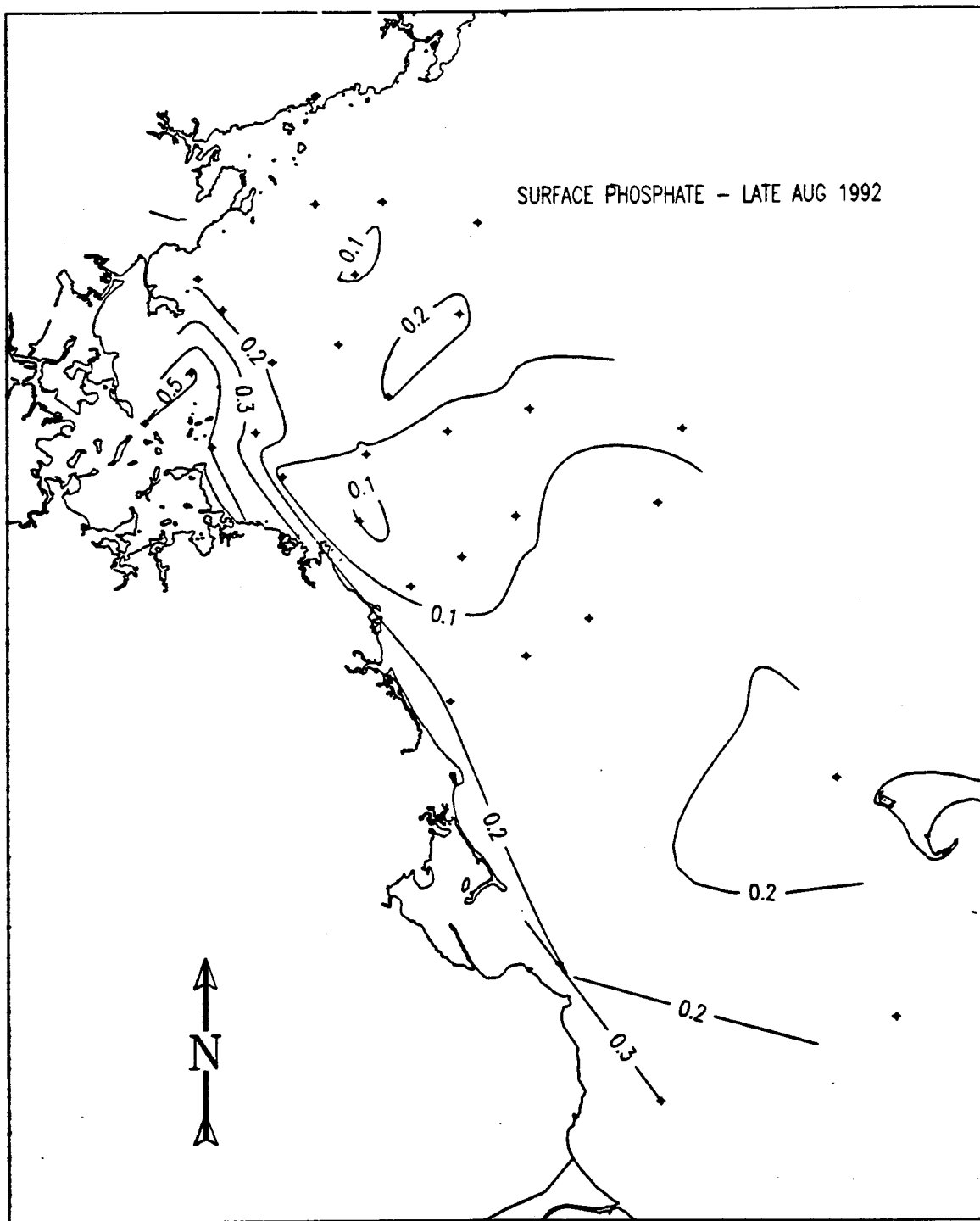
Figure 3-9   Surface phosphate (μM) in the region in late August 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.1 μM.
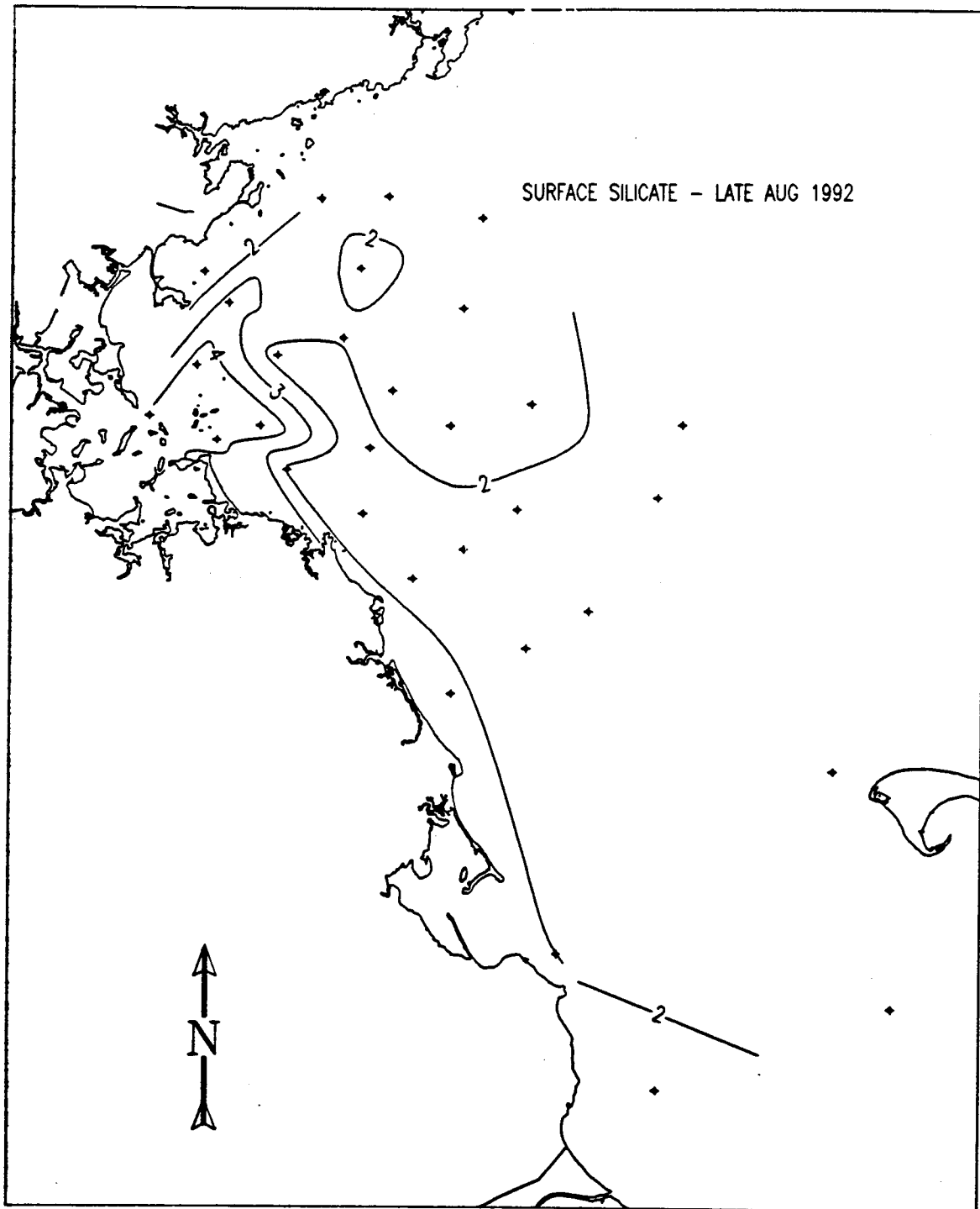
Figure 3-10 Surface silicate (μM) in the region in late August 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 μM.
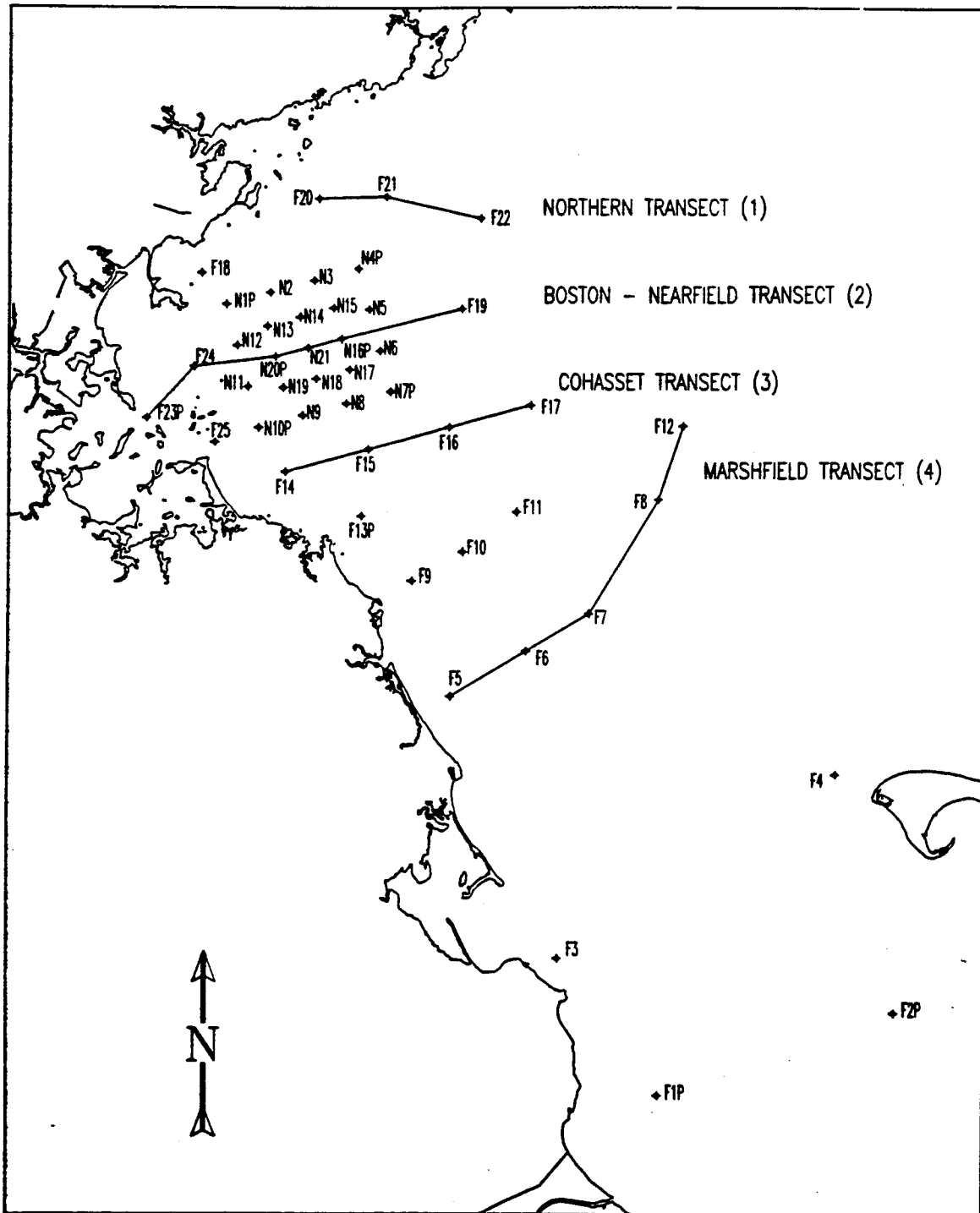
Figure 3-11   Map showing position of four standard transects for which vertical contour plots were produced in following Figures 3-12 to 3-16.

NORTHERN TRANSECT (T051TE)

Minimum = 5.33 Maximum =19.43

BOSTON - NEARFIELD TRANSECT (T052TE)

Minimum = 5.01 Maximum =19.58

COHASSET TRANSECT (T053TE)

Minimum = 4.83 Maximum =18.97

MARSHFIELD TRANSECT (T054TE)

Minimum = 4.29 Maximum =19.14
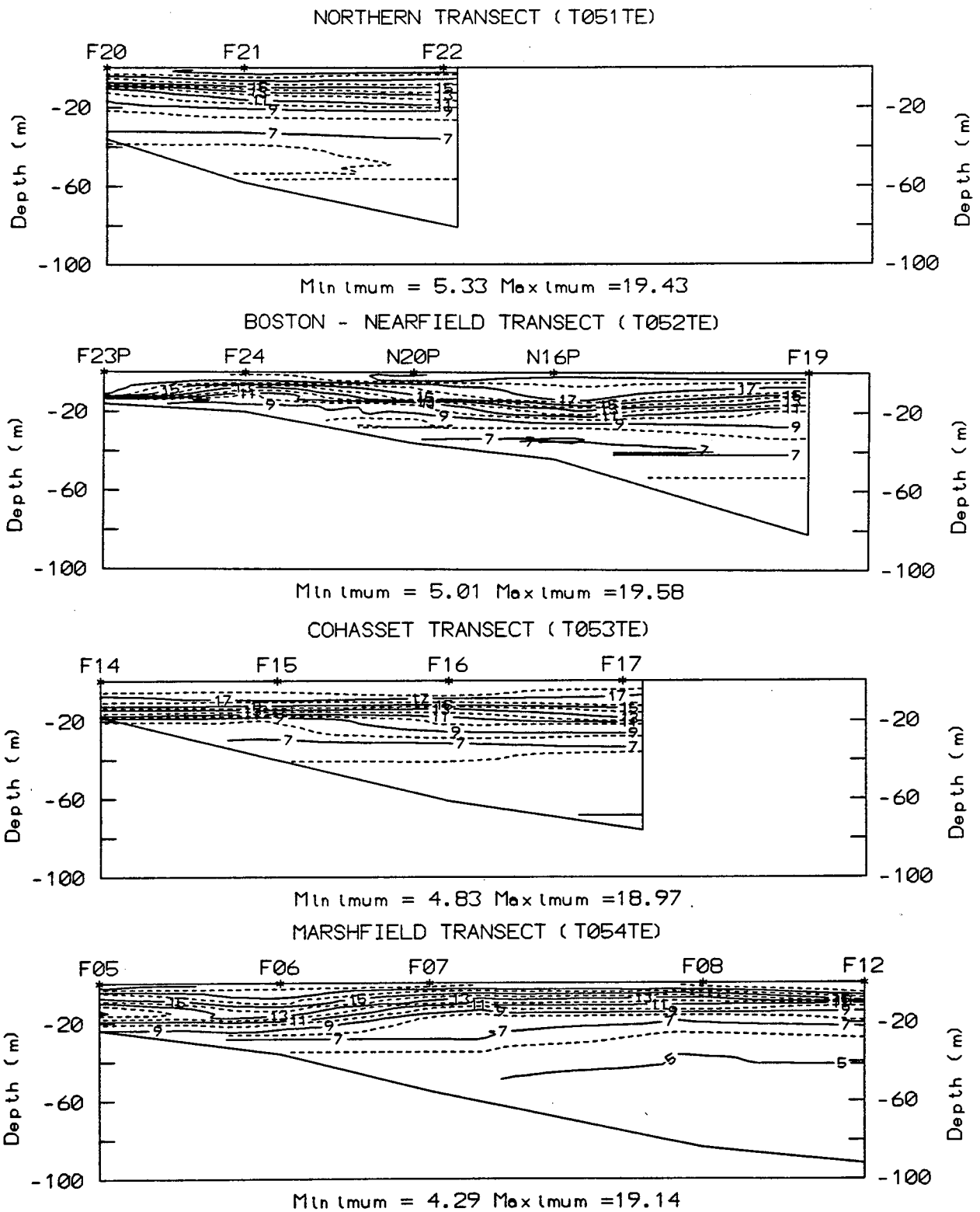
Figure 3-12   Vertical section contours of temperature in late August for standard transects (see Figure 3-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 1.0°C.

NORTHERN TRANSECT (T051SA)

F20   F21   F22

Depth (m)

-20

-60

-100

Minimum =30.60 Maximum =31.88

BOSTON - NEARFIELD TRANSECT (T052SA)

F23P   F24   N20P   N16P   F19

Depth (m)

-20

-60

-100

Minimum =30.41 Maximum =32.41

COHASSET TRANSECT (T053SA)

F14   F15   F16   F17

Depth (m)

-20

-60

-100

Minimum =30.69 Maximum =31.91

MARSHFIELD TRANSECT (T054SA)

F05   F06   F07   F08   F12

Depth (m)

-20

-60

-100

Minimum =30.73 Maximum =31.97
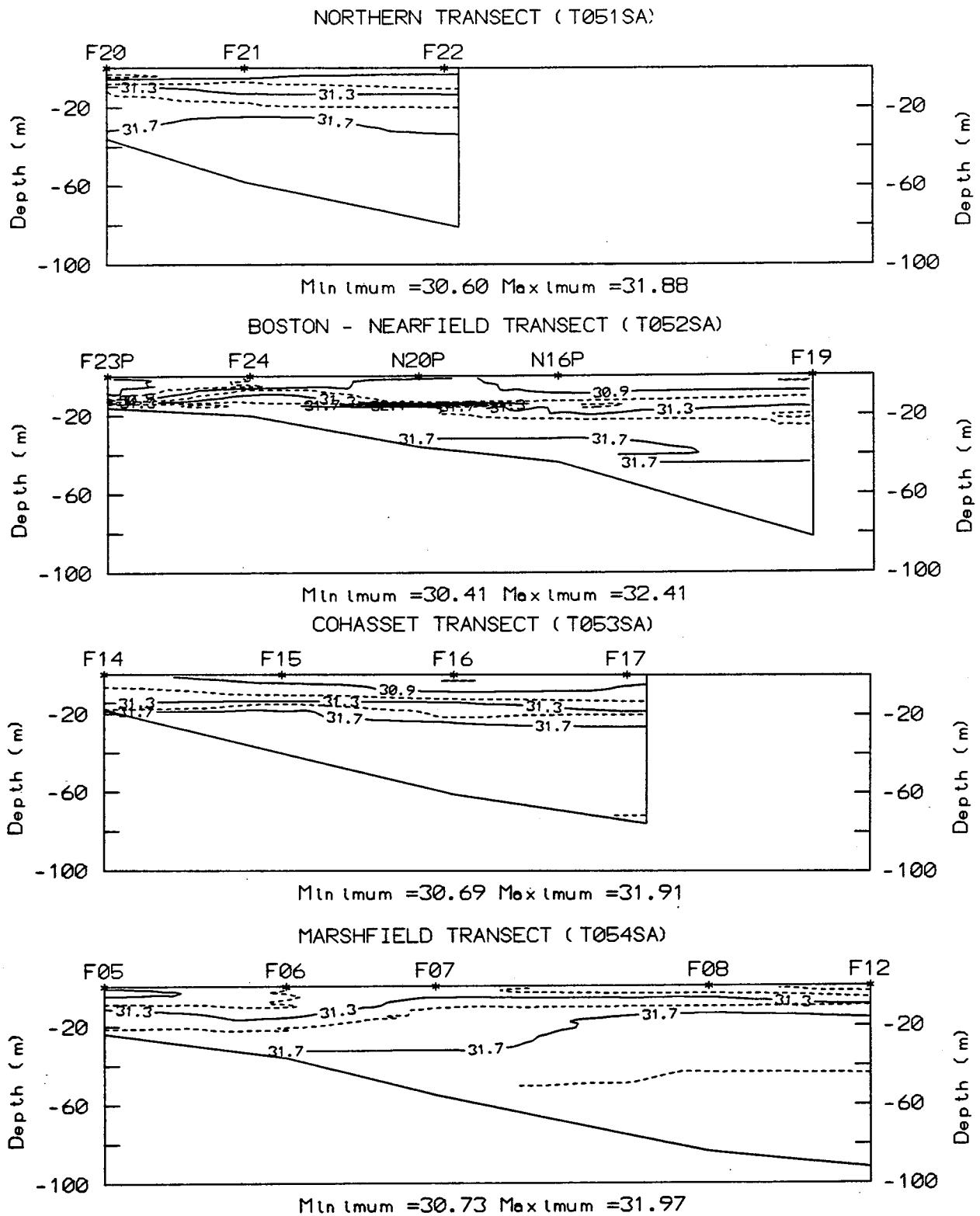
Figure 3-13 Vertical section contours of salinity in late August for standard transects (see Figure 3-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 0.2 PSU.

NORTHERN TRANSECT (T051CH)

Minimum = 0.59 Maximum =10.23

BOSTON - NEARFIELD TRANSECT (T052CH)

Minimum = 0.22 Maximum =10.67

COHASSET TRANSECT (T053CH)

Minimum = 0.67 Maximum = 3.75

MARSHFIELD TRANSECT (T054CH)

Minimum = 0.65 Maximum = 4.96
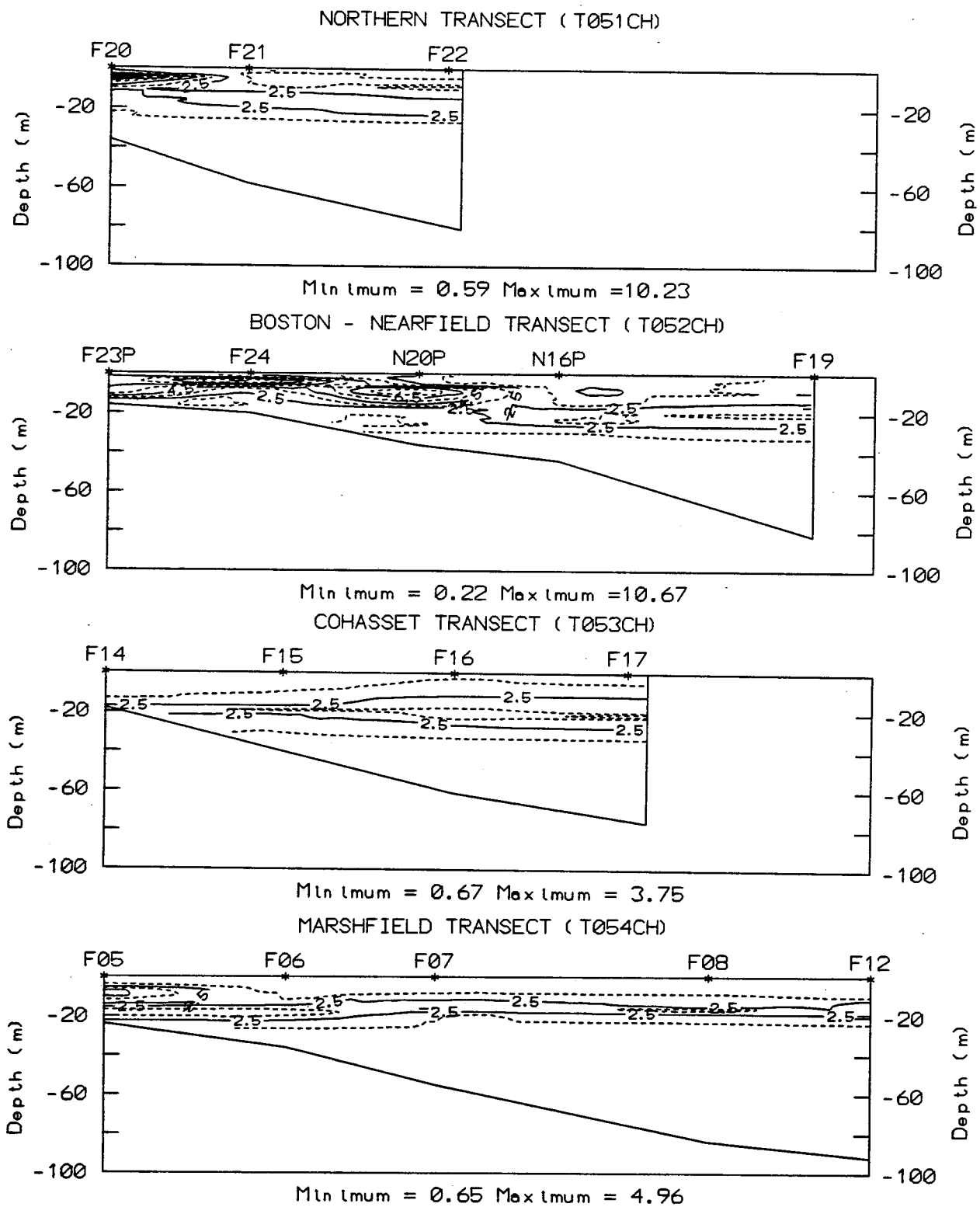
Figure 3-14 Vertical section contours of fluorescence (as μg Chl L^{-1}) in late August for standard transects (see Figure 3-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 1 μg L^{-1}.

NORTHERN TRANSECT (T051IN)

Minimum = 0.02 Maximum = 6.75

BOSTON - NEARFIELD TRANSECT (T052IN)

Minimum = 0.19 Maximum = 4.04

COHASSET TRANSECT (T053IN)

Minimum = 0.04 Maximum = 8.90

MARSHFIELD TRANSECT (T054IN)

Minimum = 0.16 Maximum = 10.64
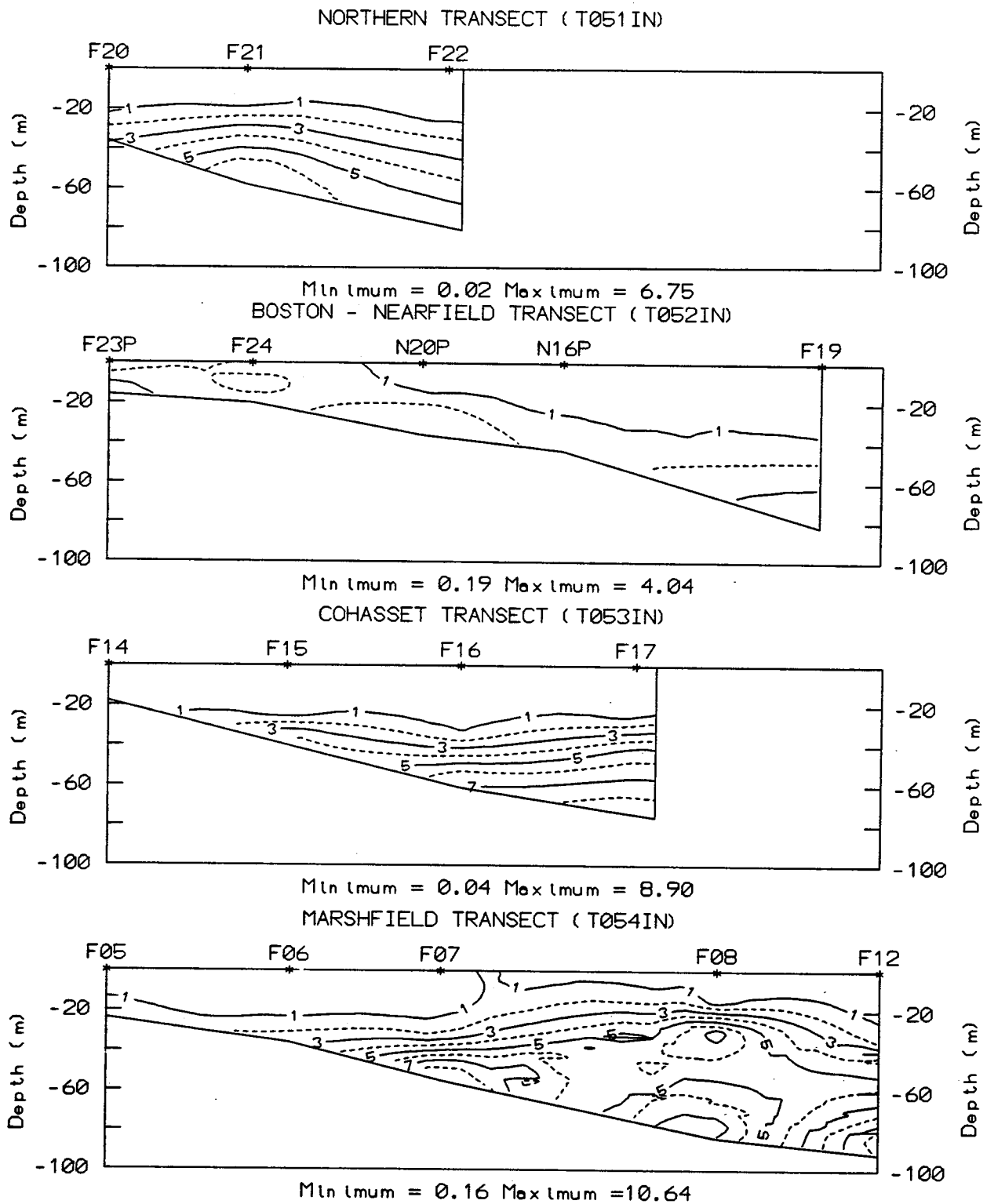
Figure 3-15   Vertical section contours of dissolved inorganic nitrogen (μM) in late August for standard transects (see Figure 3-11). The data used to produce contours are from discrete bottle samples as given in Appendix A. The contour interval is 1μM.

Minimum = 2.16 Maximum = 9.21

BOSTON - NEARFIELD TRANSECT (T052SO)

Minimum = 1.43 Maximum = 9.26

COHASSET TRANSECT (T053SO)

Minimum = 1.39 Maximum = 8.88

MARSHFIELD TRANSECT (T054SO)

Minimum = 1.18 Maximum =14.89
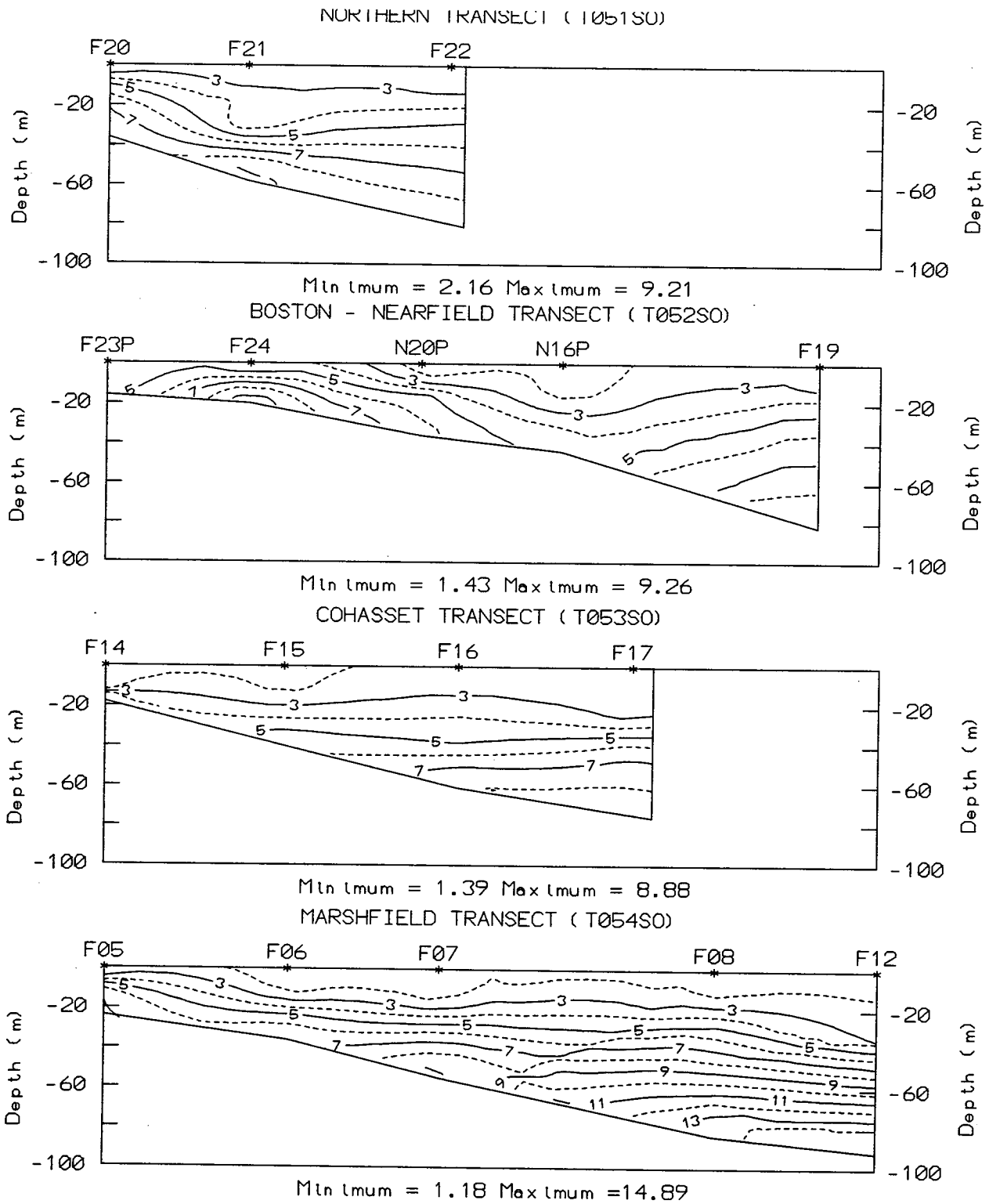
Figure 3-16 Vertical section contours of silicate (μM) in late August for standard transects (see Figure 3-11). The data used to produce contours are from discrete bottle samples as given in Appendix A. The contour interval is 1μM.
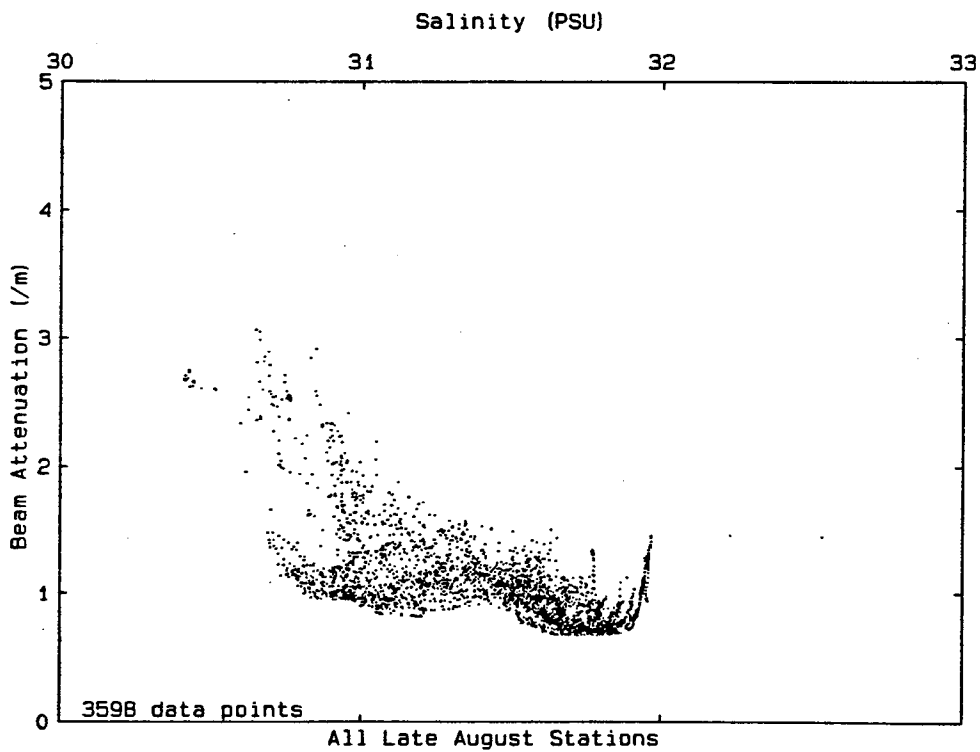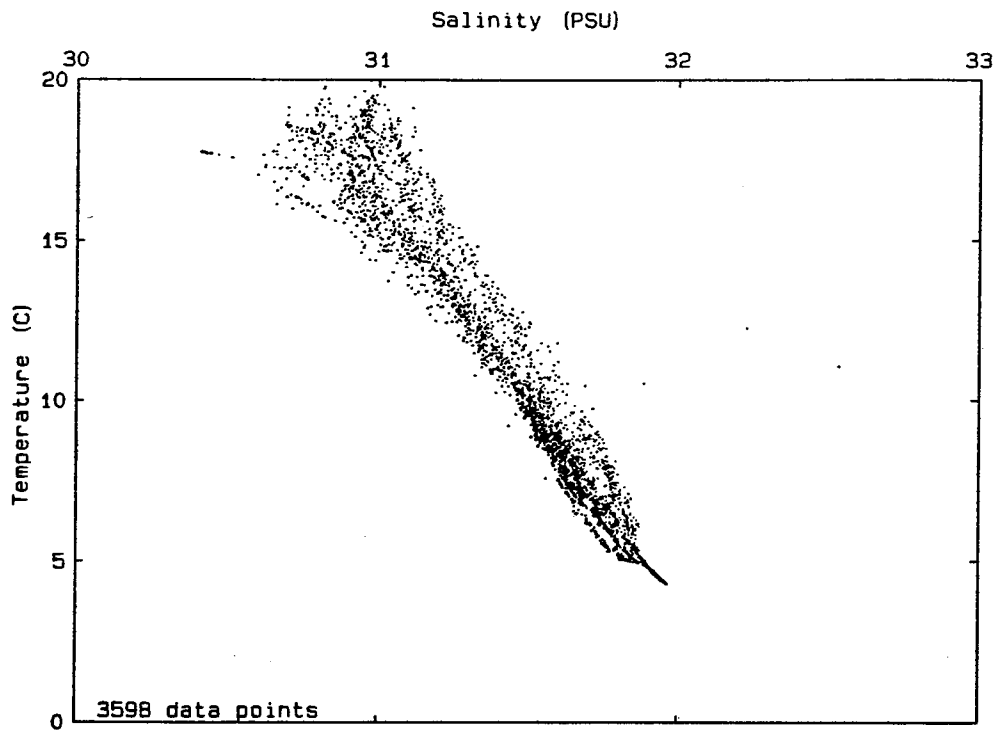
Figure 3-17a Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in late August 1992. Individual station cast plots that were used to produce this composite are in Appendix C.
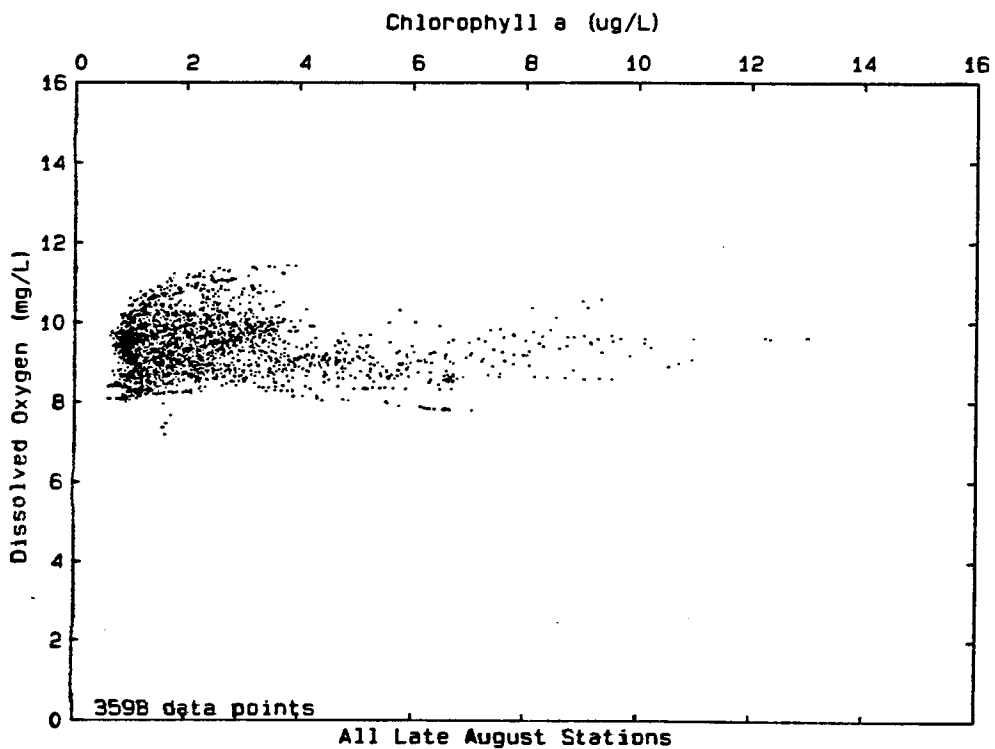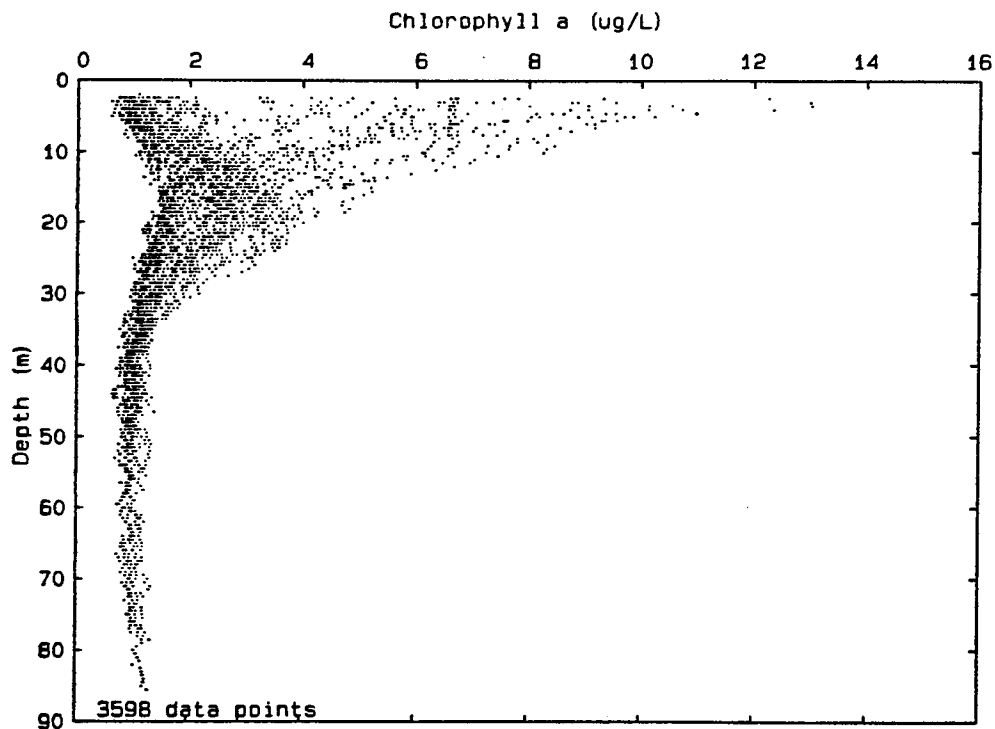
Figure 3-17b Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in late August 1992. Individual station cast plots that were used to produce this composite are in Appendix C. Chlorophyll was estimated from fluorescence and DO was calibrated with titrations (see Appendix A).

Chlorophyll a (ug/L)

Chlorophyll a (ug/L)
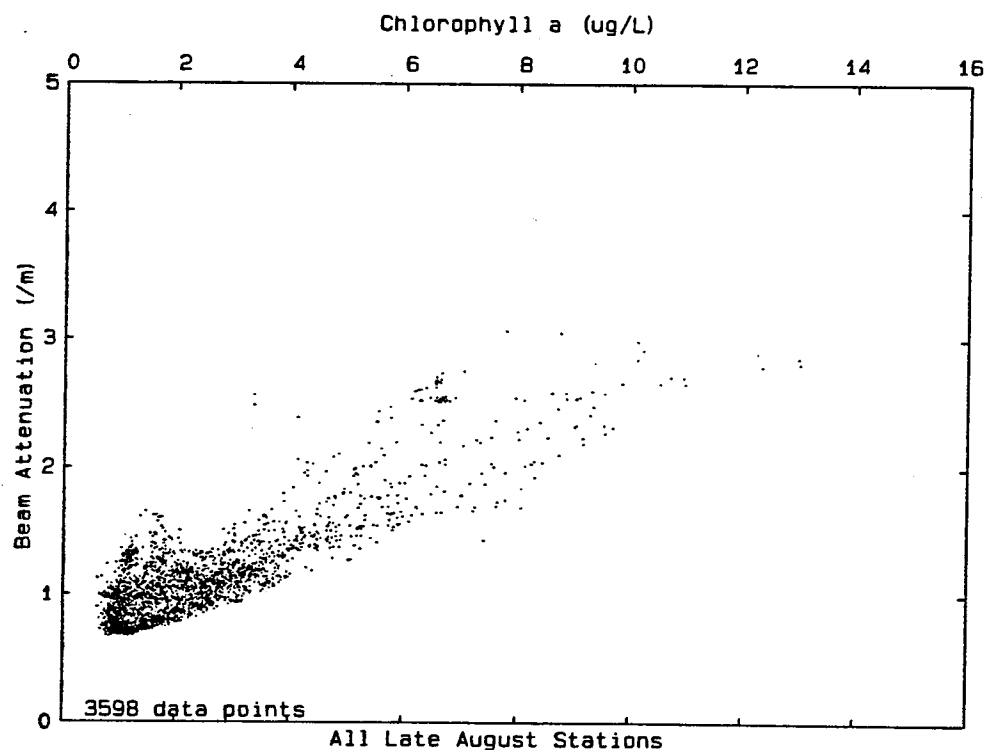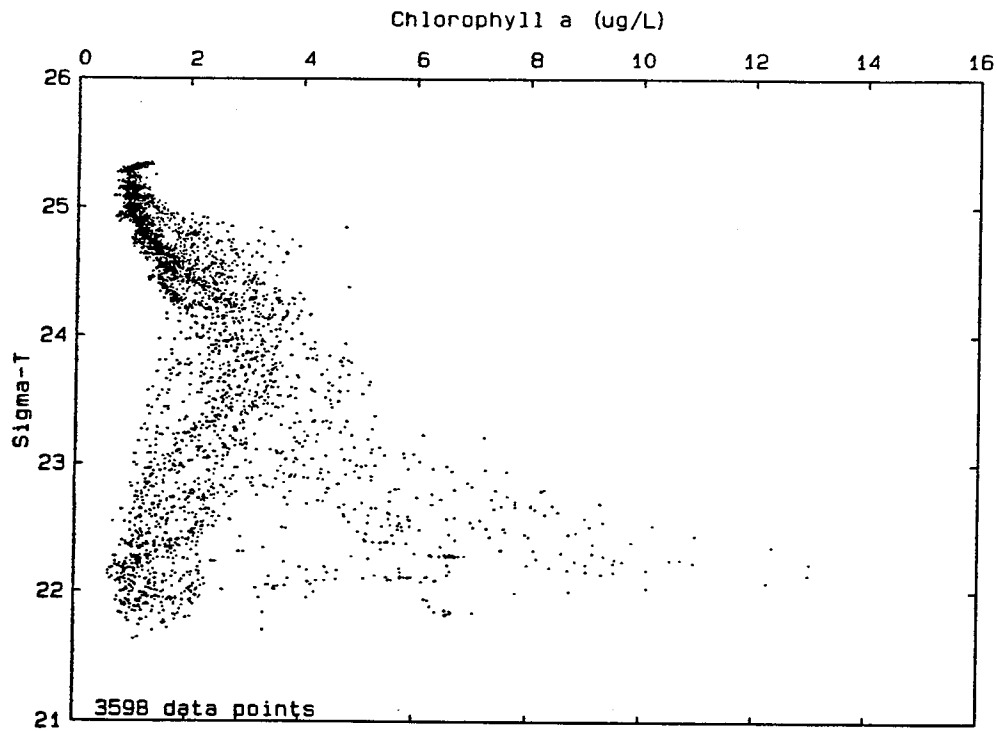
All Late August Stations

Figure 3-17c Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in late August 1992. Individual station cast plots that were used to produce this composite are in Appendix C. Chlorophyll was estimated from fluorescence (see Appendix A).
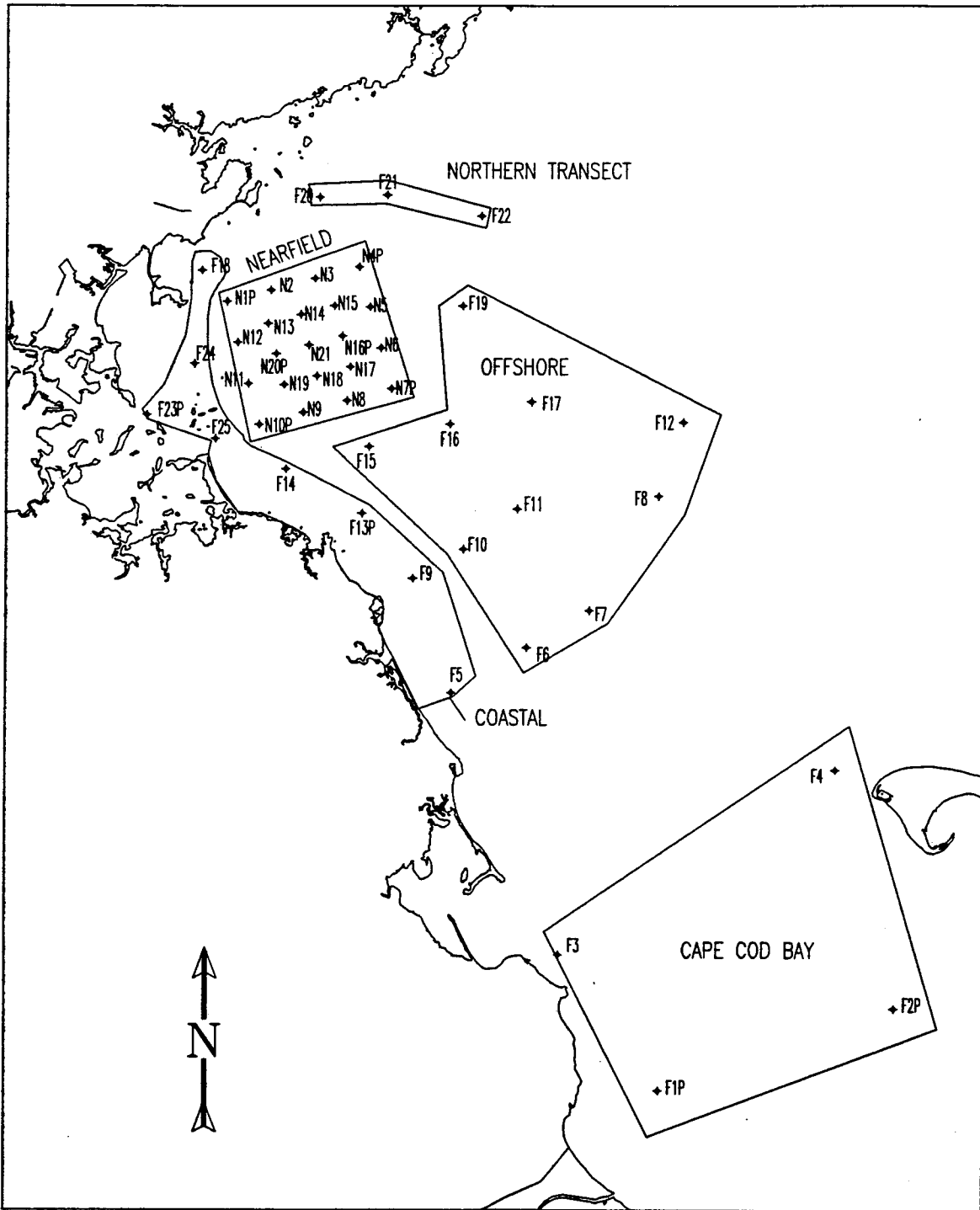
Figure 3-18 Map to show station groups designated in Figures 3-19 through 3-25. Massachusetts Bay was separated into 4 groups based on water depth and geographic position.

DIN vs. PO4
Late August

NO3 vs. PO4
Late August

■ Coastal   □ Northern Transect   ▲ Nearfield
✳ Offshore   ＋ Cape Cod Bay
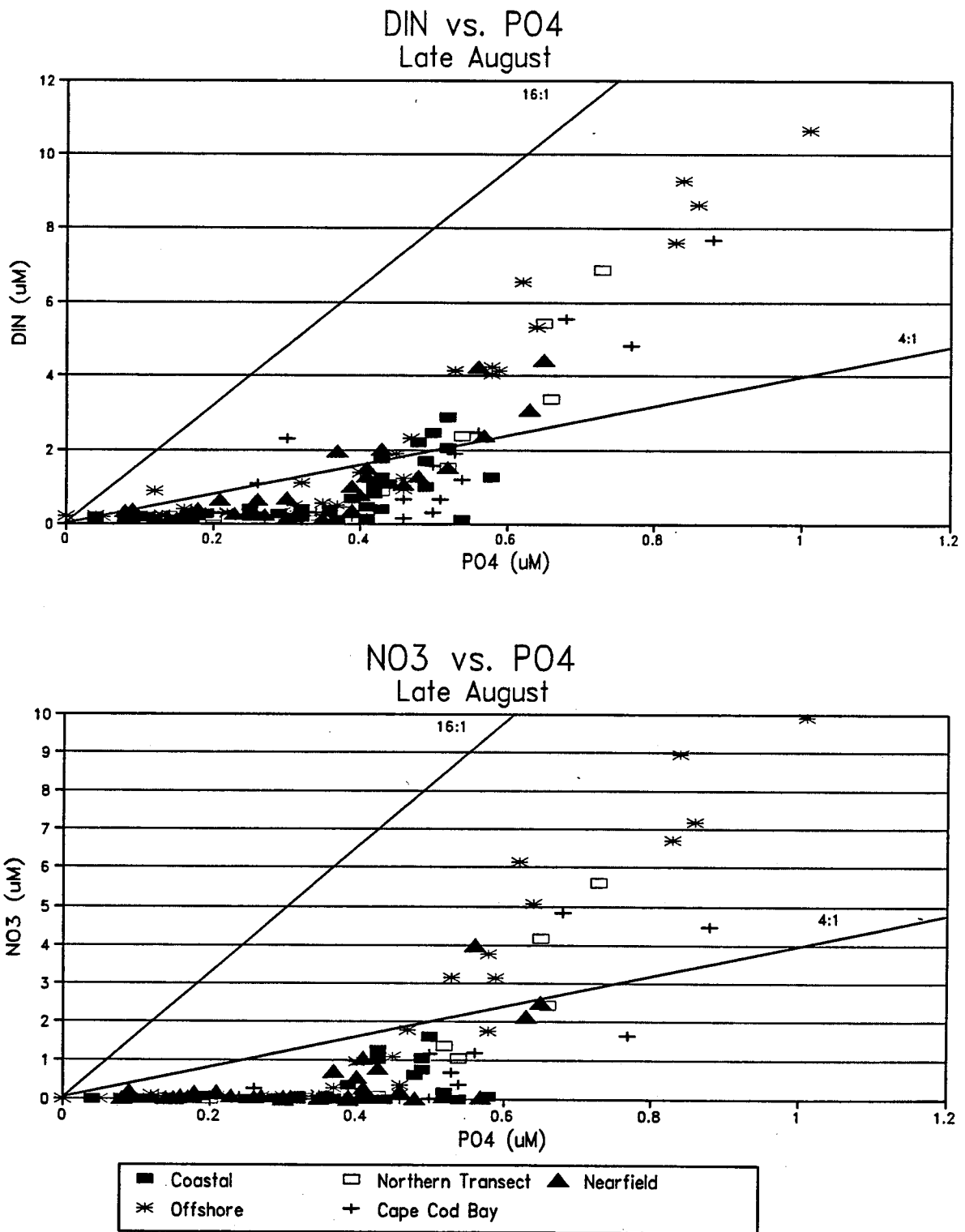
Figure 3-19a   Scatter plots of nitrogen forms vs. phosphate during late August 1992. All stations and depths are included, and data are given in Appendix A. Lines show constant proportions of nitrogen relative to phosphorus across a range of N:P ratios.

DIN vs. SiO4
Late August

N03 vs. SiO4
Late August

Legend:
- ■ Coastal
- □ Northern Transect
- ▲ Nearfield
- ✳ Offshore
- + Cape Cod Bay
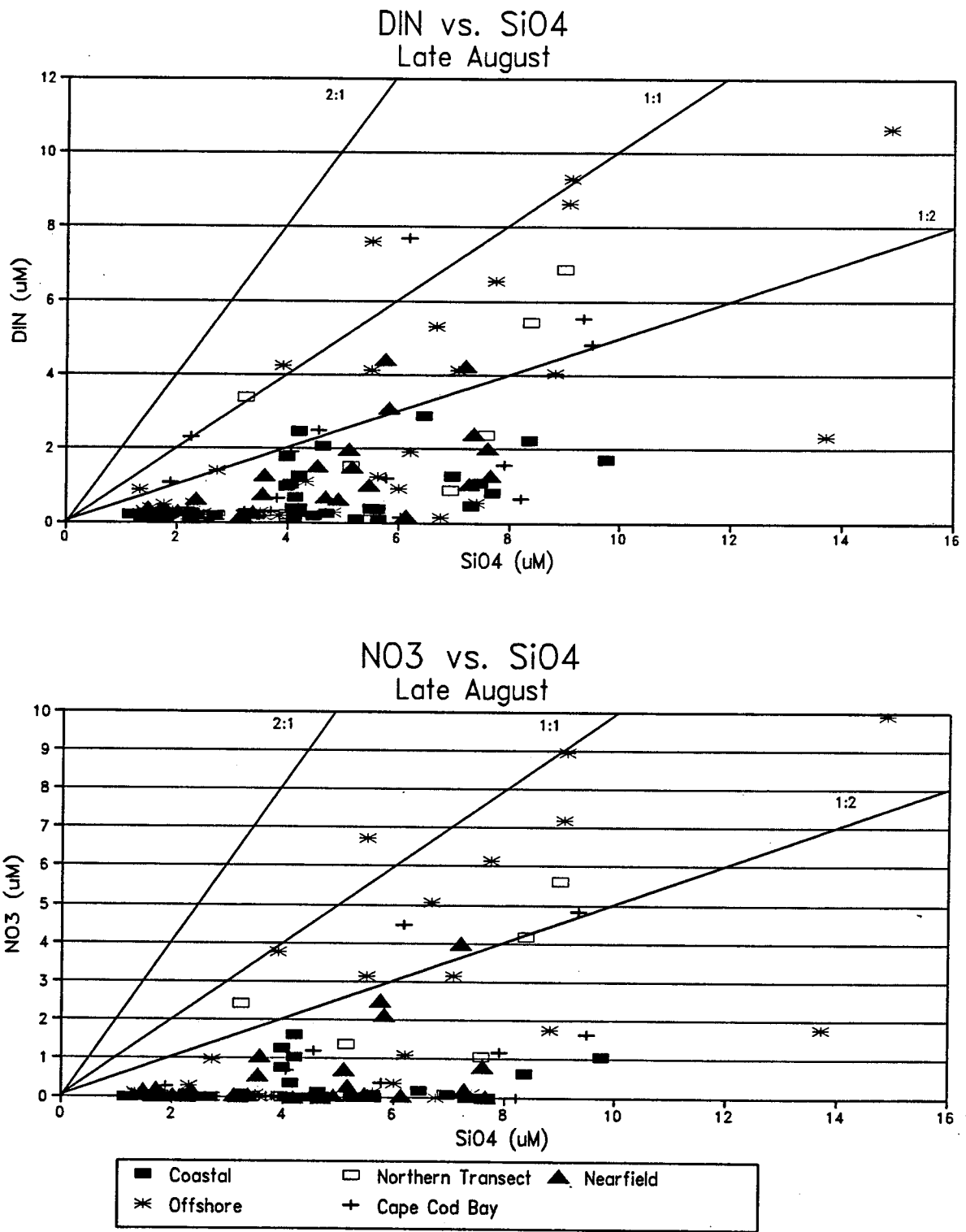
Figure 3-19b Scatter plots of nitrogen vs. silicate during late August 1992. All stations and depths are included, and data are given in Appendix A. Lines show constant proportions of nitrogen relative to silicate across a range of N:Si ratios.

DIN vs. Salinity
Late August
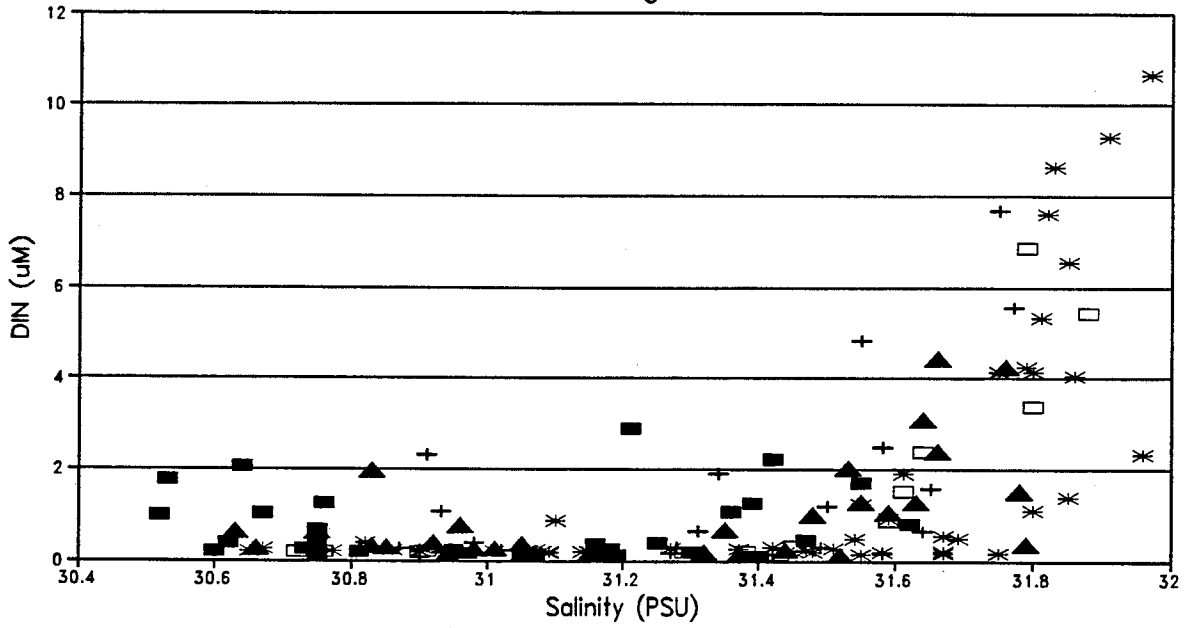
DIN vs. Sigma-T
Late August
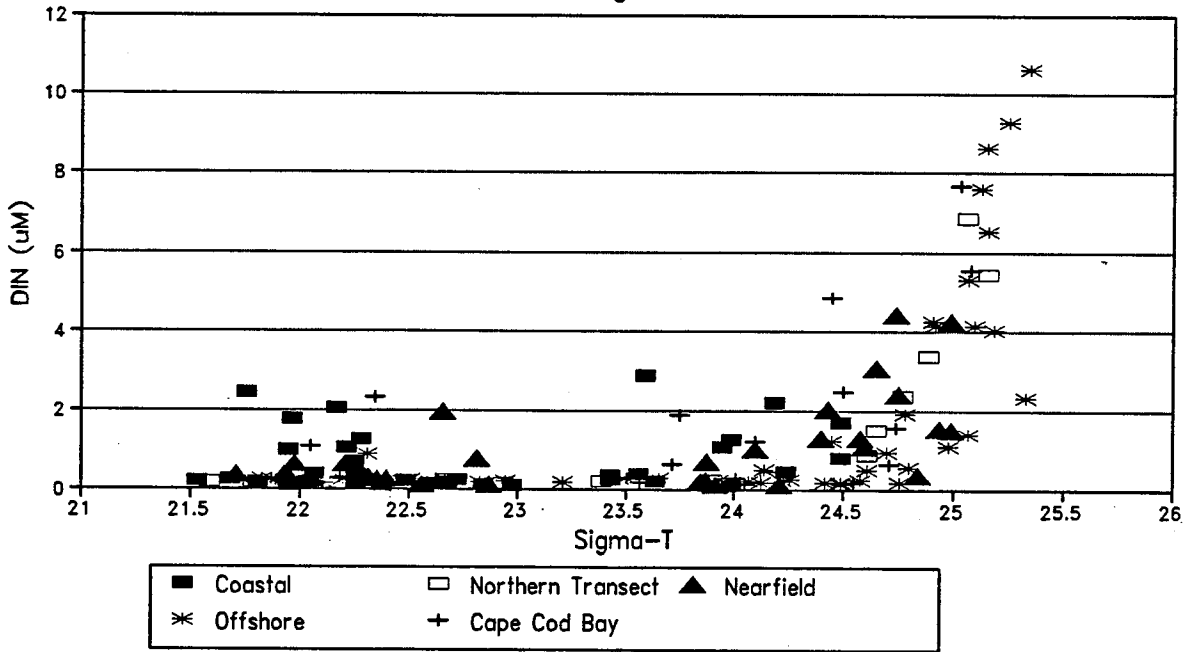
Figure 3-20 Dissolved inorganic nitrogen vs. salinity and σ_T in late August 1992. All stations and depths are included, and data are given in Appendix A.

NH4 vs. Salinity
Late August
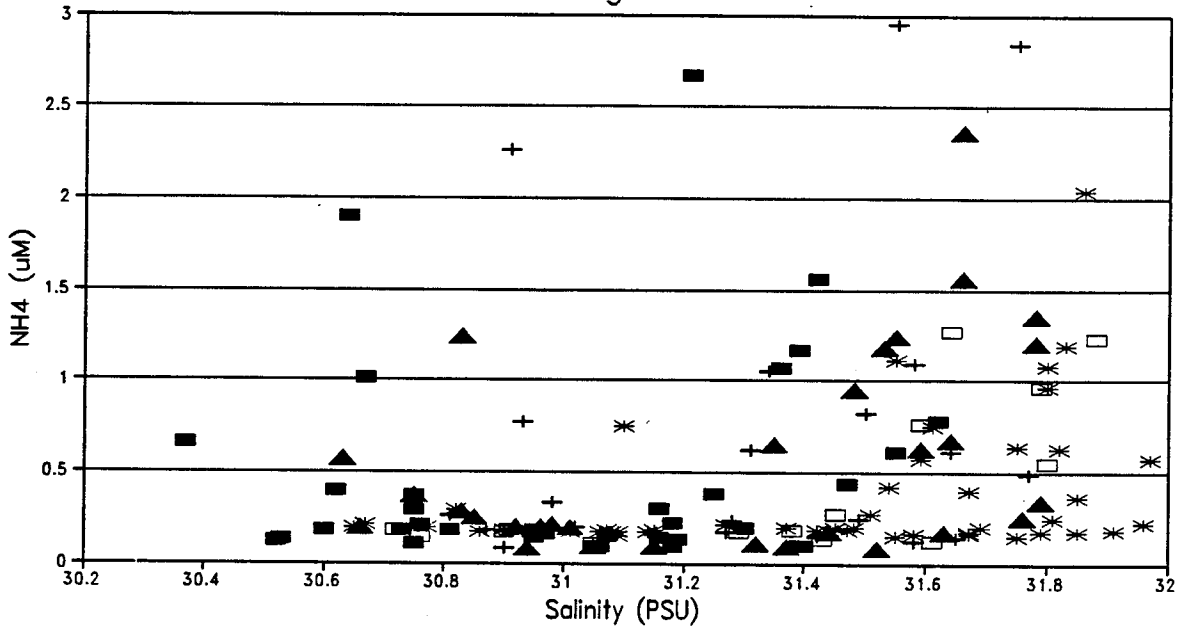
NH4 vs. Sigma-T
Late August
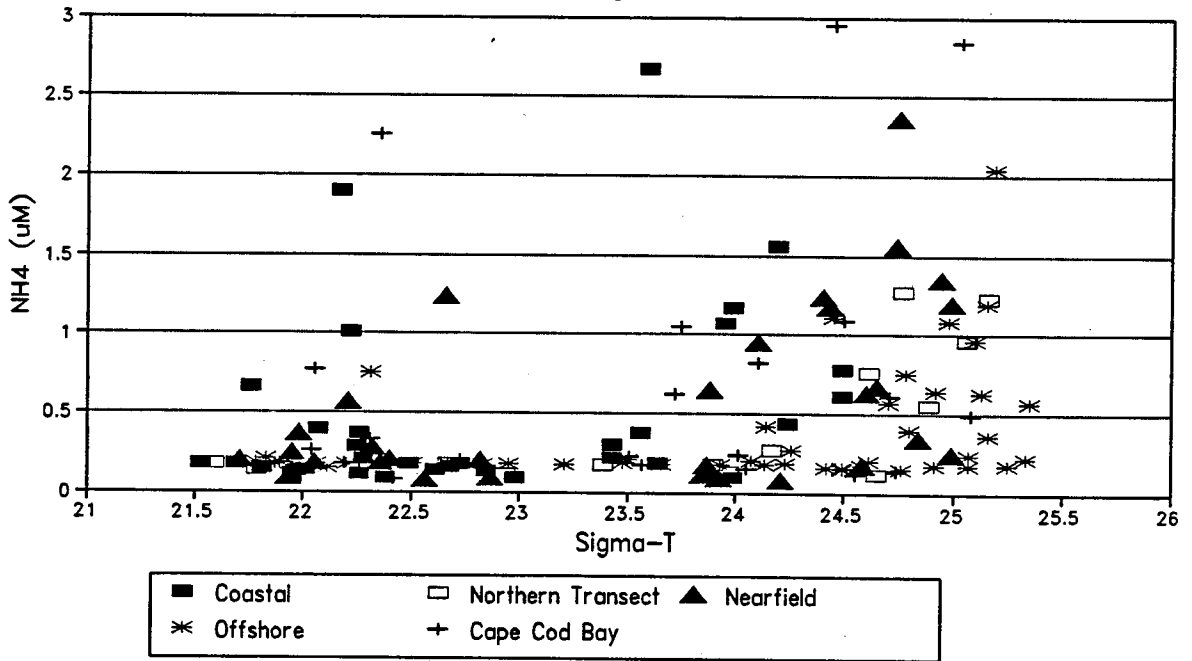
Figure 3-21 Ammonia vs. salinity and σ_T in late August 1992. All stations and depths are included, and data are given in Appendix A.

PO4 vs. Salinity
Late August
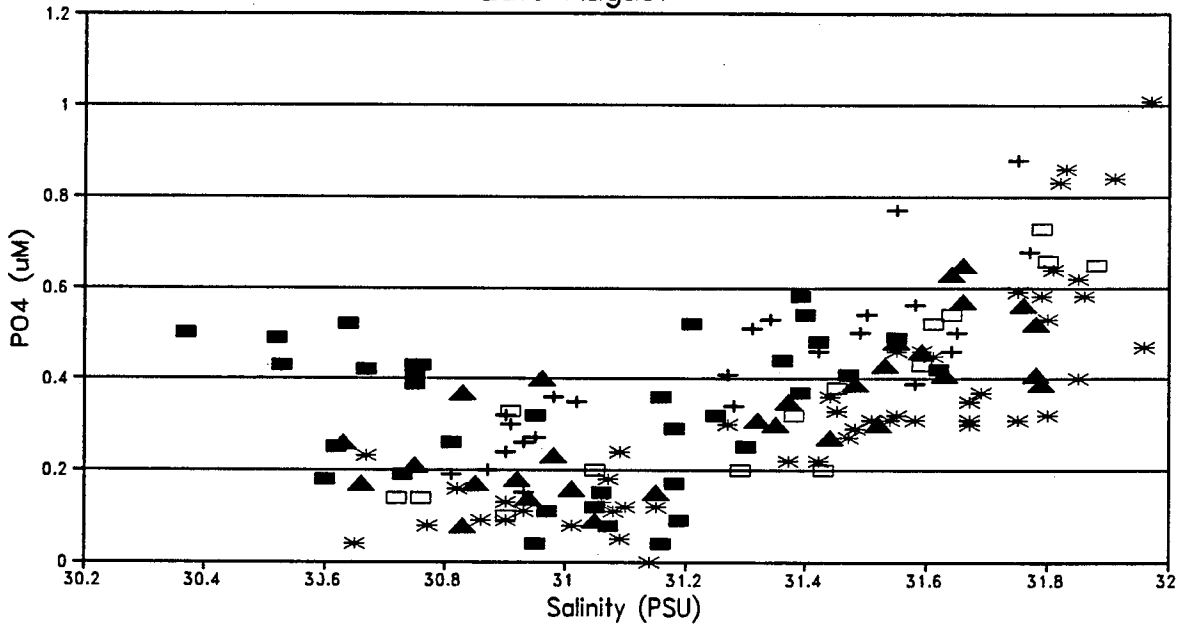
PO4 vs. Sigma-T
Late August

■ Coastal	□ Northern Transect	▲ Nearfield
✳ Offshore	+ Cape Cod Bay	
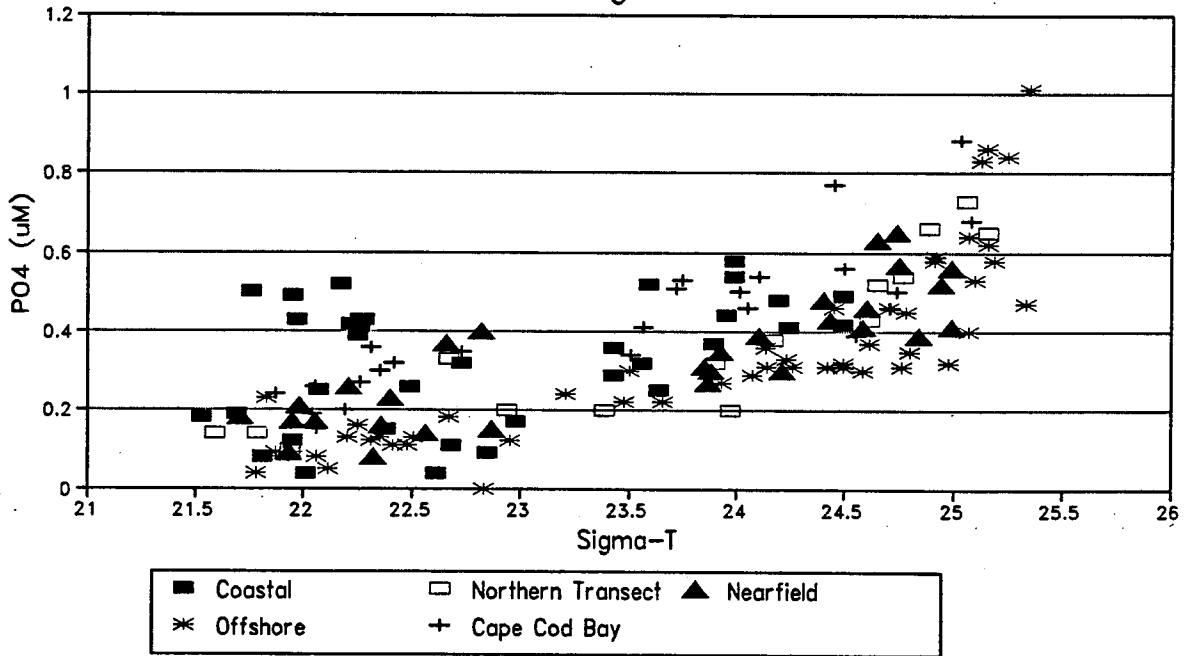
Figure 3-22 Phosphate vs. salinity and σ_T in late August 1992. All stations and depths are included, and data are given in Appendix A.
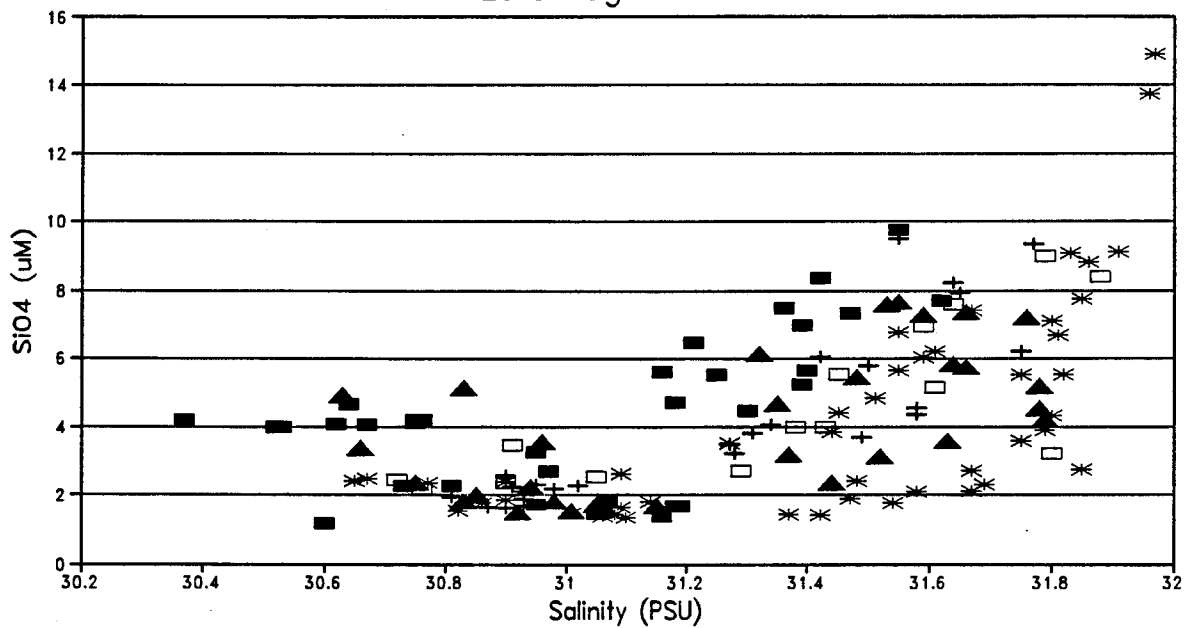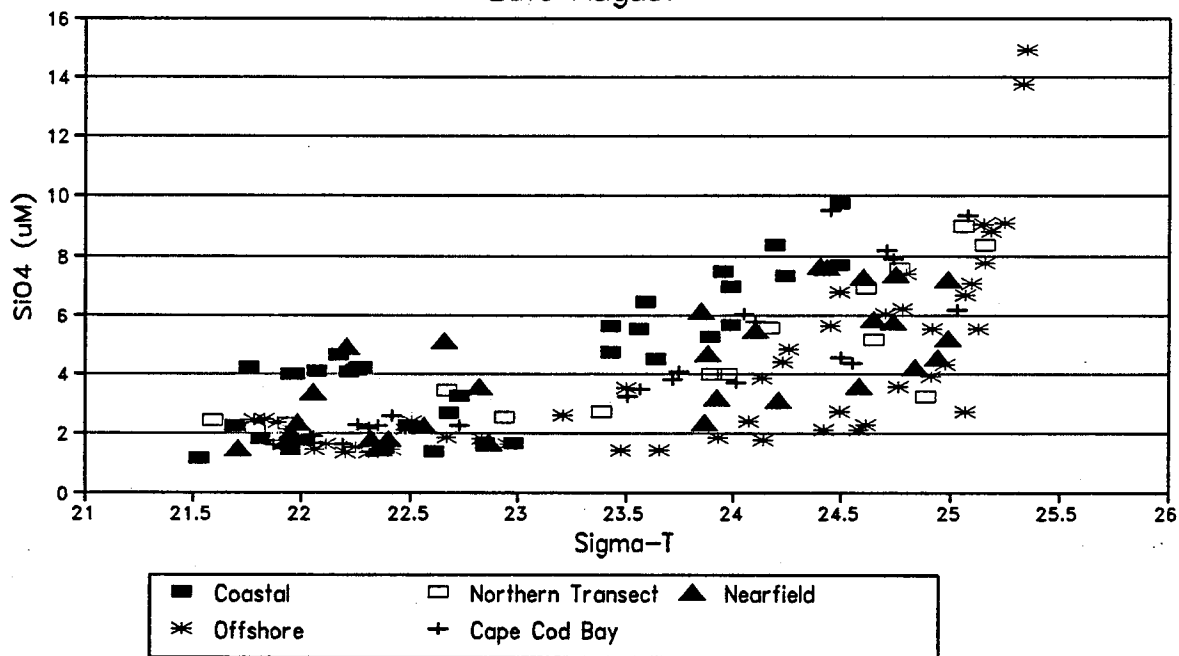
Figure 3-23 Silicate vs. salinity and σ_T in late August 1992. All stations and depths are included, and data are given in Appendix A.
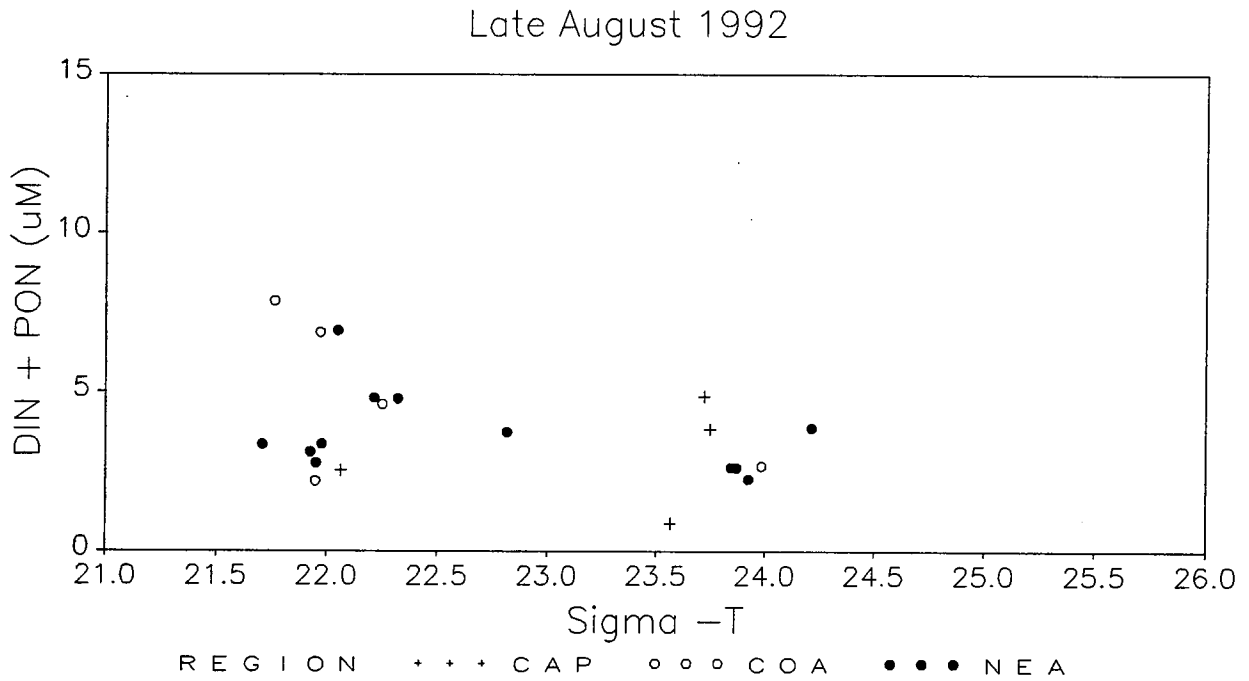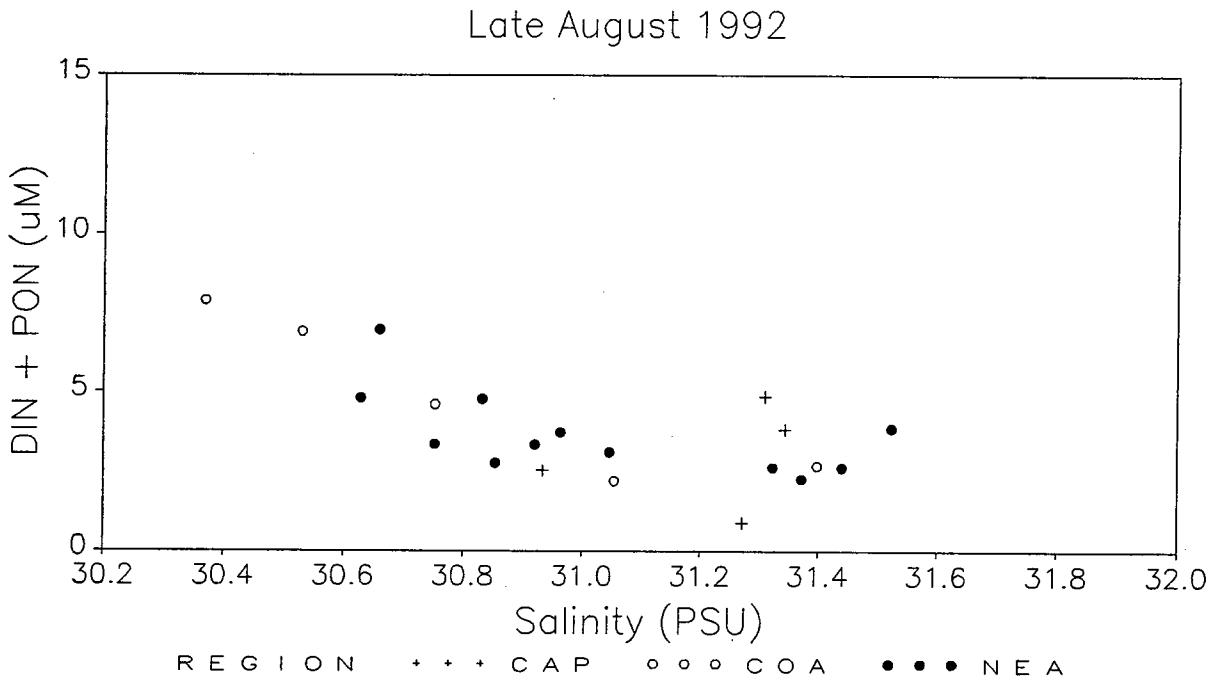
Figure 3-24 The sum of dissolved inorganic nitrogen and particulate organic nitrogen vs. salinity and σ_T in late August 1992. Data are from BioProductivity stations and special station F25 and are given in Appendix A. Note that the symbols for different regions are slightly different from Figures 3-19 to 3-23.

Late August 1992

REGION   + + + C A P   o o o C O A   ● ● ● N E A

Late August 1992

REGION   + + + C A P   o o o C O A   ● ● ● N E A
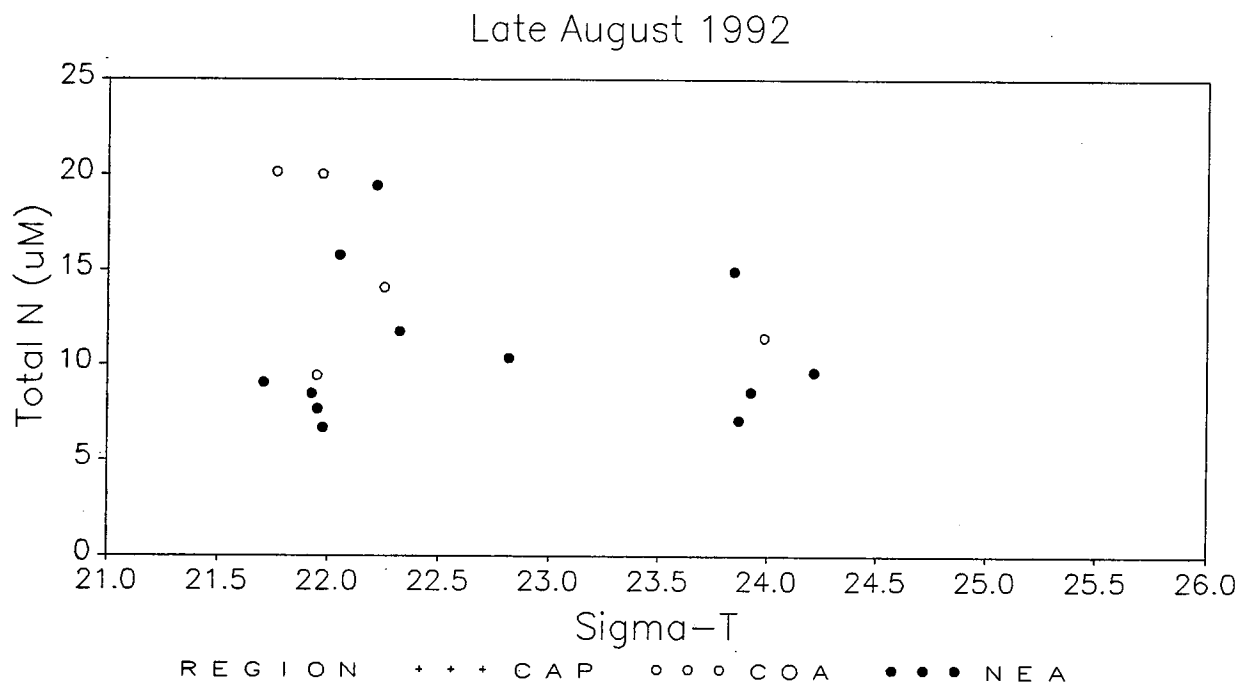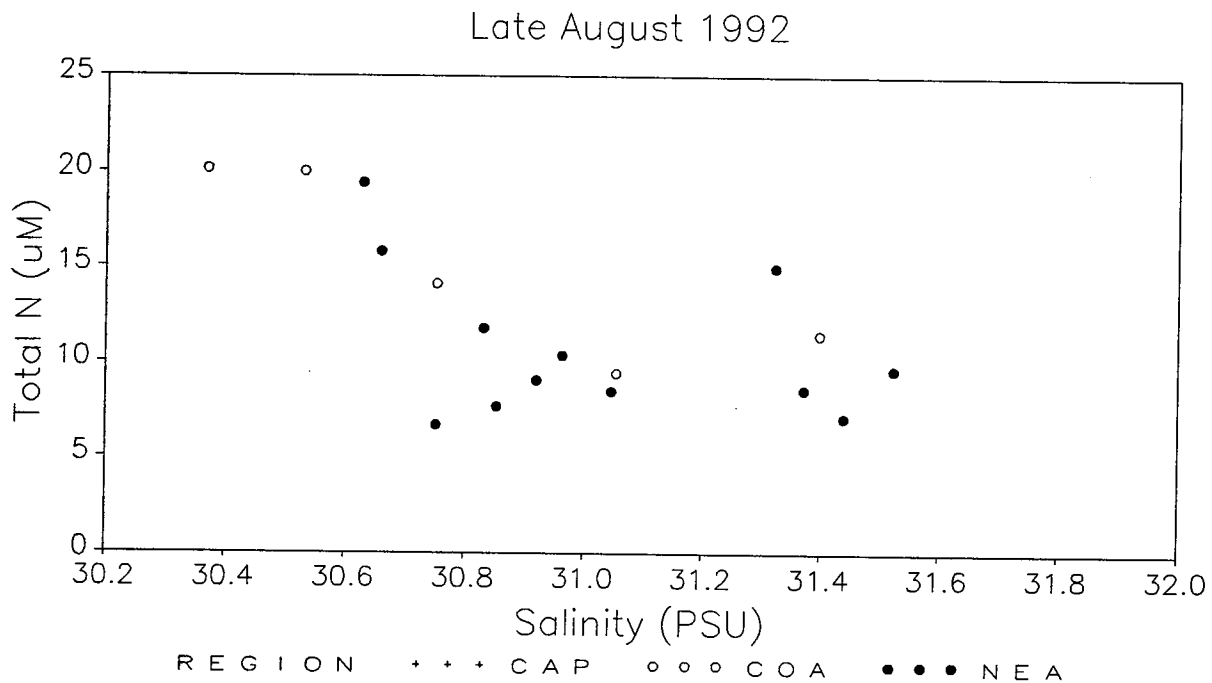
Figure 3-25   The sum of total dissolved nitrogen and particulate organic nitrogen (=total nitrogen) vs. salinity and σ_T in late August 1992. Data are from BioProductivity stations and special station F25 and are given in Appendix A. Groups are the same as given in Figure 3-18. Note that the symbols for different regions are slightly different from Figure 3-19 to 3-23. Total N was not estimated at some stations because both TDN and PON concentrations were not available (Appendix A).
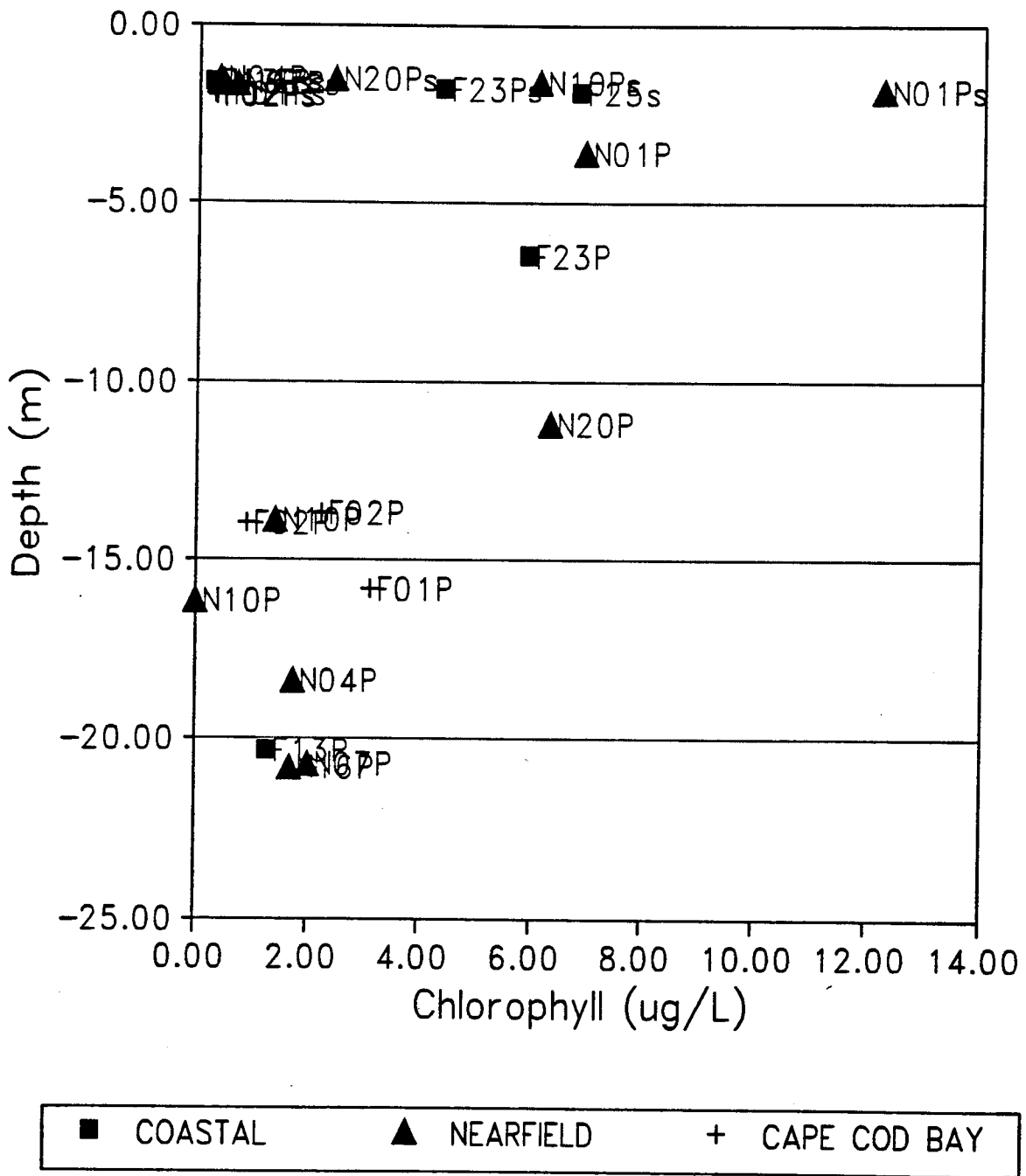
Figure 3-26 Surface and deeper chlorophyll at BioProductivity stations and special station F25 as a function of depth in late August 1992.
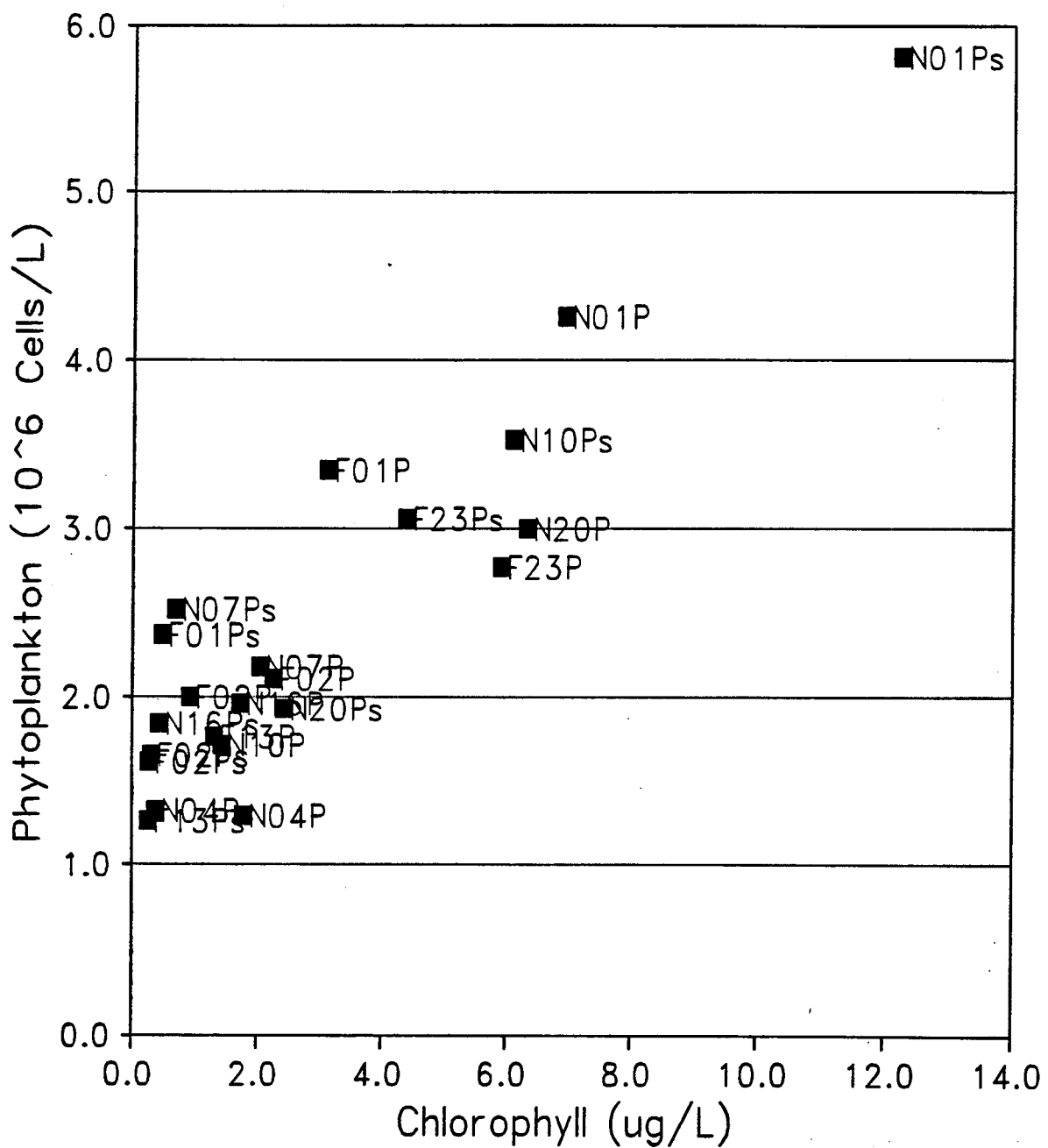
Figure 3-27 Total phytoplankton abundance vs. extracted chlorophyll at BioProductivity stations in late August 1992. Data are given in Appendices A and F.

Phytoplankton – Late August 92
(Surface Sample)

Millions of Cells per Liter

Station

Cast 1

Cast 2

Diatoms Dinoflag Microflag Others
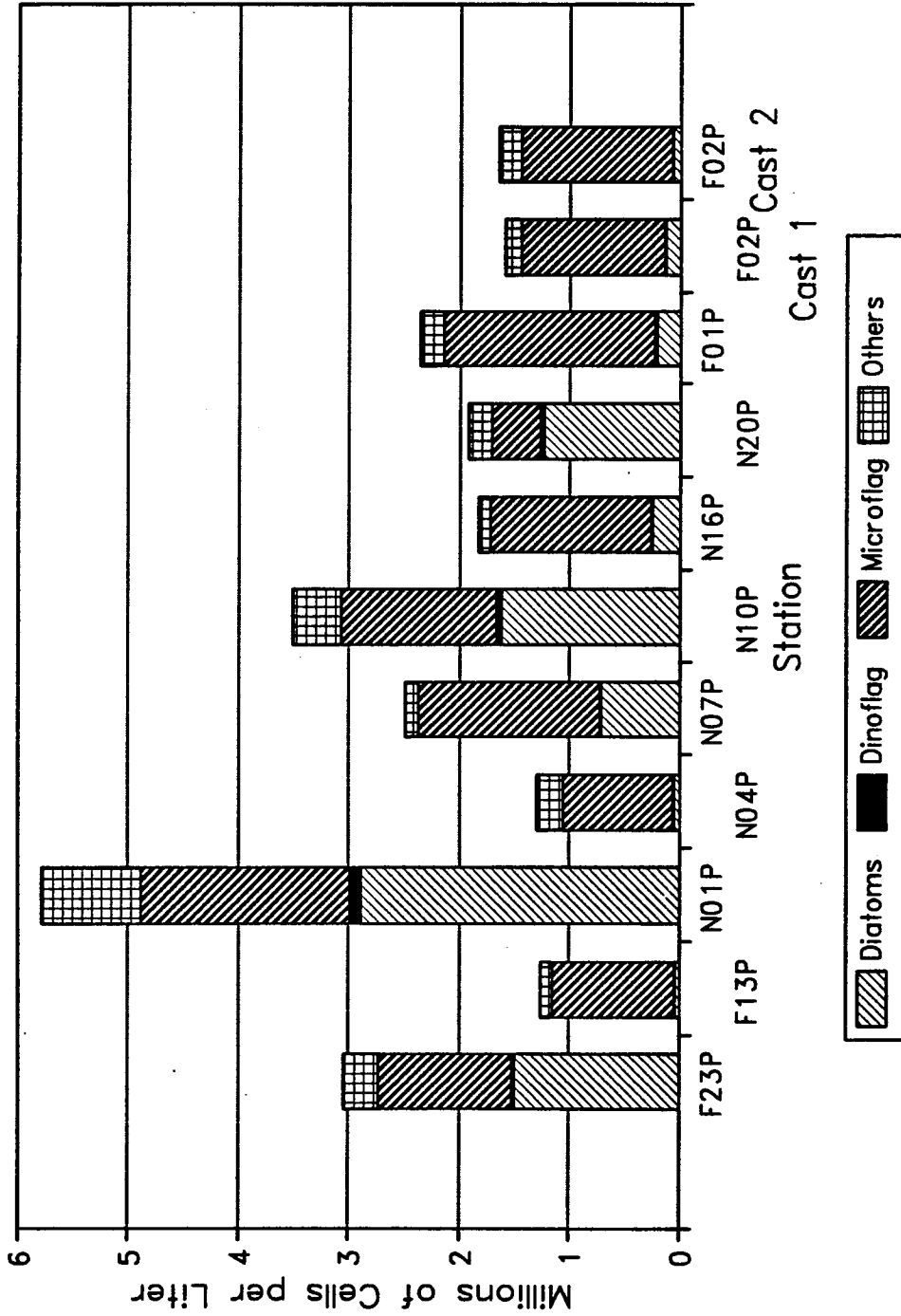
Figure 3-28 Total phytoplankton abundance, by taxonomic groups, at BioProductivity stations in late August 1992. Data are given in Appendix F.

PHYTOPLANKTON SPECIES ABUNDANCE
STATION NO4P — LATE AUGUST 92
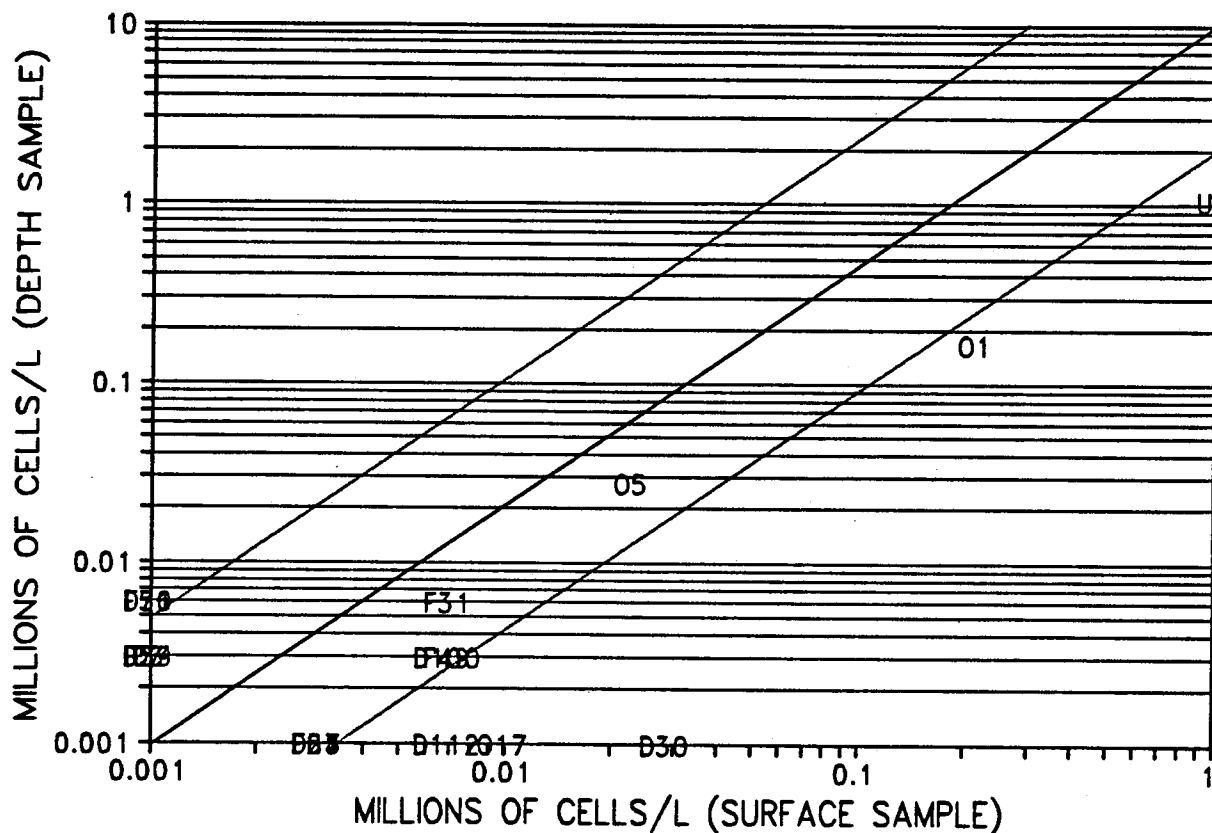
Figure 3-29   Comparison of phytoplankton taxonomic composition of surface and deeper
samples at station N4P in late August 1992. Full species codes are given in
Appendix F, but the alphabetical prefix indicates the following: D= diatom, F=
dinoflagellate, U= microflagellates, O= other. Solid bold middle line shows 1:1
relationship, finer lines show 1:5 and 5:1 isopleths.
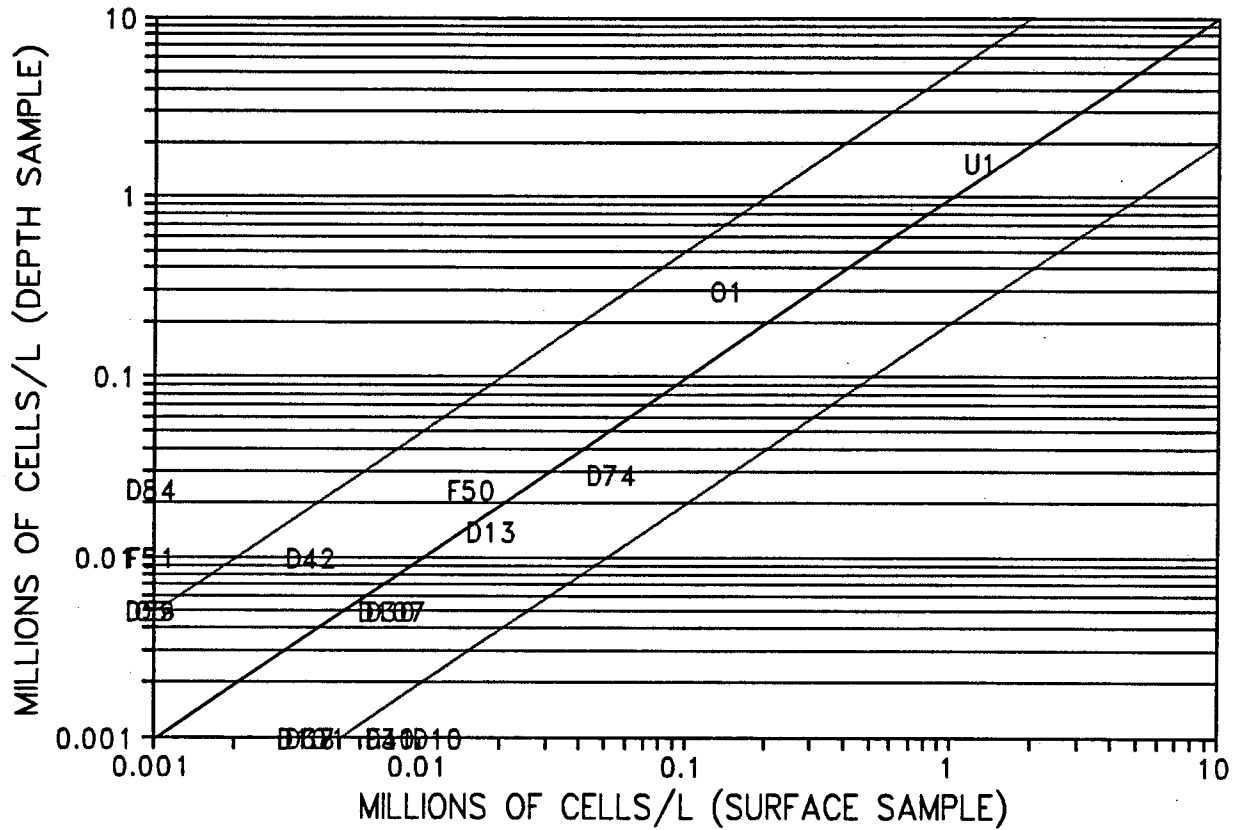
Figure 3-30a   Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F2P in late August 1992 on cast 1. Species codes are given in Appendix F.

PHYTOPLANKTON SPECIES ABUNDANCE
STATION FO2P − LATE AUGUST 92 − CAST 2
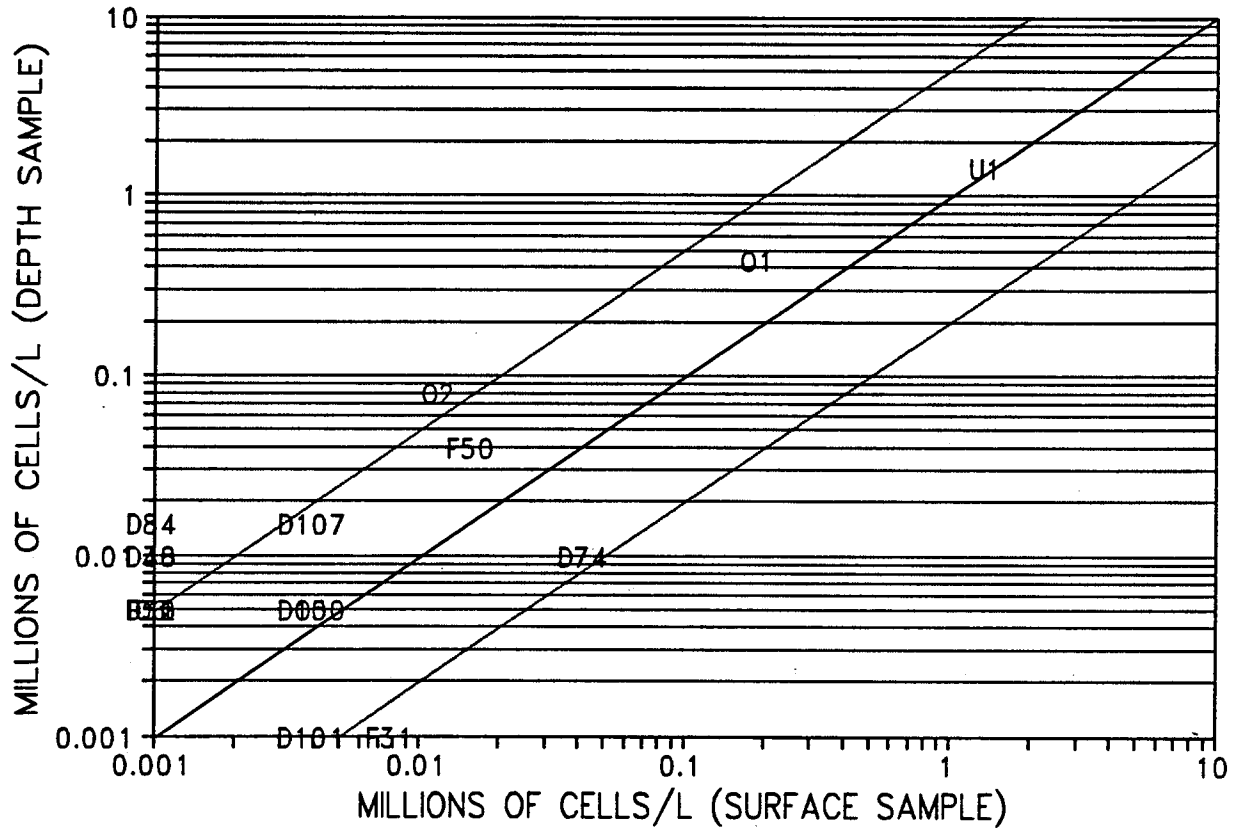
Figure 3-30b   Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F2P in late August 1992 on cast 2. Species codes are given in Appendix F.
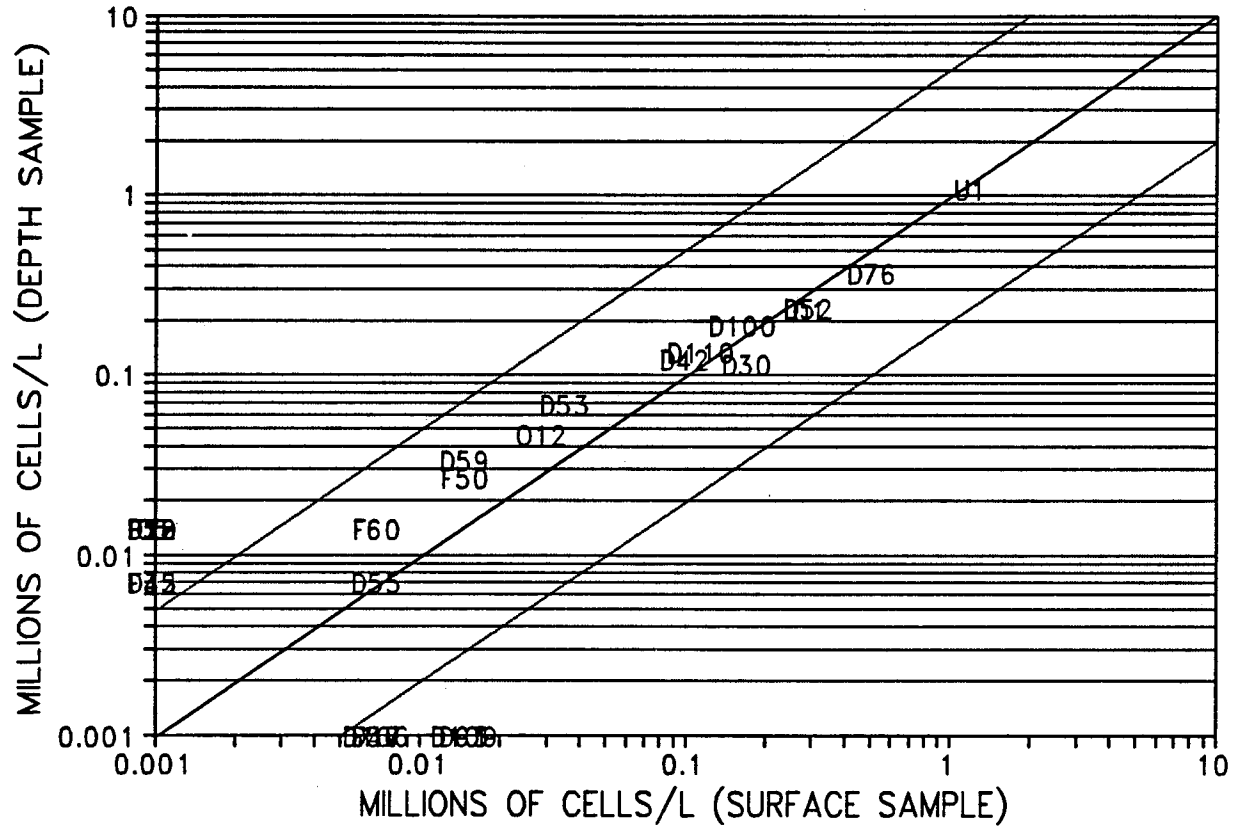
Figure 3-31 Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F23P in late August 1992. Species codes are given in Appendix F.
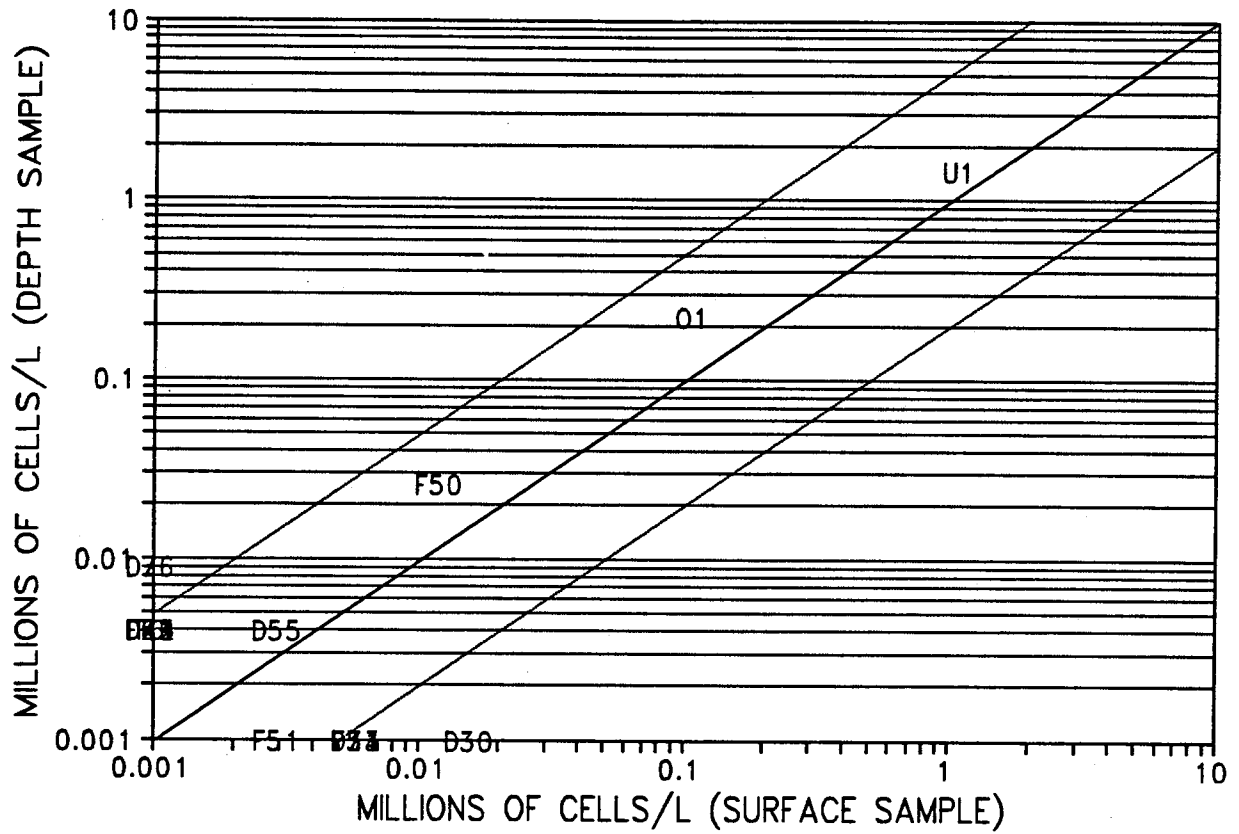
Figure 3-32 Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F13P in late August 1992. Species codes are given in Appendix F.

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

STATION F23P CHLA MAXIMUM
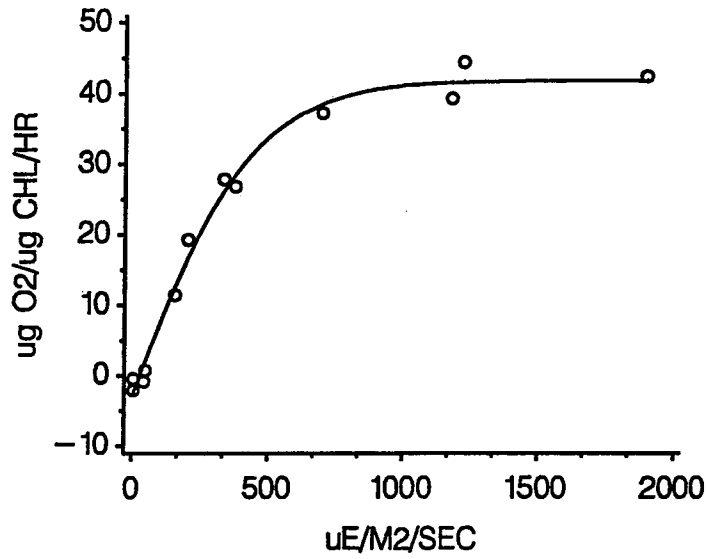
MODEL FROM PLATT AND JASSBY, 1976
CRUISE NUMBER 10, AUG 1992

STATION N7P CHLA MAXIMUM
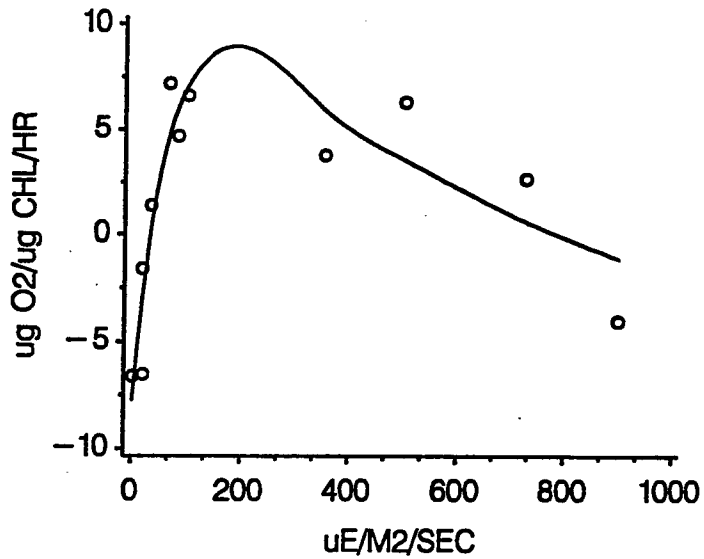
MODEL FROM PLATT ET AL, 1980
CRUISE NUMBER 10, AUG 1992

Figure 3-34 Selected net production (P) vs. irradiance (I) curves in late August 1992. Data are chlorophyll-normalized rates see Appendix E.
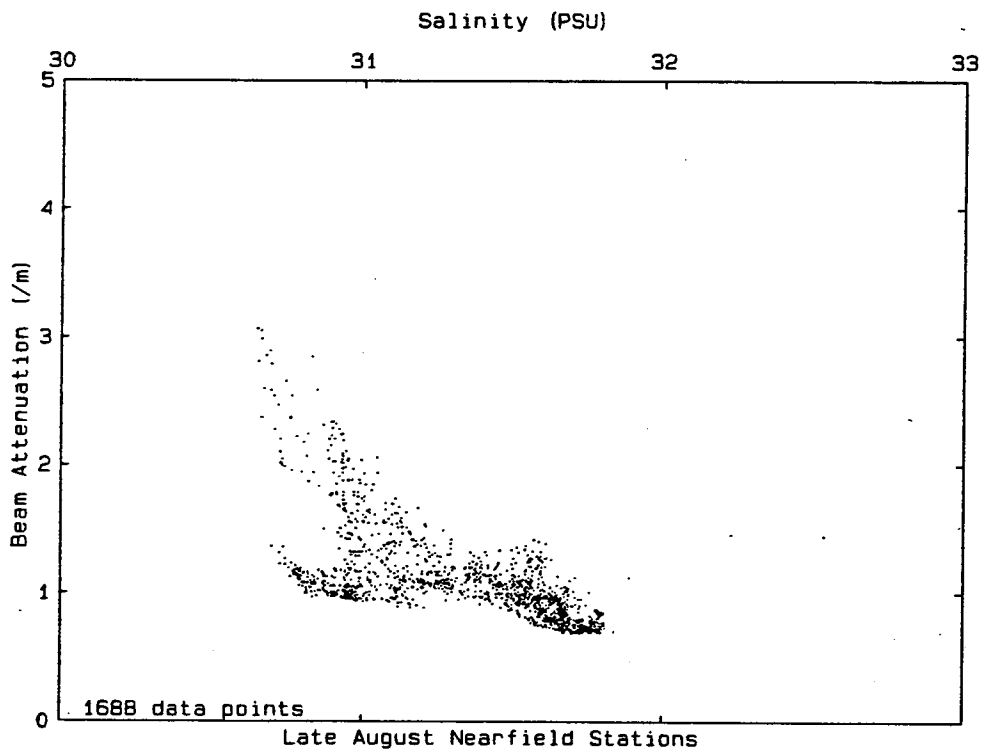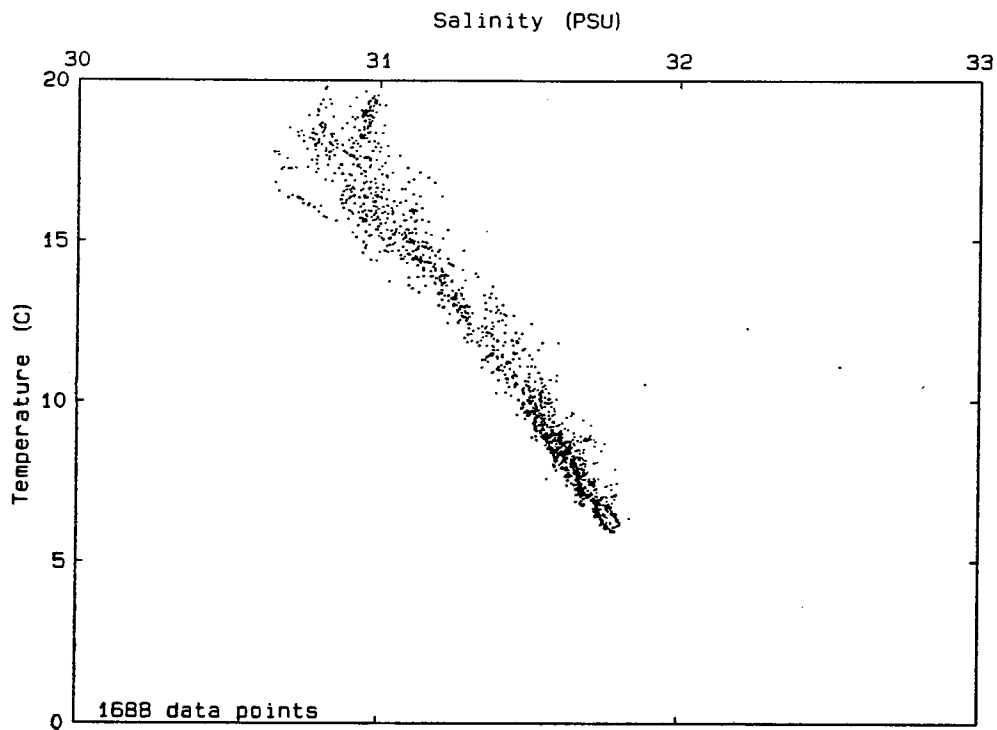
Figure 3-35a Scatter plots for nearfield stations only. Compare to Figure 3-17. Data include sampling of the nearfield during the farfield survey (six "P" stations) and the nearfield survey (21 stations).
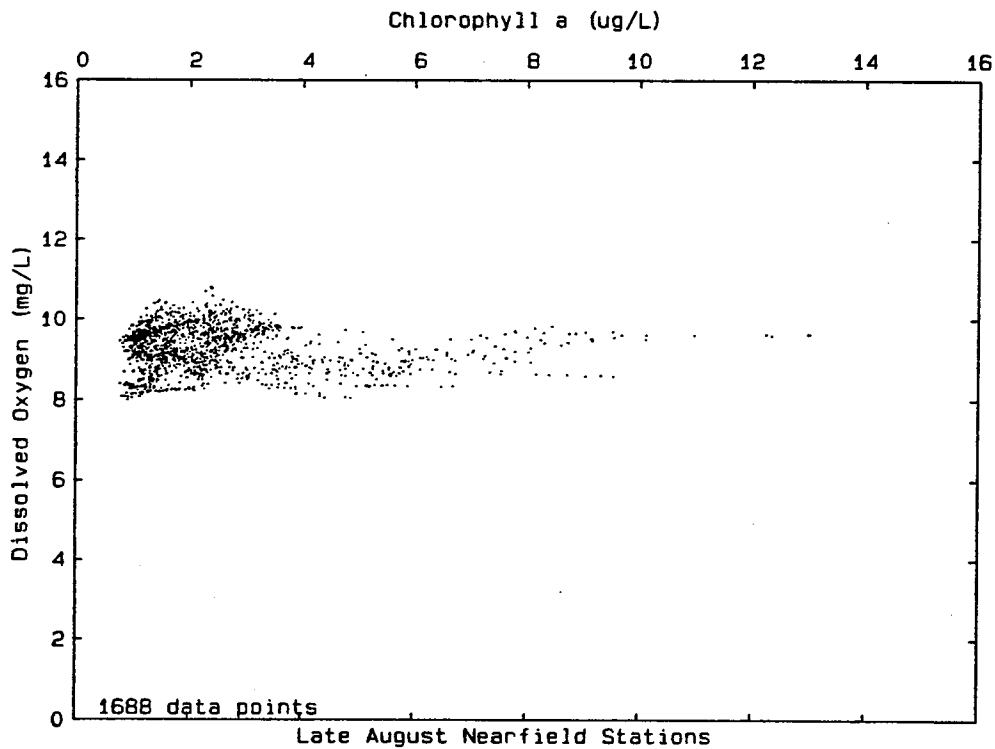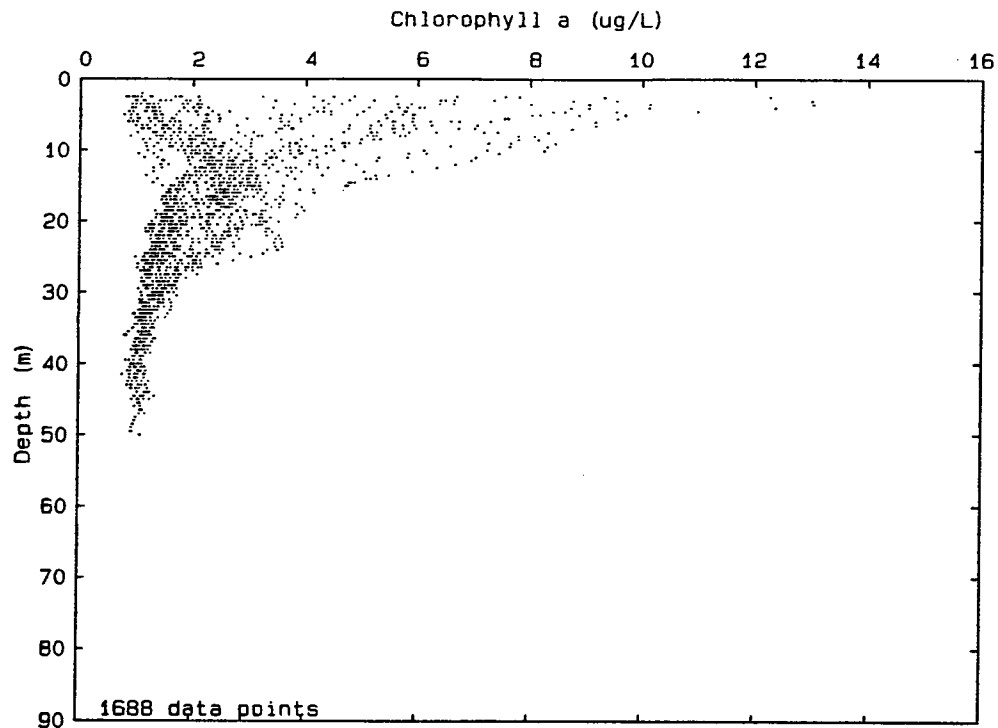
Figure 3-35b Scatter plots for nearfield stations only. Compare to Figure 3-17. Data include sampling of the nearfield during the farfield survey (six "P" stations) and the nearfield survey (21 stations). Chlorophyll was estimated from fluorescence and DO was calibrated with titrations (Appedix A).
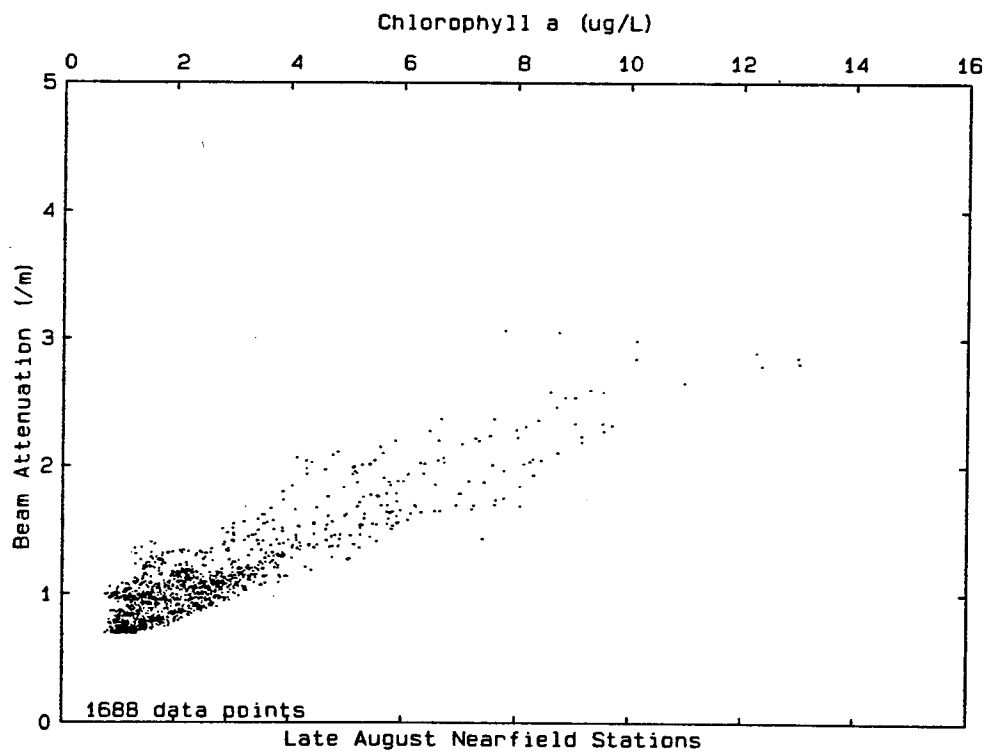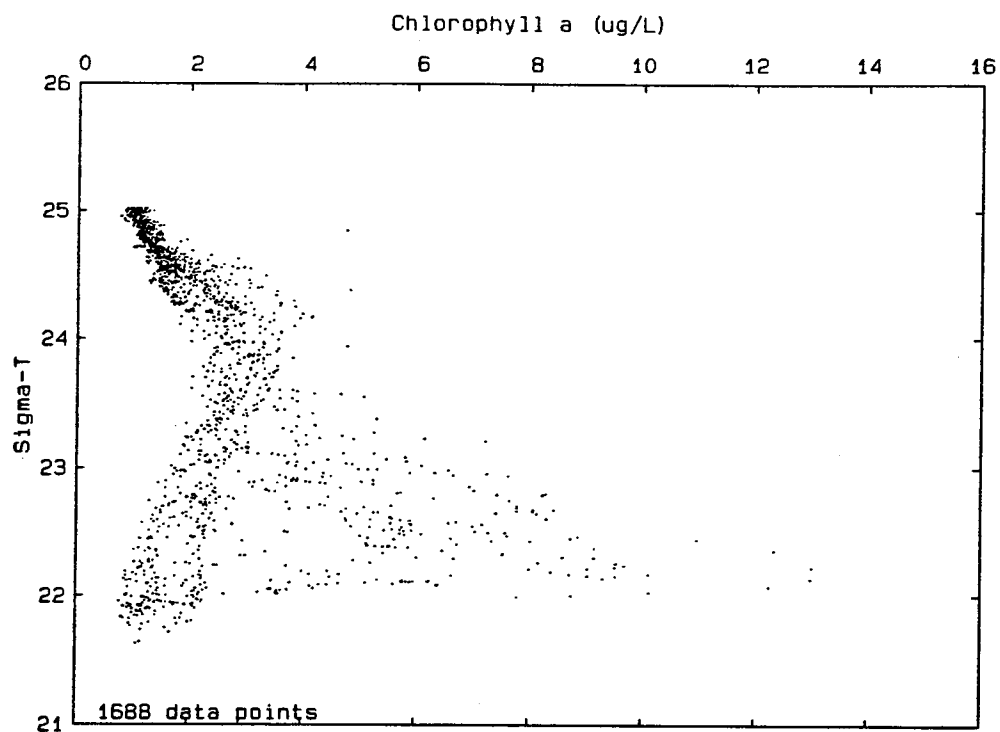
Figure 3-35c   Scatter plots for nearfield stations only. Compare to Figure 3-17. Data include sampling of the nearfield during the farfield survey (six "P" stations) and the nearfield survey (21 stations). Chlorophyll was estimated from fluorescence (see Appendix A).
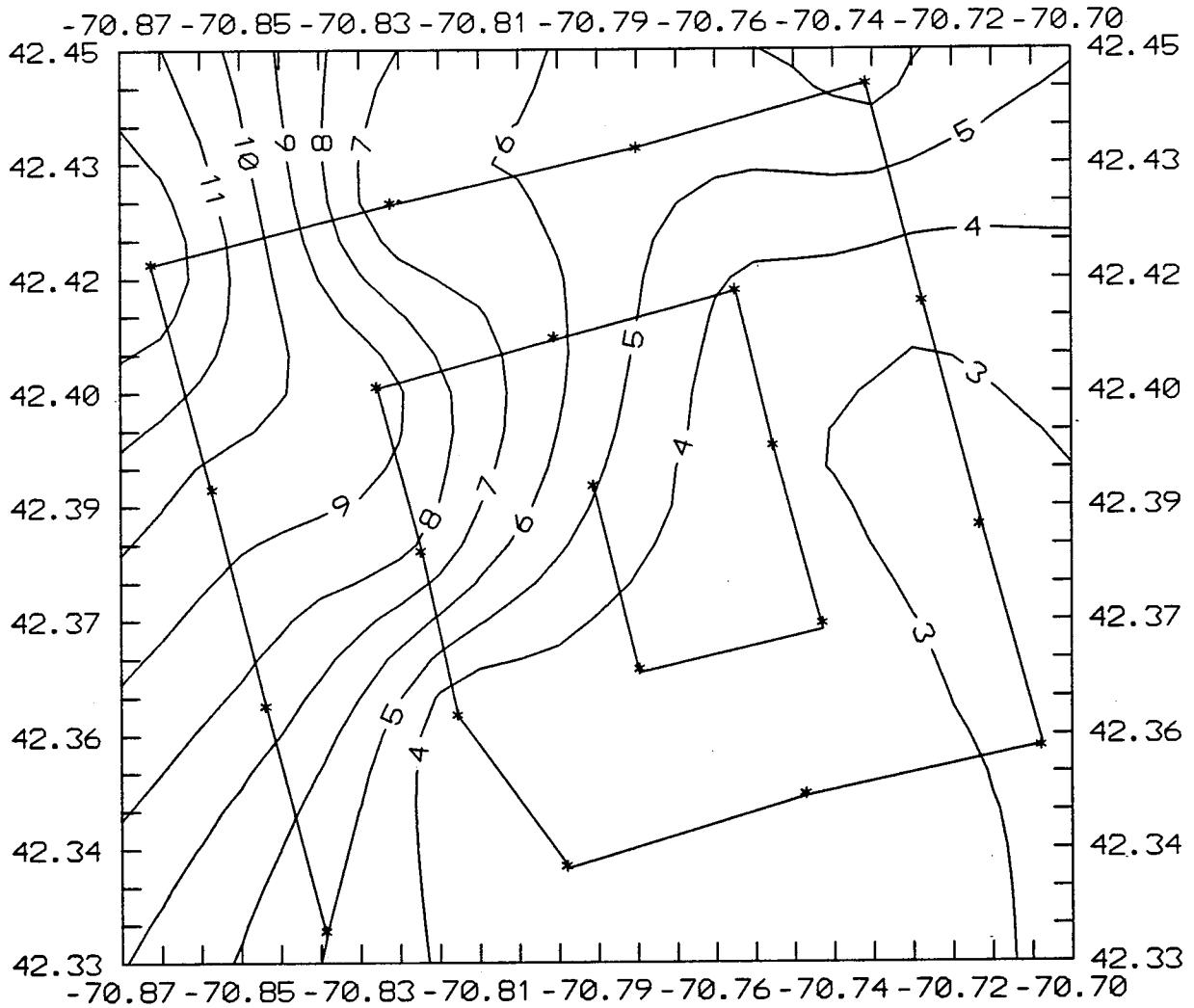
Figure 3-36 Chlorophyll maximum at each nearfield station from vertical profile day (Appendix B). Track shows sampling, starting at southwest corner of nearfield. Chlorophyll maximum may not be at the same depth at different stations.

DIN vs. Depth
Late August

Figure 3-37   DIN vs. Depth in late August 1992. Nearfield data are from sampling on both the farfield (six "P" stations) and nearfield (21 stations) portions of the survey.

Sigma-T Along Outer Northern Track

N01P   N02   N03   N04P

N101SI Minimum =22.25 Maximum =24.89

Sigma-T Along Inner Northern Track

N13   N14   N15

N103SI Minimum =22.44 Maximum =24.85

Sigma-T Along Inner Southern Track

N19   N18   N17

N105SI Minimum =22.31 Maximum =24.93

Sigma-T Along Outer Southern Track

N10P   N09   N08   N07P

N107SI Minimum =22.24 Maximum =24.88
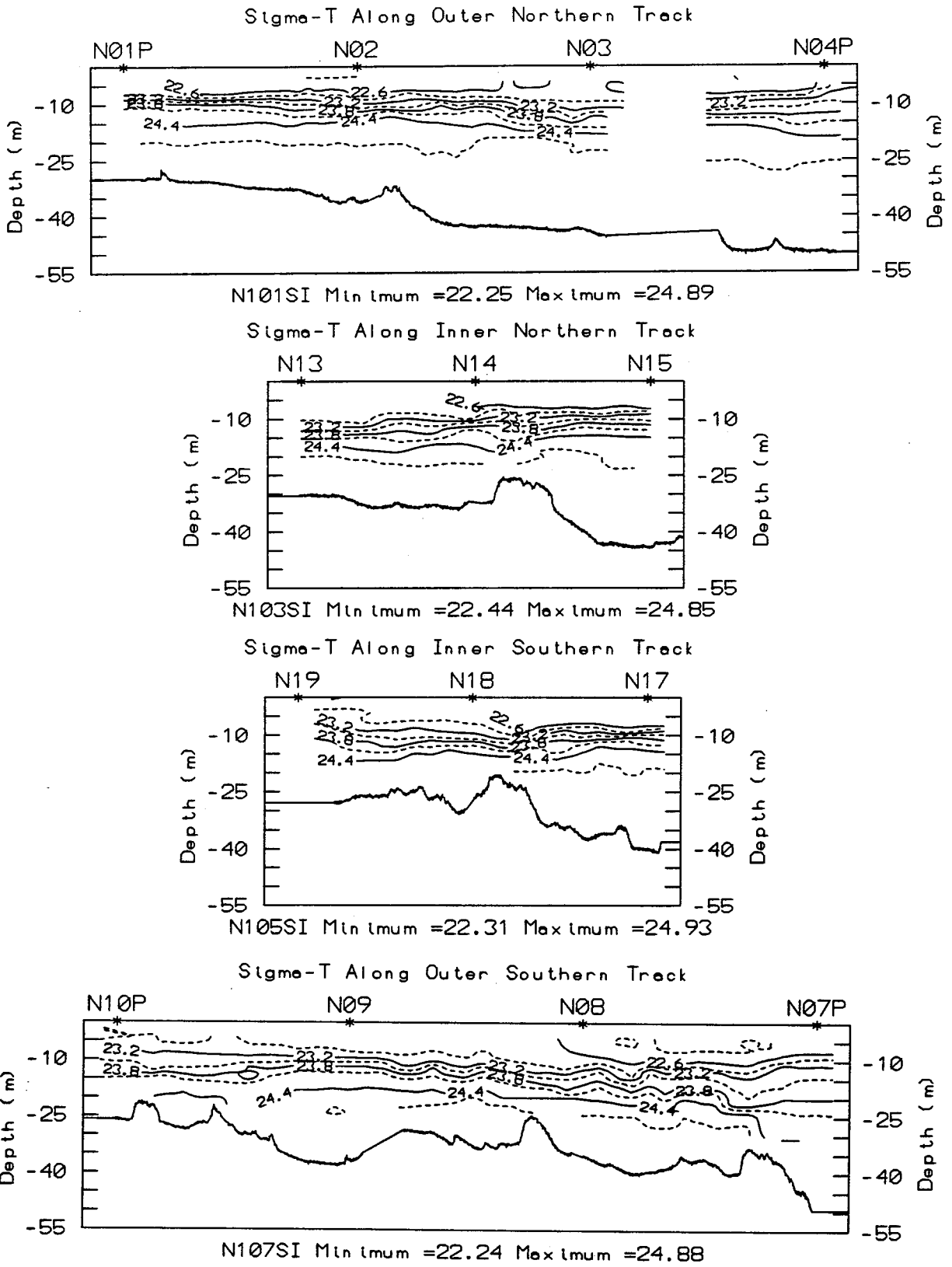
Figure 3-38a Vertical section contours of σ_T generated for tow-yos in late August 1992. The view is towards the North. The contour interval is 0.2 σ_T.

Sigma-T Along Outer Western Track

N10P   N11   N12   N01P

N102SI Minimum =22.50 Maximum =24.77

Sigma-T Along Inner Western Track

N19   N20P   N13

N104SI Minimum =22.68 Maximum =24.70

Sigma-T Along Inner Eastern Track

N17   N16P   N15

N106SI Minimum =22.33 Maximum =24.95

Sigma-T Along Outer Eastern Track

N07P   N06   N05   N04P

N108SI Minimum =22.18 Maximum =24.98
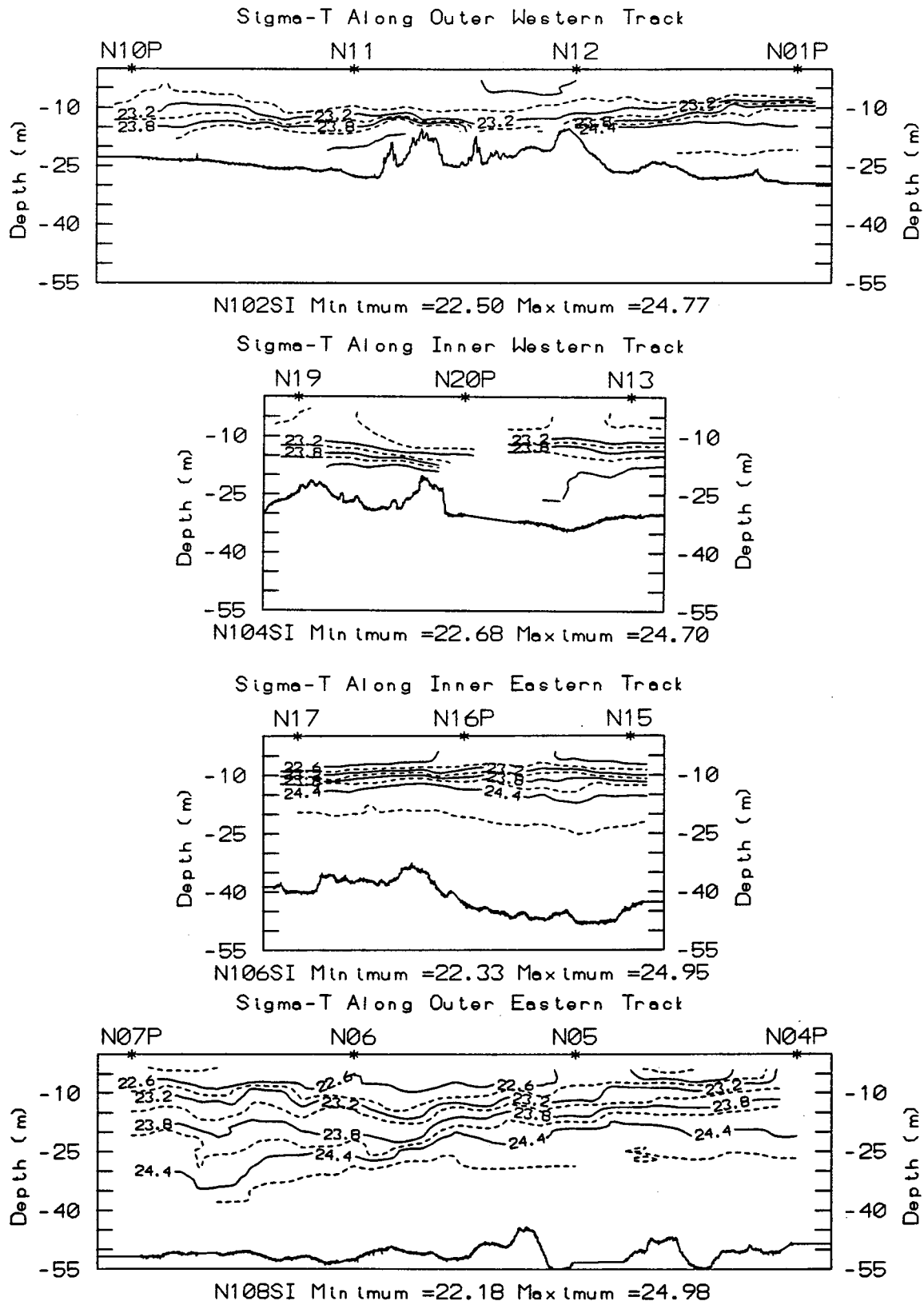
Figure 3-38b   Vertical section contours of σ_T generated for tow-yos in late August 1992. The view is towards Boston Harbor. The contour interval is 0.2 σ_T.

Chlorophyll a (ug/L) Along Outer Northern Track

N01P   N02   N03   N04P

Depth (m)   -10   -25   -40   -55

Depth (m)   -10   -25   -40   -55
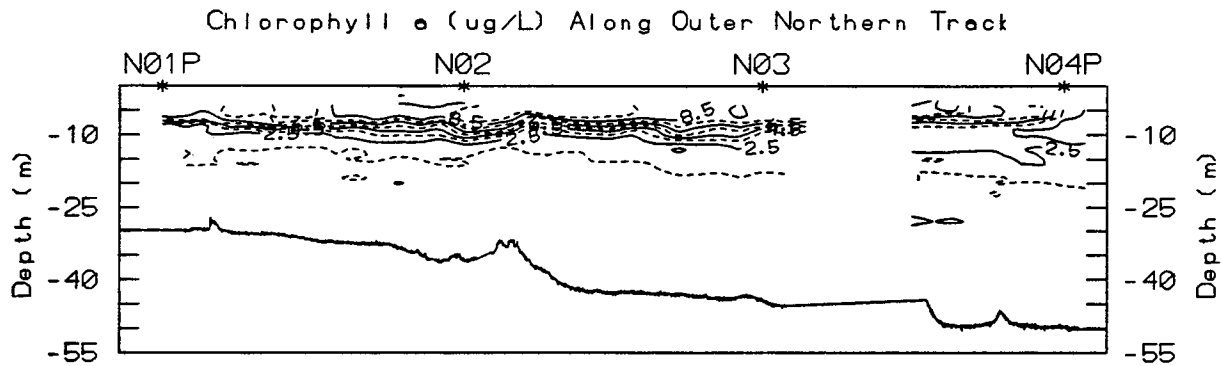
N101CH Minimum = 0.21 Maximum =10.13

Chlorophyll a (ug/L) Along Inner Northern Track

N13   N14   N15

Depth (m)   -10   -25   -40   -55

Depth (m)   -10   -25   -40   -55
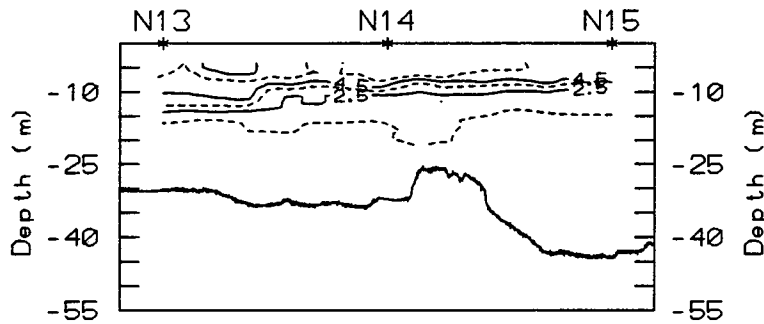
N103CH Minimum = 0.54 Maximum = 6.92

Chlorophyll a (ug/L) Along Inner Southern Track

N19   N18   N17

Depth (m)   -10   2.5   -25   -40   -55

Depth (m)   -10   2.5   -25   -40   -55
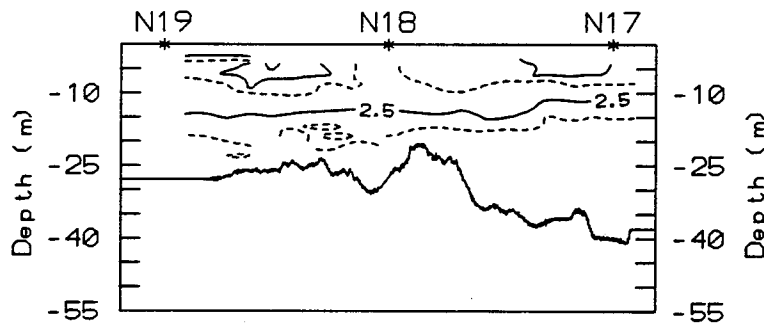
N105CH Minimum = 0.66 Maximum = 4.79

Chlorophyll a (ug/L) Along Outer Southern Track

N10P   N09   N08   N07P

Depth (m)   -10   2.5   -25   -40   -55

Depth (m)   -10   -25   2.5   -40   -55
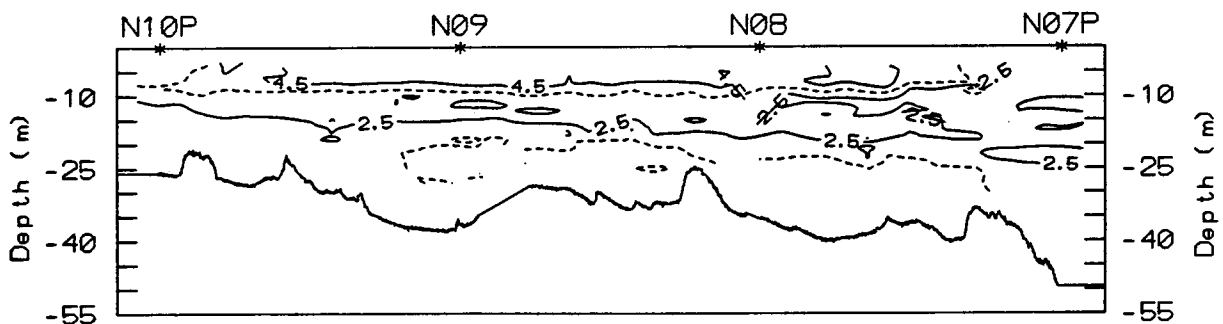
N107CH Minimum = 0.71 Maximum = 5.33

Figure 3-39a Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yos in late August 1992. The view is towards the North. The contour interval is 1.0 μg L^{-1}.

Chlorophyll a (ug/L) Along Outer Western Track

N10P N11 N12 N01P

N102CH Minimum = 0.55 Maximum = 8.88

Chlorophyll a (ug/L) Along Inner Western Track

N19 N20P N13

N104CH Minimum = 0.88 Maximum = 5.25

Chlorophyll a (ug/L) Along Inner Eastern Track

N17 N16P N15

N106CH Minimum = 0.64 Maximum = 5.57

Chlorophyll a (ug/L) Along Outer Eastern Track

N07P N06 N05 N04P

N108CH Minimum = 0.79 Maximum = 5.37
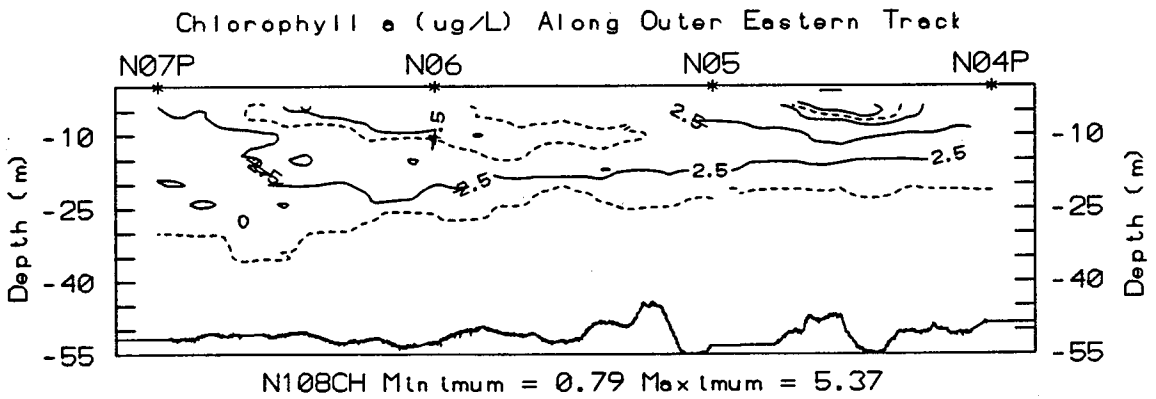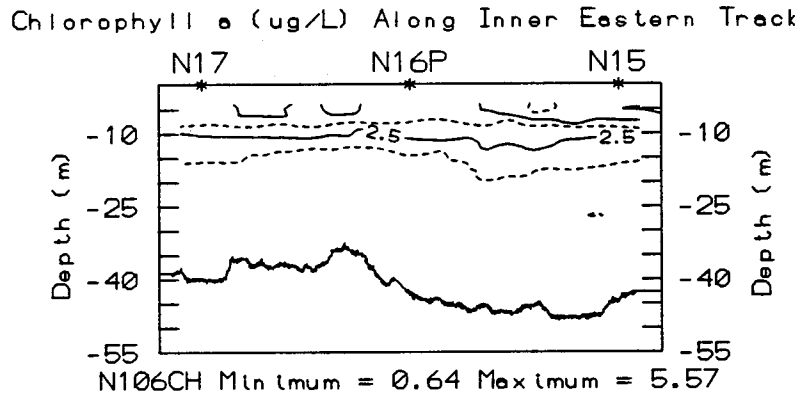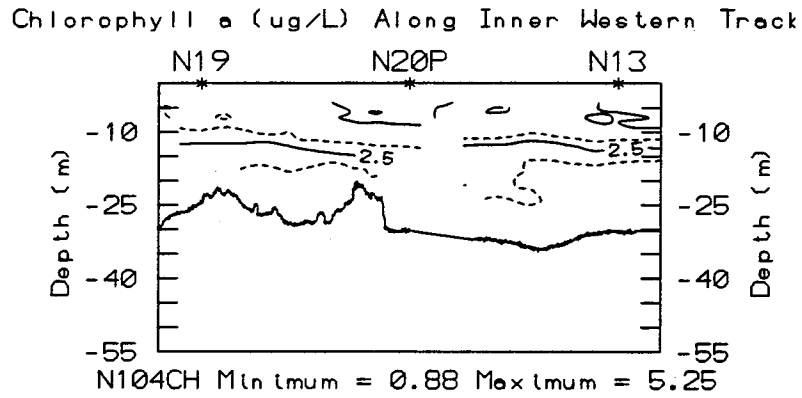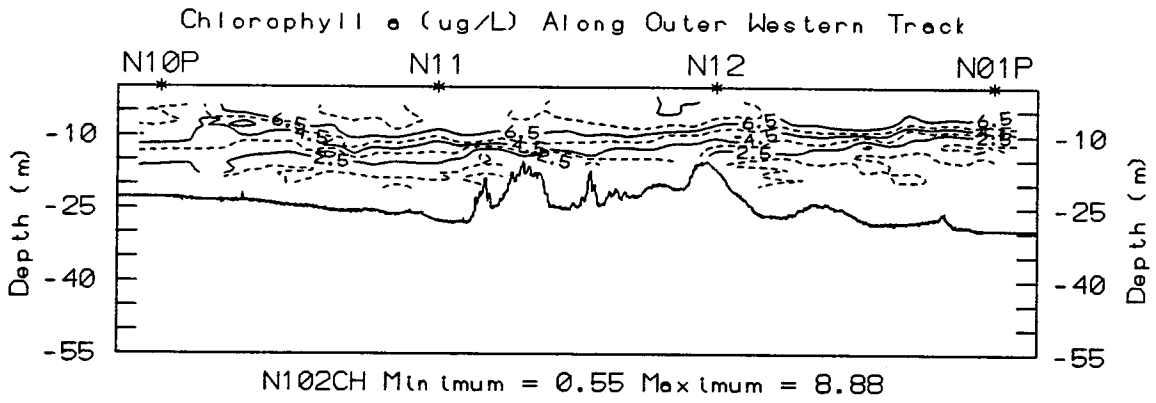
Figure 3-39b Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yos in late August 1992. The view is towards the Boston Harbor. The contour interval is 0.2 σ_T.

4.0 SEPTEMBER NEARFIELD SURVEY RESULTS

4.1 Distribution of Water Properties from Vertical Profiling

Data from the vertical profiling day (September 9) are given in Appendix A (upcast bottle measurements) and Appendix B (downcast vertical profiles). Composite plots of all nearfield stations are given in Figure 4-1. Compared to just two weeks earlier in late August, surface waters had cooled several degrees and they were also more saline. The T-S plot shows greater variability in salinity for a given temperature, relative to August, but in general higher salinities were seen in September. Thus, the temperature range was about 6 to 17 °C and the salinity range about 31 to 32 PSU. It was noted that cooler surface temperatures were seen along the inshore set of stations (N10P, N11, N12); these were cooler than offshore surface waters by as much as 2-3 °C (Appendix A).

Beam attenuation reached very high levels at some stations with salinity near 31 PSU, and accompanying these high attenuation readings were some very high chlorophyll (fluorescence) concentrations (Figure 4-1). High fluorescence ($>5 \mu g L^{-1}$) was found in near surface water at N10P, N11, and N12 — the same stations with cooler surface waters. Most other stations had peak fluorescence levels at about 10 to 20 m depth, in the range of 3 to 5 $\mu g L^{-1}$. Figure 4-2 illustrates where the peak fluorescence occurred across the field, showing that station N12 was the local maximum and there the highest values were within the top 2 m.

The distribution of nutrients with depth showed some variation across the stations (Figures 4-3 and 4-4). The concentration of ammonia in surface waters was not especially high, but the range in surface waters was not much different from range in deeper waters. Silicate and nitrate had the strongest patterns of increase with depth below a low-nutrient surface layer. However, for silicate, nitrate, *and* phosphate, the deeper waters had higher nutrients and the trends with depth suggested a nutrient-depleted surface layer with underlying higher-nutrient subpycnocline waters.

4.2 Distribution of Water Properties from Towing

On the towing day (September 10), the complete inner box was done clockwise (N19-N20P-N13-N14-N15-N16P-N17-N18-N19) followed by the complete outer box counterclockwise (N07P-N04P-N01P-N10P-N07P). Figures 4-5 and 4-6 display contoured section tracks, others are provided in Appendix D.

Temperature sections (Appendix D) strongly illustrate that surface waters were cooler toward the shore, confirming results of the previous day. The thermocline was not horizontally smooth, but rather had strong undulations over km distances.

In contrast to late August, the pycnocline (Figure 4-5) was not as sharp as it had been at shallow stations and it stretched over the top 20 to 25 m of the water column in most of the field. This weakening of the sharp density gradient between surface and bottom waters is prelude to an Autumn overturn where the water column becomes well-mixed again.

A fairly uniform (throughout the region) subsurface fluorescence maximum was indicated within the pycnocline at about 10 to 20 m depth. Values here reached about 3 to 4 μg L^{-1}. At all inshore track stations (N10P-N01P) higher fluorescence was seen at about 10 m. But an intense, very thin layer of very high chlorophyll was located around the northwest corner of the nearfield. This was a continuous, expansive feature extending from N01P south to N12 (Figure 4-6a) and east to N03 (Figure 4-6b). However, the higher fluorescence was not detected at the inner track stations.

4.3 Water Types and Analysis of Small-Scale Variability

By virtue of the pattern of sampling, the southwest corner of the field, where tidal dynamics have been seen, was only sampled once on the tow day near mid-tide. It was sampled about 2 hr from high tide on the previous day, so the role of any tidal dynamics cannot be addressed. However, relative to the previous day, the towing data suggest an extensive patch of high fluorescence had moved a bit to the North, perhaps a kilometer or more and perhaps also a bit to the East (compare Figure 4-2 and 4-6); in particular high values were seen at the inner track's northwest corner on September 9 but not on September 10. This movement could be tidal or could be advection due to surface current drift, but our data cannot resolve such an issue.

With respect to water types, it was suggested by the data that the nearfield was a hydrographic region with cooler water at the surface, grading to warmer offshore water and general weakening of the pycnocline as air temperatures continued their seasonal decrease. Due to this pycnocline weakening some disruption of the previously strong pattern of nutrients with depth might be expected and this indeed was observed. An intense bloom of phytoplankton covered a good portion of the northwest corner of the nearfield, but distinctive physical or geochemical features associated with this biological feature were not immediately obvious. Further analysis of these survey data might be able to identify biophysical or biogeochemical relationships.

Salinity (PSU)

Salinity (PSU)

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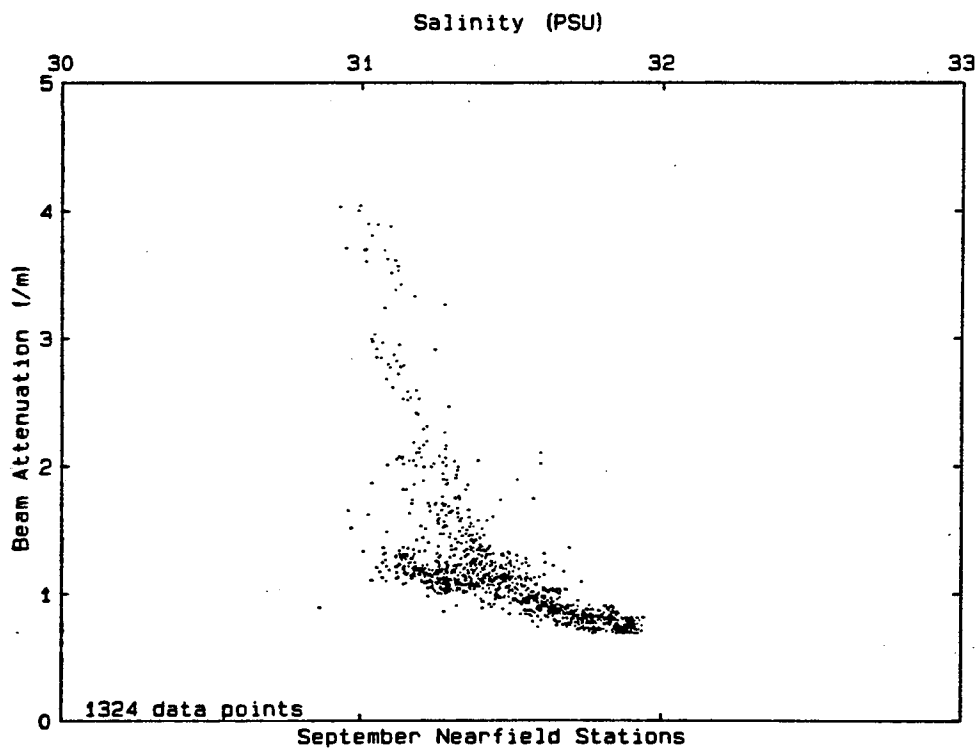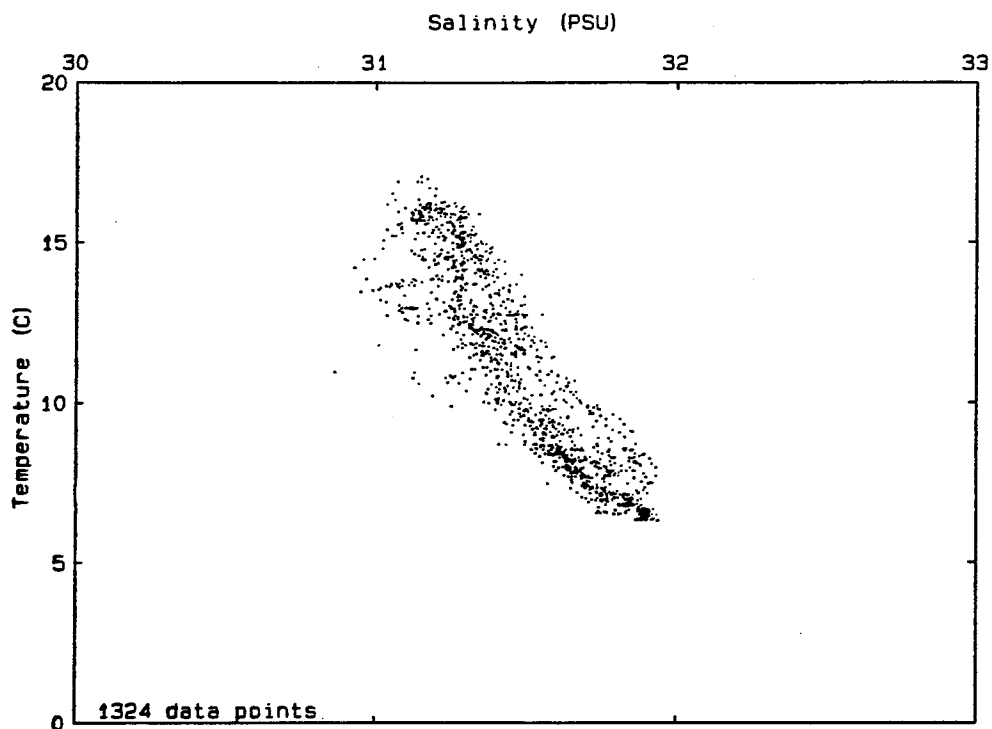
Figure 4-1a Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in September 1992. Individual station casts that were used to produce this composite are in Appendix B.

Chlorophyll a (ug/L)

1282 data points

Chlorophyll a (ug/L)

1282 data points

September Nearfield Stations

Figure 4-1b Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in September 1992. Individual station casts that were used to produce this composite are in Appendix B. Chlorophyll was estimated from fluorescence and DO was calibrated with titrations (see Appendix A).

Chlorophyll a (ug/L)

0   2   4   6   8   10   12   14   16

26

25

Sigma-T

24

23

22

21

1325 data points

Chlorophyll a (ug/L)

0   2   4   6   8   10   12   14   16

5

4

Beam Attenuation (/m)

3

2

1

0

1325 data points

September Nearfield Stations
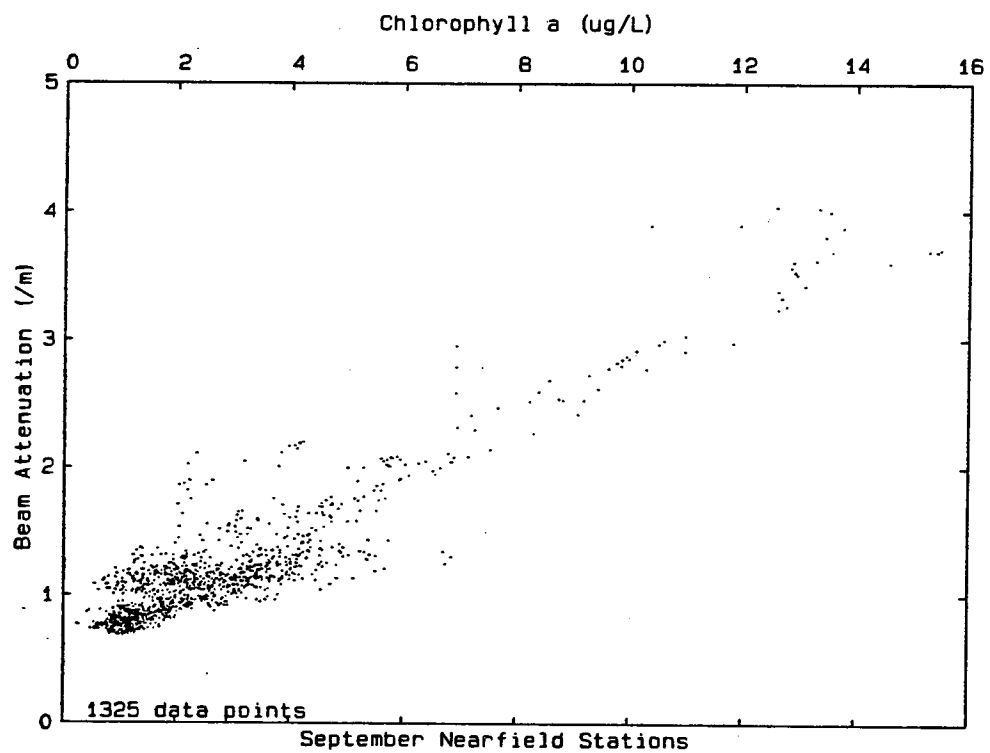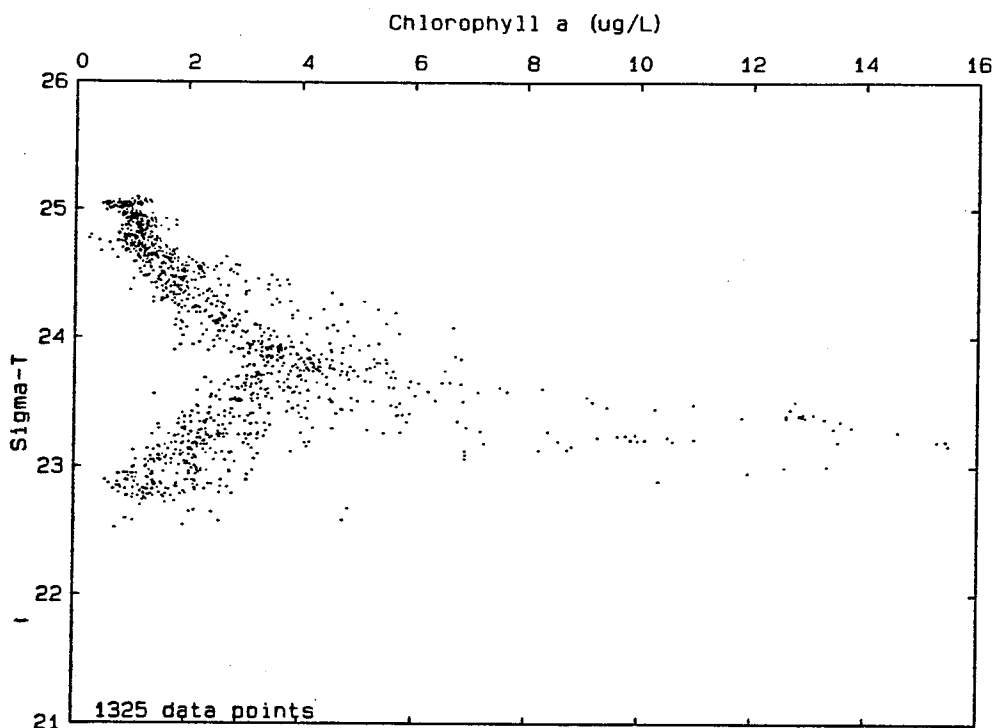
Figure 4-1c Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in September 1992. Individual station casts that were used to produce this composite are in Appendix B. Chlorophyll was estimated from fluorescence (see Appendix A).

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. Chlorophyll maximum may not be at the same depth at different stations.
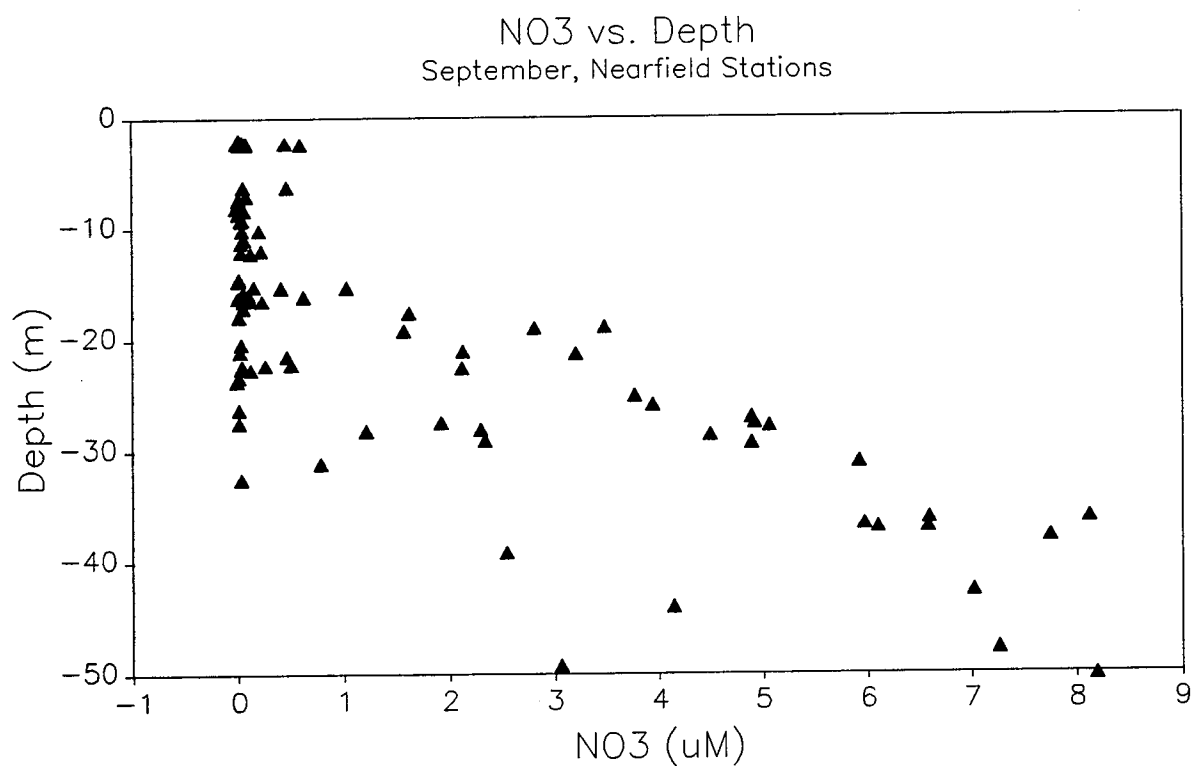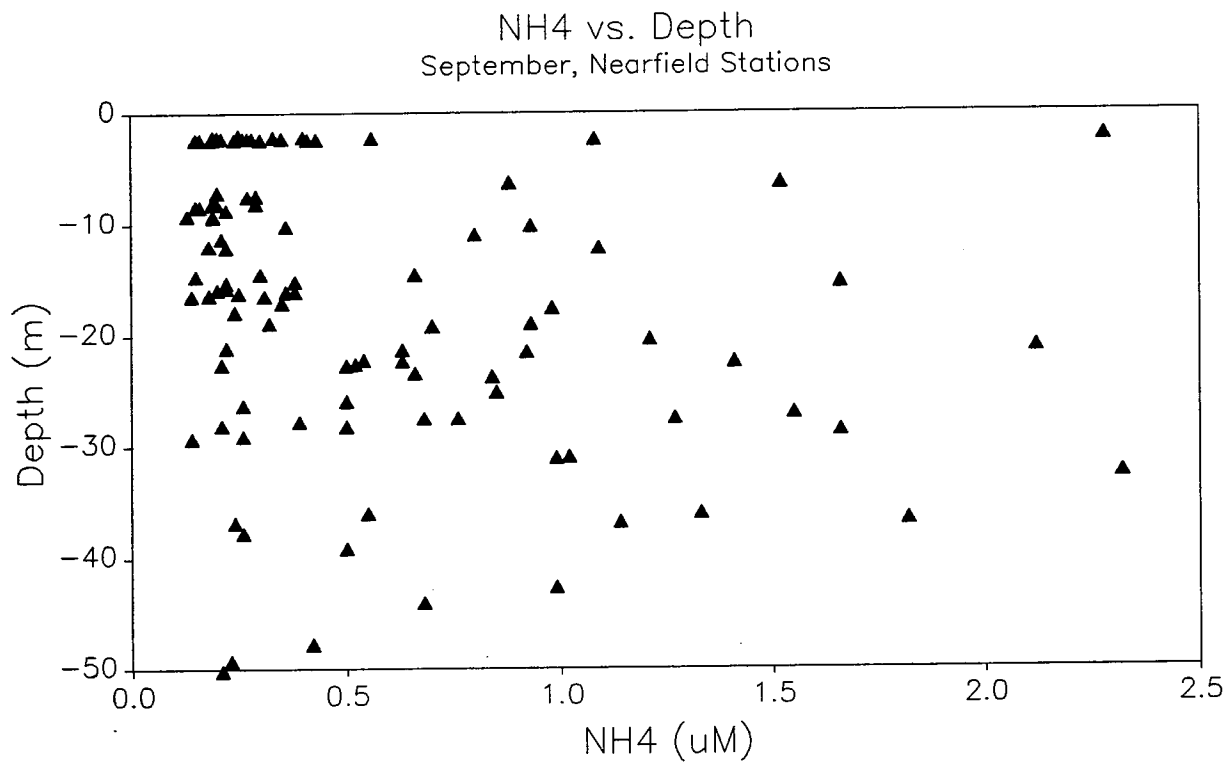
Figure 4-3   NH$_4$ and NO$_3$ vs. depth in September 1992.
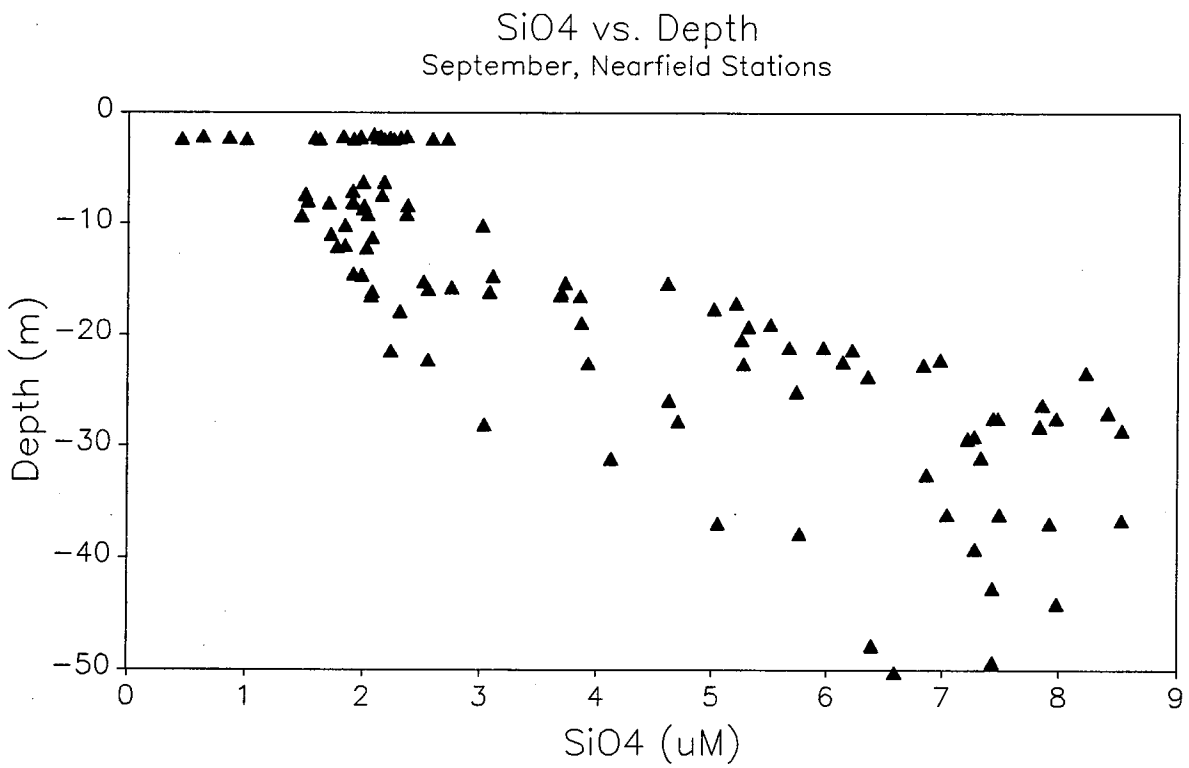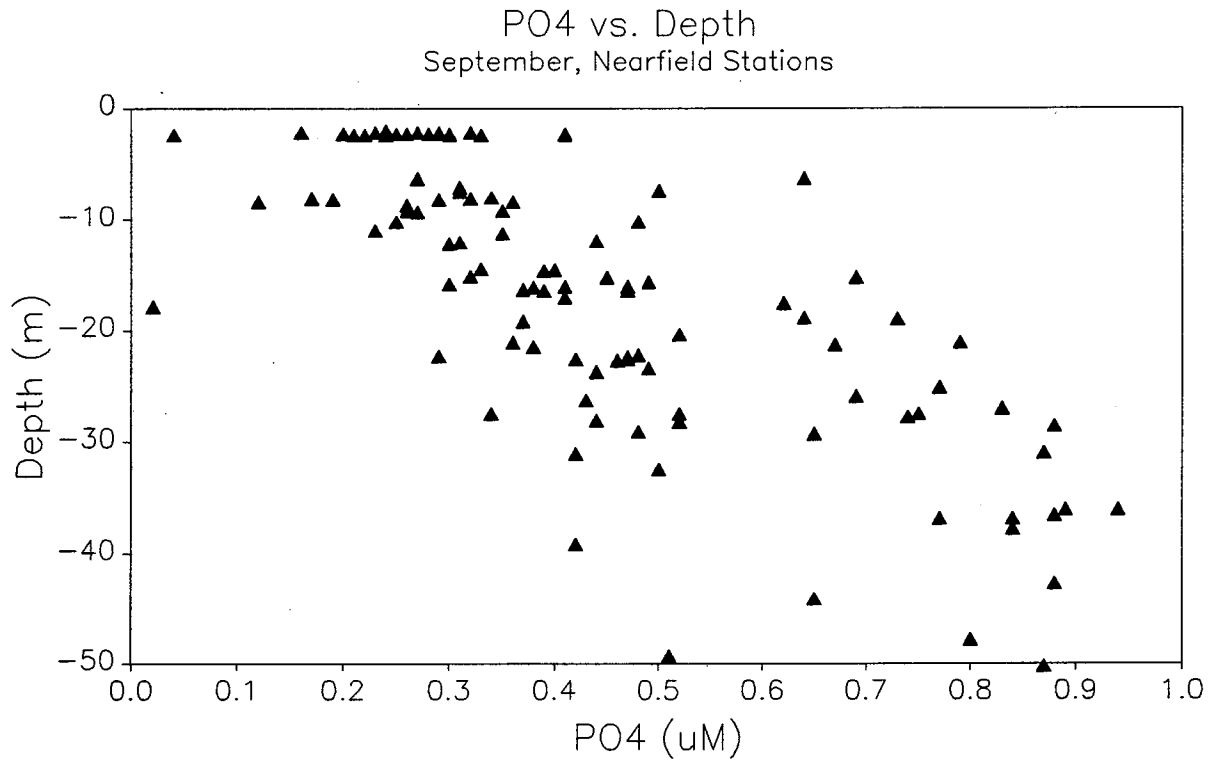
Figure 4-4   PO$_4$ and SiO$_4$ vs. depth in September 1992.

Sigma-T Along Outer Northern Track

N01P   N02   N03   N04P

N111SI Minimum =22.79 Maximum =24.90

Sigma-T Along Inner Northern Track

N13   N14   N15

N113SI Minimum =22.87 Maximum =24.94

Sigma-T Along Inner Southern Track

N19   N18   N17

N115SI Minimum =22.73 Maximum =24.93

Sigma-T Along Outer Southern Track

N10P   N09   N08   N07P

N117SI Minimum =22.67 Maximum =25.03
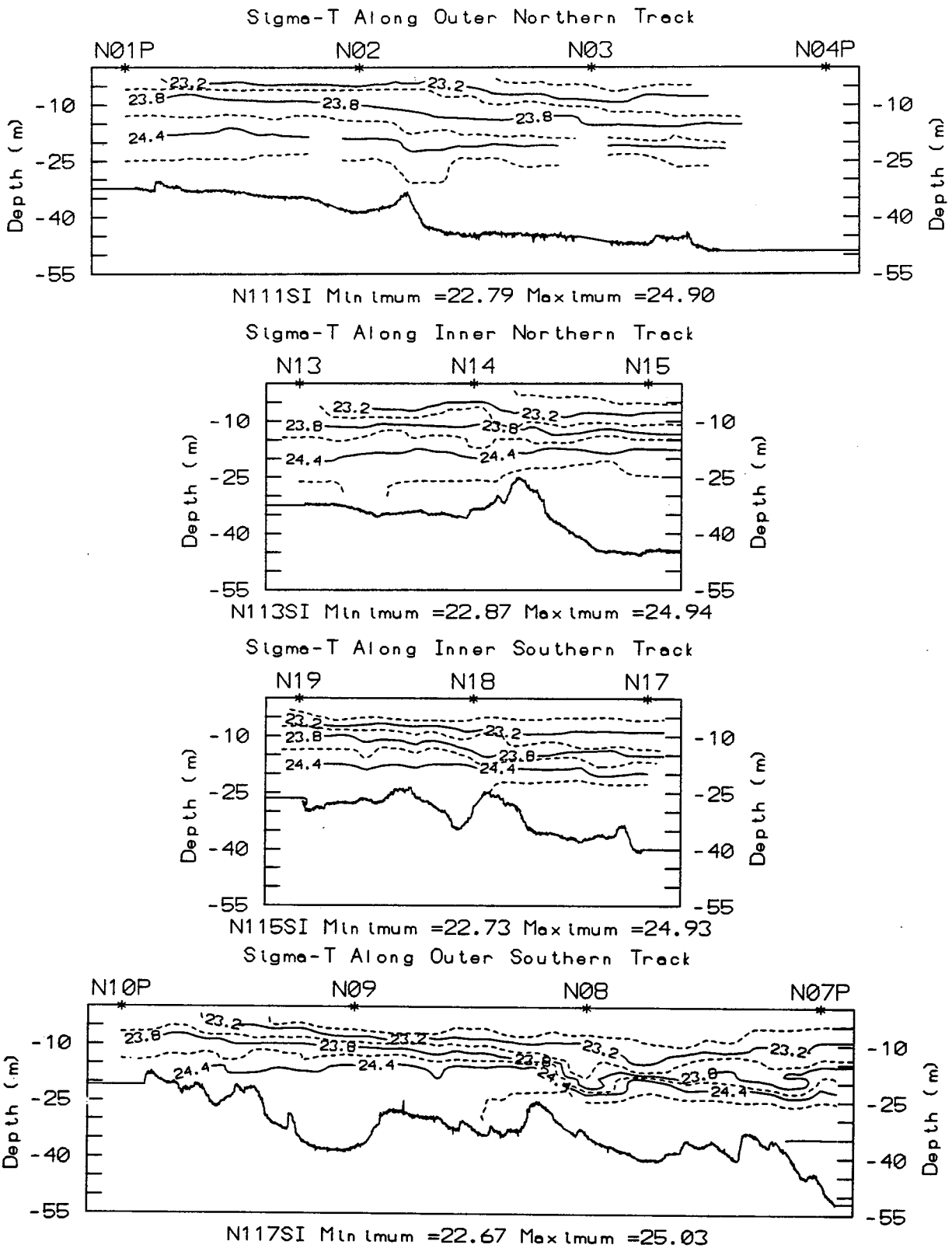
Figure 4-5a Vertical section contours of σ_T generated for tow-yos in September 1992. The view is towards the North. The contour interval is 0.3 σ_T.

Sigma-T Along Outer Western Track

N10P   N11   N12   N01P

N112SI Minimum =22.89 Maximum =24.74

Sigma-T Along Inner Western Track

N19   N20P   N13

N114SI Minimum =22.81 Maximum =24.71

Sigma-T Along Inner Eastern Track

N17   N16P   N15

N116SI Minimum =22.73 Maximum =24.97

Sigma-T Along Outer Eastern Track

N07P   N06   N05   N04P

N118SI Minimum =22.65 Maximum =25.01
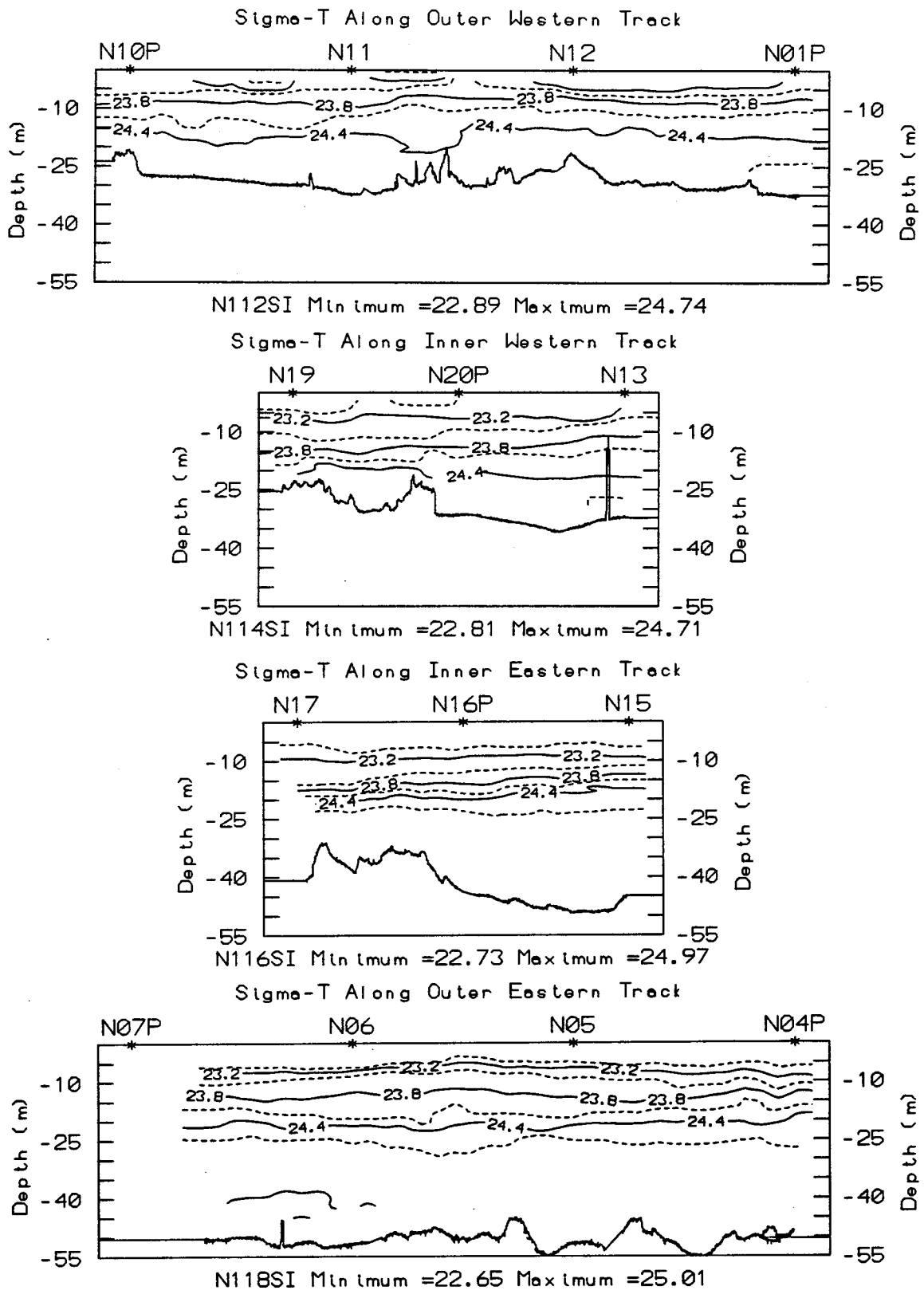
Figure 4-5b **Vertical section contours of σ_T generated for tow-yos in September 1992. The view is towards Boston Harbor. The contour interval is 0.3 σ_T.**

Chlorophyll a (ug/L) Along Outer Northern Track

N01P   N02   N03   N04P

Depth (m)
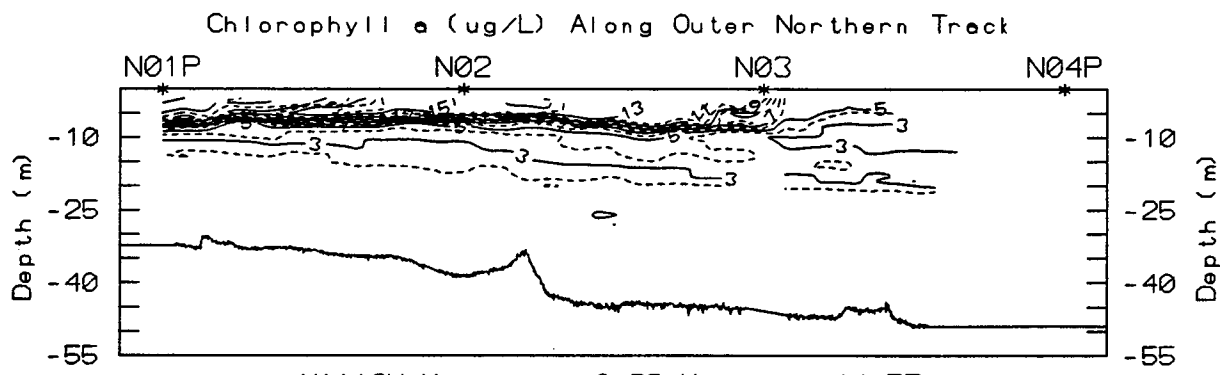
N111CH Minimum = 0.98 Maximum = 16.77

Chlorophyll a (ug/L) Along Inner Northern Track

N13   N14   N15

Depth (m)
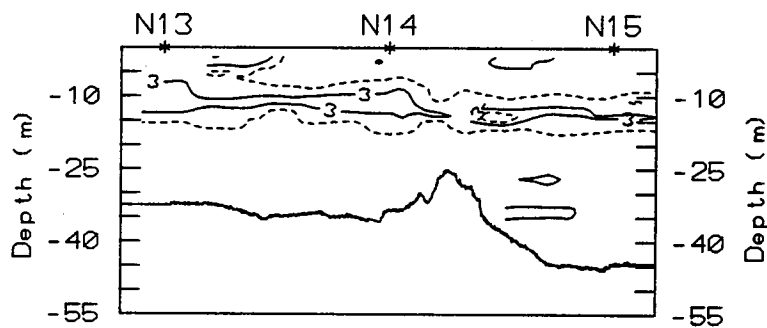
N113CH Minimum = 0.93 Maximum = 4.46

Chlorophyll a (ug/L) Along Inner Southern Track

N19   N18   N17

Depth (m)
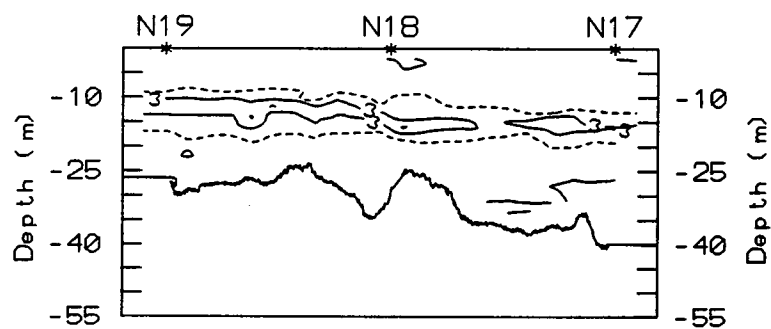
N115CH Minimum = 0.81 Maximum = 4.10

Chlorophyll a (ug/L) Along Outer Southern Track

N10P   N09   N08   N07P

Depth (m)
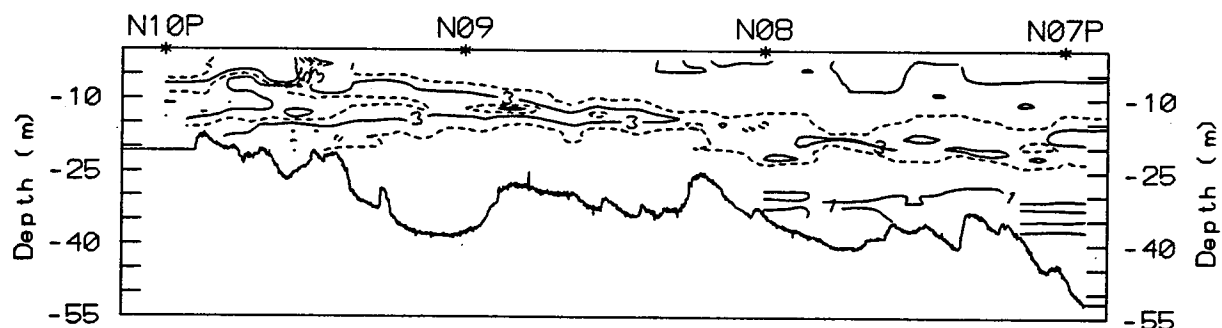
N117CH Minimum = 0.68 Maximum = 8.32

Figure 4-6a Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yos in September 1992. The view is towards the North. The contour interval is 1 μg L^{-1}.

Chlorophyll a (ug/L) Along Outer Western Track
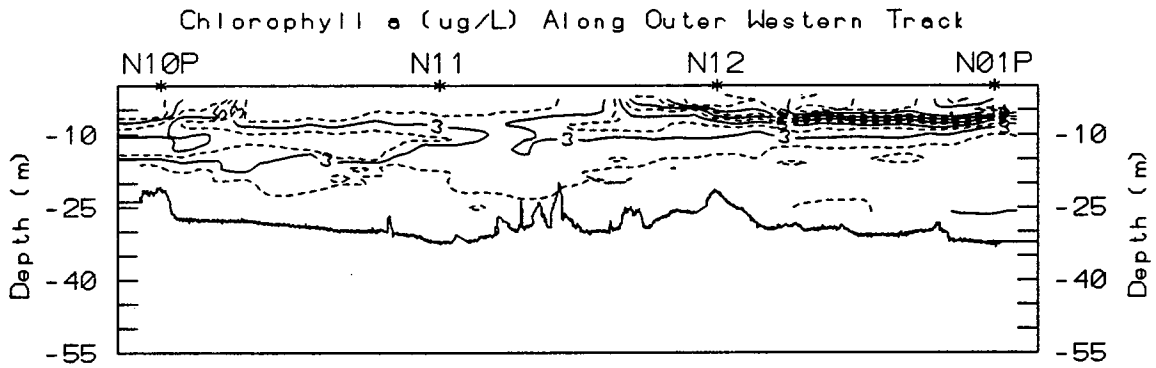
N112CH Minimum = 0.85 Maximum = 13.02

Chlorophyll a (ug/L) Along Inner Western Track
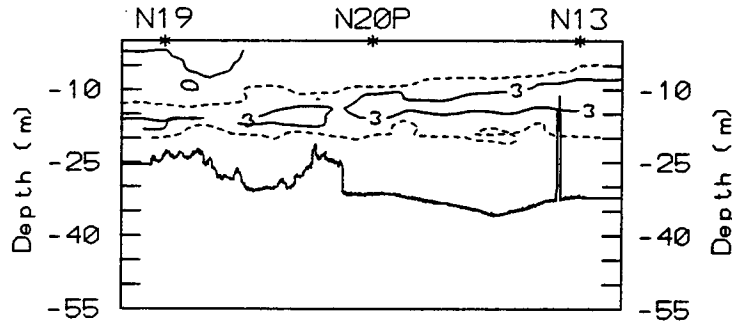
N114CH Minimum = 0.71 Maximum = 3.62

Chlorophyll a (ug/L) Along Inner Eastern Track
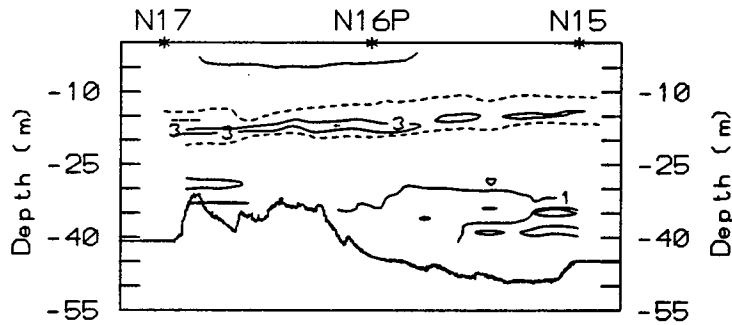
N116CH Minimum = 0.35 Maximum = 4.00

Chlorophyll a (ug/L) Along Outer Eastern Track
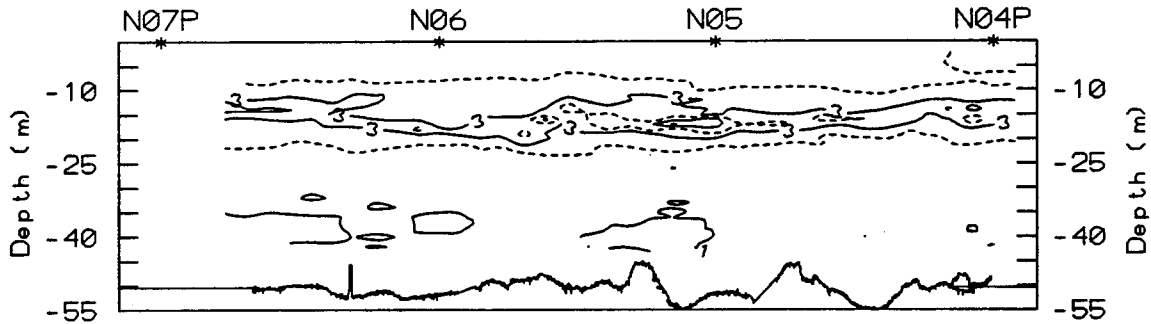
N118CH Minimum = 0.47 Maximum = 6.08

Figure 4-6b Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yos in September 1992. The view is towards Boston Harbor. The contour interval is 1 μg L^{-1}.

5.0 OCTOBER 1992 COMBINED FARFIELD AND NEARFIELD SURVEY RESULTS

5.1 Farfield Survey

5.1.1 Horizontal Distribution of Water Properties

In October, the sampling of surface waters of the Bay revealed only a small difference across the Bays (ranging from about 12 to 13.3 °C), but a latitudinal pattern down the Bays axis. These were slightly warmer temperatures at the southern end in Cape Cod Bay (Figure 5-1). In sharp contrast, surface salinity displayed a slight but general shore-to-sea gradient, but no latitudinal distinction (Figure 5-2).

Sigma-T (density) roughly parallelled the salinity pattern (Figure 5-3). High surface water density values (>23.8), in addition to being characteristic of offshore waters, were found along the coast off Nahant Bay and Salem.

Beam attenuation was not particularly high in surface waters and ranged only from about 1 to 1.6 m^{-1} (Figure 5-4). Lower values were observed offshore and in Cape Cod Bay and higher values were found outside Boston Harbor and along the South shore coast. Fluorescence roughly followed the pattern of beam attenuation and ranged from <2 to >5 μg L^{-1} (Figure 5-5). High values were seen in the middle of the Northern transect, in addition to being found outside the Harbor and at selected points along the South shore.

All dissolved inorganic nutrients showed a common feature of high surface water concentrations radiating out from the Harbor area (peaking at F24) into western Massachusetts Bay across most of the nearfield region (figures 5-6 to 5-10). Thus, the surface nutrients paralleled the salinity gradient in this area. Offshore and Cape Cod Bay stations still had virtually undetectable N in surface waters, but both phosphate and silicate were present in easily detectable concentrations at these locations.

5.1.2 Water Properties Along Selected Vertical Sections

Figure 5-11 shows the stations used in standard transects for which various parameters are contoured (Figures 5-12 through 5-16). The transects for temperature show that a two-layer system was still present

5-1

with a weak and usually broad pycnocline usually starting at about 15 to 20 m. Across the transects there was a gradual deepening of the thermocline to towards deeper waters. Bottom waters were less than 7 °C, but this was the maximum for the year to date. The depth of the 7 °C isotherm varied across the four transects (Figure 5-12).

There was small vertical structure for salinity across much of the Bays (Figure 5-13). Both the Boston - Nearfield and Cohasset transects suggest a coastal surface layer of fresher water; near the Harbor, this appears as a graded layer of water extending out to the middle of the nearfield between station N20P and N16P.

The transects for chlorophyll fluorescence showed either 1) uniform layers grading from highest values near the surface to lower values at about 20 to 30 m, with little chlorophyll below this, or 2) similar layers, but with an isolated patch of higher chlorophyll in near surfacewater. The Northern and Boston - Nearfield transects are examples of the latter and the Cohasset and Marshfield transects are examples of the former (Figure 5-14).

With respect to nutrients (Figures 5-15 and 5-16), DIN and silicate had similar patterns. In general, low (or depleted) concentrations graded rather regularly to high bottom water concentrations. There were some differences in the bottom water concentrations at similar depths across the four transects (see Figures). However, the most interesting pattern appeared across the Boston - Nearfield transect. DIN showed high surface water concentrations of DIN from F23P out to N20P, with a peak at F24. Silicate showed a similar gradient out from shore, but was highest at F23P, so the contours look a bit different.

5.1.3 Analysis of Water Types

High-resolution *in situ* data for all stations (Figure 5-17) showed that the temperature range was about 6.2 to 13.5 °C, with a salinity range of (mostly) 31.25 to 32.25 PSU. T-S plots by geographic station groupings (Figure 5-18) are given in Appendix C. The coastal and nearfield groups had some stations with fresher water at the surface compared to other groups, as also shown in the standard transect sections.

Associated with lower salinity was slightly higher beam attenuation and higher fluorescence (Figure 5-17). Higher beam attenuation was seen at high salinity (and low fluorescence) near the bottom of vertical profiles in some the deep basin stations. It is apparent from Figure 5-17 that the chlorophyll maximum often was distributed somewhat uniformly in a surface mixed layer, no longer being found regularly as a distinct deep subsurface maximum.

With respect to nutrients, there was a strong relationship between DIN and PO_4 (Figure 5-19). There was very little distinction among groups in the N/P pattern. Again, there was a positive intercept for P, i.e., phosphate was detected where DIN was virtually zero. But the *increase* of the two nutrients, with only a couple anomalous samples, showed nearly a 16:1 relationship. Slightly more scatter is apparent looking only at nitrate, primarily because many coastal and nearfield samples had a significant ammonia concentration, whereas offshore situations did not. The DIN—silicate relationship was not as strong as the DIN—PO_4 pattern, but there was little geographic distinction possible and most points had N/Si ratios of 1:1 or less (Figure 5-19). Several coastal water samples were notable exceptions, with slightly more enrichment of N relative to silicate, but even then the N/Si ratio was no more than 2:1.

Nutrient—salinity and nutrient—density plots showed a characteristic of higher values at lowest salinity (density), lowest values at intermediate salinity, and again some high values at higher salinity. Of course, the low salinity-high nutrients were a distinguishing feature of some coastal waters around Boston Harbor and a few nearfield stations. Ammonia concentration, independent of salinity, was a good discriminator for some of the near-Harbor stations because it did not increase as a function of depth (and therefore had no ascending arm at higher salinity). For higher salinity (deeper) water, no group discriminations are possible. The nearfield had a high degree of variation in nutrient content at a given salinity. Finally, at intermediate salinity there were some Cape Cod Bay samples that had relatively high silicate; these were at station F01 and F03, which may have been distinctive in part because the water column was relatively well-mixed physically.

Unfortunately, there were analytical problems with some of the PON samples. Reliable concentrations were available for about half of the samples, all but one being from the nearfield region (Appendix A). Thus, little can be said about the patterns of DIN and PON or total N relative to geography. However, Figures 5-24 and 5-25 do suggest that there was a factor of two variation in concentrations of these

combined forms of nitrogen in the nearfield and the plots begin to suggest that higher values might be associated with fresher and less dense water.

In summary, Table 5-1 compiles the range of surface conditions by geographic groups. In general, there were not strong physical differences within or among groups, either at the surface or over depth. Some coastal waters could be distinguished at the surface by slightly higher levels of chlorophyll, but rather readily also by higher nutrients. Deeper waters everywhere were similar with respect to nutrient content. Overall, only subtle trends across the two Bays were evident and stronger trends were seen as a function of distance from shore.

5.1.4 Distribution of Chlorophyll and Phytoplankton

Data from the discrete bottle sampling, with chlorophyll measured directly by standard extraction (rather than estimated from fluorescence), are displayed in Figure 5-26. The data confirm that Harbor-edge stations and the nearfield BioProductivity stations had generally higher chlorophyll than Cape Cod Bay stations. Chlorophyll and total phytoplankton counts were correlated (Figure 5-27). However, the Cape Cod Bay stations, like in late August, appeared to have higher counts per unit of chlorophyll than the main body of stations from western Massachusetts Bay.

Diatoms were generally more prevalent in October throughout the study region than had been the case in late August (Figure 5-28). Dinoflagellates were a minor component. The community was thus a mixed microflagellate—diatom community, where cryptomonads ("Other" in Figure 5-28) were also a significant component. Total counts across stations varied only within a about factor of two, a small range.

The dominant taxa were very similar across stations and across sample depths (Tables 5-2 and Table 5-3). Besides microflagellates and cryptomonads, there were three common diatoms — *Rhizoselenia delicatula*, *Leptocylindrus minimus*, and *Thalassiosira* sp. A second *Rhizoselenia* species, *R. fragilissima*, was among the dominants in Cape Cod Bay stations. Figures 5-29 to 5-33 give selected station examples. These provide additional demonstrations that the total composition and taxa abundances between surface and deeper samples usually were very similar — only a few minor taxa were found to vary notably in abundance as a function of depth.

There were similar large dinoflagellate taxa present across most stations and at different depths of a given station (Tables 5-4 and 5-5). Dinoflagellates were rare; few counts exceeded 100 individuals L^{-1} and most were less than 25 individuals L^{-1}.

5.1.5 Distribution of Zooplankton

Total zooplankton counts were in the range of 34,571 to 85,161 individuals m^{-3}. Other than the high (N10P) and low (F01P) samples, stations were not very different (Figure 5-33). As in August, copepods (adults, copepidites, and nauplii) constituted the majority of the community.

As had been the case all year, dominant taxa were *Oithona similis* and *Paracalanus parvus*. Oithona was the top dominant at every station except F23P at the edge of Boston Harbor, where *Acartia tonsa* was the top species. *Paracalanus* was ranked second in half the cases, the exceptions being F23P (*Oithona similis*), N10P and F13P (*Acartia tonsa*), F02P and F01P (*Centropages typicus*). Note that *Acartia tonsa*, typically thought of as estuarine species type, was also present to a significant level and N01P and N20P. In short, all coastal and nearfield areas proximal to Boston Harbor had *Acartia* among the top few dominants. Full taxonomic listing by stations is given in Appendix G.

5.1.6 Whole-Water Metabolism Incubations

For the P-I incubations, only station N20P at the surface was not fit by either model (see methods). More cases were fit by the hyperbolic function than the model with a photoinhibition term. Even those fit by the model with photoinhibition did not show strong depression of rates with irradiance as high as 1000 to 2000 μE m^{-2} sec^{-1}. As usual, maximum net production rates (P$_{max}$) were reached by about 200 to 500 μE m^{-2} sec^{-1}. Note that irradiance as a function of depth at each station is given in Appendix B.

Chlorophyll-normalized P$_{max}$ was about 15 to 25 μg O$_2$ (μg Chl)$^{-1}$ hr^{-1} in most cases and thus similar across the Bays. About three samples (N20P chl max, N04P chl max, and N04P surface) were lower than this, in the range of 5 to 10 μg O$_2$ (μg Chl)$^{-1}$ hr^{-1} and one was higher (F02P surface). Normalized and volumetric rates are given in Appendix E, along with all P-I graphs. Figure 5-34 shows two examples of well-modeled P-I relationships.

With respect to dark respiration, t-tests for significance between initial and final dissolved oxygen concentrations showed that only six out of 30 cases (= 3 depths times 10 BioProductivity stations) had significantly lower final values. These cases occurred either at the surface or chlorophyll maximum sampling depth, none were in deeper bottom water (see Appendix E).

5.2 Nearfield Survey

5.2.1 Distribution of Water Properties from Vertical Profiling

A temperature-salinity scatter plot for the nearfield stations, from high-resolution *in situ* data, is shown in Figure 5-35. The data from the 21 stations form a fairly tight group, and the range of temperature was restricted, and salinity was slightly higher, compared to the previous month. The stations where surface salinity was a bit lower cause the bend in the upper left of the T-S cloud.

Beam attenuation was measured to be over a small range, but in general it still reflected chlorophyll (fluorescence) concentrations (Figure 3-35). Chlorophyll was highest in the lightest water near the surface and Figure 5-35 shows that most stations had high chlorophyll fairly uniformly throughout the surface layer, dropping sharply to low levels below.

Figure 5-36, which provides the maximum chlorophyll observed at each vertical profile independent of its depth of occurrence, provides a perspective on the data — the field did not have a high degree of variation in the intensity of chlorophyll biomass. Nevertheless, a spatial pattern was evident. The pattern showed a body of water in the middle of the field that had lower values (<4 μg L^{-1}). Surrounding waters had slightly higher maxima, and the highest for the field was seen in the southwest corner at N10P, which was sampled near mid-tide on an ebbing cycle.

The range in surface (0-10 m) DIN concentrations in the nearfield was from near zero to about 7 μM (Figure 5-37). Most surface samples were less than 3 μM; it was primarily the inshore corner stations (N10P, N01, N02), and also N20P, that had some higher surface DIN. Aside from those few samples, there was a strong pattern of DIN with depth in this nearfield group of stations. Concentrations rose sharply to as high as 10 to 12 μM below 20 to 30 m.

5.2.2 Distribution of Water Properties from Towing

On October 17, the entire track of the inner and outer boxes were towed. The sequence was the inner box first, counterclockwise starting at N19, followed by the outer box, also counterclockwise from N10P and returning there. Temperature sections for the tracks are given in Appendix D, sigma-T and chlorophyll are given in Figures 5-38 and 5-39, respectively.

The density plots show a fairly uniform field, with the weak pycnocline from about 12 to 25 m, a bit deeper offshore along the eastern edge. The only disruptions of this weak stratification were detected near the middle of the field (N18-N17) and, more notably, at the southwestern corner (N10P), which was stratified at the second occupation, but not the first (Figure 5-38a).

Compared to the smoothness of the physical structure, chlorophyll distribution was much more patchy. In general, there was a chlorophyll surface layer, extending to near the top of the pycnocline, that had chlorophyll levels of about 3 μg L^{-1}. However, this was highly discontinuous horizontally or was sometimes overlain by higher values; the effect of the discontinuities is to suggest surface patches of higher or lower concentrations. As examples, high-chlorophyll patches were near N11 and N02 and a low-chlorophyll patch was near N19 (Figure 5-39a).

5.2.3 Water Types and Analysis of Small-Scale Variability

The preceding section gives a sense of spatial variability in surface biology (chlorophyll) that is not fully explained by physical variability. Whether the chlorophyll variations, which are not large, were coupled with geochemical variations might be possible to discern with further analysis of these survey data.

Again, short-term temporal changes were seen at stations visited twice in the towing day. For example, N19 visited near low tide had chlorophyll lower than it did when it was revisited about 4 hrs later. Station N10P had higher surface chlorophyll on its second visit, with low tide approaching (Figure 5-39b).

Overall, the nearfield at this time did not have a wide range of physical, chemical, or biological properties. The major processes creating variability appeared to be the fresher outflow of higher-nutrient water from inshore and tidal action — both most influential along the shallower side of the field.

TABLE 5-1. ANALYSIS OF SURFACE WATER TYPES

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 - 12.9	30.8 - 31.4	~1.3 - 1.6	3 - 5	Medium-to-high N and Si
Northern Transect	Transect along northern entrance to Mass. Bay, (F20-F22) surface water	<12 - 12.6	<31.4 - 31.5	~1.2 - 1.3	3 - 5	Low N and Si
Nearfield	Within nearfield sampling grid	~12 - 12.5	31.2 - 31.4	~1.3 - 1.4	2 - 3	Medium N and Si
Offshore	Mainstem Mass. Bay (~ greater than 40m)	12.4 - 12.9	31.4 - 31.6	~1.2 - 1.4	2 - 3	Low N and Si
Cape Cod	All Cape Cod Bay stations	~13 - 13.5	31.3 - 31.7	<1 - 1.3	<2 - 3	Low N, low-medium Si

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-μm 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 2000μE/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.

Additional sampling was done in late August and October to estimate bottom water dark respiration (oxygen). 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.

In October, for a limited set of stations, production at saturating light intensities was also measured using the ^{14}C technique. Methods and results of these measurements, and comparisons with oxygen measurements, are presented in Appendix H.

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.

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-μ 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-μm 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-μm 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-μm 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).

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

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

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

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

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

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. Copepod nauplii of small species cannot be reliably separated into genus under a dissecting scope. Therefore, 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. 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. The routine sampling scheme for the September nearfield survey did not provide bottle samples that coincided with the lowest readings by the sensor. The extrapolations using sensor data for that survey are thus to be viewed with caution.

2.4 Data Management and Processing

Samples were given unique sample/event identification numbers or specially coded with event identifier information. 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

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

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

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 LATE AUGUST 1992 COMBINED FARFIELD AND NEARFIELD SURVEY RESULTS

3.1 Farfield Survey

3.1.1 Horizontal Distribution of Water Properties

In late August, the range in near surface water temperature was about 17.2 to 19.6 °C (Figure 3-1) throughout Massachusetts and Cape Cod Bays (hereafter, the "Bays"). There was no obvious general temperature distinction between the Bays. Nearshore surface water temperatures were often ≤18 °C; this was so for western Massachusetts Bay just offshore from the Boston Harbor area and the western shore of Cape Cod Bay. An exception was a warmer nearshore cell along the coast from about Cohasset to Marshfield, for which the temperature was ≥19.25 °C. Offshore in both Bays, surface temperatures were generally >18 °C and the highest values were observed in Massachusetts Bay.

Salinity in near-surface waters ranged from about 30.4 to over 31 PSU (Figure 3-2). Highest values were in the middle of the region. Fresher water was noted around Boston Harbor and hugging the coastline to the South. Accordingly, a density gradient was seen radiating from Boston Harbor and away from shore along the South shore from Cohasset to Marshfield (Figure 3-3). A tongue of denser water (<30.8 PSU and density <21.9 [Figure 3-3]) appeared at the northern edge of Massachusetts Bay offshore. Cape Cod Bay stations had a small range of surface salinity, about 30.8 to 30.9 PSU and also a small range in density (Figure 3-3).

Beam attenuation was high along the coast of western Massachusetts Bay and graded outward from Boston Harbor, Nahant, and Cohasset (Figure 3-4). Otherwise, surface waters offshore and through Cape Cod Bay had fairly low beam attenuation, from about 1.0 to 1.4 m^{-1}. The pattern for fluorescence was very similar to that of beam attenuation (Figure 3-5). Peak surface fluorescence was seen at the northwest corner of the nearfield (N01P) off Nahant. Values >2 μg L^{-1} were observed from Boston Harbor through the middle of the nearfield and, coastally, north of Cohasset and off Plymouth. Offshore and Cape Cod Bay had low fluorescence in surface waters.

Dissolved inorganic nitrogen (DIN) was low in surface waters throughout the Bays. Slightly higher values were apparent outside Boston Harbor and in western Cape Cod Bay off Plymouth (Figure 3-6).

3-1

Nitrate was virtually depleted, except at Boston Harbor, and ammonia was the primary form of N in DIN where it exceeded 1 μM (Figures 3-7 and 3-8).

In contrast to DIN, both phosphate and silicate were detectable throughout the surface waters in the Bays (Figures 3-9 and 3-10). Surface water geographical distributions of both phosphate and silicate were similar to DIN however, in that higher values were coastal — particularly those at the station at the edge of Boston Harbor.

3.1.2 Water Properties Along Selected Vertical Sections

The water column was strongly stratified. For individual station profiles see Appendix B; here we show sections from standard transects (Figure 3-11). For temperature (Figure 3-12), there was no distinct surface layer, but usually a gradual decrease from 17 to 19 °C at the surface to about 7-9 °C at about 20-30 m. Deepest bottom waters were about 5 °C. Station F23P, at the exit to Boston Harbor, was mixed nearly top to bottom; otherwise, the isotherms extending from shallow to deeper waters were rather smooth across the four sections. Note that the eastern half of the nearfield between N20P and N16P and eastward (towards F19) on the Boston-Nearfield transect was deep enough to have bottom waters that were sub-thermocline ($\approx$ 35-40 m, roughly the 7 °C isotherm). Offshore, the main thermocline was somewhat shallower (e.g. F07 to F12 on Marshfield Transect, which extends over Stellwagen Basin).

In general, salinity sections had patterns similar to temperature (Figure 3-13). Bottom waters were usually > 31.7 PSU and were > 31.9 PSU in deep waters of Stellwagen Basin. A finger of less saline water was evident from Boston Harbor to the surface near station N20P located in the middle of the nearfield. This station was near a transition point marking the intersection of offshore and inshore waters along the Boston - Nearfield transect (see also density sections, Appendix C). A surface feature of slightly less saline water was shown also across the Cohasset transect.

Characteristically, a mid-depth fluorescence maximum of about 2.5 μg L^{-1} was seen most everywhere across the transects, centered at approximately 20 m, or within the pycnocline (Figure 3-14). Shallower, near-coastal waters (e.g., F20 of the Northern transect; F23P, F24, and N20P of the Boston-Nearfield transect, and F05 of the Marshfield transect) usually had higher fluorescence values (about 5 to 10 μg L^{-1})

and these were found closer to the surface than elsewhere. The high values along the Boston - Nearfield transect appeared to be associated with water shoaling from the Harbor (near the surface of F24), or at 10-15 m depth at stations seaward of the transition between inshore and offshore water (between stations F24 and N20P).

Nutrient distributions are shown across the transects in Figures 3-15 and 3-16. Excepting Boston Harbor, DIN was uniformly low (<1 μM) to about 20 m depth, the position of the characteristic subsurface chlorophyll maximum. Below this, concentrations increased, sharply in most cases to values of 6 to 10 μM. Interestingly, DIN in bottom water below 20 m across the Boston - Nearfield transect was somewhat lower than at equivalent depths at the other transects; silicate did not show this same anomaly. Silicate concentrations generally increased throughout the water column to near-bottom water values of about 9 to 14 μM, the highest values being at depth in Stellwagen Basin. The transition of inshore-offshore waters along the Boston - Nearfield transect was evident as a shoaling of higher silicate toward the surface at F24.

3.1.3 Analysis of Water Types

Table 3-1 summarizes the range of various parameters in the surface waters throughout the Bays by geographic station groupings; much overlap among water properties was seen. High resolution data from all vertical profiles (Appendix B), surface to bottom, have been used to produce scatter plots (Figure 3-17). The composite plots show all stations throughout the Bays; plots by station groups (as in Figure 3-18) are given in Appendix C.

The total range in temperature was from <5 to about 20 °C. The accompanying range in salinity was about 30.5 to almost 32 PSU. Deep basin water was therefore still cold and saline, not very affected by the seasonal warming of the upper waters. There were not marked differences in the T-S relationship by station groups. For example, the Cape Cod Bay stations had virtually the same T-S plot as the Northern Transect stations. There were some small differences among individual stations. Salinity and temperature were slightly lower, towards the surface only, at a few of the coastal stations (Boston Harbor). Additionally, the nearfield appeared to have some stations similar to near-Harbor coastal waters and others exactly like offshore waters.

Beam attenuation, well correlated with fluorescence (Figure 3-17). Both reached high values at lower salinity; attenuation generally dipped to low values at salinity greater than 31 PSU. Interestingly, beam attenuation (but not fluorescence) rose slightly in near-bottom waters, especially Stellwagen Basin, and this was seen as a slight increase at high salinity near the bottom of some vertical casts (Appendix B).

As noted previously, higher fluorescence values were seen to peak at an intermediate depth of about 20 m (and intermediate density values), as shown in Figure 3-17. But, for both coastal stations and nearfield stations that had inshore water properties, even higher chlorophyll was noted nearer the surface, i.e. above 15 m. There was no strong relation between dissolved oxygen and fluorescence across the stations (Figure 3-17). Dissolved oxygen varied only over about a 3 mg L^{-1} range over all Bays sampling. One can consult the vertical profiles for relationships between dissolved oxygen and depth across the stations.

To assess geochemical variations among the standard station geographic groupings (Figure 3-18), we examined nutrients relative to each other and to physical properties of salinity and density. To begin, plots of N vs. P (Figure 3-19a) suggested that 1) there was little ability to discriminate among groups with respect to N/P ratios, 2) that phosphate was detectable where little or nitrate (NO_3) or DIN was detected, and 3) most samples had an N/P ratio less than 8:1. The graph depicts an *increase* in N and P from near surface values (with a phosphate intercept and zero N) to high values at depth. Note that this *increase* follows about a 16:1 ratio; i.e. the increases nearly parallel the 16:1 isopleth even though there is an offset.

There was also a significant amount of silicate detected when N forms were depleted (Figure 3-19b). For samples below the surface, many offshore and Northern Transect stations had slightly higher N for a given silicate concentration — these had N/Si ratios around 1:1. In contrast, most coastal, nearfield, and Cape Cod Bay deeper waters had N/Si ratios about 1:2 or less. Note that the difference between DIN and NO_3 vs. silicate and phosphate plots is small because there was not much ammonia.

Examination of nutrients relative to salinity or density (Figures 3-20 to 3-25) showed in general that nutrients were highest at high salinity or density (deeper waters) and were also slightly enriched at some low salinity coastal and nearfield stations. Offshore stations tended to have lower ammonia concentrations at high salinity (bottom waters) than other groups (Figure 3-21). Moreover, the offshore group also tended to have slightly lower phosphate and silicate than other groups, comparing equivalent salinity

samples at salinity >31.2. In part this may be because a given salinity tended to be nearer the surface offshore. The coastal group of stations had about the highest silicate concentrations associated with high salinity samples and Cape Cod Bay, along with the coastal group, had relatively high phosphate at higher salinity. The nearfield had samples with geochemical signatures in some cases that were consistent with inshore coastal water and in other cases that were consistent with the offshore or Northern Transect group.

Total dissolved nitrogen (TDN) ranged from about 5 to 15 μM (Appendix A) across the stations and was highest at stations F23P and F25 (exit points from Boston Harbor), in addition to N10P (the southwest corner of the nearfield, which receives Harbor water — Kelly *et al.*, 1992, 1993) and F13P (off Cohasset). PON was generally about 2-6 μM. Most of the DIN and PON fraction thus was as PON. There was a pattern of DIN and PON with salinity (Figure 3-24). If one draws a conservative mixing line between fresher and saltier endmembers, the points largely fall below the line, which suggests a sink for nitrogen at intermediate salinities. Note that a range of DIN and PON concentrations were observed at a given σ_T surface (Figure 3-24). For example, the higher concentrations (15-20 μM) at low σ_T are from stations near the Harbor and illustrate the Harbor's input of N when compared to some nearfield stations that had 5-10 μM N at the same σ_T surface. These comments also apply for total N (TDN and PON), as shown in Figure 3-25.

The water mass properties of surface waters are summarized in Table 3-1. In capsule, some geochemical distinctions are evident in the more offshore waters among different parts of the Bays, but there are not really any marked physical-property distinctions. The main differences apparent across the Bays seemed related to coastal and inshore processes at individual stations, especially around the Nahant-Boston Harbor-Cohasset area. The Harbor appeared to be acting as a freshwater, nutrient, and chlorophyll source to surface waters in western Massachusetts Bay, which was otherwise a relatively nutrient- and chlorophyll-poor condition.

3.1.4 Distribution of Chlorophyll and Phytoplankton

Figure 3-26 shows chlorophyll concentrations at the BioProductivity stations, based on standard chemical techniques. These samples were the basis for calibrating the fluorometer (Appendix B), and not surprisingly provide similar results. Highest concentrations (above 4 μg L^{-1}) were noted in the upper

12 m of coastal (Boston Harbor) and shallow nearfield stations, N01P, N10P, and N20P. In contrast, for example, the two Cape Cod Bay stations had higher chlorophyll at about 15 m depth, but even there the values were $\leq 3 \ \mu g \ L^{-1}$.

As shown in Figure 3-27, there was a strong linear correlation between chlorophyll and phytoplankton counts at the BioProductivity stations. Interestingly, station F01P and the surface sample at N07P seemed to have slightly higher cell counts than other samples, relative to chlorophyll.

The gross composition of the near-surface phytoplankton community is given in Figure 3-28. In general, there were few dinoflagellates. Most stations were dominated, numerically, by microflagellates, with cryptomonads ("Other") also being important. However, there were a few stations that were a mixed microflagellate-diatom community. These stations included, most notably, the surface samples of F23P at the edge of the Harbor, and N01P, N10P, and N20P in the nearfield — all cases where the total diatom community was in excess of 1 million cells L^{-1}.

Tables 3-2 and 3-3 show the phytoplankton composition of surface and deeper (whole-water) samples, in terms of the most dominant taxa. As noted, microflagellates uniformly dominated as the top taxa. Fewer diatoms were among the dominants in Cape Cod Bay, both in surface and deeper samples. The diatom community had a mixture of species, including *Chaetoceros* sp. ($>10 \ \mu$m), *Rhizoselenia delicatula*, and two species of *Leptocylindrus*. Interestingly, *Chaetoceros* sp. ($>10 \ \mu$m) and *Leptocylindrus minimus* were only in surface samples. On the whole however, there were not strong taxonomic differences (among dominants) noted between surface and deeper samples at the stations. The similarity in taxa between surface and deeper samples can be seen in plots for selected stations (Figure 3-29 to 3-32). Note that in one case (N04P) the surface concentrations were higher, but the dominants were similar. Replicate casts at station F02P were similar taxonomically (qualitatively and quantitatively) between surface and chlorophyll maximum samples, as well as between casts. F23P, probably the most well-mixed (physically) water column, had very similar composition and abundances in the two samples. F13P had slightly higher abundances of most dominants at the deeper sample.

Tables 3-4 and 3-5 show results of the special sampling for large dinoflagellates. The numerical abundances quantified by this method confirm that dinoflagellates were present in relatively low numbers throughout the Bays. Only one sample (N01P surface), which had very high numbers of total cells

Table 5-2. Top 5 dominant phytoplankton taxa in near surface samples collected in October 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) 0.442	(2) 0.623	(1) 0.586	(1) 0.609	(2) 0.549	(2) 0.435	(1) 0.629	(1) 0.553	(1) 0.887	(1) 0.784	(1) 0.553
Cryptomonads	(2) 0.206	(3) 0.363	(3) 0.149	(3) 0.205	(3) 0.146	(3) 0.253	(3) 0.250	(3) 0.351	(3) 0.274	(3) 0.179	(3) 0.258
Chaetoceros sp. <10 μm*										(5) 0.039	
Leptocylindrus minimus		(5) 0.046		(4) 0.055	(4) 0.062	(4) 0.087	(4) 0.112	(5) 0.034			(4) 0.072
Unidentified naked Dinoflagellate											
Rhizoselenia fragilissima										(4) 0.074	
Cerataulina pelagica											
Thalassiosira spp.			(4) 0.061	(5) 0.038	(5) 0.044		(5) 0.076	(4) 0.064			
Unidentified Centrales		(4) 0.051				(5) 0.030			(4) 0.026		
Rhizoselenia delicatula	(3) 0.199	(1) 0.797	(2) 0.383	(2) 0.234	(1) 0.837	(1) 0.616	(2) 0.567	(2) 0.518	(2) 0.360	(2) 0.398	(2) 0.496
Cyanophyceae	(4) 0.025										(5) 0.038
Rhizoselenia alata									(4) 0.026		
Thalassionema nitzschoides	(4) 0.025										
Merismopedia sp.			(5) 0.054								

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

Table 5-3. Top 5 dominant phytoplankton taxa near the chlorophyll maximum collected in October 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) 0.467	(1) 0.855	(1) 0.530	(1) 0.744	(1) 0.787	(2) 0.548	(2) 0.548	(2) 0.531	(1) 0.606	(2) 0.442	(2) 0.374
Cryptomonads	(3) 0.168	(3) 0.381	(3) 0.106	(3) 0.212	(3) 0.197	(3) 0.268	(3) 0.080	(3) 0.347	(3) 0.301	(4) 0.069	(3) 0.093
Chaetoceros sp. <10 μm*						(5) 0.023					
Leptocylindrus minimus	(5) 0.024	(5) 0.040	(5) 0.055		(4) 0.073	(4) 0.045	(5) 0.049	(4) 0.059			(4) 0.070
Unidentified naked Dinoflagellate				(5) 0.029							
Rhizoselenia fragilissima									(4) 0.088	(3) 0.076	(5) 0.042
Cerataulina pelagica				(4) 0.037							
Thalassiosira spp.	(4) 0.041		(4) 0.079		(5) 0.050		(4) 0.053	(5) 0.046			
Unidentified Centrales		(4) 0.058							(5) 0.042		
Rhizoselenia delicatula	(2) 0.190	(2) 0.832	(2) 0.421	(2) 0.278	(2) 0.590	(1) 0.544	(1) 0.844	(1) 0.590	(2) 0.539	(1) 0.598	(1) 0.581
Cyanophyceae						(5) 0.023					
Rhizoselenia alata										(5) 0.045	
Thalassionema nitzschoides							(5) 0.049				
Merismopedia sp.											
Prorocentrum minimum		(5) 0.040									

(): rank; taxa are included if >4 individuals were counted
Number: millions of cells L^{-1}
*May be C. socialis

Table 5-4. All identified taxa in near surface screened (20 um) samples collected in October 1992.

SPECIES	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P	F02P-2
CERATIUM FUSUS		78	12	50	71	26	48	23	143	168	111
CERATIUM LINEATUM			5								
CERATIUM LONGIPES		18	6	15	11	3	9	5	11	17	18
CERATIUM SPP.	2	6			3			3			
CERATIUM TRIPOS		50	8	63	77	8	26	8	101	95	56
DICTYOCHA FIBULA						2					
DICTYOCHA SPECULUM	9	14	26	6	18	17	24	14	8	11	5
DINOPHYSIS ACUMINATA							2		3		
EBRIA TRIPARTITIA		9	5	3	5	3	9	17		2	3
GONYAULAX SPINIFERA						2					
GYMNODINIUM SPP.			3	2		2				3	
GYMNODINIUM SPP. (30UM)									6		
GYRODINIUM SPIRALE	5		2	8		8		26			
GYRODINIUM SPP.		5	5	8	32	6	15		3		17
HETEROCAPSA TRIQUETRA			3			3	3				
HETEROSIGMA AKASHIWO								6			
MESODINIUM RUBRUM	6	5	41	5	5	3	2	32		2	
OBLEA SPP.			3		11	3	5	2			
PROROCENTRUM MICANS	11	5	26	6	15	12	11	62			
PROROCENTRUM MINIMUM	20	9	20	8	11	9	8	33	21	11	3
PROROCENTRUM TRIESTINUM	5										
PROTOPERIDINIUM (CF) BREVIPES											
PROTOPERIDINIUM DEPRESSUM					2		2				
PROTOPERIDINIUM PELLUCIDUM	2		5		2	12	2	11			
PROTOPERIDINIUM PENTAGONUM					3	2	5			3	
PROTOPERIDINIUM SPP.	65	141	51	27	189	107	81	98	62	56	
PROTOPERIDIUM MINUSCULLUM					6	2		2			3
SCENEDESMUS SPP.			2								
SCRIPPSIELLA TROCHOIDEA	6	2	3			6	5	3	6	2	

Values are cells/L

Table 5-5. All identified taxa near the chlorophyll maximum in screened (20 um) samples collected in October 1992.

SPECIES	F23P	F13P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P	F02P-2
CERATIUM FUSUS		95	5	74	90	5	69	11	90	146	227
CERATIUM LINEATUM				3							
CERATIUM LONGIPES	3	17	6	20	32	3	23	3	5	24	30
CERATIUM SPP.		8			5		2				
CERATIUM TRIPOS		81	3	33	59	3	44	11	78	132	171
DICTYOCHA FIBULA											
DICTYOCHA SPECULUM	3	18	8	3	11	9	8	9	9	6	15
DINOPHYSIS ACUMINATA											
EBRIA TRIPARTITIA	9	2	12	3	5	2	3	8		2	3
GONYAULAX SPINIFERA				2		3					
GYMNODINIUM SPP.		5	6	3	2			2			5
GYMNODINIUM SPP. (30UM)											
GYRODINIUM SPIRALE	5		3	9		12		5			3
GYRODINIUM SPP.	2	23	3	33	5	5	20	18		5	14
HETEROCAPSA TRIQUETRA			2					2			
HETEROSIGMA AKASHIWO	2					3			3		
MESODINIUM RUBRUM	17	8	23	18		8	2	11	2		
OBLEA SPP.	5				9	5	6				
PEDIASTRUM SPP. COLONY	2										
PROROCENTRUM MICANS	18	26	18	5	5	18	6	36	8	11	12
PROROCENTRUM MINIMUM	6	12	27	23	14	21	8	27			
PROROCENTRUM TRIESTINUM			2								
PROTOPERIDINIUM (CF) BREVIPES								2			
PROTOPERIDINIUM DEPRESSUM	2			2	2	2		5			
PROTOPERIDINIUM PELLUCIDUM	9		11		2	5	3	5	2	5	
PROTOPERIDINIUM PENTAGONUM		5	2	2		6	2	2			
PROTOPERIDINIUM SPP.	50	176	101	83	123	144	200	56	38	24	41
PROTOPERIDIUM MINUSCULLUM	2		2			2	2				
SCENEDESMUS SPP.											
SCRIPPSIELLA TROCHOIDEA	5	5	5	2		3					

Values are cells/L

SURFACE TEMPERATURE – OCT 1992
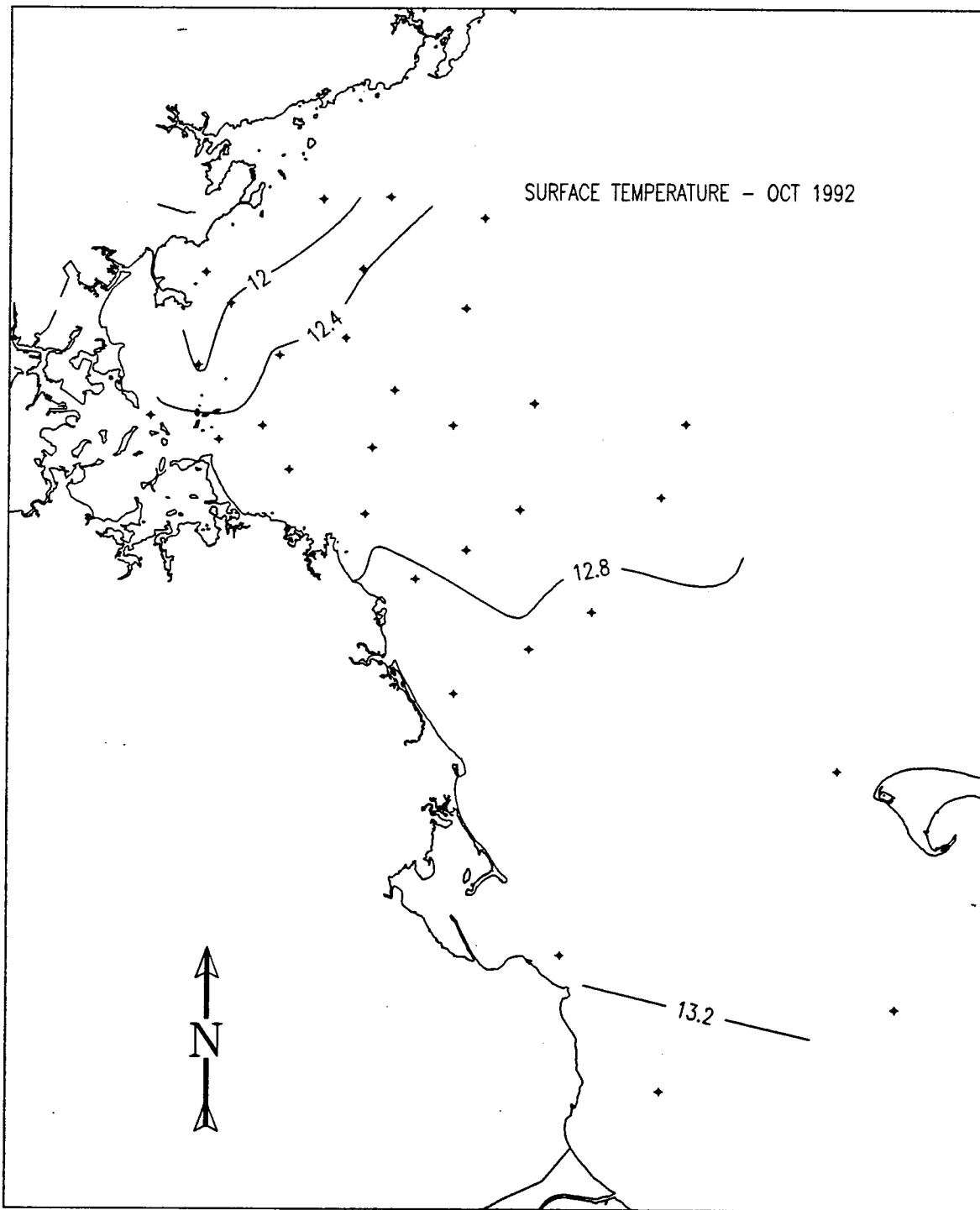
Figure 5-1 Surface temperature (°C) in the region in October 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.4°C.
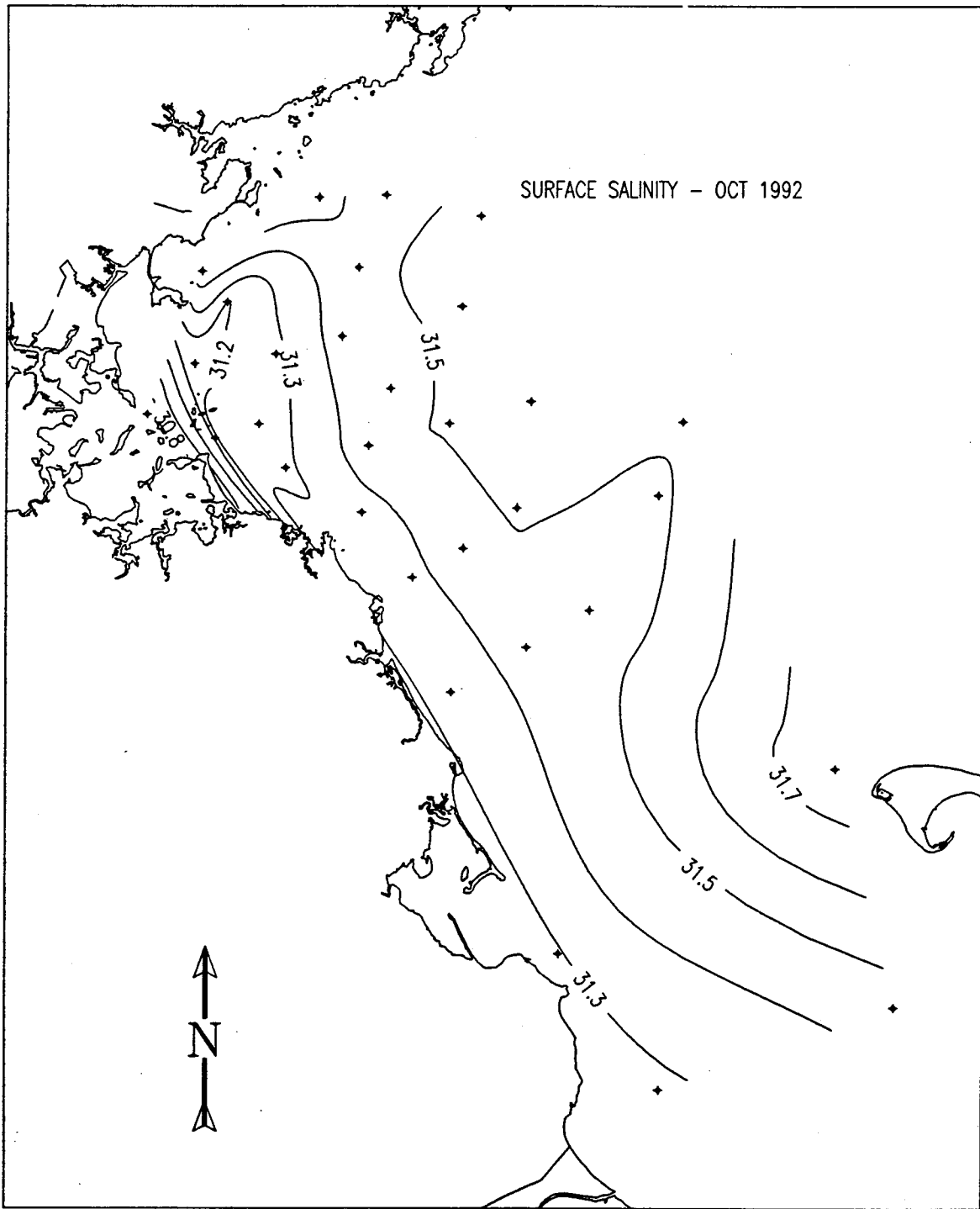
Figure 5-2 Surface salinity (PSU) in the region in October 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.1 PSU.

Figure 5-3   Surface σ_T in the region in October 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 units.

SURFACE BEAM ATTENUATION – OCT 1992
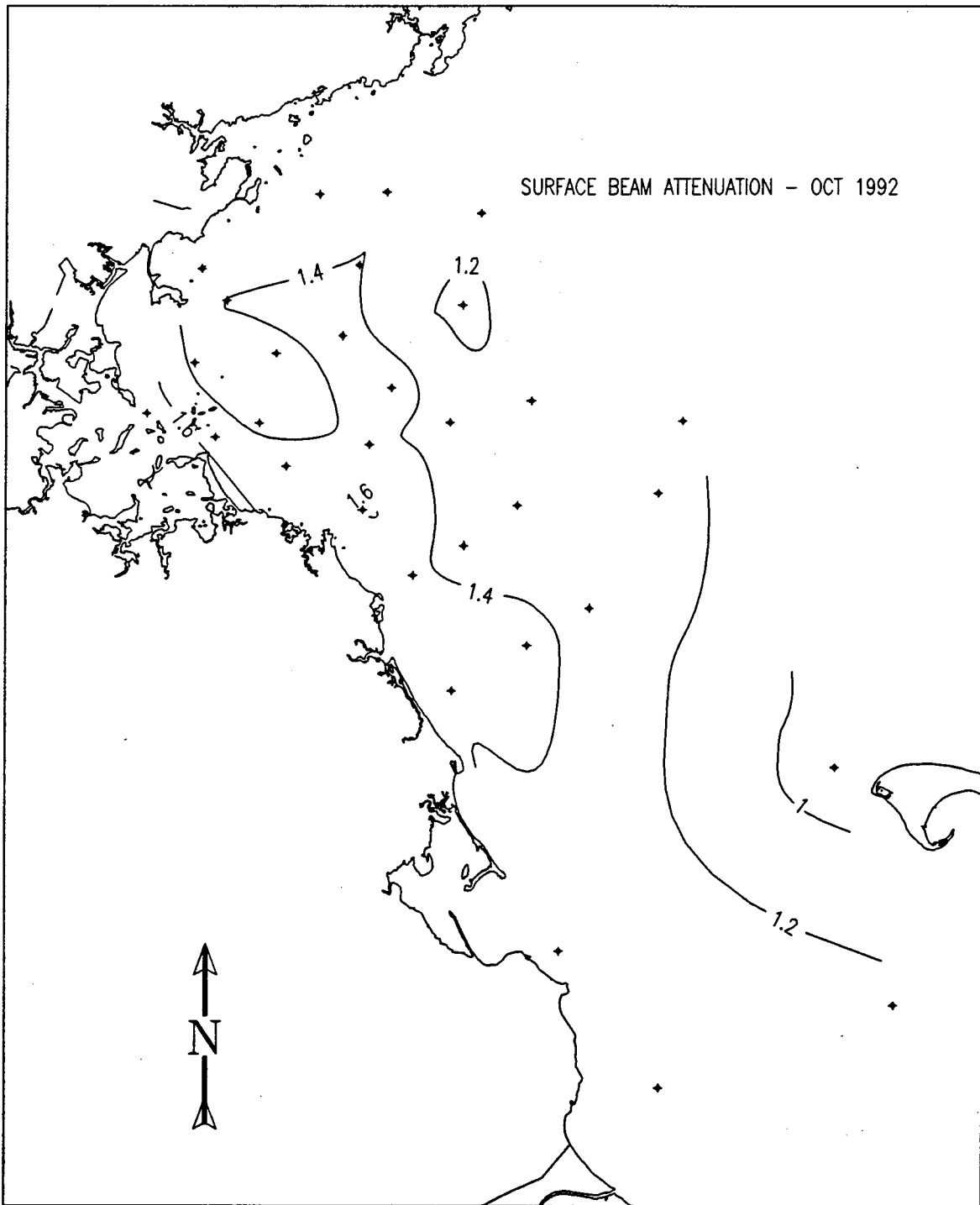
Figure 5-4 Surface beam attenuation (m^{-1}) in the region in October 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.2 m^{-1}.

SURFACE FLUORESCENCE – OCT 1992
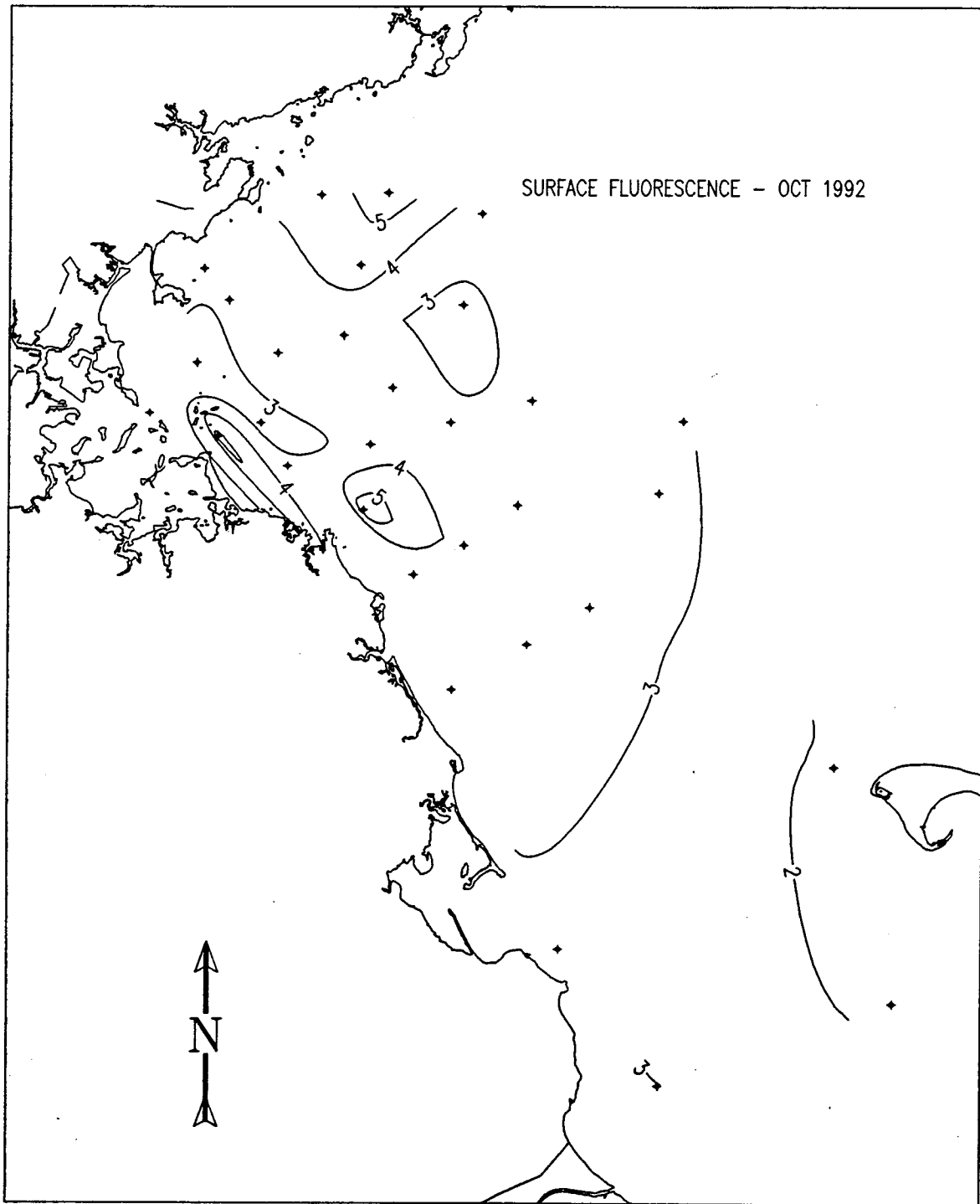
Figure 5-5   Surface *in situ* fluorescence (as μg Chl L^{-1}) in the region in October 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 μg L^{-1}.

SURFACE DISSOLVED INORGANIC NITROGEN - OCT 1992

Figure 5-6   Surface dissolved inorganic nitrogen (DIN, μM) in the region in October 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.

SURFACE AMMONIA — OCT 1992
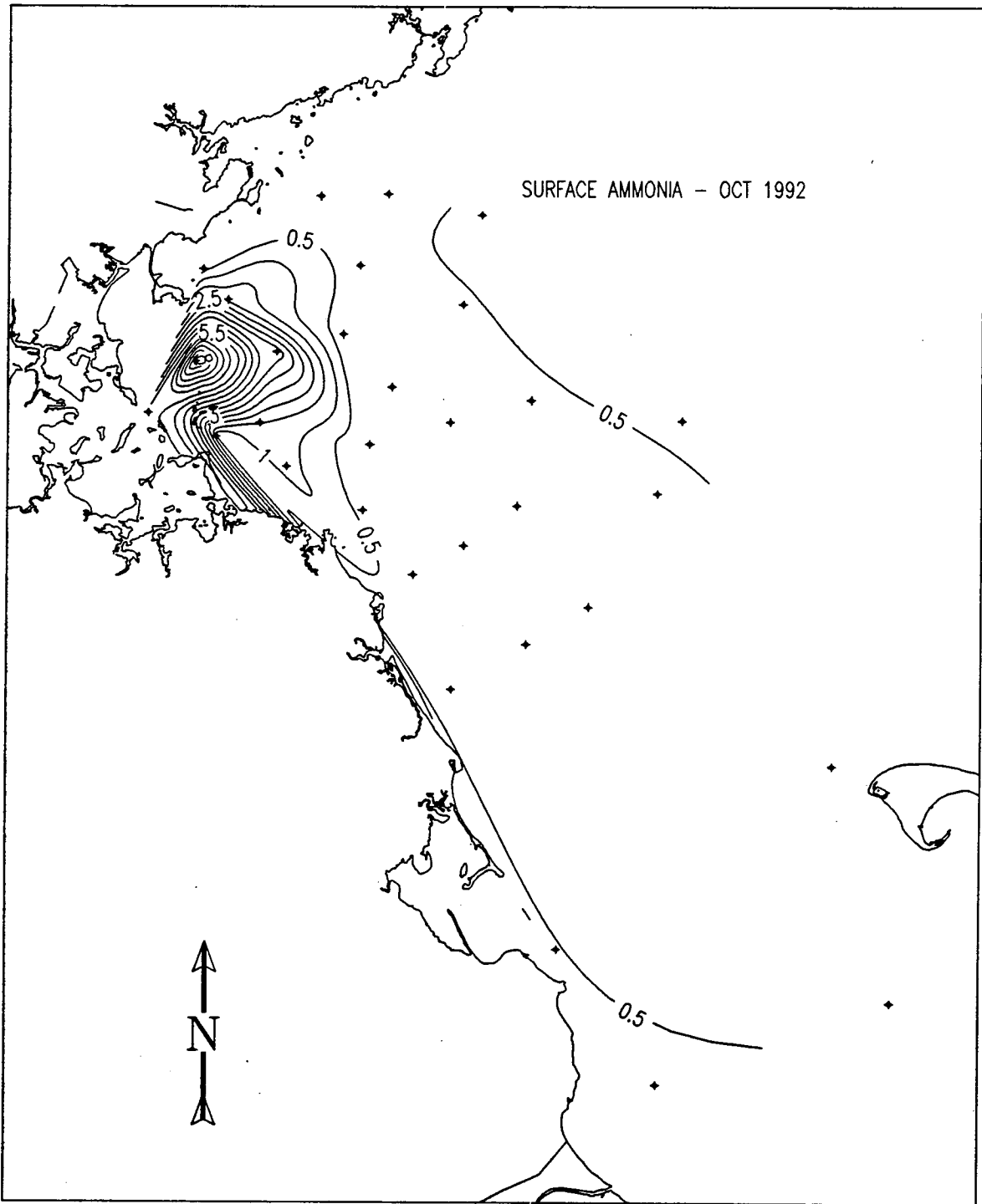
Figure 5-7   Surface ammonia (μM) in the region in October 1992. Data are from Appendix
A, the surfacemost sample at all farfield survey stations, including the
BioProductivity stations within the nearfield grid. The contour interval is 0.5
μM.
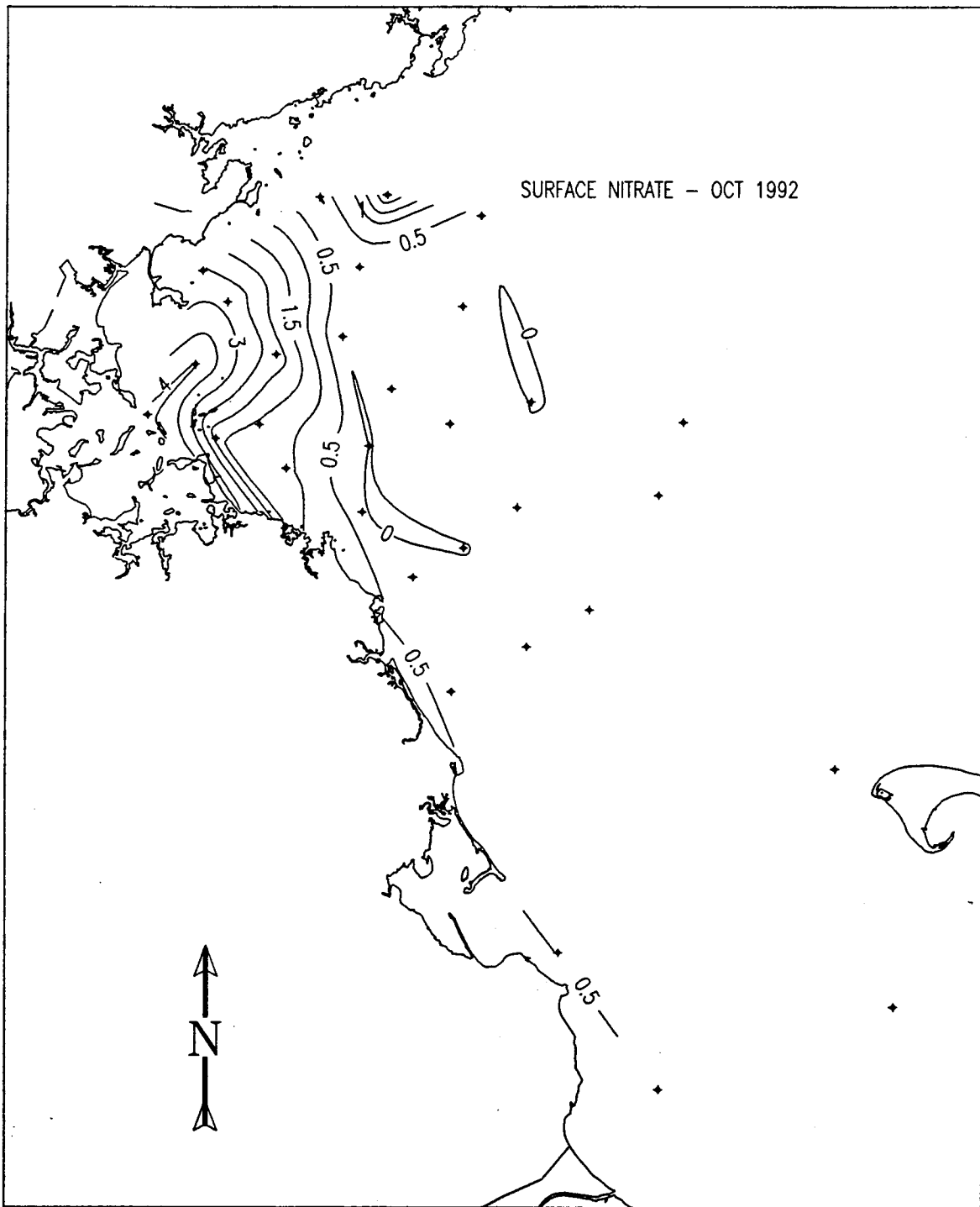
Figure 5-8 Surface nitrate (μM) in the region in October 1992. Data are from Appendix A, the surfacemost sample at all farfield survey stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.5 μM.
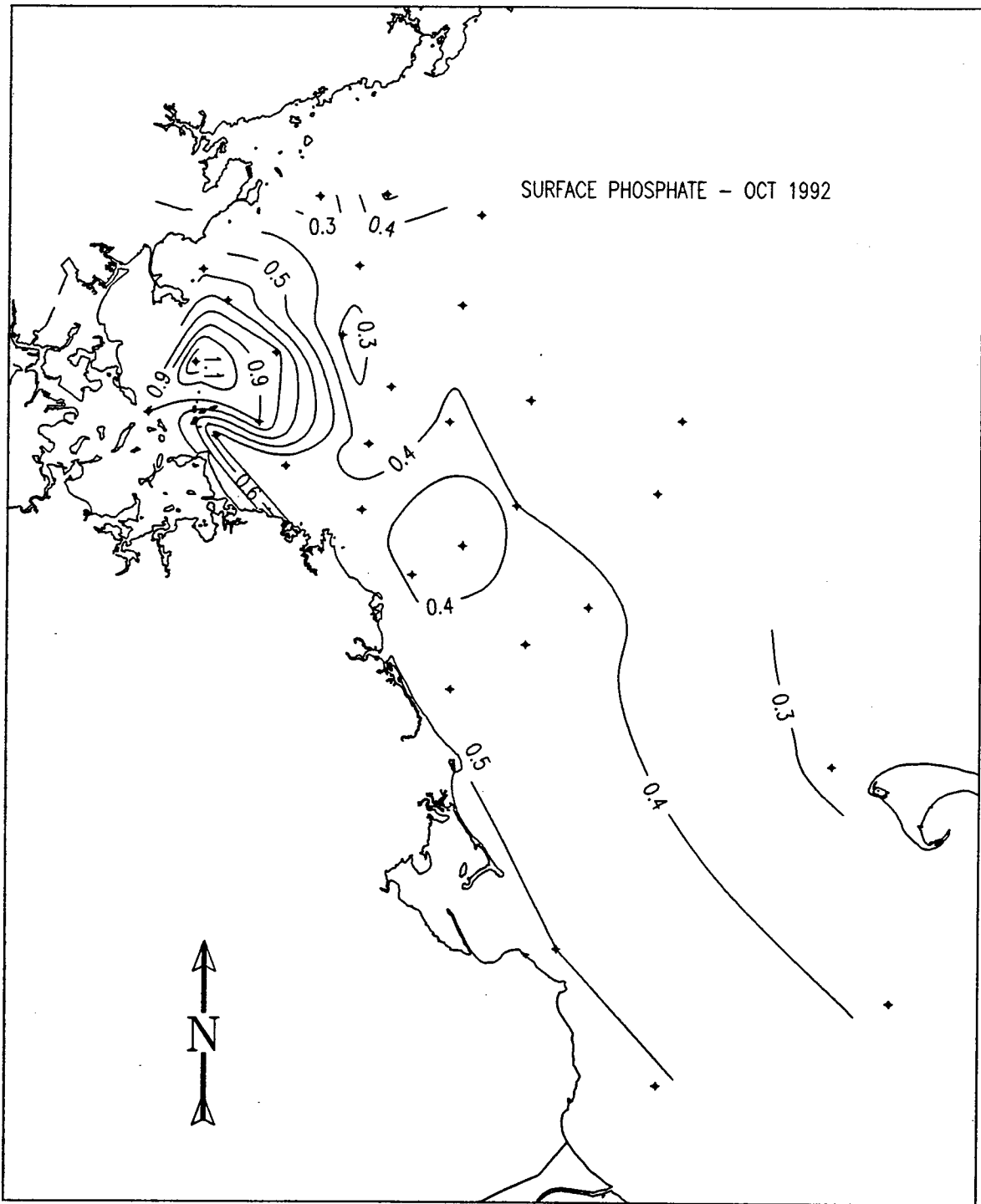
Figure 5-9 Surface phosphate (μM) in the region in October 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 0.1 μM.
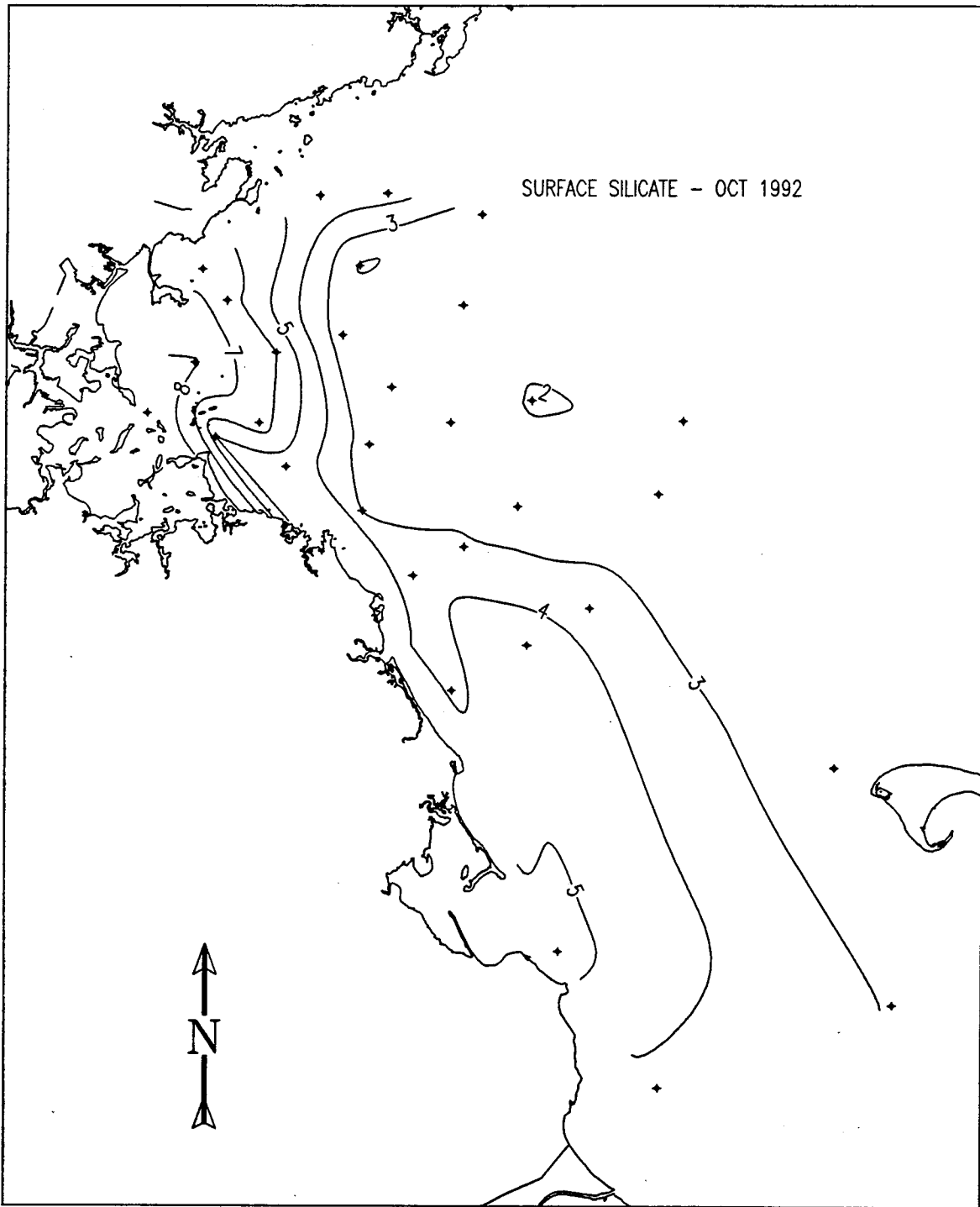
Figure 5-10   Surface silicate (μM) in the region in October 1992. Data are from Appendix A, the surfacemost sample at all farfield stations, including the BioProductivity stations within the nearfield grid. The contour interval is 1.0 μM.

NORTHERN TRANSECT (1)

BOSTON – NEARFIELD TRANSECT (2)

COHASSET TRANSECT (3)

MARSHFIELD TRANSECT (4)
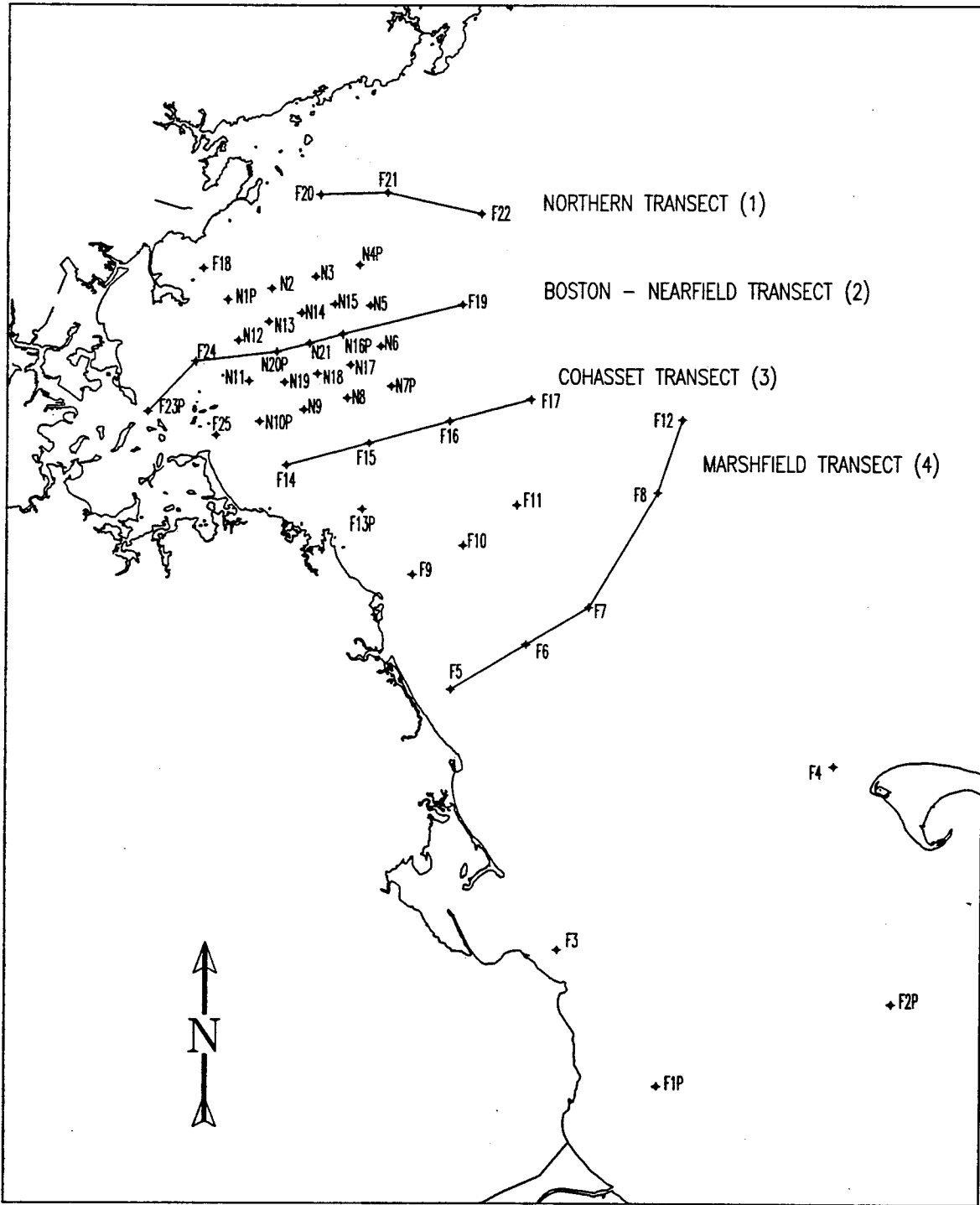
Figure 5-11   **Map showing position of four standard transects for which vertical contour plots were produced in following Figures 5-12 to 5-16.**

NORTHERN TRANSECT (T061TE)

Minimum = 6.60 Maximum = 12.60

BOSTON - NEARFIELD TRANSECT (T062TE)

Minimum = 6.85 Maximum = 12.49

COHASSET TRANSECT (T063TE)

Minimum = 6.30 Maximum = 12.65

MARSHFIELD TRANSECT (T064TE)

Minimum = 6.23 Maximum = 13.21
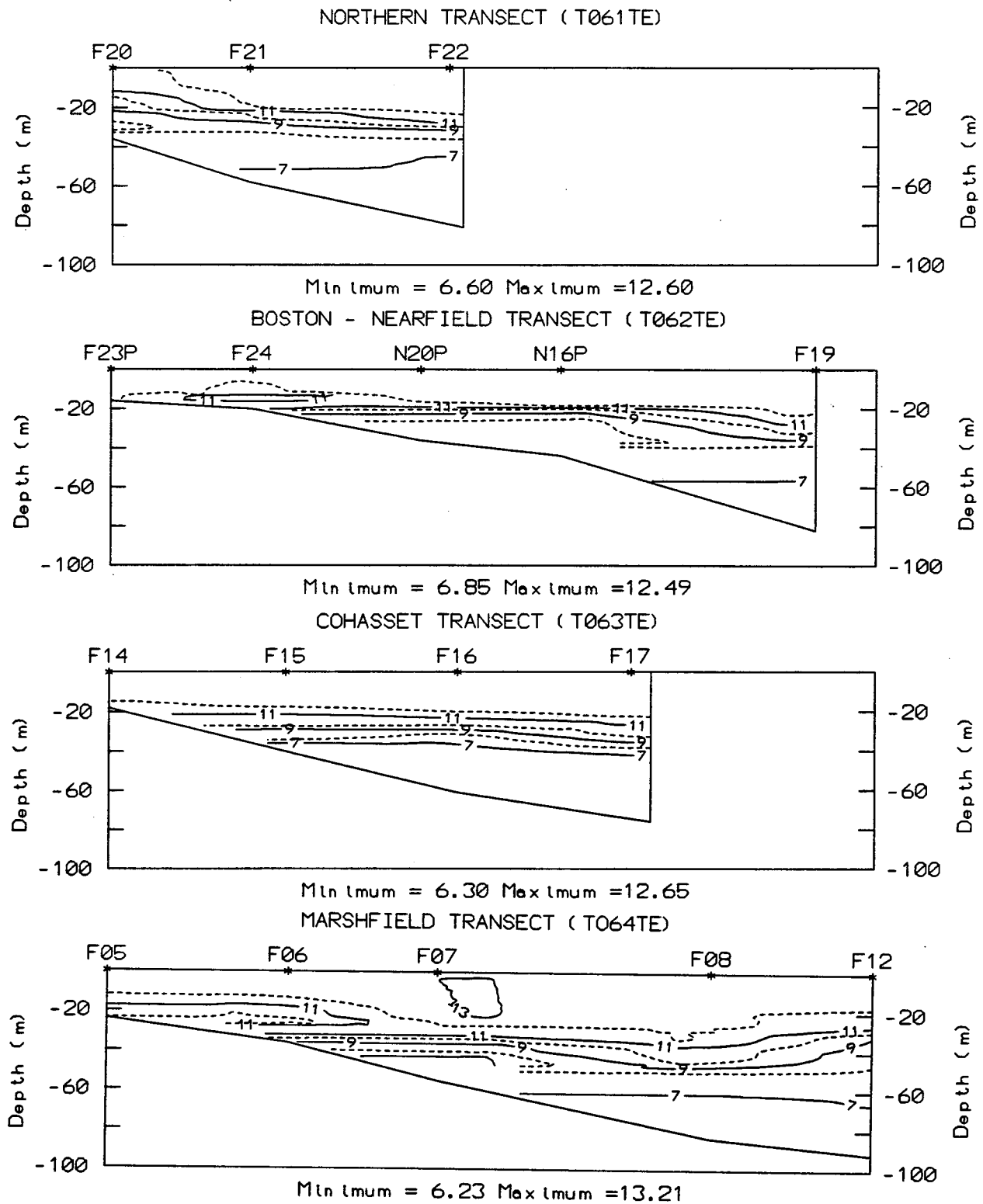
Figure 5-12 Vertical section contours of temperature in October for standard transects (see Figure 5-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 1.0°C.

NORTHERN TRANSECT (T061SA)

Minimum =31.45 Maximum =32.24

BOSTON - NEARFIELD TRANSECT (T062SA)

Minimum =30.81 Maximum =32.24

COHASSET TRANSECT (T063SA)

Minimum =31.28 Maximum =32.21

MARSHFIELD TRANSECT (T064SA)

Minimum =31.37 Maximum =32.01
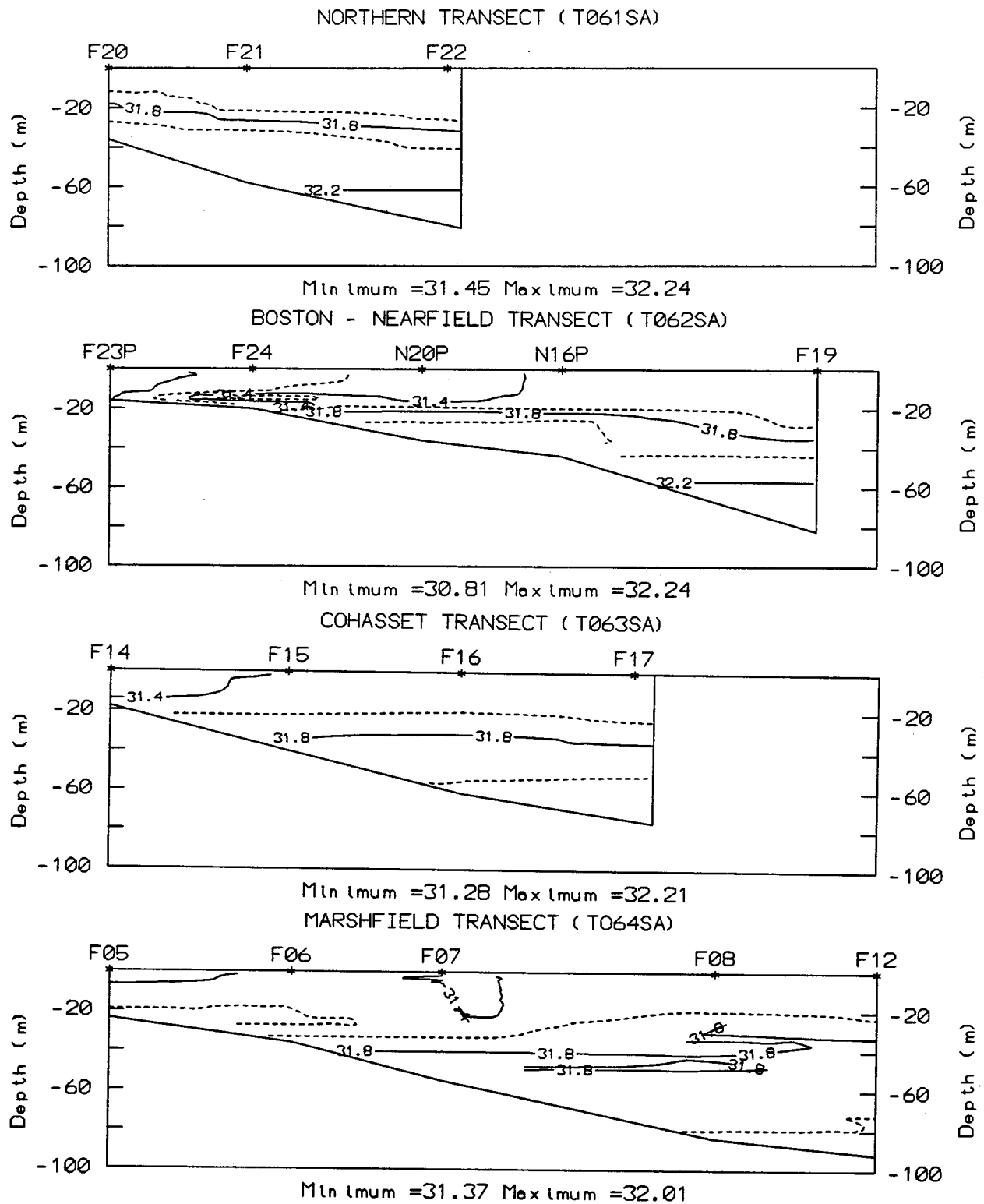
Figure 5-13   **Vertical section contours of salinity in October for standard transects (see Figure 5-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 0.2 PSU.**

NORTHERN TRANSECT (T061CH)

Minimum = 0.56 Maximum = 6.03

BOSTON - NEARFIELD TRANSECT (T062CH)

Minimum = 0.57 Maximum = 5.39

COHASSET TRANSECT (T063CH)

Minimum = 0.54 Maximum = 5.46

MARSHFIELD TRANSECT (T064CH)

Minimum = 0.71 Maximum = 5.16
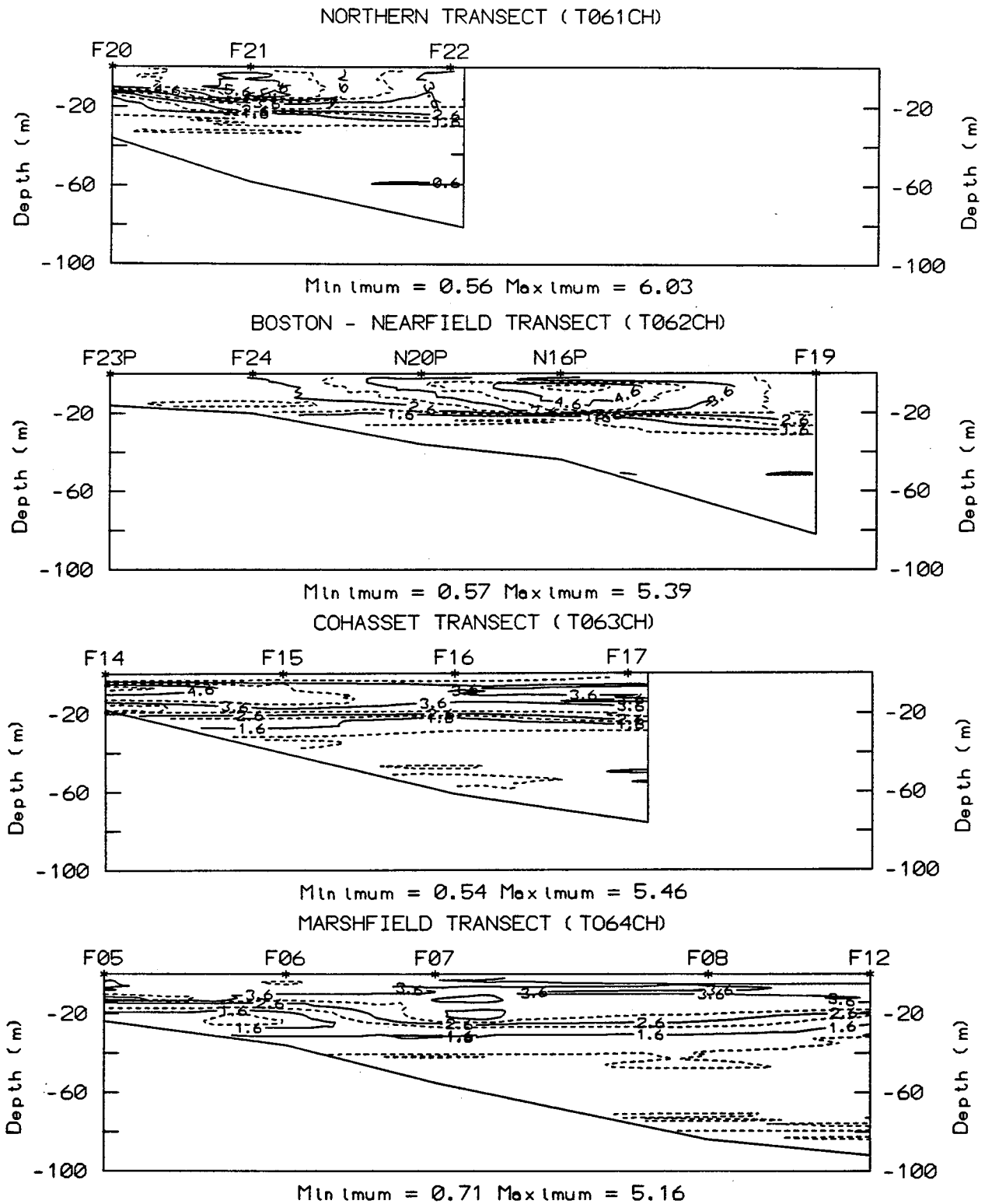
Figure 5-14   Vertical section contours of fluorescence (as μg Chl L^{-1}) in October for standard transects (see Figure 5-11). The data used to produce contours are from high-resolution continuous vertical profiles taken from the downcast at each station. The contour interval is 0.5 μg L^{-1}.

NORTHERN TRANSECT (T061IN)

F20   F21   F22

Depth (m)
-20
-60
-100

-20
-60
-100
Depth (m)

Minimum = 0.05 Maximum =11.47

BOSTON - NEARFIELD TRANSECT (T062IN)

F23P   F24   N20P   N16P   F19

Depth (m)
-20
-60
-100

-20
-60
-100
Depth (m)

Minimum = 0.25 Maximum =15.04

COHASSET TRANSECT (T063IN)

F14   F15   F16   F17

Depth (m)
-20
-60
-100

-20
-60
-100
Depth (m)

Minimum =-0.07 Maximum =11.14

MARSHFIELD TRANSECT (T064IN)

F05   F06   F07   F08   F12

Depth (m)
-20
-60
-100

-20
-60
-100
Depth (m)

Minimum =-0.13 Maximum = 9.61
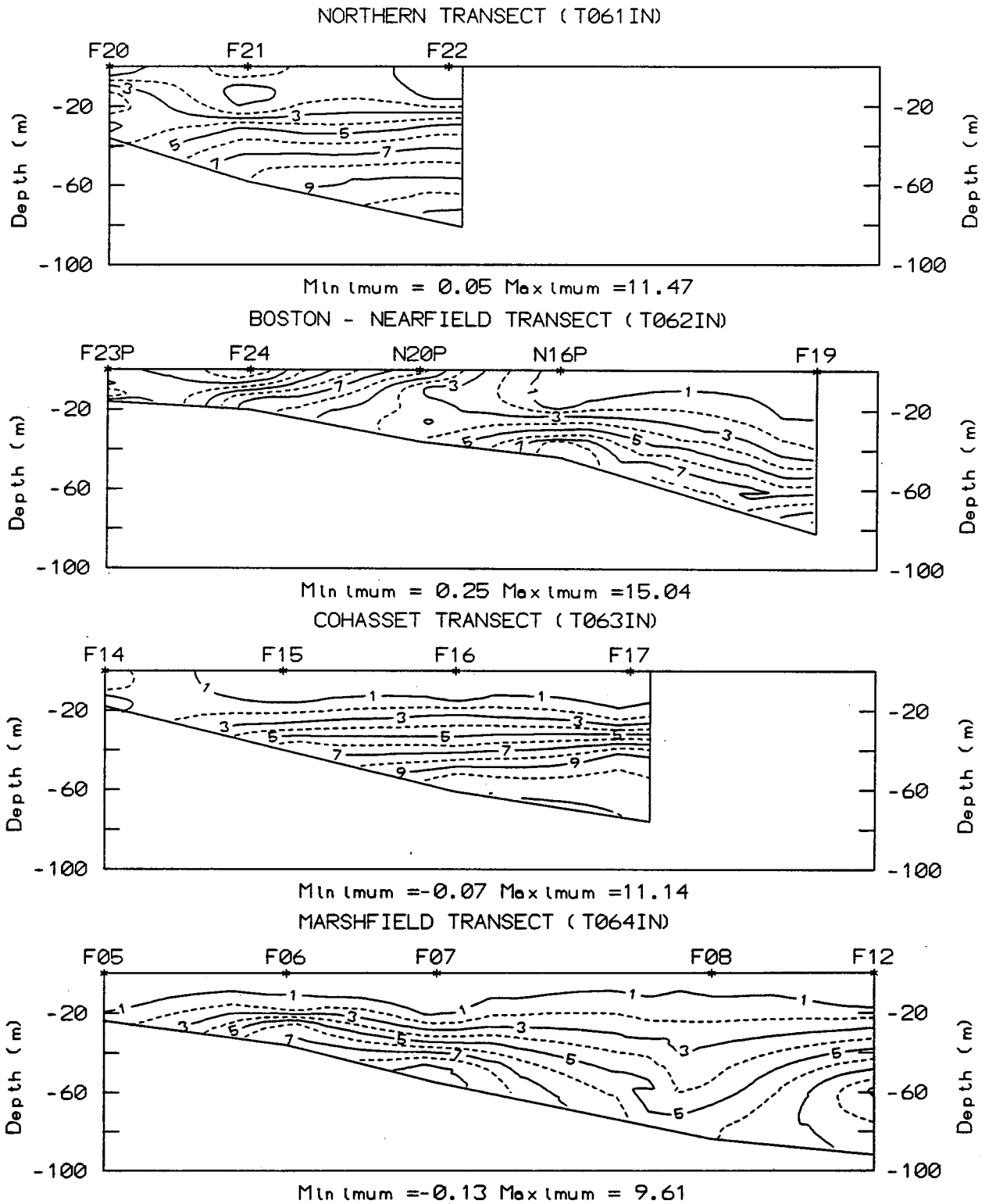
Figure 5-15 Vertical section contours of dissolved inorganic nitrogen (μM) in October for standard transects (see Figure 5-11). The data used to produce contours are from discrete bottle samples as given in Appendix A. The contour interval is 1μM.

NORTHERN TRANSECT (T061SO)

Minimum = 2.34 Maximum =10.73

BOSTON - NEARFIELD TRANSECT (T062SO)

Minimum = 2.44 Maximum =11.16

COHASSET TRANSECT (T063SO)

Minimum = 1.85 Maximum =15.17

MARSHFIELD TRANSECT (T064SO)

Minimum = 2.08 Maximum =13.11
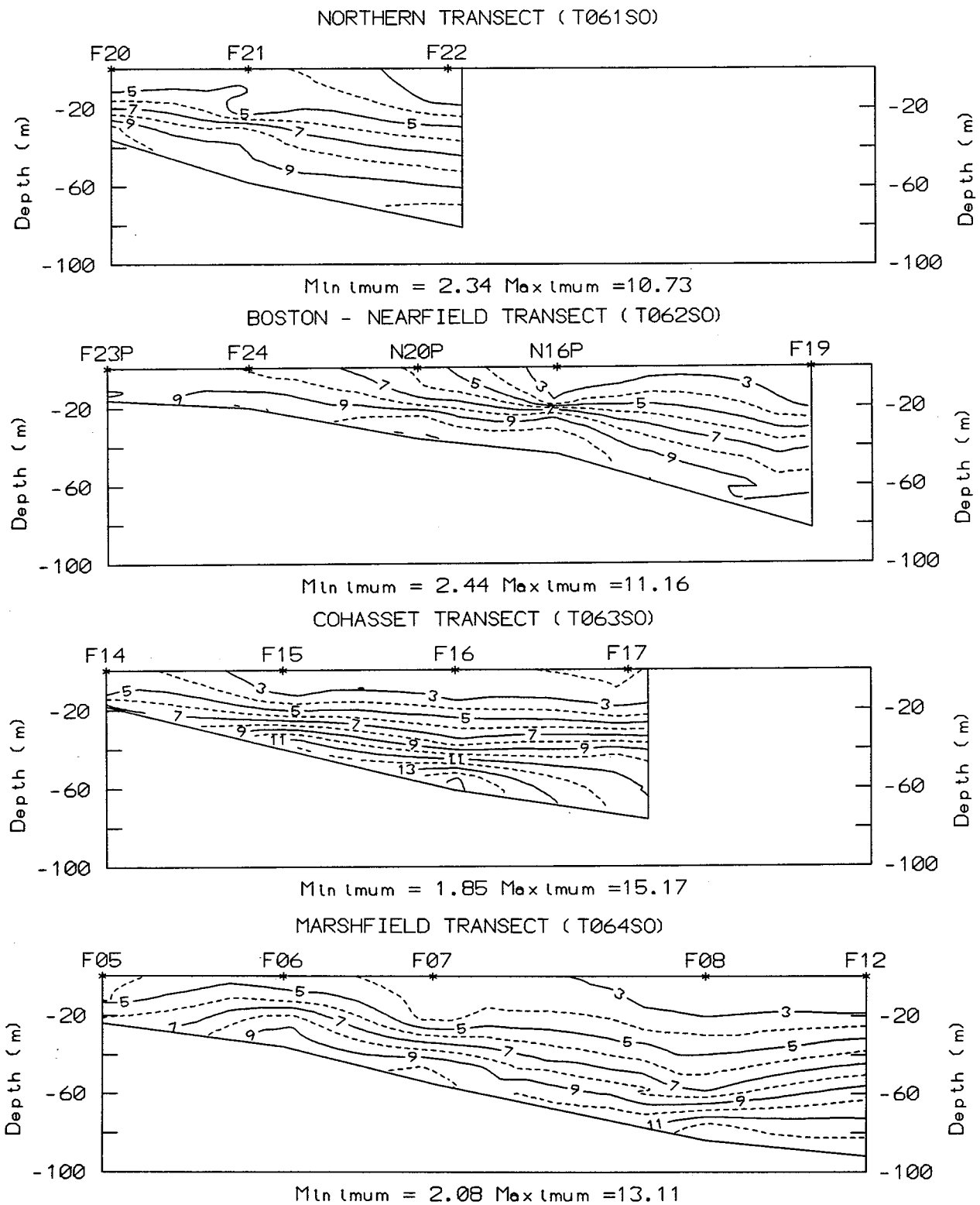
Figure 5-16   Vertical section contours of silicate (μM) in October for standard transects (see Figure 5-11). The data used to produce contours are from discrete bottle samples as given in Appendix A. The contour interval is 1μM.

Salinity (PSU)

3637 data points

Salinity (PSU)

3637 data points

All October Stations
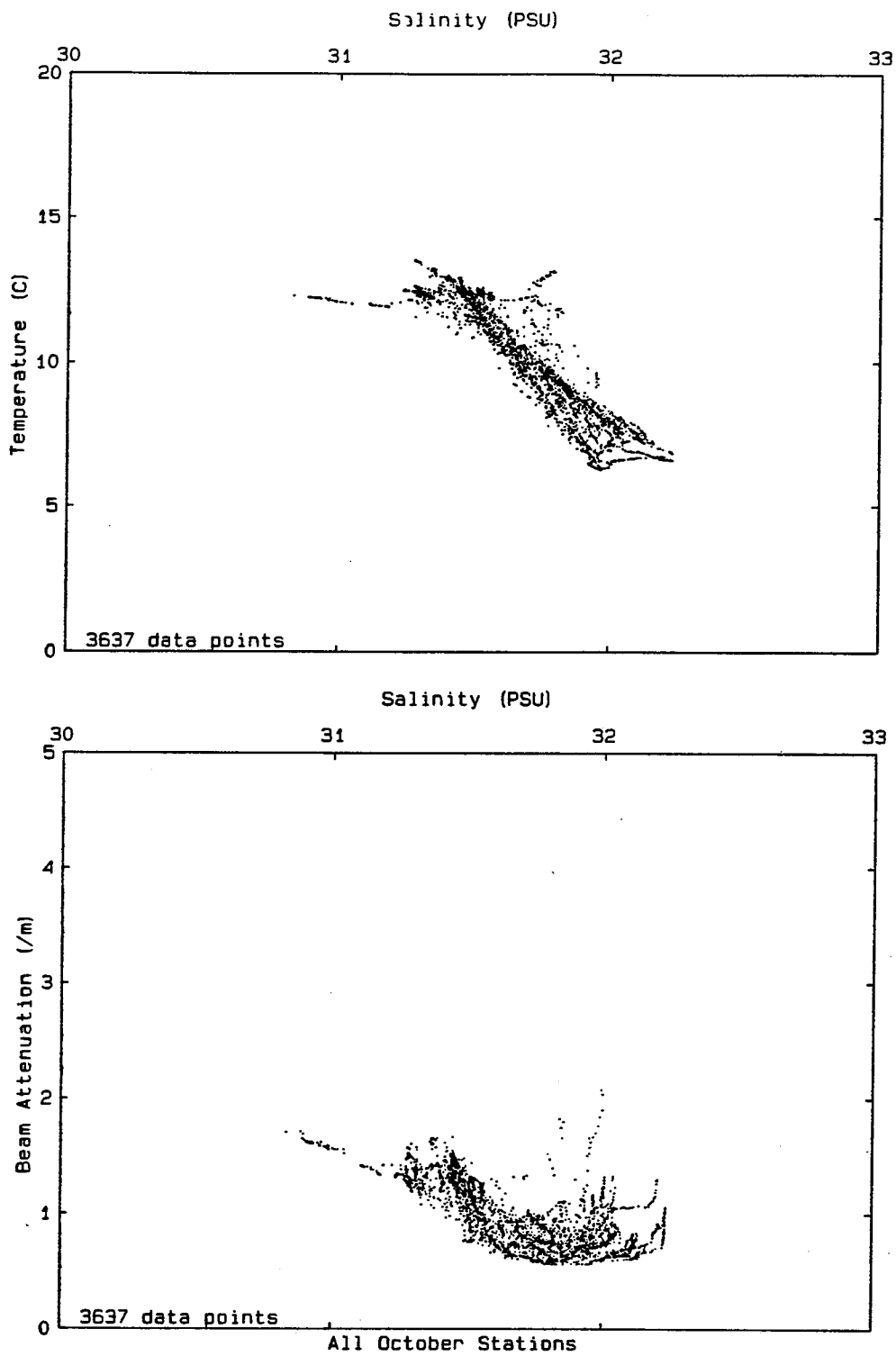
Figure 5-17a   Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in October 1992. Individual station cast plots that were used to produce this composite are in Appendix C.

Chlorophyll a (ug/L)

Depth (m)

3637 data points

Chlorophyll a (ug/L)

Dissolved Oxygen (mg/L)

3637 data points

All October Stations
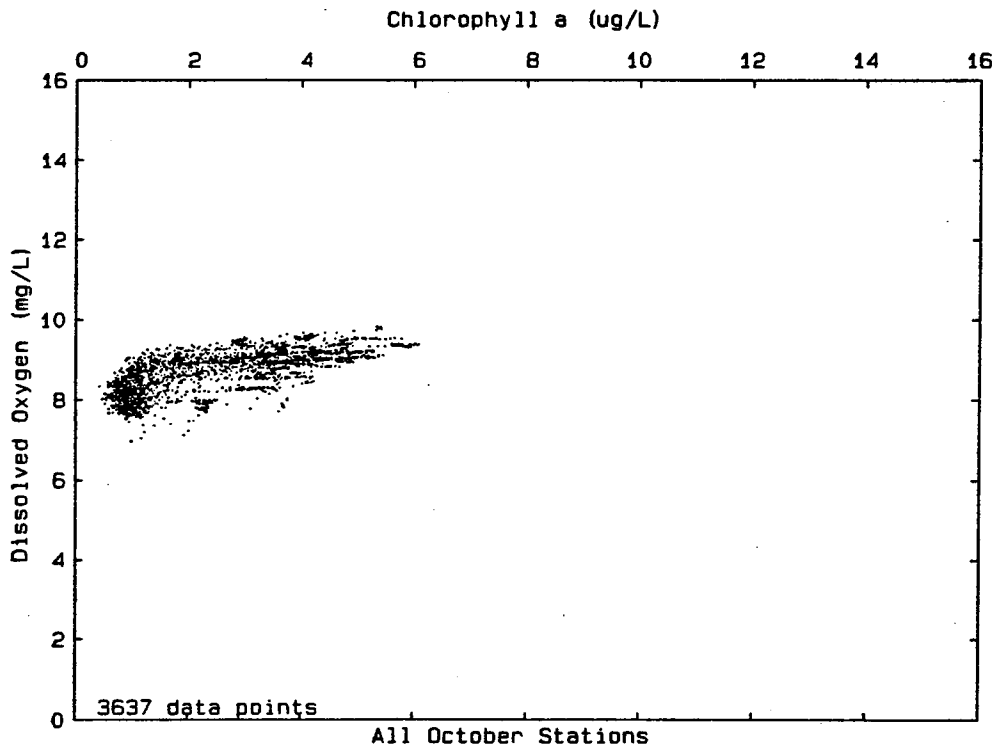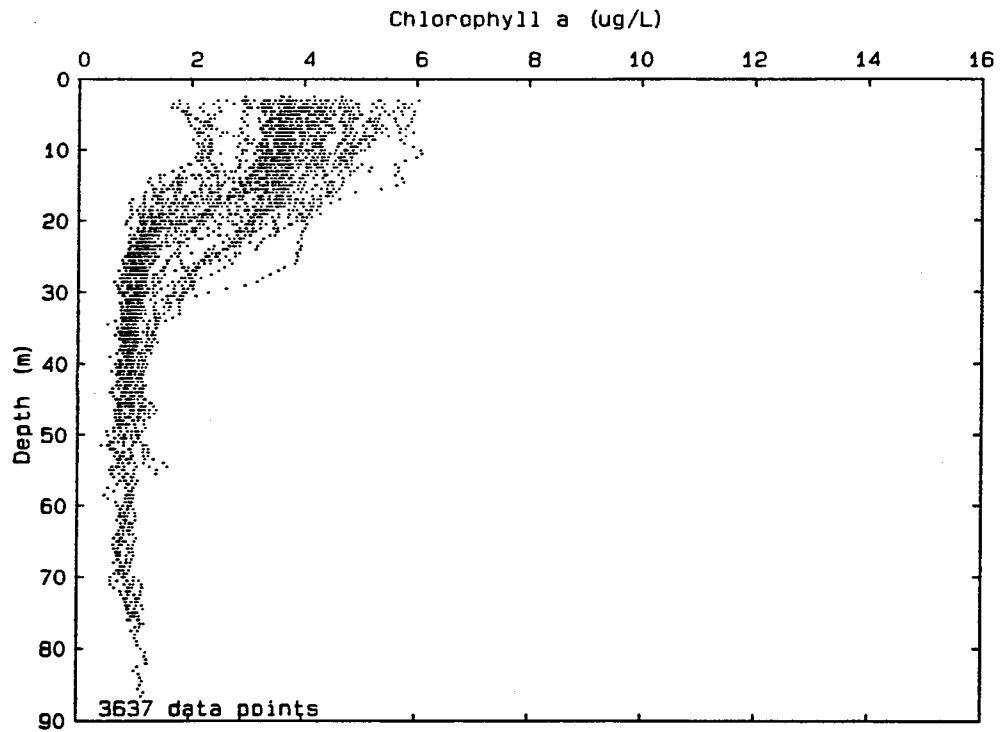
Figure 5-17b   Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in October 1992. Individual station cast plots that were used to produce this composite are in Appendix C. Chlorophyll was estimated from fluorescence and DO was calibrated with titrations (see Appendix A).

Chlorophyll a (ug/L)

0   2   4   6   8   10   12   14   16

26

25

Sigma-T

24

23

22

21

3637 data points

Chlorophyll a (ug/L)

0   2   4   6   8   10   12   14   16

5

4

Beam Attenuation (/m)

3

2

1

0

3637 data points

All October Stations
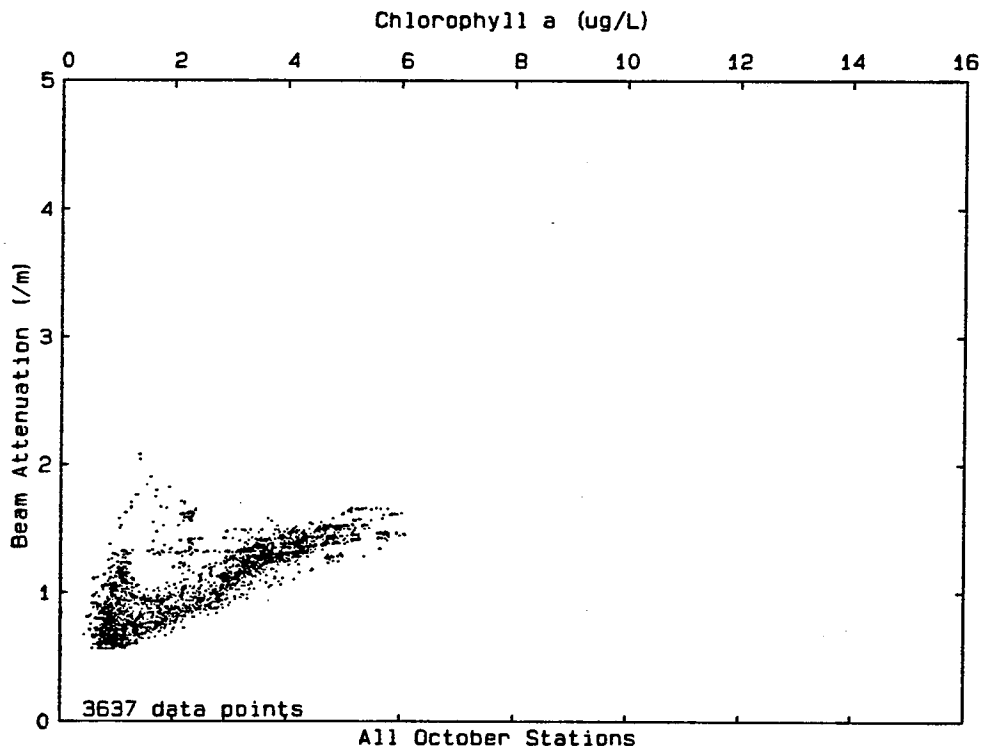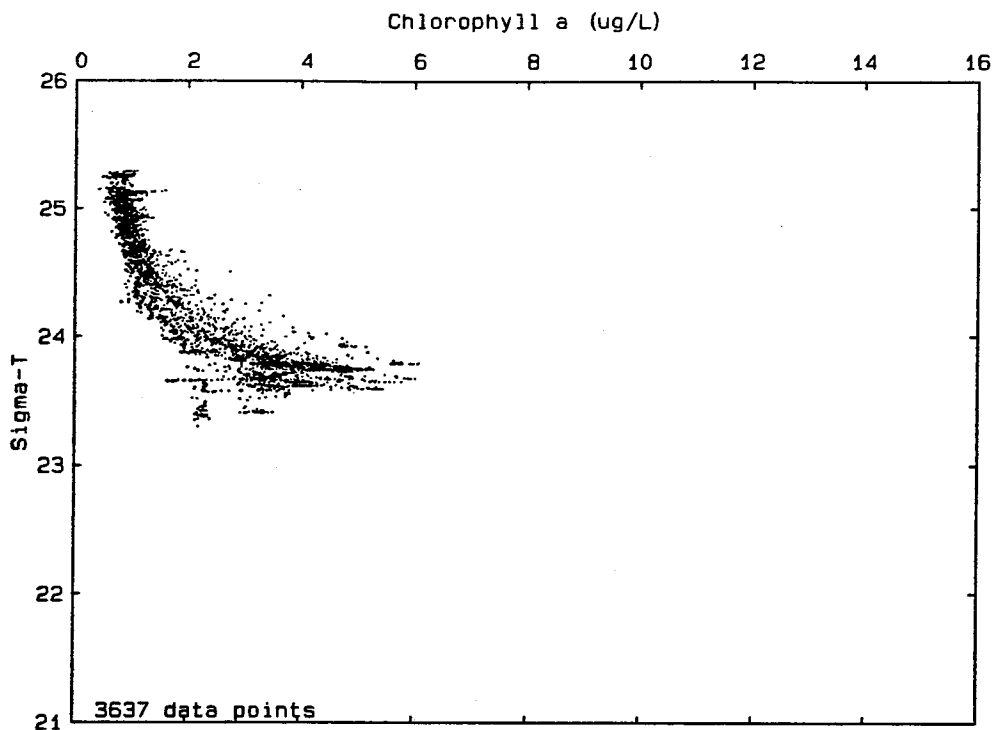
Figure 5-17c   Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in October 1992. Individual station cast plots that were used to produce this composite are in Appendix C. Chlorophyll was estimated from fluorescence (see Appendix A).
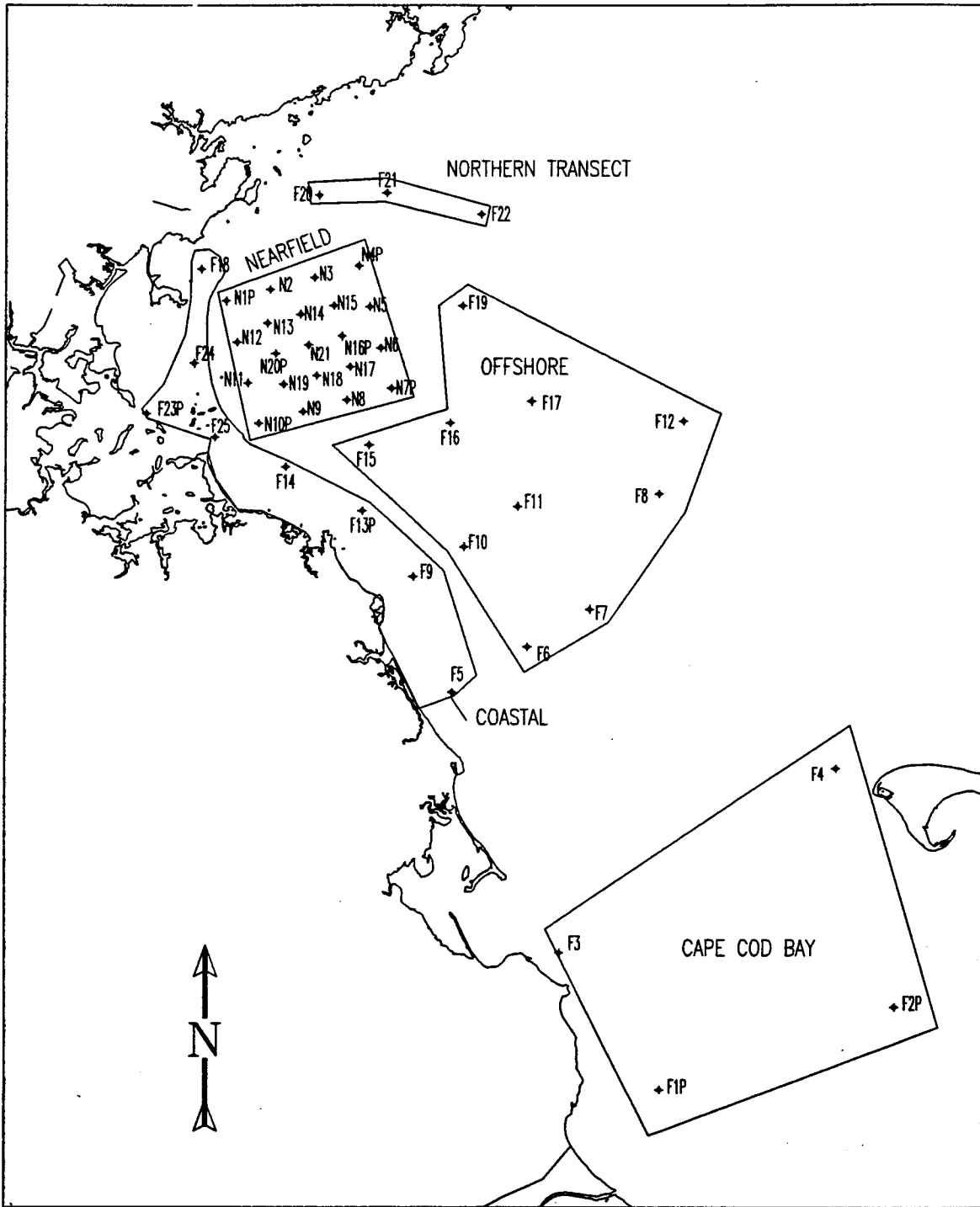
Figure 5-18 Map to show station groups designated in Figures 5-19 through 5-25. Massachusetts Bay was separated into 4 groups based on water depth and geographic position.

DIN vs. PO4
October

NO3 vs. PO4
October

Legend:
- ■ Coastal
- □ Northern Transect
- ▲ Nearfield
- ✳ Offshore
- + Cape Cod Bay
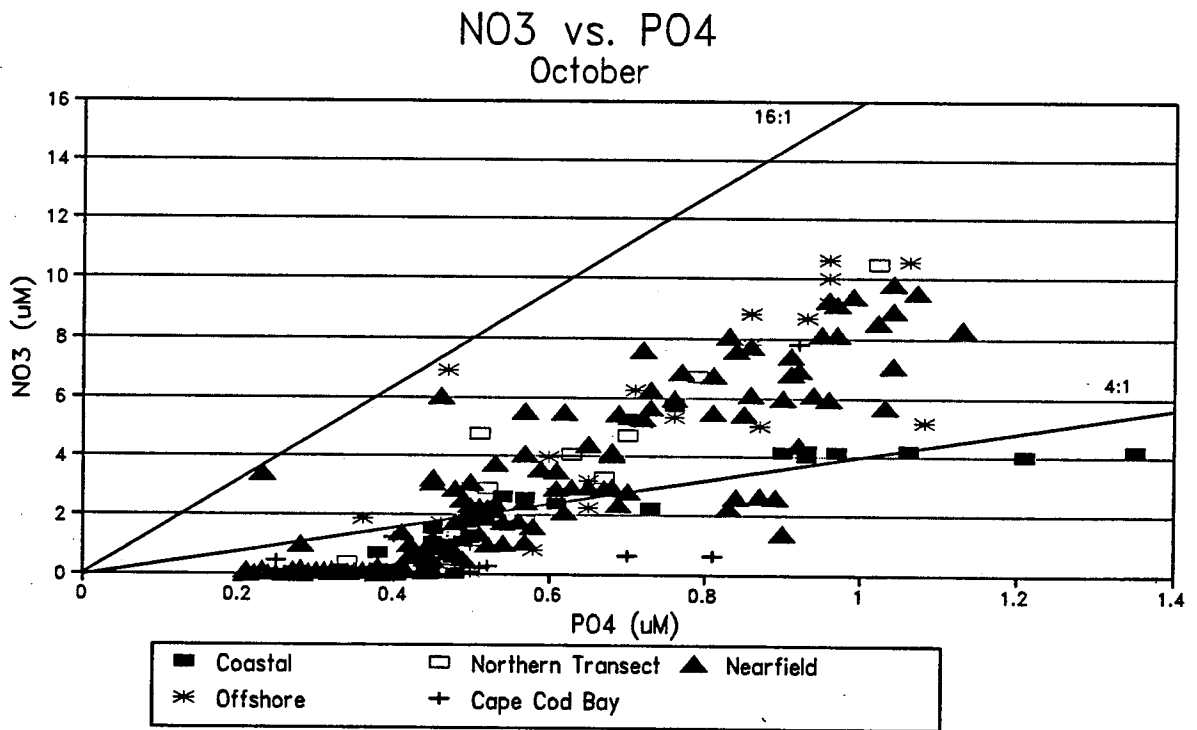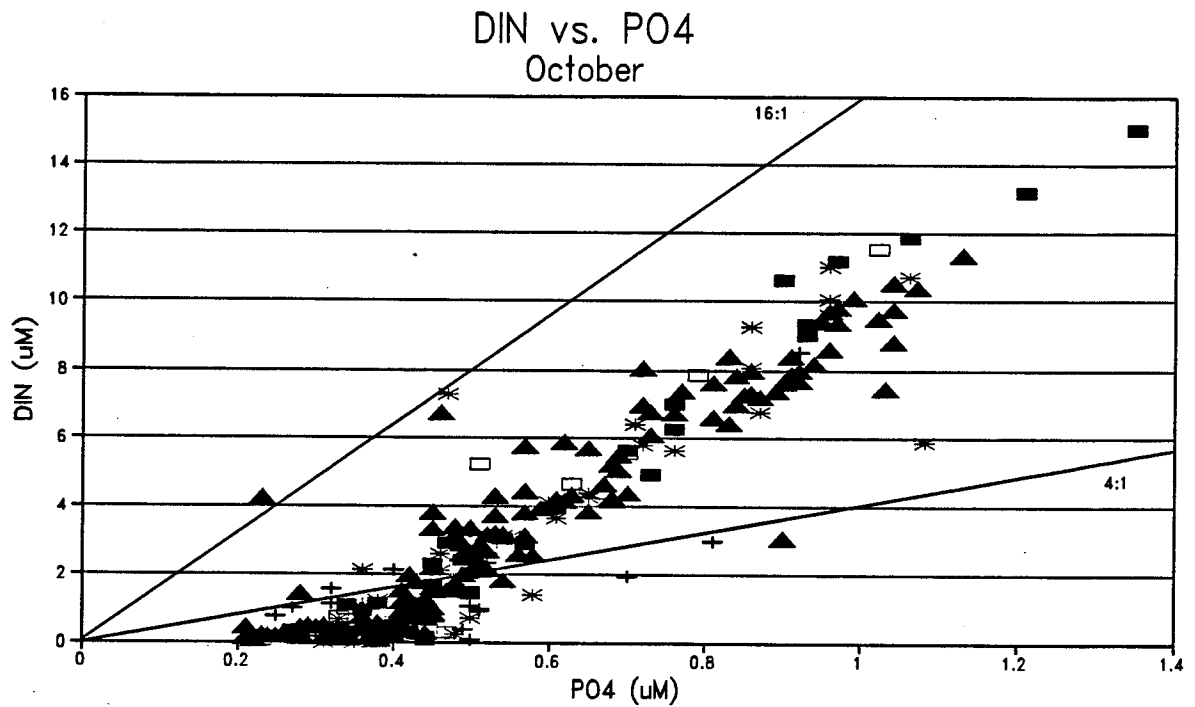
Figure 5-19a   Scatter plots of nitrogen forms vs. phosphate during October 1992. All stations and depths are included, and data are given in Appendix A. Lines show constant proportions of nitrogen relative to phosphorus across a range of N:P ratios.
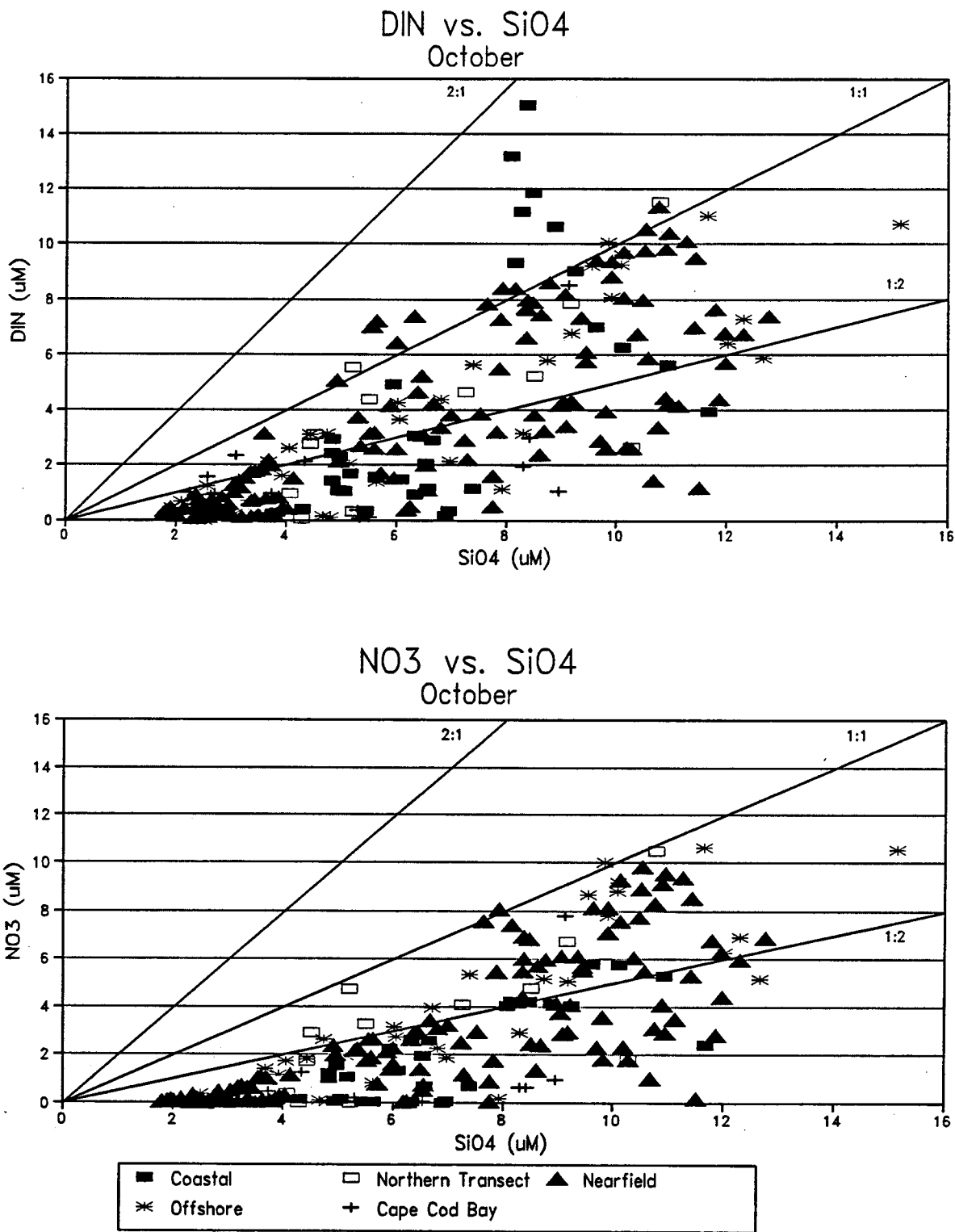
Figure 5-19b   Scatter plots of nitrogen vs. silicate during October 1992. All stations and depths are included, and data are given in Appendix A. Lines show constant proportions of nitrogen relative to silicate across a range of N:Si ratios.
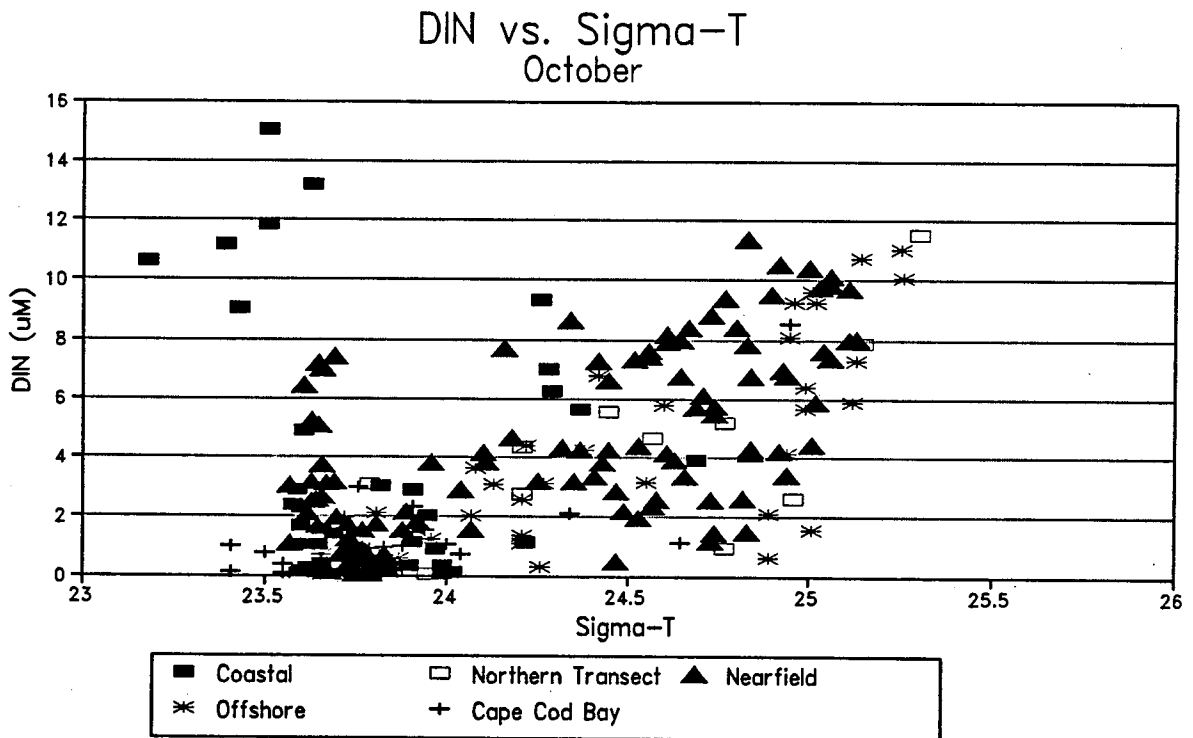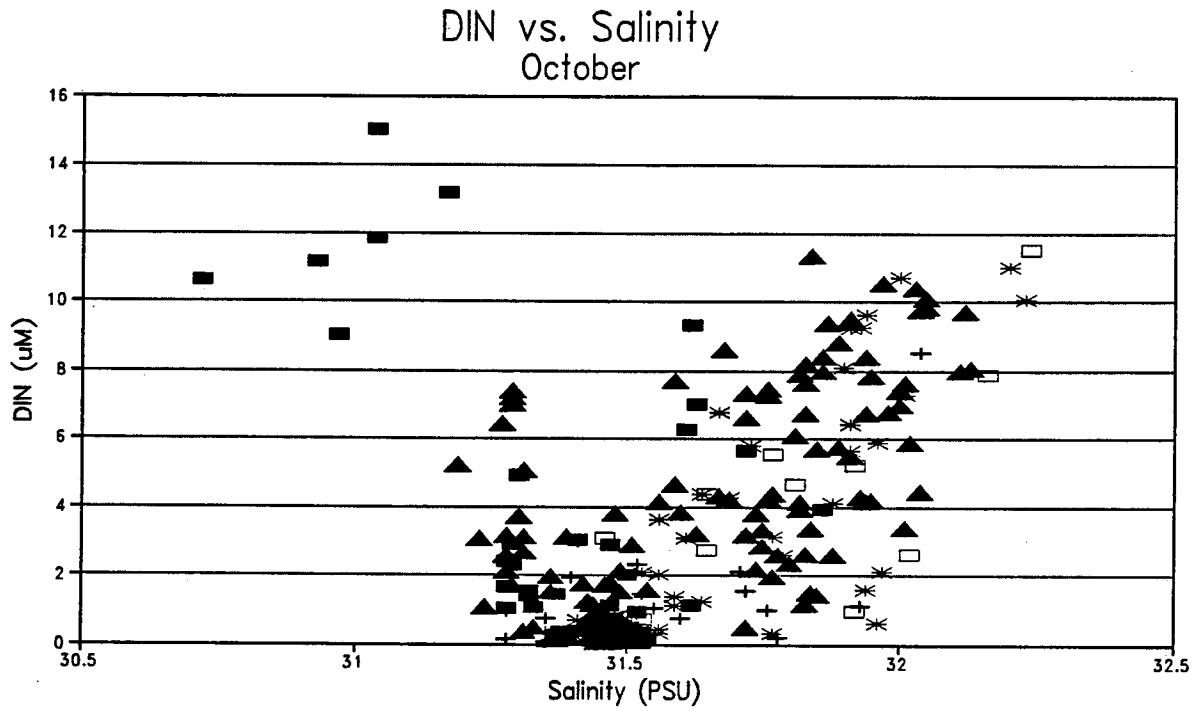
Figure 5-20 Dissolved inorganic nitrogen vs. salinity and σ_T in October 1992. All stations and depths are included, and data are given in Appendix A.
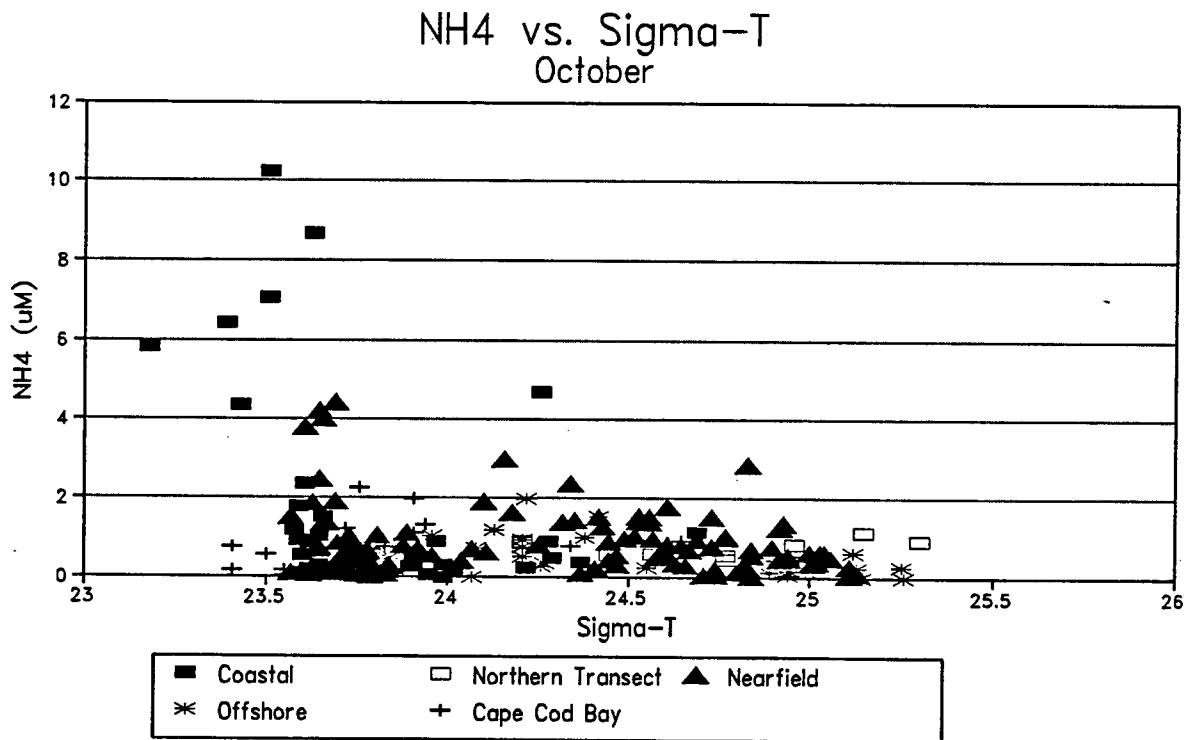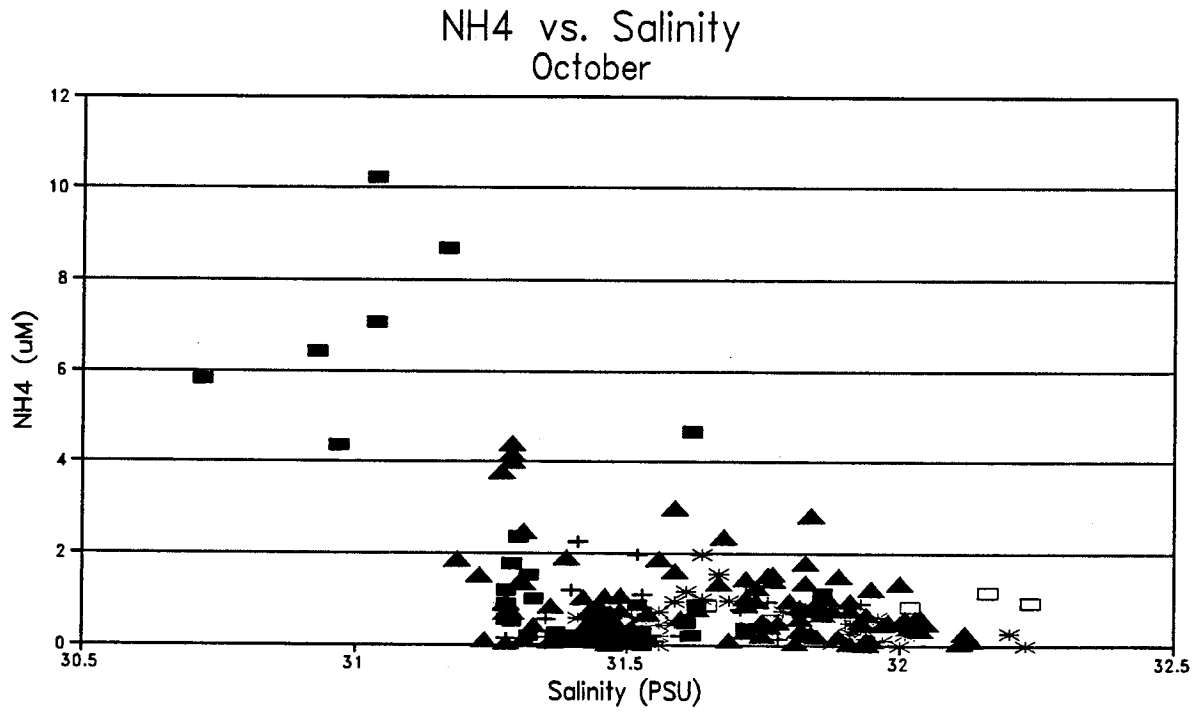
Figure 5-21 Ammonia vs. salinity and σ_T in October 1992. All stations and depths are included, and data are given in Appendix A.
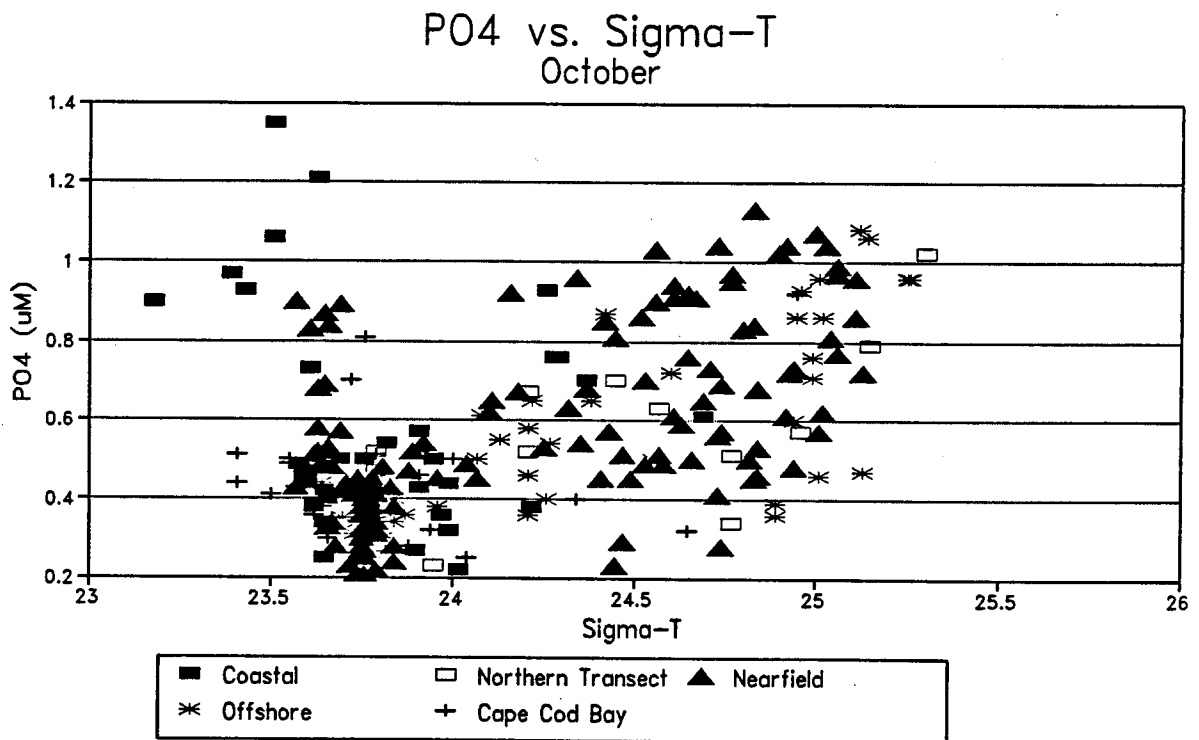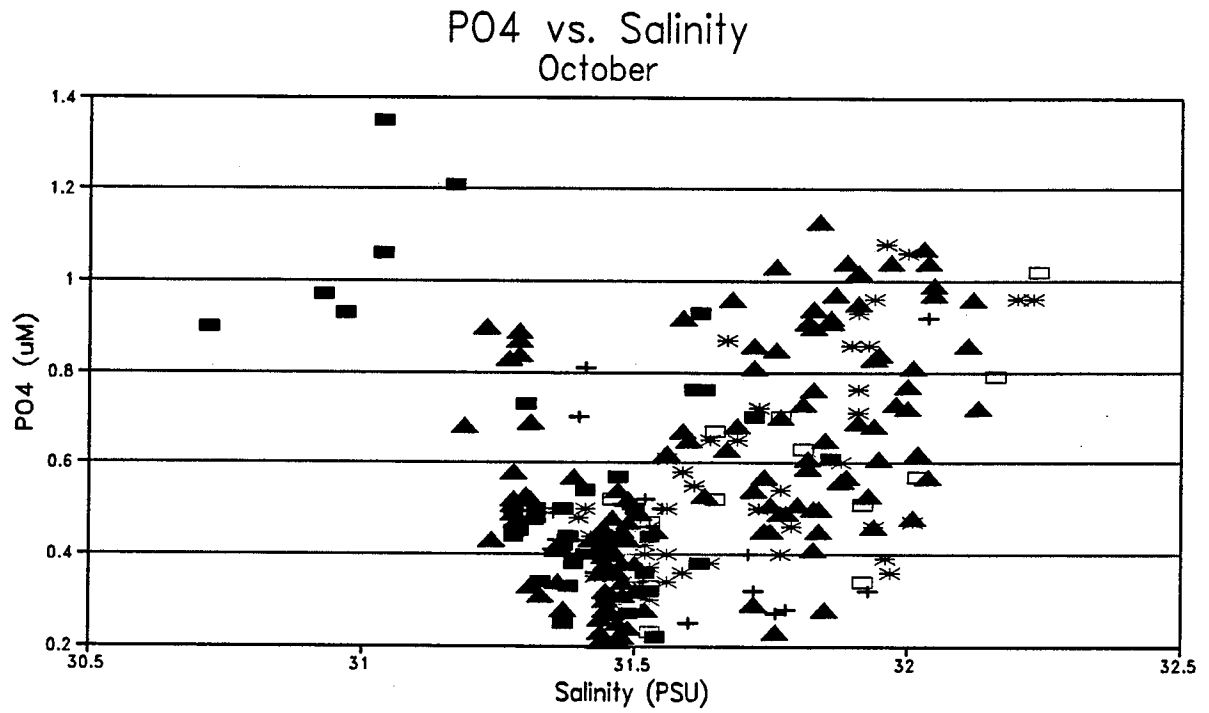
Figure 5-22 Phosphate vs. salinity and σ_T in October 1992. All stations and depths are included, and data are given in Appendix A.

SiO4 vs. Salinity
October

SiO4 vs. Sigma-T
October

| ■ Coastal | □ Northern Transect | ▲ Nearfield |
| ✳ Offshore | + Cape Cod Bay | |
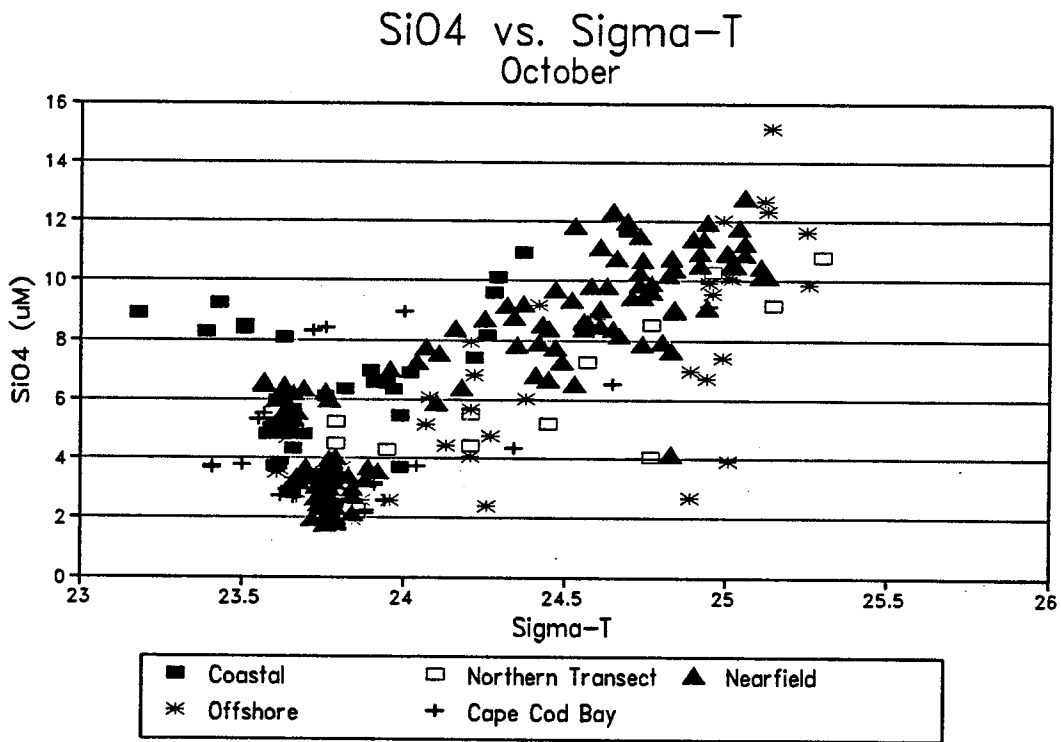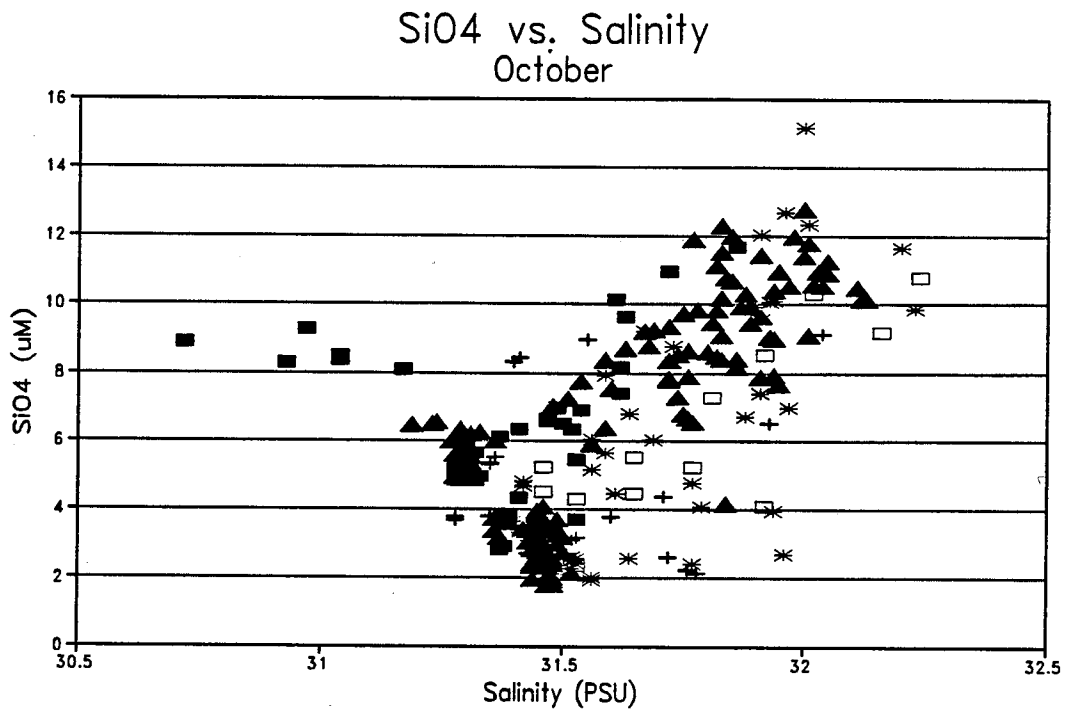
Figure 5-23 Silicate vs. salinity and σ_T in October 1992. All stations and depths are included, and data are given in Appendix A.

October 1992

REGION + + + C A P   o o o C O A   ● ● ● N E A

October 1992

REGION + + + C A P   o o o C O A   ● ● ● N E A
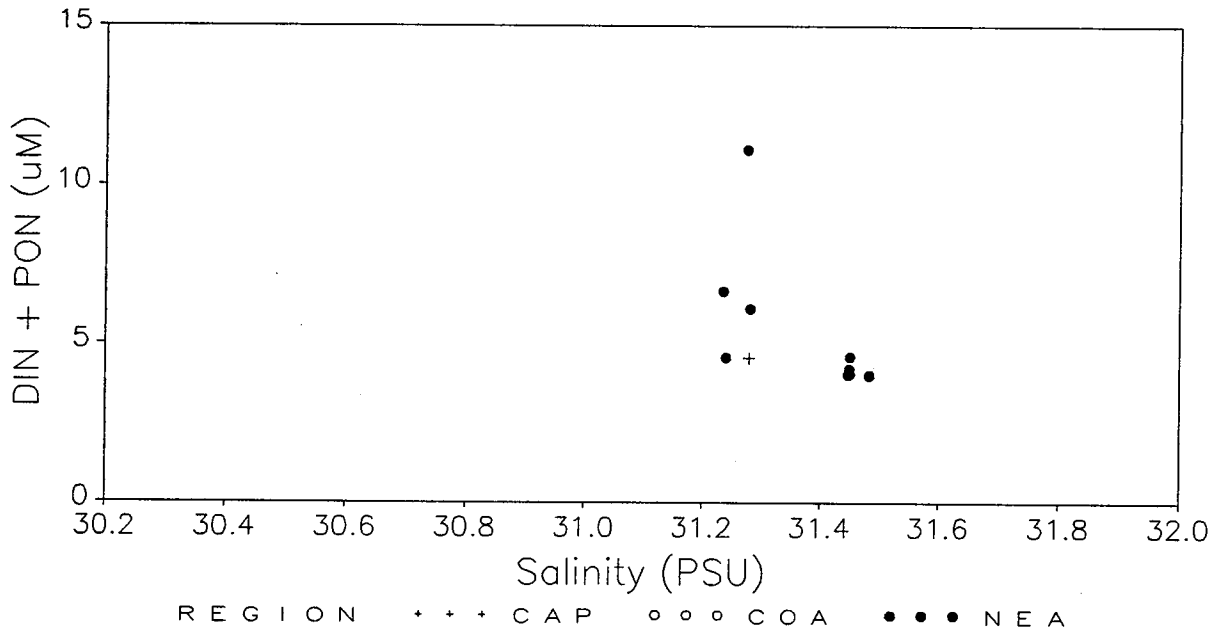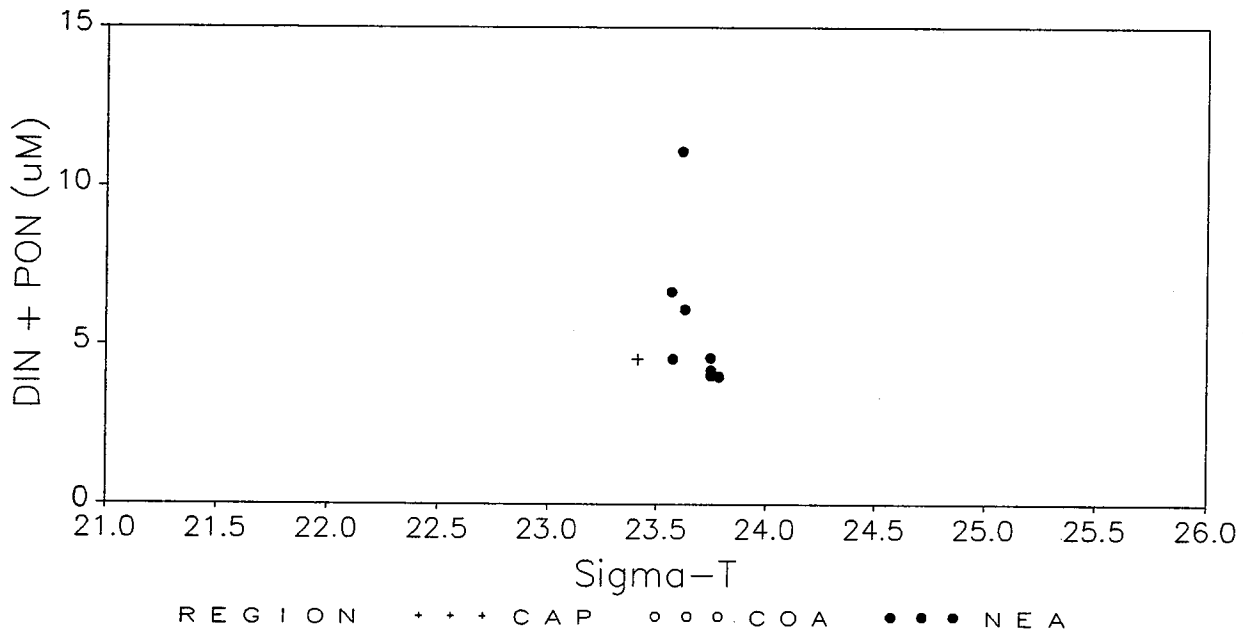
Figure 5-24 The sum of dissolved inorganic nitrogen and particulate organic nitrogen vs. salinity and σ_T in October 1992. Data are from BioProductivity stations and special station F25 and are given in Appendix A. The station groups are coded as given in Figure 5-18. Note that the symbols for different regions are slightly different from Figures 5-19 to 5-22. PON was not estimated for some stations (Appendix A).
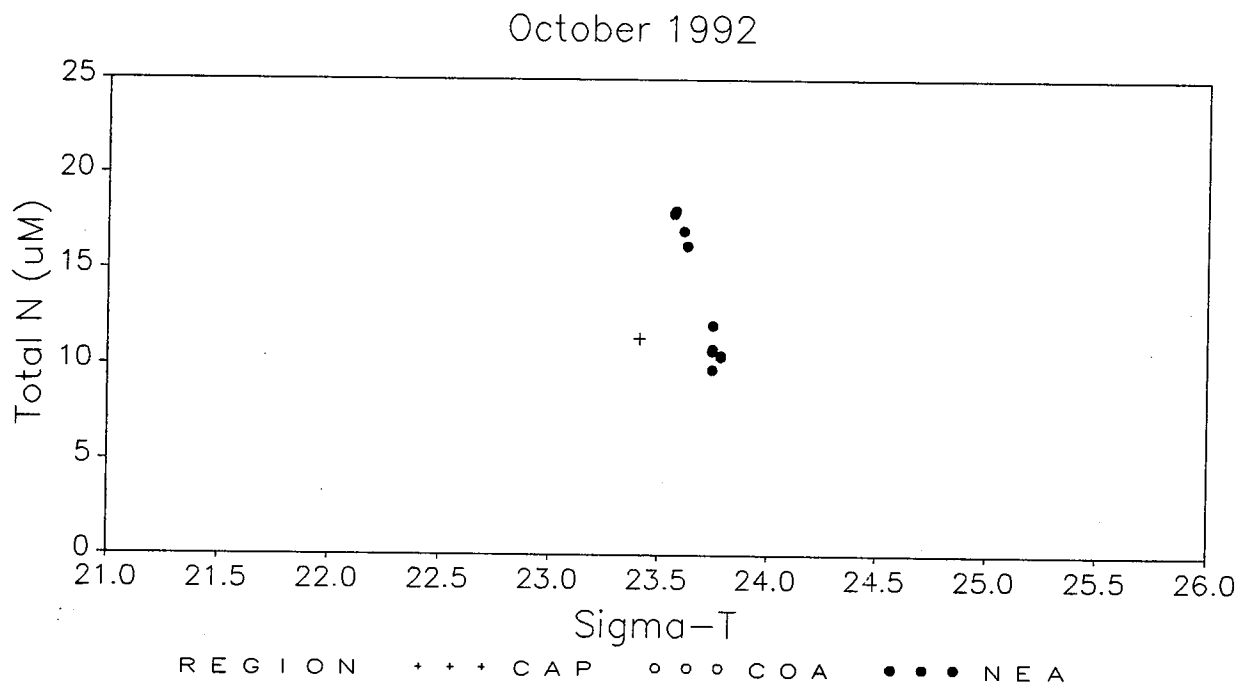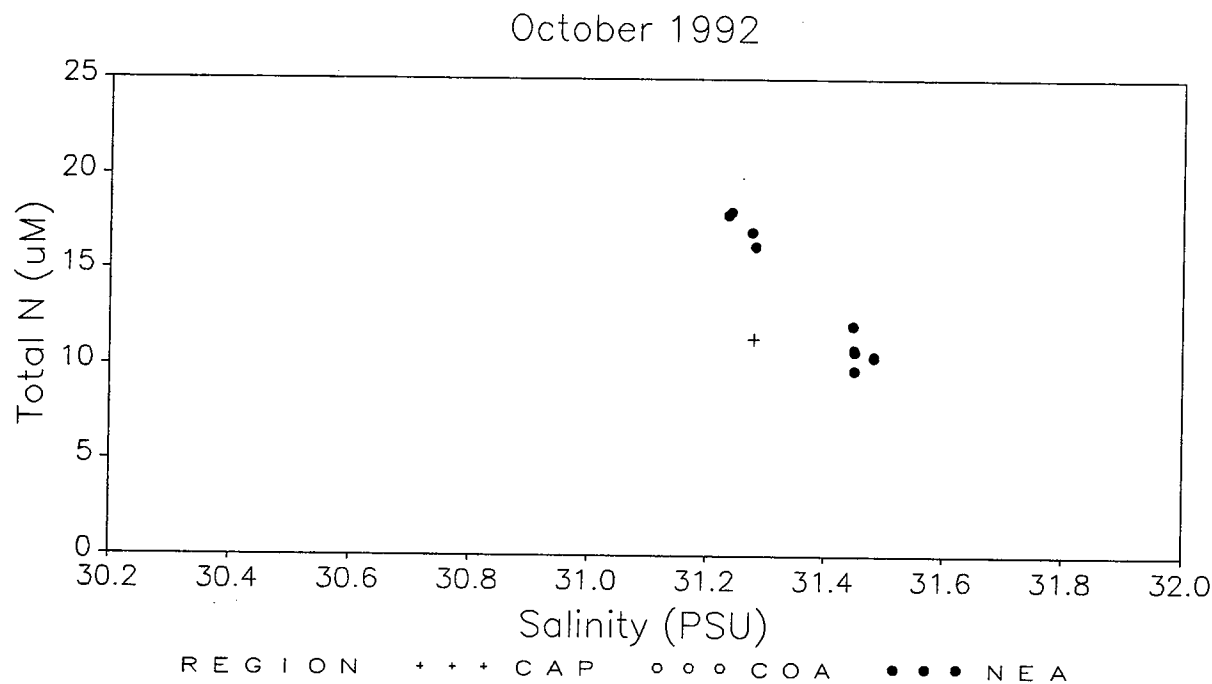
Figure 5-25 The sum of total dissolved nitrogen and particulate organic nitrogen (=total nitrogen) vs. salinity and σ_T in October 1992. Data are from BioProductivity stations and special station F25 and are given in Appendix A. Groups are the same as given in Figure 5-18. Note that the symbols for different regions are slightly different from Figures 5-19 to 5-22. PON was not estimated for some stations (Appendix A).
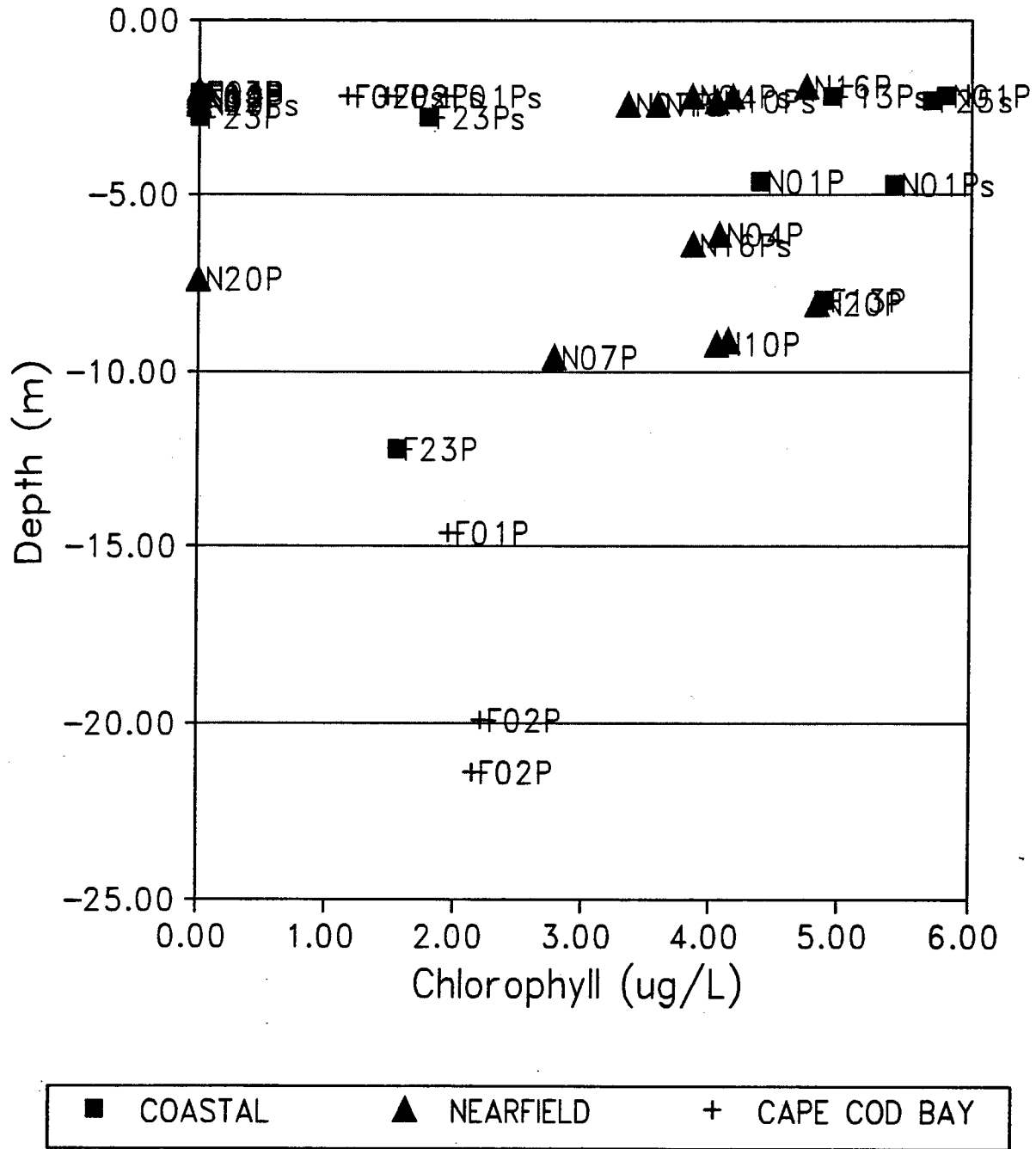
Figure 5-26 Surface and deeper chlorophyll at BioProductivity stations and special station F25 as a function of depth in October 1992.
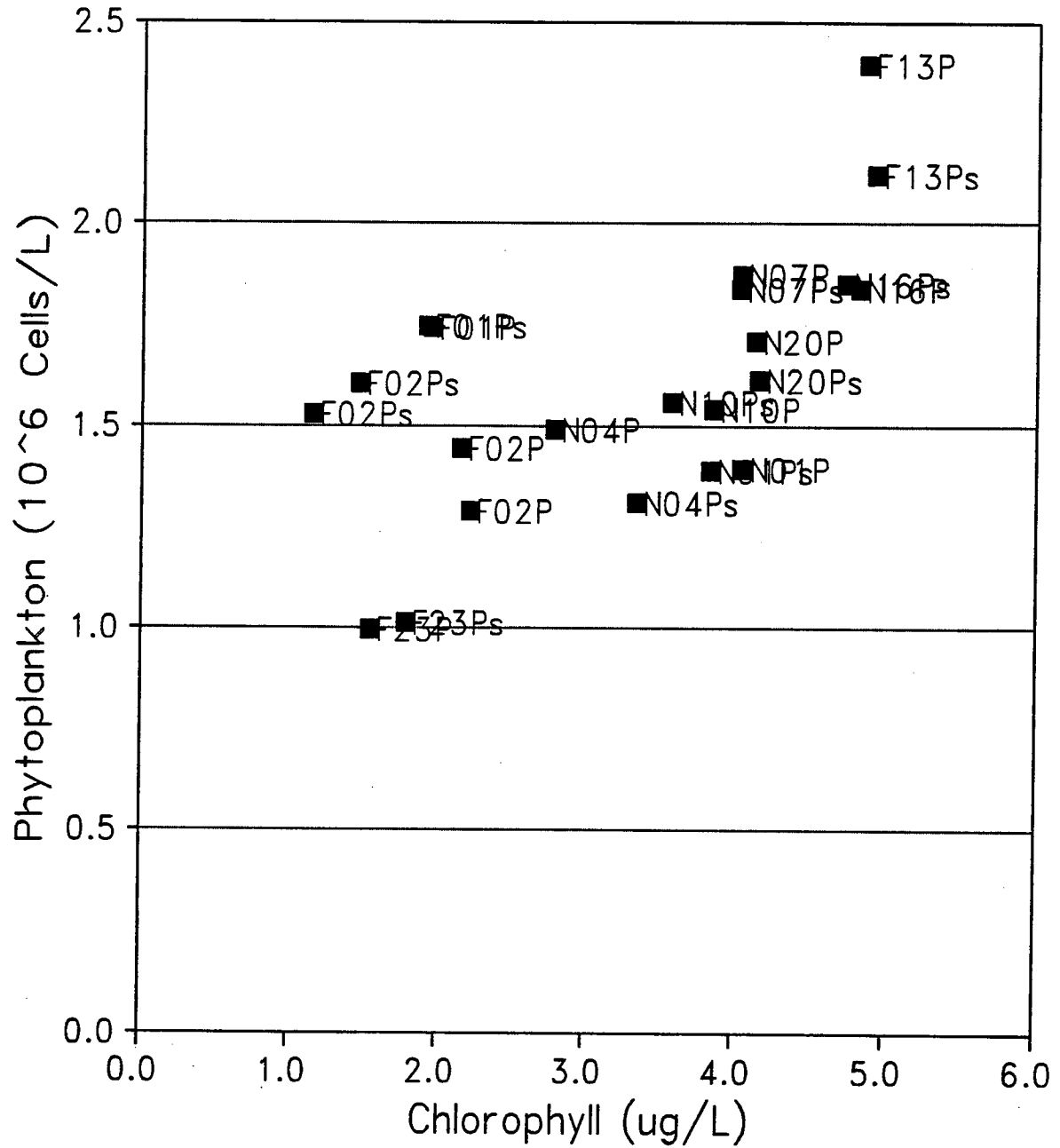
Figure 5-27 Total phytoplankton abundance vs. extracted chlorophyll at BioProductivity stations in October 1992. Data are given in Appendices A and F.
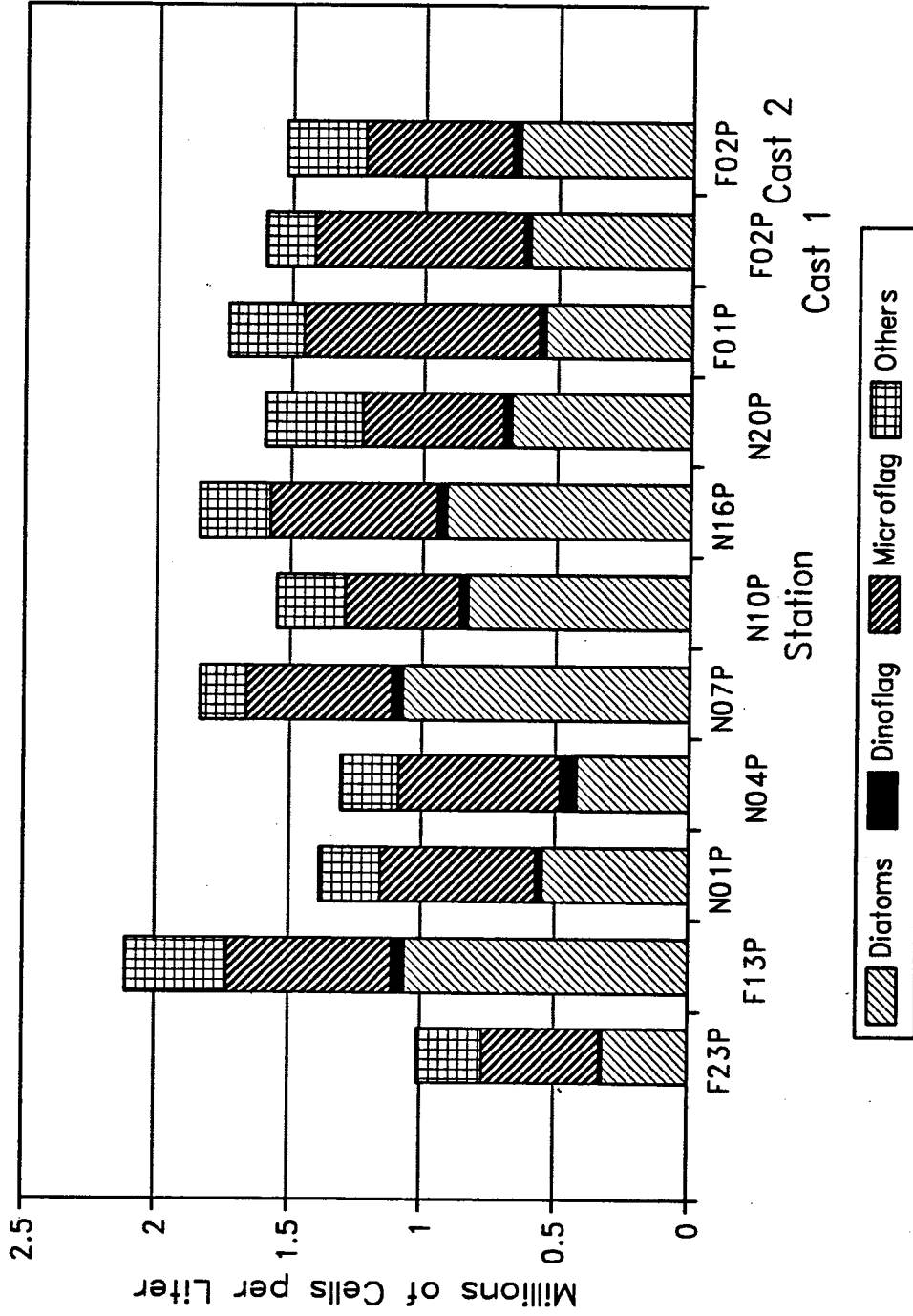
Figure 5-28 Total phytoplankton abundance, by taxonomic groups, at BioProductivity stations in October 1992. Data are given in Appendix F.

PHYTOPLANKTON SPECIES ABUNDANCE
STATION N04P — OCTOBER 92
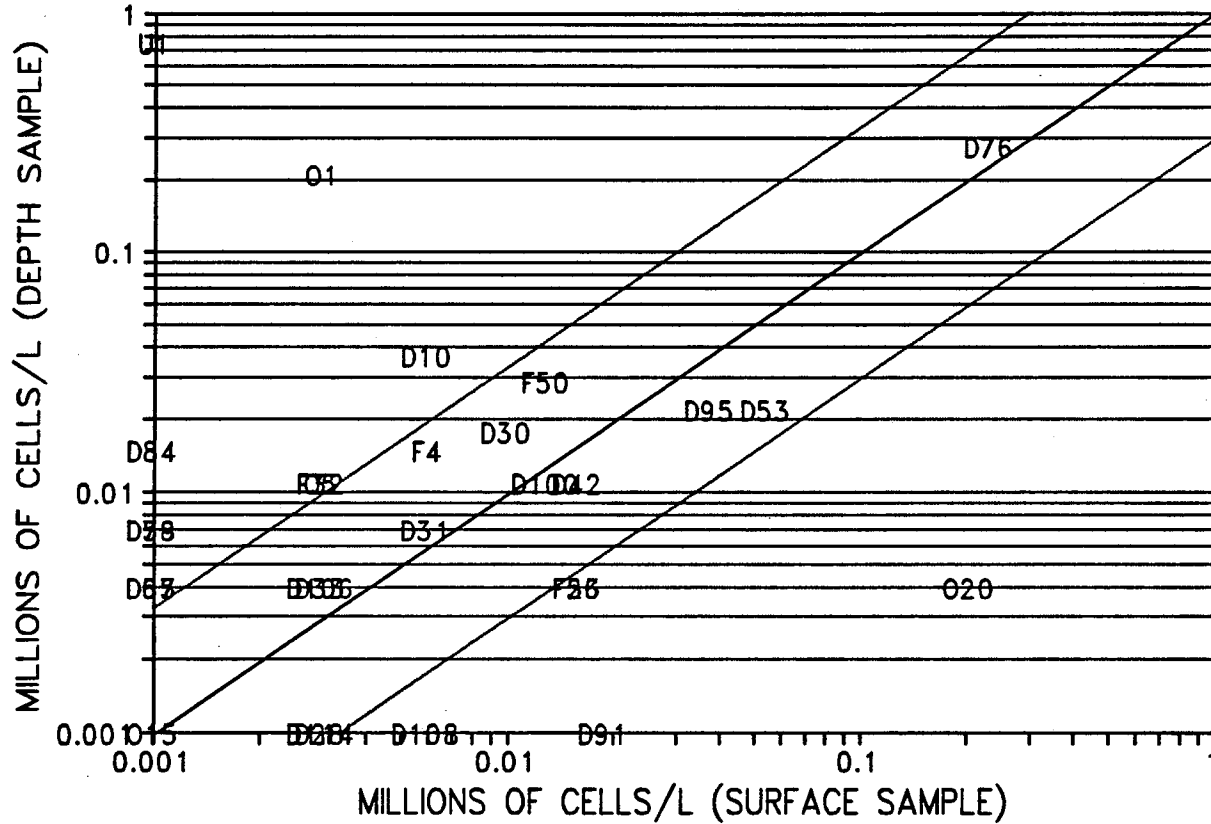
Figure 5-29 Comparison of phytoplankton taxonomic composition of surface and deeper samples at station N4P in October 1992. Full species codes are given in Appendix F, but the alphabetical prefix indicates the following: D= diatom, F= dinoflagellate, U= microflagellates, O= other. Solid bold middle line shows 1:1 relationship, finer lines show 1:5 and 5:1 isopleths.

PHYTOPLANKTON SPECIES ABUNDANCE
STATION FO2P – OCTOBER 92 – CAST 1
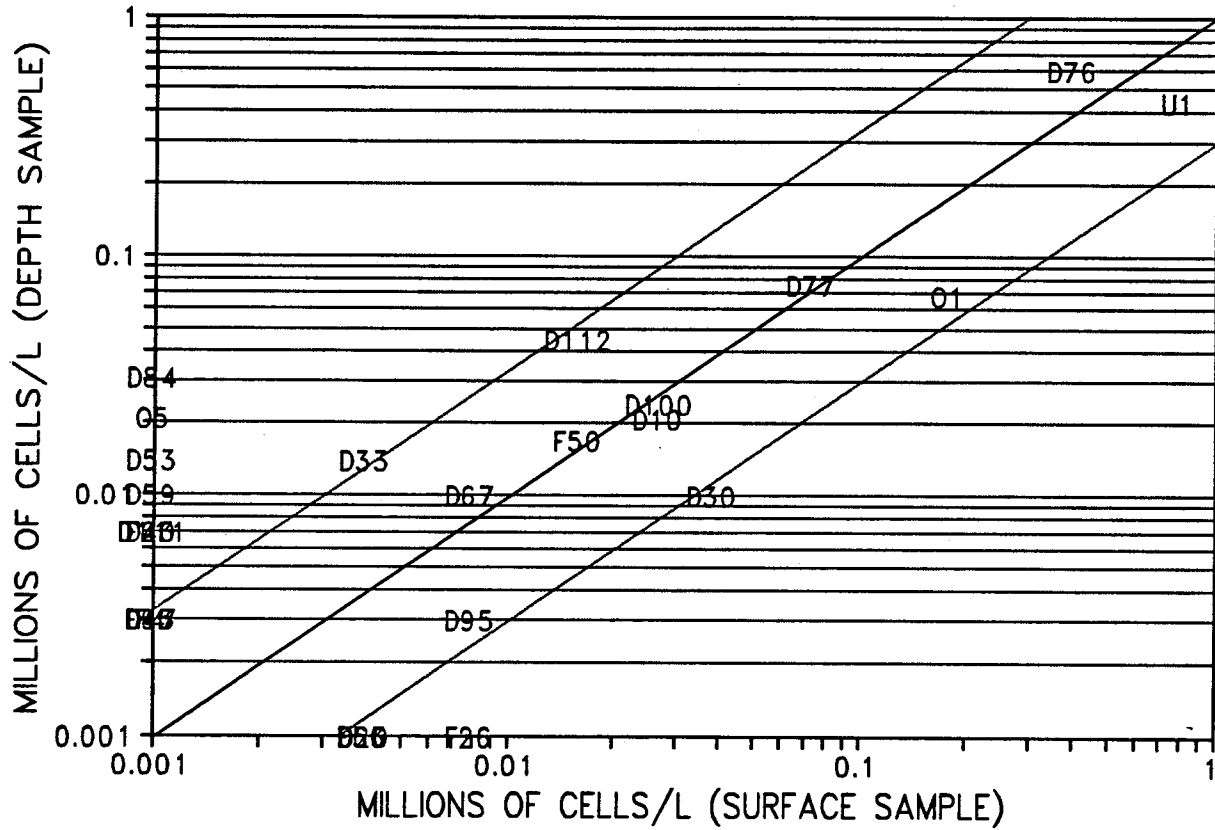
Figure 5-30a Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F2P in October 1992 on cast 1. Species codes are given in Appendix F.

PHYTOPLANKTON SPECIES ABUNDANCE
STATION F02P — OCTOBER 92 — CAST 2
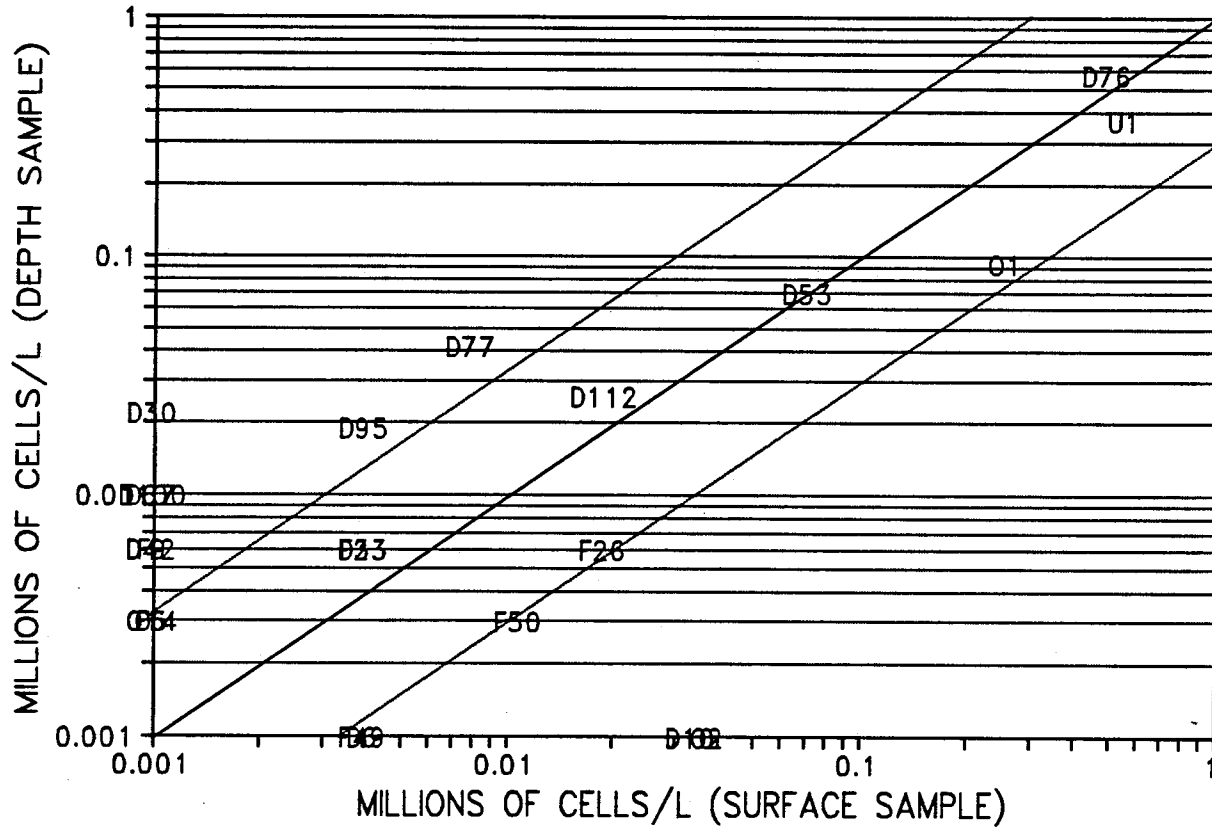
Figure 5-30b Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F2P in October 1992 on cast 2. Species codes are given in Appendix F.
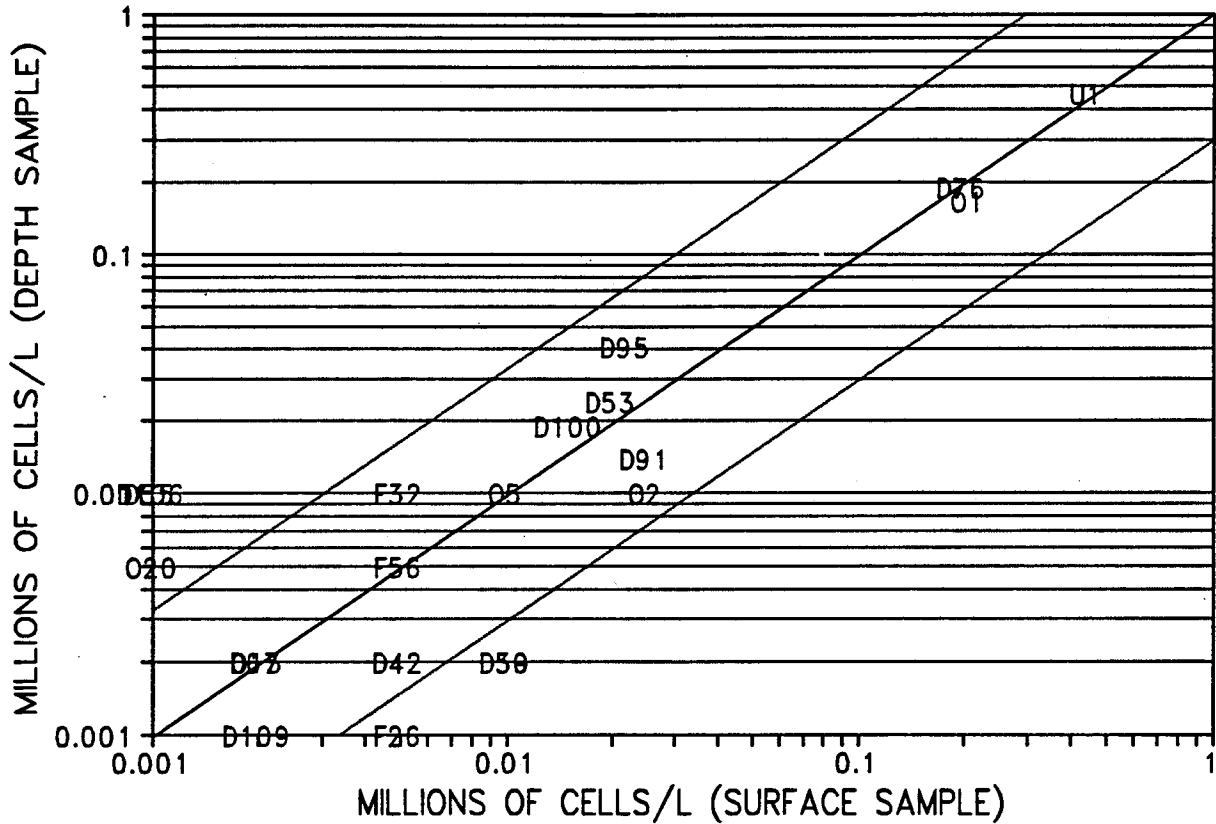
Figure 5-31 Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F23P in October 1992. Species codes are given in Appendix F.

PHYTOPLANKTON SPECIES ABUNDANCE
STATION F13P – OCTOBER 92
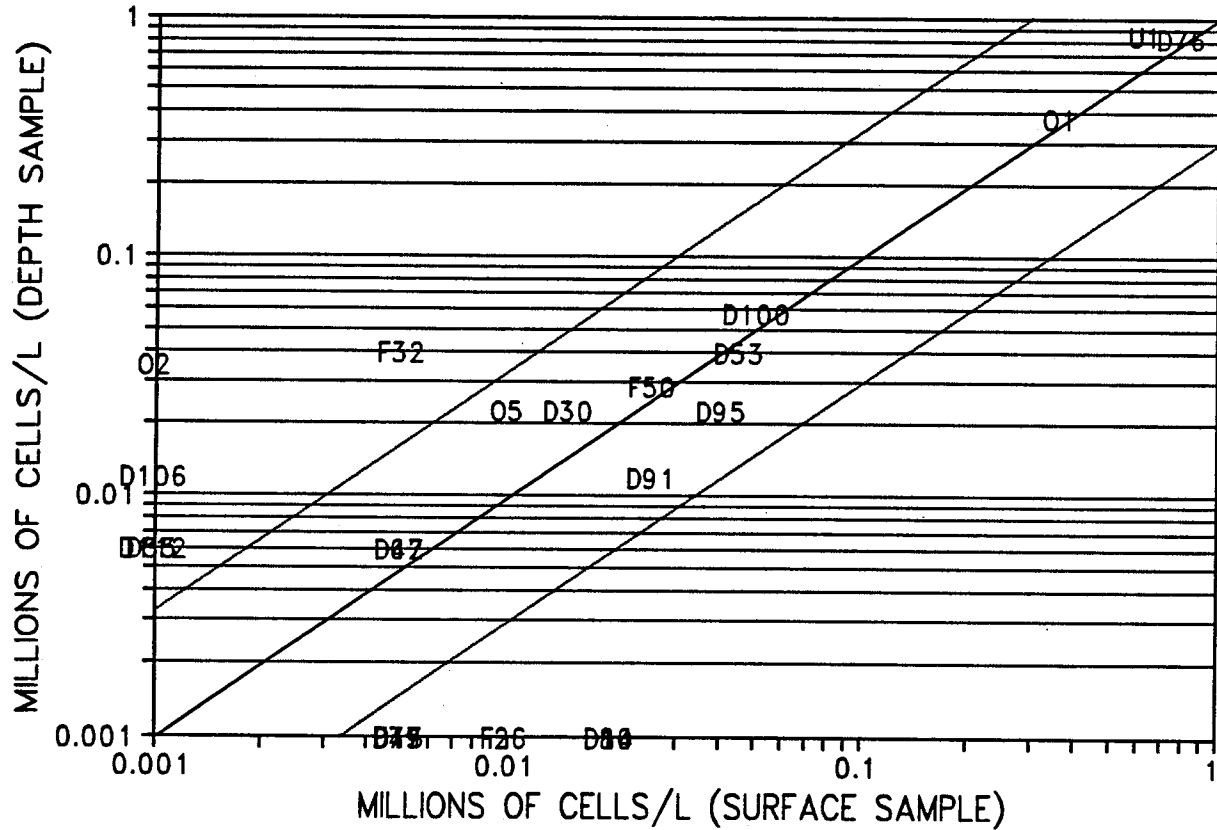
Figure 5-32 Comparison of phytoplankton taxonomic composition of surface and deeper samples at station F13P in October 1992. Species codes are given in Appendix F.

Zooplankton – October 92
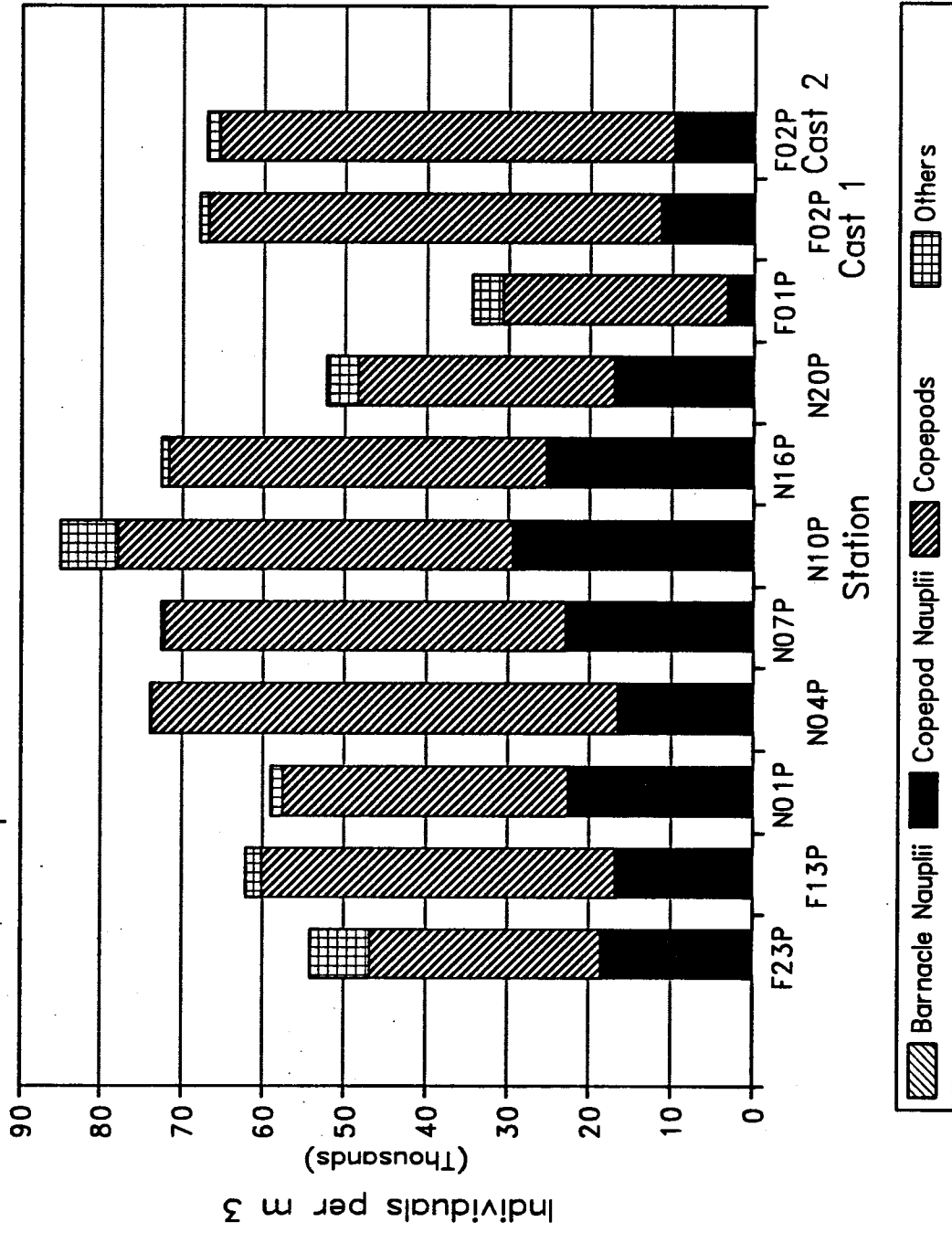
Figure 5-33 Zooplankton abundance, by groups, at BioProductivity stations in October 1992. Data are given in Appendix G.

STATION F23P CHLA MAXIMUM

ug O2/ug CHL/HR

uE/M2/SEC
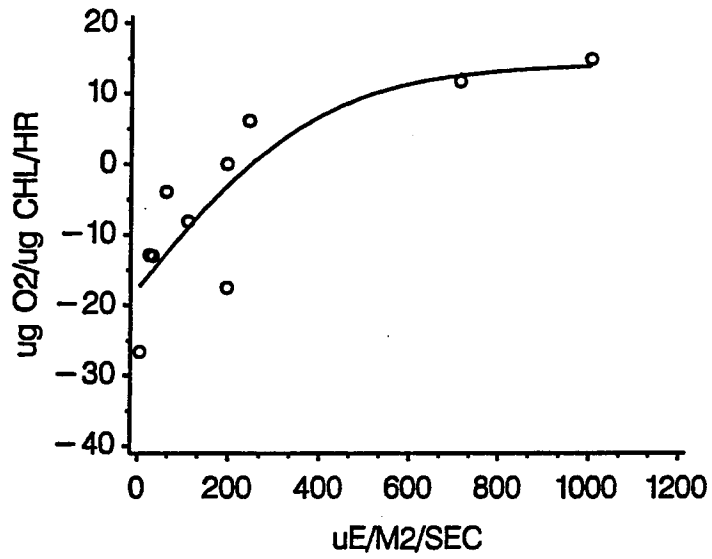
MODEL FROM PLATT AND JASSBY, 1976
CRUISE NUMBER 12, OCT 1992

STATION F2P CHLA MAXIMUM

ug O2/ug CHL/HR

uE/M2/SEC
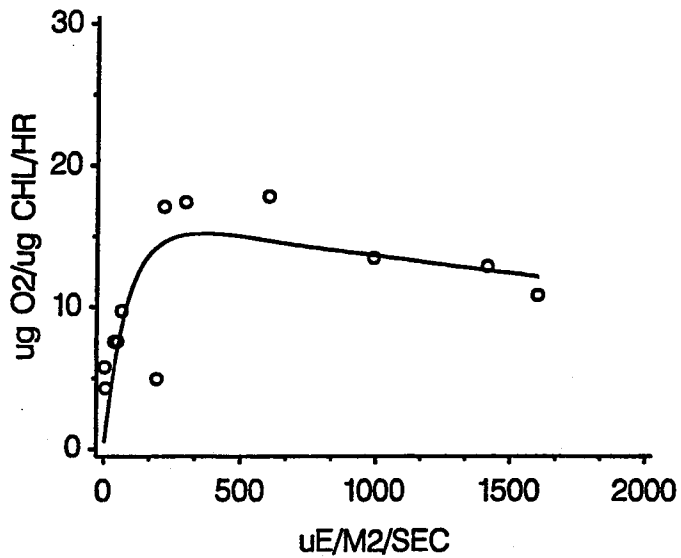
MODEL FROM PLATT ET AL, 1980
CRUISE NUMBER 12, OCT 1992

Figure 5-34 Selected net production (P) vs. irradiance (I) curves in October 1992. Data are chlorophyll-normalized rates see Appendix E.
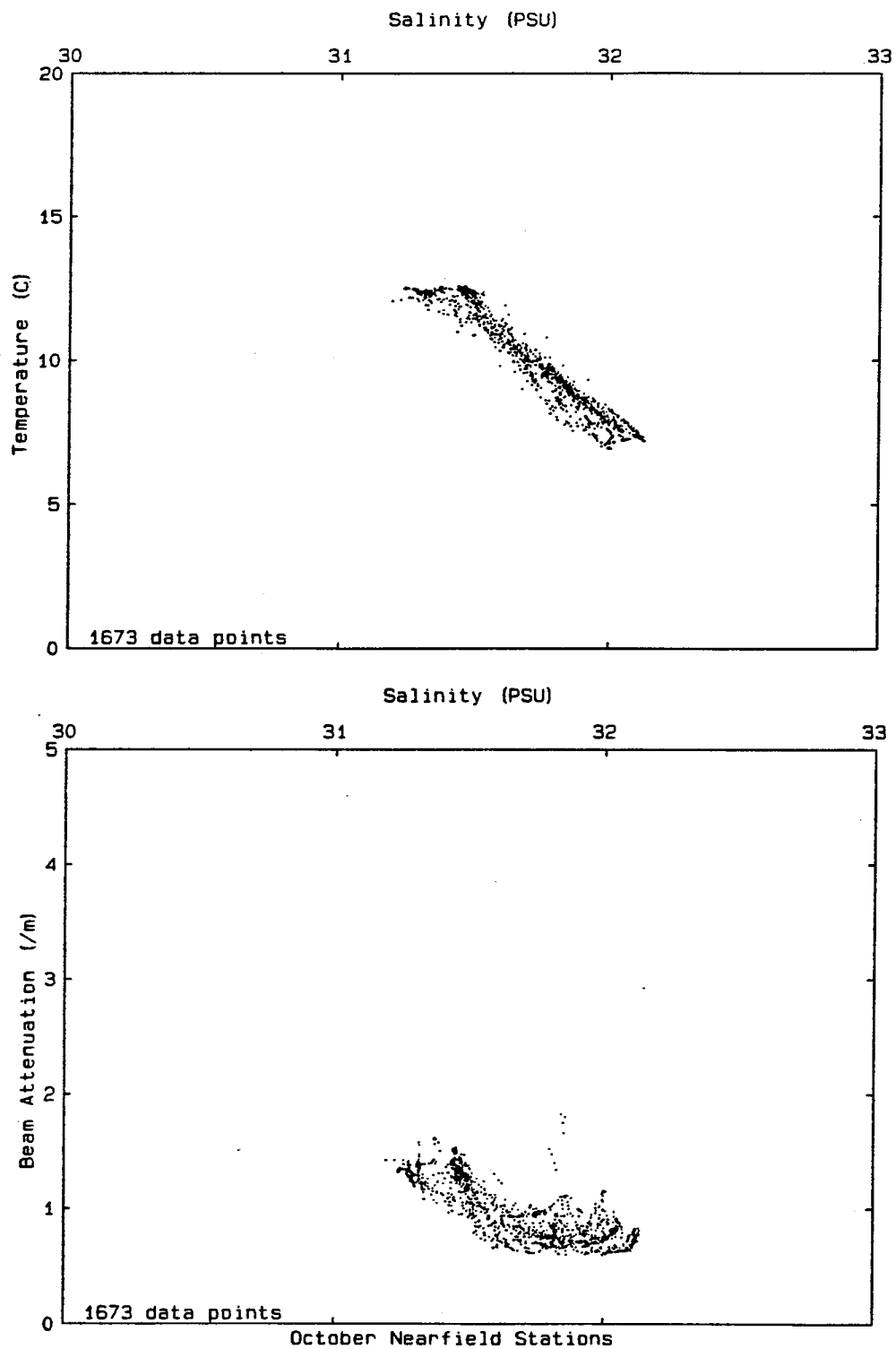
Figure 5-35a Scatter plots for nearfield stations only. Compare to Figure 5-17. Data include sampling of the nearfield during the farfield survey (six "P" stations) and the nearfield survey (21 stations).

Chlorophyll a (ug/L)

1673 data points

Chlorophyll a (ug/L)

1673 data points

October Nearfield Stations
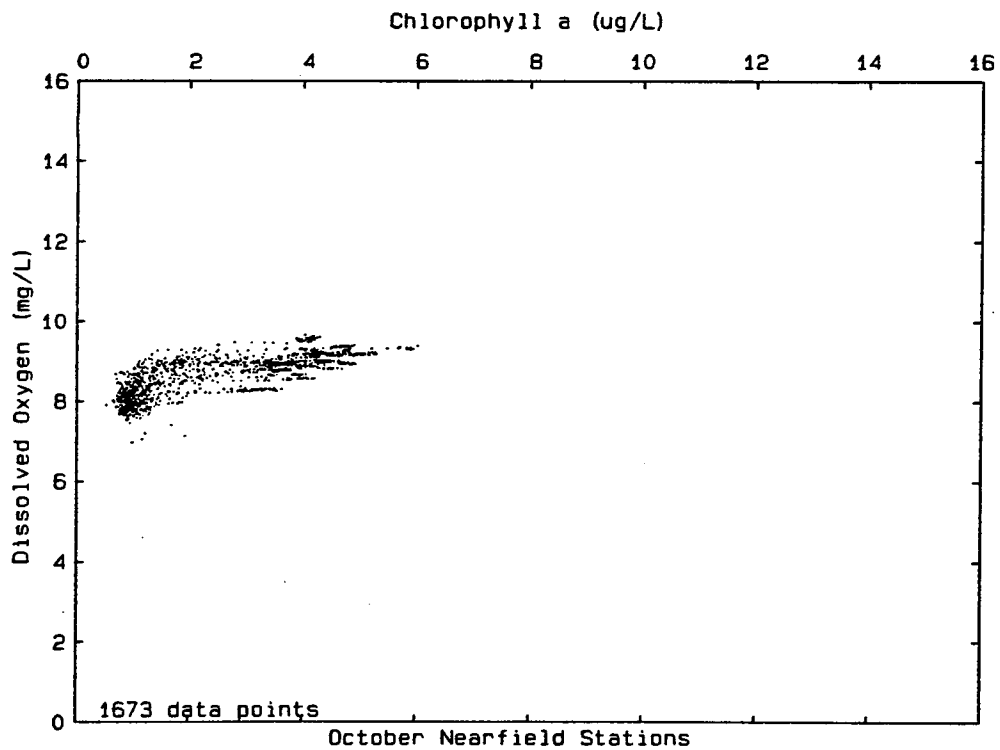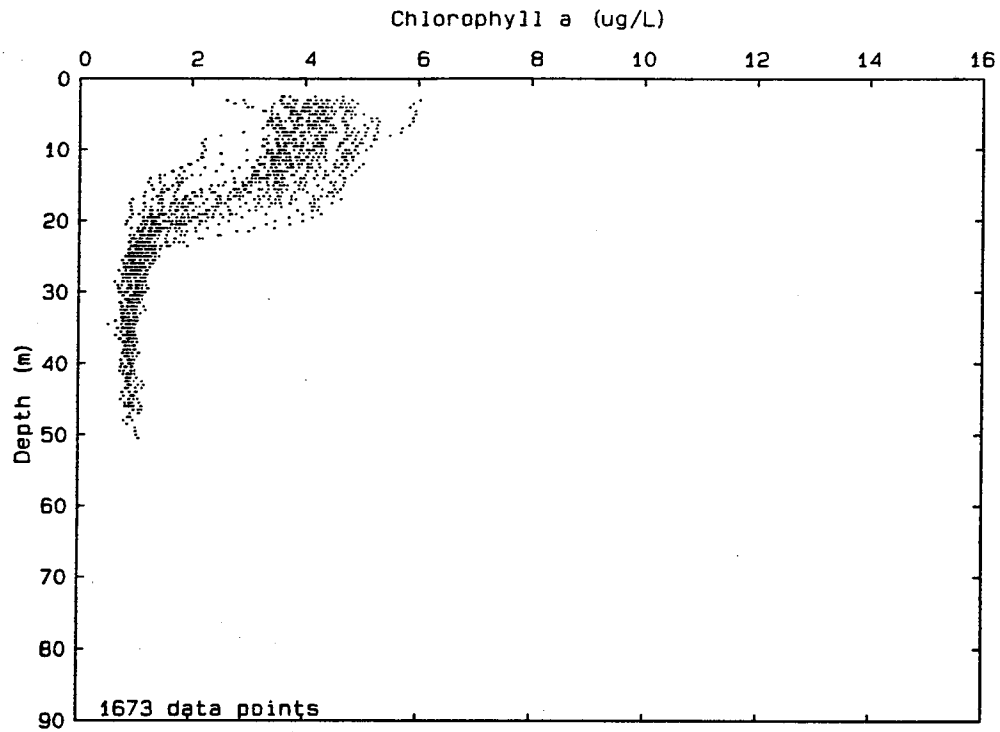
Figure 5-35b Scatter plots for nearfield stations only. Compare to Figure 5-17. Data include sampling of the nearfield during the farfield survey (six "P" stations) and the nearfield survey (21 stations). Chlorophyll was estimated from fluorescence and DO was calibrated with titrations (see Appendix A).

Chlorophyll a (ug/L)

Chlorophyll a (ug/L)

October Nearfield Stations
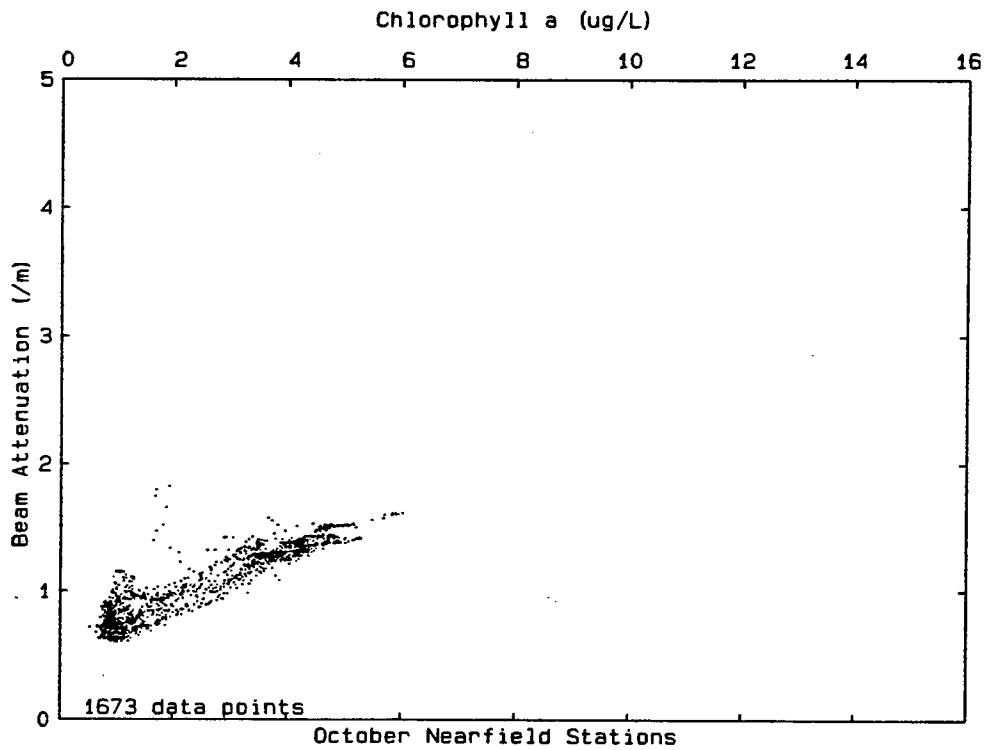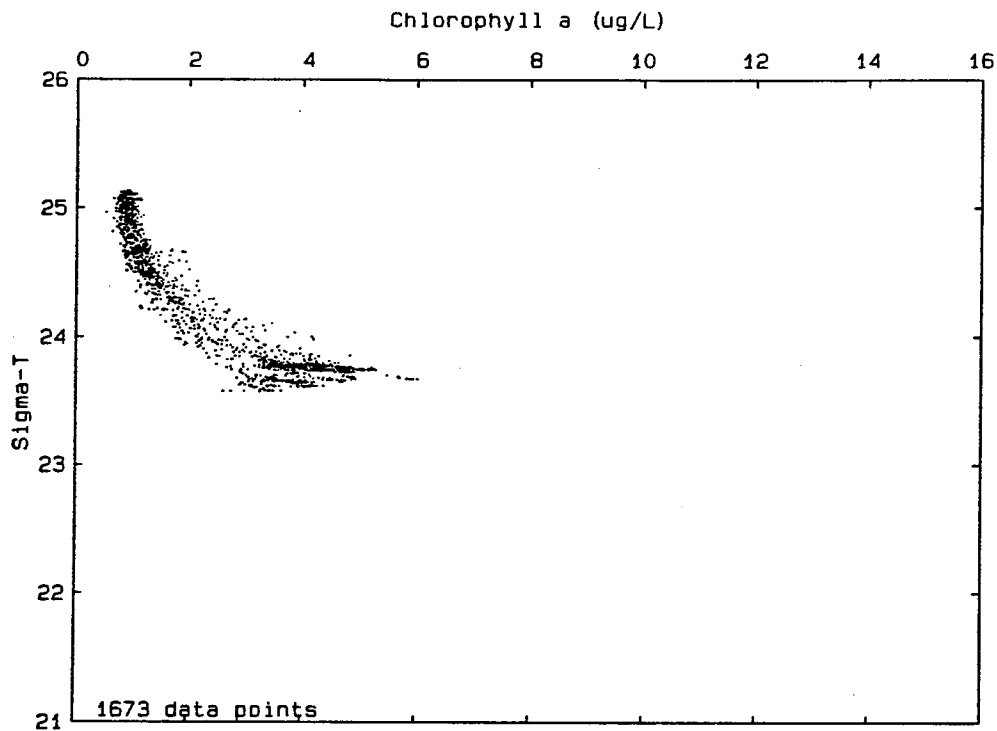
Figure 5-35c Scatter plots for nearfield stations only. Compare to Figure 5-17. Data include sampling of the nearfield during the farfield survey (six "P" stations) and the nearfield survey (21 stations). Chlorophyll was estimated from fluorescence (see Appendix A).

Chlorophyll a Maximum during October
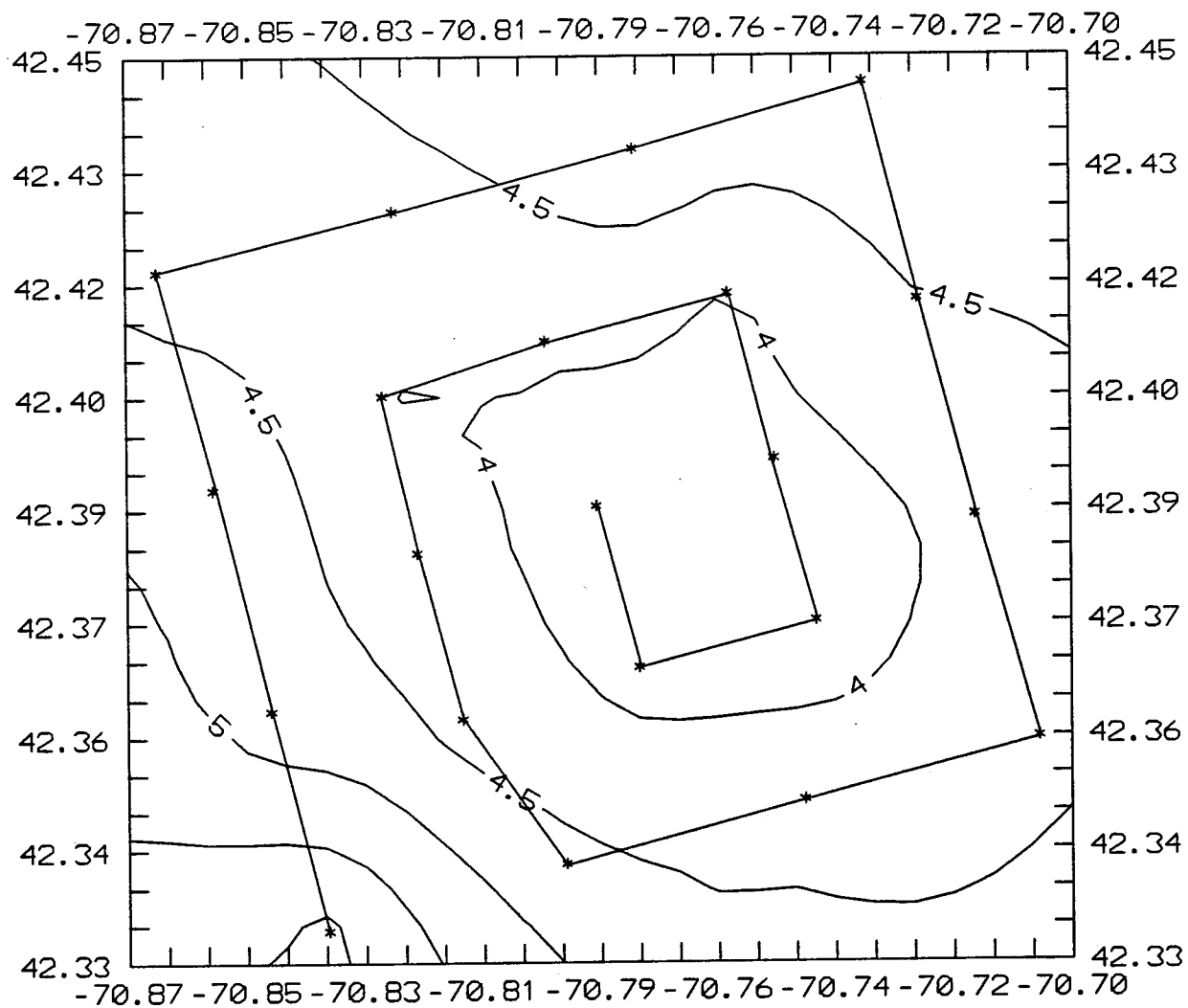
Figure 5-36 Chlorophyll maximum at each nearfield station from vertical profile day (Appendix B). Track shows sampling, starting at southwest corner of nearfield. Chlorophyll maximum may not be at the same depth at different stations.

Figure 5-37 DIN vs. Depth in October 1992. Nearfield data are from sampling on both the farfield (six "P" stations) and nearfield (21 stations) portions of the survey.

Sigma-T Along Outer Northern Track

N01P   N02   N03   N04P

N131SI Minimum =23.69 Maximum =25.09

Sigma-T Along Inner Northern Track

N13   N14   N15

N133SI Minimum =20.77 Maximum =24.91

Sigma-T Along Inner Southern Track

N19   N18   N17

N135SI Minimum =23.76 Maximum =24.64

Sigma-T Along Outer Southern Track

N10P   N09   N08   N07P

N137SI Minimum =23.72 Maximum =24.87
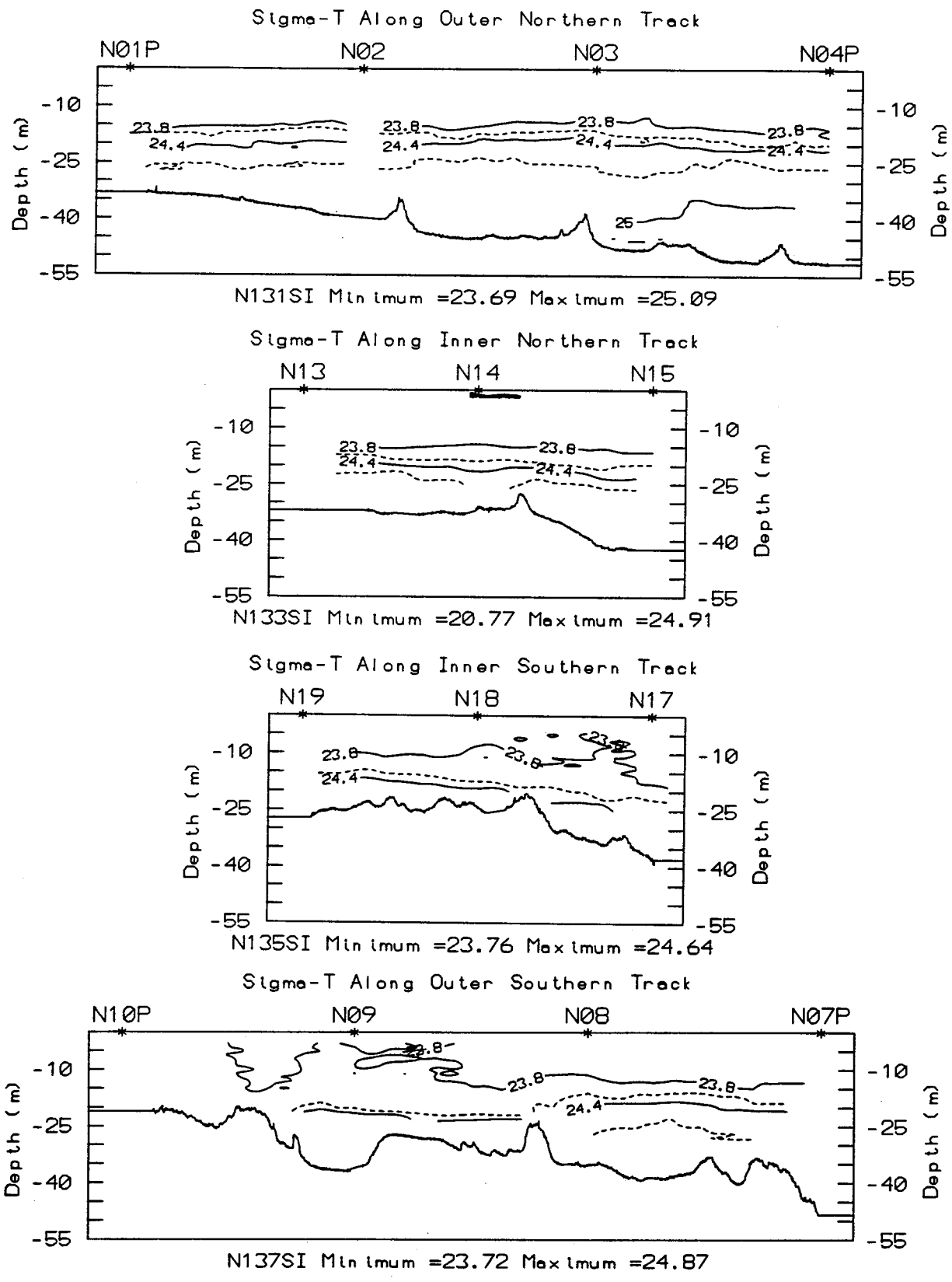
Figure 5-38a   Vertical section contours of σ_T generated for tow-yos in October 1992.
The view is towards the North. The contour interval is 0.2 σ_T.

Sigma-T Along Outer Western Track

N10P   N11   N12   N01P

N132SI Minimum =23.67 Maximum =24.76

Sigma-T Along Inner Western Track

N19   N20P   N13

N134SI Minimum =23.65 Maximum =24.81

Sigma-T Along Inner Eastern Track

N17   N16P   N15

N136SI Minimum =23.71 Maximum =24.85

Sigma-T Along Outer Eastern Track

N07P   N06   N05   N04P

N138SI Minimum =23.66 Maximum =25.13
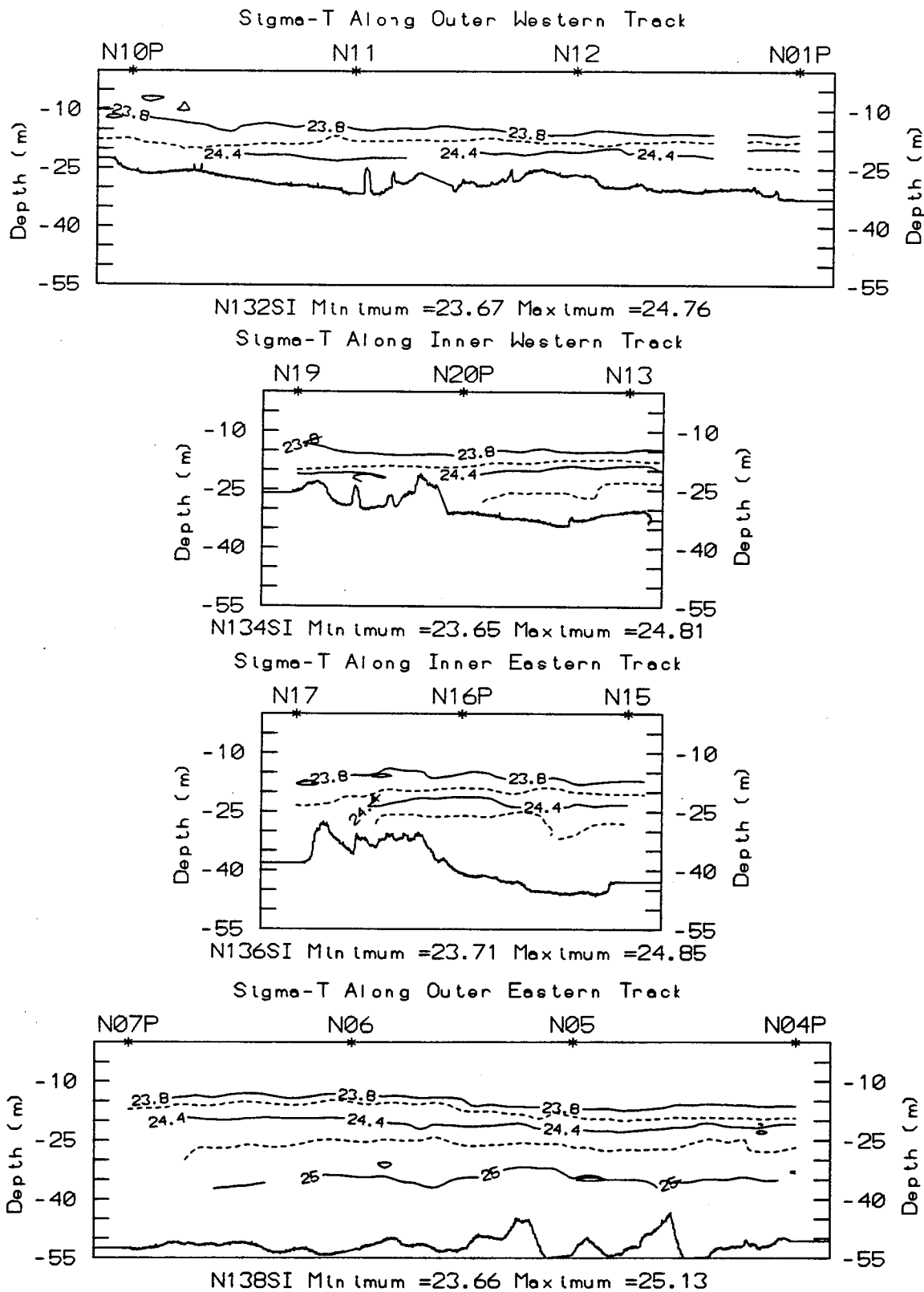
Figure 5-38b   Vertical section contours of σ_T generated for tow-yos in October 1992. The view is towards Boston Harbor. The contour interval is 0.2 σ_T.

Chlorophyll a (ug/L) Along Outer Northern Track

N01P   N02   N03   N04P

N131CH Minimum = 0.53 Maximum = 4.49

Chlorophyll a (ug/L) Along Inner Northern Track

N13   N14   N15

N133CH Minimum = 0.79 Maximum = 5.35

Chlorophyll a (ug/L) Along Inner Southern Track

N19   N18   N17

N135CH Minimum = 0.92 Maximum = 3.50

Chlorophyll a (ug/L) Along Outer Southern Track

N10P   N09   N08   N07P

N137CH Minimum = 0.83 Maximum = 3.59
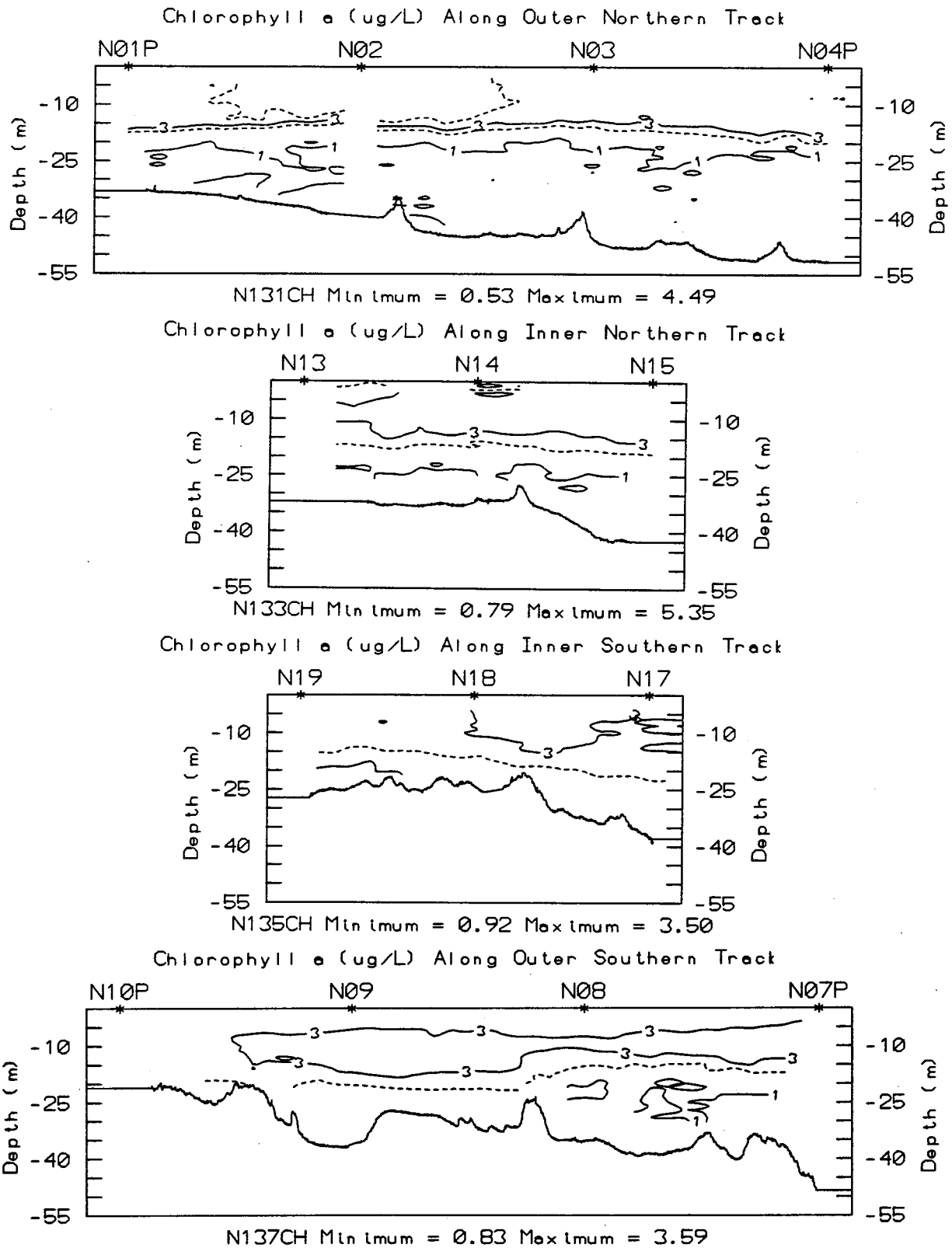
Figure 5-39a   Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yos in October 1992. The view is towards the North. The contour interval is 1 μg L^{-1}.

Chlorophyll a (ug/L) Along Outer Western Track

N10P   N11   N12   N01P

N132CH Minimum = 0.92 Maximum = 4.64

Chlorophyll a (ug/L) Along Inner Western Track

N19   N20P   N13

N134CH Minimum = 0.84 Maximum =16.64

Chlorophyll a (ug/L) Along Inner Eastern Track

N17   N16P   N15

N136CH Minimum = 0.80 Maximum = 3.94

Chlorophyll a (ug/L) Along Outer Eastern Track

N07P   N06   N05   N04P

N138CH Minimum = 0.65 Maximum = 3.82
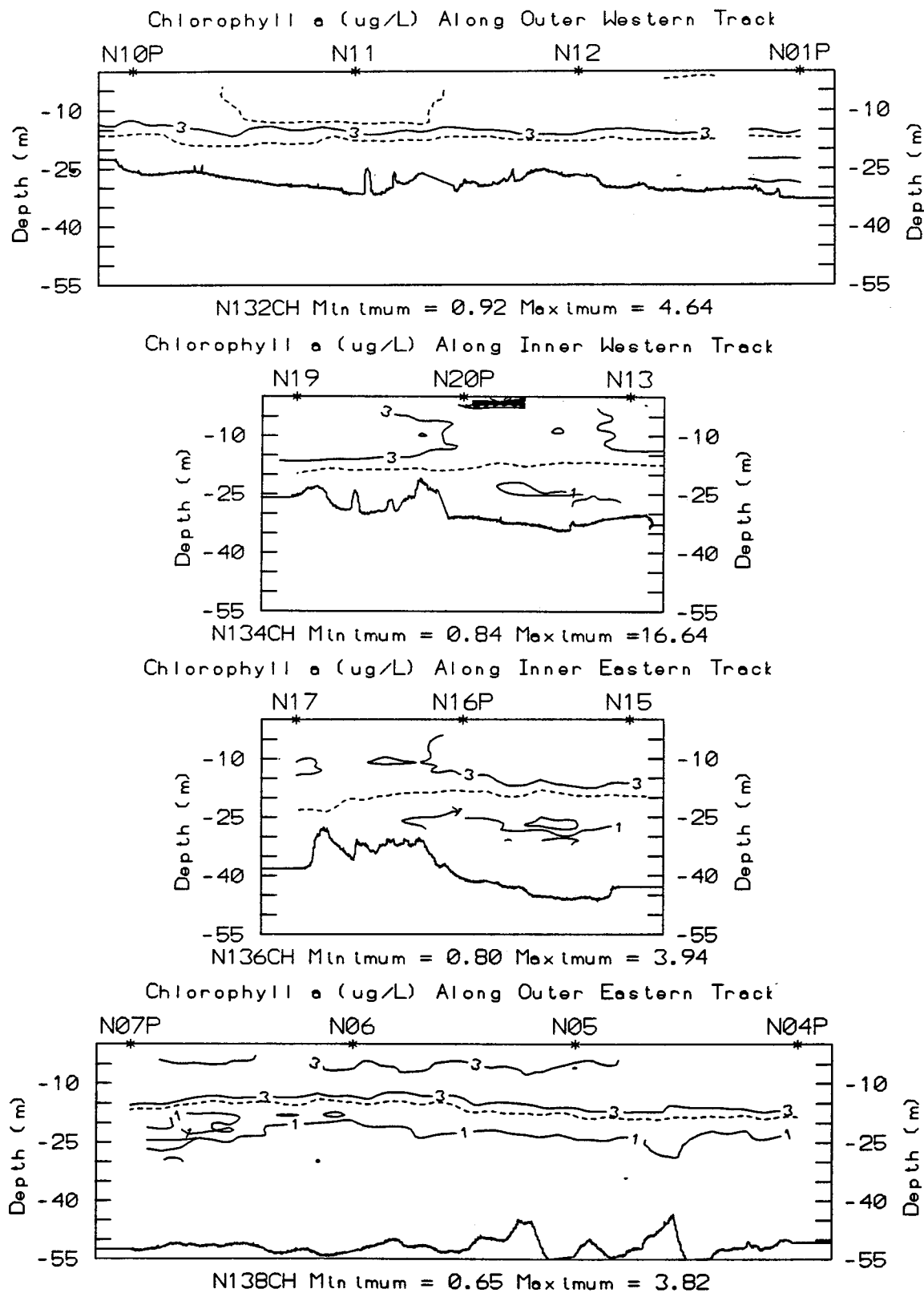
Figure 5-39b   Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yos in October 1992. The view is towards the Boston Harbor. The contour interval is 1 μg L^{-1}.

6.0 NOVEMBER 1992 NEARFIELD SURVEY RESULTS

6.1 Distribution of Water Properties from Vertical Profiling

Vertical profiles were conducted on November 9 and only 15 of the 21 nearfield stations were occupied. Profiles of parameters from *in situ* sensing were essentially straight up and down at each cast; thus, the water had completed Fall overturn since mid-October.

Temperature was between about 9 and 9.5 °C (full range). Salinity varied only from about 31.2 to 31.8 PSU across depth and stations (Figure 6-1a).

Beam attenuation was recorded from about 0.7 to 0.98 m^{-1}. Chlorophyll fluorescence showed little profile with depth and across the field ranged from a little less than 2 to about 4 μg L^{-1} (Figures 6-1b and 6-1c). As shown in Figure 6-2, higher chlorophyll was seen in the middle of the nearfield.

The nutrient concentrations nevertheless had some variability across the field (Figures 6-3 and 6-4). Ammonia varied from 0 to 3.5 μM, with no depth pattern. Similarly, nitrate varied from about 0 to 7 μM. DIN ranged from 0 to 8.5 μM. Phosphate varied from about 0.2 to 1.0 μM. For silicate, most values, straight up and down with depth, were at 1 μM, but some were slightly over 4, and two deep samples were greater than 7 μM.

Quick inspection of Appendix A shows that high nutrients, for all forms, were recorded at N01P and N10P, the inshore corners of the nearfield. Note that the stations between these corners, N11 and N12, were not sampled. The offshore corners, N04P and N07P had high nitrate, phosphate, and silicate concentrations at samples taken below 40 m. Station N02 near the northwest corner had slightly elevated silicate at depth.

6.2 Distribution of Water Properties from Towing

For the tow day, the inner box was towed counterclockwise, starting at N19. This was followed by towing the outer box counterclockwise, starting at N10P. For the outer box three legs were completely towed, but due to daylight constraints only vertical profiles (rather than continuous horizontal tows) were

conducted at the four stations across the inshore western track. A slight density gradation was apparent running seaward from the southwestern corner (N10P) (Figure 6-5). Otherwise, no physical structure was apparent.

Chlorophyll (Figure 6-6) had more dynamic range. It appeared that there were some small mid-water patches of higher chlorophyll ($> 3 \mu g \, L^{-1}$), as well as some surface heterogeneity across the field. Even so, no values were very high.

6.3 Water Types and Analysis of Small-Scale Variability

It was quite clear that variability in physical parameters was extremely low and the water column could hardly have been more uniformly mixed from top to bottom. In spite of this, some geochemical and biological variability was still seen both horizontally and vertically, primarily at small scales. Broad spatial trends in any type of parameter were not immediately apparent, however. Although the two inshore stations (N01P and N10P) sampled for nutrients on the vertical profiling day had higher values, a concomitantly higher chlorophyll response was not seen at these stations on either day of sampling.

Salinity (PSU)

30   31   32   33

Salinity (PSU)

30   31   32   33
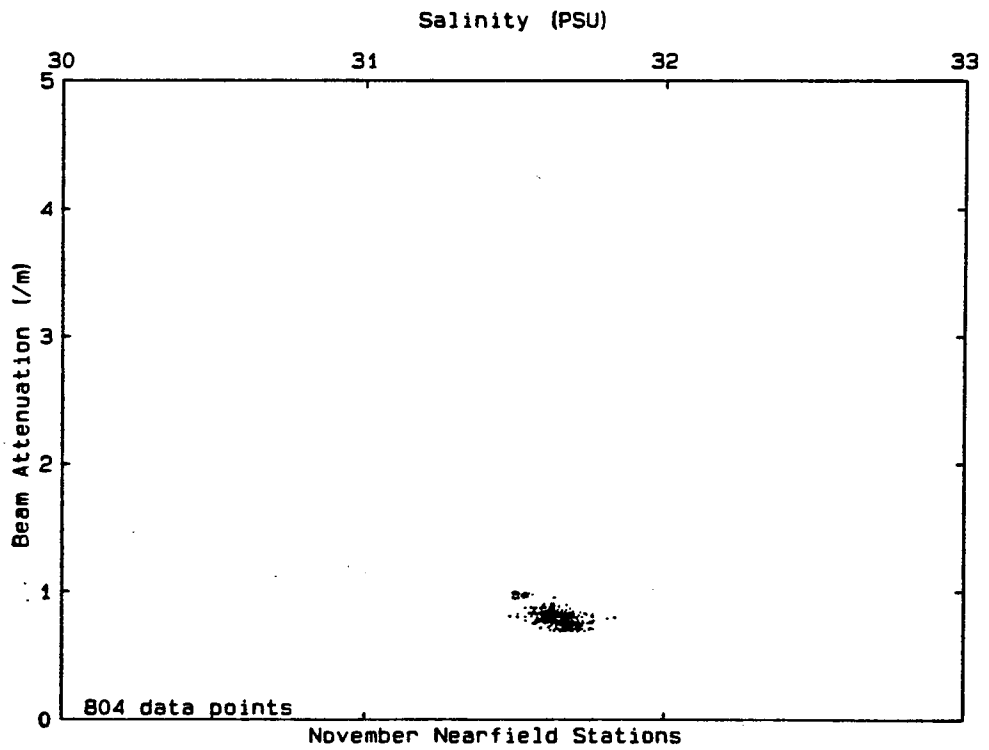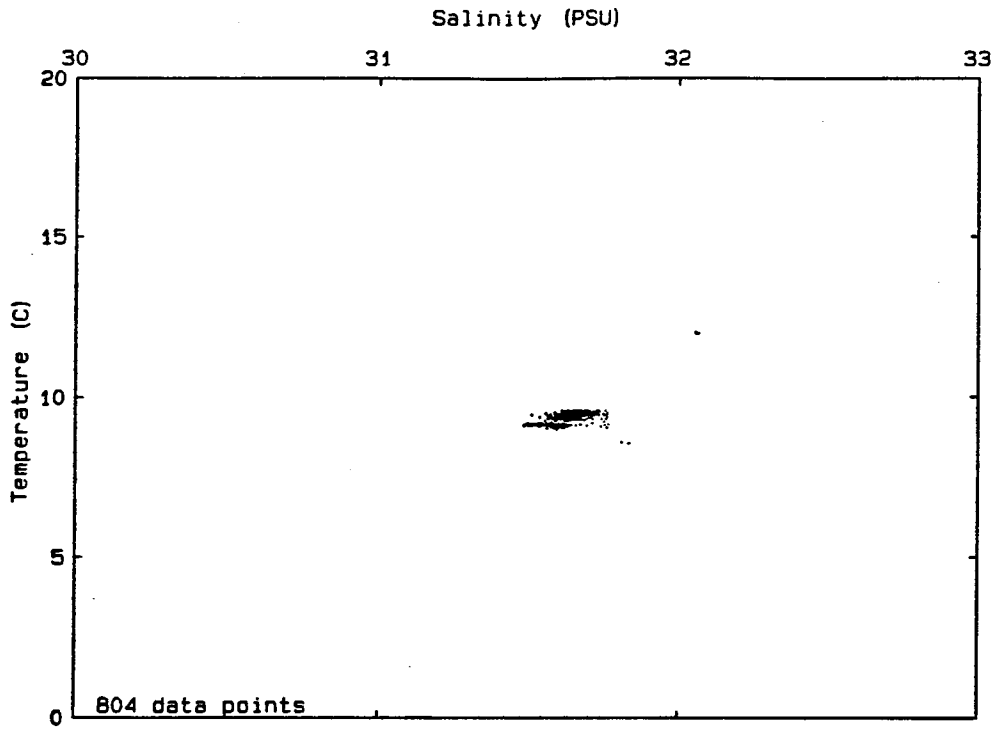
Figure 6-1a Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in November 1992. Individual station casts that were used to produce this composite are in Appendix B.

Chlorophyll a (ug/L)

714 data points

Chlorophyll a (ug/L)

714 data points

November Nearfield Stations

Figure 6-1b Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in November 1992. Individual station casts that were used to produce this composite are in Appendix B. Chlorophyll was estimated from fluorescence and DO was calibrated with titrations (see Appendix A).

Chlorophyll a (ug/L)

Chlorophyll a (ug/L)

November Nearfield Stations
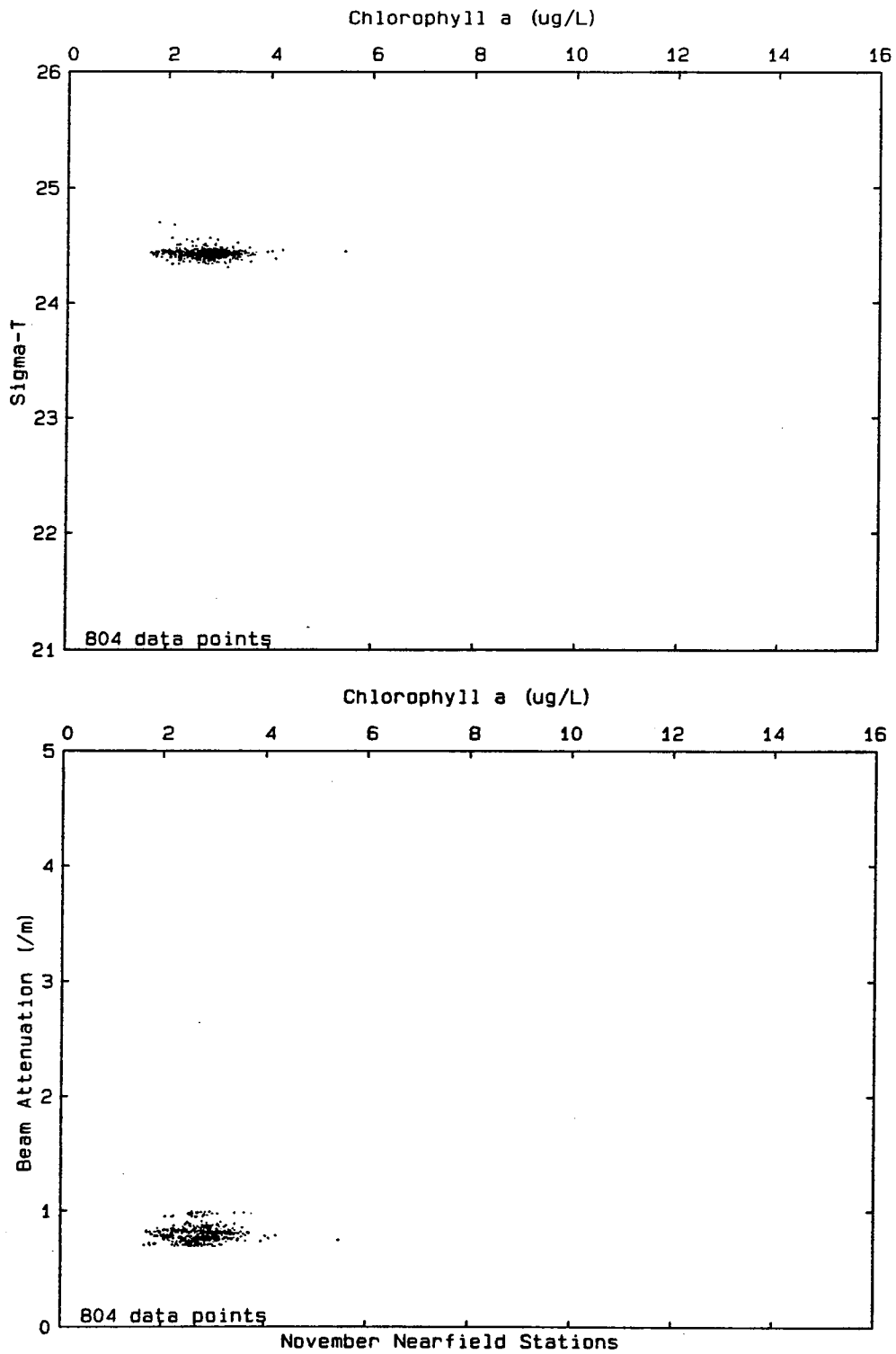
Figure 6-1c   Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all nearfield stations occupied in November 1992. Individual station casts that were used to produce this composite are in Appendix B. Chlorophyll was estimated from fluorescence (see Appendix A).

Figure 6-2 Chlorophyll maximum at each nearfield station from vertical profile day (Appendix B). Track shows sampling, starting at middle of nearfield and proceeding clockwise. Not all 21 stations were sampled. Chlorophyll maximum may not be at the same depth at different stations.

NH4 vs. Depth
November, Nearfield Stations
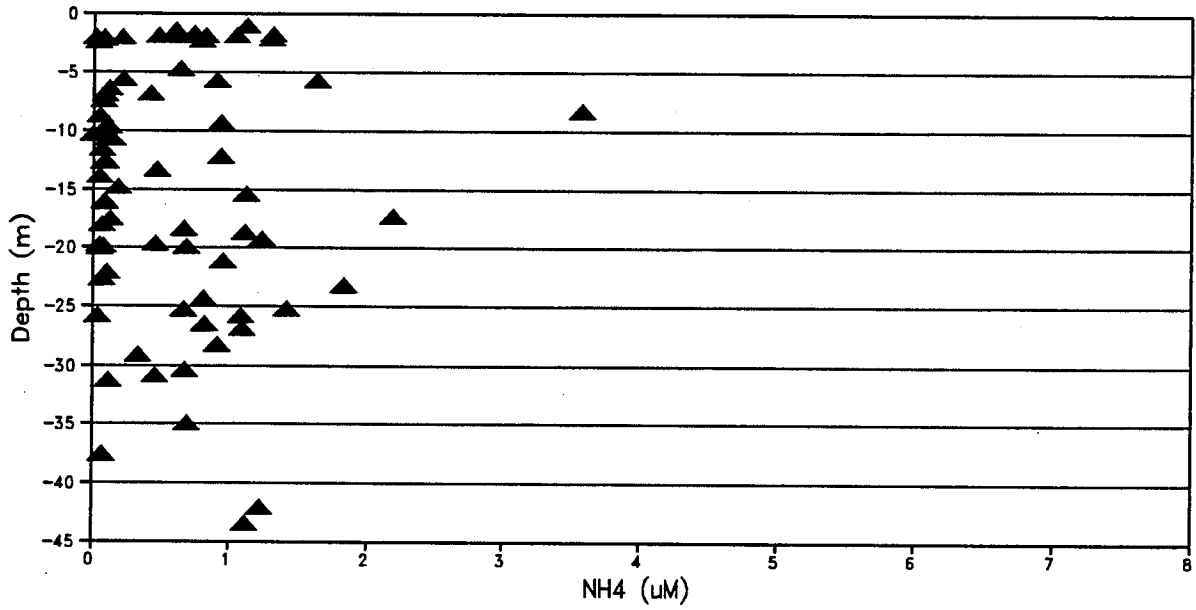
NO3 vs. Depth
November, Nearfield Stations
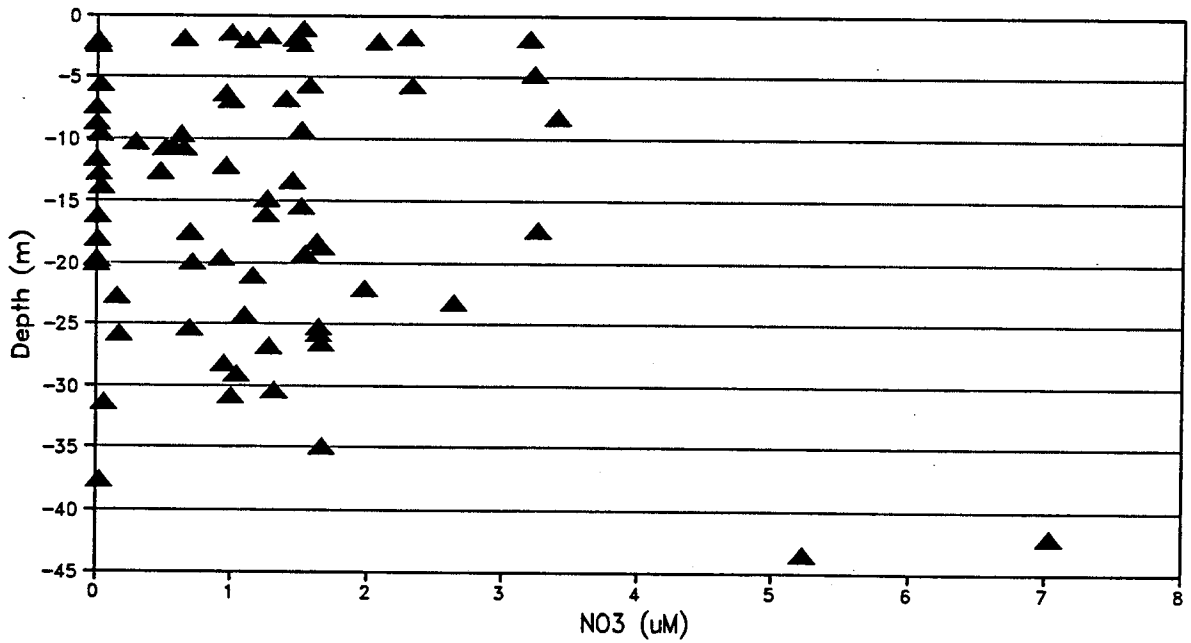
Figure 6-3 NH_4 and NO_3 vs. depth in November 1992.

PO4 vs. Depth
November, Nearfield Stations

SiO4 vs. Depth
November, Nearfield Stations
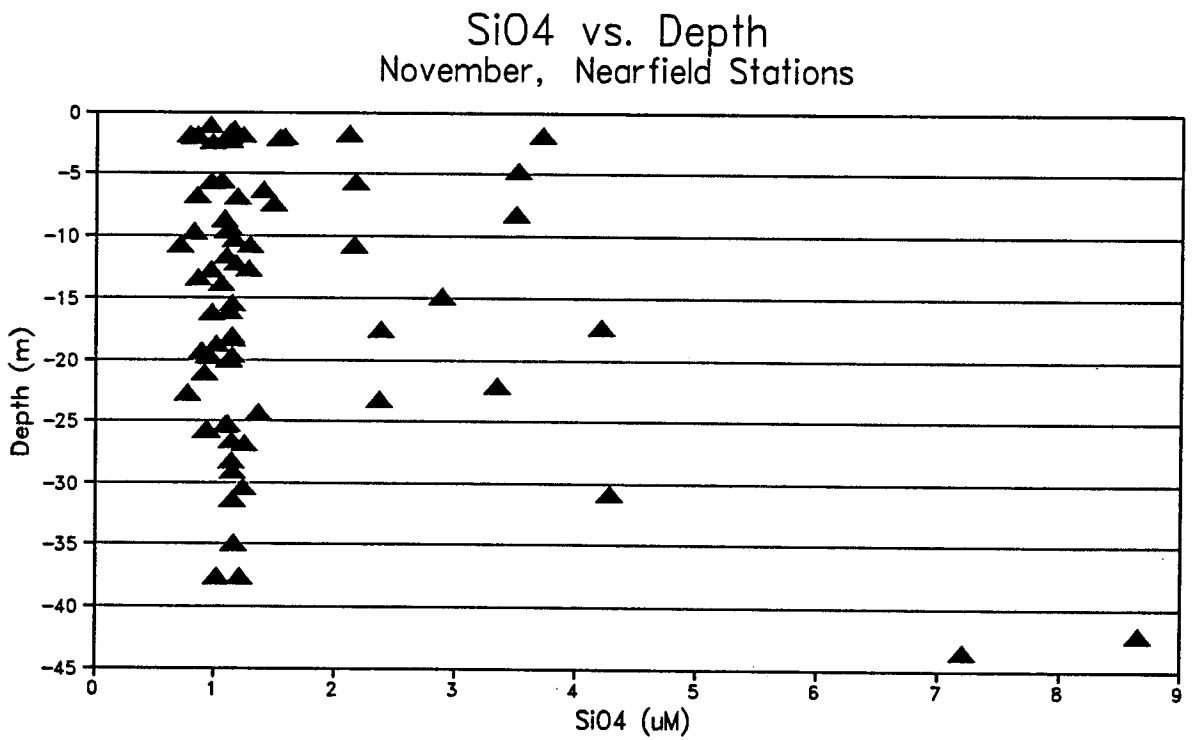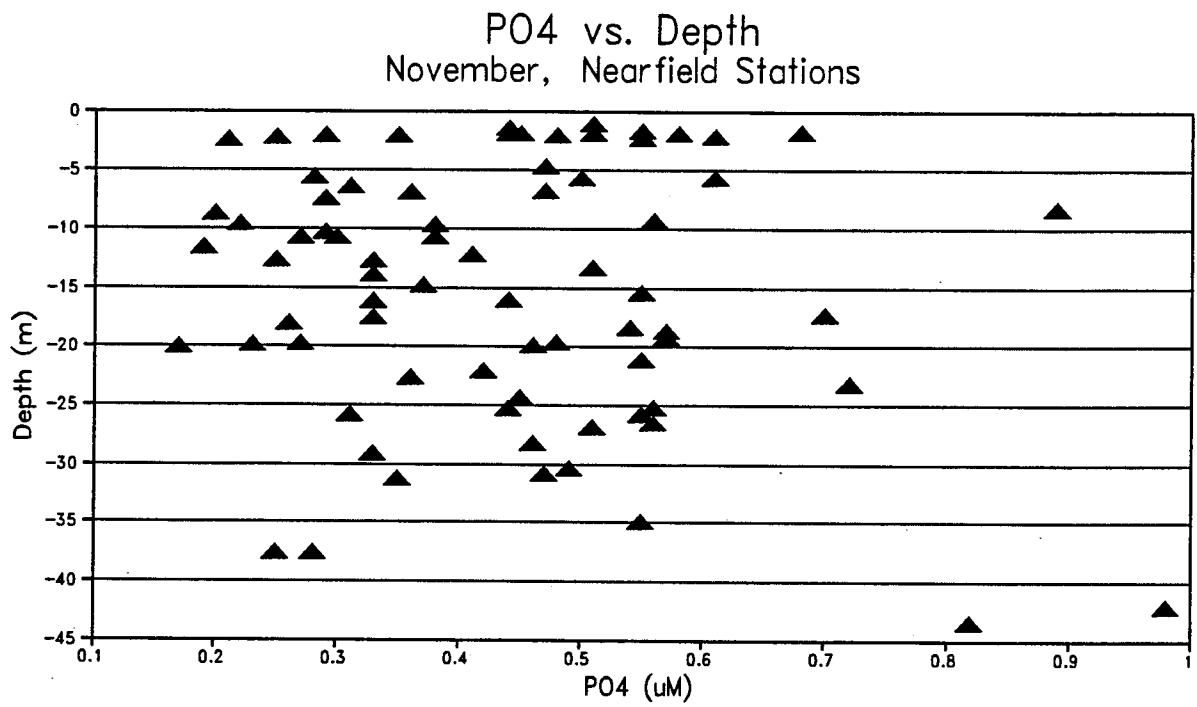
Figure 6-4   PO$_4$ and SiO$_4$ vs. depth in November 1992.

Sigma-T Along Outer Northern Track

N01P   N02   N03   N04P

N141SI Minimum =24.38 Maximum =24.45

Sigma-T Along Inner Northern Track

N13   N14   N15

N143SI Minimum =24.41 Maximum =24.46

Sigma-T Along Inner Southern Track

N19   N18   N17

N145SI Minimum =24.42 Maximum =24.48

Sigma-T Along Outer Southern Track

N10P   N09   N08   N07P

N147SI Minimum =24.27 Maximum =24.45
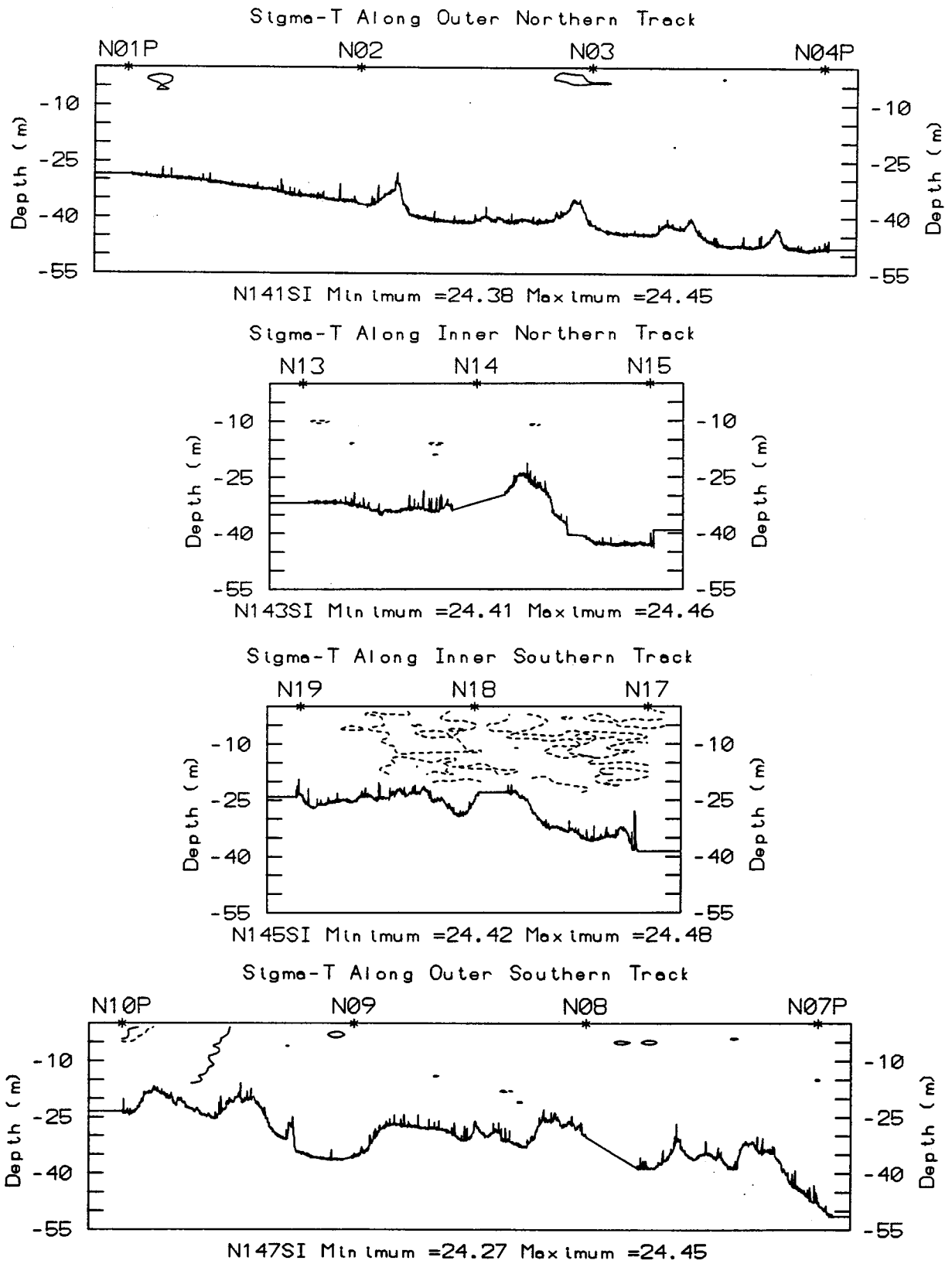
Figure 6-5a Vertical section contours of σ_T generated for tow-yos in November 1992. The view is towards the North. The contour interval is 0.2 σ_T.

Sigma-T Along Outer Western Track

N10P   N11   N12   N01P

Depth (m)
-10   -10
-25   -25
-40   -40
-55   -55

N142SI Minimum =24.27 Maximum =24.44

Sigma-T Along Inner Western Track

N19   N20P   N13

Depth (m)
-10   -10
-25   -25
-40   -40
-55   -55

N144SI Minimum =24.41 Maximum =24.47

Sigma-T Along Inner Eastern Track

N17   N16P   N15

Depth (m)
-10   -10
-25   -25
-40   -40
-55   -55

N146SI Minimum =24.41 Maximum =24.47

Sigma-T Along Outer Eastern Track

N07P   N06   N05   N04P

Depth (m)
-10   -10
-25   -25
-40   -40
-55   -55

N148SI Minimum =24.40 Maximum =24.47
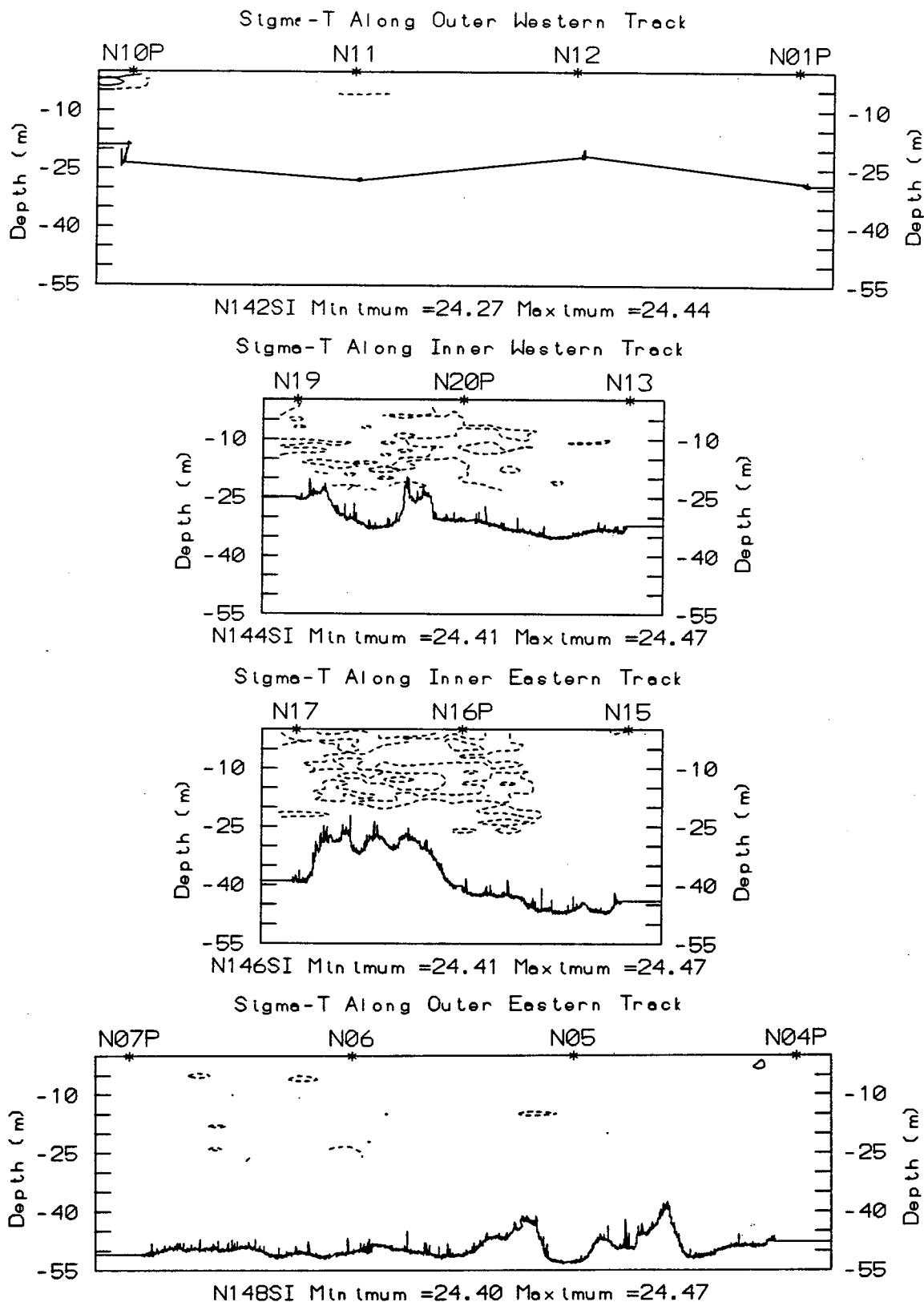
Figure 6-5b Vertical section contours of σ_T generated for tow-yos in November 1992. The view is towards Boston Harbor. The contour interval is 0.2 σ_T. Note that vertical profiles were conducted at N11 and N12; no towing was conducted from N01P to N10P.

Chlorophyll a (ug/L) Along Outer Northern Track

N01P   N02   N03   N04P

Depth (m)
-10   -25   -40   -55
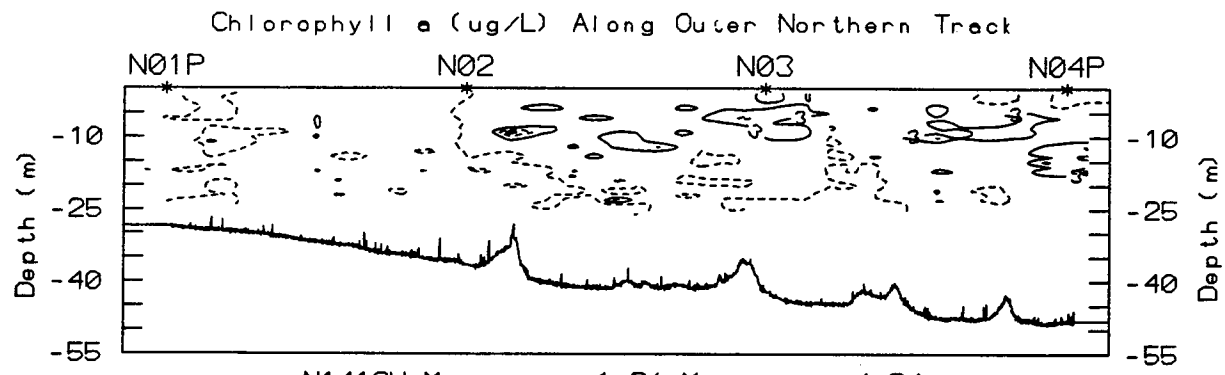
N141CH Minimum = 1.96 Maximum = 4.24

Chlorophyll a (ug/L) Along Inner Northern Track

N13   N14   N15

Depth (m)
-10   -25   -40   -55
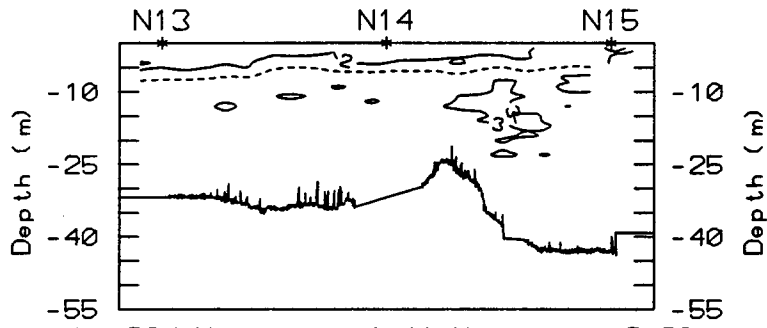
N143CH Minimum = 1.61 Maximum = 3.30

Chlorophyll a (ug/L) Along Inner Southern Track

N19   N18   N17

Depth (m)
-10   -25   -40   -55
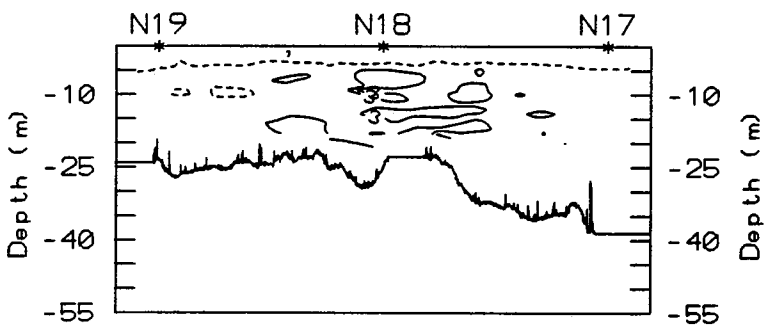
N145CH Minimum = 2.08 Maximum = 3.46

Chlorophyll a (ug/L) Along Outer Southern Track

N10P   N09   N08   N07P

Depth (m)
-10   -25   -40   -55
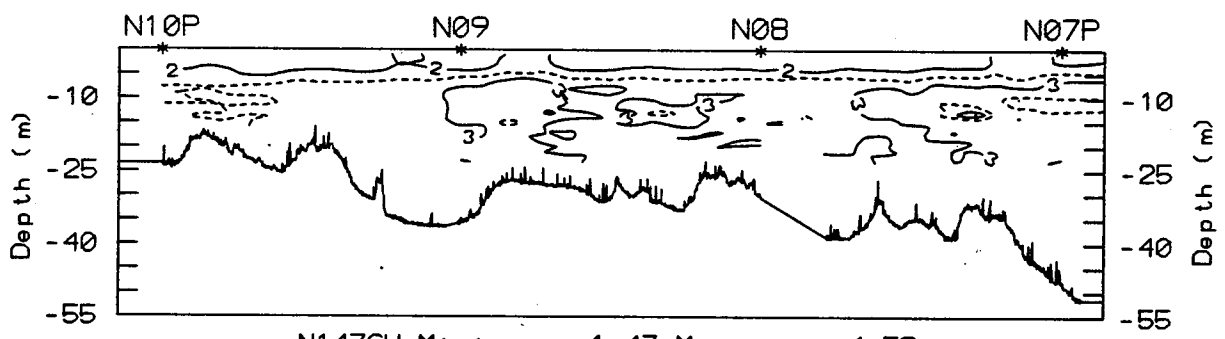
N147CH Minimum = 1.47 Maximum = 4.52

Figure 6-6a Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yos in November 1992. The view is towards the North. The contour interval is 0.5 μg L^{-1}.

Chlorophyll a (ug/L) Along Outer Western Track
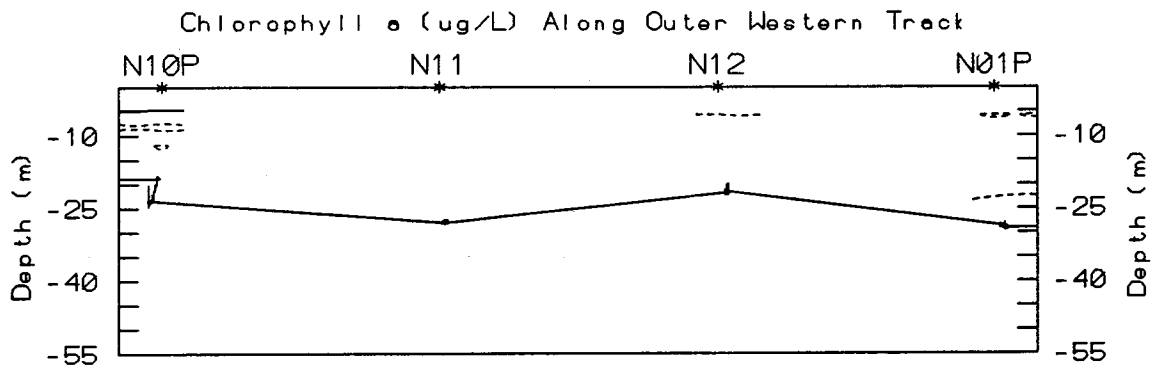
N142CH Minimum = 1.47 Maximum = 2.91

Chlorophyll a (ug/L) Along Inner Western Track
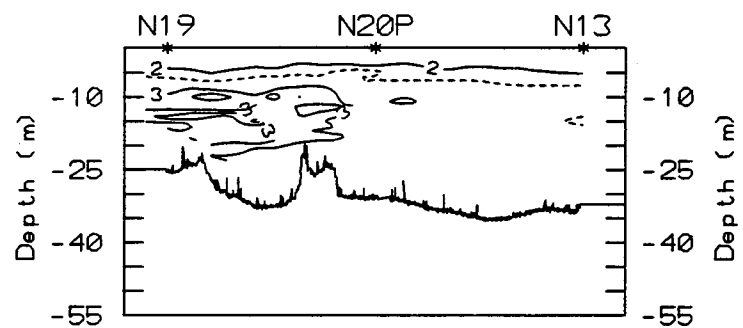
N144CH Minimum = 1.54 Maximum = 3.63

Chlorophyll a (ug/L) Along Inner Eastern Track
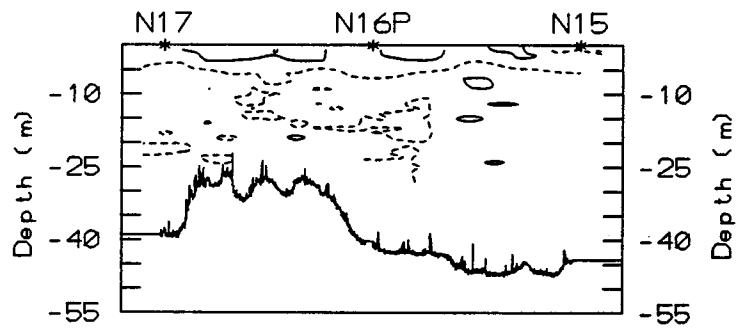
N146CH Minimum = 1.81 Maximum = 3.32

Chlorophyll a (ug/L) Along Outer Eastern Track
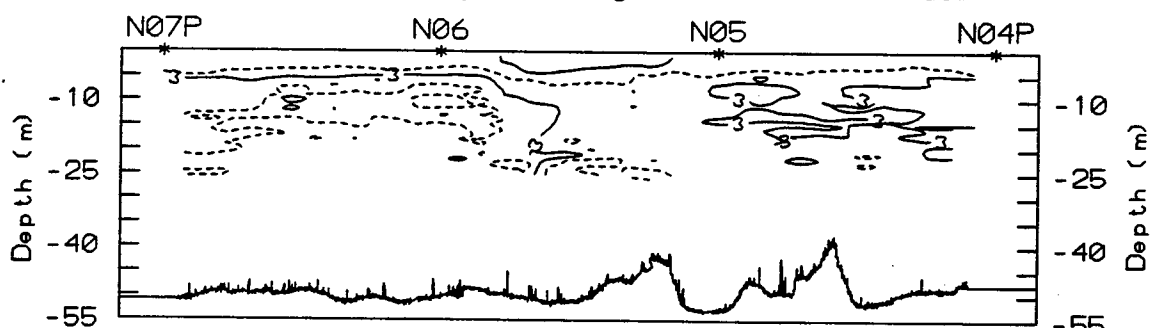
N148CH Minimum = 1.71 Maximum = 4.35

Figure 6-6b Vertical section contours of fluorescence (as μg Chl L^{-1}) generated for tow-yos in November 1992. The view is towards Boston Harbor. The contour interval is 0.5 μg L^{-1}. Note that vertical profiles were conducted at N11 and N12; no towing was conducted from N01P to N10P.

7.0 DISCUSSION

7.1 Water Properties (Physical and Chemical), late August to November

7.1.1 Scales of Variability Across the Study Area

Accompanying the full regional-scale constriction of temperature range from August to October was a general shift in salinity by about 0.25 to 0.5 PSU (Figure 7-1). By October, most local and mesoscale thermal features that had made for a complex surface pattern in August were no longer evident, and these had been overridden by a regional gradient, albeit slight, in surface temperature from North to South — warmer in Cape Cod. In contrast, in October the main mesoscale feature with respect to surface salinity was more related to coastal, fresher water, which produced a shore-to-sea gradient, especially in western Massachusetts Bay.

Chemically, there were regional changes from August to October. Over this time, the general condition changed from very depleted, near-undetectable DIN concentrations (surface to at least 20 m depth) to more frequently detectable, higher concentrations in the surface and also higher concentrations at depth (Figures 7-2 to 7-4). Although not as depleted at the surface as was N, both phosphate and silicate both showed the general trend, from late August to October, of increased concentrations throughout the water column.

Concomitant with these overall Bays-scale trends was the clearer emergence of the distinctive geochemical qualities of the coastal group of stations in October (Figures 7-2 to 7-6). For most dissolved inorganic nutrients, in August, only a few coastal stations near Boston Harbor had distinctive (higher) nutrient concentrations and then only at the surface. Nutrients became a more powerful group discriminator by October, when the same coastal stations had more pronounced surface enrichments. Moreover, some of the nearfield concentrations, both at surface and at depth became more distinguishable from offshore, Northern Transect, and Cape Cod Bay stations with respect to silicate and DIN.

Based on the above discussion of Baywide distributions and also the geographical distinctions based on dissolved inorganic nutrients earlier in the year (Kelly *et al.*, 1992, 1993), a tentative conclusion may be reached. For 1992, when the strongest vertical stratification and greatest thermal disparity between

surface and bottom water layers occurred (late August), the geographic differences, using dissolved nutrient concentrations, were most difficult to see or characterize. This is an intriguing notion, worthy of some further analysis, perhaps by examining nutrients across different depth strata.

7.1.2 Variability in the Nearfield

The nearfield region was surveyed each month from August through November (included in Figure 7-1). This period documented changes occurring as surface water temperatures fell from their peak recorded annual values ($\approx$ 20 °C) and intense vertical stratification, through a Fall overturn of the water column, to a condition of extremely well-mixed and uniformly cool temperature ($\approx$ 9 °C). The period also encompassed a transition from strong inshore-offshore gradients across the nearfield to near physical uniformity.

In August, as discussed above, the nearfield was similar geochemically to most of the Bays. In this case, the chemical properties in the nearfield were less a restricted *subset* of the Bays conditions (with respect to concentrations, and nutrient-nutrient as well as nutrient-physical relationships) and more representative of the *full* set of Bays conditions. Only a select few near-Harbor stations had enriched dissolved nutrient surface conditions relative the rest of the entire region. By October, the relative Bay-wide consistency in nutrient (dissolved inorganic) conditions had eroded and the data clearly showed that the nearfield had dissolved nutrient concentrations that were intermediate to inshore coastal and offshore deep waters. In October, physical patterns supported the notion of surface dispersion of nutrients from inshore, spreading over a substantial portion of the nearfield and creating a spatial gradient of nutrients much broader than noted in late August. The September pattern of DIN in the nearfield was roughly intermediate between August and October, suggesting progressive change (Figure 7-7). November was sharply different with respect to DIN (Figure 7-8), in part due to the well mixed conditions, but in part due to unknown factors that created a fair amount of dissolved nutrient variability in spite of strong physical uniformity.

7.1.3 Coherence of Nearfield and Farfield Station Properties

Most of the nearfield was physically and geochemical similar to other parts of the Bays in late summer, although some subtle distinctions were possible. One idea for additional study is the notion, in part suggested by these data, that temporal changes may markedly influence local, mesoscale, and regional

water properties and cause some of the variety of distributional patterns observed in the region. For example, in late August there was strong stratification throughout most of the study area and only minor regional-scale physical or geochemical variability, aside from that seen in the immediate area influenced by Harbor exchange. In this case, the variability in water properties may perhaps be seen as more local and mesoscale derived. At this time, the nearfield was geochemically similar to the farfield, including Cape Cod Bay. In contrast, the nearfield and farfield areas in October may have been more a part of a continuum of regional- (latitudinal) scale physical oceanographic trends, as well as influenced by some mesoscale geochemical features (e.g. broad-scale coastal freshwater input and nutrient enrichment). It is interesting that in October, the time when the physics suggested some larger-scale patterns of variability and perhaps less dominating influence of local sources of variability than in August, that there seemed to be less coherence in nutrient properties of the nearfield and some Cape Cod Bay stations.

7.1.4 Special Features and Comparison to Previous Studies

Some previous studies have involved hydrographic surveys during the same months of the year as reported here for 1992. These include recent studies of Townsend *et al.* (1991), who had stations in Massachusetts Bay that were occupied in October 1989 and in August 1990. Geyer *et al.* (1992) surveyed both Massachusetts and Cape Cod Bay stations in October 1990, and a northern Massachusetts Bay survey in late September 1990.

In general, the temperature and salinity ranges in a given month and a given location, across all surveys, were within about 2 °C and 0.5 PSU. Two features, 1) slightly warmer offshore surface water (August) and 2) slightly warmer surface water in Cape Cod Bay (vs. Massachusetts Bay water — October), that were apparent for 1992 surveys (Figures 3-1 and 5-1) were also apparent in the earlier work, respectively 1) from Townsend *et al.* (August 1990) and 2) from Geyer *et al.* (October 1990).

7.2 Water-Column/Nutrient Dynamics, late August to November

7.2.1 Vertical Structure and Breakdown of Stratification

For the farfield survey, comparing late August and October conditions showed the expected thermal distinction between a surface layer and the underlying bottom water layer — a sharper transition from about 18-20 °C to about 5-6 °C in August, and a less sharp gradient from near 12 °C at the surface to <7 °C in the bottom waters at 60 m depth or more in October (cf. Figures 3-12 and 5-12). While this seasonal de-evolution of stratification was happening, the bottom waters were still mostly isolated from the surface and the nutrient concentrations in the deeper waters usually were a bit higher in October. To a limited extent, nutrients were slightly higher nearer the surface in October than they were in August (cf. Figure 3-15 and 5-15); the area where this was most evident was the set of coastal stations.

Across the nearfield the conditions of very depleted DIN and silicate in surface waters in August were replaced by high surface concentrations in October. Although perhaps a bit related to thermal changes and weakening of the thermocline, the high surface nutrients to the center of the nearfield were associated with lower salinity. Thus, the usual notion that breakdown of vertical stratification renews surface nutrients in the Fall seems to need revision in this case, since the nutrients were elevated at the surface even when a distinct thermocline and pycnocline was still in place.

For the nearfield, full overturn of the water column must have occurred during late October in 1992. In general, this action did broadly renew surface nutrients and decrease the nutrients in deeper waters. Somewhat surprisingly, there was substantial nutrient variability across the nearfield shortly after overturn (Figure 7-8).

7.2.2 Inshore — Offshore Gradients, Including Boston Harbor Mouth

Salinity and dissolved inorganic nutrient gradients in surface waters as a function of distance from Boston Harbor were more evident, and spatially more dispersed, in October.

7.2.3 Influence of Water From Northern Rivers

In August, there was some suggestion of a near-surface lens of warmer, lighter water present from the Northern transect to the middle of Massachusetts Bay, in part extending across the western edge of the nearfield (e.g. Figure 3-12 and 3-13). However, there were not really any water mass differences in geochemistry in August or October that made the northern region of the Bay immediately distinctive. When one dissects the nutrient plots group by group in Sections 3 and 5, it is possible to see that Cape Cod Bay stations, relative to all Massachusetts Bay stations, often had slightly less nitrate relative to phosphate and perhaps slightly less silicate relative to nitrate. These basin-scale distinctions largely disappear if one includes ammonia and examines DIN. Moreover, it routinely appeared that most of the Massachusetts Bay stations away from the Harbor — including the Northern transect stations, the offshore stations, and many of the nearfield stations — were highly similar with respect to nutrients.

7.2.4 Special Features and Comparison to Previous Studies

Data in Geyer et al. (1992) for October 16-18, 1990 show approximately the same range for dissolved inorganic nutrients in the Bays as recorded in the October survey in 1992 and a similar increase in concentrations as a function of depth. The Geyer et al. (1992) data also showed a gradient of decreasing nutrients in surface waters moving offshore from Boston Harbor. DIN patterns with depth, distance from the Harbor, and total range of concentration observed for August 1990 and October 1989 in Massachusetts Bay by Townsend et al. (1991) were highly similar to these data for 1992 for the same area in Massachusetts Bay (cf. Kelly, 1991, for summary of DIN spatial and depth trends from data of Townsend et al., 1992).

7.3 Biology in Relation to Water Properties and Nutrient Dynamics, late August and October

7.3.1 Phytoplankton — Zooplankton Relationships

In Figures 7-9 and 7-10, total zooplankton counts from a tow through the upper water column at a station are compared to the average values of surface and deeper chlorophyll maximum (discrete bottle) samples for chlorophyll concentration and phytoplankton counts. This represents a first-order approach to the

comparison; for example, depth-integrated fluorescence readings could be used to further investigate phytoplankton-zooplankton abundance patterns.

Where the most intense phytoplankton bloom occurred (N01P, off Nahant, in August), numbers of zooplankton were also far and away the highest. At the other extreme, the station at the edge of the Harbor (F23P) in August had relatively low zooplankton for its level of chlorophyll and phytoplankton counts, and station N10P in the southwest corner of the nearfield appeared to follow this pattern also. This condition at F23P had been noted for the previous summer survey (Kelly *et al.*, 1993). With minor exceptions like these extremes, and perhaps station N07P (Figure 7-9), the August stations were not tremendously different, especially considering the variability in replicate tows noted at F02P (Figures 7-9 and 7-10). In October, there was more range in chlorophyll concentration than there was either zooplankton or phytoplankton counts, but overall stations were less different than in August.

By looking at the two graphs it is evident that zooplankton were present generally in greater numbers in August than in October. All points considered, there appeared to be a positive relation between counts of zooplankton and phytoplankton (Figure 7-10); in contrast, a general relation between zooplankton counts and chlorophyll was not evident (Figure 7-9).

In general, few sharp regional distinctions in the zooplankton-phytoplankton relationship were striking. For example, Cape Cod Bay station conditions were mostly within the range of conditions measured in the nearfield in Massachusetts Bay. If anything, the distinctions were localized, but even then there was remarkable variability in the space of a tens of kilometers. For example, it was noted that F23P, N10P, and even N20P, all with relatively high chlorophyll, had relatively low zooplankton. But not far away from these at N01P, which had a fairly similar phytoplankton community composition, there was a *joint*, dense aggregation of plankton flora and fauna.

7.3.2 Plankton Species and Water Properties

There were relatively small taxonomic differences over space for the phytoplankton samples analyzed in August and in October. Microflagellates dominated numerically in both cases. In August, when stratified, the surface and deeper chlorophyll maximum samples were not taxonomically distinct in most cases. The main geographic distinction was that diatoms achieved slightly less dominance in Cape Cod

Bay than in Massachusetts Bay. Where higher chlorophyll was found in Massachusetts Bay, the species that were present in higher numbers were diatoms, principally *Rhizoselenia delicatula* and two species of *Leptocylindrus* (both not among Cape Cod Bay dominants) and a large *Chaetoceros* sp. With respect to water properties, the stations with enriched nutrients and influenced by water from Boston Harbor, including F23P and N10P surface water, were among those whose phytoplankton dominants included diatoms. In general, dinoflagellates were not numerous in either August of October.

In October, the entire selection of samples (surface and depth) through the Bays was taxonomically similar. A similar group of diatoms that had been pronounced in western Massachusetts Bay in August was more uniformly present throughout the Bays in October. Thus, in this case, the biological composition was regionally similar, accompanied by similar water temperatures, and persistent in spite of some (small) salinity gradients as well as a considerable range in nutrients.

7.3.3 Chlorophyll Biomass and Nutrient Distribution

There was no general relationship between chlorophyll concentration and DIN, as judged by the full data set from BioProductivity stations in either August (Figure 7-11) or October (7-12). Previously, there has been a stronger relation apparent between chlorophyll (or cell counts) and total nitrogen (Kelly *et al.*, 1993). Figure 7-13 shows variability between phytoplankton cell counts and total nitrogen in late August. For the nearfield stations, higher counts were seen at higher total N, but this was not always the case. For the coastal station samples, the higher cell counts were associated with samples having higher total N. Note that PON, and thus total N, concentrations were not available for Cape Cod Bay stations due to analytical problems (Appendix A). Similarly, in October (Figure 7-14) only a subset of stations had total N values available. The range in total N in October was within the range observed for August, but more restricted. However, the cells counts in October were all in the lower end of range observed in late August and no pattern between total N and counts was observable.

Usually, less chlorophyll was noted at the surface of a station and this is apparent from the composite scatter plot of chlorophyll fluorescence with depth in Figure 7-1 as well as in Figures 7-11 and 7-12. N01P in August and F25 in October were among the exceptions to this general rule. Usually also, less DIN was noted near the surface, although some stations near the Boston Harbor nutrient source (e.g.

F23P, N10P, N20P) did not follow this rule, and in some cases there was very little DIN difference with depth even if there was a large chlorophyll difference (e.g. N01P in August).

As noted, in August the coastal region near Boston Harbor, including N01P, F25, N20P, N10P, and F23P all had higher chlorophyll. For this select group of stations, the pattern was one of decreasing chlorophyll with increasing DIN (Figure 7-11), and to a degree it was also apparent in October (Figure 7-12) when DIN had a broader, and chlorophyll a smaller, range.

Geographically, Cape Cod Bay generally had low chlorophyll. Interestingly, in October the Cape Cod Bay stations had chlorophyll levels like F23P (Boston Harbor edge) even though F23P had much higher DIN (about 10 μM — Figure 7-12).

7.3.4 Metabolism and Environment

It was difficult to fit P-I curves for a few situations — particularly those surface conditions with very low nutrients. Most situations *could* be fit and the main body of curves were fairly similar. To an extent, perhaps little variability should be expected since the taxonomy of stations was fairly similar from place to place and time to time. We have not explicitly examined rates as a function of chlorophyll or nutrient content.

In general, midday light exceeded levels to maintain P_{max} to about 5 to 10 m in the water column (Appendix B). The 1% incident light level routinely extended to 20 m, so the subsurface chlorophyll maximum usually was above it, but the organisms at that depth were not likely growing at maximum rates.

In comparison to previous surveys during the year, there were more instances when a significant rate of respiration was detected. Many of these instances were related to either higher temperature or higher concentration of chlorophyll, or both.

7.3.5 Special Features and Comparison to Previous Studies

Cura (1991) summarized much of the historical record of chlorophyll measurements. Those tabulated for the months of August through November range form about 0.1 to 29.3 μg L^{-1}. Both extracted chlorophyll samples (Figures 7-11 and 7-12), as well as calibrated fluorometry readings (Figure 7-1) for our 1992 studies, fall within this large span. Peak values were measured in August and in September within the nearfield, each time near the northwest corner. Townsend et al.'s (1991) surveys during August and October recorded chlorophyll values in the same range as these 1992 data and, similar to 1992, peak August values were higher than October. Geyer et al.'s fluorescence data for October 1990 showed surface values with a similar range to those seen here (Figure 5-5). Finally, a "Boston transect" survey that Geyer et al. (1992) conducted in September 1990 had peak fluorescence values in a near-surface patch that was near the middle of the nearfield region, and that the same region in mid-October had lower fluorescence.

The dominant phytoplankton species seen in the 1992 surveys included those seen at this time of the year in previous studies (cf. Cura, 1991; Smayda, 1992). In particular, species of the large diatom, *Rhizoselenia*, a major dominant in 1992, have been common in the late summer and early autumn. Recent equivalent data sets to the 1992 data for zooplankton are not, to our knowledge, available for comparison.

Townsend et al.'s (1991) data for P-I incubations, by 14-C, in August show P_{max} reached by about 250 to 500 μE m^{-2} sec^{-1} and P_{max} across 4 stations (near Boston Harbor, through the nearfield, to deepwater over Stellwagen Basin: 1-3 depths each) that varied by about a factor of 2-3. Their results overall for October were similar to their August results. Thus, the basic form of P-I pattern was similar to our results with oxygen incubations, which covered more stations and suggested perhaps greater variability in relative range of P_{max} (see Appendix E); however, we have conducted no detailed comparison of results.

Cura (1991) summarized previous net production measurements in the Massachusetts Bay. For the period August to November, he listed 14 individual measurements, mostly from the nearfield region. Greater than an order of magnitude variation in integrated water-column rates of net production was noted. Water column production rates have not been calculated from the 1992 survey data, but given the wide range

in chlorophyll at the metabolism stations (Figures 7-11, 7-12) and the patterns in chlorophyll-normalized P-I curves, one would expect variability in rates at least equivalent to that of previous studies.

7.4 Recommendations

We have no additional recommendations for sampling based on the data from these surveys. As noted previously, it would be reasonable to review objectives for sampling the inshore edge of the nearfield, given variability in this area, and throughout the nearfield in general. Interpretation of the results of hydrocast sampling could be enhanced by studies that were explicitly designed to examine short-term coupling of physical and biogeochemical dynamics.
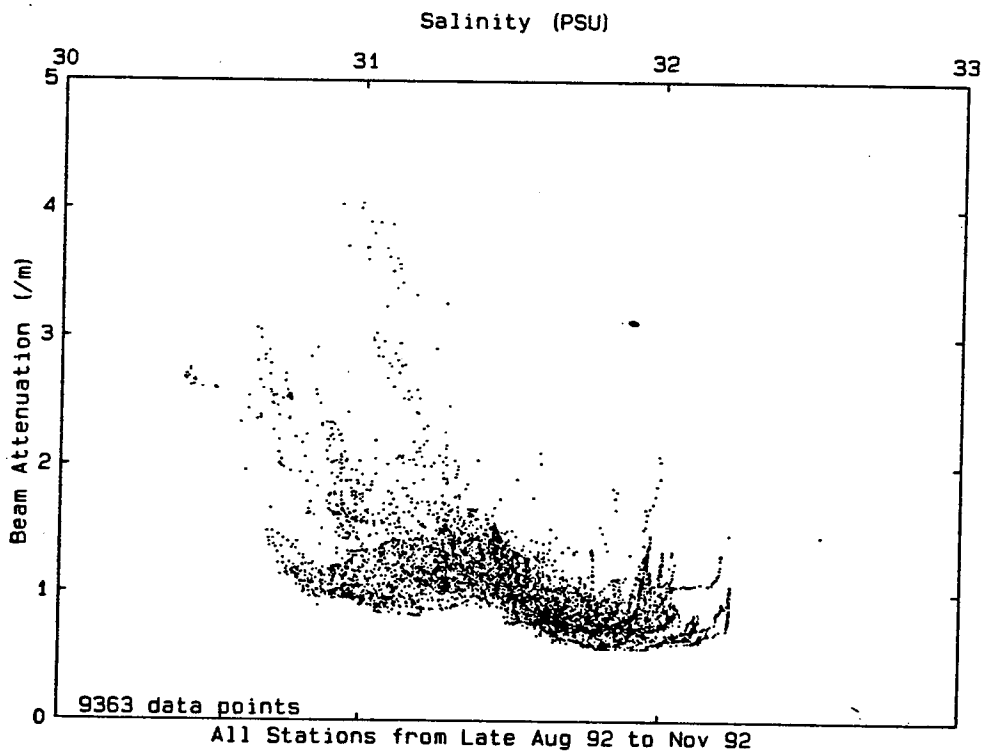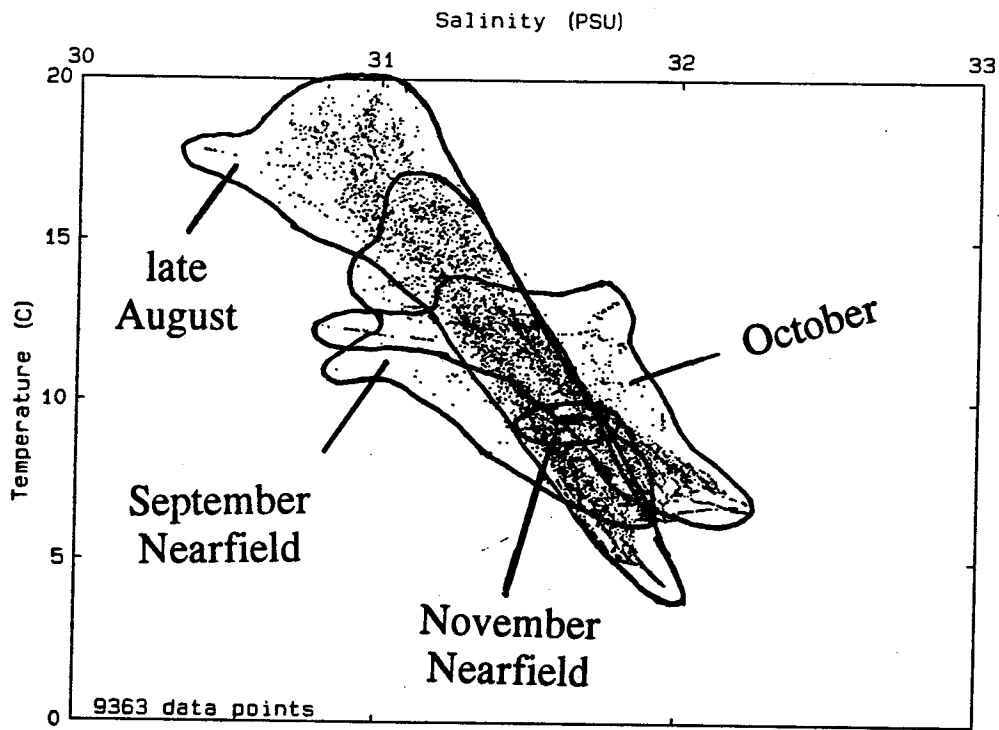
Salinity (PSU)

Salinity (PSU)

All Stations from Late Aug 92 to Nov 92

Figure 7-1a Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all stations occupied from late August through November 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.
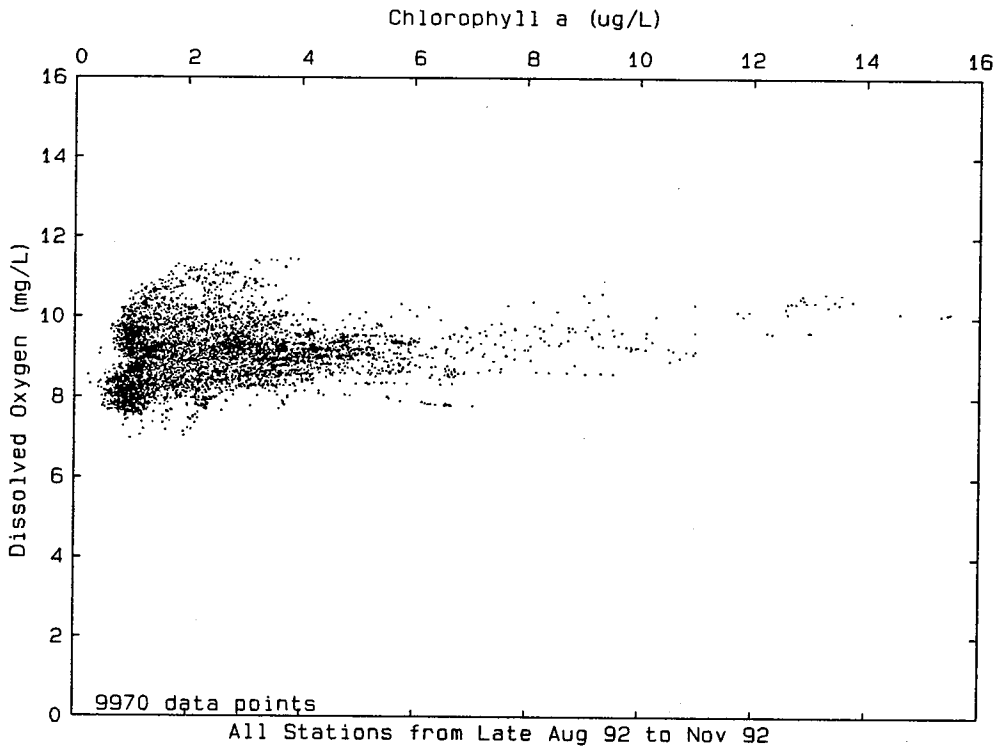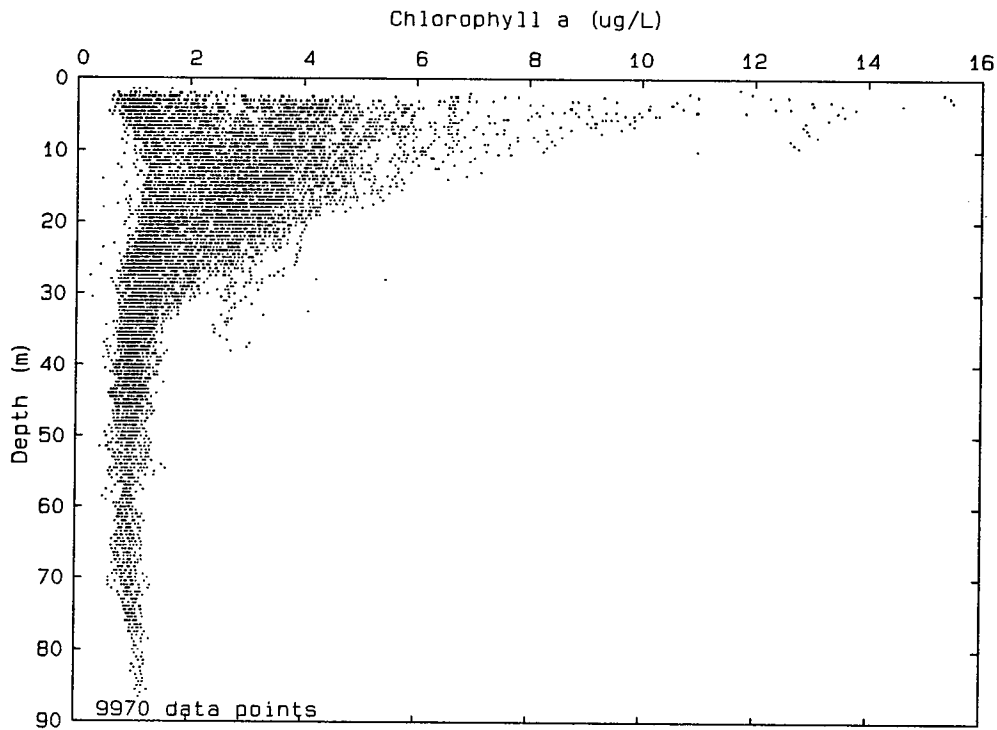
Chlorophyll a (ug/L)

0   2   4   6   8   10   12   14   16

Depth (m)
0
10
20
30
40
50
60
70
80
90

9970 data points

Chlorophyll a (ug/L)

0   2   4   6   8   10   12   14   16

Dissolved Oxygen (mg/L)
16
14
12
10
8
6
4
2
0

9970 data points

All Stations from Late Aug 92 to Nov 92

Figure 7-1b Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all stations occupied from late August through November 1992. Individual station casts that were used to produce this composite are in Appendix B. Chlorophyll was estimated from fluorescence and DO was calibrated with titrations (see Appendix A).
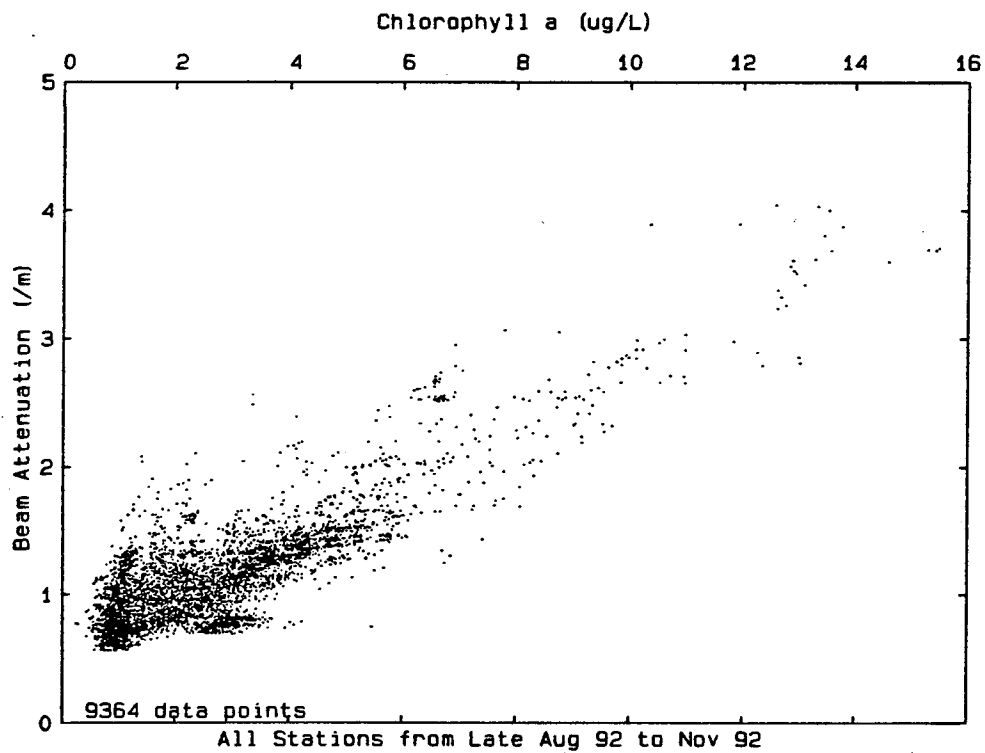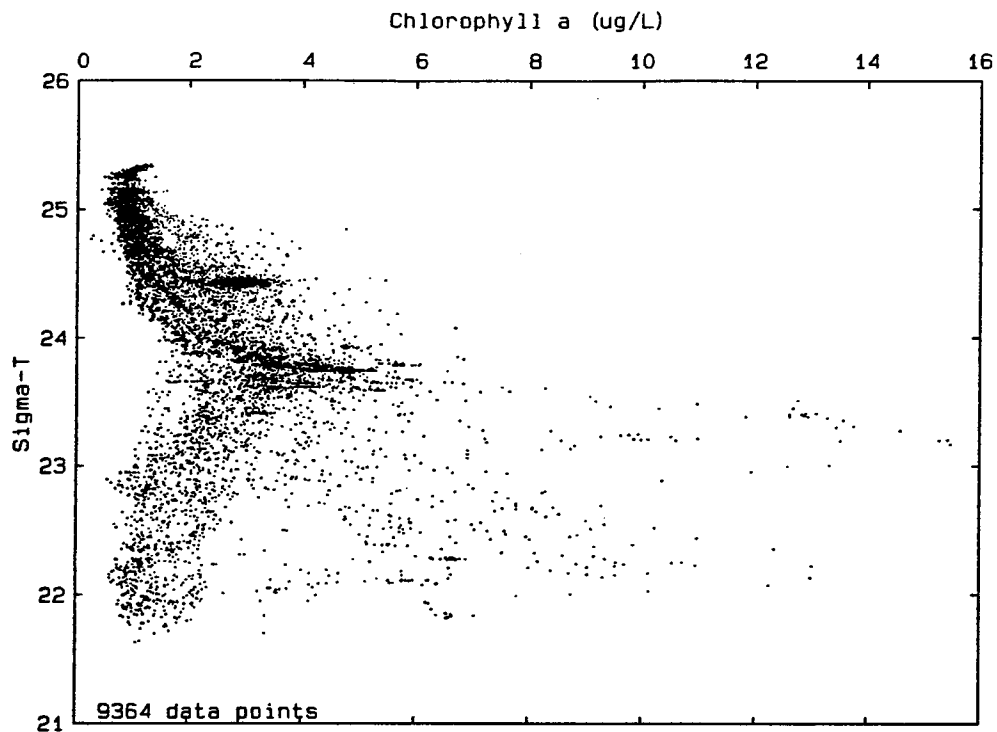
Figure 7-1c Scatter plots of data acquired by *in situ* sensor package during vertical downcasts at all stations occupied from late August through November 1992. Individual station casts that were used to produce this composite are in Appendix B. Chlorophyll was estimated from fluorescence (see Appendix A).
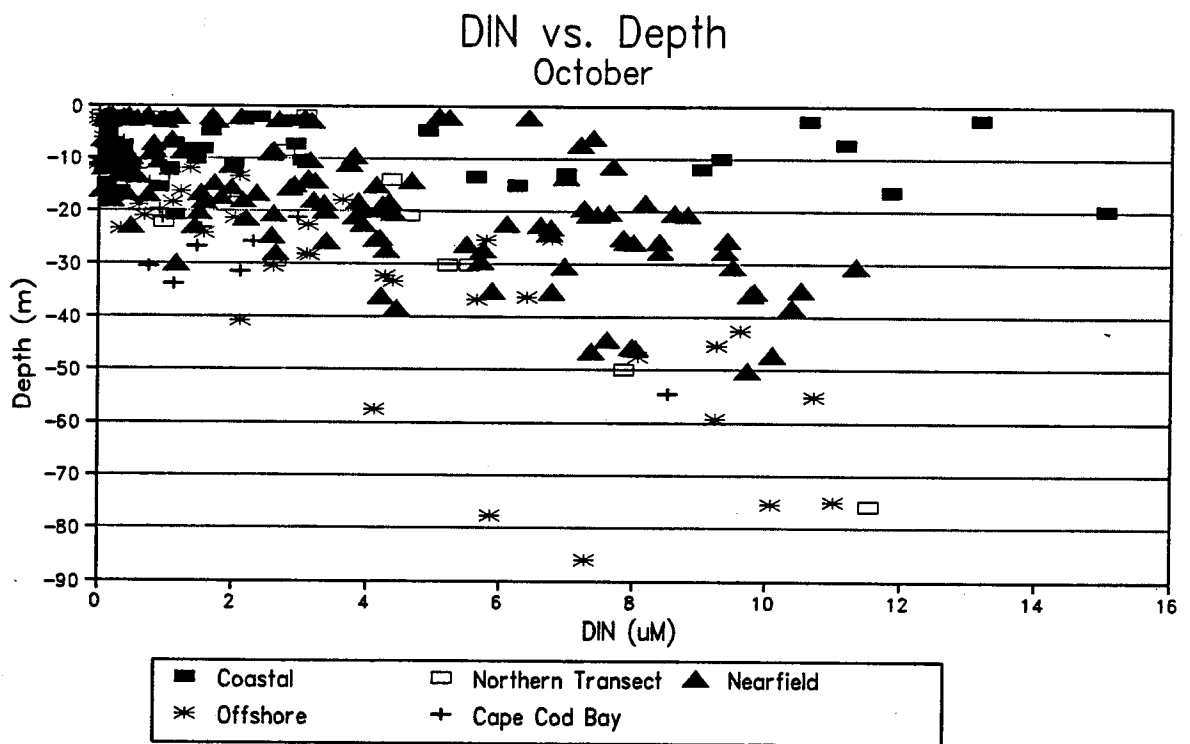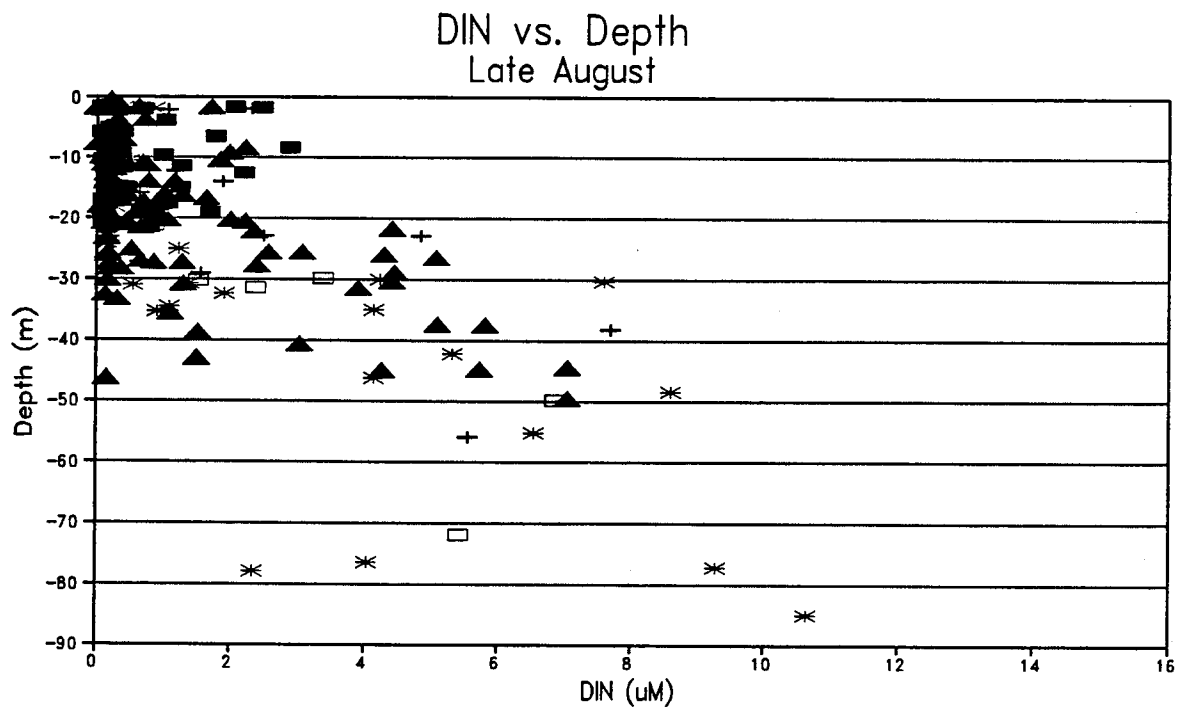
DIN vs. Depth
Late August

DIN vs. Depth
October

Figure 7-2   Dissolved inorganic nitrogen vs. depth for all stations on combined survey cruises in late August and October 1992. Stations groups are as given in Figure 3-18. Data are given in Appendix A.
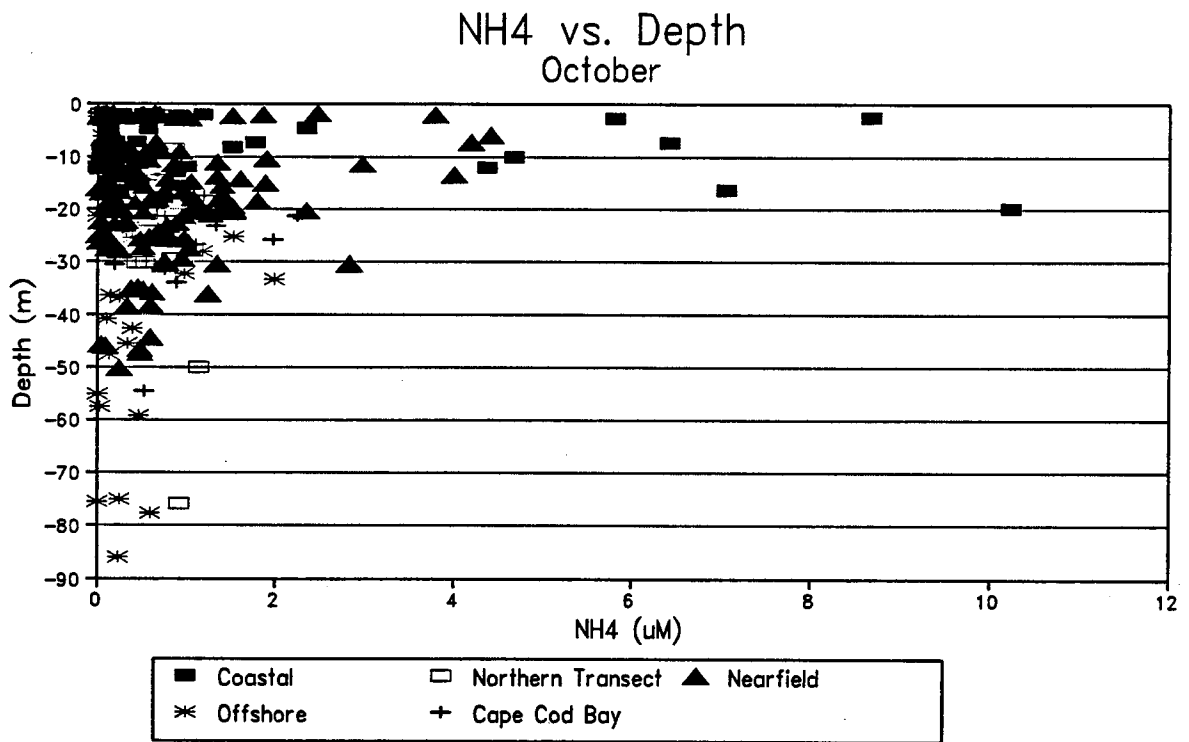
NH4 vs. Depth
Late August

NH4 vs. Depth
October

Figure 7-3   NH₄ vs. depth for all stations on combined survey cruises in late August and October 1992. Stations groups are as given in Figure 3-18. Data are given in Appendix A.
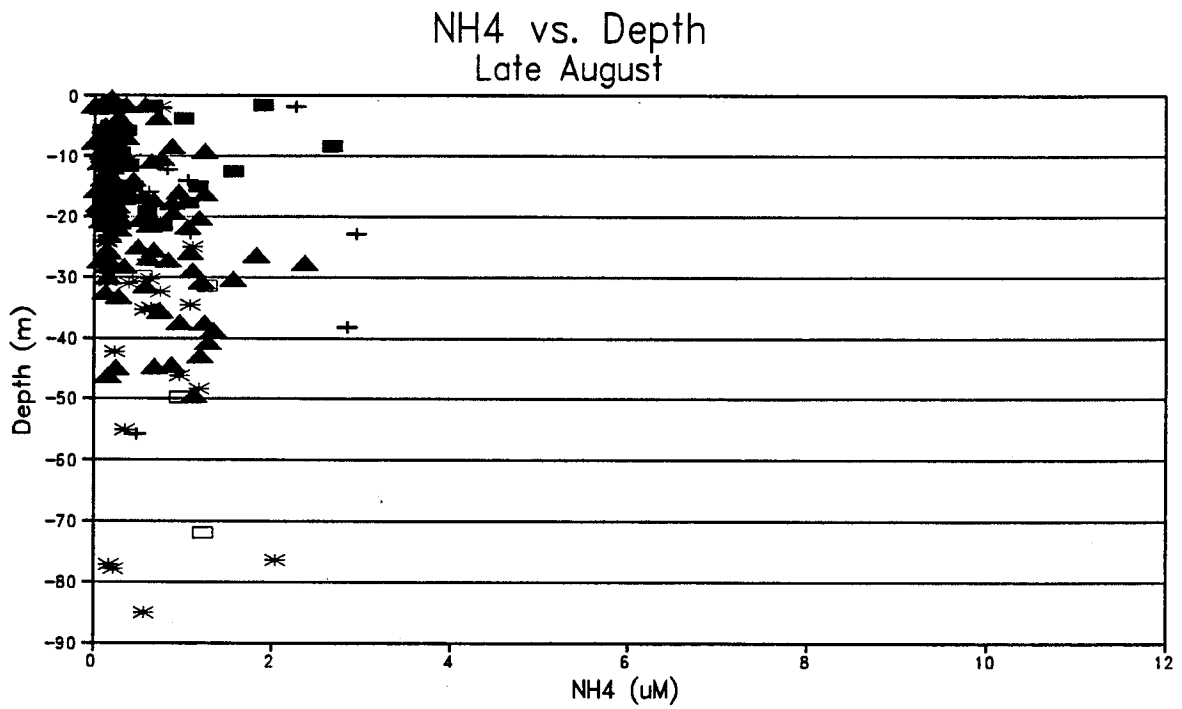
Figure 7-4 Nitrate vs. depth for all stations on combined survey cruises in late August and October 1992. Stations groups are as given in Figure 3-18. Data are given in Appendix A.
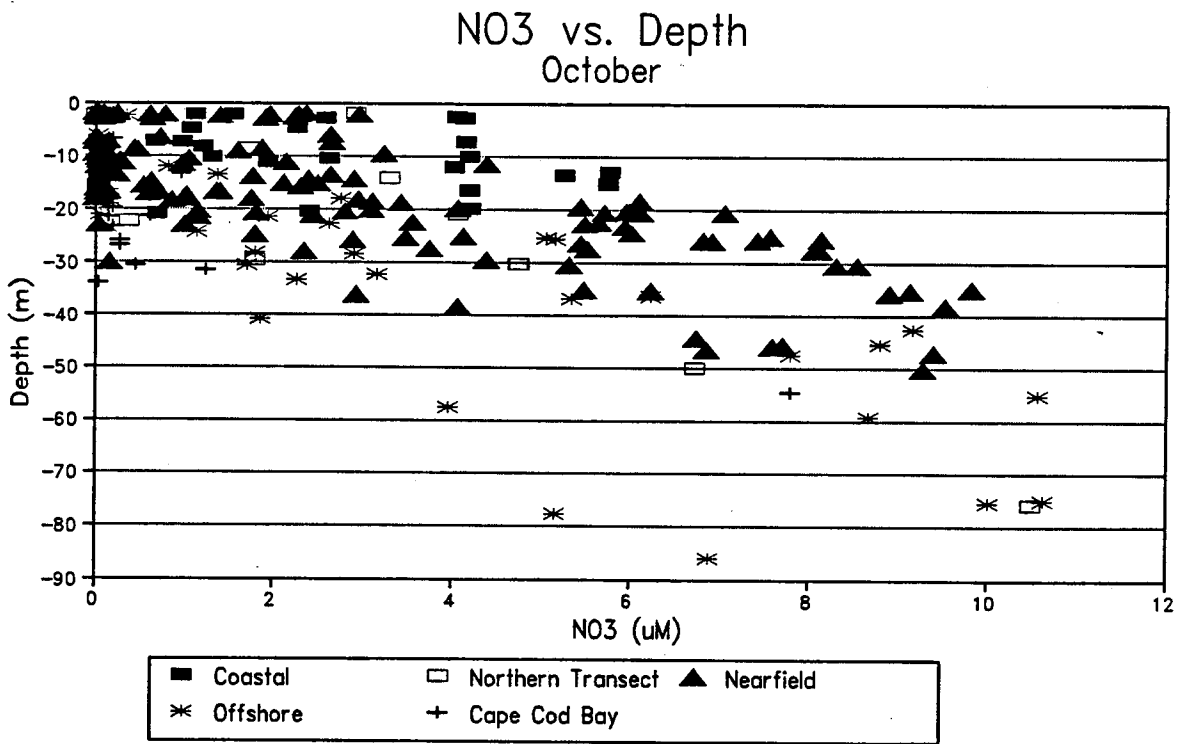
Figure 7-5 Phosphate vs. depth for all stations on combined survey cruises in late August and October 1992. Stations groups are as given in Figure 3-18. Data are given in Appendix A.
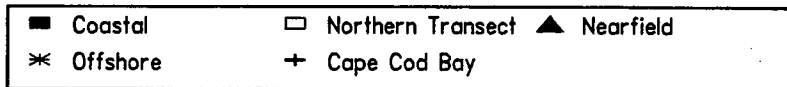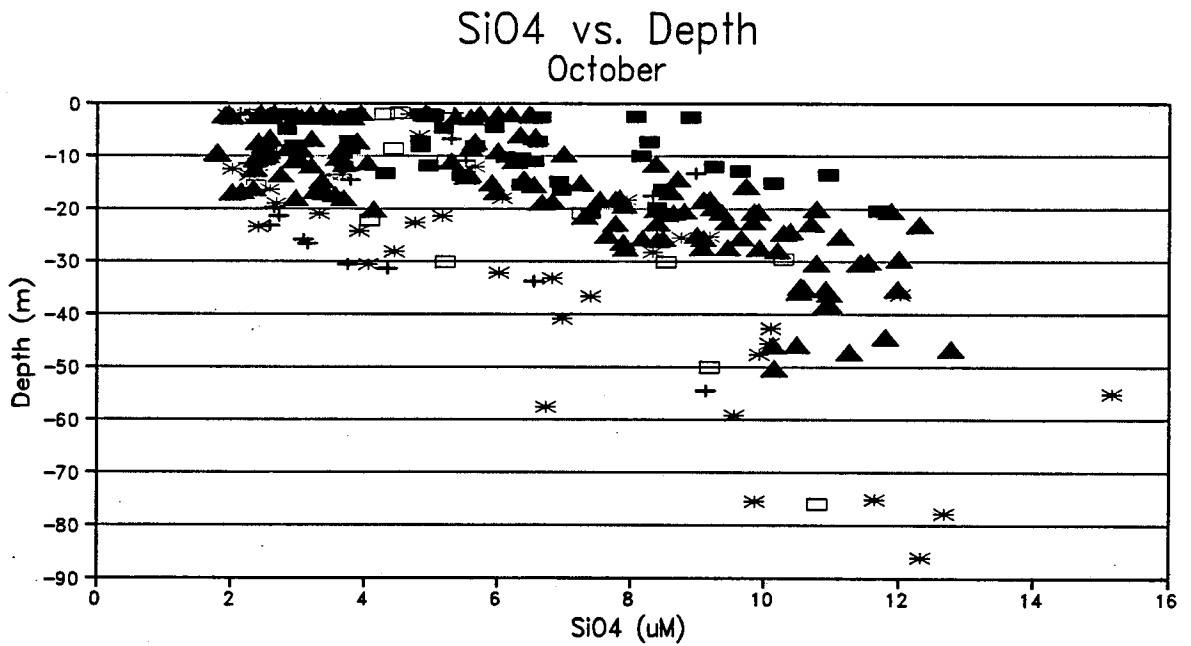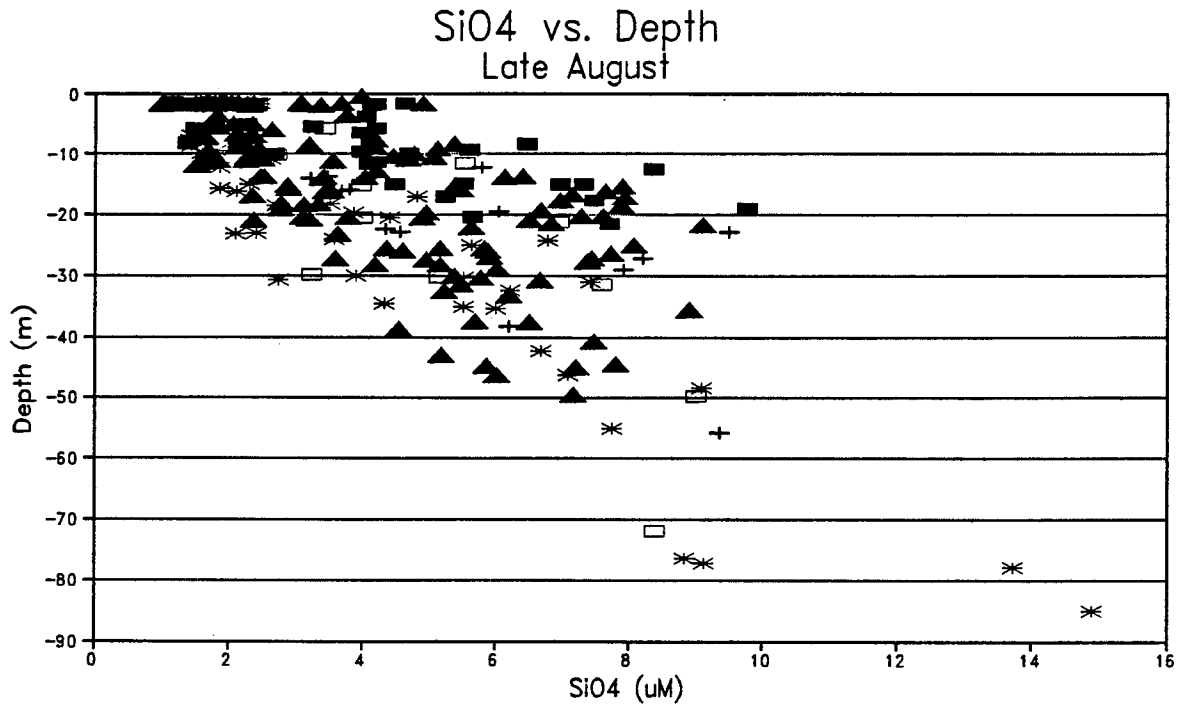
Figure 7-6 Silicate vs. depth for all stations on combined survey cruises in late August and October 1992. Stations groups are as given in Figure 3-18. Data are given in Appendix A.
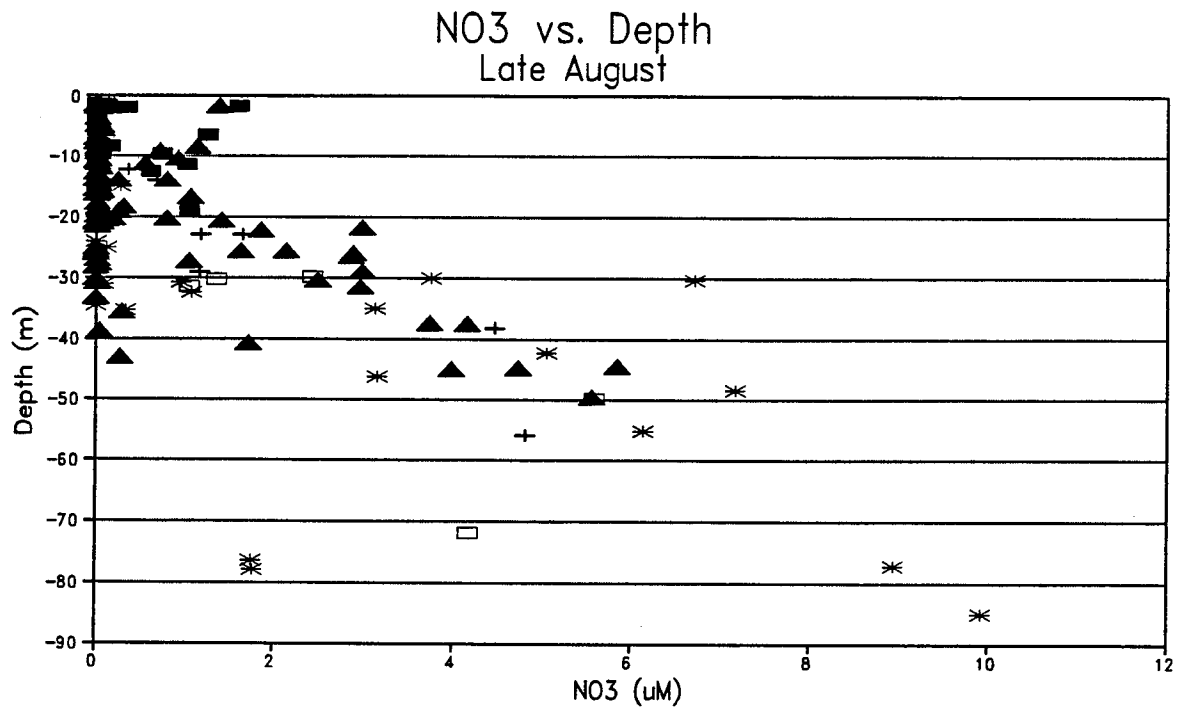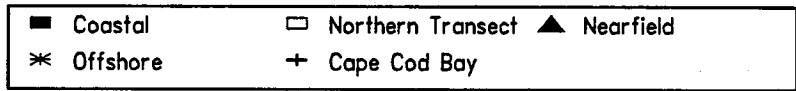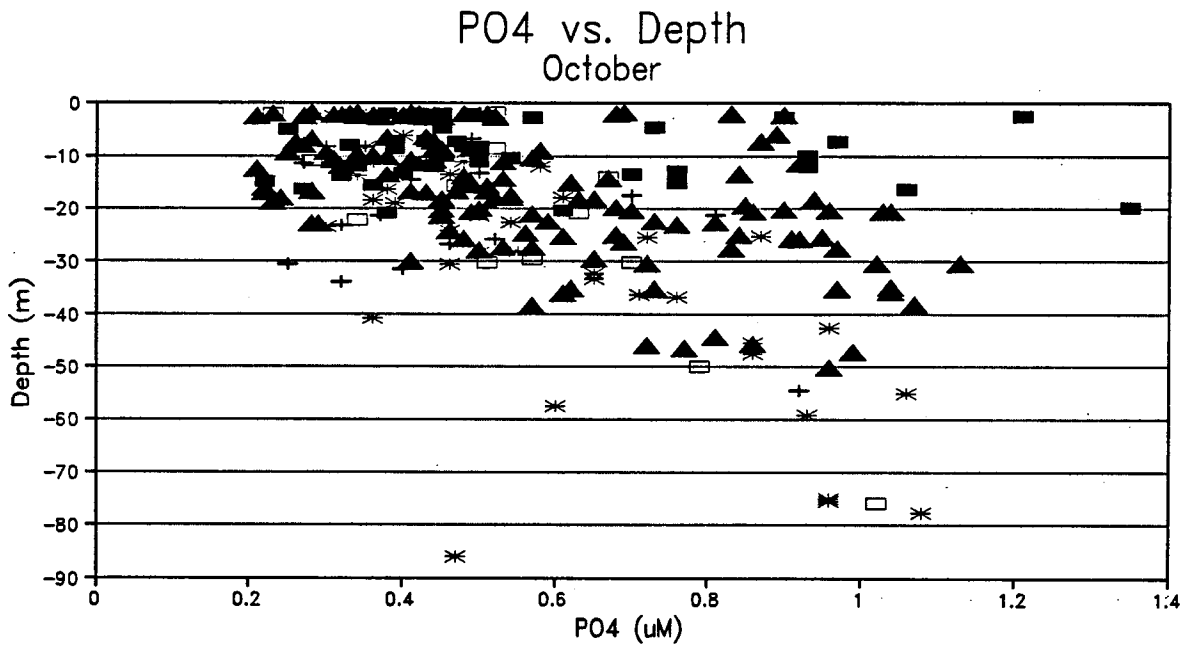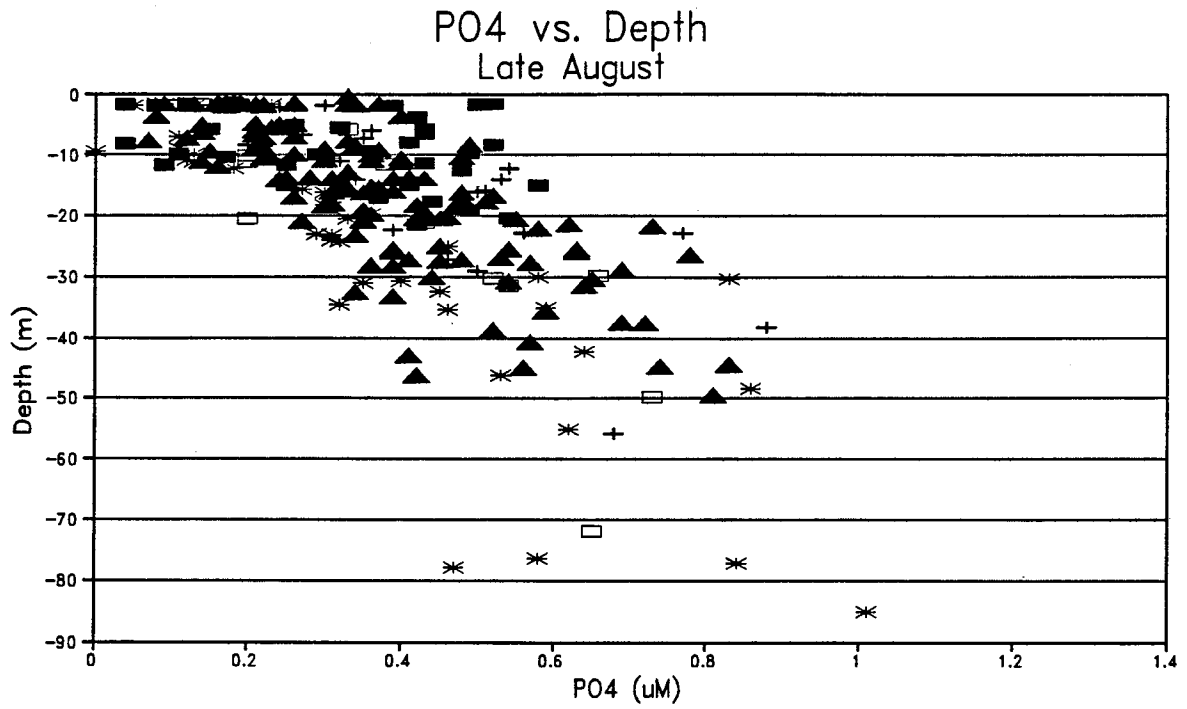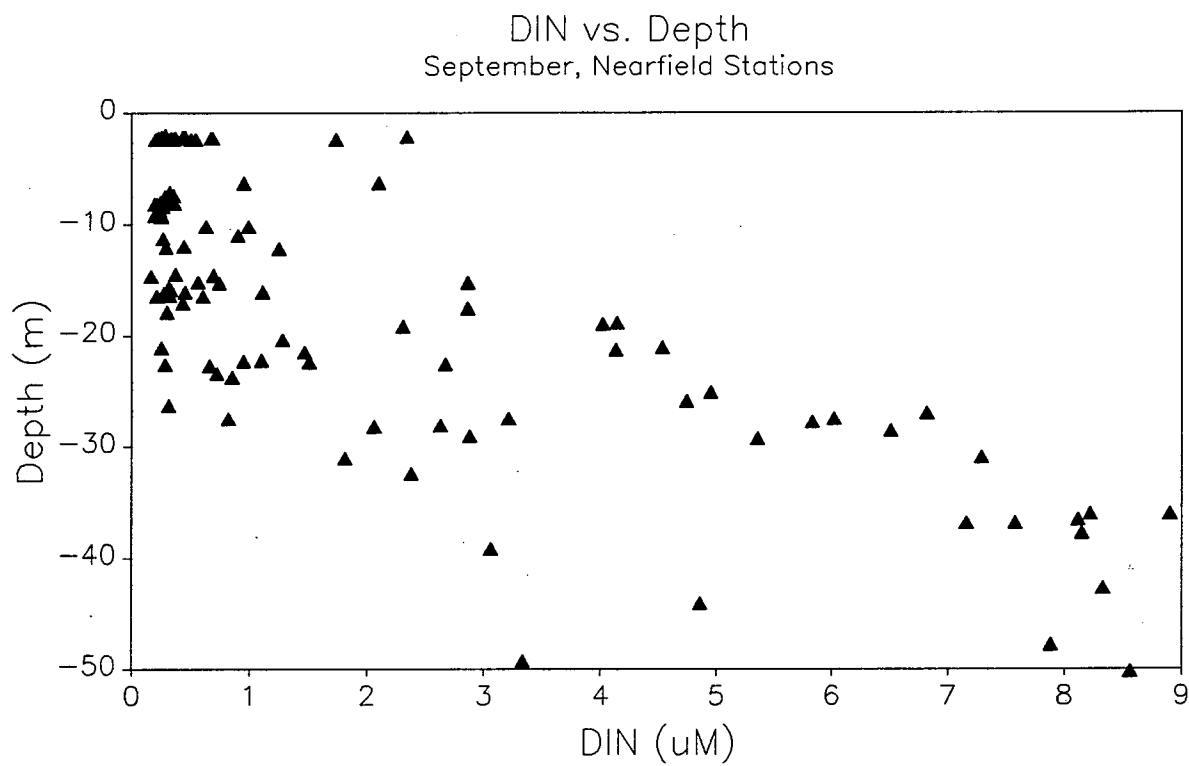
Figure 7-7   Dissolved inorganic nitrogen vs. depth at nearfield stations in September 1992. Data are in Appendix A.
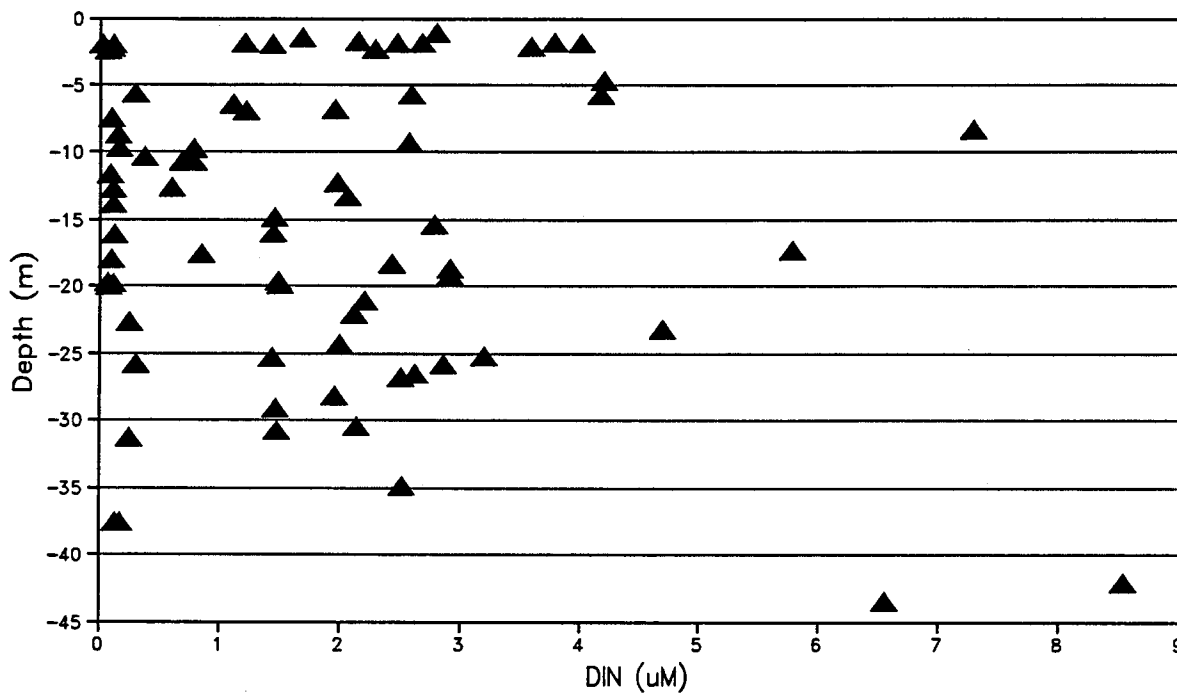
Figure 7-8 Dissolved inorganic nitrogen vs. depth at nearfield stations in November 1992. Data are in Appendix A.
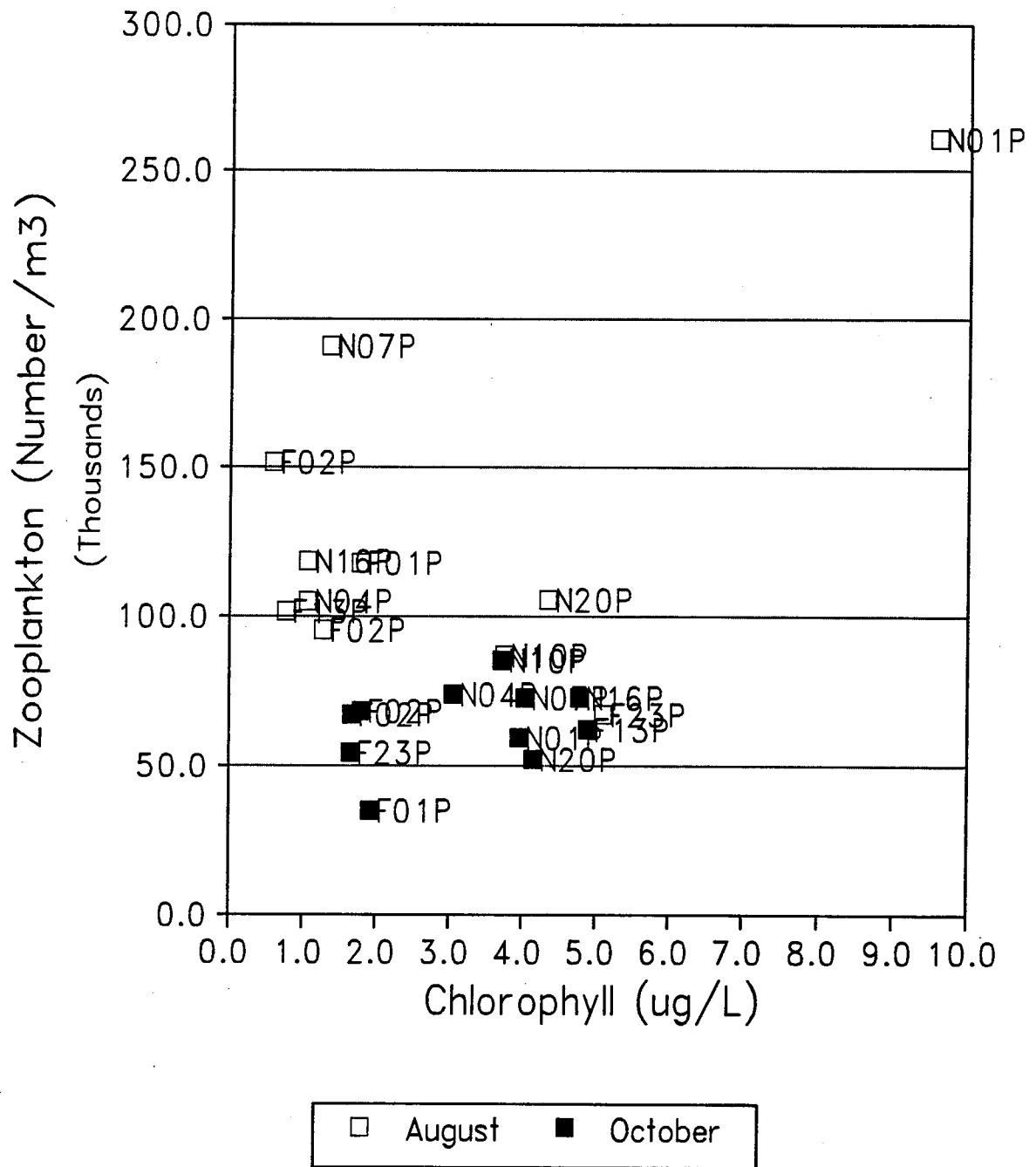
Figure 7-9 Zooplankton abundance vs. chlorophyll from all Bioproductivity stations in late August and October 1992. Data are in Appendices A and G.

300.0

250.0 ···□N01P·

Zooplankton (Number/m3)
(Thousands)

200.0 ······················□N07P··························

150.0 ·············□F02P··································

□N16P □F01P

100.0 ··□N04P□··□N20P··································
□F13P
□F02P
■N10P   □N10P
■N04N07P
■F02P
■N01P   ■F13P ■F23P
■F23P□N20P
50.0

■F01P

0.0
   0.0   1.0   2.0   3.0   4.0   5.0   6.0

Phytoplankton (10^6 Cells/L)
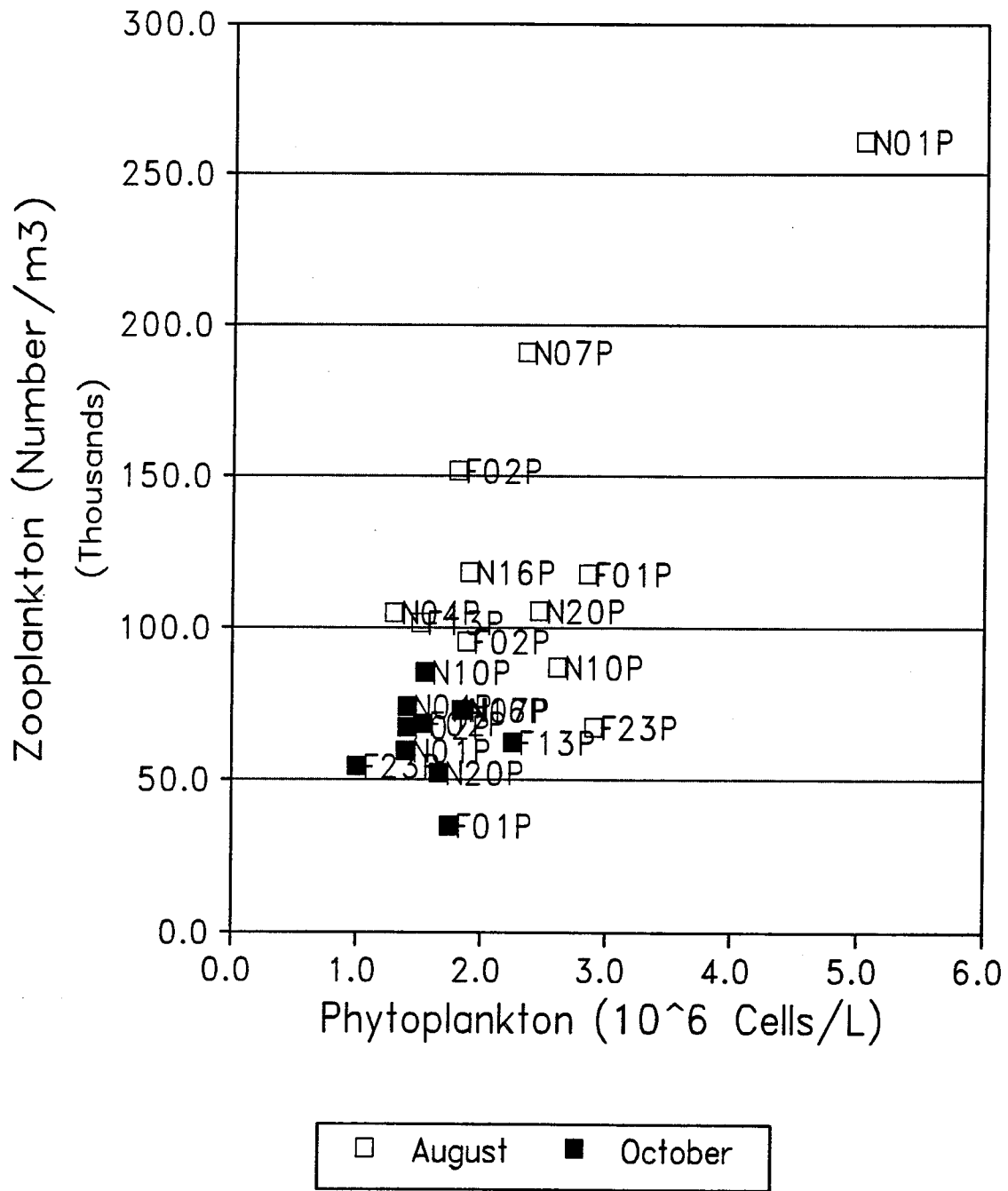
□	August	■	October

Figure 7-10 Zooplankton abundance vs. phytoplankton abundance from all Bioproductivity stations in late August and October 1992. Data are in Appendices F and G.
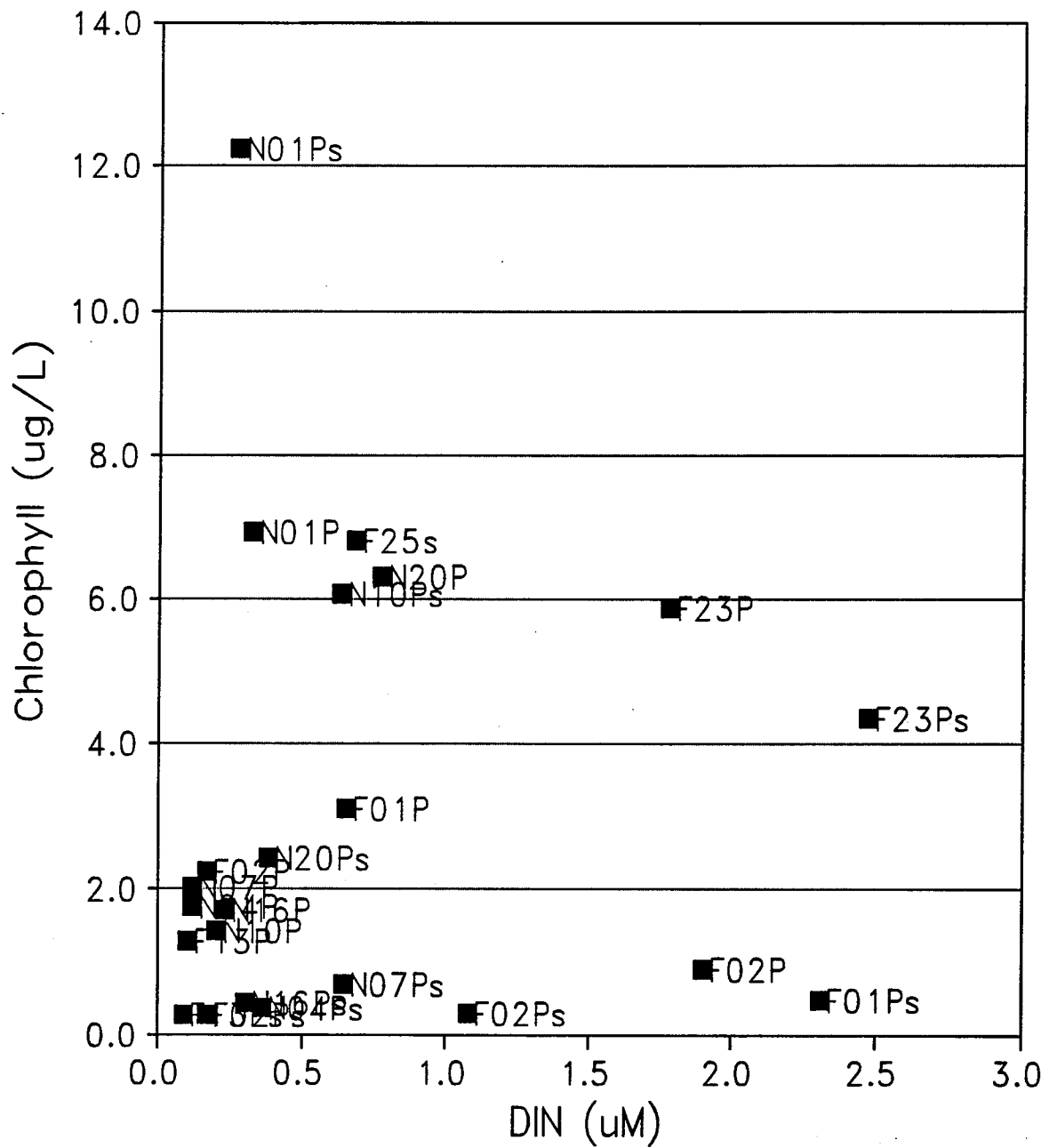
Figure 7-11 Chlorophyll vs. dissolved inorganic nitrogen from all Bioproductivity stations in late August 1992. Data are in Appendix A. The subscript "s" for each station identifies the surface sample.
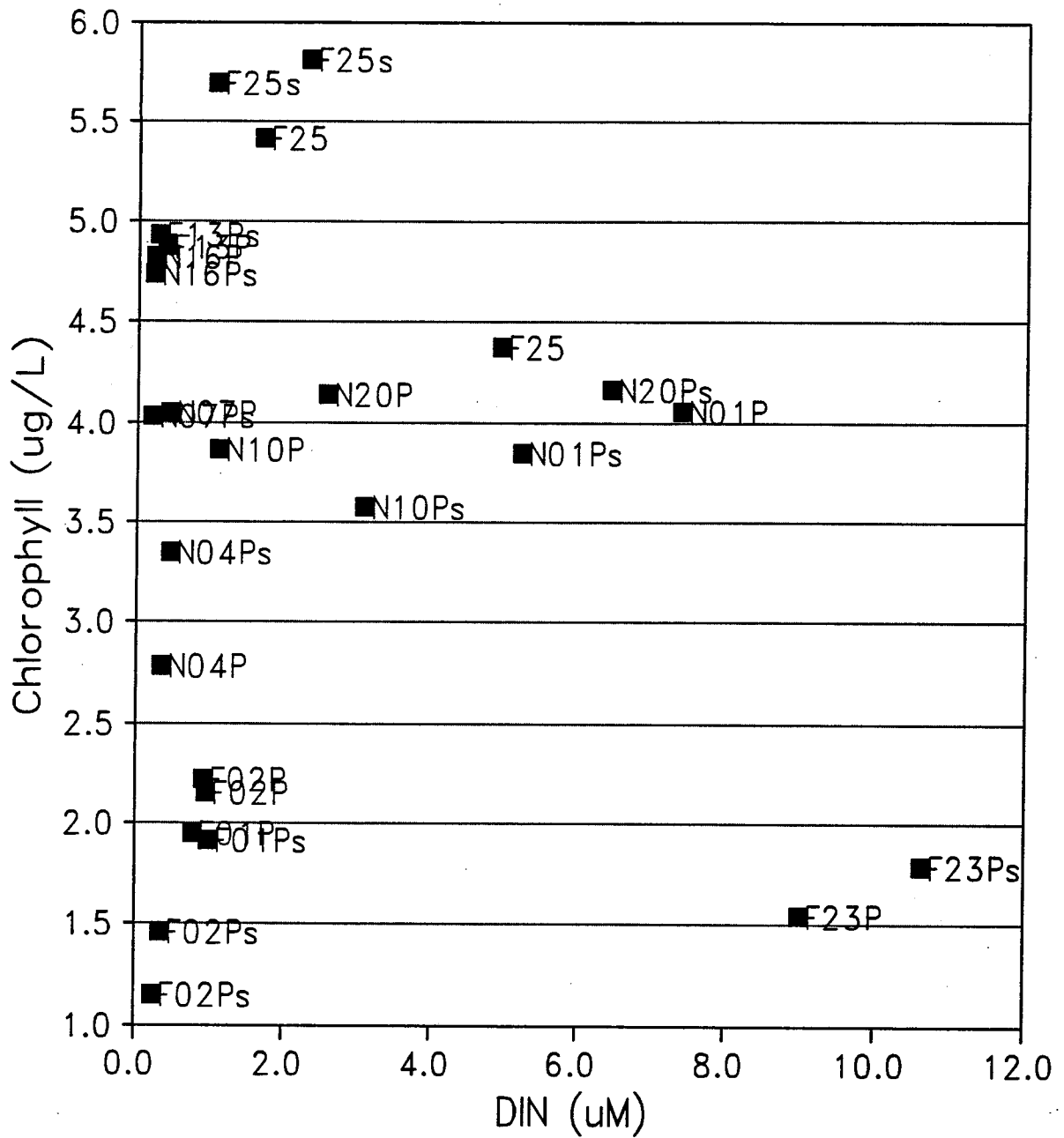
Figure 7-12 Chlorophyll vs. dissolved inorganic nitrogen from all Bioproductivity stations in October 1992. Data are in Appendix A. The subscript "s" for each station identifies the surface sample.

Late August 1992
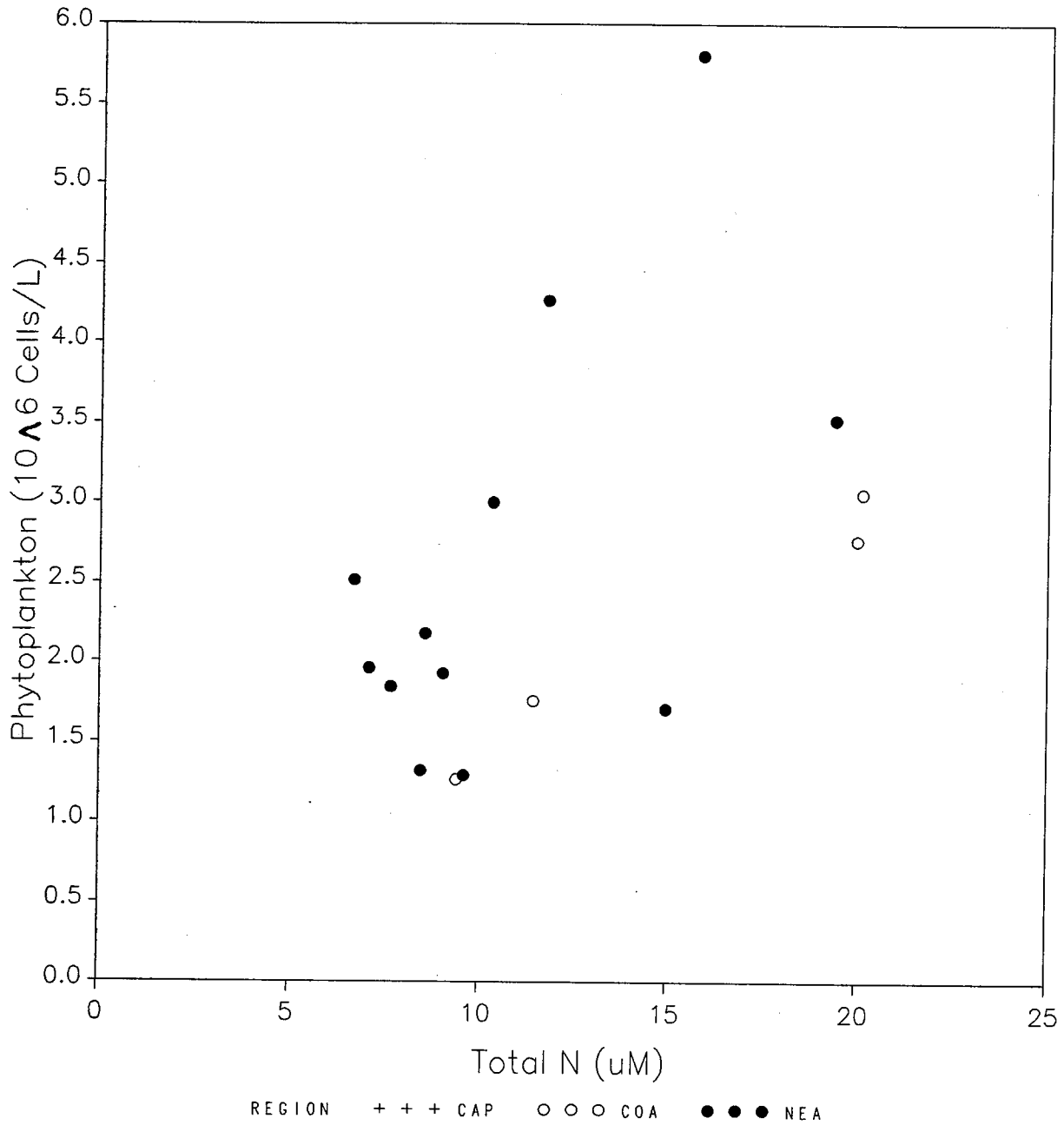
Figure 7-13 **Total phytoplankton counts vs. total nitrogen from all Bioproductivity stations in late August 1992. Data are in Appendices A and F. The stations are coded by region as in Figure 5-18. Total N estimates were available for only a subset of the BioProductivity stations (Appendix A).**

Figure 7-14 Total phytoplankton counts vs. total nitrogen from all Bioproductivity stations in October 1992. Data are in Appendices A and F. The stations are coded by region as in Figure 5-18. Total N estimates were available for only a subset of the BioProductivity stations (Appendix A).
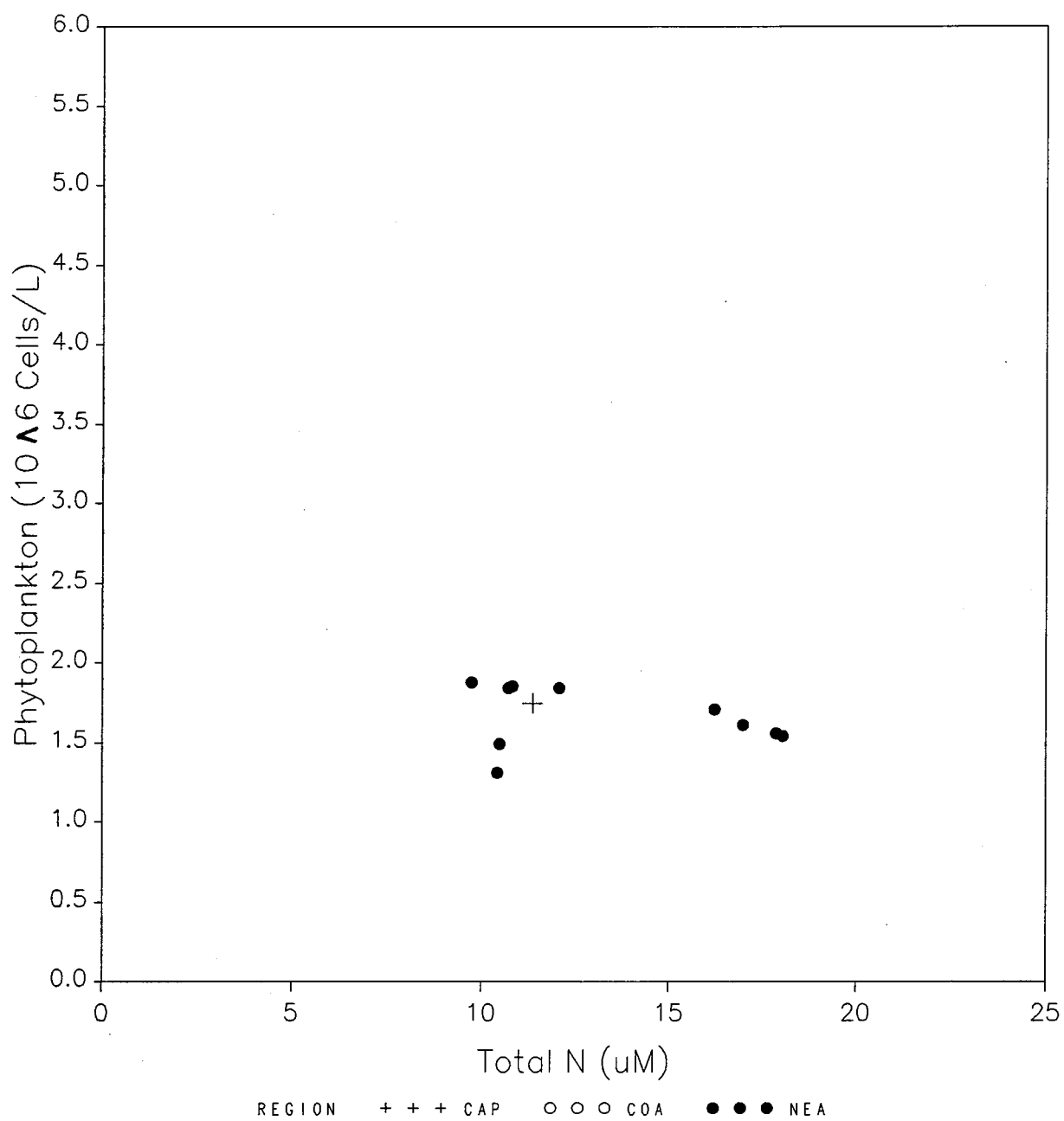
8.0 SUMMARY OF 1992 LATE SUMMER - FALL SEASON DYNAMICS

8.1 Farfield Scale

8.1.1 Water Properties in Space and Time

For properties such as temperature and salinity, the main variability occurred in the vertical dimension, and the horizontal variability across the Bays was far less impressive. In late August, there were some temperature and salinity distinctions possible — in particular some inshore waters were cooler and fresher at the surface. By October, surface thermal distinctions as a function of distance from shore were not apparent and the trend instead was regional — cooler northward. The surface salinity trend, fresher shoreward, was more uniformly evident across the Bays. The temporal progression, Baywide, involved diminishment of the vertical physical structure and lessening of many parameter's range with depth.

Nutrient distributions, to an extent, followed salinity patterns over space and time. Most distinctly, nutrients Baywide were very strongly related to vertical stratification, with generally low surface values and increasing concentration with depth. A few geochemical distinctions by area and by month were possible.

8.1.2 Ecological Dynamics

During the period, the community of plankton was typical of that seen in temperate coastal waters. Primarily the dominant taxa included microflagellates, cryptomonads, and several species of diatoms, all of which have been regularly recorded in late Summer and early Fall in the Bays. Overall, plankton species compositional differences were slight and diminished as the pycnocline weakened into October. Over the period, the intensity of chlorophyll peaks in surface waters of western Massachusetts Bay and the characteristic presence of a deep chlorophyll maximum (at ≈ 20 m) elsewhere in the Bays both became less pronounced as chlorophyll became more uniformly distributed both over the Bays and within the surface 20 m of the water column.

In general then, the temporal progression of spatial variability in biology somewhat paralleled the physical progression in that distinctive local-to-mesoscale features seemed to be evolving towards more mesoscale-to-regional scale ones.

8.2 Nearfield Scale

8.2.1 Water Properties in Space and Time

As in previous surveys earlier in 1992, parts of the nearfield appeared to be influenced by inshore water. High small-scale variability in time and space was a noted feature in most all measured water properties.

The two nearfield-only surveys provided valuable additional information on the seasonal progression and breakdown of stratification in the nearfield area.

8.2.2 Ecological Dynamics

Some of the highest chlorophyll concentrations for the year were recorded in the September nearfield survey. Patchiness and high chlorophyll in both late August and September, under generally strongly stratified conditions, were noted.

The November survey confirmed that Fall overturn in the nearfield in 1992 occurred sometime between October 17 and November 9. Interestingly, there was still considerable nutrient variability at this time when physical conditions were rather monotonously the same throughout the field. At this time also, there was much higher variability in chlorophyll distribution than in physical parameters.

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