Water quality monitoring in Massachusetts and Cape Cod Bays: February and March 1994

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FINAL

WATER QUALITY MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: FEBRUARY — MARCH 1994

by

John R. Kelly
P. Scott Libby
Carl S. Albro
John T. Hennessy
Battelle Ocean Sciences

Jeff Turner
David Borkman
University of Massachusetts — Dartmouth

Peter Doering
University of Rhode Island

prepared for:

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

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EXECUTIVE SUMMARY

This report is the first of five periodic water column reports for water quality monitoring conducted in 1994 by Battelle Ocean Sciences for the Massachusetts Water Resources Authority (MWRA) Harbor and Outfall Monitoring Project. The report includes results from one survey conducted during February and two surveys conducted during March 1994. Each of these surveys included sampling at 21 stations in the nearfield area surrounding the proposed MWRA outfall diffuser about 15 km offshore in western Massachusetts Bay. The February and early March surveys were combined farfield/nearfield surveys that included sampling at 25 additional stations throughout Massachusetts Bay and Cape Cod Bay. Relative to water quality monitoring in 1992-1993, minor design changes were instituted with these surveys, including relocation of several stations to the boundary along the northeast perimeter of Massachusetts Bay from Cape Ann to Stellwagen Bank and changes in the location of metabolism measurements. In this report, data on physical, chemical, and biological measurements at the stations are presented and interrelationships among parameters are examined for standard hydrographic surveys. Unlike past periodic water quality reports for 1992 and 1993, the additional high-resolution studies conducted using towed *in-situ* instrumentation during 1994 surveys will be discussed in a separate report.

February-March 1994 was a period of vertically well-mixed conditions at most locations in the Bays. By the end of the period, some seasonal stratification, noted as thermal and salinity layering, was observed in the eastern section of the nearfield.

Broad physical gradients were persistent during the period. For example, surface waters from northern Massachusetts Bay southward to Cape Cod Bay showed a trend of decreasing temperature and salinity. Moreover, there was a consistent trend of lower temperature and fresher water in Boston Harbor and its adjacent coastal waters compared to offshore surface waters. Along with this shore-to-sea trend on the Harbor-Stellwagen Basin transect, there was a distinct decrease in turbidity, as estimated by beam attenuation, as well as a decrease in the concentration of many nutrients.

As observed in previous years (1992-1993) of MWRA monitoring, a regional-scale difference between Massachusetts and Cape Cod Bays was evident in chlorophyll concentrations during this winter-early spring period. For example, in February surface-water chlorophyll concentrations in western Massachusetts Bay were ≤ 1 $\mu g\ L^{-1}$, compared to values > 8 $\mu g\ L^{-1}$ in eastern Cape Cod Bay. Chlorophyll concentrations increased in western Massachusetts Bay in early March, but generally were less than concentrations in Cape Cod Bay. Accompanying the regional trend in chlorophyll was a geochemical distinction between western Massachusetts Bay and Cape Cod Bay surface waters. Due to the chlorophyll bloom, Cape Cod Bay waters were characteristically much lower in dissolved inorganic nitrogen, silicate, and phosphate than waters throughout Massachusetts Bay.

Several key monitoring parameters — nutrients, dissolved oxygen (DO), chlorophyll, and phytoplankton (at the surface of station N10P) — were measured on each of the three surveys. Other key parameters — phytoplankton and zooplankton — were measured at 10 "BioProductivity" stations and only during the farfield surveys in each month. Specific findings for each of the key parameters during February-March are summarized as follows:

- Nutrients — In February and early March, there was little vertical variation in nutrient concentrations, although there were some regional distinctions. In particular, high DIN, NH_4, and SiO_4 concentrations were usually noted in and around the Harbor. In the nearfield in late March, nutrients were depleted in the surface layer, but not in bottom waters below about 20 m. DIN concentrations in nearfield surface waters were similar to those measured in previous years during February and early March, and were generally 6-12 μM. Early in the period, there appeared to be a broad relationship of decreasing nutrients with increasing salinity, as has been typically observed in past years. By late March, this trend was reversed, as nutrients tended to increase with increasing salinity, a pattern that simply reflects the general depletion in fresher surface waters compared to more saline bottom waters.

- DO — Under freezing conditions, instrument problems occasionally prevented DO measurements. For available measurements, DO was high and unusually saturated to supersaturated, reflecting the net growth of phytoplankton and relatively vigorous vertical mixing during the period. Differences between surface and bottom waters were not noted.

- Chlorophyll — The main regional trends (i.e., the differences between Cape Cod Bay and Massachusetts Bay) were highlighted above. Typically, in Cape Cod Bay throughout the period and in Massachusetts Bay when chlorophyll rose above 1-2 $\mu g\ L^{-1}$, concentrations were highest below the surface. The mid-depth peaks in concentration often occurred at 10-20 m, and these were evident even when virtually no vertical temperature, salinity, or density stratification was present. In spite of higher nutrient concentrations near the Harbor, chlorophyll concentrations were generally higher in the nearfield than in the Harbor and there were poor correlations between chlorophyll and nutrients, including total nitrogen. This trend might be due to higher inshore turbidity; during this period, conditions were generally more light limiting than nutrient limiting.

- Phytoplankton — Regionally, total phytoplankton counts illustrated the same trend as chlorophyll. In Cape Cod Bay, counts were typically $> 3 \times 10^6$ cells L^{-1}, whereas counts at all Massachusetts Bay, Harbor, coastal, and nearfield stations were typically $< 0.5 \times 10^6$ cells L^{-1} during the period. Several diatom species, typically dominant components of a winter-spring phytoplankton community that usually blooms in temperate marine waters, accounted for the majority of the total cells in Cape Cod Bay in February. However, the diatom dominance was followed by a bloom of *Phaeocystis pouchetii* in March. This potential nuisance organism, a mucilage-producing species, had also bloomed in spring 1992, and some ecological parallels between 1992 and 1994 events are mentioned. The phytoplankton succession in Cape Cod Bay both related to and influenced the nutrient trends in that Bay. Temporal trends in Massachusetts Bay at station N10P (a sentinel monitoring station examined at each survey) indicated some minor fluctuations in species and a tendency for greater diatom dominance in March, but the data suggested that no distinct bloom event had yet occurred at this station in the southwest corner of the nearfield.

Zooplankton and primary production data were collected only on the farfield surveys in February and early March, and they provided the following specific results:

- Zooplankton — Counts were higher where chlorophyll was high (Cape Cod Bay), but sometimes high counts were found in the nearfield where chlorophyll was not high; therefore, across the study area, a general relationship between the abundance of phytoplankton and zooplankton did not exist. Principal zooplankton dominants, in terms of abundance, typically were the small forms *Oithona similis* and *Paracalanus parvus*. In general, copepods and their nauplii made up most of the individuals in all samples. In March, a number of shallow water stations near Boston Harbor showed a seasonal appearance of barnacle nauplii, a usual occurrence noted during MWRA monitoring.

- Metabolism — Primary production measurements were made at two stations, one at the edge of Boston Harbor (station F23P) and another in the middle of the nearfield (station N16P). No incubations were performed to estimate respiration. A new design strategy of incubating samples from four depths at a station was instituted, and calculations related to this design are presented and evaluated. Calculated production rates ranged from < 0.25 g C m^{-2} d^{-1} to > 3 g C m^{-2} d^{-1}. In both February and March, production was higher at station N16P. Overall, there was a strong relationship between chlorophyll and production. It is hypothesized that, relative to the nearfield station, light was more limiting to production rates and chlorophyll concentrations at the Harbor station.

Final discussion and summary of the winter-early spring period of 1994 emphasizes, in a preliminary fashion, some of the interannual variations that have been observed for this season from 1992 to 1994. Comments are made regarding the constancy, across years, in the regional difference between Cape Cod Bay and Massachusetts Bay. Similarities and differences among years provide an initial basis for discussing baseline variability (pre-outfall commissioning in the Bay) and the difficulties this will present for interpretation of monitoring results.

CONTENTS

Note to reader: Appendices A-F are bound separately from this technical report. To request the Appendices, contact the MWRA and ask for one of the MWRA Miscellaneous Publications entitled "APPENDICES TO WATER QUALITY MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: FEBRUARY AND MARCH 1994".

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1.0 INTRODUCTION

This report is the first of five periodic water column reports for water quality monitoring conducted in 1994 for the Massachusetts Water Resources Authority (MWRA) Harbor and Outfall Monitoring Project. The report includes results from three surveys conducted during February and March; each of these surveys included sampling at 21 stations in the nearfield area. The February and early March surveys were combined farfield/nearfield surveys that covered 25 additional stations throughout Boston Harbor and Massachusetts and Cape Cod Bays. Data on physical, chemical, and biological measurements at the stations are presented and interrelationships of these measurements are examined.

The structure of this report is as follows:

Section 1.	Background information on the water quality surveys conducted in 1994.
Section 2.	Field, laboratory, and data analysis methods.
Sections 3-5.	Results of surveys, in chronological order (February farfield/nearfield survey, early March farfield/nearfield survey, late March nearfield survey).
Section 6.	Discussion of the winter/early spring surveys.

All tables and figures are presented at the end of each section. An extensive set of appendices is bound separately. The appendices provide supporting tables and plots that represent the data stored in the MWRA database.

1.1 Background

The MWRA is implementing a long-term monitoring plan for the future MWRA effluent outfall that will be located in Massachusetts Bay (Figure 1-1). The purpose of the monitoring is to verify compliance with the conditions of the NPDES discharge permit and to assess the potential environmental impact of effluent discharge into Massachusetts Bay. A detailed description of the monitoring and its rationale is provided in the Effluent Outfall Monitoring Plan (MWRA, 1991).

To help establish the present conditions with respect to water properties, nutrients, and other important parameters of eutrophication, the MWRA contracted with Battelle Ocean Sciences to conduct baseline water-quality surveys throughout Massachusetts Bay during 1992 to 1994. Results of the 1992 surveys were presented in a series of three periodic reports (Kelly *et al.*, 1992; Kelly *et al.*, 1993a,b), summarized in an annual report (Kelly *et al.*, 1993c), and used to examine nutrient issues related to the offshore outfall (Kelly, 1994). The results of the 1993 surveys were presented in a series of five periodic reports (Kelly *et al.*, 1994a,b,c,d; Libby *et al.*, 1994).

Serving the MWRA's need for rapid dissemination of data and information, the periodic report series also provides a preliminary synthesis of monitoring results. The technical approach used in 1994 to implement the water quality portion of this monitoring plan is presented in a combined work/quality assurance project plan (CW/QAPP) (Albro *et al.*, 1993) that was developed specifically for water quality monitoring. The CW/QAPP describes the technical activities performed at sea and in the laboratory, as well as the data quality requirements and assessments, project management, and a schedule of activities and deliverables. In addition, individual survey plans were submitted to MWRA for each survey to provide important operational details. The survey reports submitted for the three surveys discussed in this periodic report describe actual survey tracks, samples collected, and other survey details (Dragos, 1994; West, 1994; Albro, 1994). The survey plans and reports should be consulted for pertinent information concerning each of the surveys. Data reports on nutrients, plankton, and pelagic metabolism have been submitted to MWRA for the surveys conducted during February and March 1994; these data are included in the appendices to this report.

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 as follows:

Physical Oceanography

- Obtain high-resolution measurements of water properties throughout Massachusetts Bay.
- Use vertical-profile data at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (tens of kilometers) 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 (kilometers) 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 at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (tens of kilometers) and temporal (seasonal) variability in nutrient concentrations and to provide supporting data to help to interpret biological data.
- Use vertical-profile data along transects of closely spaced stations within the nearfield area for analysis of smaller-scale spatial (kilometers) and temporal (semi-monthly) variability in nutrient concentrations, and develop a three-dimensional understanding 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 at selected sites in Massachusetts and Cape Cod Bays for analysis of large-scale spatial (tens of kilometers) 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 explain observed change.
- Provide data to help 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 1994 Baseline Water Quality Monitoring Program

Throughout 1993 and 1994, Battelle and its subcontractors, the University of Rhode Island (URI) and the University of Massachusetts at Dartmouth (UMD), have been conducting surveys similar to those initiated in 1992. The schedule of surveys conducted in 1994 is given in Table 1-1. The survey schedule was designed to match the 1992 and 1993 schedules. The surveys discussed in this report were conducted during February 8 and 15-18 (W9401), March 1-2 and 5-7 (W9402), and March 22-23 (W9403).

1.4 Summary of Accomplishments: February to Late March 1994

For the combined farfield/nearfield surveys in February (W9401) and early March (W9402), *in-situ* measurements were taken and samples were collected at the stations shown in Figure 1-1. Samples for laboratory analyses were collected to obtain the following types of data:

- Dissolved inorganic nutrients: nitrate, nitrite, ammonium, phosphate, and silicate.
- Chlorophyll *a* and phaeopigments in extracts of filtered water.
- *In-situ* fluorometric measurements of chlorophyll, optical-beam transmittance (attenuation), light irradiance, salinity, temperature, and dissolved oxygen.
- Total suspended solids and dissolved oxygen in discrete water samples.
- Organic nutrients: dissolved carbon, nitrogen, and phosphorus; particulate carbon and nitrogen.
- Phytoplankton and zooplankton identification and enumeration.
- Rates of water-column production (^{14}C) vs. irradiance from shipboard incubations.

For the nearfield surveys, one 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 analysis and archival purposes.

A second day of the nearfield survey was dedicated to high-resolution "tow-yo" profiling with an *in-situ* sensor array (as described above, minus irradiance). The towfish was used to obtain the profiles by oscillating from near surface to near bottom as the ship progressed at 4 to 7 kt along the nearfield tracks between the vertical stations.

Samples collected for analysis (rather than for archiving) have been analyzed, and *in-situ* sensor measurements have been calibrated and processed. Both types of data are presented in this report and all are summarized in accompanying Appendices A through F.

Table 1-1 **Schedule of water quality surveys for calendar year 1994. This report provides data from the surveys conducted in February and March (shown in bold).**

SURVEY	DATES
W9401 (Combined Farfield/Nearfield)	February 8 and 15-18
W9402 (Combined Farfield/Nearfield)	March 1-2 and 5-7
W9403 (Nearfield)	March 22-23
W9404 (Combined Farfield/Nearfield)	April 5-10
W9405 (Nearfield)	April 27-28
W9406 (Nearfield)	May 22
W9407 (Combined Farfield/Nearfield)	June 21-25
W9408 (Nearfield)	July 7
W9409 (Nearfield)	July 27-28
W9410 (Nearfield)	August 11
W9411 (Combined Farfield/Nearfield)	August 23-27
W9412 (Nearfield)	September 7
W9413 (Nearfield)	September 28-29
W9414 (Combined Farfield/Nearfield)	October 11-15
W9415 (Nearfield)	November 2-3
W9416 (Nearfield)	November 30 - December 1

2.0 METHODS

Field sampling equipment and procedures, sample handling and custody, sample processing and laboratory analysis, and instrument performance specifications and data quality objectives are discussed in the water quality monitoring CW/QAPP (Albro *et al.*, 1993). The plan is detailed and should be consulted for standard survey methods. In general, only deviations from the CW/QAPP are described in this report. Stations, samples, and other survey specific information are given in detail in the individual survey reports.

2.1 Field Procedures

2.1.1 Hydrographic and Water Sampling Stations

The combined farfield/nearfield surveys for 1994 represent a continuation of the baseline water quality monitoring conducted in 1992 and 1993 for the MWRA Harbor and Outfall Monitoring Project. However, relative to 1992-1993, there were several sampling design modifications. These were, in part, made in response to discussions at a January 1994 Nutrient Workshop (see Hunt and Steinhauer, 1994). Six new stations, located in Boston Harbor (F30B and F31B) and Massachusetts Bay (F26, F27B, F28, and F29), were added and six previous farfield stations (F04, F08, F09, F11, F20, and F21) were eliminated. In addition, the number of stations where biological measurements are made was increased from 10 stations to 14 stations. For the four new biology stations, samples from 1994 have been archived; thus, 1994 biology data presented in this report are for the same stations described for 1992-1993. Productivity measurements are now being made at only two stations (F23P and N16P). These two stations are being sampled twice, once on each of two separate days, during the farfield survey. Productivity is estimated from samples taken at four, rather than the previous two depths; these include all hydrocast bottle depths except the bottom bottle and are characterized as surface, mid-surface, chlorophyll maximum (or mid-depth), and mid-bottom. The high-resolution tow-yo sampling frequency was modified. Several survey designs were planned, the principal one being a repeated ebb-flood tide Harbor-nearfield transect. The results of high-resolution profiling will be discussed in a separate report covering all of the high-resolution surveys in 1994.

Tables 2-1 summarizes the planned sampling, and indicates the types of measurements and samples taken at nearfield and farfield stations. For a combined farfield/nearfield survey, additional measurements were made at a subset of 14 biology/productivity stations (8 farfield and 6 nearfield); 10 of these stations were termed "BioProductivity" stations during the 1992 and 1993 surveys and are labeled with a "P" (see Figure 1-1). This nomenclature has been retained for these stations even though productivity measurements are only being made at stations F23P and N16P. The four newly designated "Biology" stations are sampled during the farfield surveys; station F06 and three new stations that are labeled with a "B" (F27B, F30B, and F31B; see Figure 1-1). The six "P" stations in the nearfield were sampled for a broad suite of parameters as part of the farfield survey and again during hydrographic profiling (dissolved nutrient stations on the vertical sampling day of the nearfield survey).

During the farfield survey, *in-situ* measurements and dissolved inorganic nutrient samples were obtained at 31 stations plus the 2 repeated productivity stations. At the biology/productivity stations, additional samples were taken for the analyses of dissolved and particulate organic nutrients, total suspended solids, chlorophyll, and plankton identification and enumeration. In addition to this suite of measurements, water column production was estimated during two separate occupations of stations F23P and N16P. At stations F25 and F24, additional samples were collected for the determination of dissolved and particulate organic nutrients.

On the vertical profiling day of the nearfield survey, *in-situ* measurements and dissolved inorganic nutrient samples were obtained from 21 nearfield stations. Surface phytoplankton samples were taken at the six biology/productivity stations. During both the farfield and nearfield surveys, additional discrete seawater samples were obtained to calibrate the *in-situ* oxygen and fluorescence sensors. Principal deviations from these planned stations and samples have been reported in the survey report prepared after the completion of each survey.

2.1.2 Productivity Measurements

Productivity measurements differed slightly from those described in the CW/QAPP. At the request of MWRA and due to the preference of the Outfall Monitoring Task Force, only the ^{14}C method was used to estimate primary production; the oxygen light-dark method was not used. At four depths during each occupation of stations F23P and N10P, ^{14}C primary production was measured by exposing samples to a light gradient as described by Albro *et al.* (1993) for the oxygen method. Fifteen 300-mL BOD bottles were inoculated with 2.5 μCi of ^{14}C-sodium bicarbonate. Three bottles were incubated in the dark. The remaining 12 bottles were exposed to irradiance levels ranging from about 20 to 2000 $\mu E\ m^{-2}\ sec^{-1}$, with several bottles exposed in the range of 200-600 $\mu E\ m^{-2}\ sec^{-1}$. Samples for dissolved inorganic carbon (DIC) were taken from the same GO-FLO bottle as samples used for productivity incubations. DIC was analyzed as described in the next section and was used in calculating primary production rates (Section 2.3).

2.1.3 Respiration Measurements

Respiration data collected in 1992 were reviewed prior to the 1993 surveys. During the winter sampling season, the cold temperatures and very low respiration rates made it difficult to measure significant changes in dissolved oxygen over reasonable incubation times. It was determined that respiration measurements would not be made during the winter combined farfield/nearfield surveys.

2.2 Laboratory Procedures

Table 2-2 summarizes laboratory methods for chemistry and biology samples as detailed in the CW/QAPP. The DIC method used by URI is a "purge-and-trap" method (I.O. Corp., 1984) and was not described in the CW/QAPP. Samples are collected in a 40-mL screw-cap VOC vial with a septum. The bottle is filled and overflown, the sample is then "killed" with mercury chloride, and the bottle is sealed. In the laboratory, the vial is placed in a total carbon analyzer where the vial septum is pierced. A sample is then

withdrawn, acidified, bubbled with nitrogen (N_2), and the carbon dioxide (CO_2) in the gas stream is caught on a molecular sieve. The sieve is heated to 200°C, releasing the CO_2 into a new stream of N_2, the carrier gas that transports the CO_2 to an IR detector where the CO_2 content is measured.

The difference between analytical replicates, estimated from samples taken and reported in the first periodic report (Kelly *et al.*, 1993d), averaged less than 1% ($x \pm \sigma$ = 0.47% ± 0.73%, range = 0.08-2.68%, n = 12). The average difference between sample replicates from a GO-FLO bottle was less than 1% ($x \pm \sigma$ = 0.25% ± 0.31%, range = 0.01-0.81%, n = 6).

2.3 Data Analyses

To calculate production rates, the data for light bottles were first corrected by subtracting uptake measured in dark bottles. Volumetric production rates were then calculated, as described in the CW/QAPP (Albro *et al.*, 1993). The dark-bottle uptake was calculated as the mean of the three dark bottles, excluding samples where a value was an outlier, as determined by statistical testing using the Dixon Criterion (Appendix E).

The Dixon Criterion (Natrella, 1963) evaluates the relative range between values in an ordered set. Thus, if three values (X_1, X_2, and X_3) are arranged from lowest to highest, the criterion for the *highest* value being an outlier is

$$X\_3 = (X_3 - X_2)/(X_3 - X_1)$$

The criterion for the *lowest* value being an outlier is

$$X\_1 = (X_2 - X_1)/(X_3 - X_1)$$

These calculated values are compared to a tabled value. For example, if X_3 or X_1 exceed 0.941, then there is a 95% chance that the value in question is an outlier.

X_3 and *X_1* are calculated for each set of three dark-bottle replicates. When *X_3* or *X_1* exceeds the tabled value of 0.941 for $n=3$, the outlier is rejected and not used in calculations. Appendix D provides results of testing for data collected on surveys W9401 and W9402.

The P-I curve modeling for ^{14}C differed slightly from that described for oxygen in the CW/QAPP. A sequence of two models was used to fit data from ^{14}C incubations. Dark-corrected values were normalized to chlorophyll determined for the sample depth being measured. Following this, a sequence of two models was used to fit the data.

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

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

where

P_B = production (chlorophyll-normalized)

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

$a = \alpha I/P_{SB}$

$b = \beta I/P_{SB}$

α = initial slope of the rise in net production with light increasing from zero irradiance [units of (μgC μgChl^{-1} hr^{-1})/(μE m^{-2} sec^{-1})], calculated from I (light irradiance level, μE m^{-2} sec^{-1}) and P_{SB}.

In the CW/QAPP and in the first periodic report for 1993 (Kelly *et al.*, 1993d), the second model used was a hyperbolic tangent function (Platt and Jassby, 1976). Although Platt *et al.* (1980) claim equivalence of the two models in terms of α and P_{max}, Frenette *et al.* (1993) have shown this not to be the case. For the second model, following the suggestion of Frenette *et al.* (1993), the negative exponential formulation given by Webb *et al.* (1974) was used.

Here, $P_B = P_{max} [1 - e (-\alpha I/P_{max})]$

P_{max} = light-saturated maximal productivity and

α = the initial slope for the curve where productivity is proportional to light intensity (I).

The two models are equivalent where the photoinhibition term (b) is zero. Note that use of this second model marks a return to that used in initial modeling for 1992, minus only a respiration term (cf. Kelly *et al.*, 1992).

The parameters in each model were fit simultaneously by least squares using the NLIN procedure in SAS (1985) for each incubation series that measured paired P_B and irradiance. Fitting was accomplished where parameters were estimated if, within 50 iterations, the model converged on a suitable simultaneous fit (SAS, 1985). A derivative-free method was used that compares favorably with methods using partial derivatives (Frenette *et al.*, 1993). If the three-parameter model (Platt *et al.*, 1980) fitting did not converge on a fit, the two-parameter model (Webb *et al.*, 1974) was used.

Volumetric production rates, chlorophyll-normalized P-I curves, and model coefficients (Appendix D) were used to calculate integrated water column rates of production. These were expressed as a rate per square meter of surface following the procedure described by Kelly *et al.* (1993c) which is briefly described in the following text.

Because irradiance varies throughout the day and stations are sampled at different times, the light conditions were standardized. Within a survey, the average incident irradiance (I_o) measured by the deck cell during a midday (1000 to 1400 h) period was used to standardize conditions. Then, for each station, an extinction coefficient (k) was determined by regressing $\ln(I_z/I_o)$ vs. depth, where I_z is the irradiance at depth z, and the slope of the resultant line estimates k. The coefficient (k) was then used with the survey I_o to generate the standardized light profile using the model $I_o = I_z e^{-kz}$ and to determine $Z_{0.5\% Io}$, the depth where photosynthetically active radiation equals 0.5% I_o. Estimated production rates (See below) were expressed per square meter of surface and integrated to $Z_{0.5\% Io}$. A 1% to 0.5% isolume is commonly accepted as the level to which net production (in excess of respiration) is achieved by plankton.

Next, for each station and each incubation series ("surface," "mid-surface," "mid-depth," or "mid-bottom" sample), the fitted P-I model was combined with the standardized light profile to yield chlorophyll-normalized production rates (μg C μg Chl^{-1} h^{-1}) at 0.5-m intervals to coincide with 0.5-m bin-averaged chlorophyll values generated from a vertical downcast. To calculate depth-integrated rates, the predicted hourly, chlorophyll-normalized rate was then multiplied by the chlorophyll fluorescence at each depth interval from the surface to the $Z_{0.5\% Io}$. The values were then appropriately summed over depth and units were converted to m^{-2} from a volumetric basis.

The above procedure estimated hourly midday rates (μg C m^{-2} h^{-1}). Conversion to full day-time rates was made by multiplying by a factor of 7 which recognizes that about 55-60% of the production generally occurs during the 4-h period (1000-1400 h) when the irradiance is highest (Vollenweider, 1966). Final modeled rates provide an estimate of daytime primary production as g C m^{-2} d^{-1}.

The same procedure was applied to data for each incubation from the set of four samples incubated at a station, yielding independent estimates of production at each station occupation. For each survey including productivity measurements, all independent estimates are listed in a table that summarizes P-I modeling results (provided in detail in Appendix D).

Also, for each occupation of each station, an estimate of integrated water column production was calculated based on a composite of the four independent estimates. The composite estimate was calculated by combining model results from incubations, where the results from a given incubation were applied over a depth above and below the incubation sample's collection depth half-way to the next sample's collection depth. Thus, by using different P-I curves to extrapolate over appropriate portions of the water column, a composite production profile (by 0.5-m intervals) was developed. The rates over the composite profile were then appropriately summed over depth. Units were converted to m^{-2} from a volumetric basis, and a conversion to full daytime primary production rates (g C m^{-2} d^{-1}) was made as described above for the individual incubation depth samples. A comparison of this calculation scheme with a direct trapezoidal integration is presented in Section 6.

Table 2-1. Field samples and measurements [cf. Albro *et al.*, 1993]

Parameter	Stations	Sample Volume	Sample Containers	Shipboard Processing/ Preservation
Following samples are subsampled from water collected with Poly Vinyl Chloride Niskin GO-FLO Bottles				
Dissolved Inorganic Nutrients	All	60 mL	100 mL Polyethylene bottle	Pass through a filter. Fix with chloroform.
Dissolved Oxygen	14 Biology/ Productivity and 3 Farfield	300 mL	300 mL Glass BOD	Fix per Oudot *et. al.* (1988). Titrate within 24 hours.
Dissolved Organic Carbon	14 Biology/ Productivity and F25	50 mL	100 mL amber glass bottle	Pass through a pre-ashed glass fiber filter. Fix with 0.5 mL of phosphoric acid.
Dissolved Organic Nitrogen	14 Biology/ Productivity and F25	20 mL	50 mL glass digestion tube	Pass through a filter. Digest within 8 hours.
Dissolved Organic Phosphorus	14 Biology/ Productivity and F25	20 mL	50 mL glass digestion tube	Pass through a filter. Digest within 8 hours.
Particulate Organic Carbon	14 Biology/ Productivity and F25	50 mL	Whatman GF/F glass fiber filter	Pass through a pre-ashed glass fiber filter. Freeze (-5°C).
Particulate Organic Nitrogen	14 Biology/ Productivity and F25	50 mL	Whatman GF/F glass fiber filter	Pass through a pre-ashed glass fiber filter. Freeze (-5°C).
Total Suspended Solids	14 Biology/ Productivity	200 mL	Petri dish	Pass through a filter. Freeze (-5°C)
Chlorophyll *a*/ Phaeopigments	14 Biology/ Productivity	2 x 10 mL	Whatman GF/F glass fiber filter	Pass through filter. Fix with 1% $MgCO_3$ solution, wrap in foil, store over desiccant, and refrigerate.
Phytoplankton (Whole Water)	14 Biology/ Productivity	800 mL	1000 mL glass bottle	Preserve with Utermohl's solution.
Phytoplankton (Screened Water)	14 Biology/ Productivity	2000 mL	100 mL Polyethylene bottle	Strain through a 20 μm mesh; wash retained organism into a jar. Fix with Utermohl's solution.
^{14}C Production	2 Biology/ Productivity	300 mL	300 mL Glass BOD	Inoculate with 2.5 μCi of $NA_2{}^{14}CO_3$ and incubate.
Following sample is collected with a vertically towed net				
Zooplankton	14 Biology/ Productivity	800 mL	1000 mL glass bottle	Wash into jar. Fix with a 5-10% Formalin solution.
The following measurements are collected by the Battelle Ocean Sampling System				**Precision**
Conductivity	All	---	Floppy disk	0.01 mS/cm
Temperature	All	---	Floppy disk	0.001 °C
Pressure	All	---	Floppy disk	0.01 decibars
Dissolved Oxygen	All	---	Floppy disk	0.05 mg/L
Chlorophyll *a* Fluorescence	All	---	Floppy disk	0.01 μg/L
Transmissometry	All	---	Floppy disk	0.01 m^{-1}
In situ Irradiance	All	---	Floppy disk	1 $\mu E\ m^{-2}\ s^{-1}$
Surface Irradiance	All	---	Floppy disk	1 $\mu E\ m^{-2}\ s^{-1}$
Bottom Depth	All	---	Floppy disk	1 m
Navigational Position	All	---	Floppy disk	0.00017 deg

Table 2-2. Laboratory analyses and methods [from Albro *et al.*, 1993]

Parameter	Units	Method	Reference[1]	Maximum Holding Time	Preservation
Dissolved Ammonia	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Nitrate	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Nitrite	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Phosphate	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Silicate	μM	Technicon II AutoAnalyzer	Lambert and Oviatt (1986)	3 mo.	Chloroform
Dissolved Oxygen	mg L^{-1}	Autotitrator	Oudot *et al.* (1988)	24 h	dark/cool
Dissolved Organic Carbon	μM	O.I. Model 700 TOC Analyzer	Menzel and Vaccaro (1964)	3 mo.	Fix with 0.5 mL of phosphoric acid.
Dissolved Organic Nitrogen	μM	Technicon II AutoAnalyzer	Valderrama (1981)	3 mo.	Add reagents immediately, heat to 100°C within 8 hours.
Dissolved Organic Phosphorus	μM	Technicon II AutoAnalyzer	Valderrama (1981)	3 mo.	Add reagents immediately, heat to 100°C within 8 hours.
Particulate Organic Carbon	μM	Carlo Erba Model 1106 CHN elemental analyzer	Lambert and Oviatt (1986)	3 mo.	Dry over desiccant.
Particulate Organic Nitrogen	μM	Carlo Erba Model 1106 CHN elemental analyzer	Lambert and Oviatt (1986)	3 mo.	Dry over desiccant.
Total Suspended Solids	mg L^{-1}	Cahn Electrobalance	See Section 12.7.7	6 mo.	Dry over desiccant.
Chlorophyll *a*/ Phaeopigments	μg L^{-1}	Model 111 Turner Fluorometer	Lorenzen (1966)	2 wk	Fix with 1% $MgCO_3$ solution, wrap in foil, store over desiccant, and refrigerate.
Phytoplankton (Whole Water)	Cells L^{-1}	Sedgwick-Rafter counting chambers	Turner *et al.* (1989)	3 y	Preserved with Utermohl's solution, store at room temperature.
Phytoplankton (Screened Water)	Cells L^{-1}	Sedgwick-Rafter counting chambers	Turner *et al.* (1989)	3 y	Fix with Utermohl's solution, store at room temperature.
^{14}C Production	^{14}C hr^{-1}	Liquid Scintillation Counter (Bechman LS-3801)	Strickland and Parsons (1972)	2 wk	Scintillation fluid
Zooplankton	Cells L^{-1}	Dissecting Microscope	Turner *et al.* (1989)	3 y	Fix with a 5-10% Formalin solution, store at room temperature.

[1]See Section 20 of Albro *et al.*, 1993 for literature references.

3.0 RESULTS OF FEBRUARY 1994 COMBINED FARFIELD/NEARFIELD SURVEY (W9401)

3.1 Farfield Survey

3.1.1 Horizontal Distribution of Surface Water Properties

Caveat. *This survey was interrupted by bad weather. Numerous stations in a wide swath from Boston Harbor through the nearfield to stations F19 and F17 in Stellwagen Basin were sampled on February 8, about a week before the Bay boundary stations, Cape Cod Bay, and remaining Massachusetts Bay stations were sampled (see Dragos, 1994). Nevertheless, we have produced surface contour plots using all stations occupied on this survey (first occupation if a repeated station). The resulting displays are non-synoptic. One should view patterns at a coarse level; apparent fine-scale trends such as between individual stations may be artifacts of the interrupted sampling.*

Surface temperatures were very cold in February 1994 (Figure 3-1). All stations in Cape Cod Bay were below zero. As has been characteristic of this season, shallow inshore waters were generally the coldest ($<0.5°C$). Moving offshore, temperatures increased several degrees. The warmest surface water ($>3°C$) was found at the deep-water boundary station (F27B) in the basin outside Massachusetts Bay.

Spatial patterns for salinity broadly paralleled those for temperature (Figure 3-2). Slightly lower salinities were found in surface waters close to shore and within Cape Cod Bay. The lowest salinity (30.5 PSU) was measured in Boston Harbor and the highest salinity (32.8 PSU) was found at station F27B.

Beam attenuation was relatively high in and around Boston Harbor and also stretching southward from the Harbor along the coast, but it peaked in eastern Cape Cod Bay (Figure 3-3). The winter-spring bloom already was initiated in Cape Cod Bay, as is illustrated by Figure 3-4, which presents *in-situ* sensor data nominally as chlorophyll *a* (see Appendix A). At station F02P, the surface concentration approached 9 μg L^{-1}. Interestingly, relatively high chlorophyll was found at station F29, several kilometers northwest of

Race Point at the tip of Cape Cod, and the next highest surface chlorophyll value was in southern Massachusetts Bay in waters overlying Stellwagen Basin. Overall, there was a latitudinal gradient of decreasing chlorophyll concentration to the north, from Cape Cod Bay through Massachusetts Bay.

Dissolved inorganic nitrogen (DIN) concentrations broadly reflected the chlorophyll distribution (Figure 3-5). Lowest values were detected in Cape Cod Bay (3.5 μM) and concentrations increased northward to 10-12 μM throughout much of Massachusetts Bay. A slightly higher value (14 μM) was detected at the boundary station F27B, outside the Bay. The often observed increasing gradient from the nearfield to Boston Harbor was present; nearfield concentrations were generally 9-12 μM, compared to about 17.5 μM in and near the Harbor. Most of the DIN was in the form of nitrate (NO_3) which, therefore, displayed a similar regional pattern as DIN (Figure 3-6). Near Boston Harbor, however, more than 5 μM nitrogen was found in the form of ammonium (NH_4).

Phosphate (PO_4) concentrations were low in eastern Cape Cod Bay (Figure 3-7). Throughout most of the Bays, however, concentrations were near 1 μM. Unlike DIN, there was not a sharp PO_4 concentration gradient from Boston Harbor. Silicate (SiO_4) exhibited the most pronounced latitudinal gradient of all the nutrients, with concentrations generally decreasing from north to south through the Bays (Figure 3-8). Silicate was present in depleted concentrations (3.4 μM) in eastern Cape Cod Bay. With the exception of Boston Harbor (station F30B), the surface-water silicate concentration was highest off Cape Ann (station F26).

3.1.2 Water Properties Along Selected Vertical Sections

Due to changes in survey station design in 1994 relative to 1993, a new set of standard transects for examining vertical sections was established for the 1994 series of water column periodic reports. The Nahant Transect, Boston-Nearfield Transect, Boston-Cohasset Transect, and Marshfield Transect all run from nearshore to deep water in Stellwagen Basin (Figure 3-9). As a roughly parallel series from north to south, these four transects characterize a large portion of Massachusetts Bay. First, sections for temperature, salinity, chlorophyll, and DIN are described for this series of transects. The same

parameters are then presented for the fifth section, the Cape Ann-Stellwagen Transect (See Figure 3-9). This line of stations prescribes an arc near an imaginary boundary between Massachusetts Bay and Gulf of Maine waters — from Stellwagen Basin in mid-Massachusetts Bay, crossing Stellwagen Bank to station F27B in the deep basin outside the Bay, and terminating in shallower water near Cape Ann.
From Figures 3-10a and b, one can see a gradual horizontal banding from shore to sea, more pronounced in temperature (T) than in salinity (S). Gradients are sharpest and most striking for the two transects from Boston Harbor. In addition to the horizontal banding, temperature and salinity increased slightly in deeper water, especially at depth greater than 50 m in Stellwagen Basin. Despite small temperature and salinity gradations, the water column was well mixed from top to bottom; at virtually all stations, density profiles of σ_T were uniform over depth (Appendix B).

Chlorophyll concentrations displayed a pattern that was similar across the four transects (Figure 3-10c). Concentrations were low throughout. Offshore, the concentrations were generally >1 μg Chl *a* L^{-1}, whereas inshore and Boston Harbor concentrations were <1 μg Chl *a* L^{-1}.

For DIN, there was a different trend for each transect. North to south across the transects, observations included (1) slightly higher DIN concentrations offshore (Nahant Transect), (2) a distinct gradient from the Harbor to nearshore (Boston-Nearfield Transect), (3) an apparent local depletion of DIN in mid-water offshore (Boston-Cohasset-Transect), and (4) slightly higher DIN concentrations inshore (Marshfield Transect). Except for occasionally elevated DIN concentrations in deep-water samples, DIN concentrations were essentially uniform throughout the water column at these transect stations.

The sections for Boundary Transect (e.g. Figure 3-11) are arranged so that south is to the left (station F12, Stellwagen Basin) and north is to the right of the plots (station F26, Cape Ann). The only apparent feature was a warmer, more saline cell of water at station F27B, which is located in the basin seaward of a 40-50-m sill that forms a bathymetric boundary between the tip of Stellwagen Bank and Cape Ann. Water temperature and salinity at station F27B were similar to the deepest water at the northern entrance to Stellwagen Basin (station F22; see Figures 3-10a,b), which is located just west of the boundary sill from station F27B. Chlorophyll showed little variability, but DIN was slightly higher northward, and concentrations of DIN throughout the water column at station F27B were similar to those at station F22.

3.1.3 Analysis of Water Quality Characteristics Throughout the Bays

Scatter plots using all *in-situ* sensor data from vertical profiles are shown in Figures 3-12a and 3-12b. Individual station profiles are provided in Appendix C. Appendix C also includes separate scatter plots for groups of stations clustered by region as defined in Figure 3-13.

The temperature-salinity plot reveals an interesting feature (Figure 3-12a). Data points at lower salinity (below about 32 PSU) followed two distinct lines having temperatures separated by over 1°C. More detailed examination of the data (see Appendix C) indicated that the two lines occurred at Boston Harbor stations and reflected differences in time more than in space. The upper line, at about 0°C, was from stations F30B and F23P on February 8. The lower line included data from station F23P on February 15, as well as other coastal and Cape Cod Bay stations that were sampled on February 16. Although water quality in the Harbor varies with the tidal stage, it seems likely that the week-long persistent strong winds and very cold air temperatures (Dragos, 1994) caused significant cooling in shallow water in the Harbor and the nearfield. For example, it was also noted that the nearfield "P" stations sampled on February 8, generally had lower temperatures when repeated as part of the full nearfield survey on February 17. In contrast, salinity over these days at these nearfield stations did not vary. Therefore, advection seems less likely a mechanism for the observed temporal change than cooling, especially considering that the offshore and boundary stations, one source for advection, were characterized by higher salinity and warmer temperatures (Figure 3-12a) and Boston Harbor, another source for advection, were much less saline.

Beam attenuation, which is a measure of turbidity, decreased broadly with salinity (Figure 3-12a). Interestingly, with the observed temperature shift over time in the Harbor, there was also an increase in beam attenuation, a phenomenon consistent with strong winds that could cause resuspension of bottom sediments. No concomitant change in chlorophyll occurred at these Harbor stations. In fact, other than the two Cape Cod Bay stations (especially F02P on the eastern side and station F29 off Provincetown), the range in chlorophyll concentrations was low across stations and over depth (Figure 3-12b).

Dissolved oxygen (DO) was generally at ~100% saturation. On-deck freezing of instruments was a problem (Dragos, 1994) and reliable profiles could not be obtained at a number of stations (Appendix B).

In Figure 3-12b, a few profiles with DO as low as 90% or higher than 110% seem suspect. In general, however, the profiles in Appendix B indicate vertical uniformity in DO, which is expected under well-mixed conditions with mostly low chlorophyll concentrations. The eastern Cape Cod Bay station was high in DO (105-110% saturation), but no regional distinctions were evident in either chlorophyll or DO.

A display of DIN concentrations with depth provides a revealing view of a regional difference in nutrients (Figure 3-14a). High concentrations, often >12 μM, were found at Harbor and coastal stations (especially those closest to the Harbor). The range of DIN concentrations (mostly 9-12 μM) at offshore, boundary, nearfield, and most Cape Cod Bay stations overlapped. However, concentrations of some nearfield samples were much lower (<5 μM). Anomalous concentrations (<3 μM) were detected at one Cape Cod Bay station (F02P) and one offshore station (F16, see also Figure 3-10d). Few stations showed strong variation over depth.

Enrichment at Harbor and coastal stations was noted for NH_4, but not for $N0_3$ (Figure 3-14b). In contrast, two boundary stations were the most enriched in $N0_3$. Enrichments in PO_4 and SiO_4 at Harbor and coastal stations were also noted (Figure 3-14c); otherwise general statements made for DIN also apply to PO_4 and SiO_4. Only the single Cape Cod Bay station (F02P) was nearly depleted in silicate. It was interesting that nearfield SiO_4 concentrations were more constrained in their range than for either DIN or PO_4; moreover, the nearfield was higher in SiO_4 than many offshore stations.

A scatter plot for DIN and PO_4 suggested that the relationship between N and P was similar in most regions (Figure 3-15a). With a few exceptions, the data show a linear trend which strongly parallels a 16:1 (Redfield ratio) isopleth. The pattern also indicated a positive intercept for PO_4, suggesting that, as these two nutrients are depleted, P may still be available in measurable concentrations in the water when N falls below detection limits. Such a pattern has been commonly noted in Massachusetts Bay. The main regional distinction involved Boston Harbor, where many samples were clearly enriched with N relative to P; in some cases enrichment was evident in $N0_3$, but predominantly it occurred because of higher NH_4 concentrations.

There was considerable scatter in the N vs. SiO_4 plots (Figure 3-15b), but ratios of N/Si were confined to a range of about 1:2 to 1:1. Although the Harbor area enrichment in N was evident, Si was also enriched and the N/Si ratio was therefore similar across regions. For the nearfield samples, there appeared to be two clusters of points, one with more enriched in Si relative to the other; but both clusters of data were within the bounds detected in other regions. Nearfield nutrient variability is examined in Section 3.2.

DIN showed a broad decrease with salinity, but not as a tight relationship (Figure 3-16a). Here, it is noticeable that station F02P in Cape Cod Bay and F17 in the offshore region had distinctly low DIN concentrations for their salinity. Some deep-water samples in the offshore and boundary regions had slightly higher DIN concentrations (at high salinity); this "rising arm" feature associated with high salinity bottom water has been observed regularly during recent MWRA monitoring.

Some of the scatter in DIN relative to salinity was temporally induced. Repeated sampling (one week apart) at station F23P produced some variability at low salinity. Some of the greatest DIN variation at a given salinity occurred within the nearfield. DIN concentrations were near 12 μM at nearfield stations that were sampled early (February 8); at stations sampled later in the month (February 15, 16, and 17), some DIN concentrations approached 12 μM, but most were in the range of 6-9 μM.

There was a linear decreasing trend for NH_4 as a function of increasing salinity and this essentially drove the DIN-salinity pattern (Figure 3-16b). Similar NO_3 concentrations could be found across the range of salinity and depletion of NO_3 relative to the main body of points was found at stations within many regions. The trend for PO_4 with salinity was much like NO_3, whereas SiO_4 more closely followed the NH_4-salinity pattern (Figure 3-16c).

In general, combined forms of N (DIN + PON) and total N (TN) were higher in Boston Harbor and its adjacent coastal water compared to other areas (Figure 3-17). Cape Cod Bay concentrations were low, but fell within the range for measurements in the nearfield. Offshore and boundary station N concentrations were similar to each other and generally within the range of concentrations found in the nearfield. The nearfield and Boston Harbor areas were characterized by substantial variability in DIN +PON and TN concentrations, a variability which was due, in part, to the interrupted sampling of this February survey.

Some of this variability was also due to time-space variations in salinity; there was a general relationship between nitrogen forms and salinity across all samples (Figure 3-17).

For nutrients, some individual stations disrupted regional patterns with anomalies in local concentrations, and these appeared to relate to local biological activity. But at a broad scale, patterns of N and Si with salinity were evident and Boston Harbor was easily identifiable as a region of N and Si enrichment. Overall, these water quality trends suggest that nutrient concentrations were largely a function of active physical mixing, without generally strong biological modification, of high-nutrient water characteristic of Boston Harbor into adjacent coastal waters and then secondarily with lower nutrient water characteristic of nearfield, offshore and boundary waters. This being the case, Boston Harbor was the major source of nutrient enrichment of Massachusetts Bay at this time.

3.1.4 Distribution of Chlorophyll and Phytoplankton

At two stations in Cape Cod Bay, phytoplankton abundance exceeded 1 million cells L^{-1} (Figure 3-18). Station F02P in eastern Cape Cod Bay was experiencing a major diatom bloom, and diatom counts there were greater than 1.75 million cells L^{-1} (Figures 3-19, 3-20). Although chlorophyll concentrations (extracted analyses) at Cape Cod Bay station F01P were fairly similar to samples from other regions, phytoplankton counts were much higher. Cell counts in all nearfield, coastal, and Harbor station samples that were analyzed were <0.5 million cells L^{-1}; microflagellates were the dominant organisms (Figures 3-19, 3-20).

Microflagellates were also dominant at stations F01P and F02P, and their abundances were enhanced in Cape Cod Bay relative to the other locations (Table 3-1a,b; see also the full taxonomic listing in Appendix E). Except in Cape Cod Bay, cryptomonads were second in relative abundance at all other locations. Of the two Cape Cod Bay stations, only F02P had elevated concentrations of diatoms. The diatom species that were most abundant at station F02P included *Skeletonema costatum* and *Chaetoceros compressus*. These and other diatoms at station F02P were also present at station F01P. *S. costatum* was virtually ubiquitous throughout the Bays, but with the exception of station F02P, was found in low numbers at most

locations. *Thalassionema nitzschoides*, a common diatom found in low numbers in Massachusetts Bay, was not detected in the Cape Cod Bay samples.

From screened phytoplankton samples (Table 3-2a,b), it was apparent that a variety of dinoflagellate species was present but, across all the samples, only several individuals per liter were detected and, thus, no regional patterns were discernible.

3.1.5 Distribution of Zooplankton

Zooplankton abundance was not well correlated with phytoplankton abundance or with chlorophyll concentration (Figure 3-21). Zooplankton numbers were relatively high at station F02P, which had the diatom bloom, but they were as higher or higher at locations with very low chlorophyll (nearfield stations N07P and N16P) (Figure 3-22). Thus, unlike chlorophyll and phytoplankton, there was no apparent geographic trend in zooplankton abundance. Neither was there an obvious compositional difference across the samples; copepods and their nauplii comprised virtually the entire community. As evident from the data in Appendix F, dominant copepod species were usually *Oithona similis* or *Paracalanus parvus*.

3.1.6 ^{14}C Production Measurements

Appendix D contains many details of the ^{14}C incubation measurements and P-I curve modeling, but results of modeling and calculations for integrated water column production are summarized in Table 3-3. Although the photic zone was deep (15-40 m), production rates were low. Because of low rates, there was much scatter in P-I data and a number of curves could not be fit (Table 3-3). The full series of incubations from samples at four depths was available for station F23P at the Harbor edge from February 8 and for station N16P in the middle of the nearfield from February 15.

With one anomaly, P_{max} or P_{sb} values were in a low range of about 2-6 μg C (μg Chl)$^{-1}$ hr^{-1}. Most curves were fit without a photoinhibition term in the model. There was no apparent pattern in model parameters

as a function of depth; consequently no depth-related pattern was evident in the four independent estimates obtained for integrated water column production. Using the calculation scheme described in Section 2 (methods) to combine results of the four incubations into a single estimate, we calculated rates of 157 and 715 mg C m^{-2} d^{-1} for stations F23P on February 8 and N16P on February 15, respectively. The variation among incubations at a station was not large, which supports a contention that production at station N16P on February 15 was higher than station F23P on February 8. However, the one available estimate for station N16P on February 8 suggested that the two stations may have been more comparable on February 8. Note that because all calculations for production used a survey-specific (not station- or day-specific) irradiance level, station differences are not the result of day-to-day fluctuations in irradiance.

3.2 Nearfield Survey

3.2.1 Distribution of Water Properties from Vertical Profiling

Scatter plots for a variety of parameters measured on the nearfield survey (February 17) are shown in Figure 3-23. Patterns and ranges may be compared to all stations (Figure 3-12) as well as to separate regions (Appendix C). Results show a wide variation in temperature (>2.5 °C) with a range in salinity of about 0.6 PSU. Spatial variations in temperature and salinity portray a T-S gradient from shore to sea, with both T and S increasing slightly offshore (Outer Eastern Transect) and at increasing depth (Figures 3-24a and b). Also evident along the shallow inshore track (Outer Western Transect) and almost to the middle of the field (Inner Western Track) is a north-south gradient of increasing T and S from the southwestern corner of the nearfield (station N10P).

Beam attenuation or chlorophyll (Figure 3-23) showed little variation, but slightly higher values seemed to occur at intermediate temperature and salinities, and thus away from the southwest corner (Figure 3-24c). DIN showed no strong geographic trends. There were isolated patches with concentrations <6 μM and >12 μM, but concentrations generally ranged from 6-12 μM.

3.2.2 Water Quality Variability in the Nearfield

The principal spatial variations in the water column involved physical parameters. Gradients from shore indicated the probable presence of Boston Harbor water around the southwestern corner of the nearfield, where water is tidally exchanged with Boston Harbor (e.g., Kelly and Albro, 1994). However, neither DIN nor chlorophyll appeared to be highly influenced by the physical gradients.

A comparison of scatter plots for nearfield stations surveyed during the farfield survey (February 8 and 15) with those from the nearfield survey (February 17) indicated that a general cooling occurred over much of the field. Over the same week-long period, however, an increase in salinity and temperature was noted at eastern nearfield stations (e.g., stations N07P and N16P, see Appendix B). These features indicate the joint influence of inshore and Boston Harbor cooling (described previously), and advection of offshore water into the nearfield. Moreover, these dynamic forces acting from different directions strongly emphasize that the nearfield is a mixing ground for different waters in the Bay. As noted for geographic variations, the physical variations did not appear to produce marked variations in biological parameters.

Table 3-1a. Abundance of the top five dominant phytoplankton taxa in samples collected near the surface in February 1994.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Feb 16	Feb 08	Feb 15	Feb 15	Feb 08	Feb 17	Feb 08	Feb 08	Feb 16	Feb 16
CHAETOCEROS COMPRESSUS									0.047 (3)	0.211 (4)
CHAETOCEROS DECIPIENS	0.001 (5)									
CHAETOCEROS SPP. (10-20UM)									0.009 (5)	
CHAETOCEROS SPP.(<10UM)									0.009 (5)	
COCCONEIS SCUTELLUM	0.001 (5)									
CRYPTOMONADS	0.060 (2)	0.009 (2)	0.032 (2)	0.043 (2)	0.056 (2)	0.037 (2)	0.088 (2)	0.038 (2)	0.093 (2)	0.243 (3)
CYLINDROTHECA CLOSTERIUM			0.008 (5)							
DETONULA CONFERVACEA										0.089 (5)
DICTYOCHA SPECULUM	0.001 (5)									
GYRODINIUM SPIRALE	0.001 (5)									
GYRODINIUM SPP.	0.001 (5)									
KATODINIUM ROTUNDATUM								0.002 (5)		
LEPTOCYLINDRUS DANICUS								0.002 (5)		
MICROFLAGELLATES	0.241 (1)	0.188 (1)	0.214 (1)	0.177 (1)	0.196 (1)	0.160 (1)	0.199 (1)	0.133 (1)	0.617 (1)	1.247 (1)
NAVICULOID DIATOMS	0.006 (3)	0.004 (4)				0.004 (4)		0.002 (5)		
NITZSCHIA SPP.	0.001 (5)									
PYRAMIMONAS/TETRASELMIS SPP.	0.002 (4)									
RHIZOSOLENIA FRAGILISSIMA					0.003 (5)					
SKELETONEMA COSTATUM		0.006 (3)	0.026 (3)	0.017 (4)	0.021 (3)		0.014 (3)	0.012 (3)	0.026 (4)	1.016 (2)
THALASSIONEMA NITZSCHOIDES	0.006 (3)	0.003 (5)	0.011 (4)	0.018 (3)	0.012 (4)	0.005 (3)	0.009 (4)	0.005 (4)		
THALASSIOSIRA SPP.				0.007 (5)						
UNID. ATHECATE DINOFLAGELLATE							0.004 (5)	0.002 (5)		
UNID. CENTRALES	0.002 (4)				0.003 (5)	0.002 (5)	0.004 (5)			

Units are millions of cells L^{-1} and rankings are given in parentheses.

Table 3-1b. Abundance of the top five dominant phytoplankton taxa in samples collected near the chlorophyll maximum in February 1994.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Feb 16	Feb 08	Feb 15	Feb 15	Feb 08	Feb 17	Feb 08	Feb 08	Feb 16	Feb 16
ASTERIONELLOPSIS GLACIALIS						0.001 (5)				
CHAETOCEROS COMPRESSUS									0.028 (4)	0.095 (3)
CHAETOCEROS DECIPIENS	0.003 (5)			0.015 (5)						
CHAETOCEROS SOCIALIS		0.003 (5)								
CHAETOCEROS SPP. (10-20UM)	0.004 (4)									0.095 (3)
COCCONEIS SCUTELLUM						0.001 (5)				
CRYPTOMONADS	0.055 (2)	0.017 (2)	0.038 (2)	0.047 (2)	0.061 (2)	0.050 (2)	0.067 (2)	0.015 (2)	0.080 (3)	0.070 (5)
CYLINDROTHECA CLOSTERIUM	0.003 (5)		0.007 (5)					0.003 (5)		
DETONULA CONFERVACEA										0.083 (4)
GYMNODINIUM SPP.						0.002 (4)				
KATODINIUM ROTUNDATUM						0.001 (5)				
LEPTOCYLINDRUS DANICUS										0.070 (5)
MICROFLAGELLATES	0.283 (1)	0.214 (1)	0.230 (1)	0.229 (1)	0.176 (1)	0.177 (1)	0.153 (1)	0.090 (1)	0.776 (1)	1.133 (2)
NAVICULOID DIATOMS	0.003 (5)	0.004 (4)				0.004 (3)				
RHIZOSOLENIA DELICATULA									0.007 (5)	0.083 (4)
SKELETONEMA COSTATUM		0.006 (3)	0.024 (3)	0.016 (4)	0.024 (3)		0.016 (3)	0.010 (3)	0.101 (2)	1.374 (1)
THALASSIONEMA NITZSCHOIDES	0.008 (3)	0.004 (4)	0.009 (4)	0.017 (3)	0.010 (4)	0.002 (4)	0.008 (4)	0.007 (4)		
THALASSIOSIRA SPP.	0.003 (5)		0.007 (5)							
UNID. ATHECATE DINOFLAGELLATE	0.003 (5)	0.003 (5)				0.001 (5)				
UNID. CENTRALES					0.003 (5)		0.004 (5)	0.003 (5)		

Units are millions of cells L^{-1} and rankings are given in parentheses.

Table 3-2a. Abundance of all identified taxa in screened (20μm) samples collected near the surface in February 1994.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Feb 16	Feb 08	Feb 15	Feb 15	Feb 08	Feb 17	Feb 08	Feb 08	Feb 16	Feb 16
ALORICATE CILIATES	15	105	8	8	8	10	3	8	5	
CERATIUM FUSUS				5	5		10	5		3
CERATIUM LONGIPES		3		8		3	3		3	
CERATIUM MACROCEROS								3		
CERATIUM TRIPOS				3						
DICTYOCHA FIBULA				5		5	3			3
DICTYOCHA SPECULUM	5	3	8	8		10			13	18
DINOPHYSIS NORVEGICA	3				5	3	3			
EBRIA TRIPARTITIA										3
GYRODINIUM SPIRALE										13
PROROCENTRUM MICANS				3						
PROTOPERIDINIUM BIPES	3								3	30
PROTOPERIDINIUM BREVE	3									3
PROTOPERIDINIUM DEPRESSUM							3			
PROTOPERIDINIUM SPP.		3		3			10	5	5	13
TINTINNIDS	55	50	25	20	35	35	15	50	48	225
UNID. ATHECATE DINOFLAGELLATE						3		3		3
UNID. THECATE DINOFLAGELLATES		3	3	3						

Units are cells L^{-1}

Table 3-2b. Abundance of all identified taxa in screened (20μm) samples collected near the chlorophyll maximum in February 1994.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Feb 16	Feb 08	Feb 15	Feb 15	Feb 08	Feb 17	Feb 08	Feb 08	Feb 16	Feb 16
ALORICATE CILIATES	3	38	13	15	3	3	5	15	13	13
CERATIUM FUSUS	5		3		3	3	8	8		
CERATIUM LONGIPES				8						8
CERATIUM MACROCEROS							3			
CERATIUM TRIPOS				3						
DICTYOCHA FIBULA			3	5		3			3	5
DICTYOCHA SPECULUM		3	3	13	8	5	3		13	38
DINOPHYSIS ACUMINATA				3						
DINOPHYSIS NORVEGICA					3			5		5
EBRIA TRIPARTITIA									3	
EUTREPTIA/EUTREPTIELLA SPP.		3								
GYMNODINIUM SPP.			3							
GYRODINIUM SPIRALE					3		3			8
PEDIASTRUM SPP. COLONY			3							
PROROCENTRUM MICANS			3							
PROTOPERIDINIUM BIPES						3			3	8
PROTOPERIDINIUM BREVE									3	8
PROTOPERIDINIUM DEPRESSUM	3									3

Units are cells L^{-1}

Table 3-2b. Continued.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Feb 16	Feb 08	Feb 15	Feb 15	Feb 08	Feb 17	Feb 08	Feb 08	Feb 16	Feb 16
PROTOPERIDINIUM PALLIDUM				3				3		
PROTOPERIDINIUM SPP.	3				3	5	3	3	5	50
TINTINNIDS	70	20	18	45	40	115	28	45	33	173
UNID. ATHECATE DINOFLAGELLATE					3					3
UNID. THECATE DINOFLAGELLATES				5		3				3

Units are cells L^{-1}

Table 3-3. ^{14}C production (mg C m^{-2} d^{-1}) estimated for euphotic layer at BioProductivity stations F23P and N16P in February 1994.

	F23P 08-FEB-94				F23P 15-FEB-94				N16P 08-FEB-94				N16P 15-FEB-94			
Water depth (m)	21				25				40				42			
$Z_{(0.5\%Io)}$ (m)	25.5[5]				15.0				40.0[5]				34.5			
Sample depth (m)	2.3	4.1	9.9	15.4	2.5	6.4	10.5	17.6	2.8	8.6	18.1	28.5	2.5	9.0	18.4	28.8
Rate (mg C m^{-2} d^{-1})	137	99	151	177	-	-	-	-	289	-	-	-	761	934	467	604
Model[1]	W	P	P	W	NF	NF	NF	NF	W	NF	NF	NF	W	W	W	W
P_{SB} or P_{MAX}[2]	1.73	50.05	2.82	2.51	-	-	-	-	1.44	-	-	-	4.01	5.76	3.15	2.83
α[3]	0.100	0.015	0.037	0.061	-	-	-	-	0.026	-	-	-	0.149	0.115	0.047	0.199
β[4]	-	0.123	0.001	-	-	-	-	-	-	-	-	-	-	-	-	-

[1] P: Platt *et al.* (1980).
W: Webb *et al.* (1974).
NF: P-I incubation data was unable to be fit by either model.

[2] P_{SB}: Production parameter for Platt *et al.* model.
P_{MAX}: Production parameter for Webb *et al.* model.

[3] Parameter for both models.

[4] Parameter for Platt *et al.* model.

[5] $Z_{(0.5\%Io)}$ was greater than the profile depth at station F23P (20.5 m) and N16P (39.0 m) on February 8, 1994.

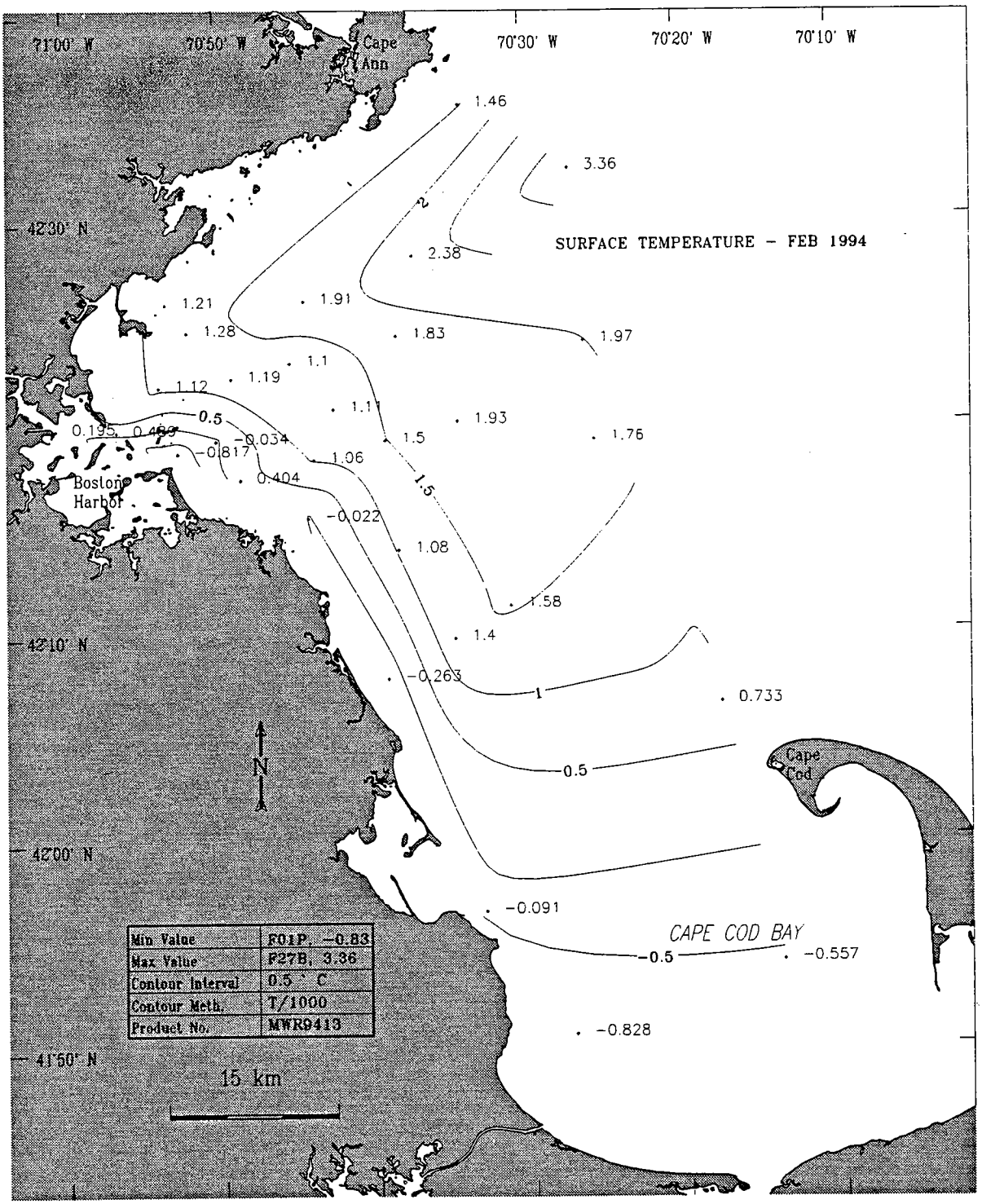


Figure 3-1. **Surface temperature (°C) in the study area in February 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

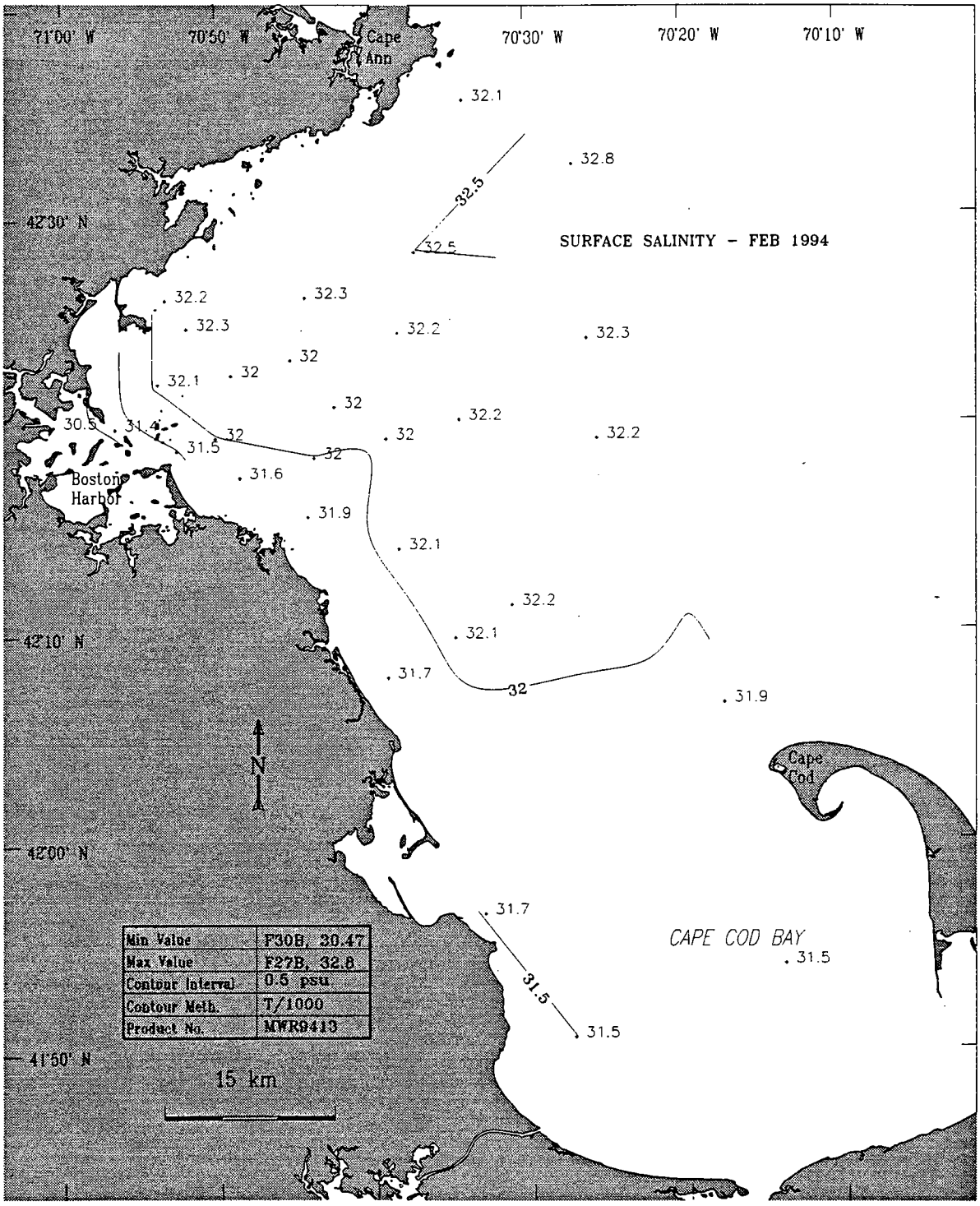


Figure 3-2. **Surface salinity (PSU) in the study area in February 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

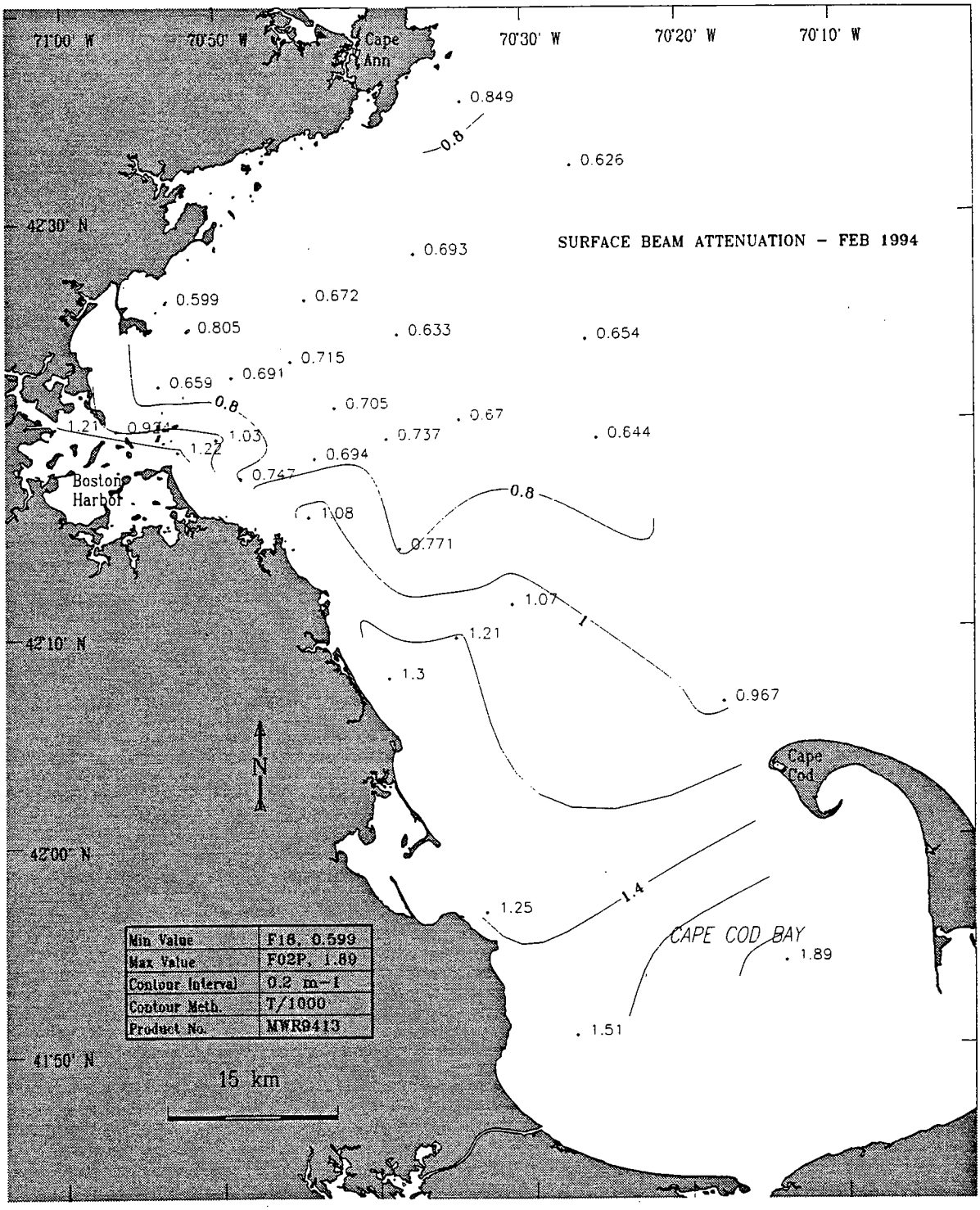


Figure 3-3. **Surface beam attenuation (m^{-1}) in the study area in February 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

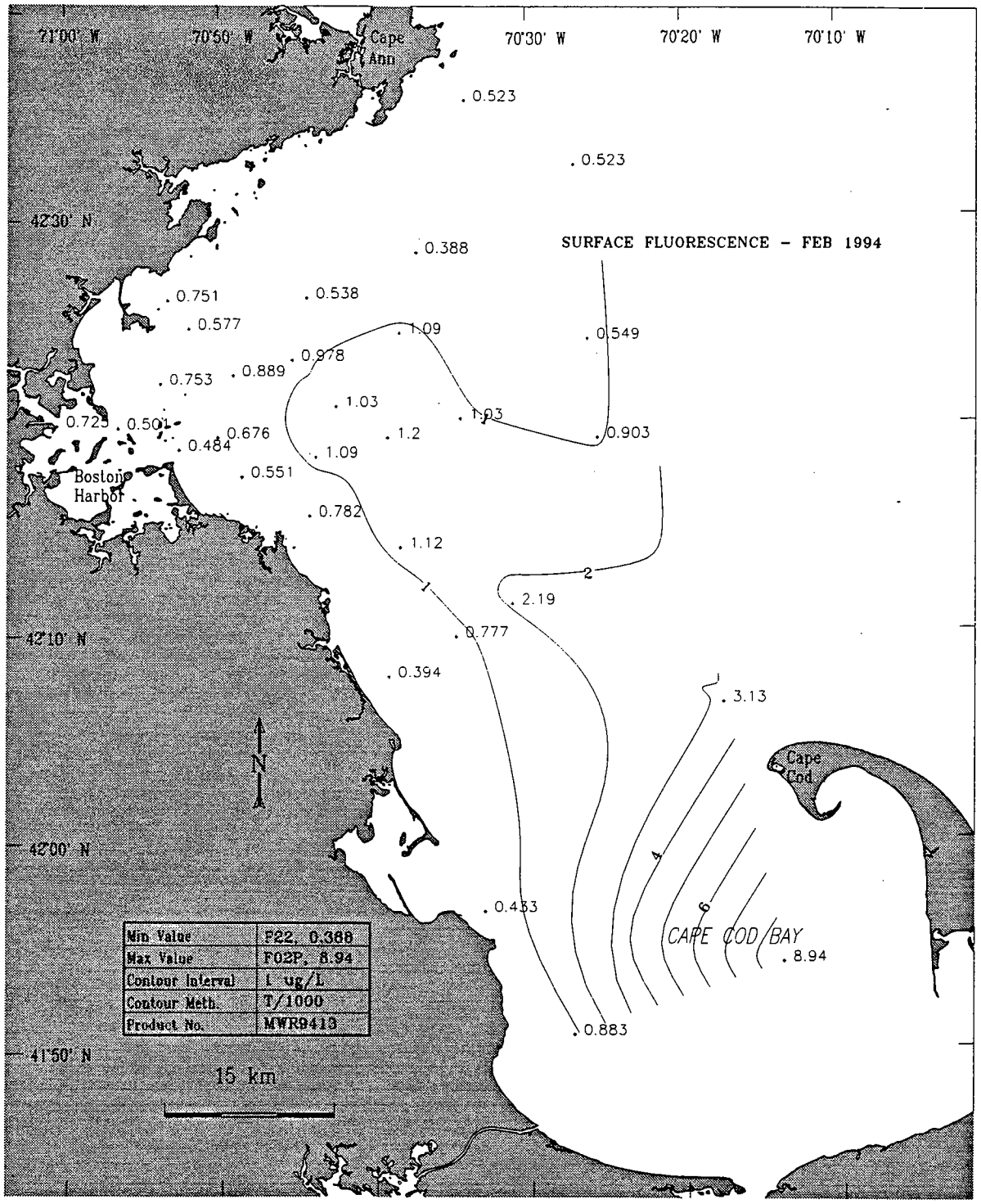


Figure 3-4. **Surface *in situ* fluorescence (as μg Chl L^{-1}) in the study area in February 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

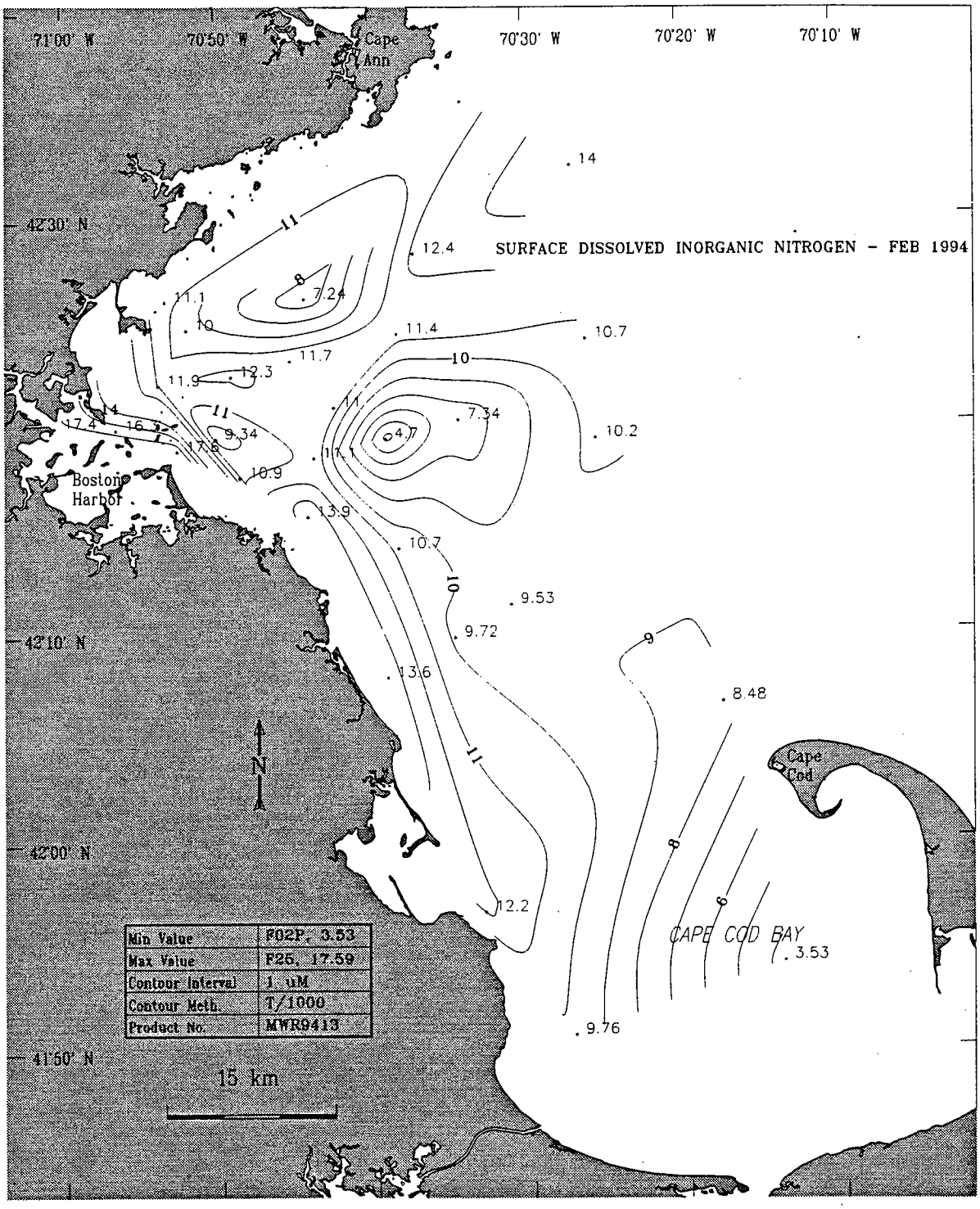


Figure 3-5. **Surface dissolved inorganic nitrogen (DIN, µM) in the study area in February 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

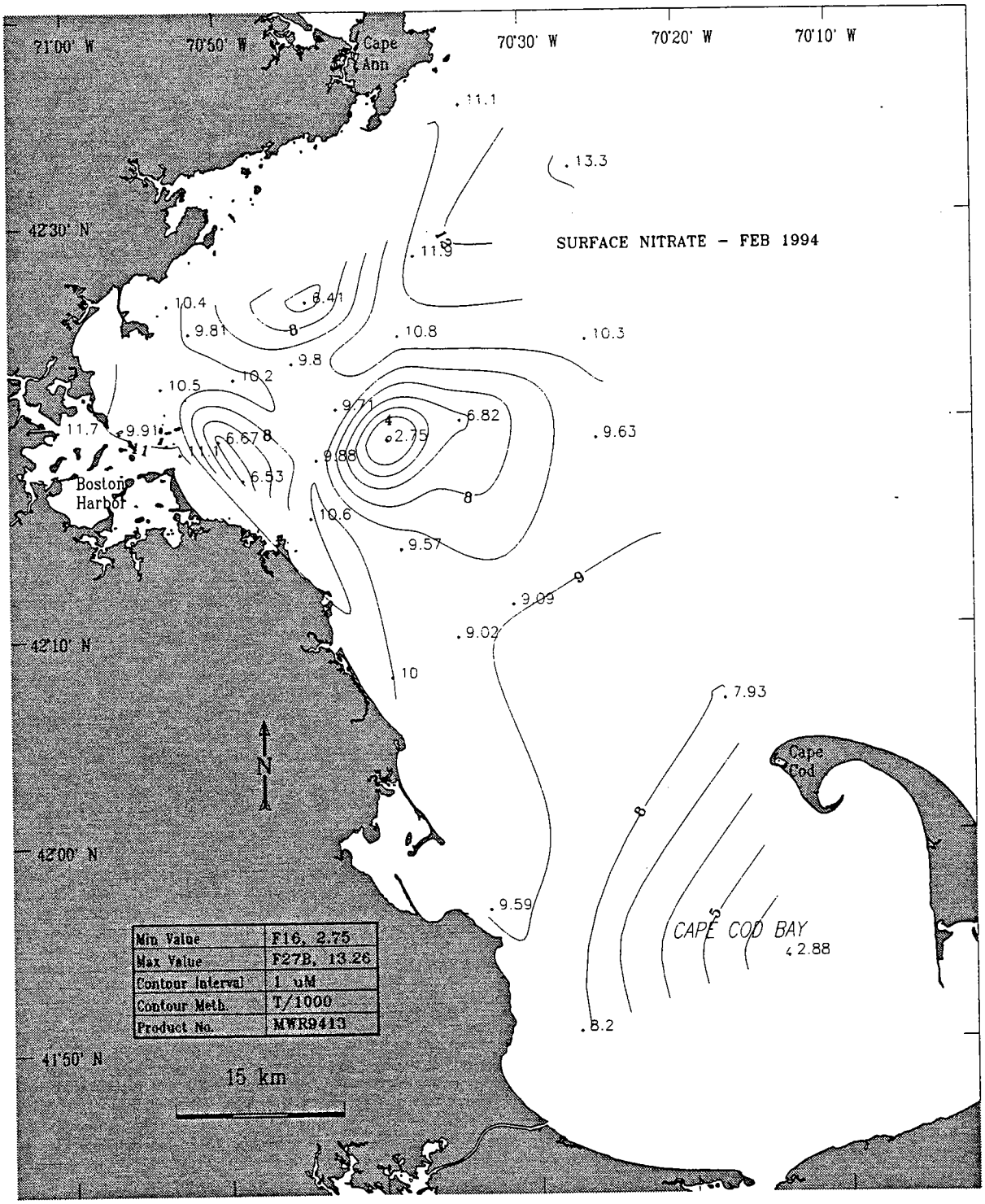


Figure 3-6. **Surface nitrate (NO_3, μM) in the study area in February 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

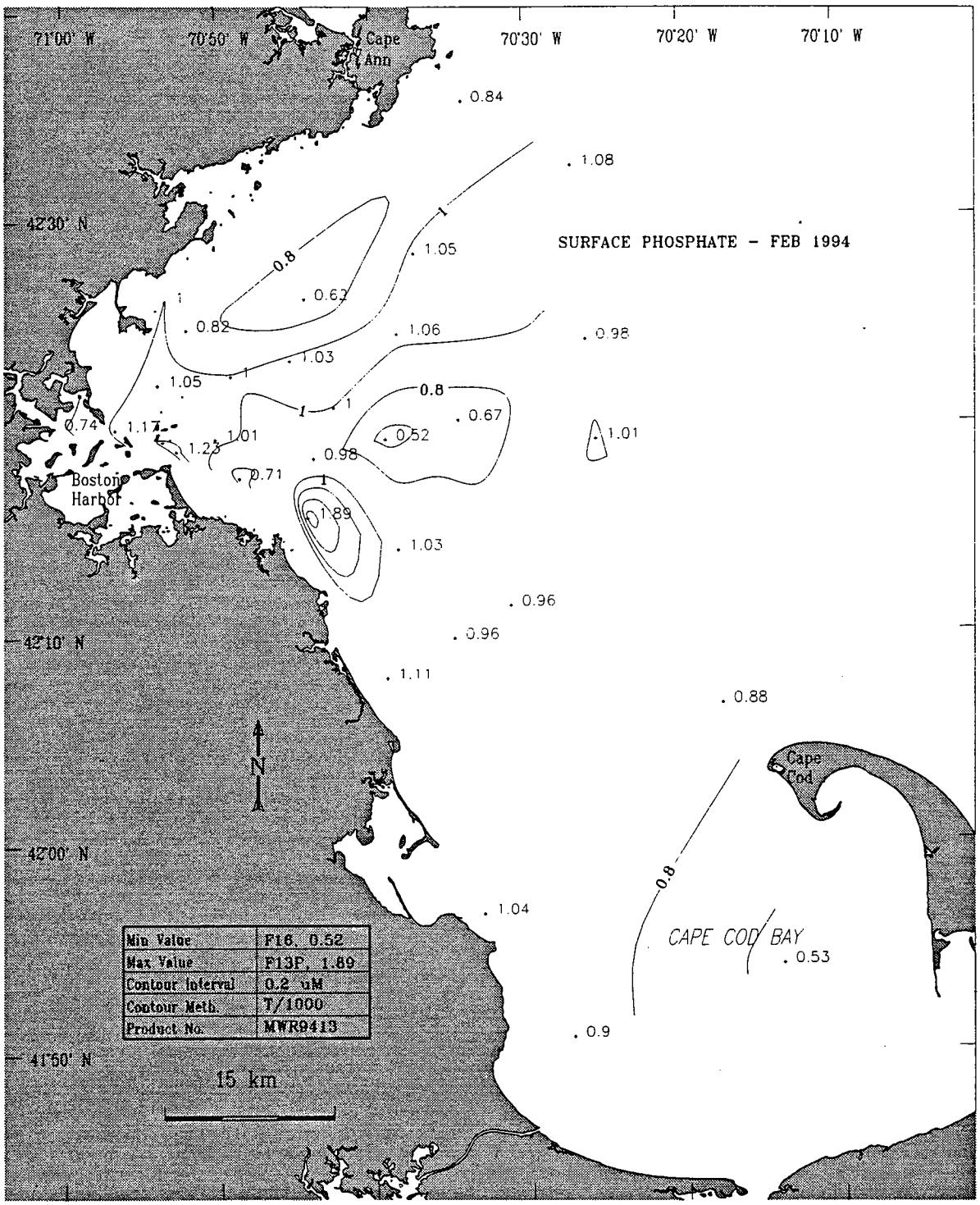


Figure 3-7. **Surface phosphate (PO_4, μM) in the study area in February 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

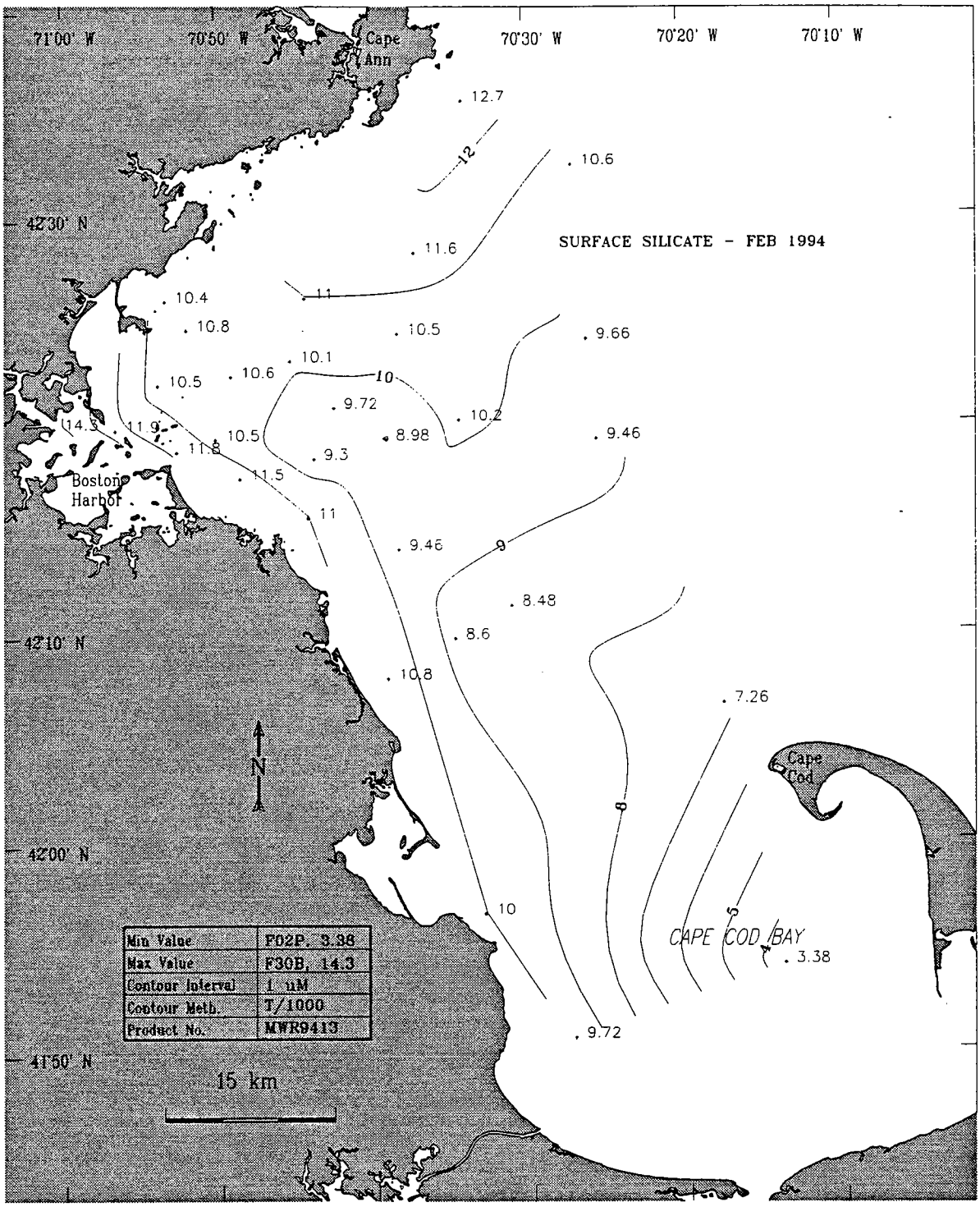


Figure 3-8. **Surface silicate (SiO_4, μM) in the study area in February 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

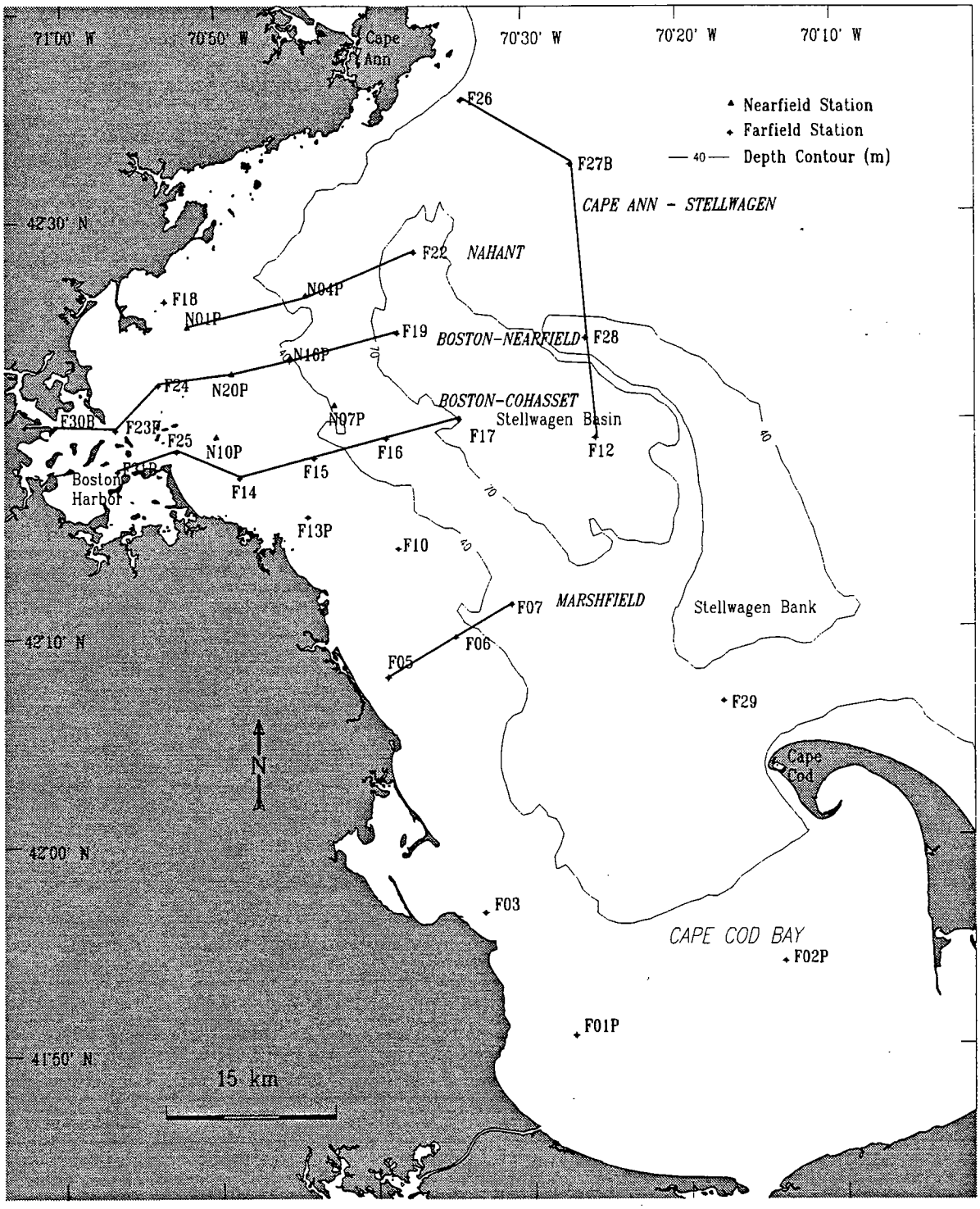


Figure 3-9. **Map showing position of five standard transects for which vertical contour plots were produced in Figures 3-10 and 3-11.**

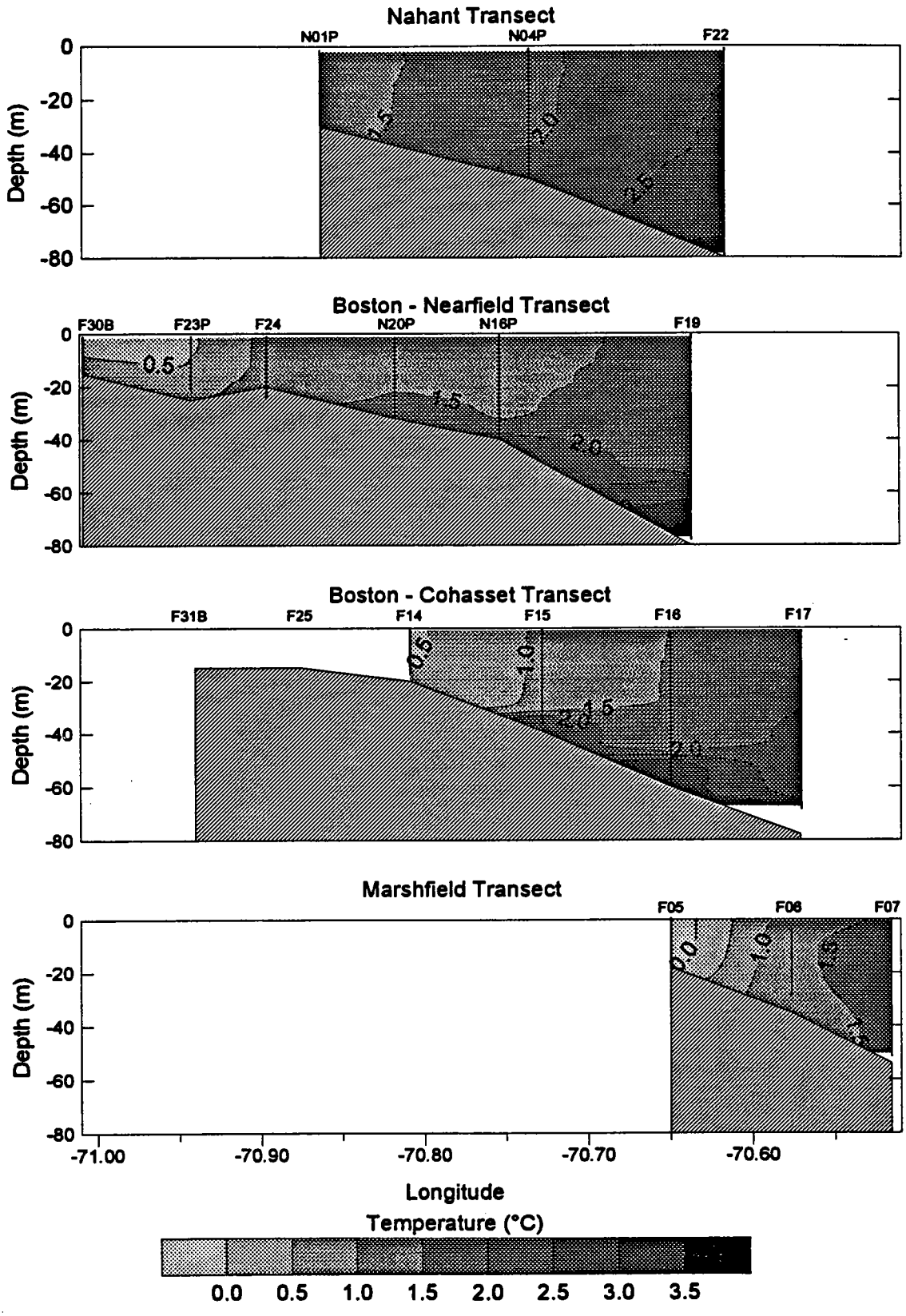


Figure 3-10a. Vertical section contours for standard transects (see Figure 3-9) on Survey W9401. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

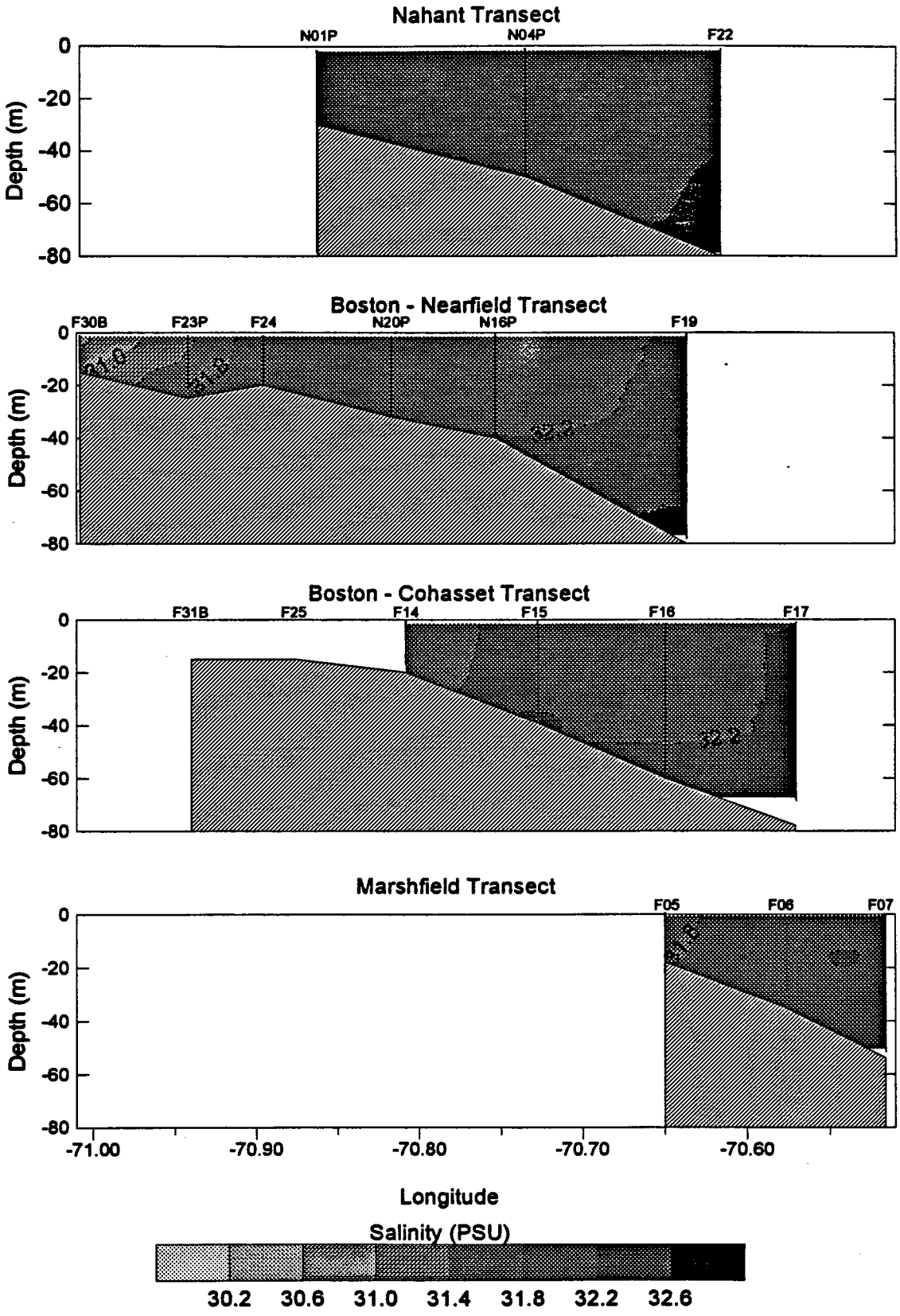


Figure 3-10b. Vertical section contours for standard transects (see Figure 3-9) on Survey W9401. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

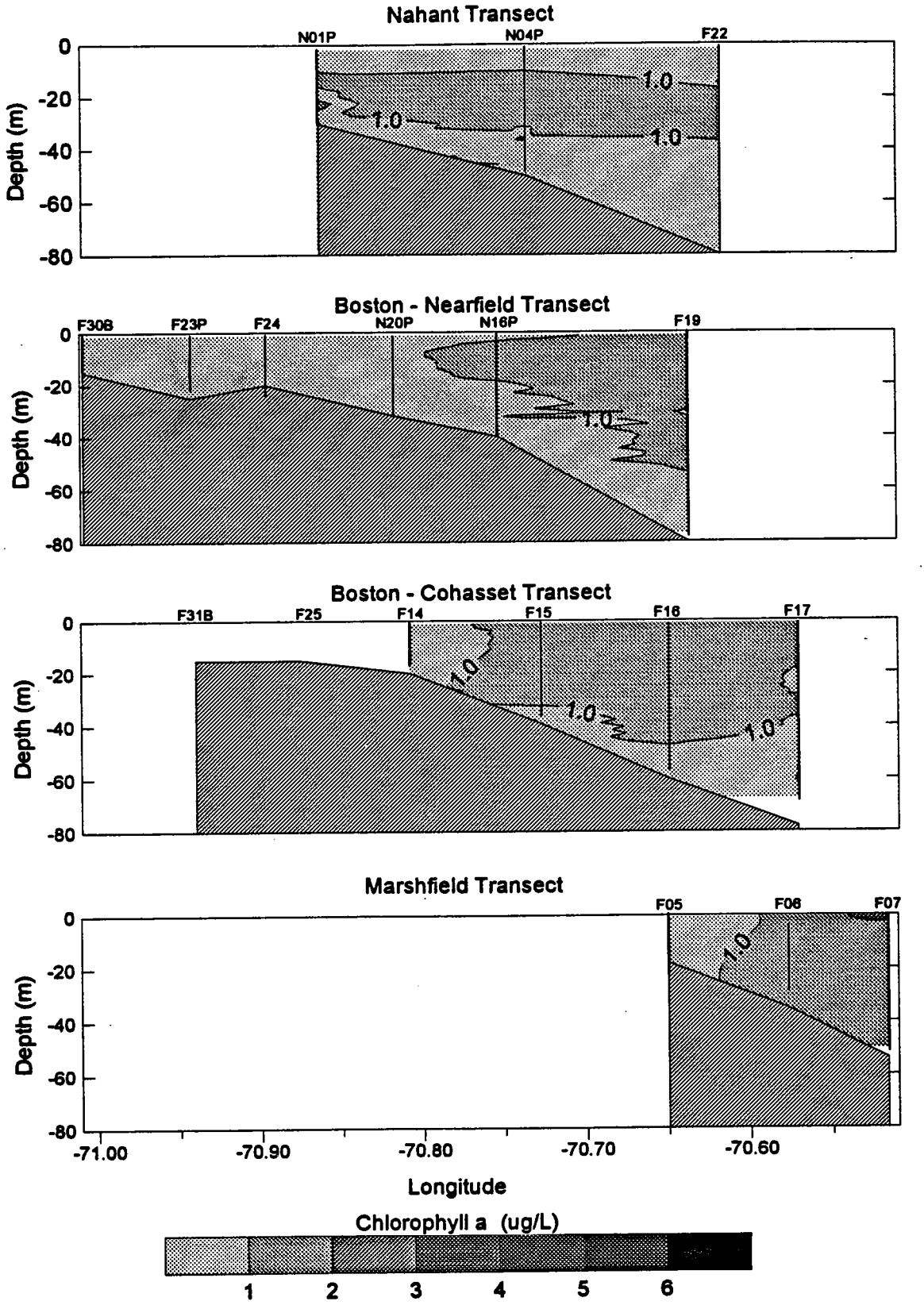


Figure 3-10c. Vertical section contours for standard transects (see Figure 3-9) on Survey W9401. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

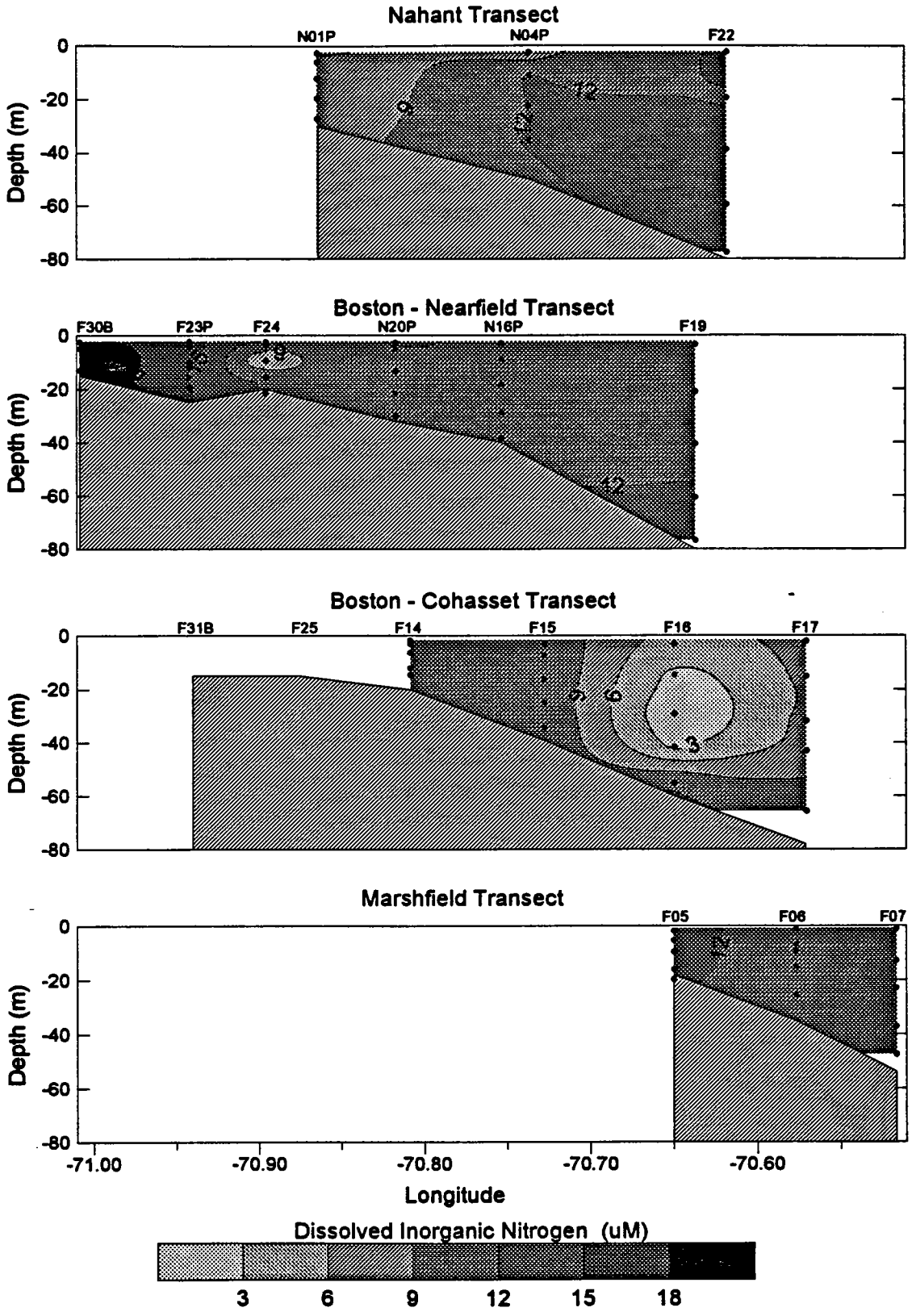


Figure 3-10d. Vertical section contours for standard transects (see Figure 3-9) on Survey W9401. The data used to produce the contours are from discrete bottle samples (Appendix A).

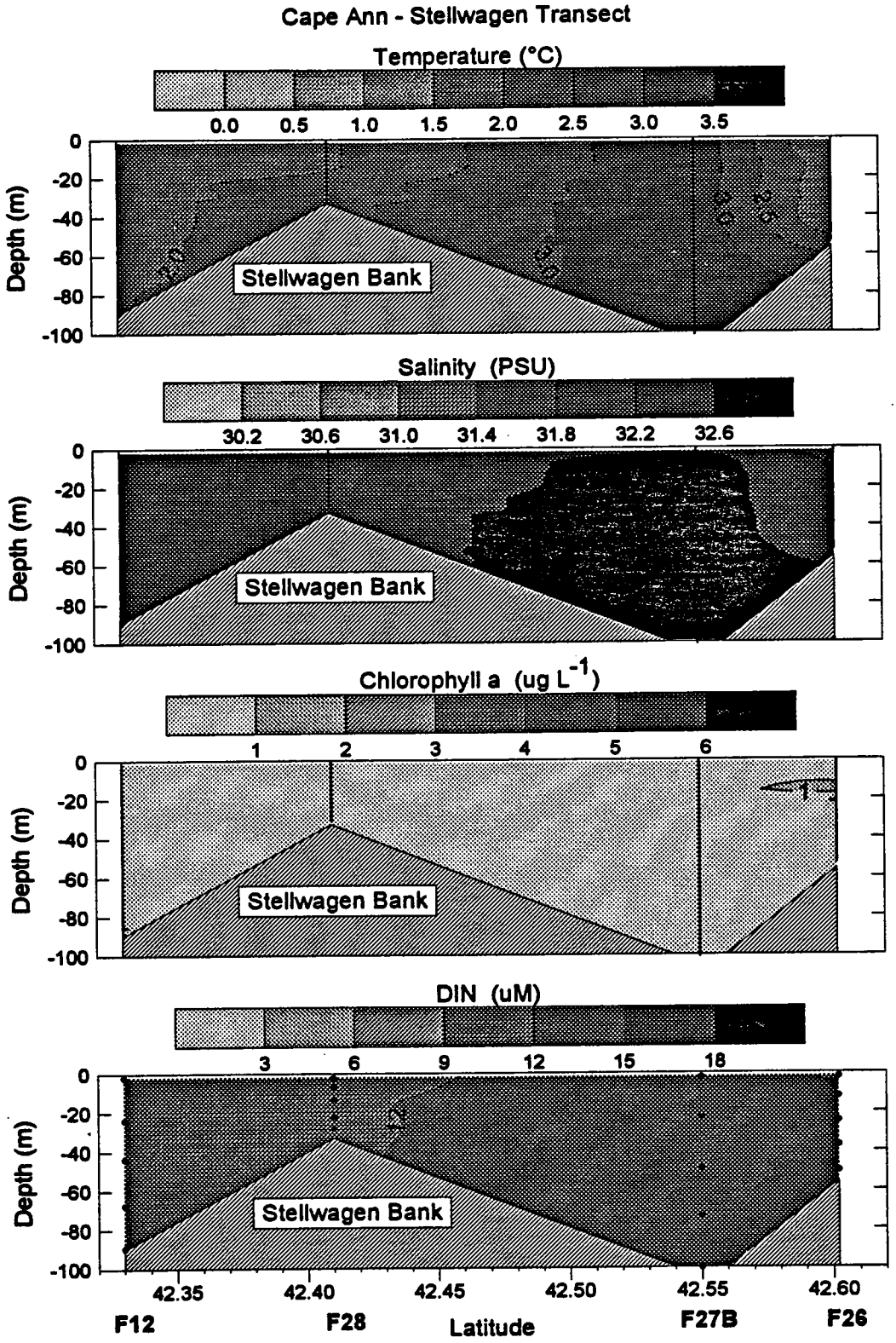


Figure 3-11. Vertical section contours for the Cape Ann - Stellwagen transect (see Figure 3-9) on Survey W9401. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station (temperature, salinity, and chlorophyll) and discrete bottle samples (DIN; Appendix A).

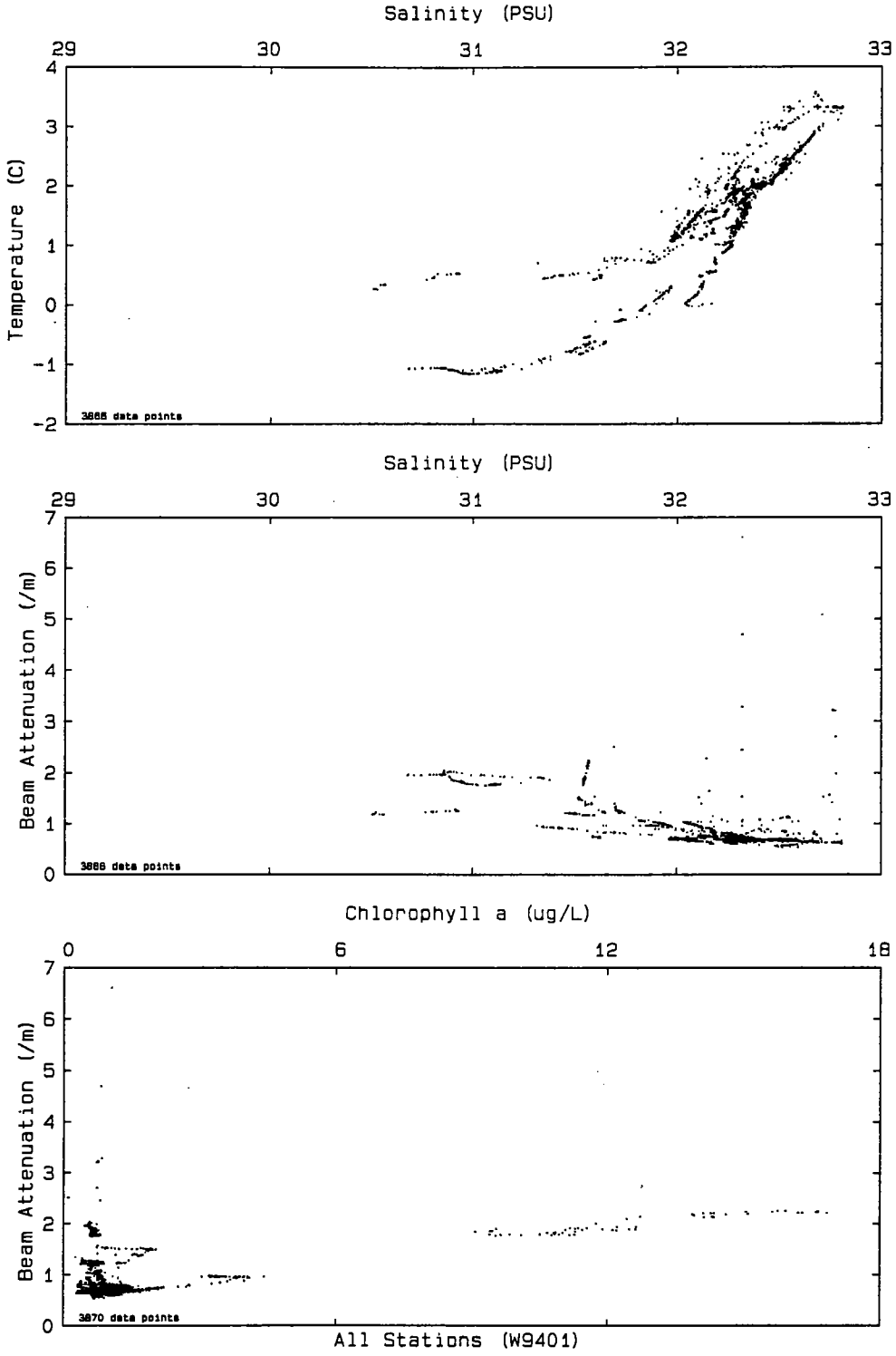


Figure 3-12a. **Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in February 1994. Chlorophyll is estimated from *in situ* fluorescence.**

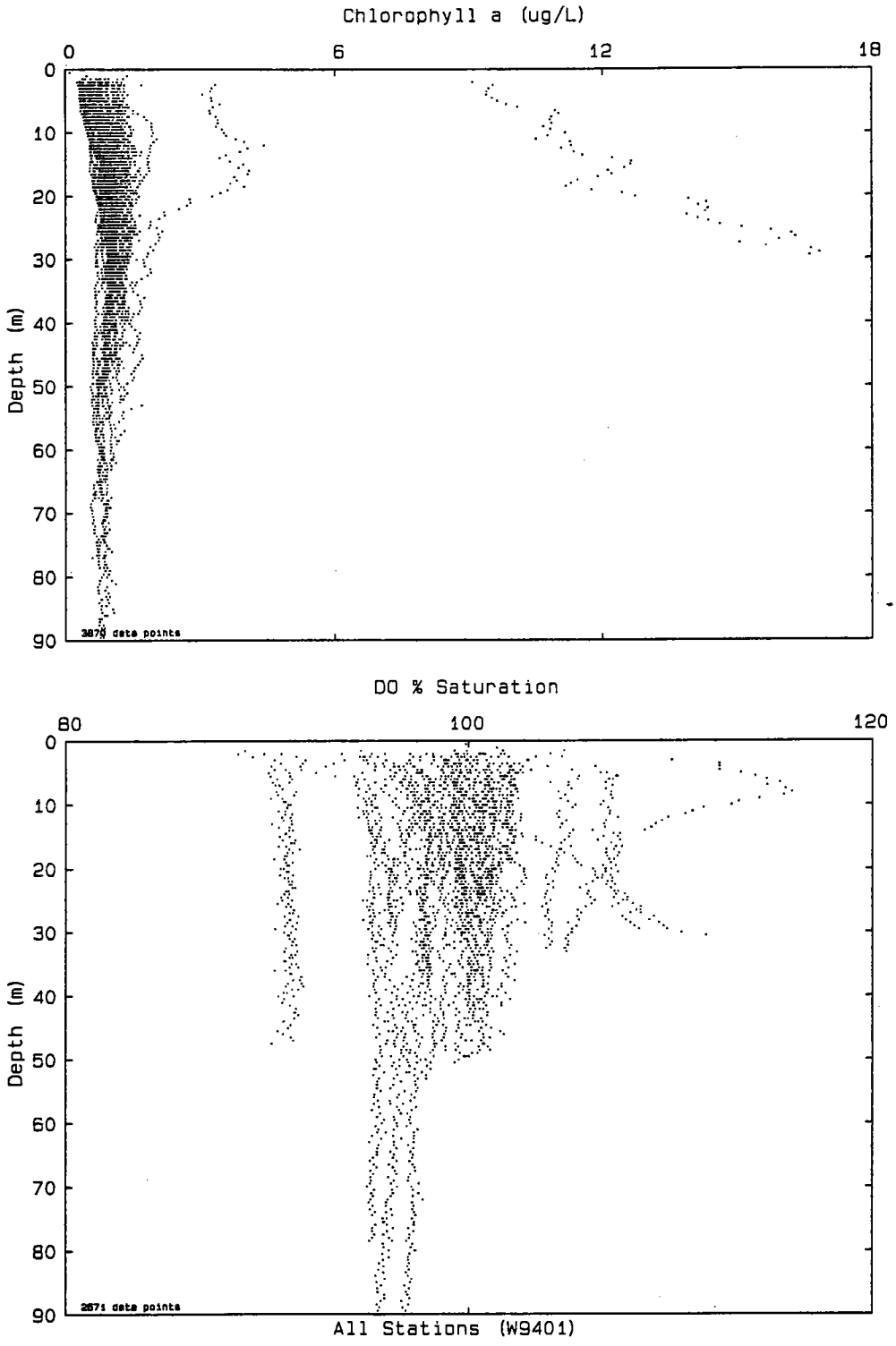


Figure 3-12b. Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in February 1994. Chlorophyll is estimated from *in situ* fluorescence.

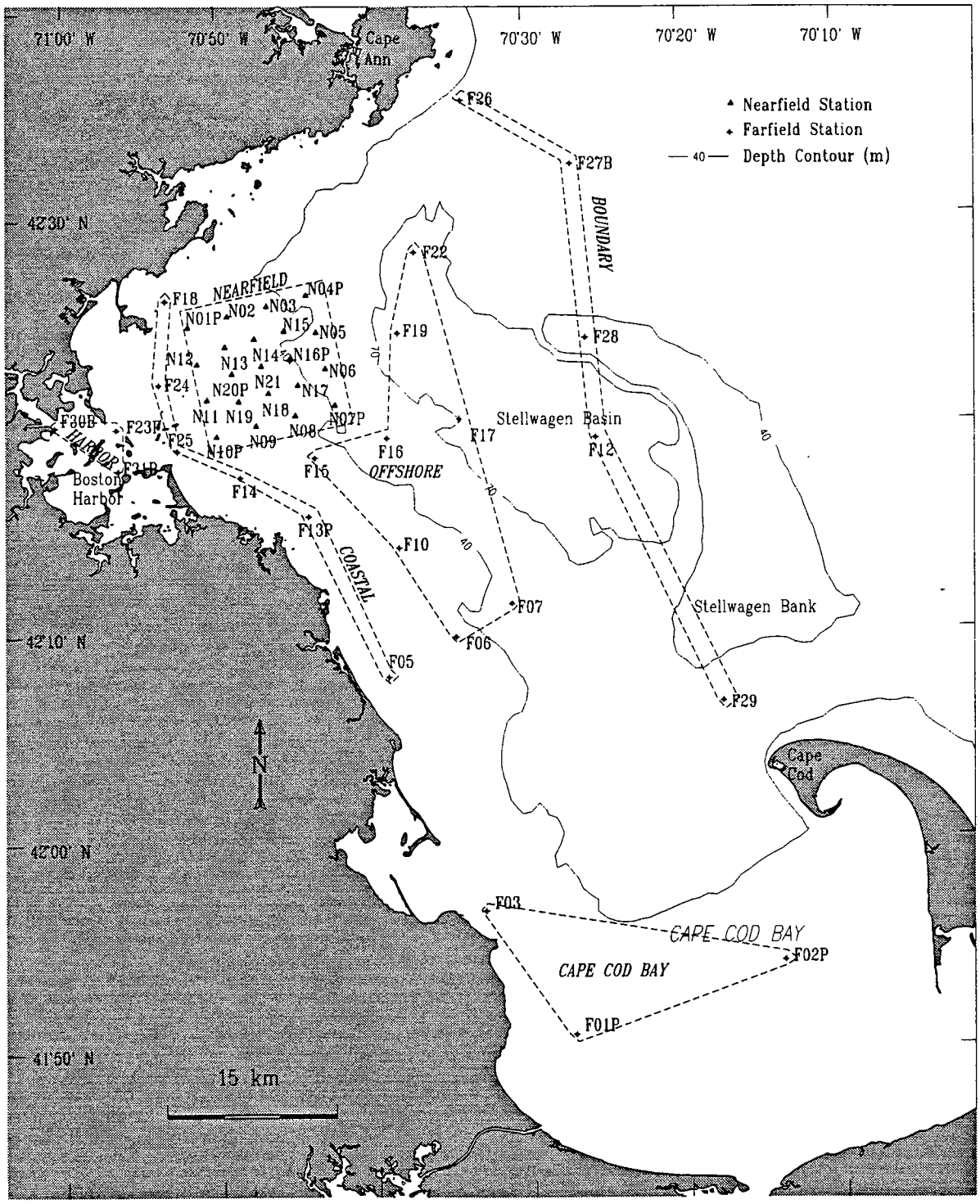


Figure 3-13. Map to show regional station groups designated in Figures 3-14 through 3-21.

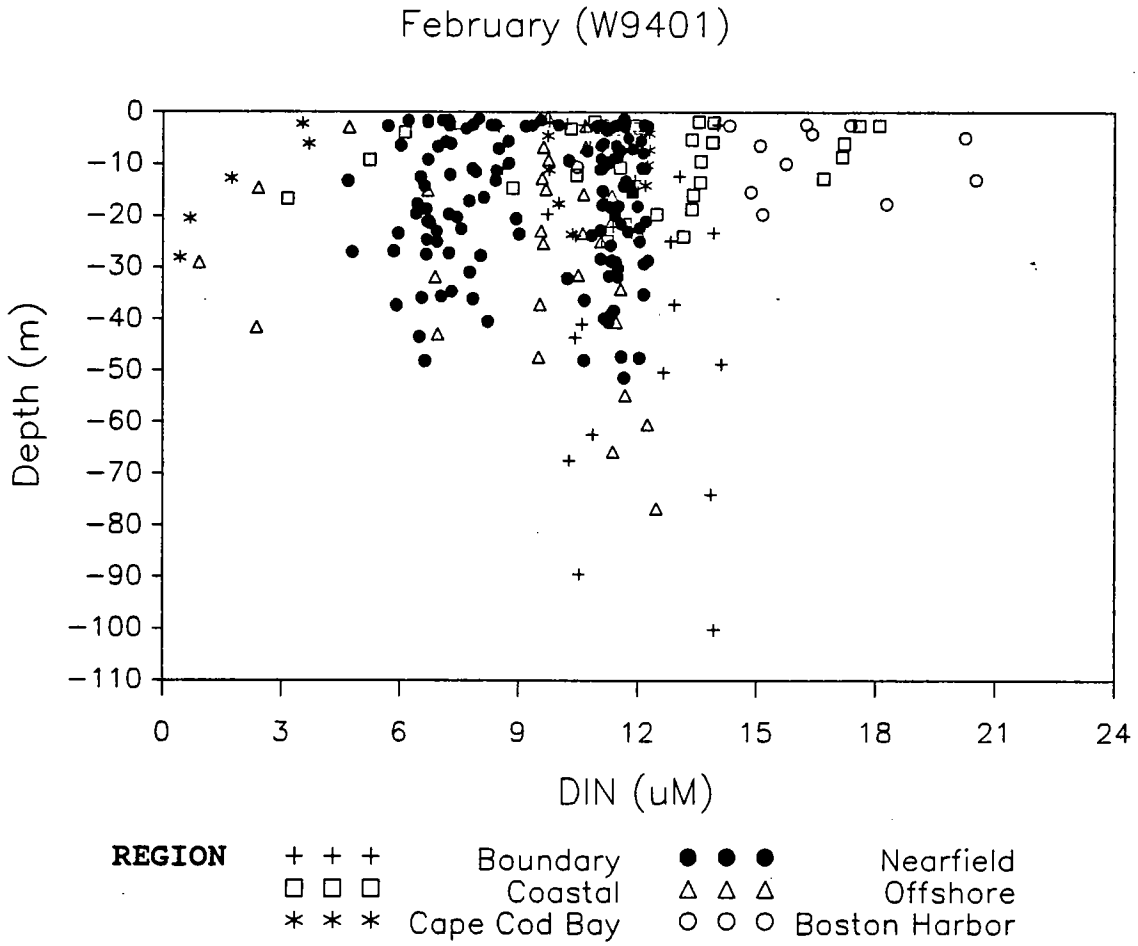
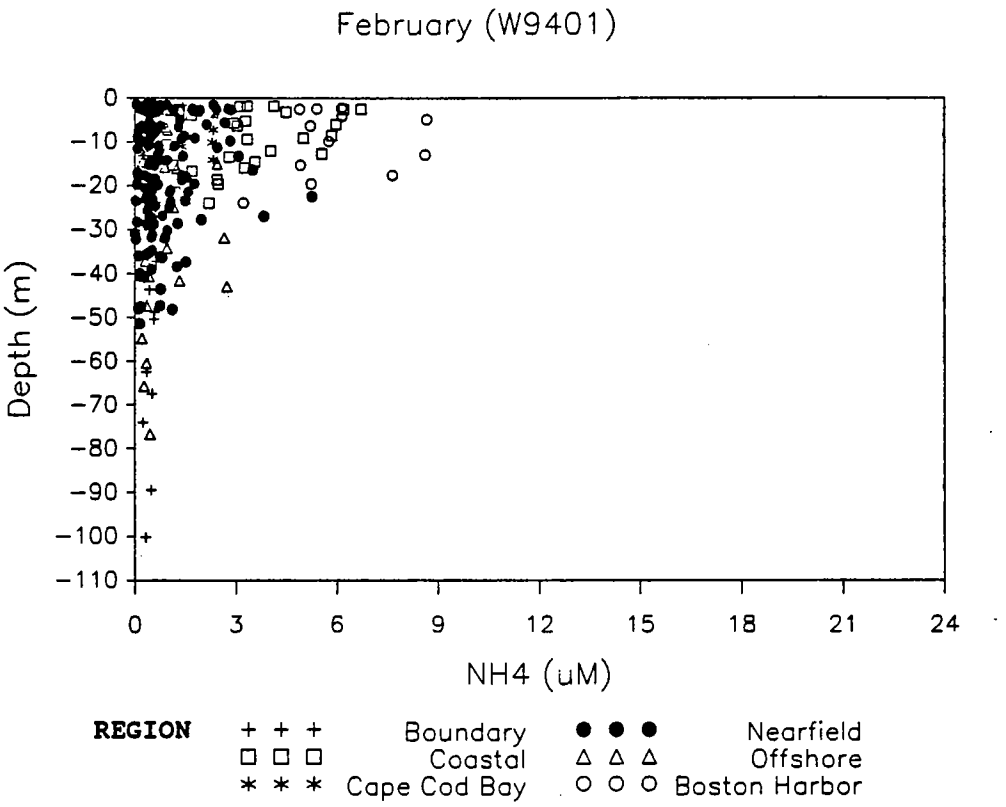


Figure 3-14a. DIN vs. depth in February 1994.



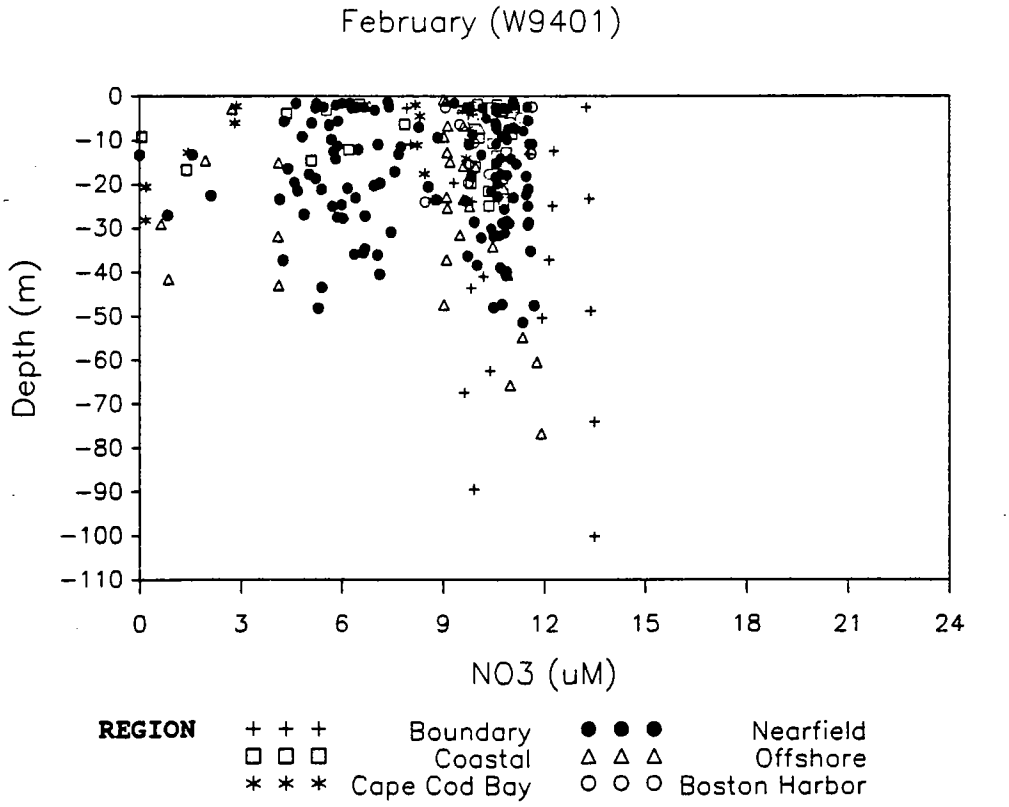
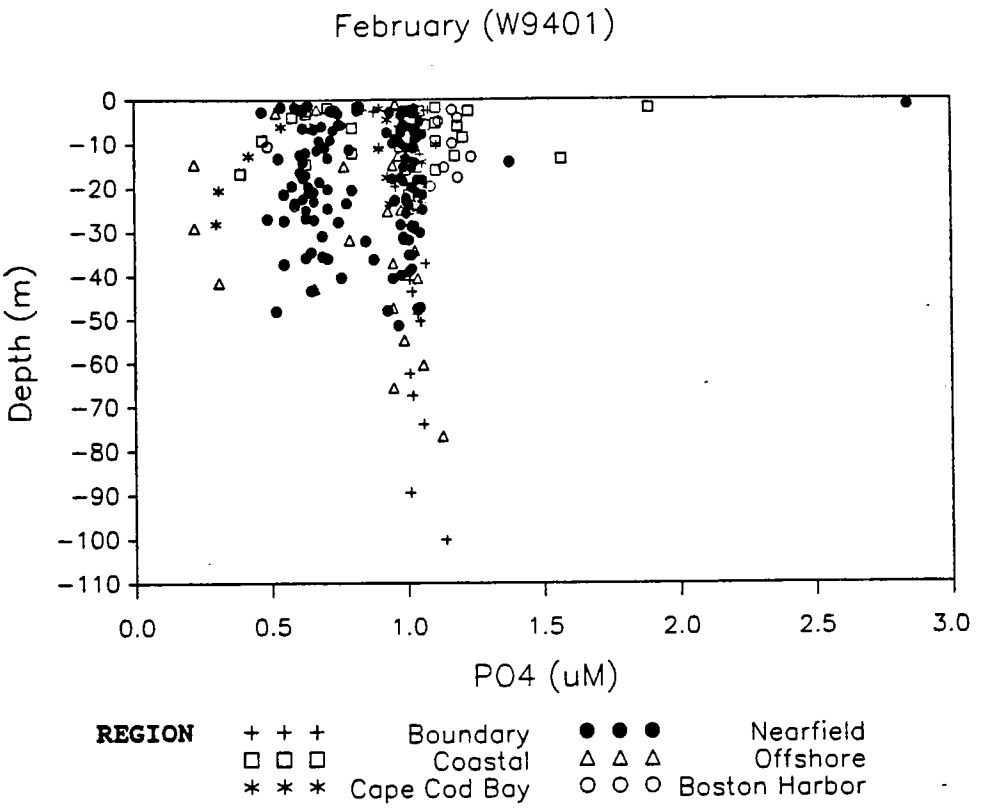


Figure 3-14b. NH_4 and NO_3 vs. depth in February 1994.



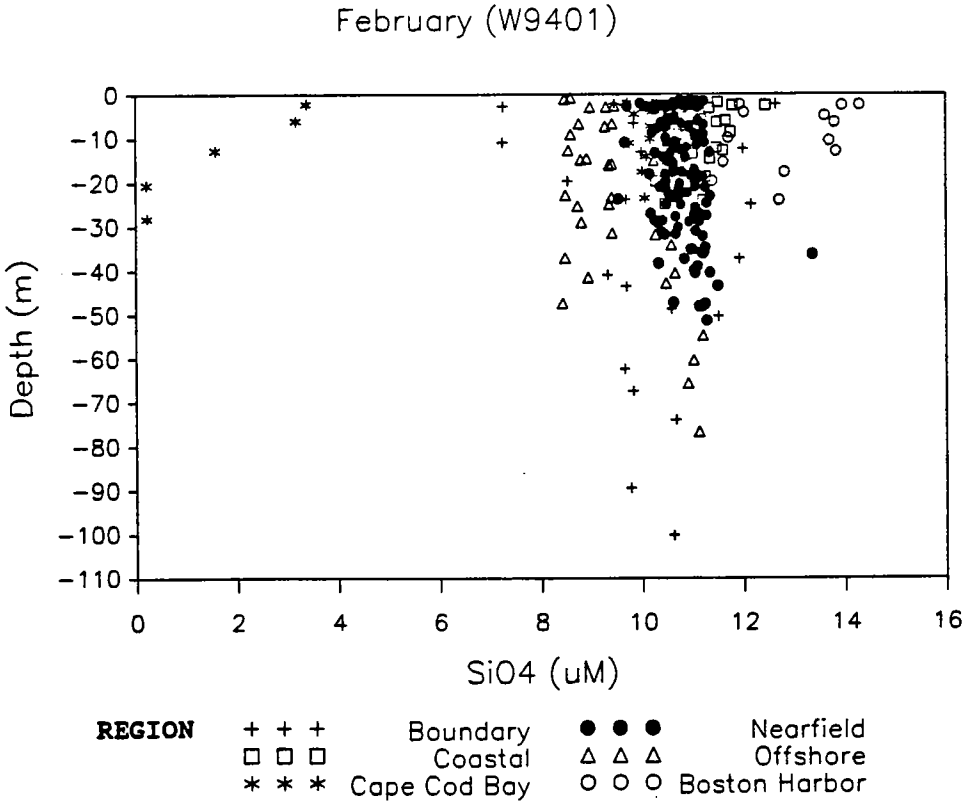
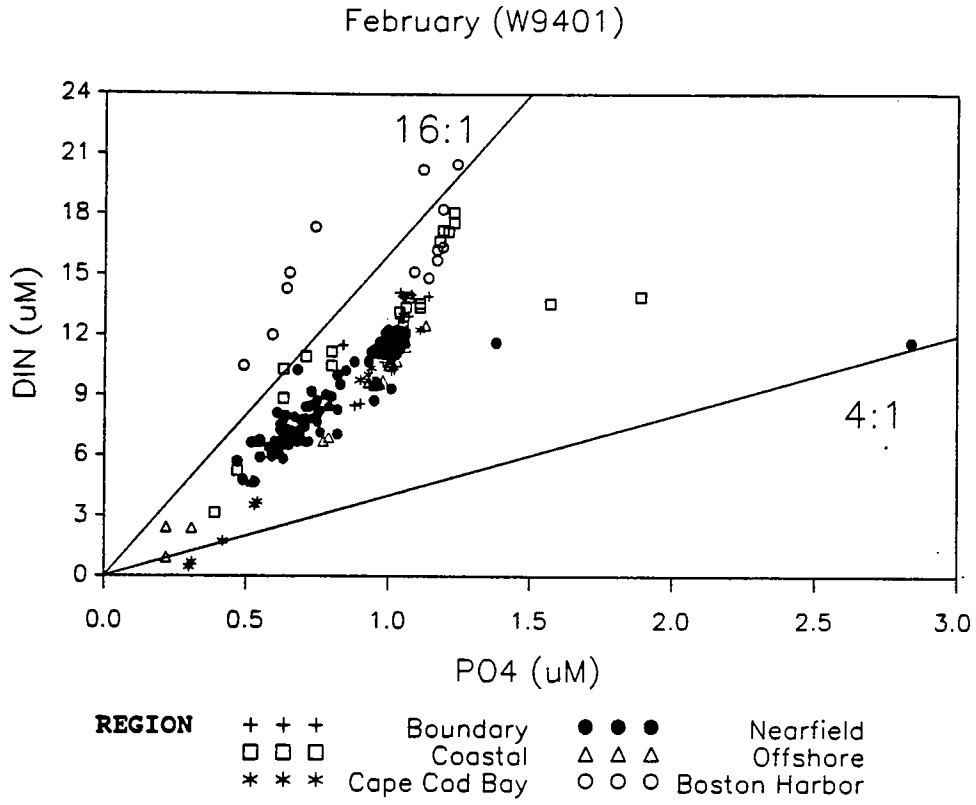


Figure 3-14c. PO_4 and SiO_4 vs. depth in February 1994.



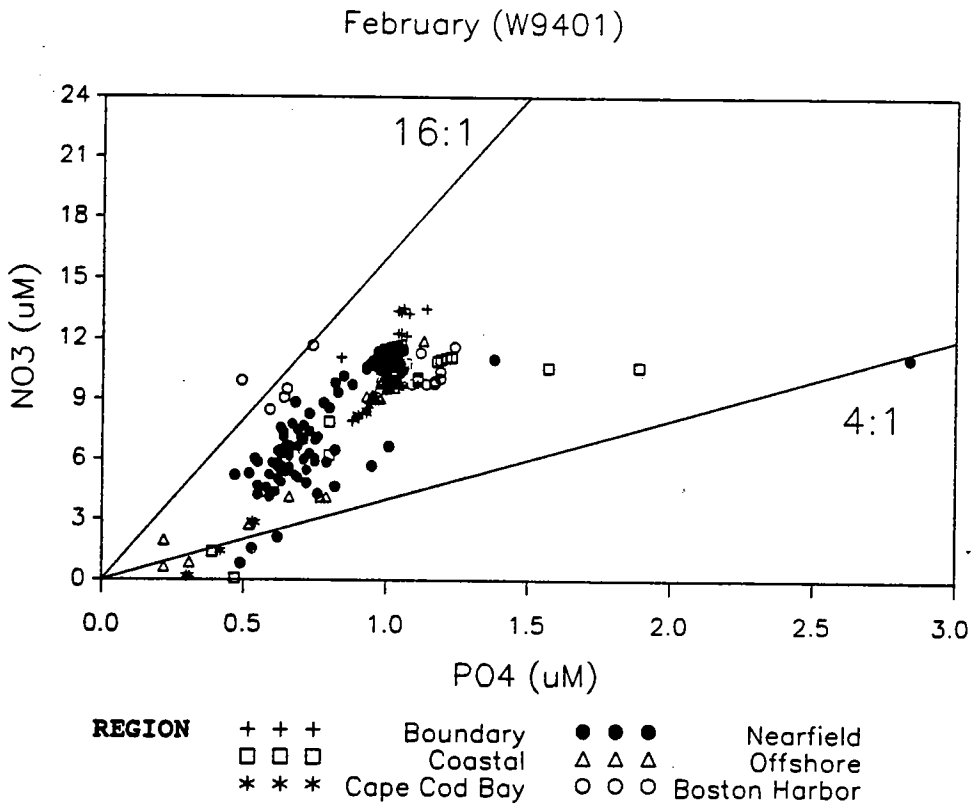
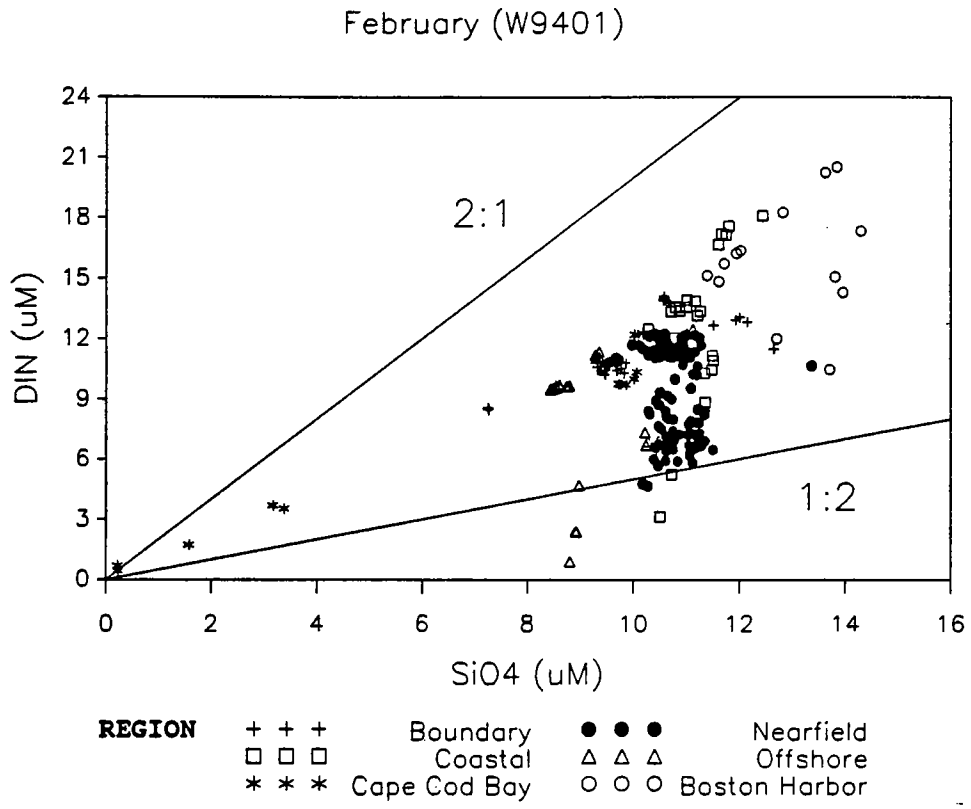


Figure 3-15a. Scatter plots of nitrogen forms vs. PO_4 in February 1994. Lines show constant proportions of nitrogen relative to phosphorus.



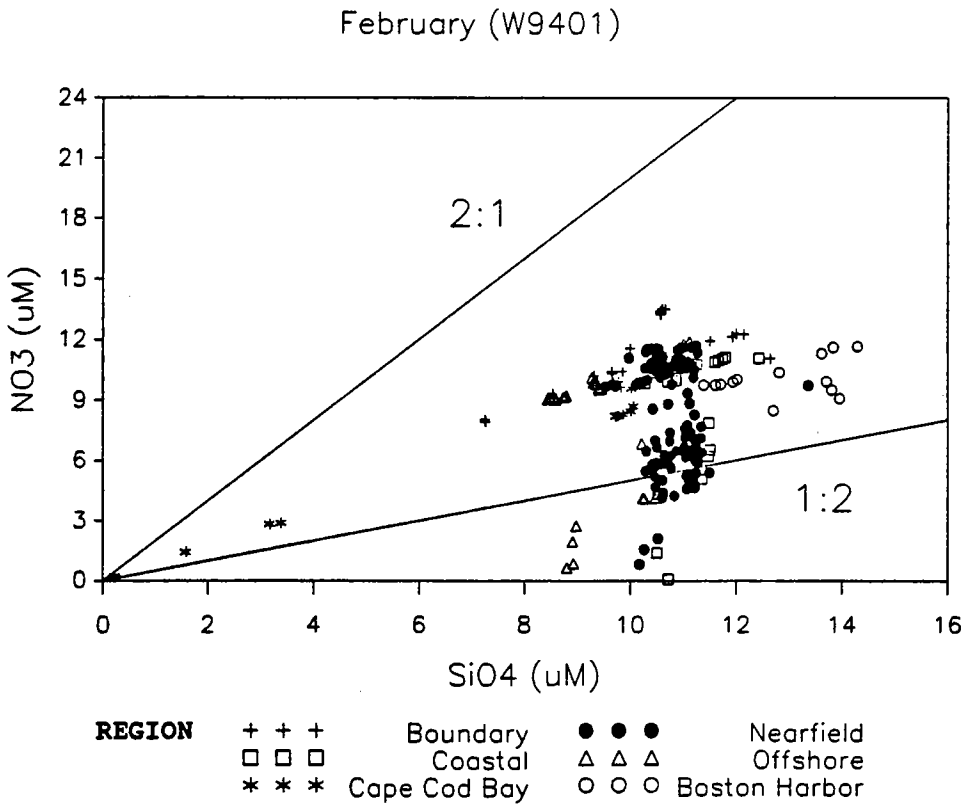


Figure 3-15b. Scatter plots of nitrogen forms vs. SiO_4 in February 1994. Lines show constant proportions of nitrogen relative to silicate.

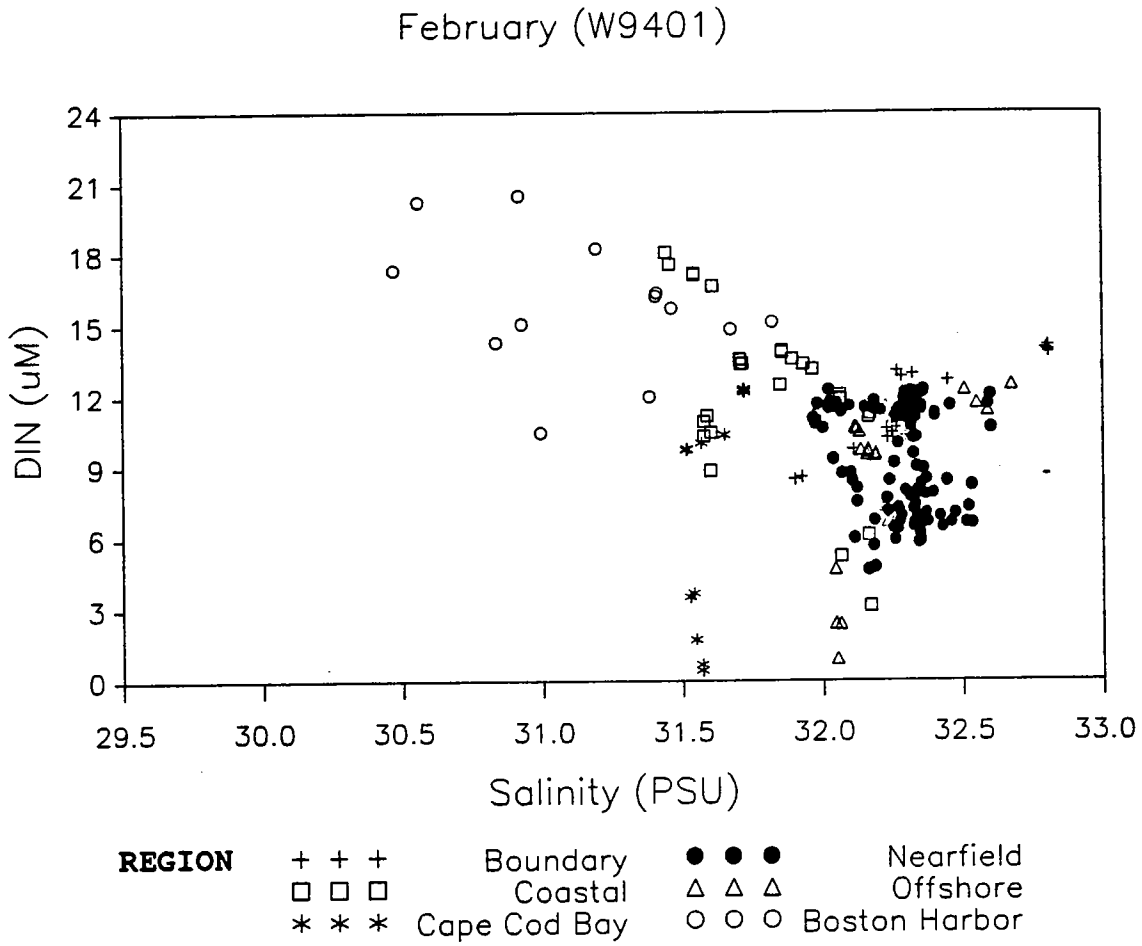
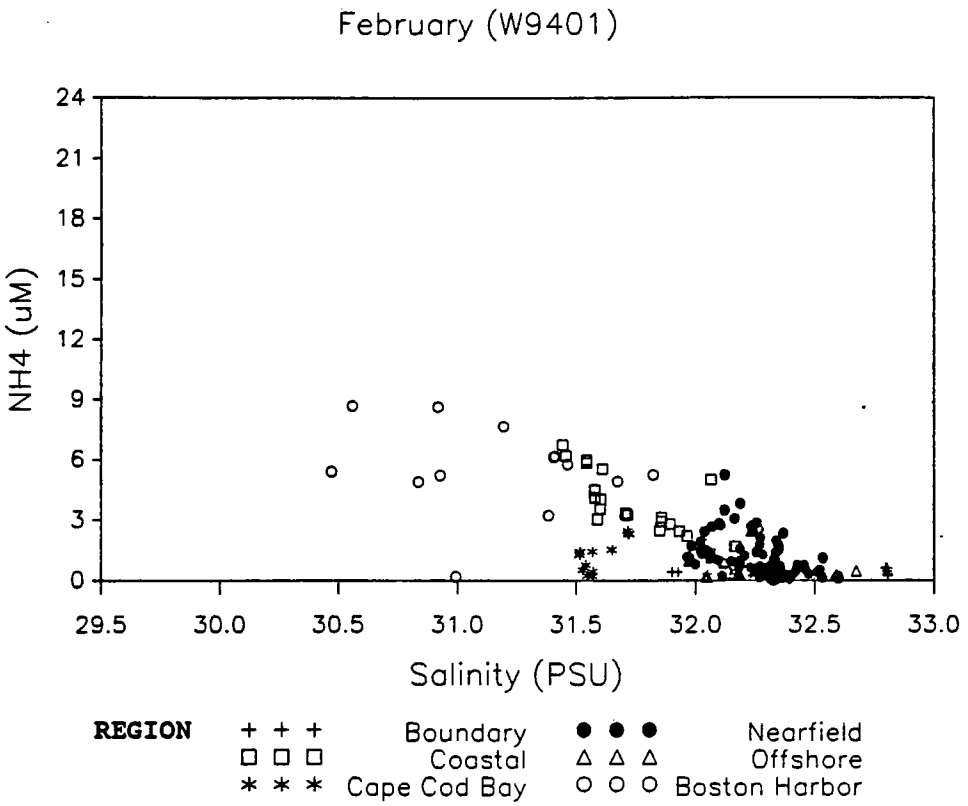


Figure 3-16a. DIN vs. salinity in February 1994.



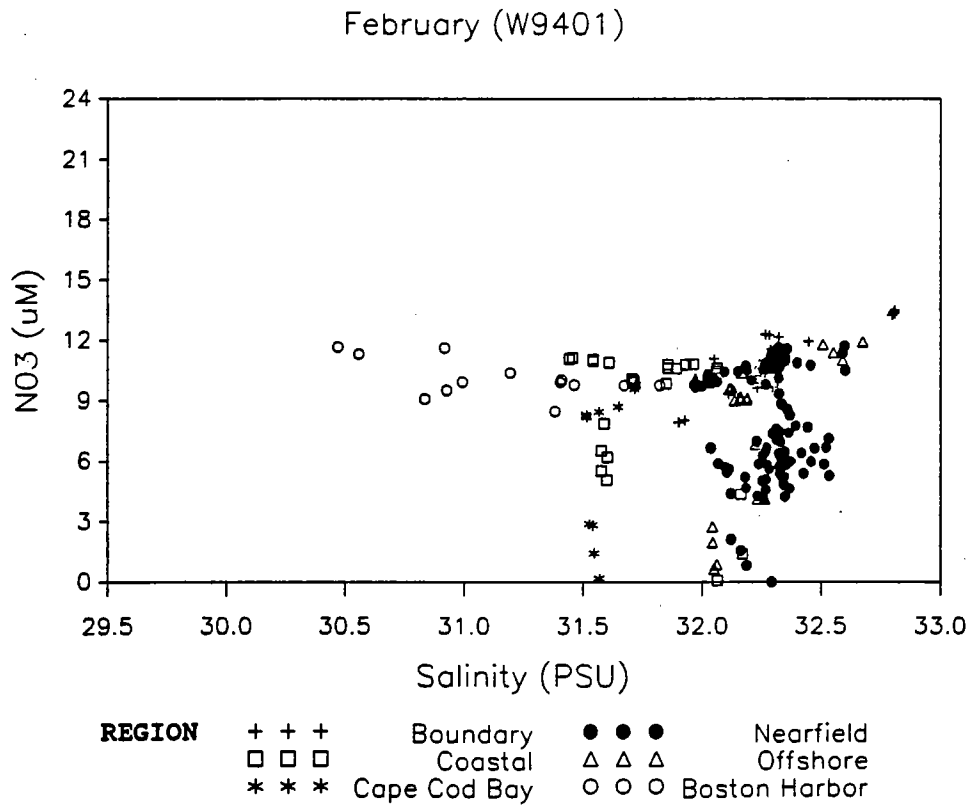
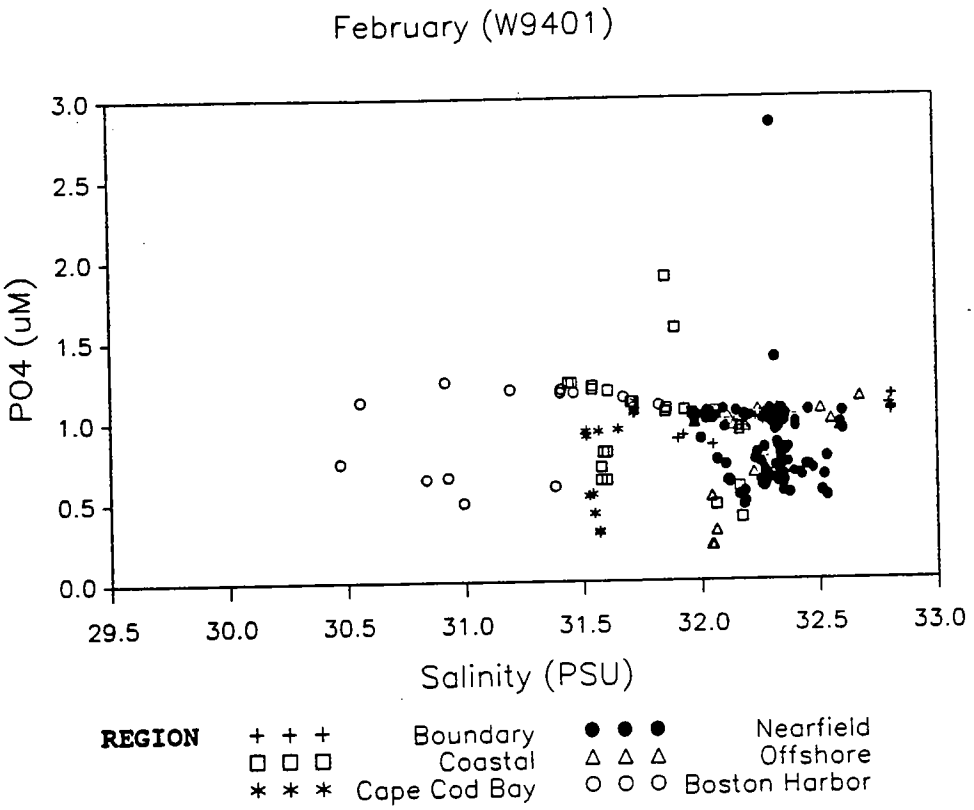


Figure 3-16b. NH_4 and NO_3 vs. salinity in February 1994.



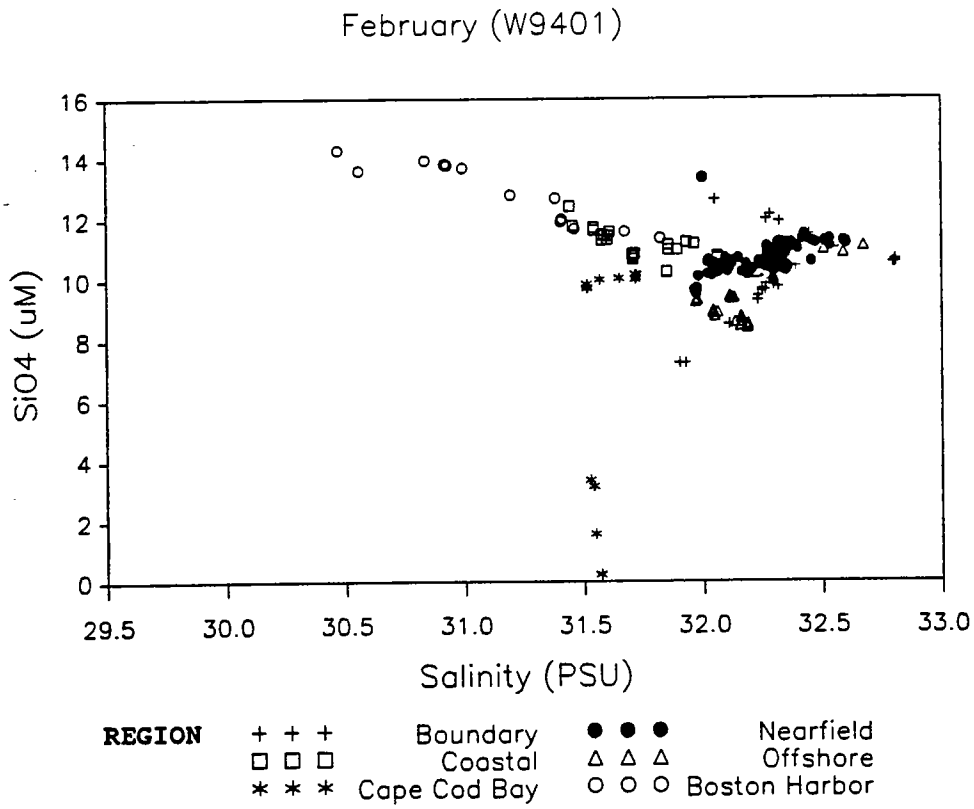
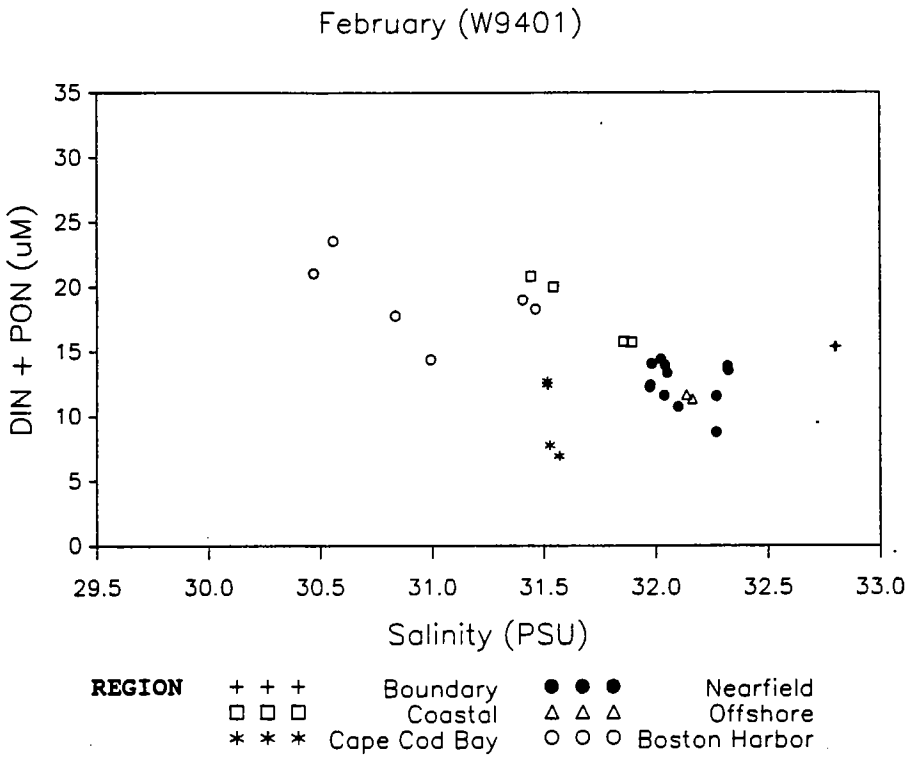


Figure 3-16c. PO_4 and SiO_4 vs. salinity in February 1994.



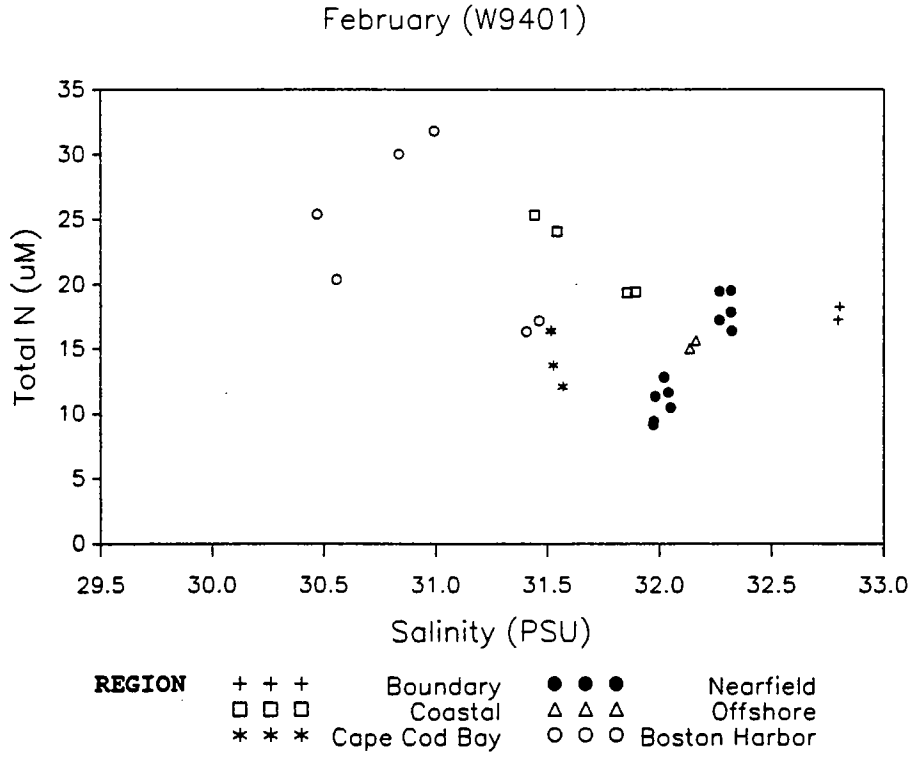


Figure 3-17. **Nitrogen forms vs. salinity in February 1994. Data are from B/P stations and special stations (Appendix A). Dissolved inorganic nitrogen = DIN, Particulate organic nitrogen = PON, Total nitrogen (TN) = Total dissolved nitrogen (TDN) + PON.**

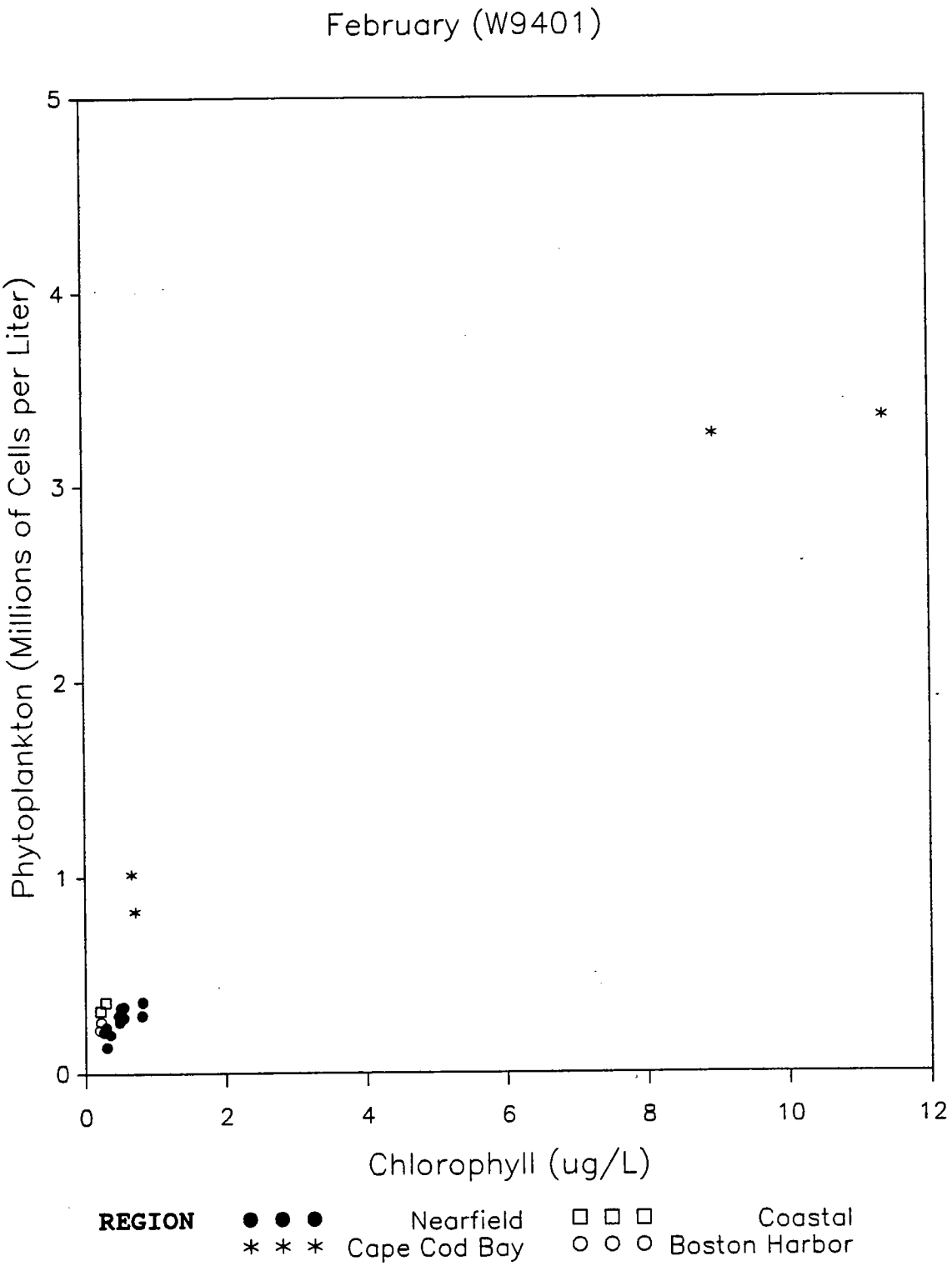


Figure 3-18. Total phytoplankton abundance vs. chlorophyll (extracted samples) at B/P stations in February 1994.

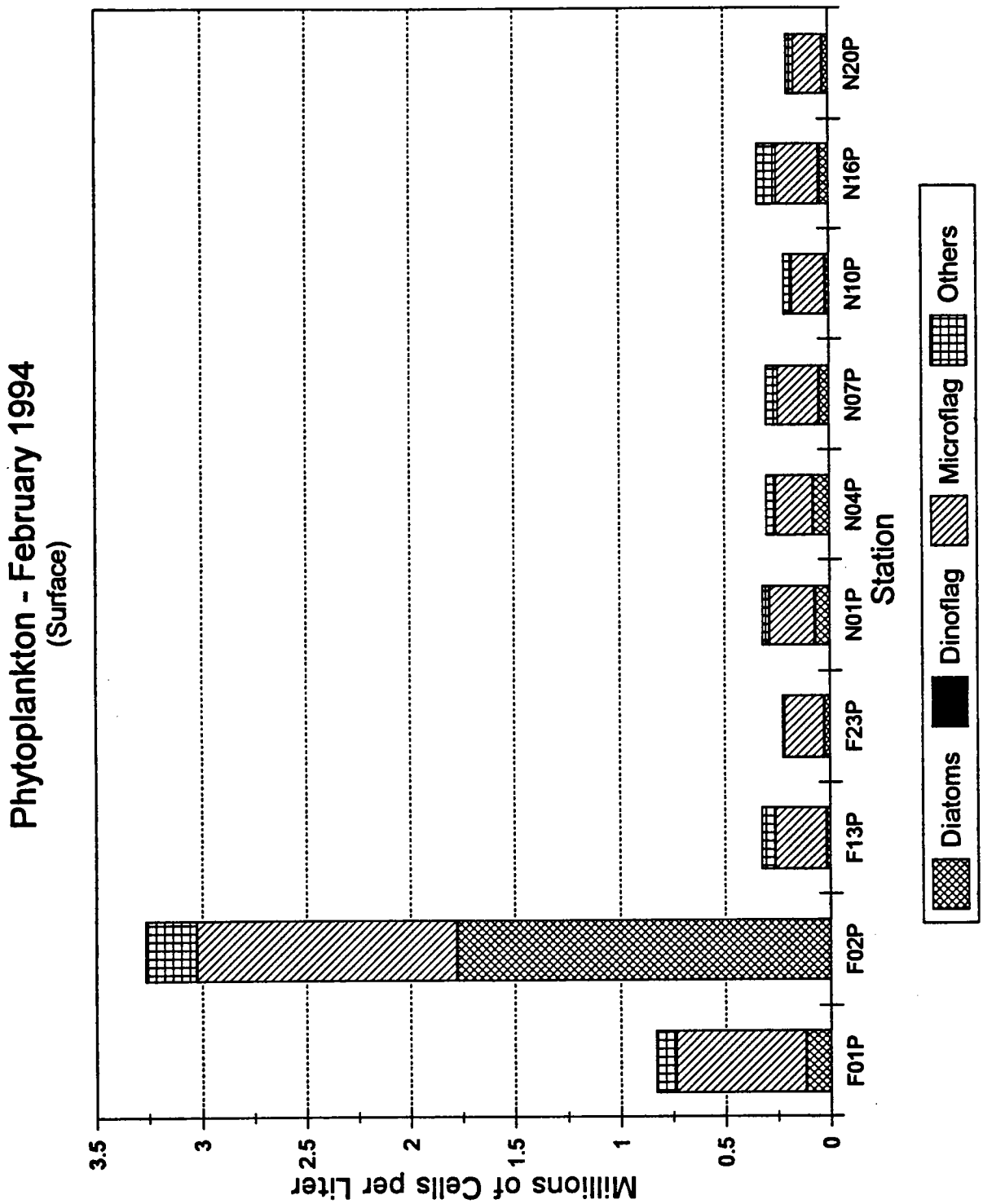


Figure 3-19. **Total phytoplankton abundance, by taxonomic group, near the surface of B/P stations in February 1994.**

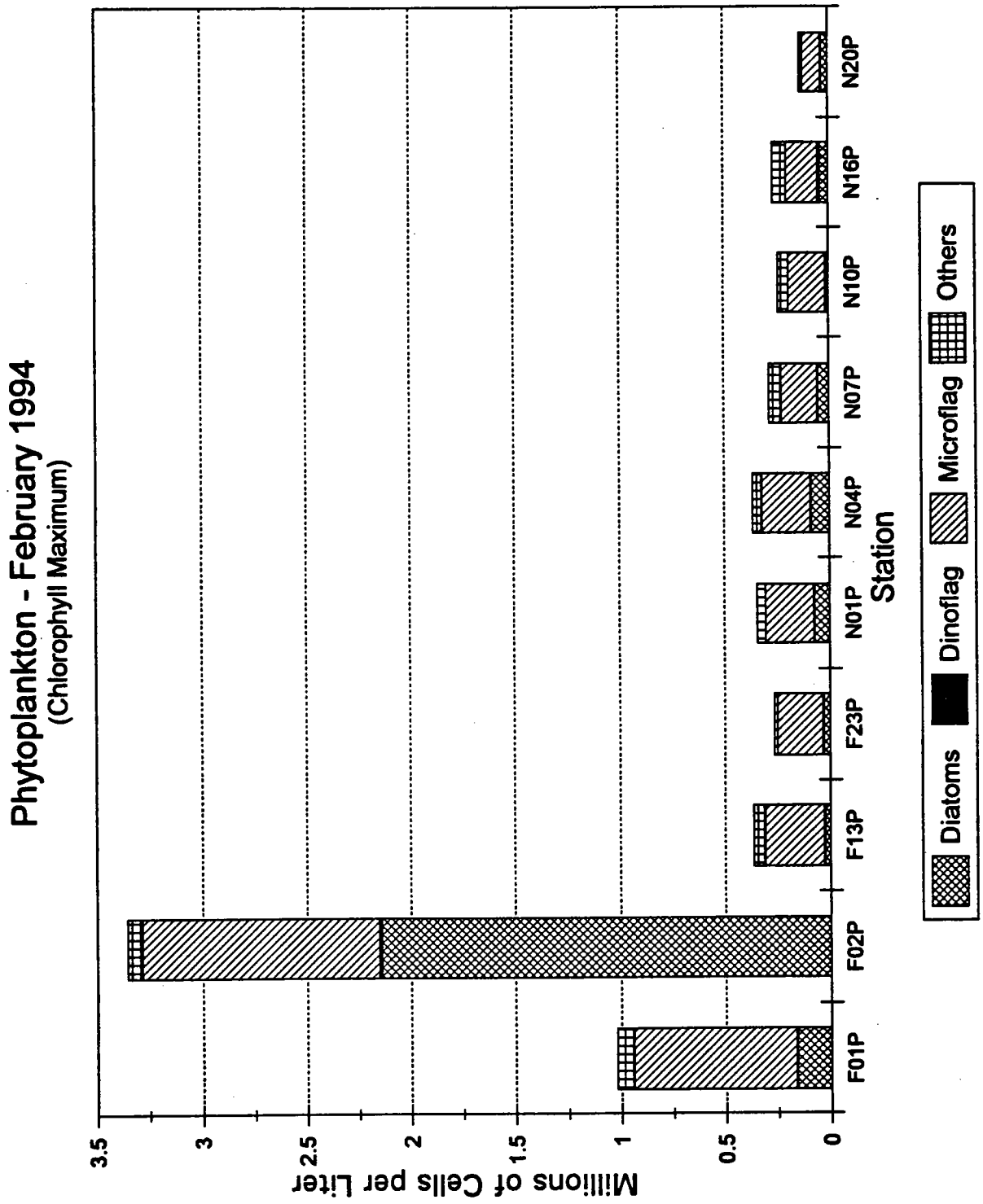


Figure 3-20. **Total phytoplankton abundance, by taxonomic group, near the chlorophyll maximum of B/P stations in February 1994.**

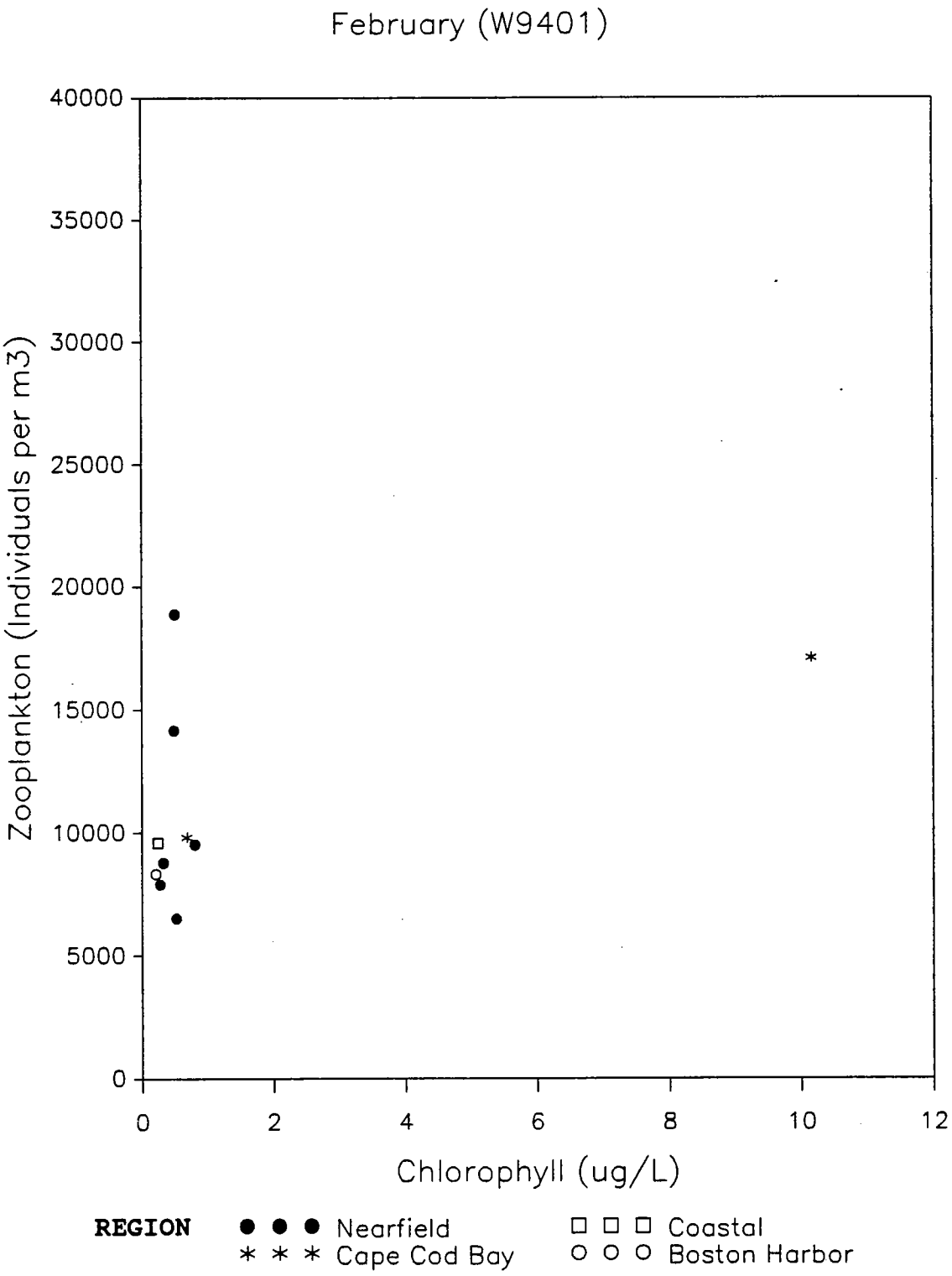


Figure 3-21. **Zooplankton abundance vs. average chlorophyll concentration (extracted samples; n=4 per station) for February 1994.**

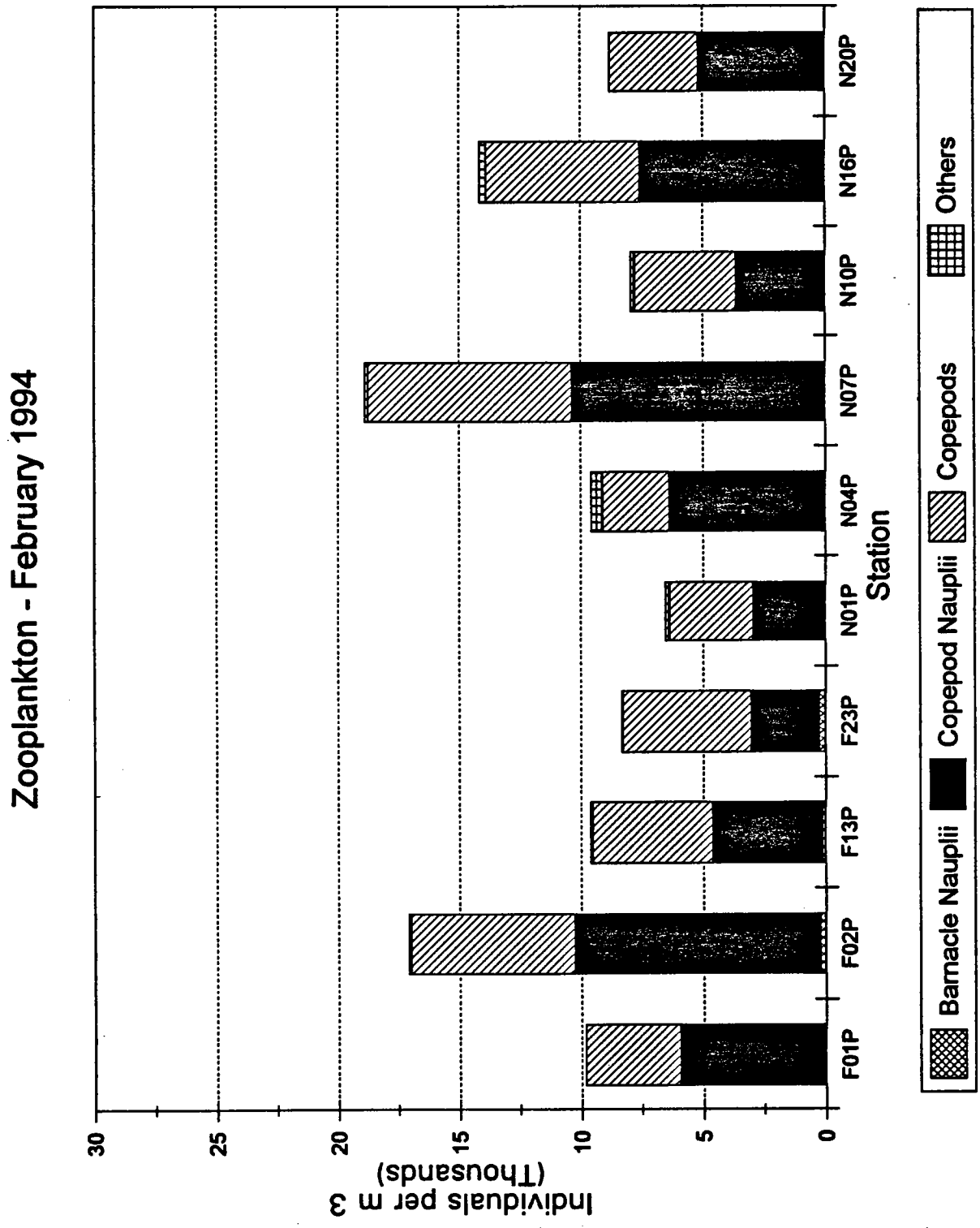


Figure 3-22. Zooplankton abundance, by groups, at B/P stations in February 1994.

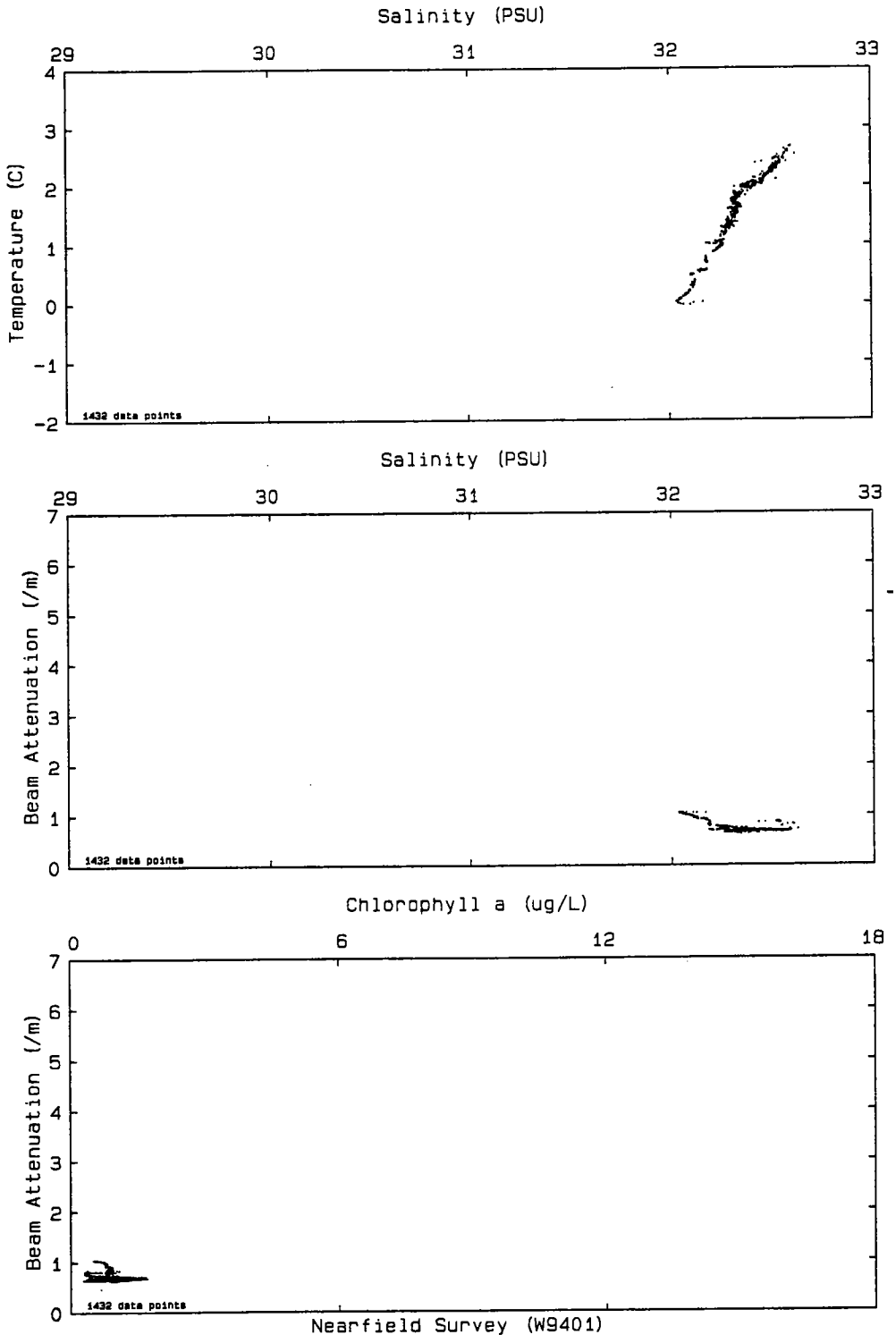


Figure 3-23a. **Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in February 1994. Chlorophyll is estimated from *in situ* fluorescence.**

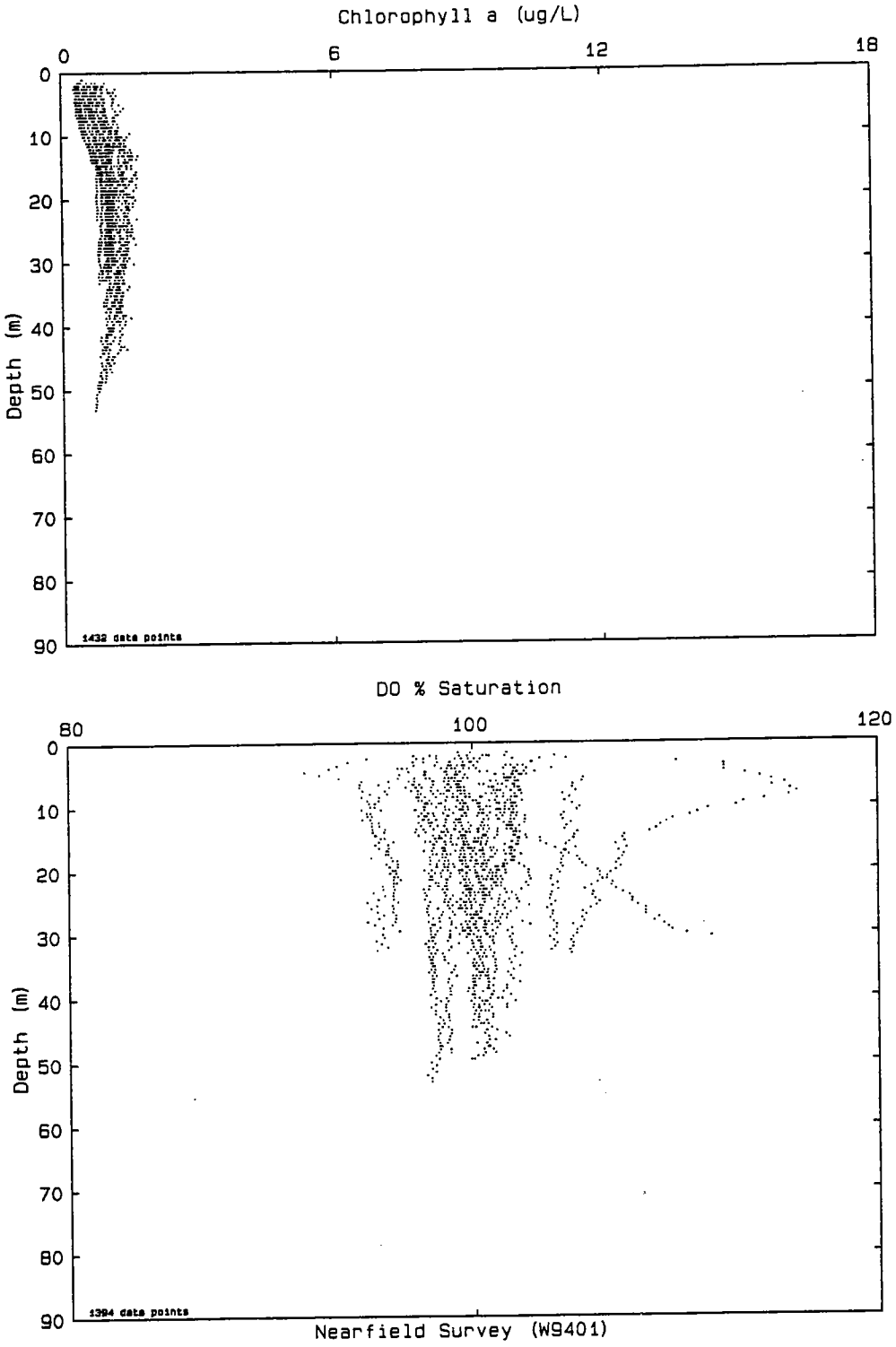


Figure 3-23b. **Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in February 1994. Chlorophyll is estimated from *in situ* fluorescence.**

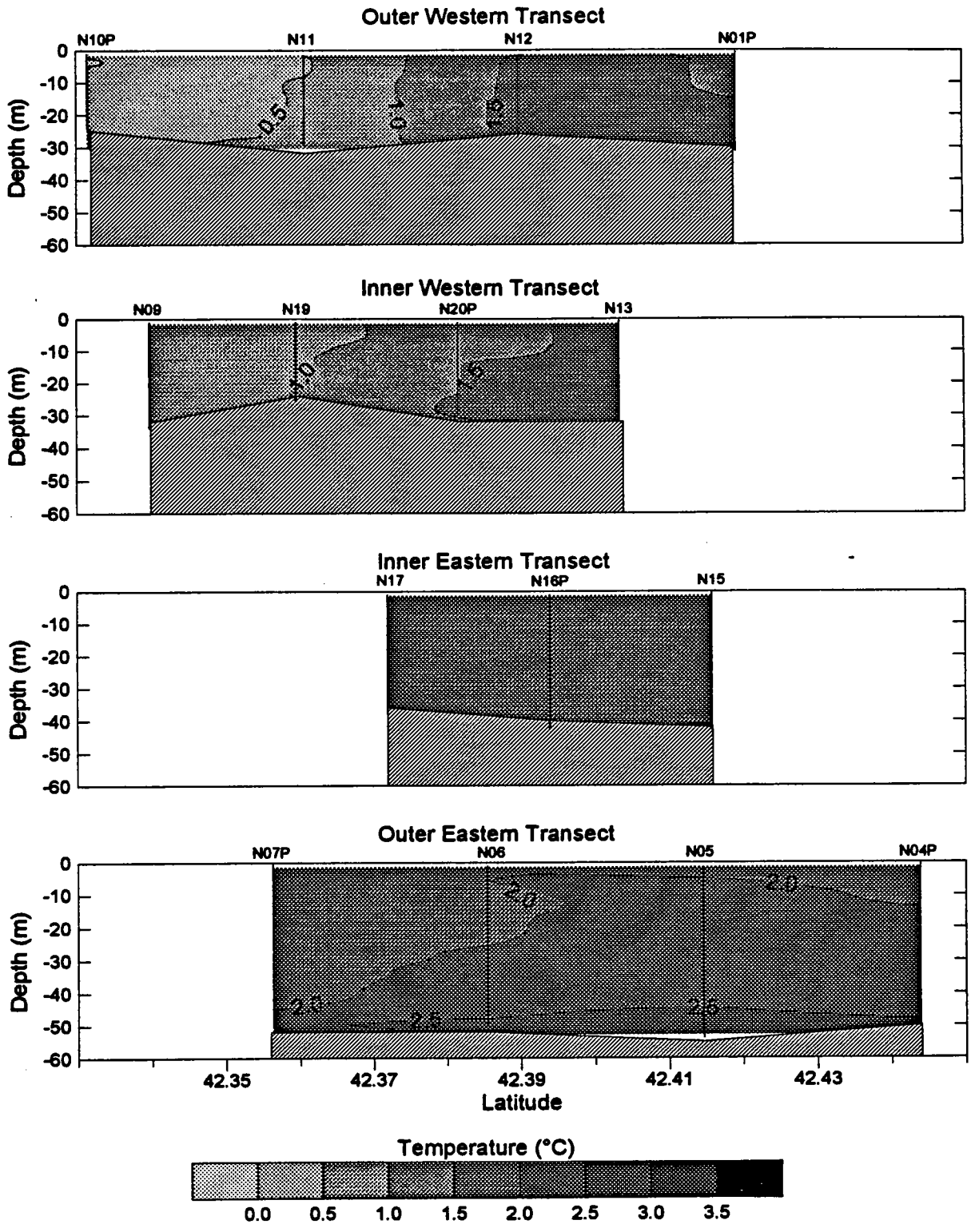


Figure 3-24a. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9401. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

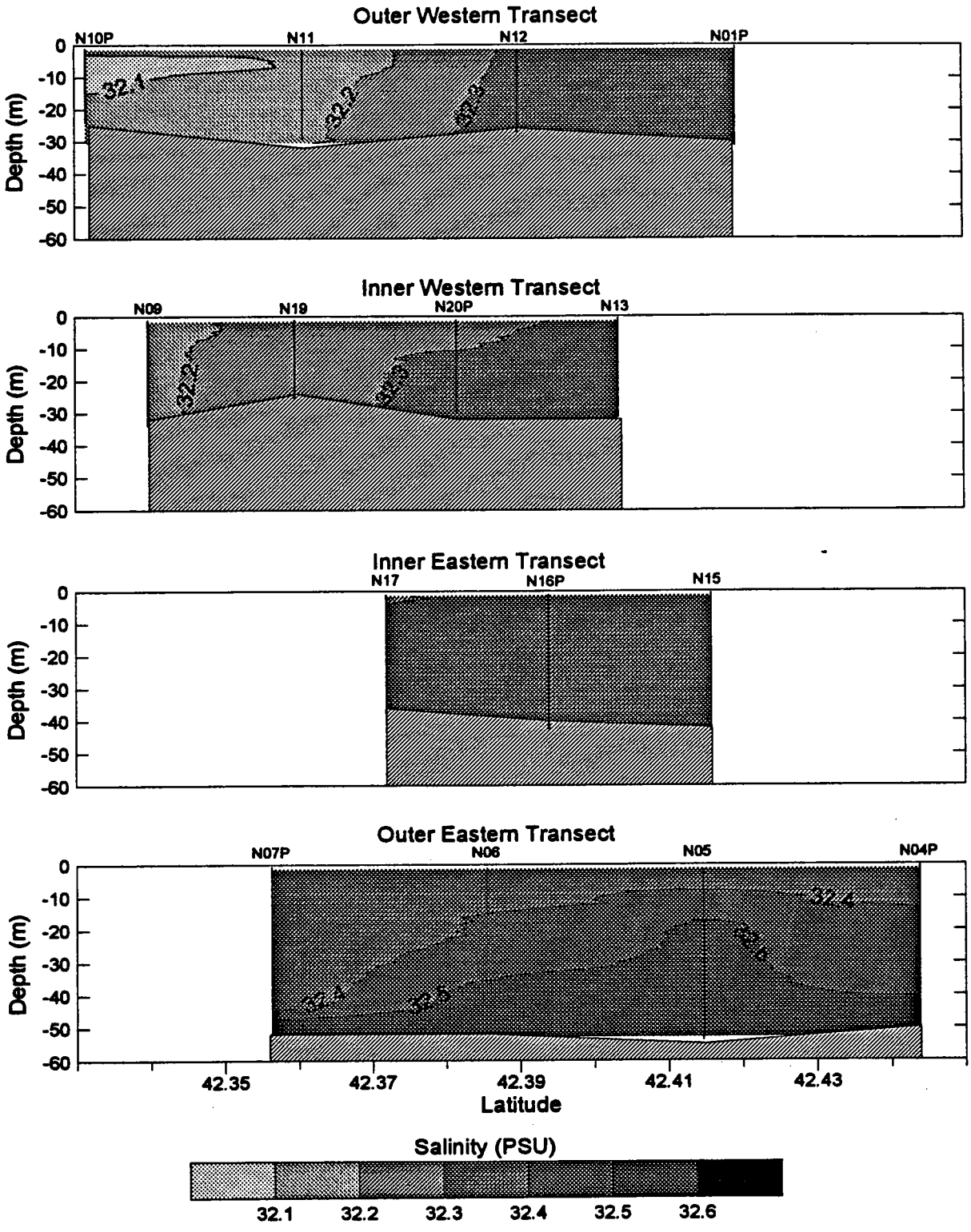


Figure 3-24b. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9401. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

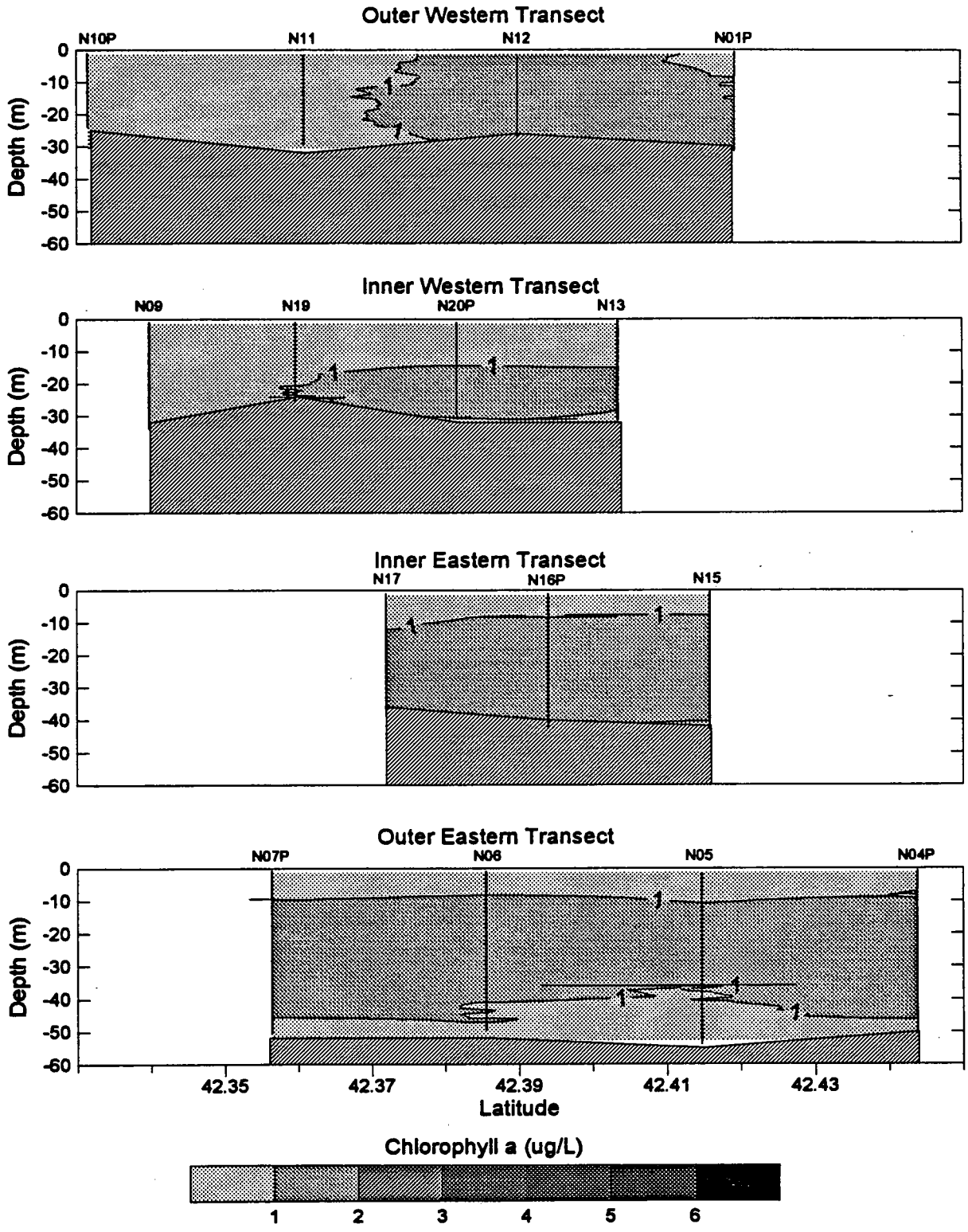


Figure 3-24c. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9401. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

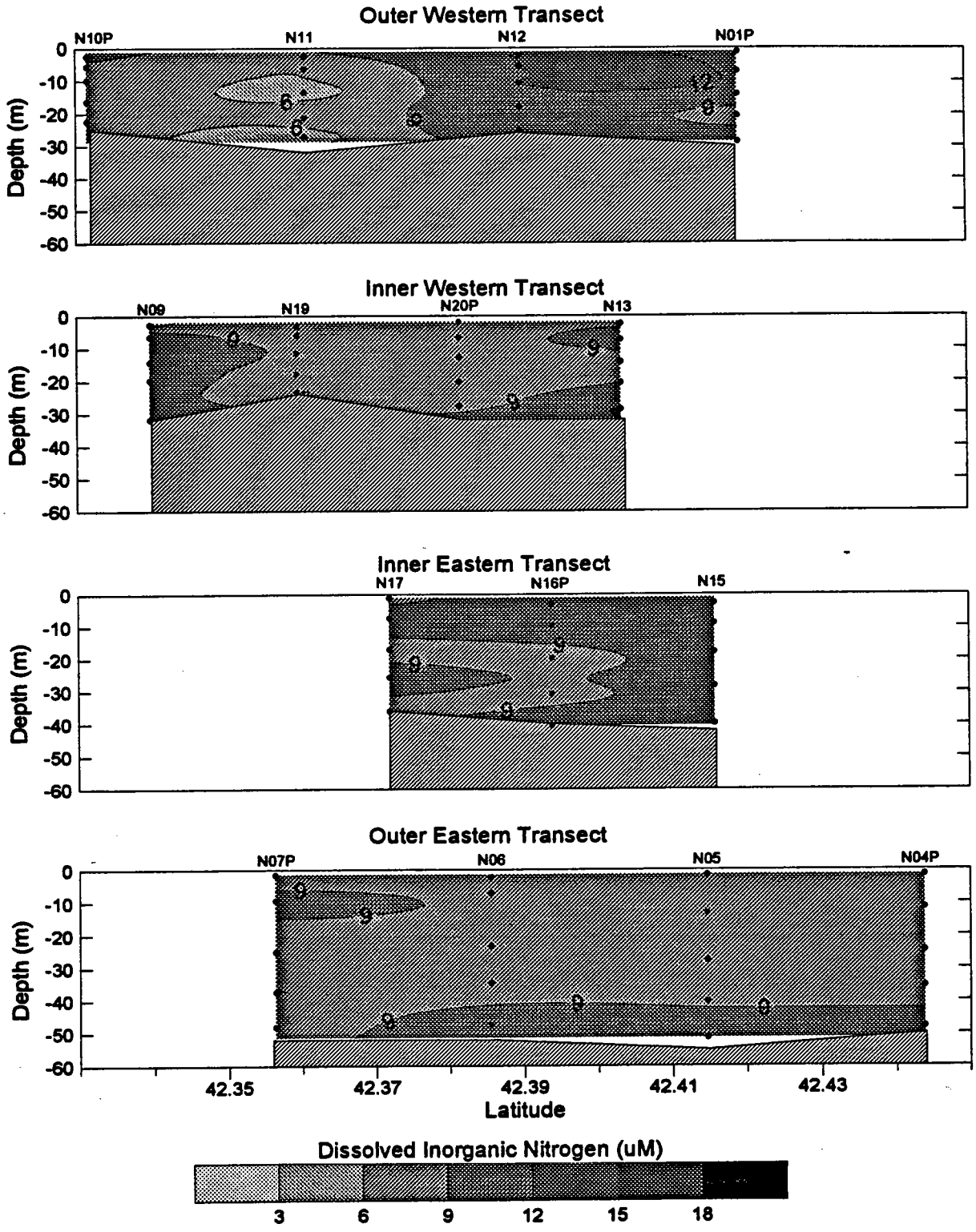


Figure 3-24d. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9401. The data used to produce the contours are from discrete bottle samples taken at each station during the nearfield sampling day (Appendix A).

4.0 RESULTS OF MARCH 1994 COMBINED FARFIELD/NEARFIELD SURVEY (W9402)

4.1 Farfield Survey

4.1.1 Horizontal Distribution of Surface Water Properties

Caveat. *As with the February survey, the March survey was interrupted by bad weather, but only for two days (West, 1994). We have produced surface contour plots using all stations (first occupation if a repeated station), but the resulting displays are non-synoptic. One should view patterns at a coarse level; some apparent fine-scale trends, such as those between individual stations, may be artifacts of the interrupted sampling.*

Surface water temperatures remained very cold in March 1994 (Figure 4-1). All stations in Cape Cod Bay were still $< 0°C$. Shallow inshore waters were generally very cold ($< 1.0°C$). Temperature gradually increased moving from shallow to deeper water, both eastward from Boston Harbor and northward from Cape Cod Bay to Massachusetts Bay. The warmest surface water ($> 2°C$) was found over Stellwagen Basin and Bank (stations F12 and F28).

Spatial patterns for salinity again broadly paralleled those for temperature (Figure 4-2) and the range in salinity was very small. Values in surface waters close to shore and within Cape Cod Bay were < 32 PSU, but the highest value was 32.8 PSU (station F12 over Stellwagen Basin). The lowest salinity (29.9 PSU) was found in Boston Harbor.

Beam attenuation was still high in and around Boston Harbor, southward along the coast, and in most of Cape Cod Bay (Figure 4-3). The highest beam attenuation reading was at station N10P, where tidal turbidity fronts have been detected (Kelly and Albro, 1994). Slightly higher turbidity was detected on the west side of Cape Cod Bay (station F01P), and the chlorophyll pattern indicated that, since February, the peak surface chlorophyll concentrations shifted from eastern to western Cape Cod Bay (Figure 4-4). Just

outside Cape Cod Bay north of Race Point (station F29), chlorophyll was still high. Generally, concentrations were near 1 $\mu g\ L^{-1}$, but at some stations in the nearfield and over Stellwagen Basin and Bank, chlorophyll concentrations were $>2\ \mu g\ L^{-1}$.

As shown in Figure 4-5, dissolved inorganic nitrogen (DIN) concentrations were nearly depleted in the heart of Cape Cod Bay (0.28 and 1.12 μM at stations F01P and F02P, respectively). Concentrations generally increased to 7-10 μM northward through much of Massachusetts Bay. DIN concentrations along the outer Bay boundary decreased from Stellwagen Bank to Cape Ann (3.9 μM). The low DIN detected in February around station F15 to F17 was still present and concentrations were even lower in March. Harbor, Harbor-edge, and tidally influenced stations (e.g., N10P) were all higher than 11 μM in DIN, and thus enriched relative to Massachusetts Bay. Most of the DIN was in the form of nitrate (NO_3) which, therefore, displayed a regional pattern similar to DIN (Figure 4-6). The enrichment near Boston Harbor, however, was mostly due to ammonium (NH_4).

Phosphate (PO_4) concentrations were low in Cape Cod Bay, but were nearly as low elsewhere in central Massachusetts Bay and near Cape Ann (Figure 4-7). Throughout most of the Bays, however, concentrations were about 0.6-0.8 μM and Boston Harbor concentrations (about 0.6 to 1 μM) were not distinctly enriched. Silicate (SiO_4) concentrations still showed a latitudinal surface water gradient that decreased from north to south through the Bays (Figure 4-8). SiO_4 was depleted in eastern Cape Cod Bay ($< 1\ \mu M$). Boston Harbor and the near-coastal area south to Cape Cod Bay was higher in SiO_4 ($>$ 8-9 μM) than the offshore waters throughout Massachusetts Bay, including the boundary stations off Cape Ann.

4.1.2 Water Properties Along Selected Vertical Sections

The Nahant Transect, Boston-Nearfield Transect, Boston-Cohasset Transect, and Marshfield Transect all run from nearshore to deep water in Stellwagen Basin and form a roughly parallel series from north to south across Massachusetts Bay (Figure 4-9). First, sections for temperature, salinity, chlorophyll, and DIN are described for this series of transects. The same parameters are then presented for the fifth

section, the Cape Ann-Stellwagen Transect, which crosses near the boundary between northern Massachusetts Bay and the Gulf of Maine (Figure 4-9).

A gradual horizontal banding from shore to sea that was evident in February persisted in early March. This banding was about equally pronounced in temperature (T) and salinity (S) (Figures 4-10a and b). Striking horizontal gradients with a slight vertical stratification were evident along the two transects starting within Boston Harbor, but little vertical gradation was evident in the Bay until deep water was encountered. Except for a few locations of very weak vertical density stratification, the water column was uniformly well mixed from top to bottom (see vertical profiles in Appendix B).

Chlorophyll concentrations were generally higher offshore (Figure 4-10c) and Boston Harbor concentrations were lower than in adjacent coastal waters. In the Bay, chlorophyll concentrations were often highest (4-5 $\mu g\ L^{-1}$) slightly below the surface, but were fairly uniform over depth at many stations. The northern three transects, excluding stations inside Boston Harbor, had similar patterns and concentration ranges. The Marshfield Transect, the southernmost of the four, had the lowest average chlorophyll concentrations.

DIN concentrations were generally higher inshore, but gradients were pronounced only around Boston Harbor (Figure 4-10d). In the nearfield and offshore, DIN concentrations often increased with increasing depth.

Along the Boundary Transect, temperature was notably cooler inshore at Cape Ann (Figure 4-11). At both the Cape Ann and Stellwagen Bank stations (F26 and F28), T-S profiles indicated well-mixed conditions. Mild stratification was apparent in the Basins. Vertical distribution of chlorophyll was fairly similar across the transect, but was slightly higher ($>4\ \mu g\ L^{-1}$) to the north. DIN concentrations were highest in deep waters of the Basins inside and outside of the Bay and, where chlorophyll was highest, DIN concentrations sometimes fell below 6 μM.

4.1.3 Analysis of Water Quality Characteristics Throughout the Bays

Scatter plots using all *in-situ* sensor data from vertical profiles are shown in Figures 4-12a and 4-12b. Individual station profiles are provided in Appendix C. Appendix C also includes separate scatter plots for groups of stations clustered by region (see Figure 4-13).

Inspection of the temperature-salinity plots (Appendix C) revealed that some regions were distinct and others were similar. For example, a tight string of points with salinity >32 PSU defined overlapping data ranges from nearfield, offshore, boundary and, to some degree, coastal stations (Figure 4-12a). Harbor stations and near-Harbor coastal stations were distinguished by lower salinity and were spread across a T range from about 0-1°C. Cape Cod Bay points were distinct for low temperatures (<0°C). Inspection of the data in Appendix B showed minor T-S differences between repeated visits to station F23P, but the differences were not as extreme as in February. Between February and March, water temperatures in the nearfield, offshore, and boundary stations generally cooled, and slightly higher salinities were recorded at deep-water locations along the boundary in March.

Beam attenuation in Harbor water showed large variations which caused the scatter at salinity below 32 PSU (Figure 4-12a). Large temporal variability in turbidity was observed on the repeated visits to station F23P (Appendix B). Boundary conditions were uniformly low in beam attenuation and Cape Cod Bay conditions were distinct for intermediate turbidity at intermediate salinity. Waters of coastal, nearfield, and offshore stations, which crossed a gradient from lower to higher salinity and chlorophyll, were generally defined by a linear decrease in turbidity with salinity and chlorophyll. Harbor water showed a distinct sharp increase in beam attenuation over a narrow increase in chlorophyll. Cape Cod Bay was distinct for high chlorophyll at intermediate salinity; in fact, virtually every point above 6 $\mu g\ L^{-1}$ in Figure 4-12b is from Cape Cod Bay.

Figure 4-12b shows that the highest chlorophyll concentrations were generally found at shallow depth below the surface; generally, subsurface peaks were evident at about 5 to 20 m. Following Cape Cod Bay, ranked in order of decreasing maximum chlorophyll concentrations, were the boundary and offshore

stations, with chlorophyll concentrations ranging between 4 and 6 $\mu g\ L^{-1}$, and then the nearfield and inshore waters.

The parameter scatter plots provide a good initial description of parameter ranges and provide perspective on broad regional variation between surveys. But inspection of the "data space" of each region also provided distinct diagnostics for certain regions (e.g., Boston Harbor, Cape Cod Bay, boundary stations). For other regions, further inspection indicated that they (particularly the nearfield and offshore, and some coastal waters) represented a continuum of conditions probably resulting from active mixing of regional waters having only minor water quality differences.

Regional differences in nutrients were also apparent, as can be seen in plots of DIN concentrations over depth (Figure 4-14a). High concentrations of DIN ($>12\ \mu M$) characterized the Harbor stations. DIN concentrations in coastal waters near the Harbor were generally in the range of 9-12 μM, or similar to the concentrations at some nearfield stations. However, the DIN concentration at most nearfield stations was 6-9 μM, a range that overlapped with the range for offshore and boundary stations (which extended to <3 μM). DIN concentrations of most Cape Cod Bay samples were $<3\ \mu M$. Although regional differences existed, at a given station there was small variation over depth in nutrient concentrations — a condition that reflects persistence of a well-mixed water column.

The regional enrichment at Harbor and coastal stations was notable for NH_4 and occasionally for $N0_3$ (Figure 4-14b). Although ammonium is usually a strong diagnostic for the Harbor, some midwater (25-50 m) samples from the boundary region and near-surface water samples from Cape Cod Bay were also enriched in NH_4 (2.5-3 μM). The PO_4 pattern across regions was similar to that for DIN, but Cape Cod Bay was not distinctly low (Figure 4-14c). Cape Cod Bay stations were most depleted in SiO_4; the regional pattern for SiO_4 concentration was very similar to the DIN pattern except that the silicate concentration range was lower in the nearfield than at the boundary and offshore stations.

A scatter plot for DIN and PO_4 suggested that the relationship between N and P was similar in most regions (Figure 4-15a). Moreover, the data generally followed the Redfield ratio (16:1), even to low nutrient concentrations in some offshore samples. However, a number of Cape Cod Bay samples had

relatively high P in the water when N was low; thus, compared to other samples, Cape Cod Bay samples had a low N/P (around 4:1). Samples from Boston Harbor and nearby coastal stations were slightly enriched in nitrogen relative to the nearfield. Nitrogen enrichment was generally due to higher NH_4 rather than to NO_3 concentrations.

In contrast, N/Si plots displayed some regional distinctions (Figure 4-15b). The N/Si ratios in the Harbor, nearfield, and much of the coastal areas were similar and generally above 1:1. Deep-water stations of the offshore and boundary station groups were generally lower in N at a given silicate concentration and, thus had lower N/Si ratios. Some samples from Cape Cod Bay were unusual in that they had a low silicate concentration. However, because nitrogen concentrations were also low at these stations, the N/Si ratio for these samples was not distinctive.

DIN concentrations generally decreased with salinity (Figure 4-16a). The decrease was evident in NH_4, but not in NO_3 concentrations (Figure 4-16b). In Cape Cod Bay, concentrations of all forms of DIN were low and nearly depleted. Across many samples, NO_3 was relatively constant (around 7-9 μM) at salinities ranging from 30 to 33 PSU, but NO_3 concentrations of some coastal, nearfield, offshore, and boundary samples were depleted below this level. There appeared to be no strong regional bias to this relative depletion other than the bias that it did not occur in the Harbor. As in February, the relationship between PO_4 and salinity was similar to that for NO_3, whereas SiO_4 resembled the DIN- and NH_4-salinity patterns (Figure 4-16c).

Considering combined N forms (DIN + PON) and total N (TN), it was evident that concentrations at Cape Cod Bay stations were relatively low for their salinity and were also low relative to other regions, independent of salinity considerations (Figure 4-17). Excluding Cape Cod Bay, the general trend was decreasing TN concentrations with increasing salinity. Moreover, Harbor stations were consistently high in TN concentrations which ranged between 18 and 32 μM, similar to the range observed in February (see Figure 3-17). TN and DIN +PON concentrations at the boundary station (F27B) were similar to those in the nearfield and distinctly lower than in the Harbor.

In summary, as in February, Boston Harbor was easily identifiable as a region of N and Si enrichment, but it was also often high in PO_4. Some grading of nutrients to deeper waters was apparent and the Harbor-nearfield area often had relatively more silicate per N than offshore and boundary waters. Finally, Cape Cod Bay proper (stations F01P and F02P) was unique in its general depletion of all three nutrients (N, P, Si).

4.1.4 Distribution of Chlorophyll and Phytoplankton

At two stations in Cape Cod Bay, phytoplankton abundance increased since February and, by early March, approached or exceeded 3 million cells L^{-1} (Figures 4-18, 4-19, 4-20). Aside from the Cape Cod Bay stations, there was no relationship between cell counts and chlorophyll (extracted analyses) over the observed range of chlorophyll (0-4 $\mu g\ L^{-1}$). Tables 4-1a and 4-1b indicate that the difference in Cape Cod Bay was taxonomic and due to a major growth of *Phaeocystis pouchetii*, found at both the surface and chlorophyll maximum depths. Samples from stations in Massachusetts Bay did not show this organism, and instead had low numbers of various diatom species and microflagellates. Full taxonomic listings from samples are provided in Appendix E.

Screened phytoplankton samples (Tables 4-2a,b) revealed a variety of large dinoflagellate species. More important, however, was that higher counts and greater numbers of species were usually found at each Cape Cod Bay station compared to those in Massachusetts Bay.

4.1.5 Distribution of Zooplankton

Zooplankton abundance increased with chlorophyll concentrations (Figure 4-21). Zooplankton numbers were highest at Cape Cod Bay stations (Figure 4-22). Higher counts were found at nearfield stations than at the Harbor-edge and coastal stations (F23P and F13P). Copepod nauplii and adults constituted the major portion of the zooplankton counts at all stations. Barnacle nauplii were significant components at stations F23P and N10P, both of which are located within the region where Harbor and Bay waters mix

tidally. Barnacle nauplii were additionally found at stations N20P and N01P in the mid- to western nearfield, and at station F13P down the coast. Their presence may suggest that a fraction of the water at those locations had an inshore, Harbor origin. Full taxonomic listings of zooplankton are provided in Appendix F.

4.1.6 ^{14}C Production Measurements

Appendix D contains many details of the ^{14}C incubation measurements and P-I curve modeling, but results of modeling and calculations for integrated water column production are summarized in Table 4-3. Production rates were low at station F23P on both dates that measurements were made. In contrast, high rates were suggested at station N16P on both dates.

At station F23P, P_{max} values were in a low range of about 2-6 μg C (μg Chl)$^{-1}$ hr^{-1}. At N16P, there was an apparent pattern in model parameters as a function of depth; P_{max} values were high for the surface incubation and decreased with depth. Using the calculation scheme described previously in the Section 2 (methods) to combine results of the four incubations into a single composite estimate, we calculated rates of 322 and 1882 mg C m^{-2} d^{-1} on March 1 for stations F23P and N16P, respectively. The March 5 estimates were 236 and 3186 mg C m^{-2} d^{-1} for stations F23P and N16P, respectively. The difference in integrated production rates between the two stations was due to several reasons: chlorophyll was higher at station N16P, volumetric production rates were higher at station N16P, and the depth of the photic zone was also generally greater at station N16P.

4.2 Nearfield Survey

4.2.1 Distribution of Water Properties from Vertical Profiling

Scatter plots for a variety of parameters measured on the nearfield survey (March 6) are shown in Figure 4-23. Patterns and ranges may be compared to all stations (Figure 4-12), as well as to separate regions

(Appendix C). T-S plots indicate a narrow variation in temperature and salinity, a result that is also evident in Figures 4-24a and b.

There was little variation in beam attenuation, but it did appear to be related to salinity (Figure 4-23). Chlorophyll and beam attenuation, however, were poorly related. Highest chlorophyll concentrations were characteristically detected in mid-water (Figure 4-23) at most stations, and concentrations in the center of the nearfield, around stations N20P and N13, were >6 $\mu g\ L^{-1}$ (Figure 4-24c). DIN showed no strong geographic trends. As in February, concentrations varied in the range of 6-12 μM.

4.2.2 Water Quality Variability in the Nearfield

At the nearfield stations, there was little variability in most water quality parameters during the survey period. Few spatial trends were noted. Given the general uniformity in physical and chemical paarmeters, it was interesting, however, that a subsurface chlorophyll maximum was present and that it occurred in spite of the general absence of vertical density stratification.

Table 4-1a. Abundance of the top five dominant phytoplankton taxa in samples collected near the surface in March 1994.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Mar 02	Mar 01	Mar 01	Mar 01	Mar 05	Mar 05	Mar 01	Mar 05	Mar 02	Mar 02
CHAETOCEROS COMPRESSUS			0.004 (5)						0.064 (4)	0.054 (5)
CHAETOCEROS DEBILIS					0.005 (5)				0.064 (4)	
CHAETOCEROS DECIPIENS					0.007 (4)					
CHAETOCEROS SPP. (10-20UM)					0.007 (4)				0.095 (3)	0.071 (3)
CHAETOCEROS SPP.(<10UM)			0.004 (5)							
CRYPTOMONADS	0.004 (5)		0.004 (5)							
LEPTOCYLINDRUS MINIMUS									0.052 (5)	0.063 (4)
MICROFLAGELLATES	0.014 (4)	0.094 (1)	0.016 (3)	0.017 (3)	0.022 (2)	0.012 (3)	0.020 (4)	0.010 (5)		0.090 (2)
NAVICULOID DIATOMS						0.007 (5)				
PARALIA MARINA			0.004 (5)							
PHAEOCYSTIS POUCHETII									3.024 (1)	2.793 (1)
SKELETONEMA COSTATUM		0.009 (5)								
THALASSIONEMA NITZSCHOIDES	0.019 (2)	0.020 (2)	0.025 (2)	0.019 (2)	0.017 (3)	0.016 (2)	0.022 (3)	0.022 (3)		
THALASSIOSIRA (CF) CONSTRICTA			0.004 (5)							
THALASSIOSIRA (cf) GRAVIDA/ROTULA	0.016 (3)	0.014 (3)		0.007 (5)	0.033 (1)	0.071 (1)	0.014 (5)	0.087 (1)	0.104 (2)	
THALASSIOSIRA ANGUSTE-LINEATA	0.004 (5)		0.075 (1)	0.066 (1)	0.007 (4)		0.038 (1)	0.012 (4)		
THALASSIOSIRA NORDENSKIOLDII	0.004 (5)			0.010 (4)						
THALASSIOSIRA SPP.	0.037 (1)	0.013 (4)	0.011 (4)	0.010 (4)	0.017 (3)	0.010 (4)	0.035 (2)	0.055 (2)		

Units are millions of cells L^{-1} and rankings are given in parentheses.

Table 4-1b. Abundance of the top five dominant phytoplankton taxa in samples collected near the chlorophyll maximum in March 1994.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Mar 02	Mar 01	Mar 01	Mar 01	Mar 05	Mar 05	Mar 01	Mar 05	Mar 02	Mar 02
CHAETOCEROS COMPRESSUS									0.169 (2)	0.071 (2)
CHAETOCEROS DEBILIS					0.008 (5)	0.006 (5)				
CHAETOCEROS SPP. (10-20UM)	0.006 (5)		0.009 (4)							
CHAETOCEROS SPP.(<10UM)		0.007 (5)							0.050 (5)	
MICROFLAGELLATES	0.017 (4)	0.075 (1)	0.041 (1)	0.017 (3)	0.012 (4)	0.011 (4)	0.020 (3)	0.008 (5)	0.071 (4)	0.065 (3)
PHAEOCYSTIS POUCHETII									2.935 (1)	2.380 (1)
SKELETONEMA COSTATUM		0.015 (2)								
THALASSIONEMA NITZSCHOIDES	0.025 (2)	0.010 (3)	0.036 (2)	0.023 (2)	0.024 (3)	0.012 (3)	0.023 (2)	0.021 (2)		
THALASSIOSIRA (CF) CONSTRICTA		0.009 (4)								
THALASSIOSIRA (cf) GRAVIDA/ROTULA	0.021 (3)				0.076 (1)	0.102 (1)	0.014 (5)	0.148 (1)	0.086 (3)	0.041 (5)
THALASSIOSIRA ANGUSTE-LINEATA			0.029 (3)	0.077 (1)	0.008 (5)		0.065 (1)	0.011 (4)		
THALASSIOSIRA NORDENSKIOLDII			0.008 (5)	0.004 (5)						
THALASSIOSIRA SPP.	0.036 (1)	0.015 (2)	0.029 (3)	0.009 (4)	0.028 (2)	0.021 (2)	0.015 (4)	0.020 (3)		0.044 (4)

Units are millions of cells L^{-1} and rankings are given in parentheses.

Table 4-2a. Abundance of all identified taxa in screened (20μm) samples collected near the surface in March 1994.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Mar 02	Mar 01	Mar 01	Mar 01	Mar 05	Mar 05	Mar 01	Mar 05	Mar 02	Mar 02
ALORICATE CILIATES	8	53	10	15			8		30	10
AMPHIDINIUM SPP.										3
CERATIUM FUSUS				5						
CERATIUM LONGIPES	3		3	3	3			5		5
CERATIUM TRIPOS				3			3			
DICTYOCHA FIBULA					8	3		3		
DICTYOCHA SPECULUM			5	8	3	5	5	5		15
DINOPHYSIS NORVEGICA			3	3			3		10	
GYMNODINIUM SPP.			5							
GYRODINIUM SPIRALE	3	3	8		3			3	18	50
GYRODINIUM SPP.		3	3						8	30
GYRODINUM ESTUARIALE							3			
MESODINIUM RUBRUM						3				
PROTOPERIDINIUM (CF) THORIANUM									13	38
PROTOPERIDINIUM BIPES									20	30
PROTOPERIDINIUM BREVE		3		3			5	3	23	5
PROTOPERIDINIUM CONICUM									18	20

Units are cells L^{-1}

Table 4-2a. Continued.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Mar 02	Mar 01	Mar 01	Mar 01	Mar 05	Mar 05	Mar 01	Mar 05	Mar 02	Mar 02
PROTOPERIDINIUM DEPRESSUM				3				3		
PROTOPERIDINIUM PELLUCIDUM										15
PROTOPERIDINIUM SPP.	10	8	13		8			3	1134	1399
SCRIPPSIELLA TROCHOIDEA									30	45
TINTINNIDS	10	20	15	10	40	18	23	10	275	358
UNID. ATHECATE DINOFLAGELLATE	3	3					3		20	20
UNID. THECATE DINOFLAGELLATES					10			3		28

Units are cells L^{-1}

Table 4-2b. Abundance of all identified taxa in screened (20μm) samples collected near the chlorophyll maximum in March 1994.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Mar 02	Mar 01	Mar 01	Mar 01	Mar 05	Mar 05	Mar 01	Mar 05	Mar 02	Mar 02
ALORICATE CILIATES	8	25	18	5	3	5		10	13	5
AMPHIDINIUM SPP.				3						
CERATIUM FUSUS				3			3			
CERATIUM LONGIPES	5			3	3	3	3			3
DICTYOCHA FIBULA			3	3	3		3	5		
DICTYOCHA SPECULUM				10	13	5	8	10	5	5
DINOPHYSIS NORVEGICA							5			5
GYMNODINIUM SPP.		3								
GYRODINIUM SPIRALE	5	5	3				3	3	40	28
GYRODINIUM SPP.		3	5							10
MESODINIUM RUBRUM		3		3						
PROTOPERIDINIUM (CF) THORIANUM									58	55
PROTOPERIDINIUM BIPES	3								8	3
PROTOPERIDINIUM BREVE	5				3			3		
PROTOPERIDINIUM CONICUM									23	10
PROTOPERIDINIUM DENTICULATUM					5					

Units are cells L^{-1}

Table 4-2b. Continued.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Mar 02	Mar 01	Mar 01	Mar 01	Mar 05	Mar 05	Mar 01	Mar 05	Mar 02	Mar 02
PROTOPERIDINIUM DEPRESSUM				8	3		3			
PROTOPERIDINIUM PELLUCIDUM								3		10
PROTOPERIDINIUM SPP.	8	5	8	8	5	3	8	5	796	626
SCRIPPSIELLA TROCHOIDEA									35	130
TINTINNIDS	33	25	13	8	40	15	18	35	328	190
UNID. ATHECATE DINOFLAGELLATE	5			5	3		5			5
UNID. THECATE DINOFLAGELLATES		3			5	3				43

Units are cells L^{-1}

Table 4-3. ^{14}C production (mg C m^{-2} d^{-1}) estimated for euphotic layer at BioProductivity stations F23P and N16P in March 1994.

	F23P 01-MAR-94				F23P 05-MAR-94				N16P 01-MAR-94				N16P 05-MAR-94			
Water depth (m)	22				29				42				42			
$Z_{(0.5\%Io)}$ (m)	19.5[5]				9.0				28.5				18.0			
Sample depth (m)	2.8	4.0	7.0	11.1	2.2	4.8	8.7	15.1	3.0	5.4	12.7	24.4	1.9	8.7	18.2	25.2
Rate (mg C m^{-2} d^{-1})	327	231	335	477	155	357	162	172	3710	2277	1504	1241	3889	2975	1912	1786
Model[1]	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
P_{SB} or P_{MAX}[2]	3.61	2.06	2.75	5.57	4.67	6.19	5.08	4.06	11.21	8.91	5.18	4.86	26.21	17.93	13.02	11.09
α[3]	0.036	0.065	0.782	0.045	0.009	0.047	0.009	0.013	0.209	0.068	0.059	0.037	0.109	0.095	0.053	0.055
β[4]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

[1] P: Platt *et al.* (1980).
W: Webb *et al.* (1974).
[2] P_{SB}: Production parameter for Platt *et al.* model.
P_{MAX}: Production parameter for Webb *et al.* model.
[3] Parameter for both models.
[4] Parameter for Platt *et al.* model.
[5] $Z_{(0.5\%Io)}$ was greater than the profile depth at station F23P (16.5 m) on March 1, 1994.

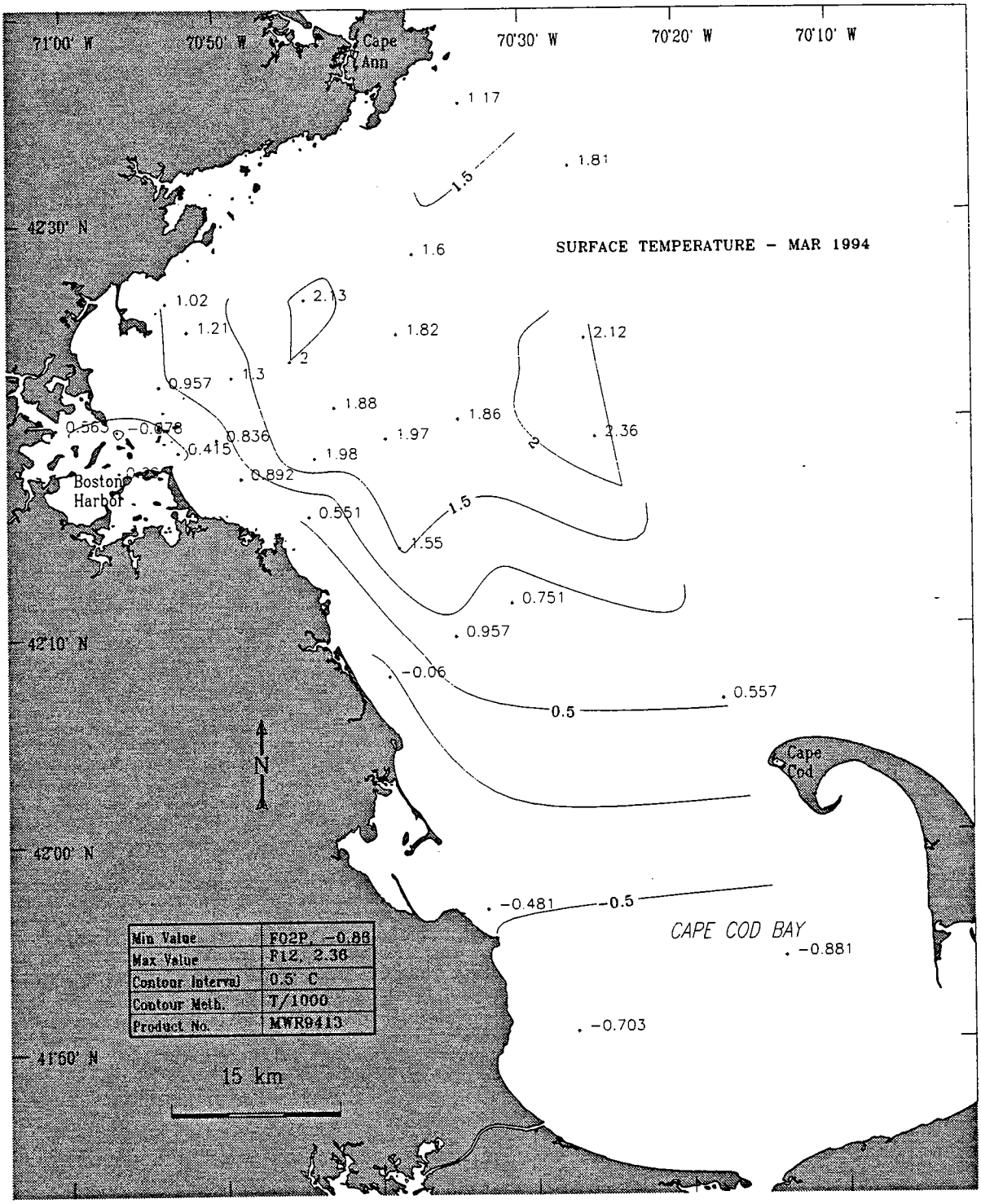


Figure 4-1. **Surface temperature (°C) in the study area in early March 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

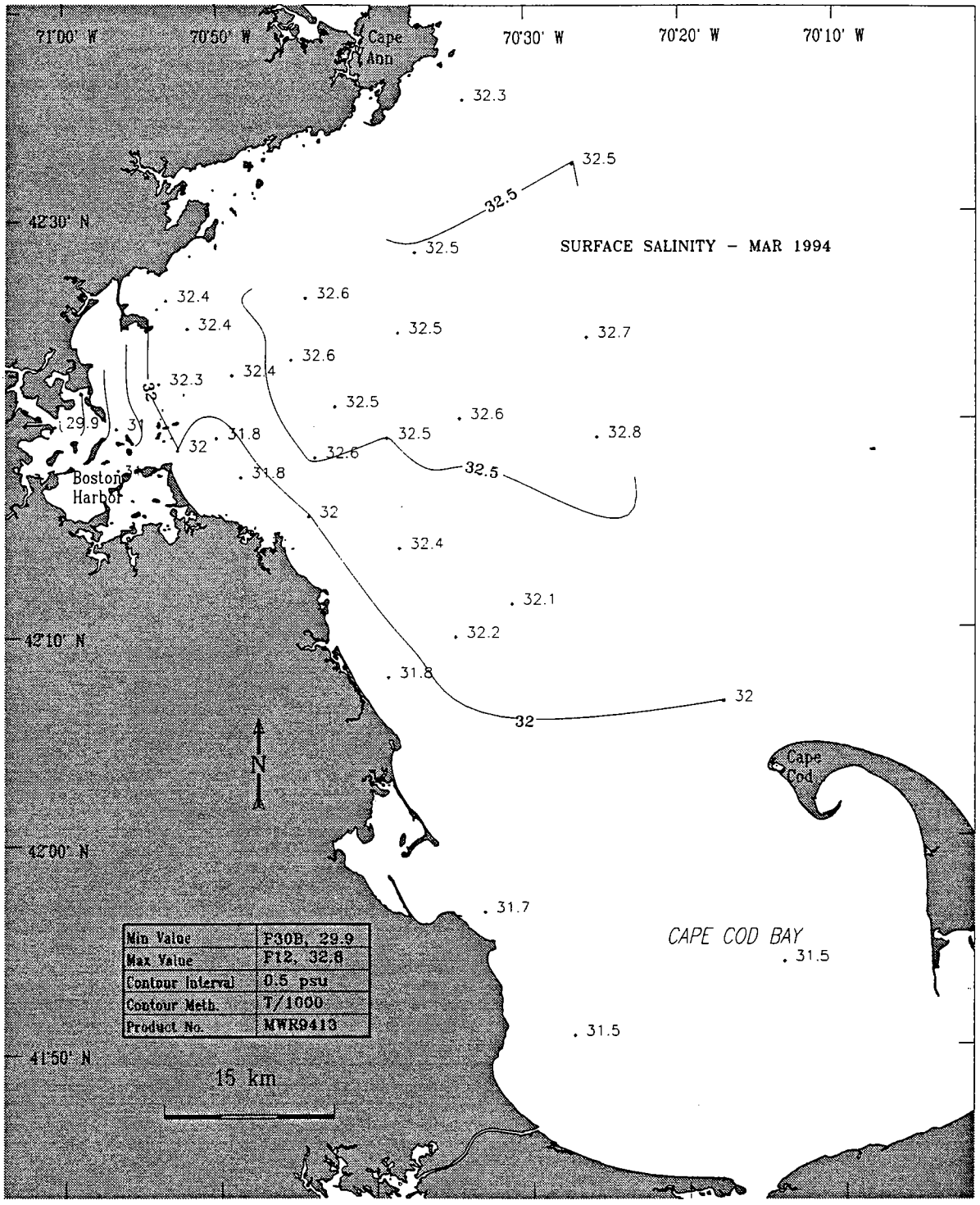


Figure 4-2. **Surface salinity (PSU) in the study area in early March 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

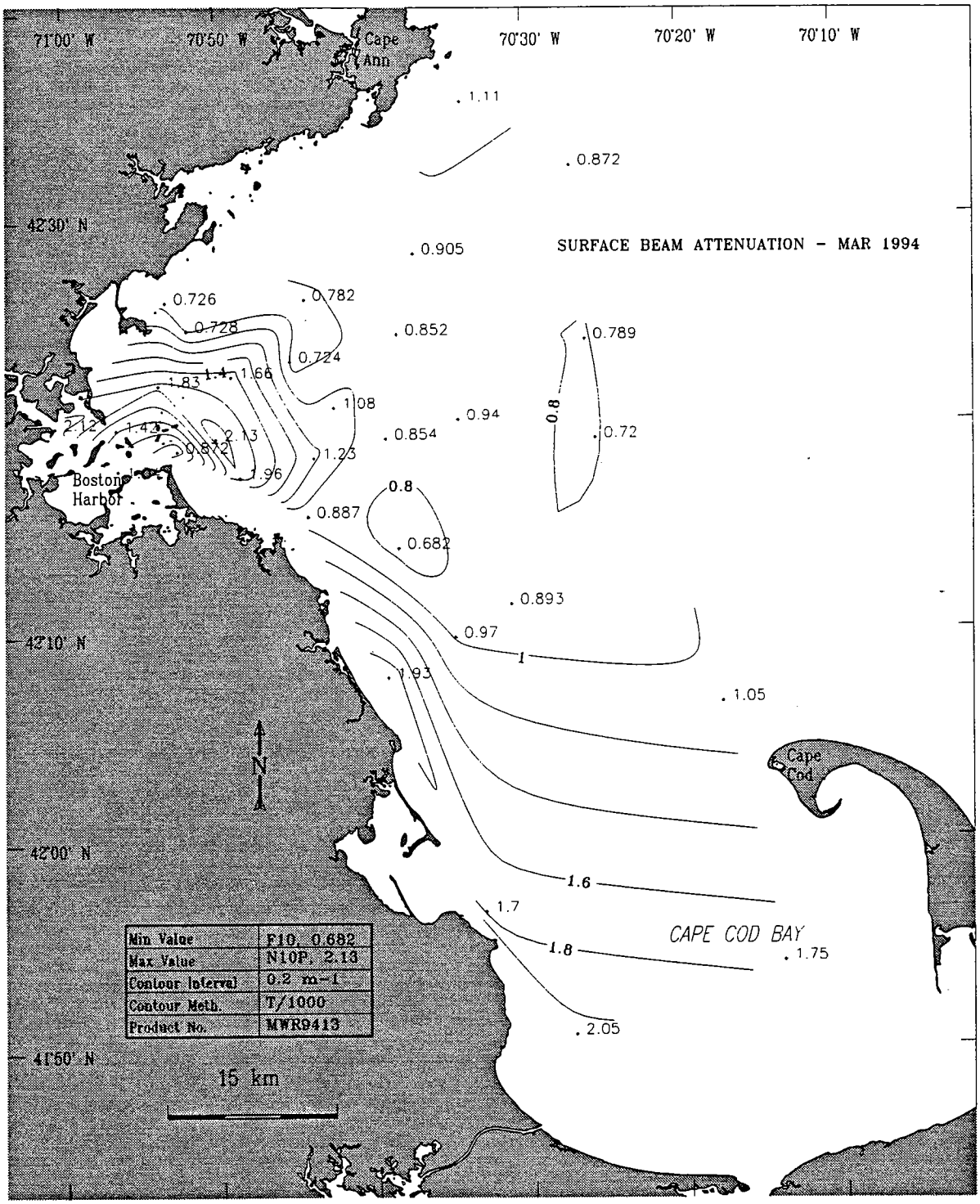


Figure 4-3. **Surface beam attenuation (m^{-1}) in the study area in early March 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

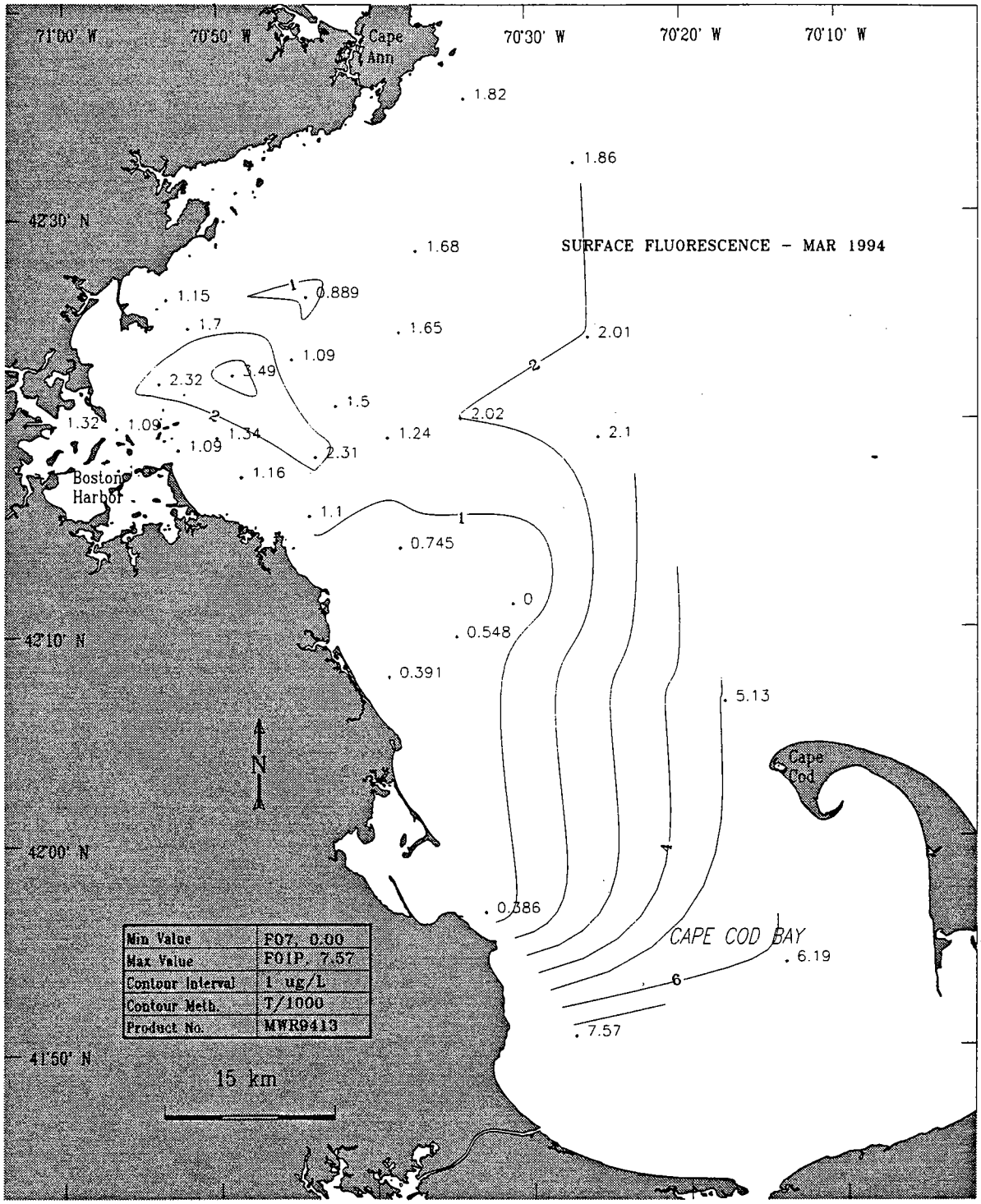


Figure 4-4. **Surface *in situ* fluorescence (as μg Chl L^{-1}) in the study area in early March 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

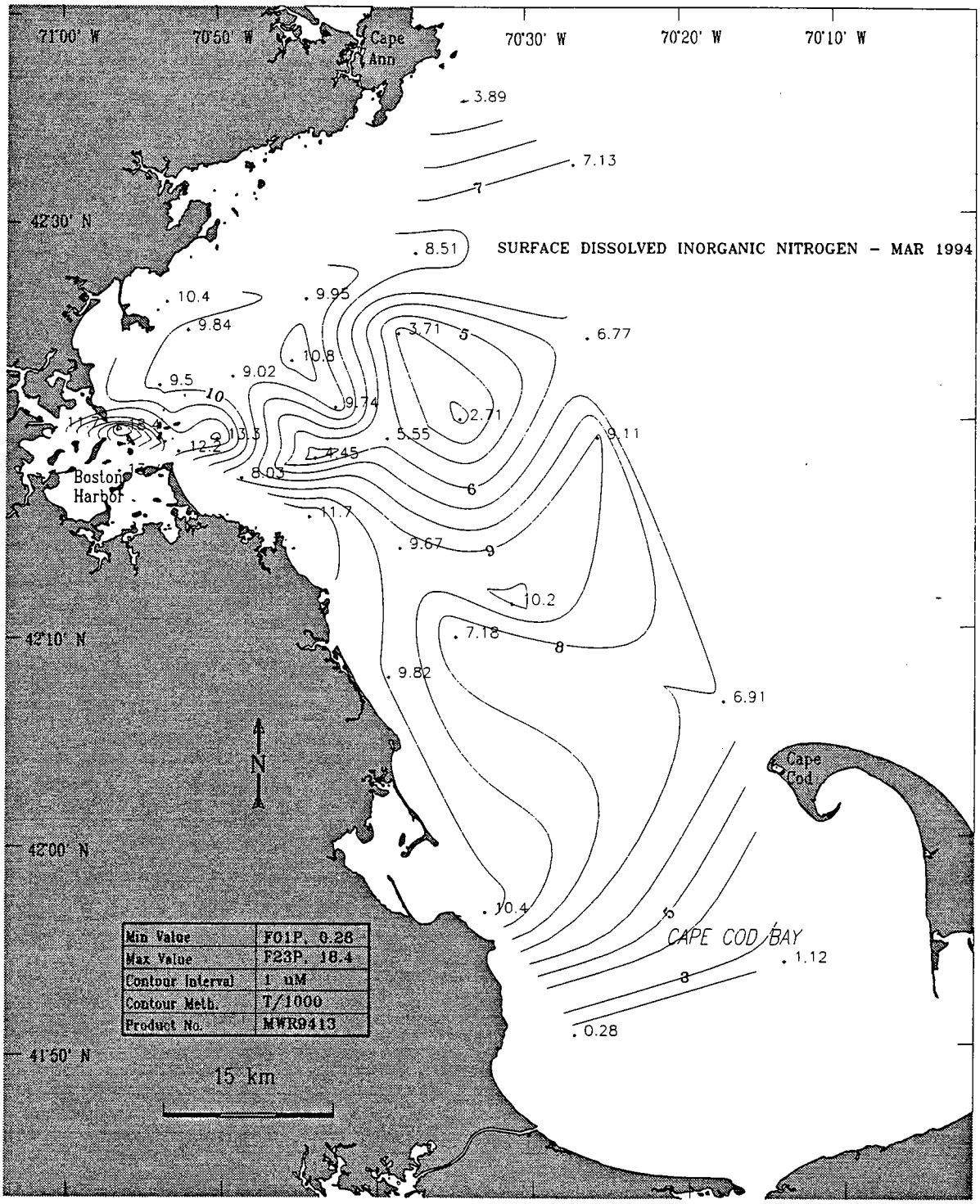


Figure 4-5. **Surface dissolved inorganic nitrogen (DIN, μM) in the study area in early March 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

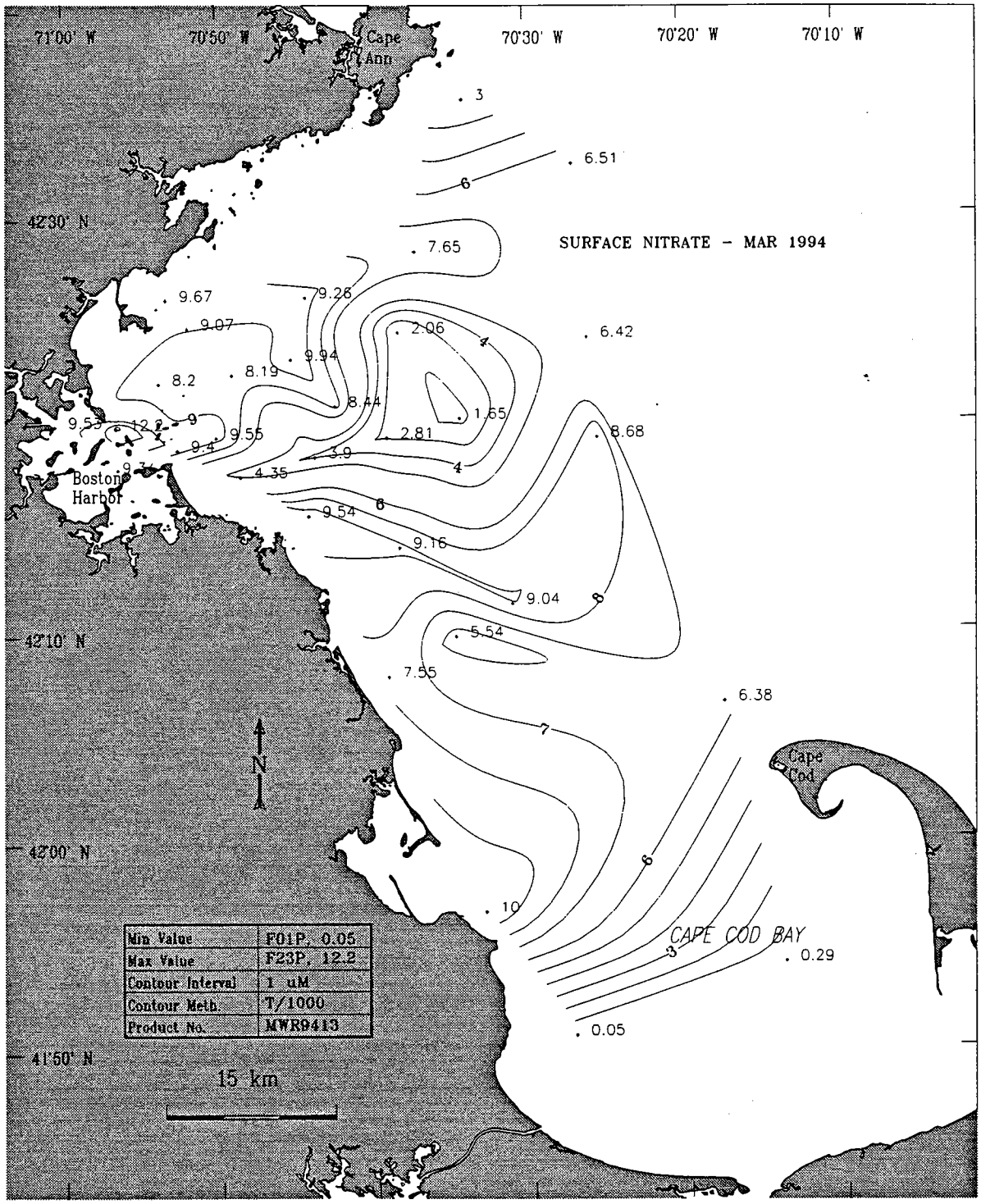


Figure 4-6. **Surface nitrate (NO_3, μM) in the study area in early March 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

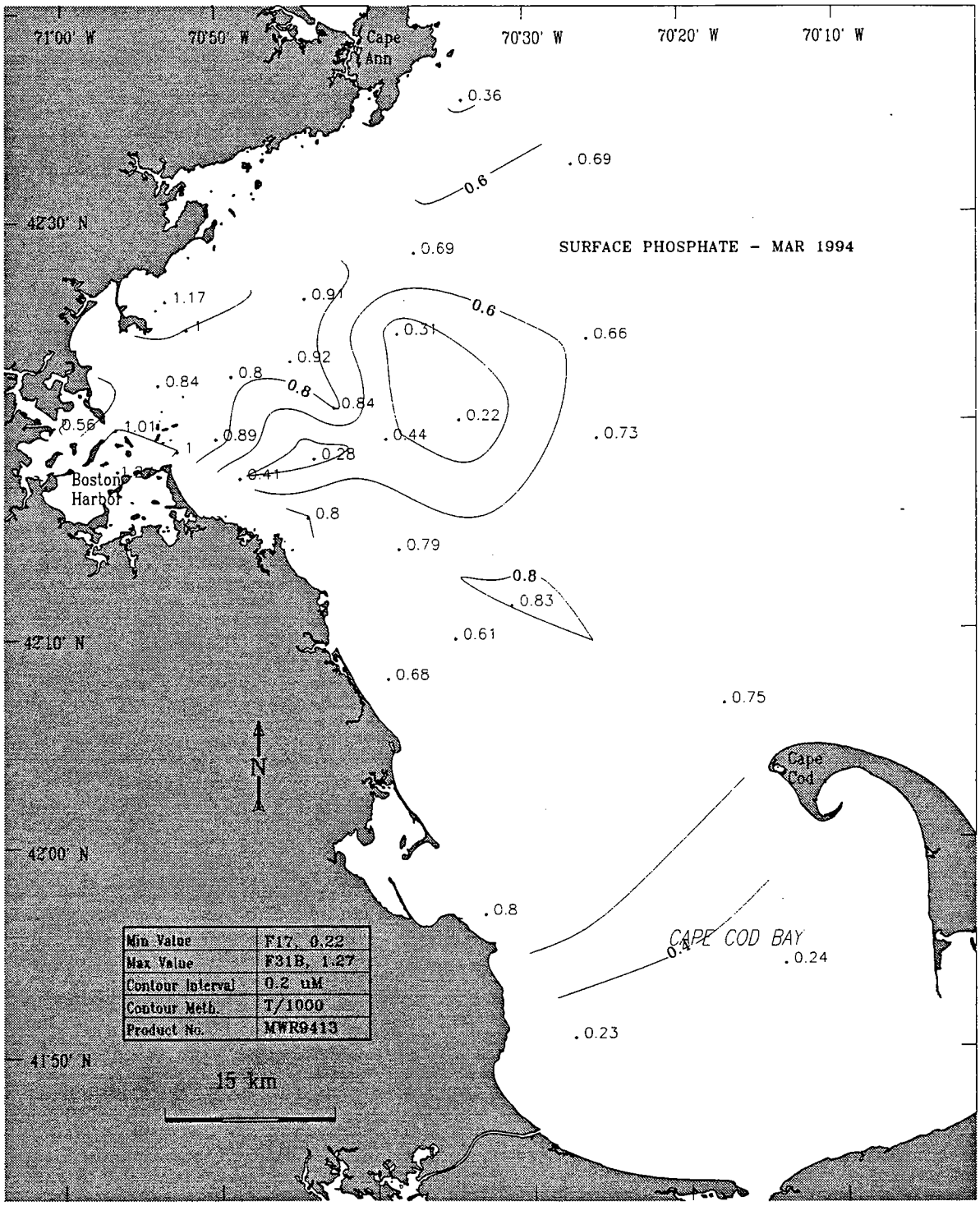


Figure 4-7. **Surface phosphate (PO_4, μM) in the study area in early March 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

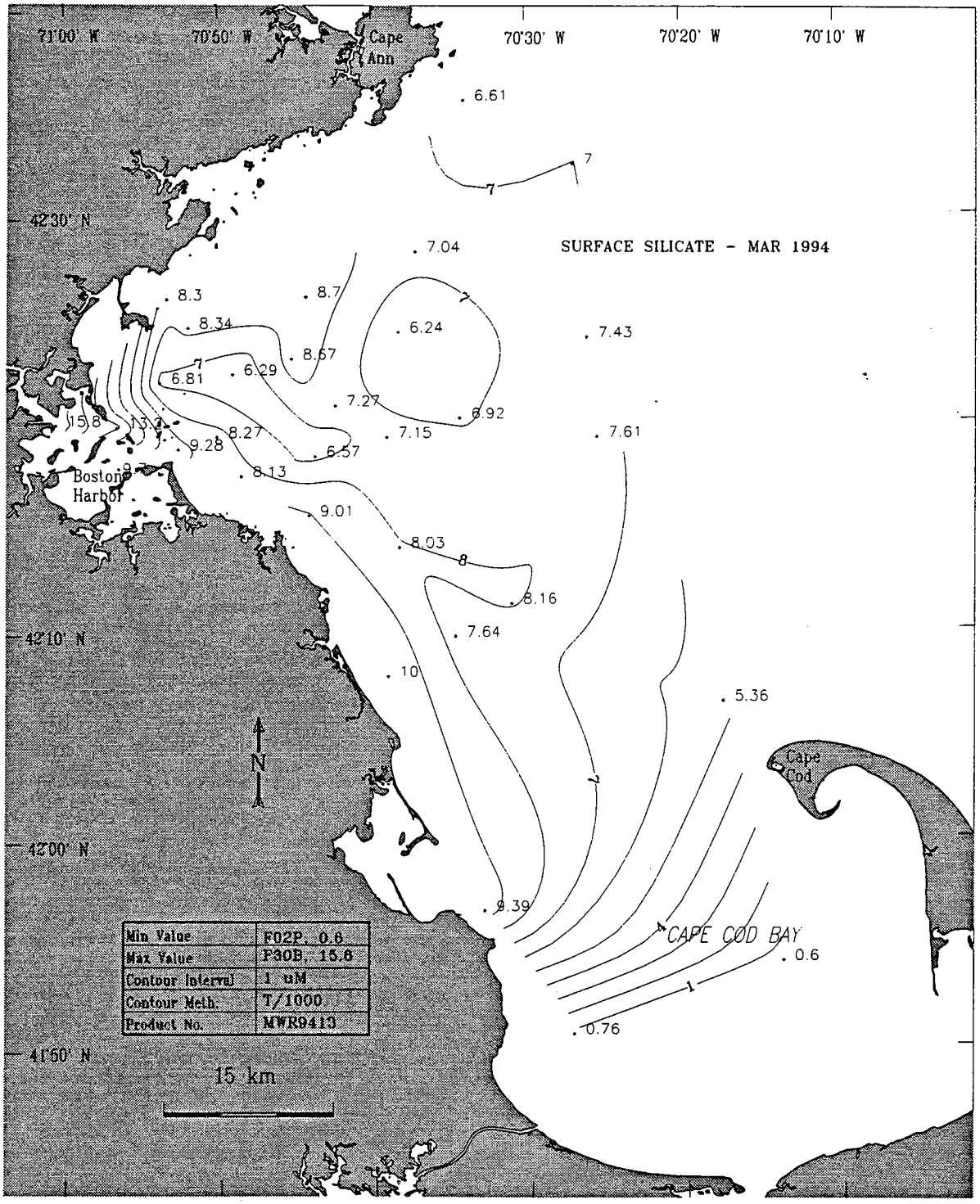


Figure 4-8. **Surface silicate (SiO_4, μM) in the study area in early March 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

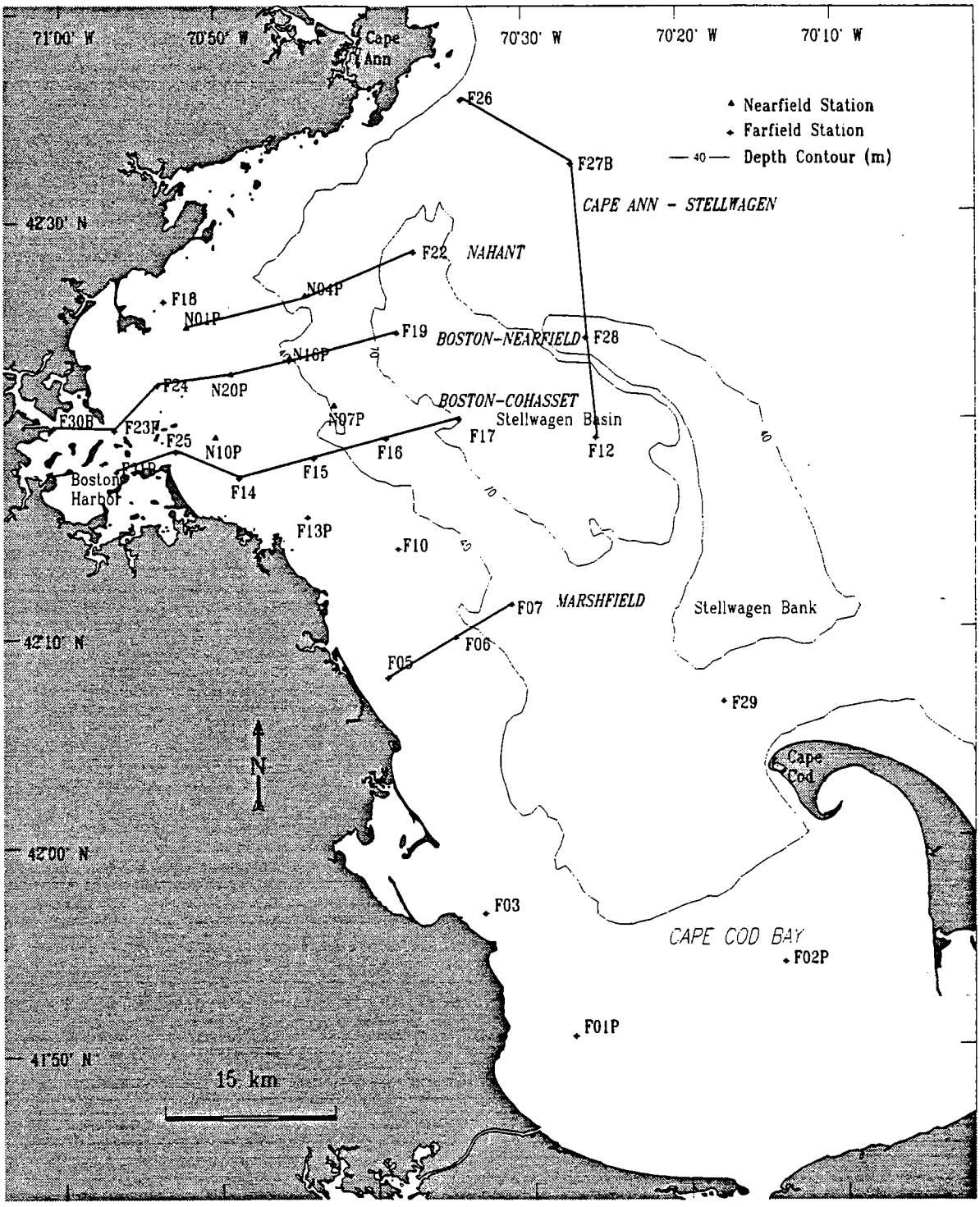


Figure 4-9. **Map showing position of five standard transects for which vertical contour plots were produced in Figures 4-10 and 4-11.**

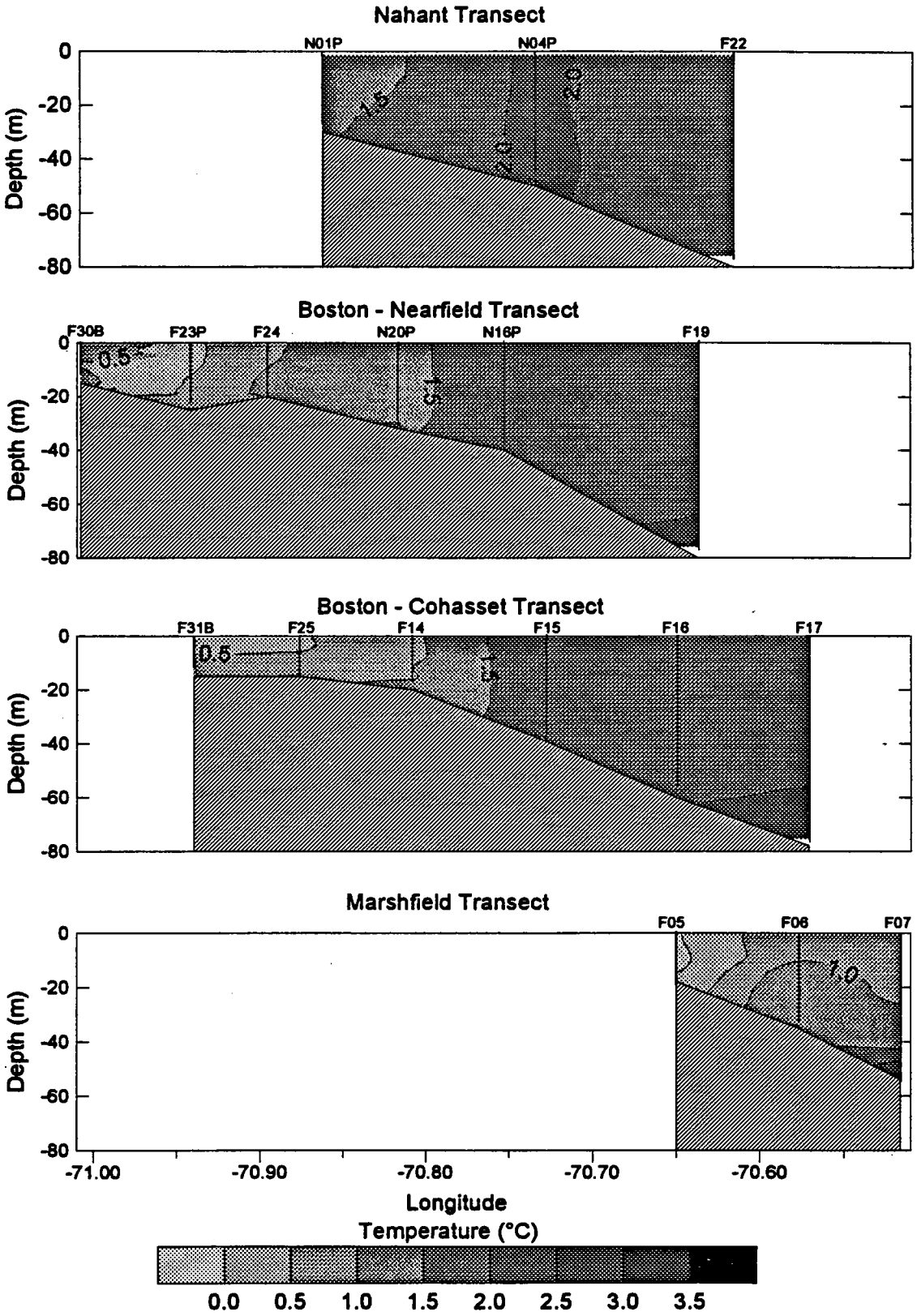


Figure 4-10a. Vertical section contours for standard transects (see Figure 4-9) on Survey W9402. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

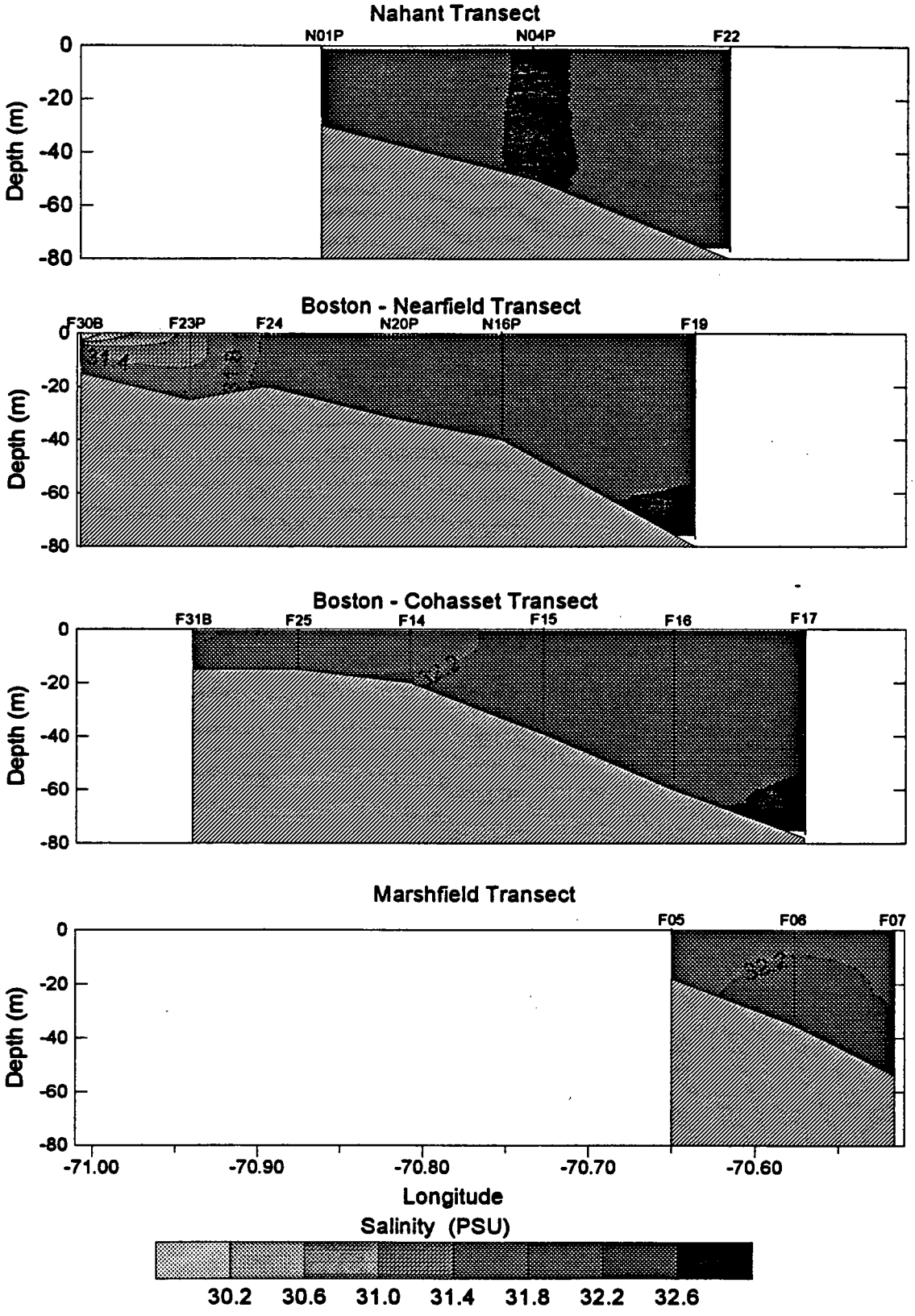


Figure 4-10b. Vertical section contours for standard transects (see Figure 4-9) on Survey W9402. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

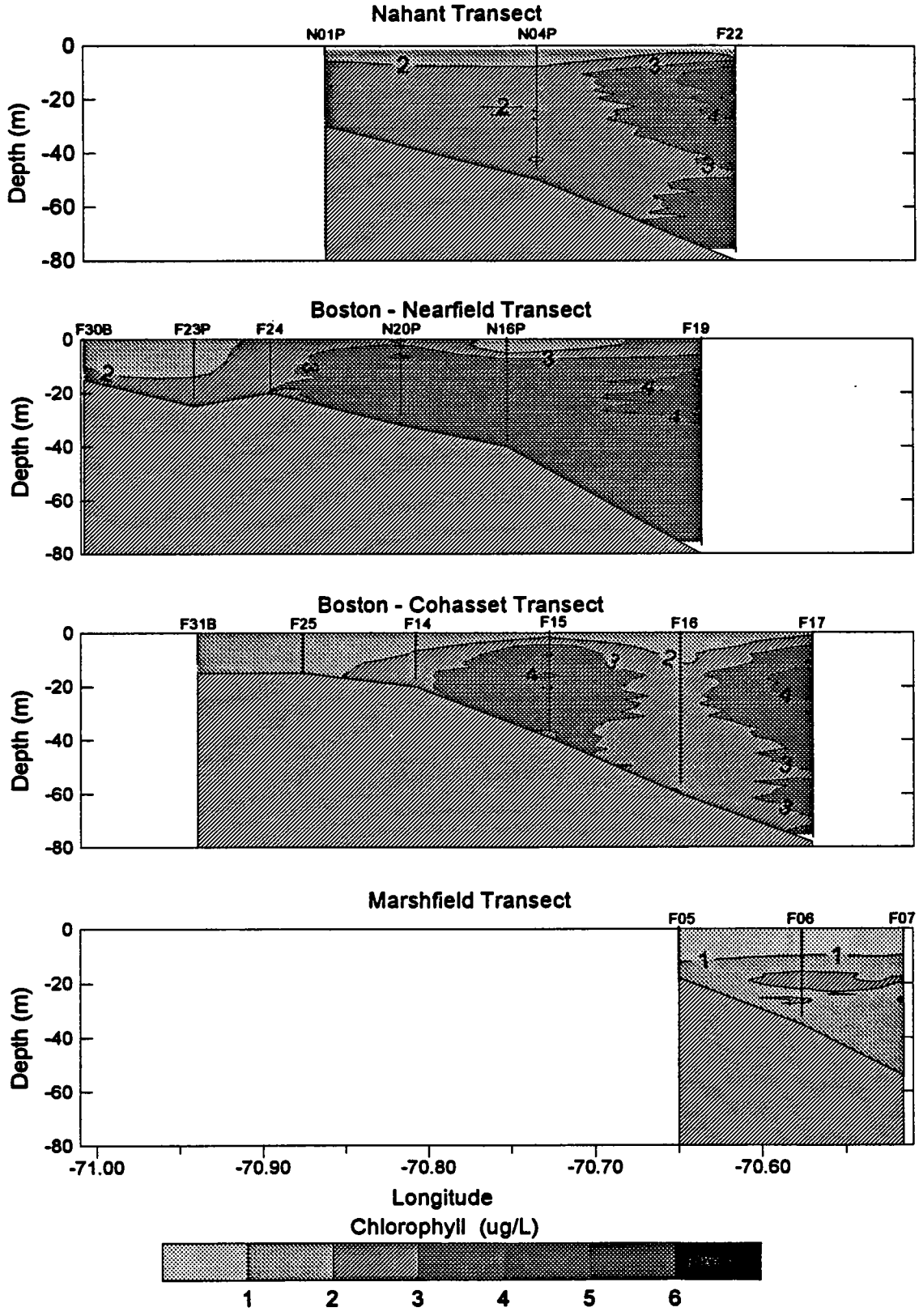


Figure 4-10c. Vertical section contours for standard transects (see Figure 4-9) on Survey W9402. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

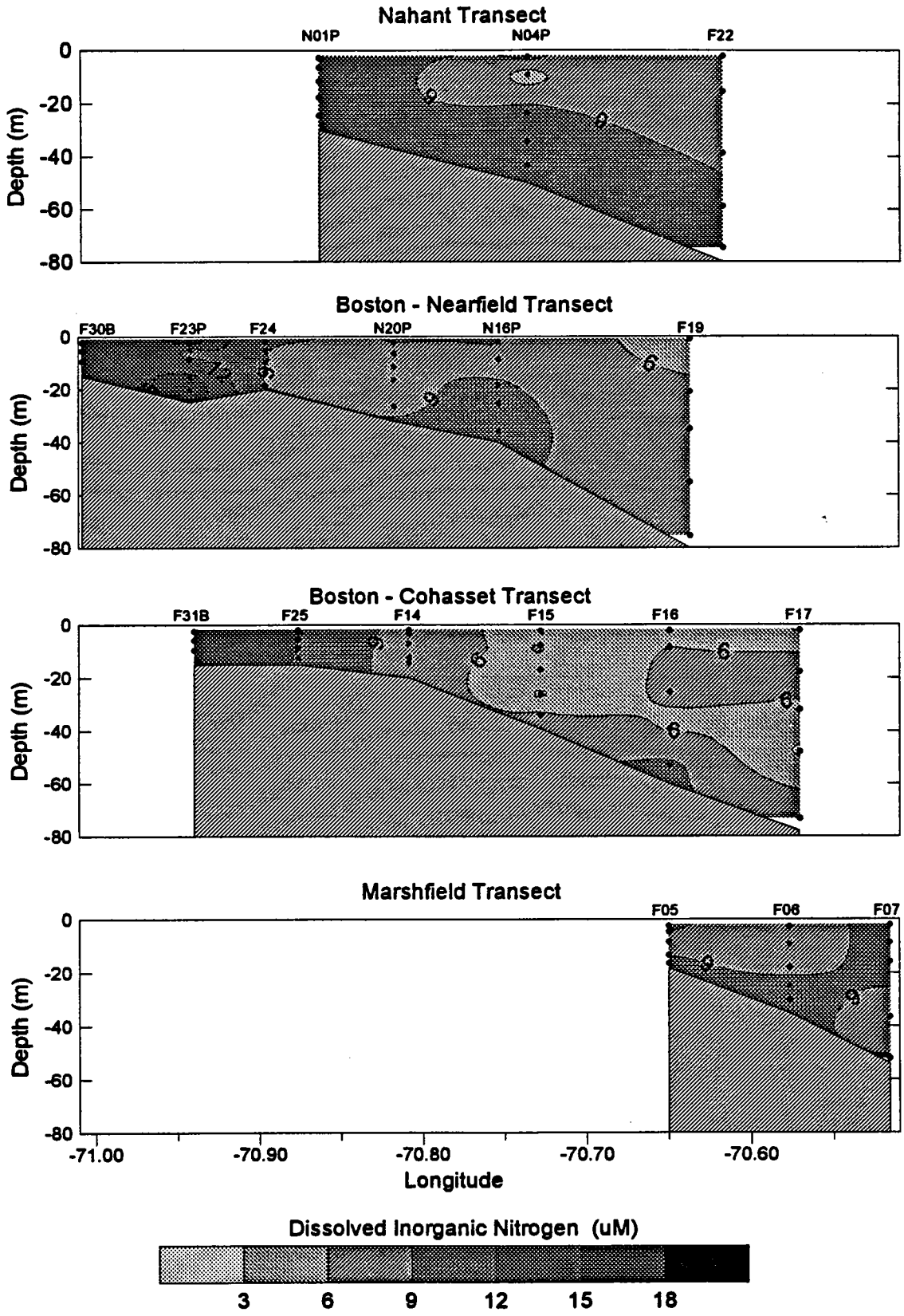


Figure 4-10d. Vertical section contours for standard transects (see Figure 4-9) on Survey W9402. The data used to produce the contours are from discrete bottle samples (Appendix A).

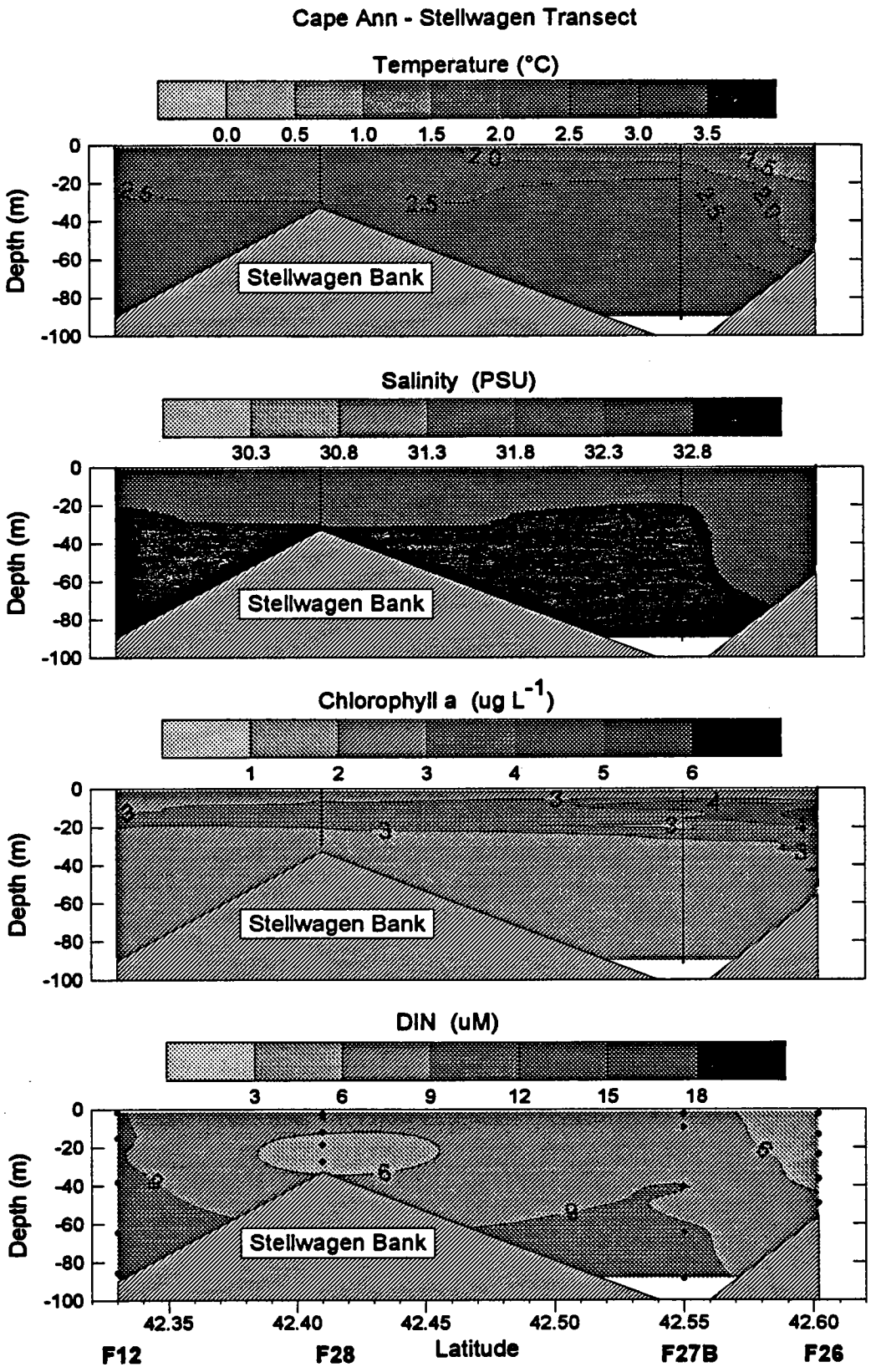


Figure 4-11. Vertical section contours for the Cape Ann - Stellwagen transect (see Figure 4-9) on Survey W9402. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station (temperature, salinity, and chlorophyll) and discrete bottle samples (DIN; Appendix A).

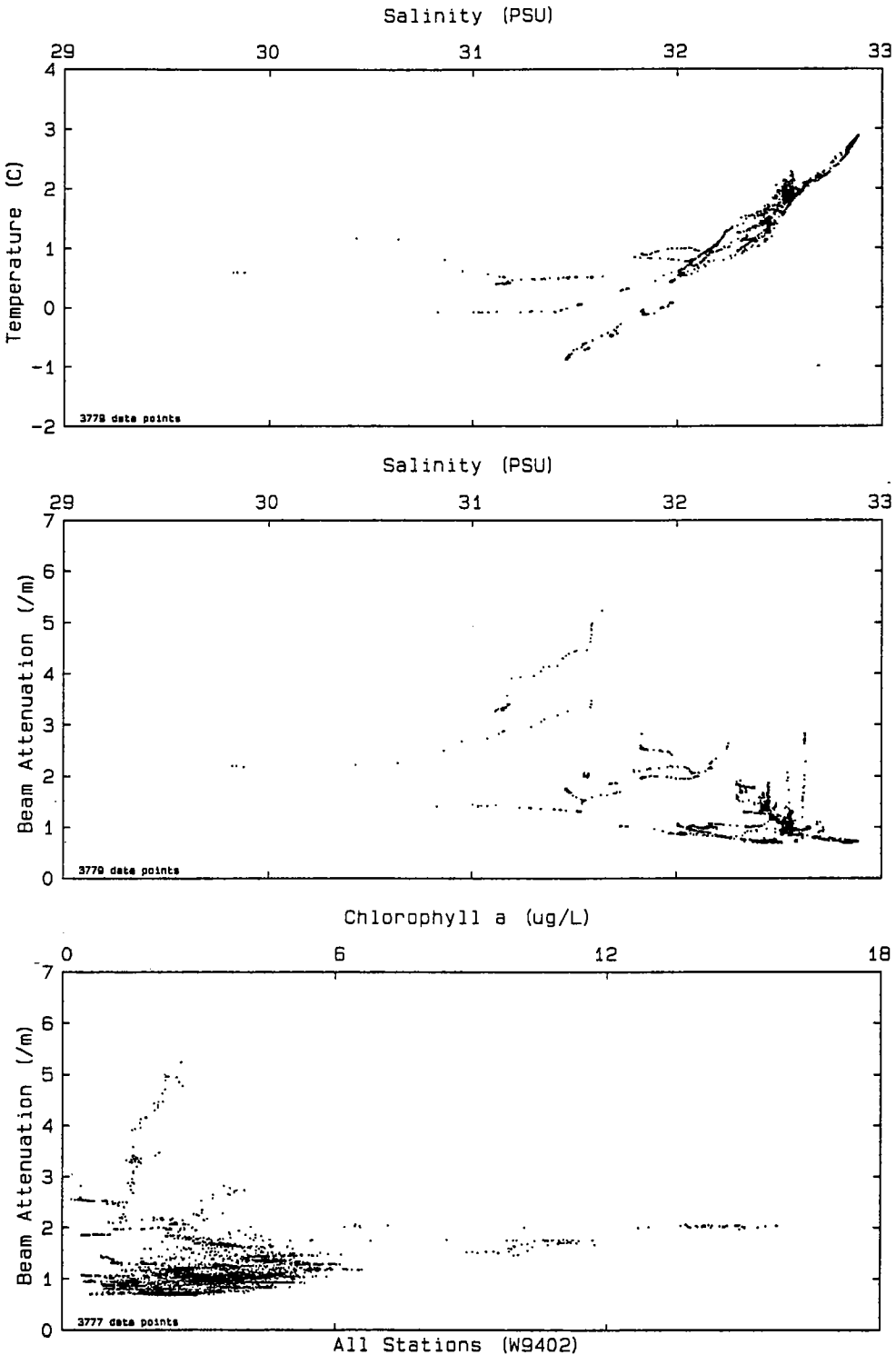


Figure 4-12a. Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in early March 1994.

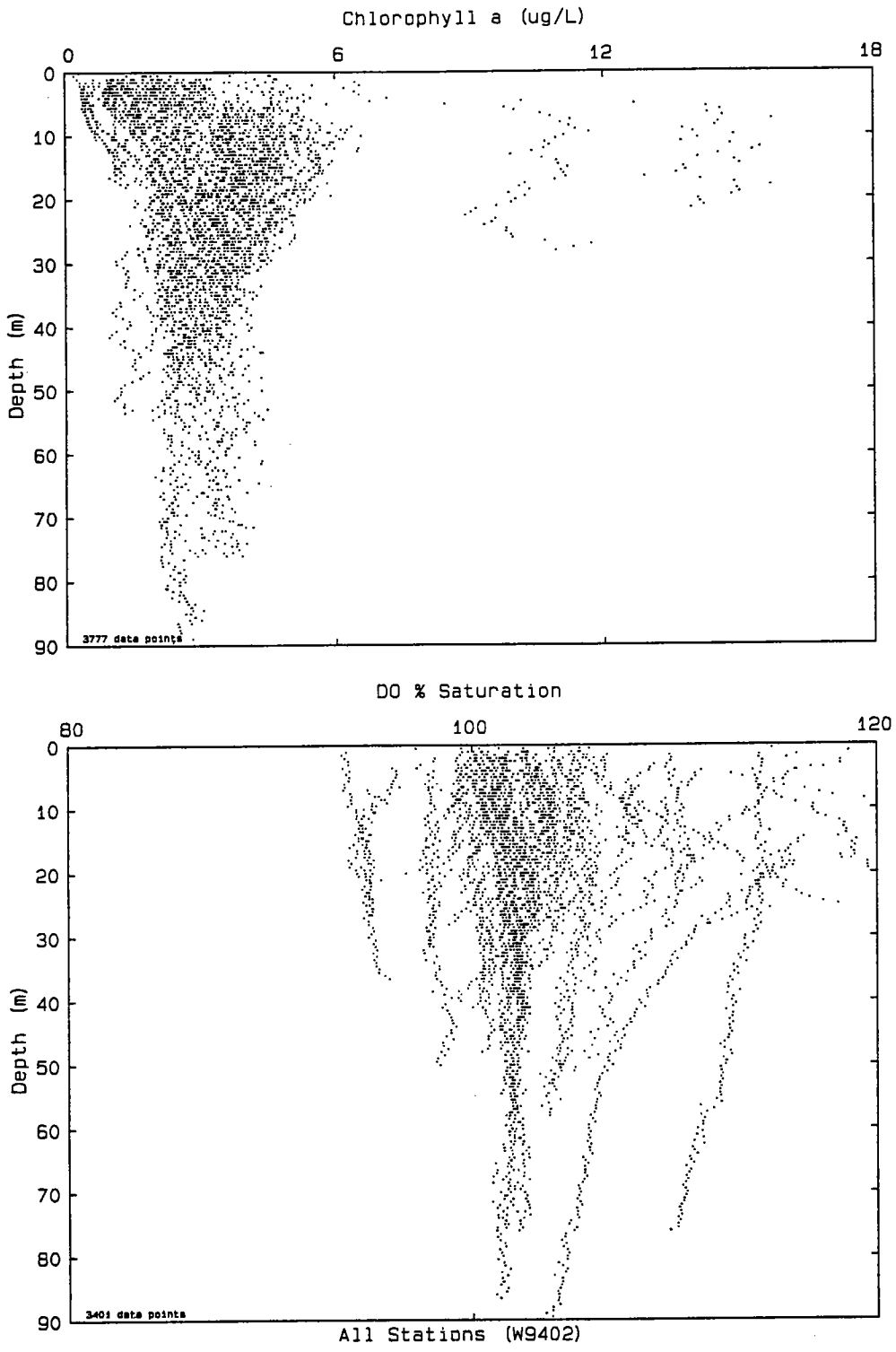


Figure 4-12b. Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in early March 1994.

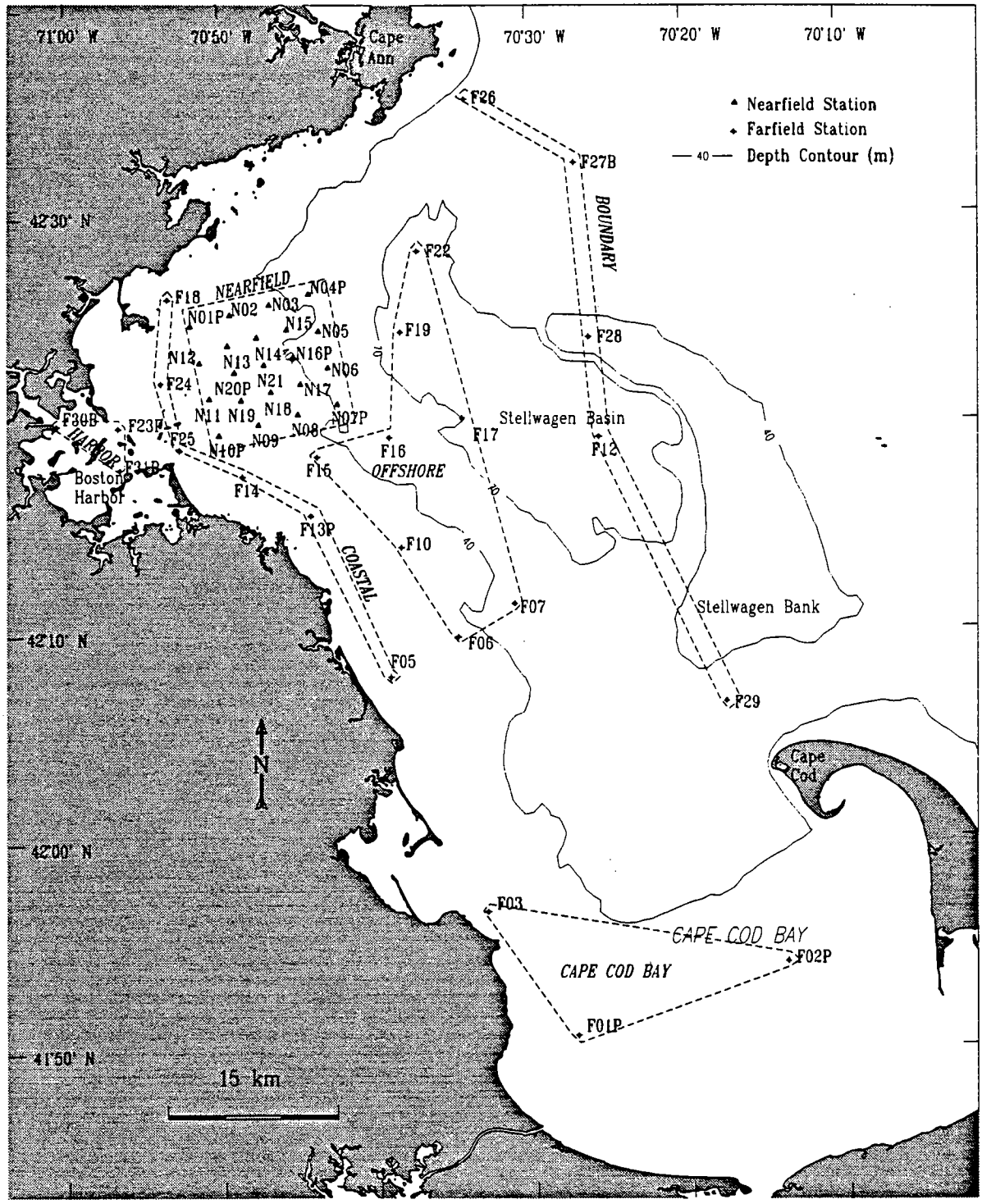


Figure 4-13. Map to show regional station groups designated in Figures 4-14 through 4-21.

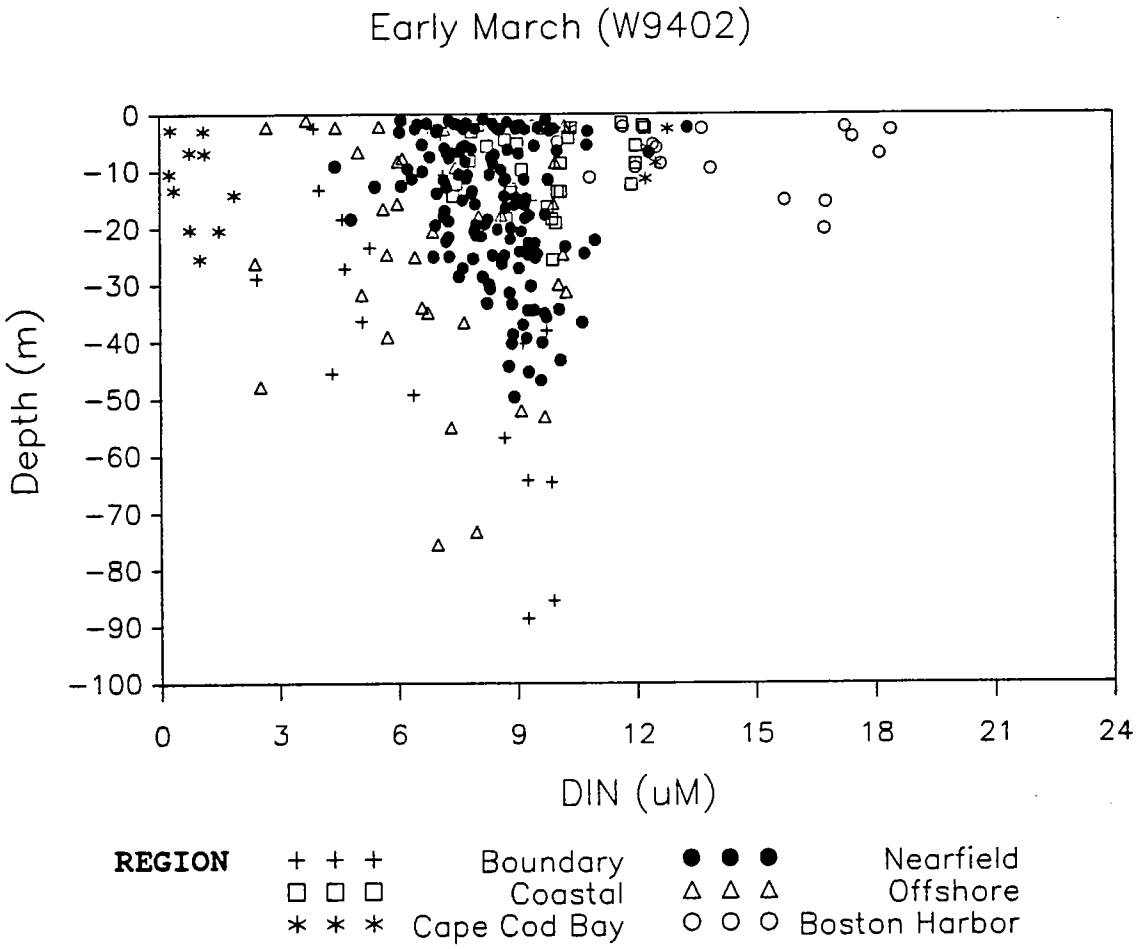


Figure 4-14a. DIN vs. depth in early March 1994.

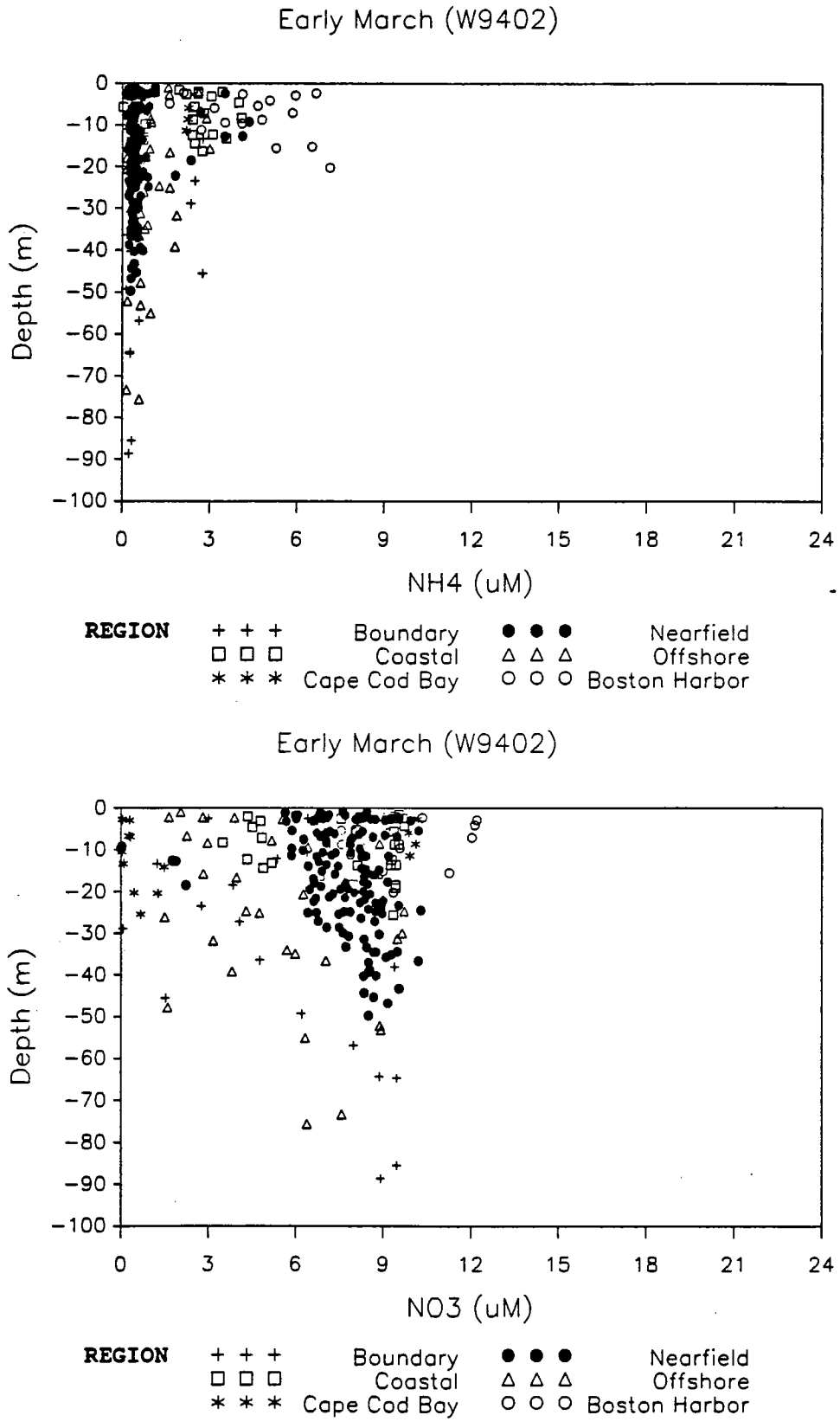


Figure 4-14b. NH_4 and NO_3 vs. depth in early March 1994.

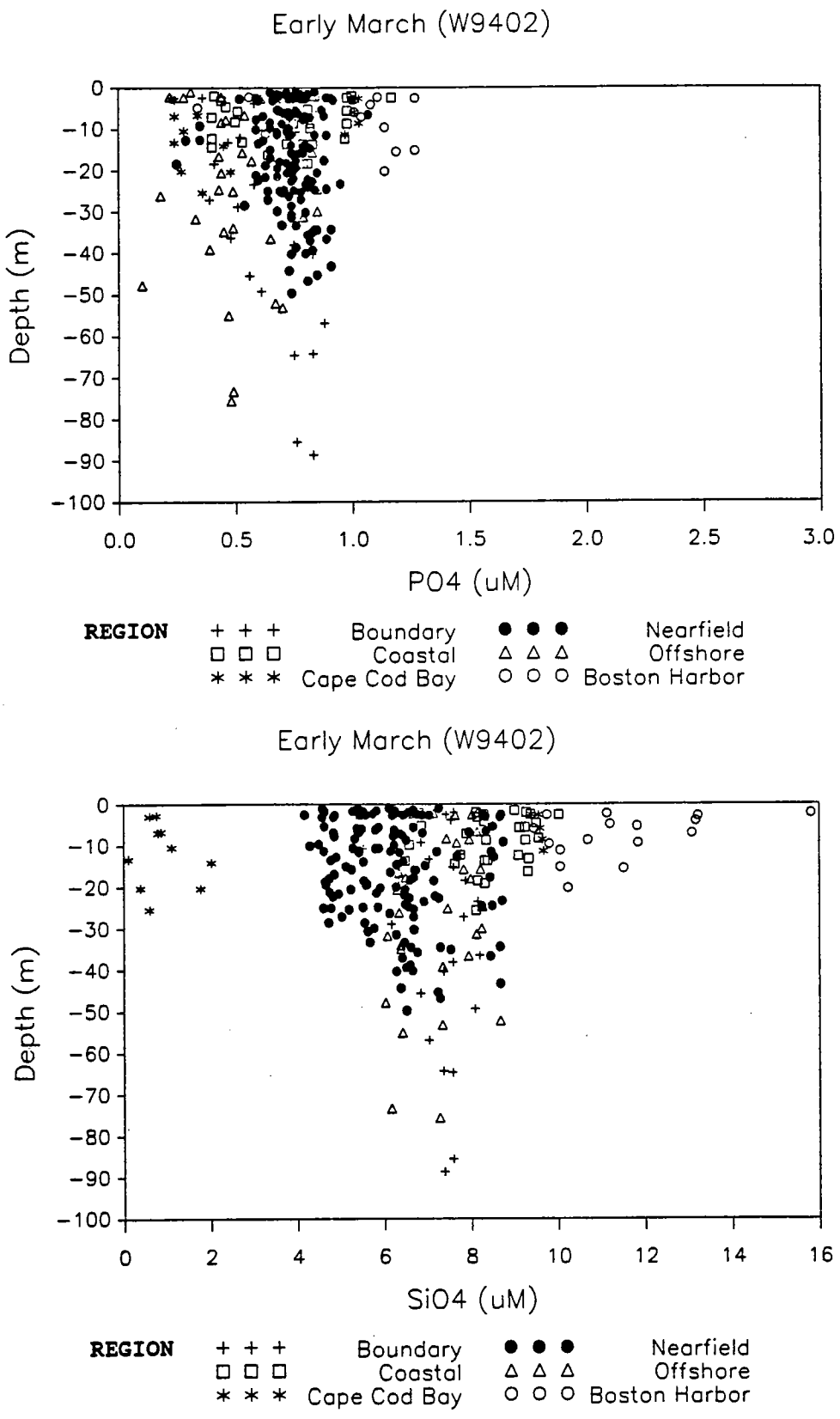
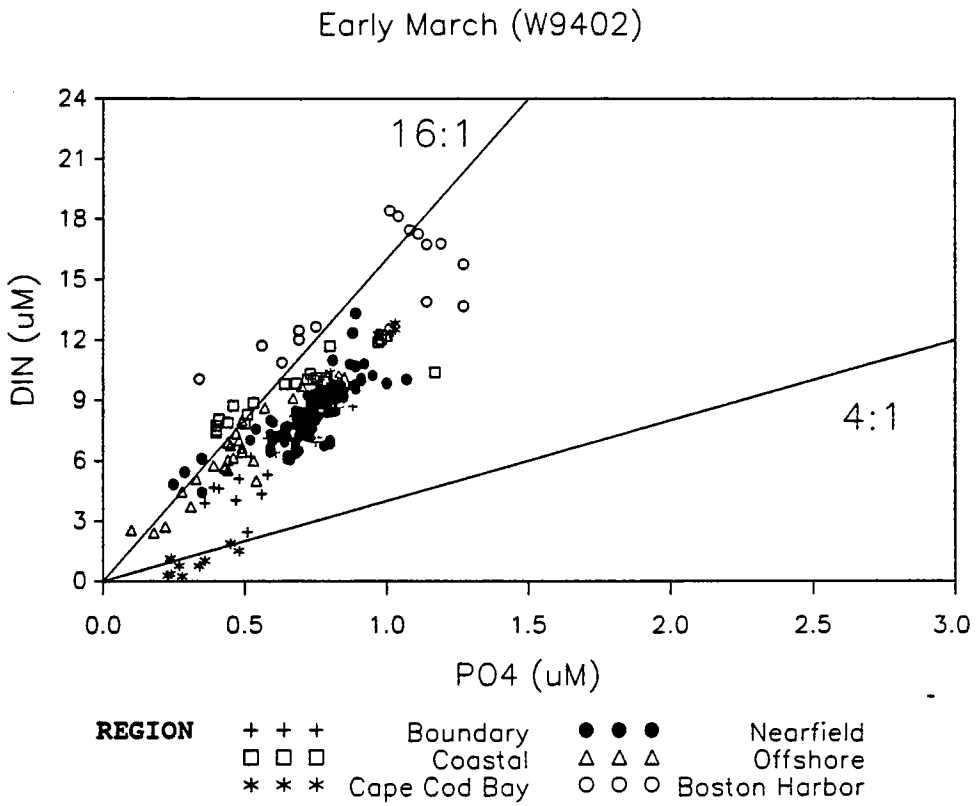


Figure 4-14c. PO_4 and SiO_4 vs. depth in early March 1994.



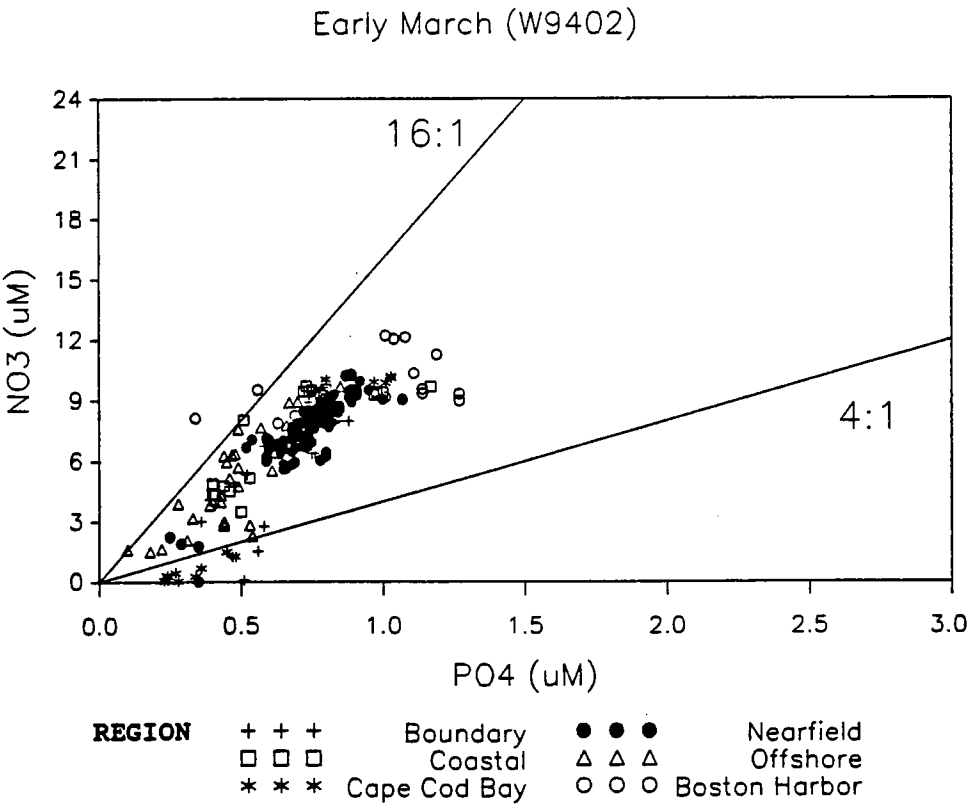
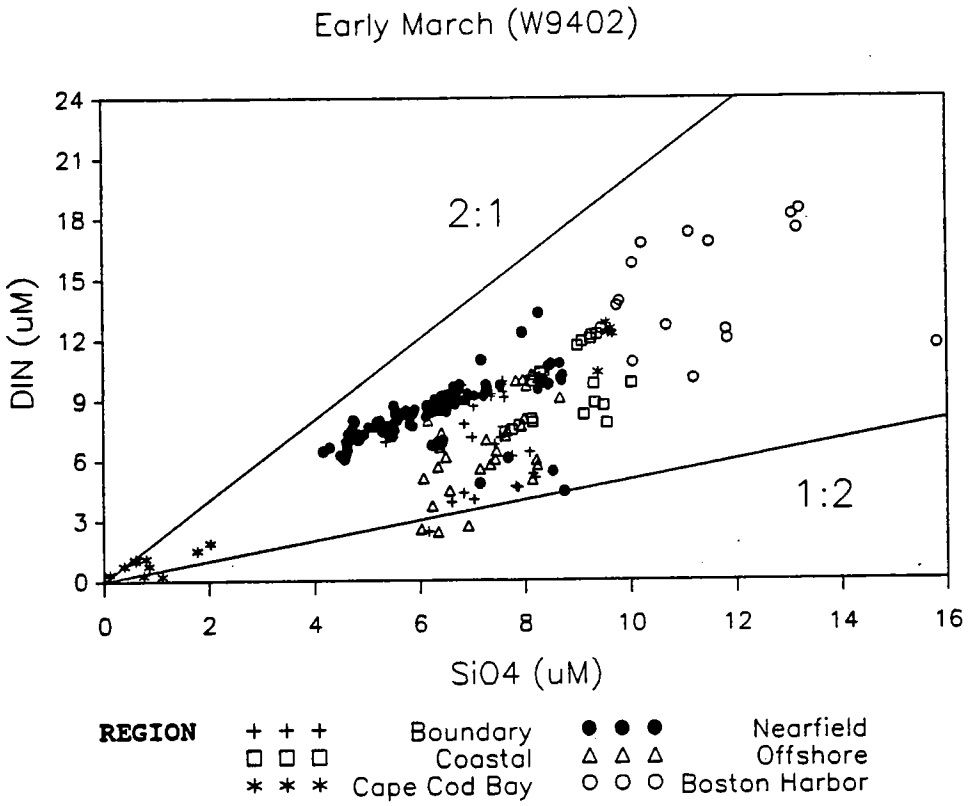


Figure 4-15a. Scatter plots of nitrogen forms vs. PO_4 in early March 1994. Lines show constant proportions of nitrogen relative to phosphate.



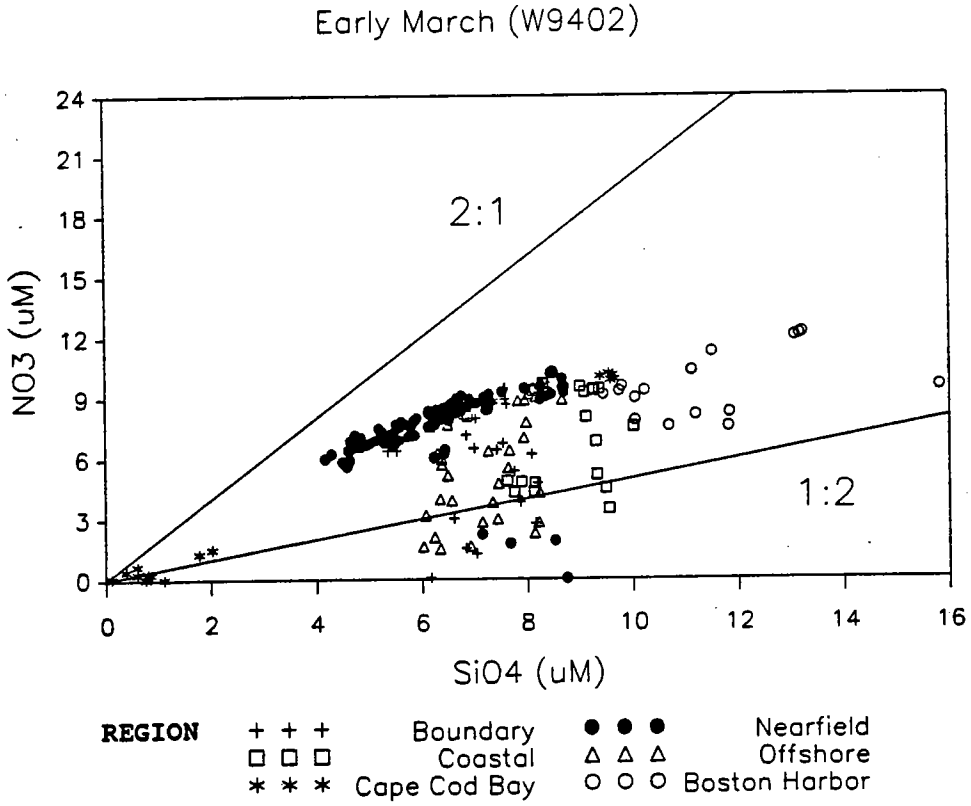


Figure 4-15b. Scatter plots of nitrogen forms vs. SiO_4 in early March 1994. Lines show constant proportions of nitrogen relative to silicate.

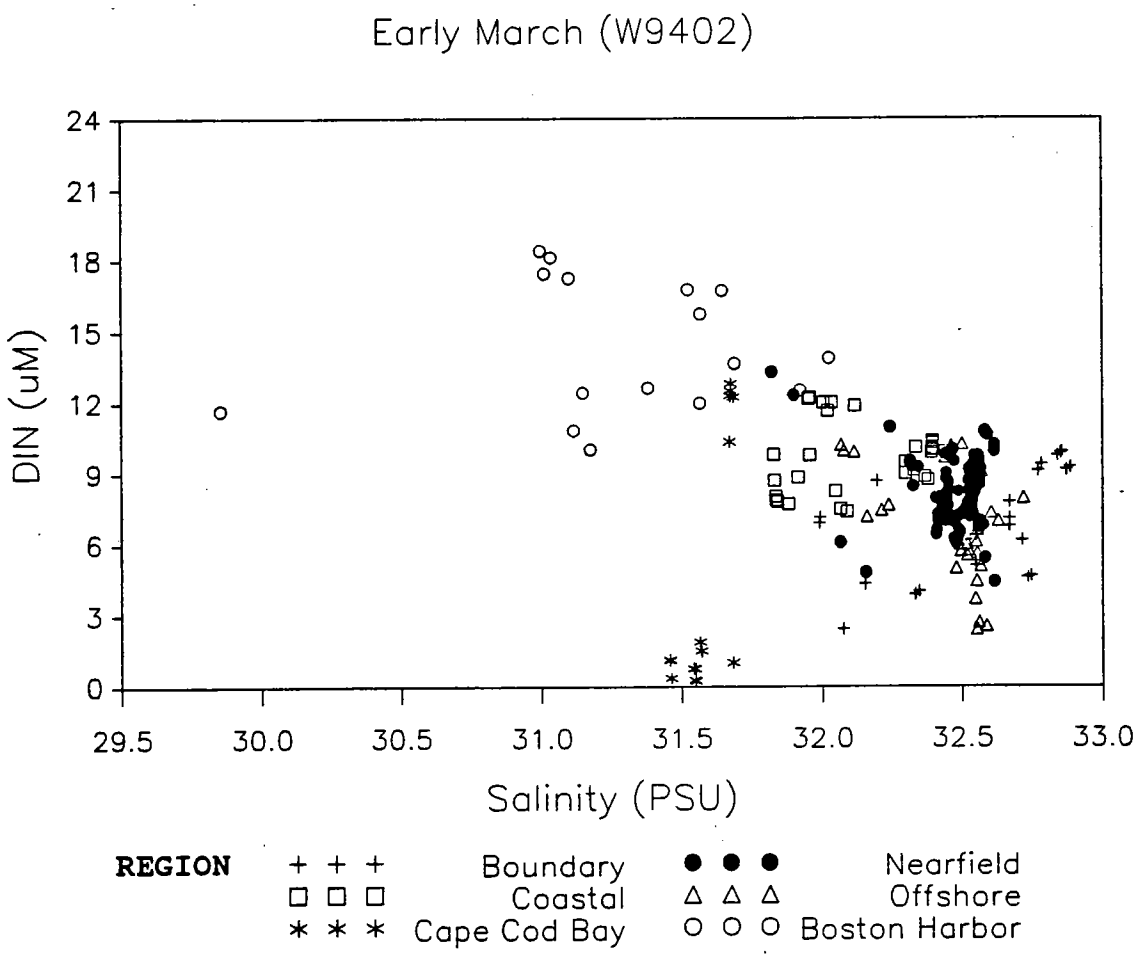
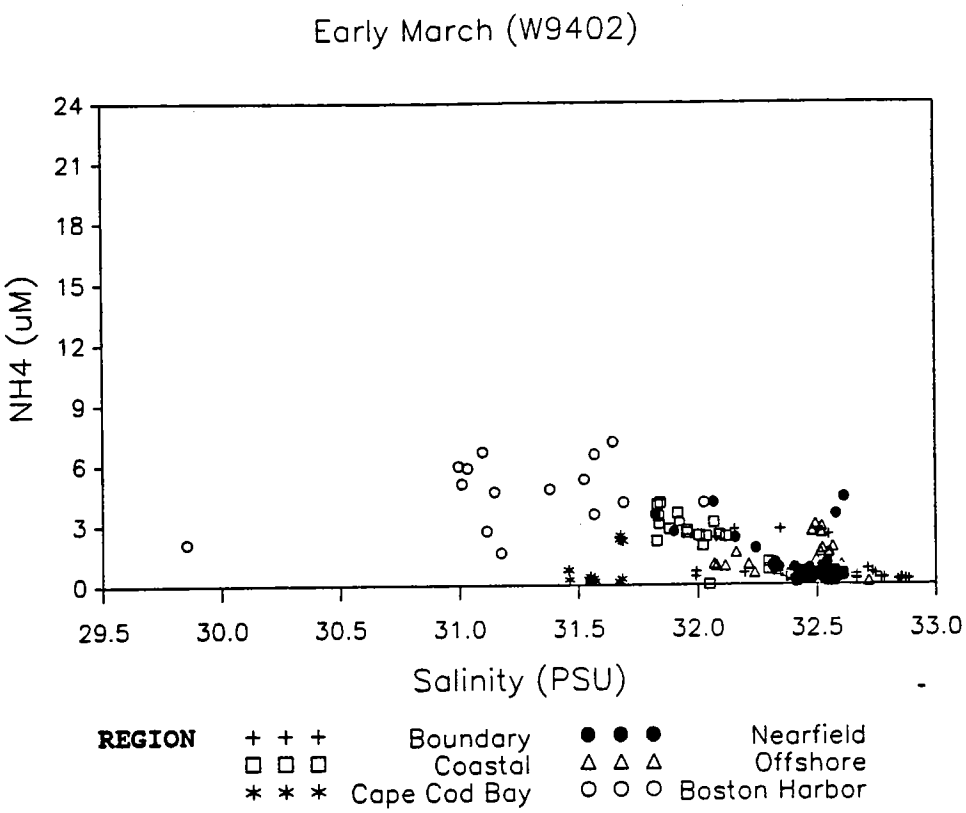


Figure 4-16a. DIN vs. salinity in early March 1994.



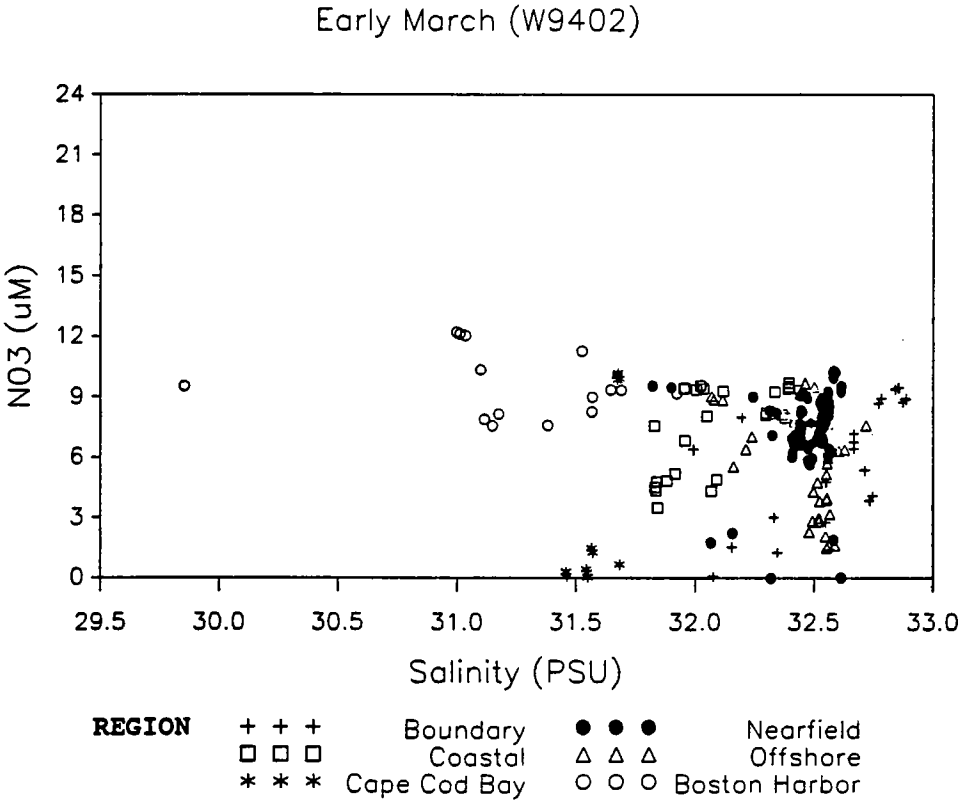
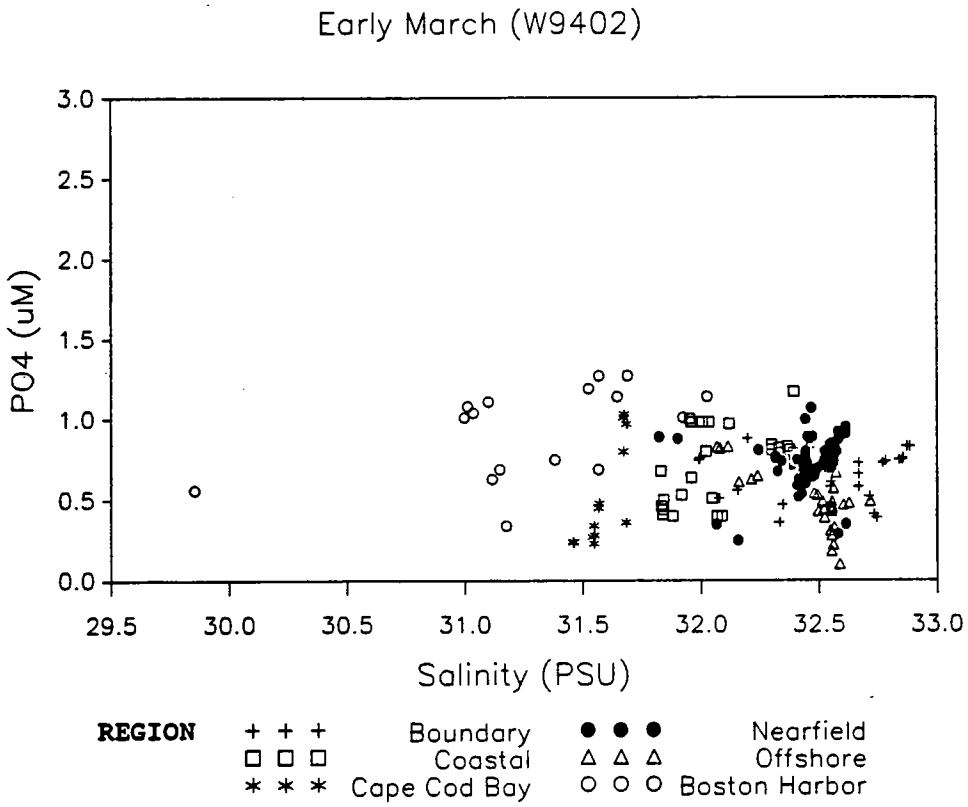


Figure 4-16b. NH_4 and NO_3 vs. salinity in early March 1994.



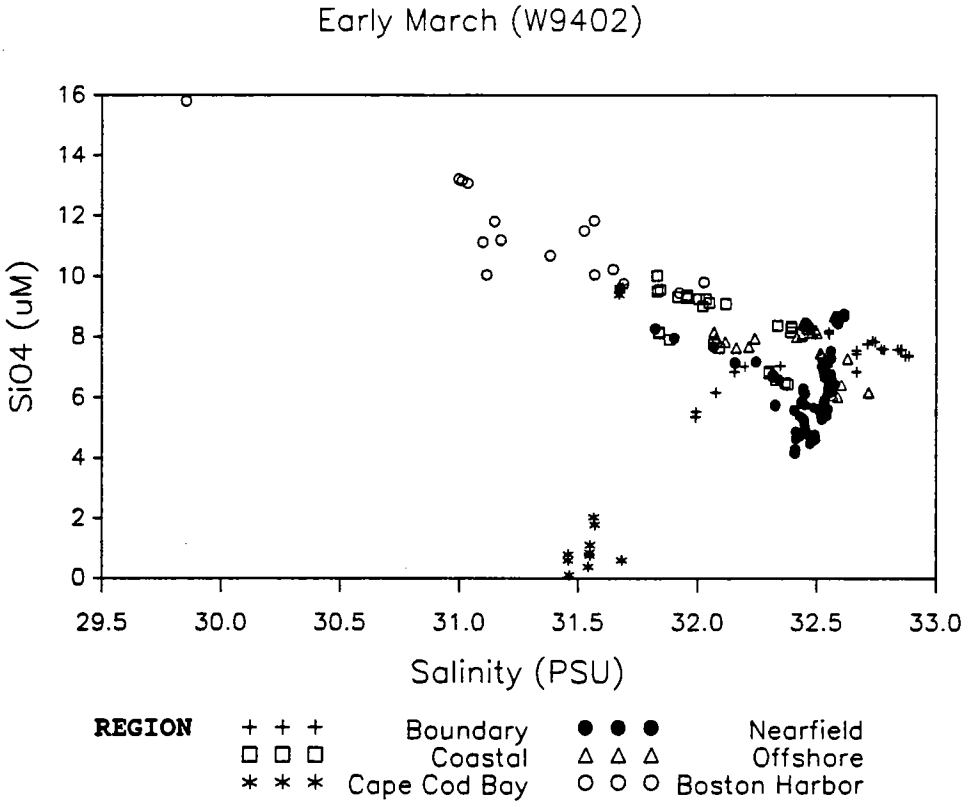


Figure 4-16c. PO_4 and SiO_4 vs. salinity in early March 1994.

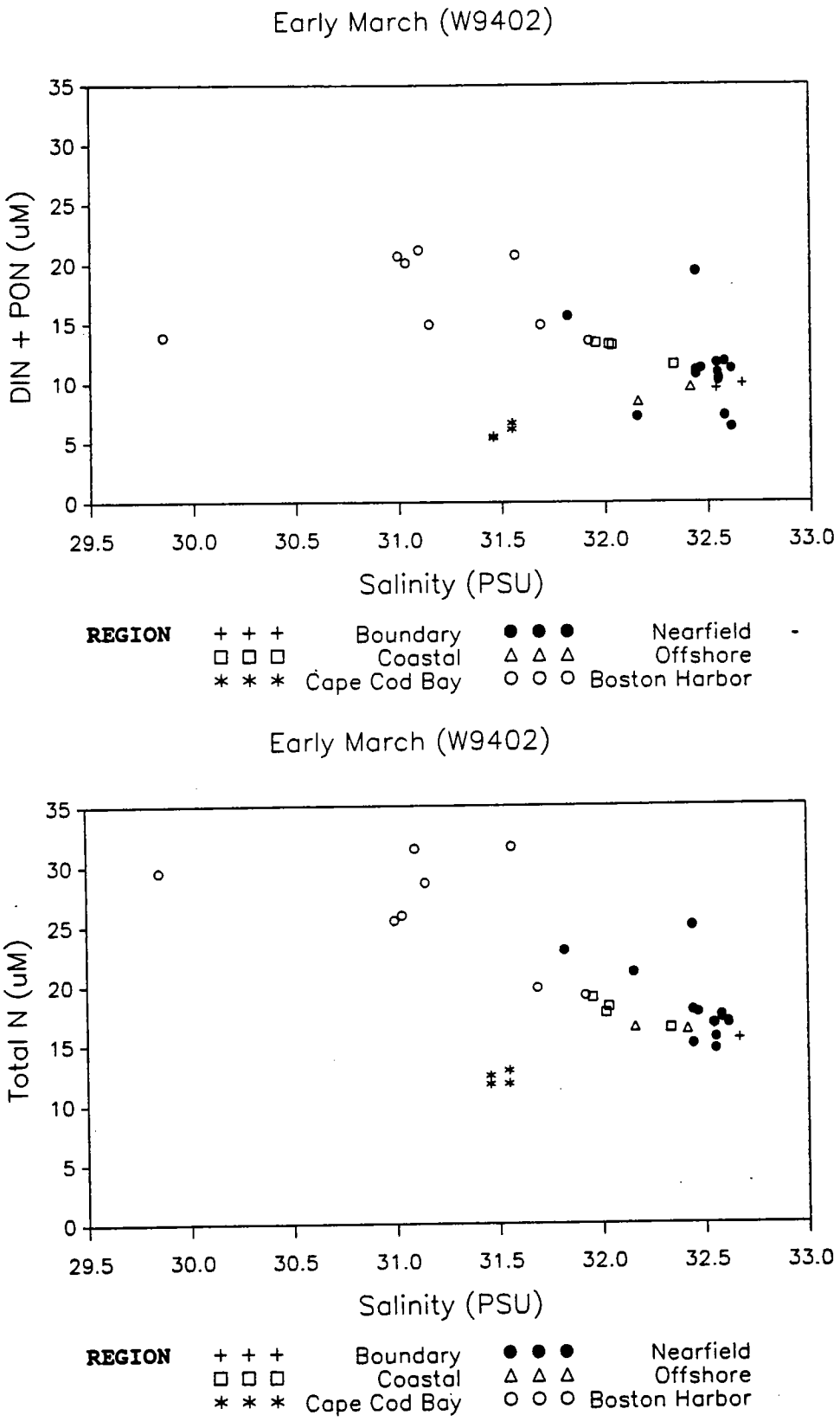


Figure 4-17. **Nitrogen forms vs. salinity in early March 1994. Dissolved inorganic nitrogen = DIN, Particulate organic nitrogen = PON, Total nitrogen (TN) = Total dissolved nitrogen (TDN) + PON.**

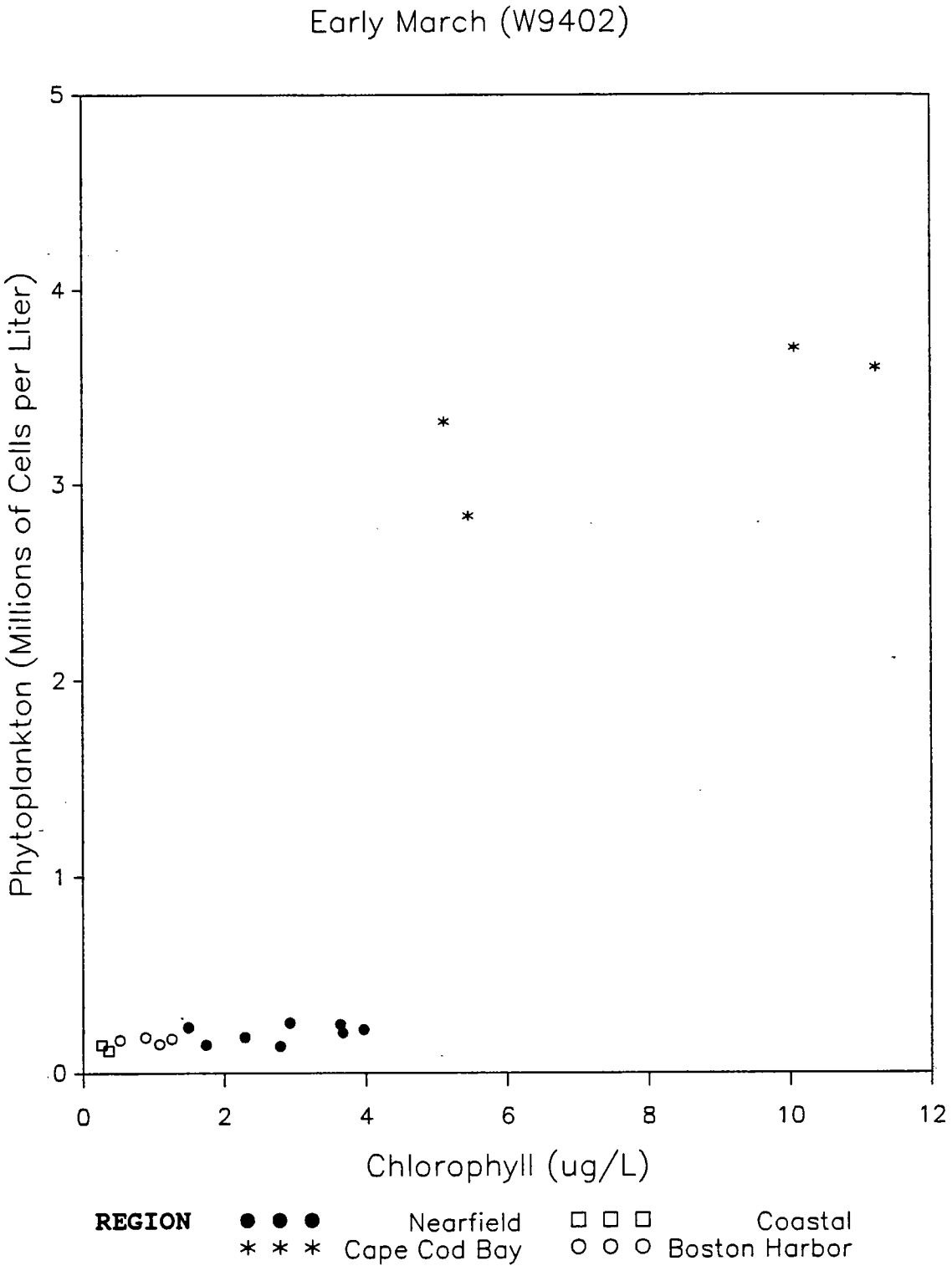


Figure 4-18. **Total phytoplankton abundance vs. chlorophyll (extracted samples) at B/P stations in early March 1994.**

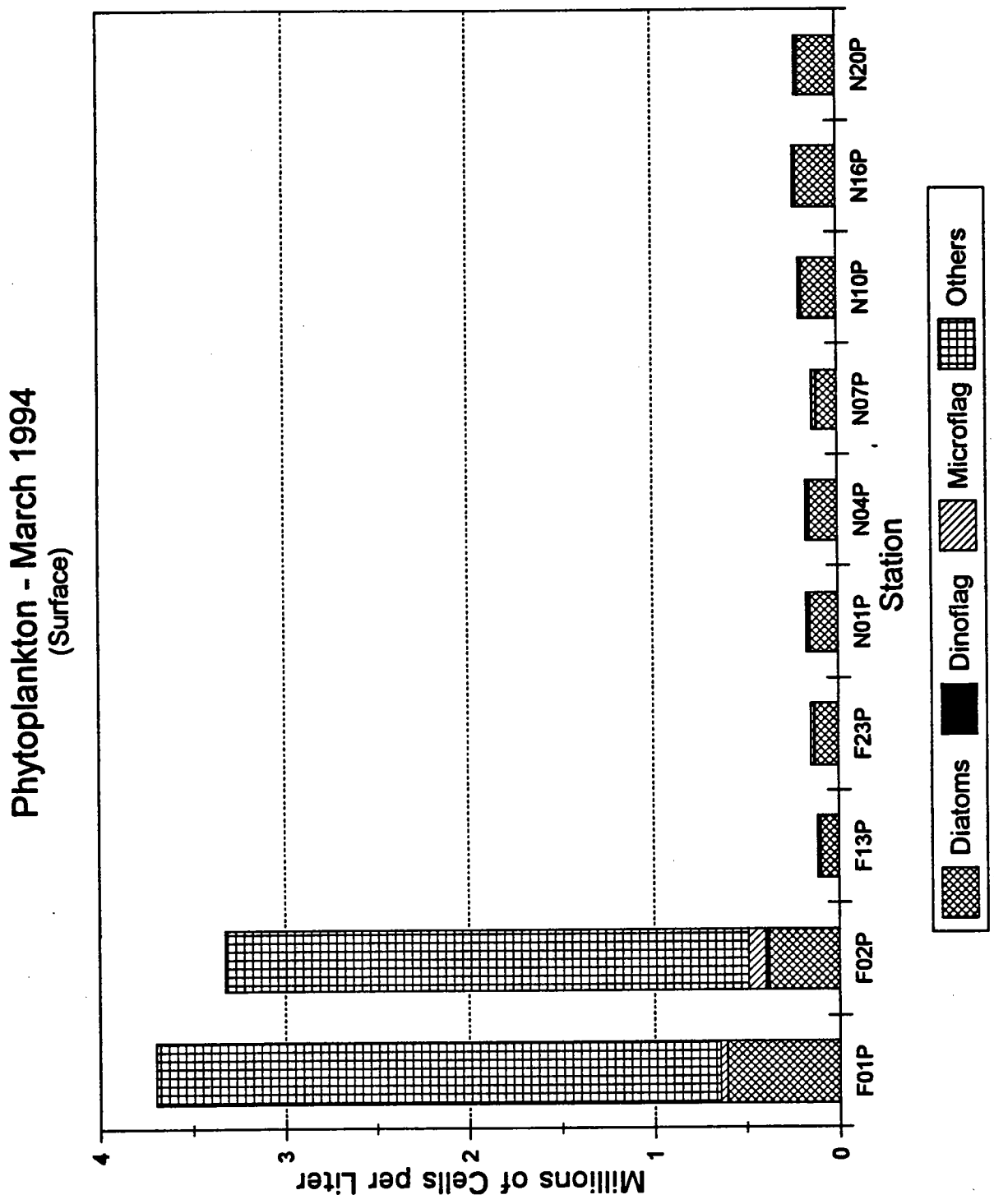


Figure 4-19. Total phytoplankton abundance, by taxonomic group, near the surface of B/P stations in early March 1994.

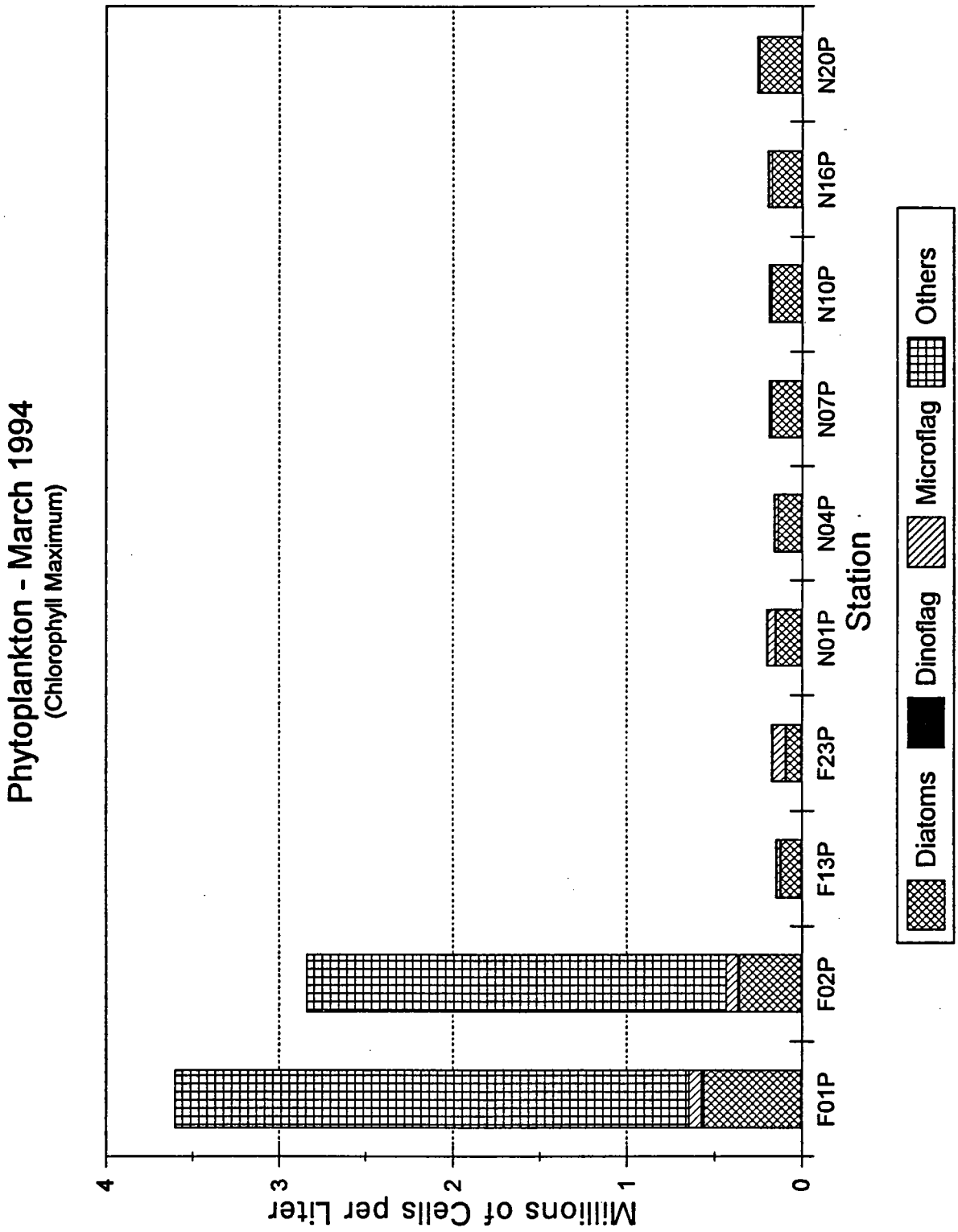


Figure 4-20. **Total phytoplankton abundance, by taxonomic group, near the chlorophyll maximum of B/P stations in early March 1994.**

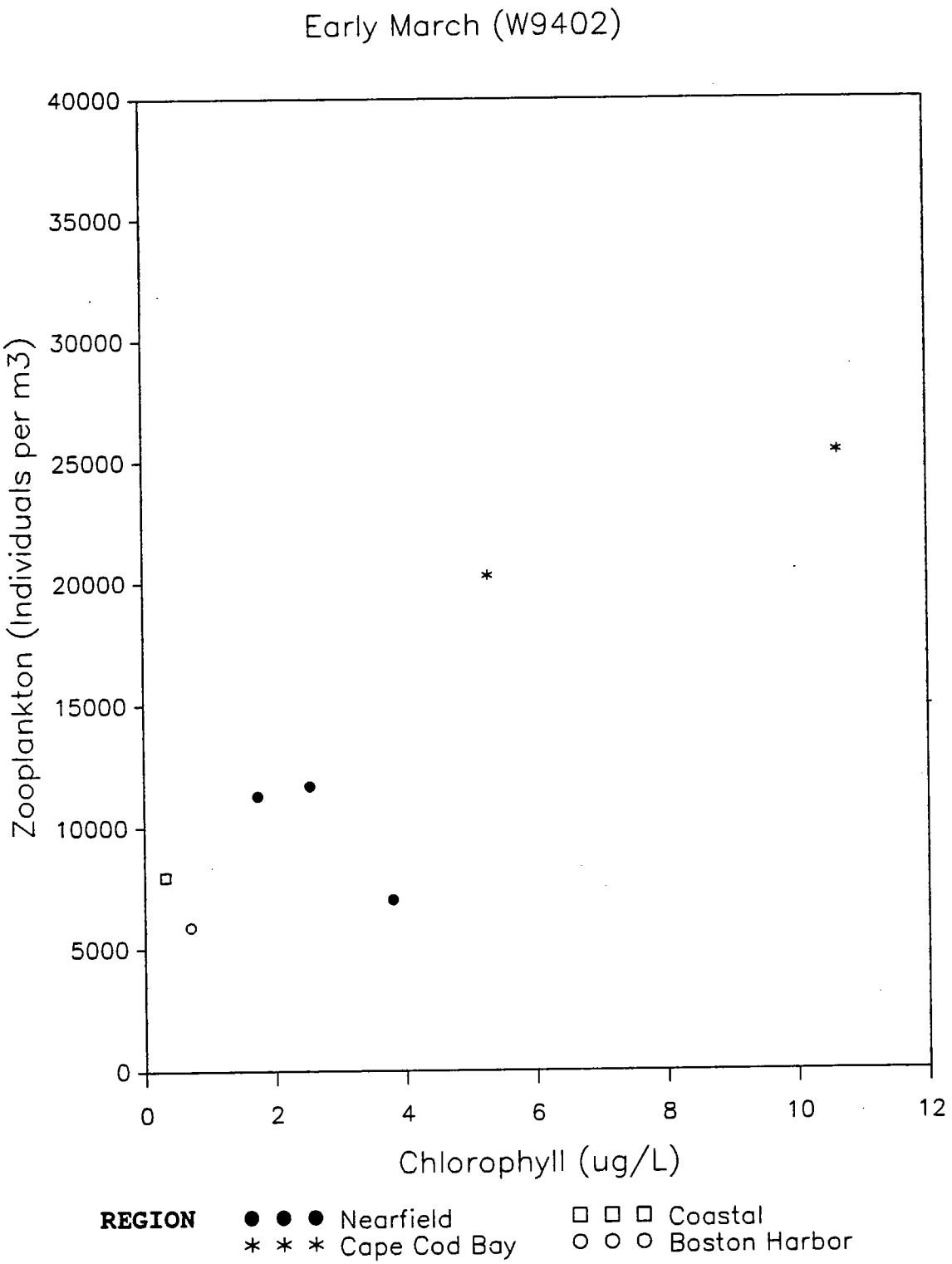


Figure 4-21. **Zooplankton abundance vs. average chlorophyll concentration (extracted samples; n=4 per station) for early March 1994.**

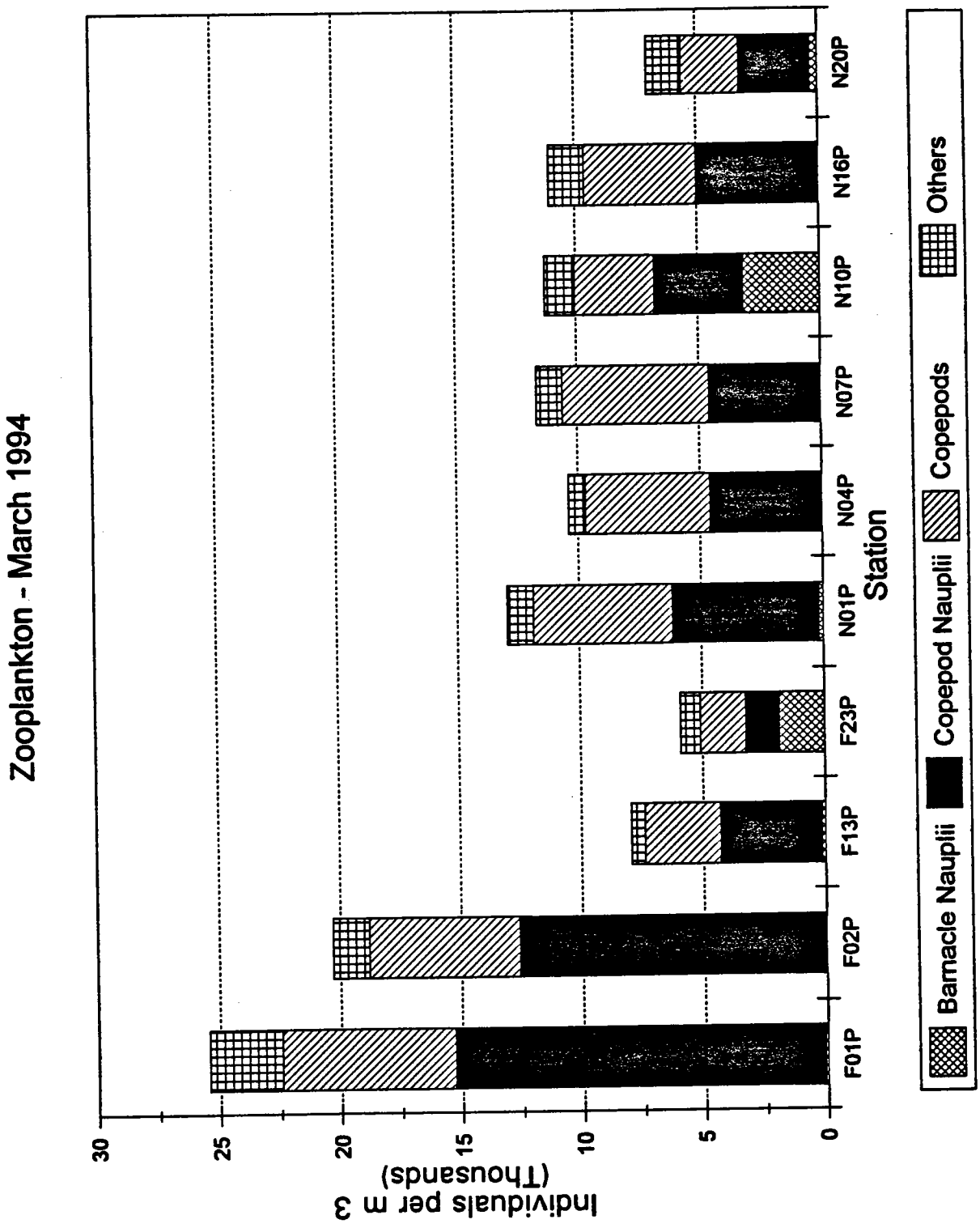


Figure 4-22. **Zooplankton abundance, by groups, at B/P stations in early March 1994.**

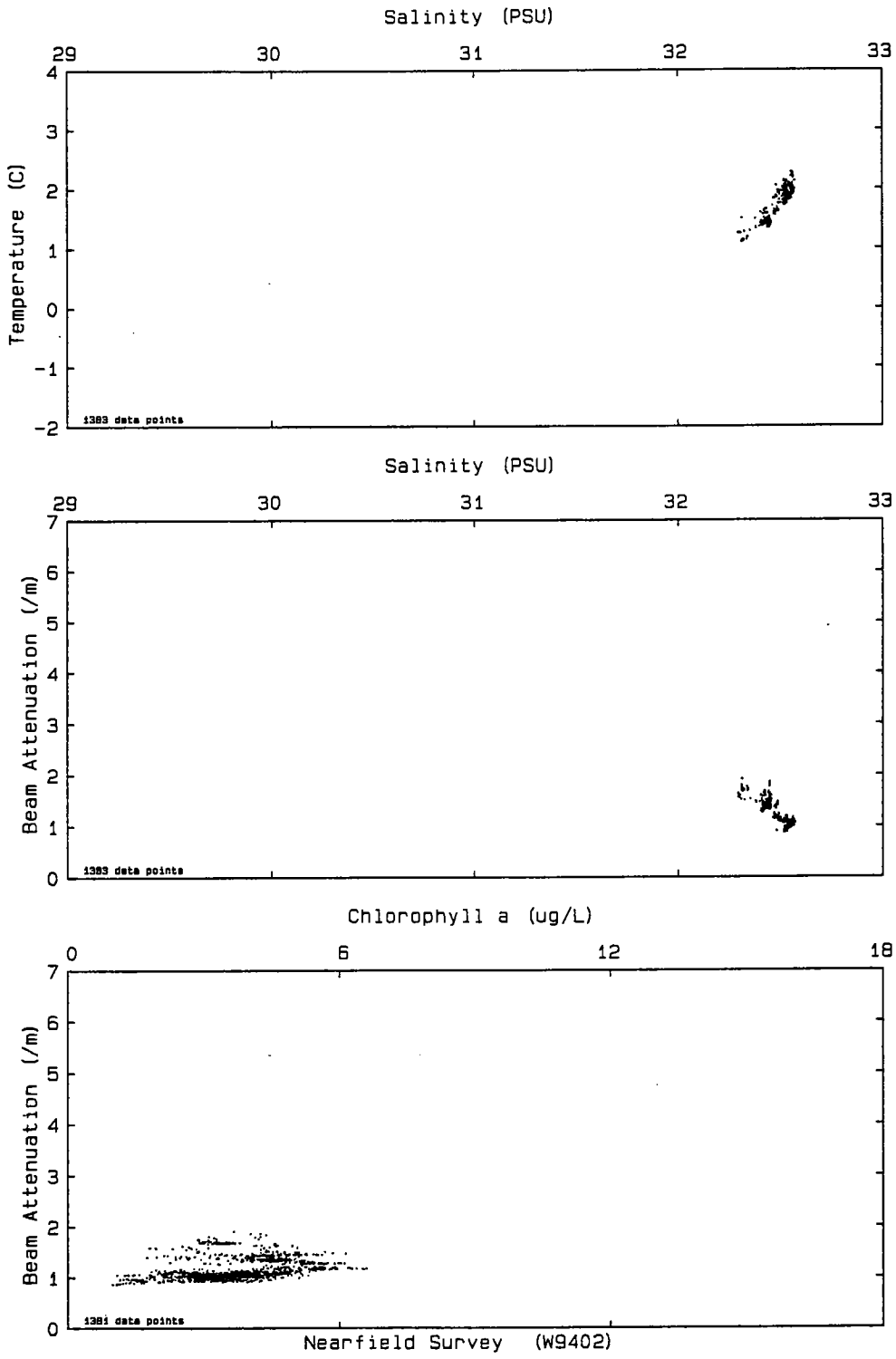


Figure 4-23a. **Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in early March 1994. Chlorophyll is estimated from *in situ* fluorescence.**

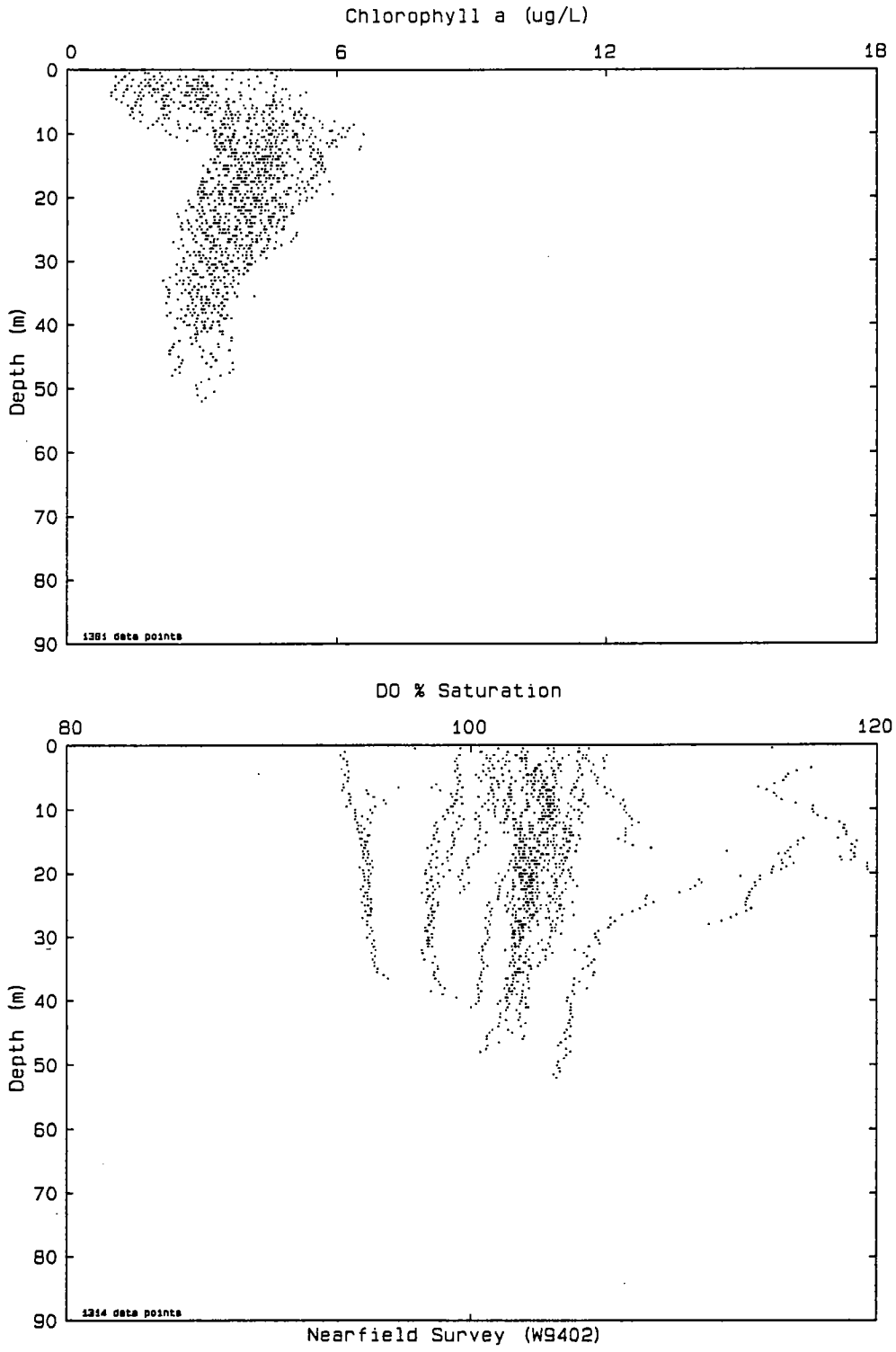


Figure 4-23b. Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in early March 1994. Chlorophyll is estimated from *in situ* fluorescence.

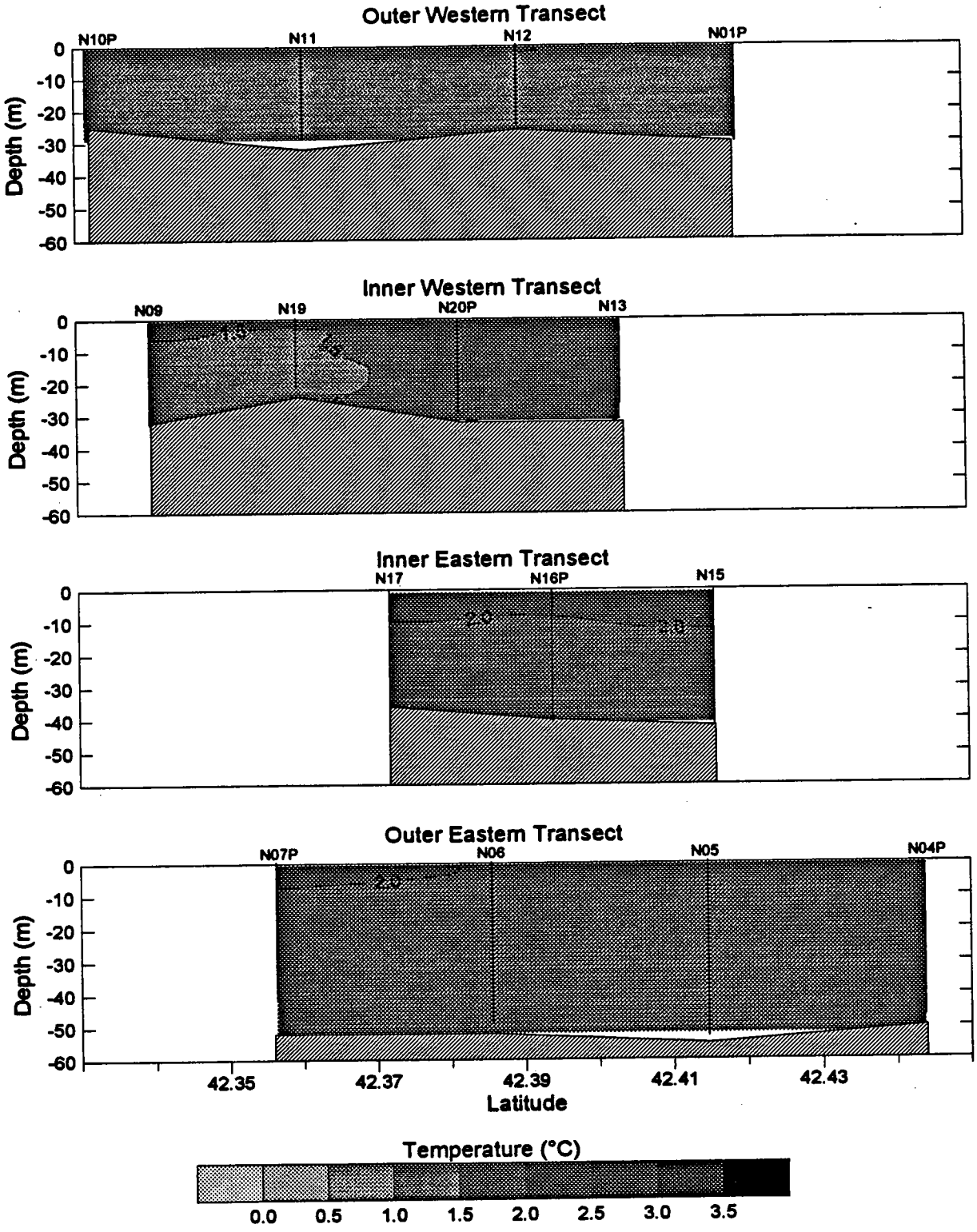


Figure 4-24a. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9402. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

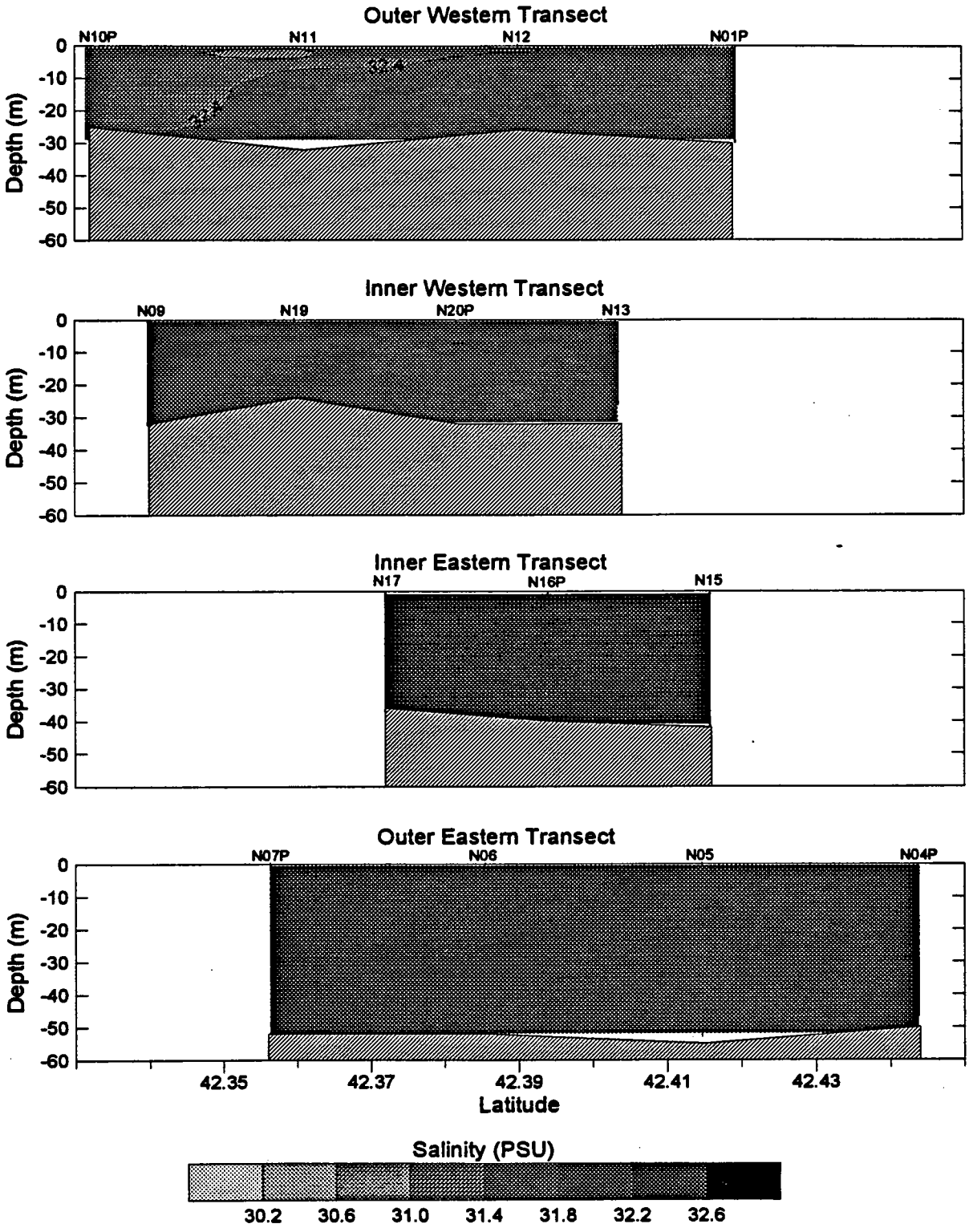


Figure 4-24b. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9402. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

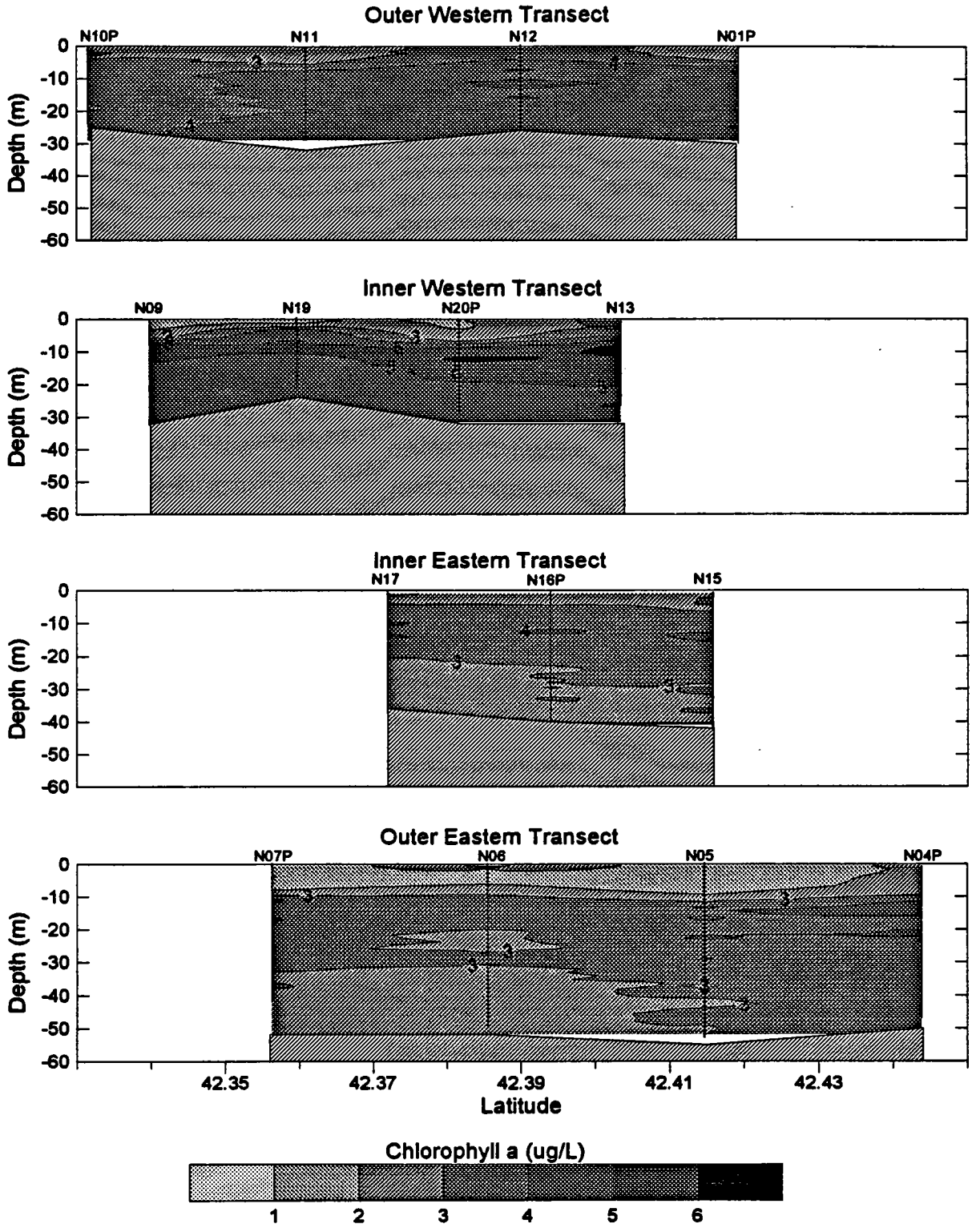


Figure 4-24c. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9402. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

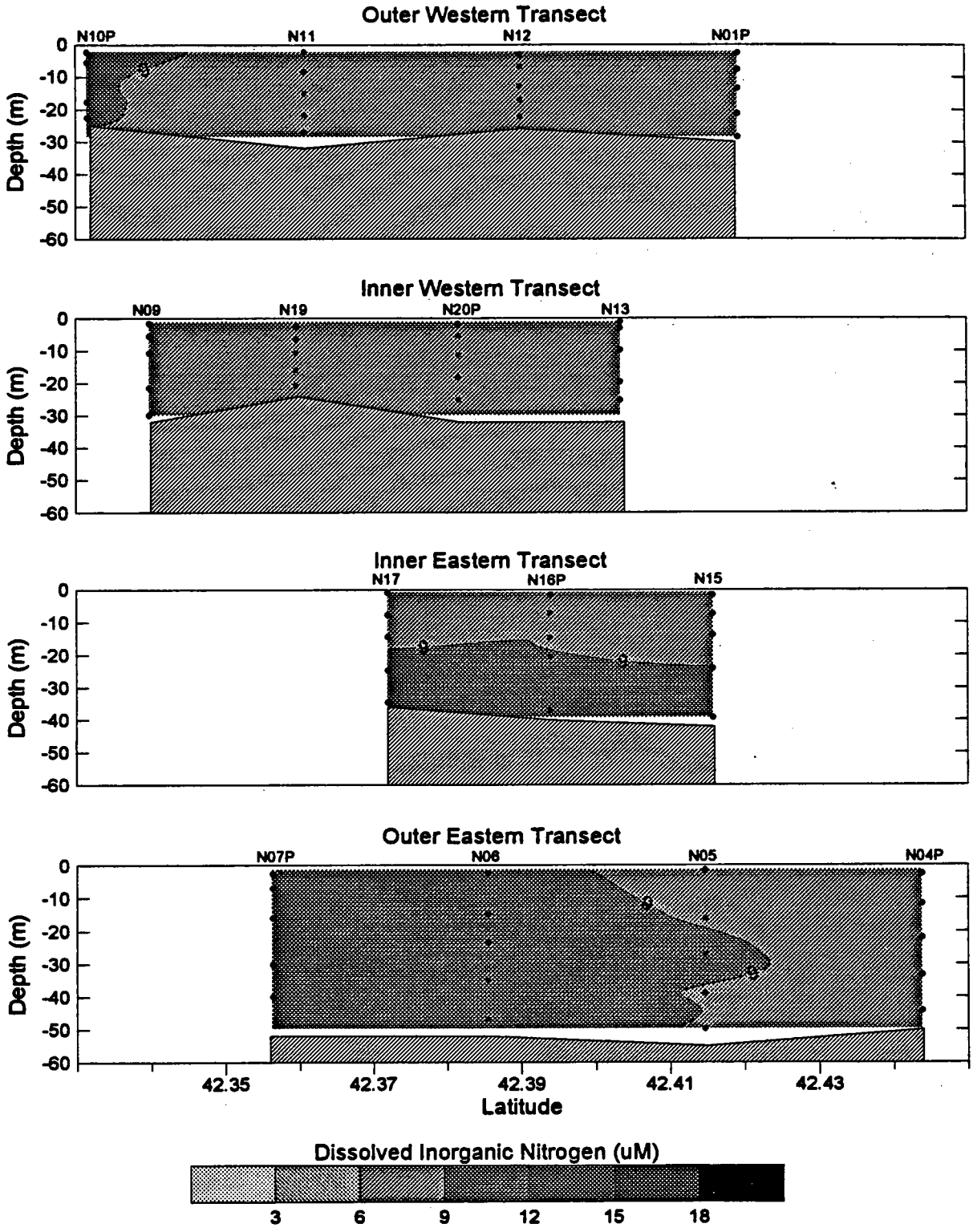


Figure 4-24d. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9402. The data used to produce the contours are from discrete bottle samples taken at each station during the nearfield sampling day (Appendix A).

5.0 RESULTS OF MARCH 1994 NEARFIELD SURVEY (W9403)

5.1 Distribution of Water Properties from Vertical Profiles

Vertical profiles were obtained at all 21 nearfield stations (Appendix B). Scatter plots of the *in-situ* sensor data are presented in Figure 5-1. Temperature varied by $<2°C$ and a salinity varied by about 0.8 PSU. The variation in temperature resulted from diurnal heating of the surface water during the course of the sampling day (Appendix B). Salinity was highest in the deep waters to the northeast and east of the nearfield (>32.5 PSU; stations N03-N06 and N15). The surface-water salinity was relatively low (<32 PSU) at these stations, and due to this vertical gradient in salinity, there was a distinct halocline (and pycnocline) near 25 m (Appendix B).

Beam attenuation showed little variation and was ~1.0 m^{-1} with a slight decrease at higher salinity. Chlorophyll (as determined by fluorescence) ranged from 0 to 4 $\mu g\ L^{-1}$ and generally increased with turbidity (Figure 5-1a). There was a subsurface chlorophyll maximum (2 to 4 $\mu g\ L^{-1}$) between 10 and 20 m at each of the nearfield stations (Figure 5-1b). Because of damage to the probe, no dissolved oxygen data were obtained during survey W9403 (see Albro, 1994).

Concentrations of dissolved nutrients were related to depth, with the highest concentrations of all nutrients found in the deeper (>25 m) offshore waters of the eastern nearfield (Figure 5-2). Nutrient concentrations in late March were much lower than they had been during the previous nearfield survey (early March, W9402). DIN ranged from 0 to 8.8 μM, with concentrations $<3\ \mu M$ in the upper 25 m. Similar depth-related patterns were observed for the distribution of NH_4 (0 to 2.3 μM) and NO_3 (0 to 6.4 μM; Figure 5-2b). Both nitrogen forms were nearly depleted in the nearfield surface waters.

Phosphate and silicate distributions followed the same pattern as the nitrogen forms (Figure 5-2c). Both nutrients, however, were not depleted in the surface waters. The PO_4 concentrations ranged from 0.1 to

0.9 μM with concentrations >0.5 μM observed at depths >25 m. SiO_4 concentrations ranged from 0.2 to 5.0 μM and were <1 μM in the upper 20 m of the water column.

The nutrient-salinity plots showed a very tight relationship of increasing nutrient concentrations with increasing salinity (Figure 5-3), a contrast to observations in previous surveys, and a consequence of increasing salinity and nutrients with depth. At stations N04P and N06, there were anomalously low DIN, NO_3, NH_4, and PO_4 concentrations at higher salinity (>32.5 PSU; Figure 5-3; Appendix A). Silicate concentrations, however, showed very little scatter versus salinity.

5.2 Water Quality Variability in the Nearfield

Vertical contours of temperature, salinity, chlorophyll (as measured by fluorescence), and DIN are presented in Figure 5-4. The vertical profile data used to produce the contours were obtained over the course of a day: stations N10P (7 am) to N01P (9 am), stations N04P (10 am) to N07P (12 pm), stations N09 (1 pm) to N13 (2 pm), and N15 (3 pm) to N17 (4 pm). The diurnal development of thermal stratification is clearly illustrated in Figure 5-4a. The inshore-offshore gradients in temperature were minimal; slightly warmer bottom-water temperatures were detected at the western nearfield stations.

The halocline at about 25 m was evident at varying degrees over much of the nearfield region (Figure 5-4b). The vertical gradient in salinity was strongest to the northeast (stations N04P and N15) where less saline surface water was observed. The less saline water observed at these stations may have resulted from increased flow from northern river sources, but no farfield station data from north of the nearfield are available to confirm this possibility.

Chlorophyll distribution was closely associated with the halocline and pycnocline that were present near 25 m (Figure 5-4c). The subsurface chlorophyll maximum was usually found directly above the pycnocline. As indicated previously and shown in Figure 5-4d for DIN, nutrient concentrations were nearly depleted in the surface layer and only reached higher concentrations at depths below ~25 m. The availability of nutrients at depth contributed to the development of the subsurface chlorophyll distribution. There was an

inshore-offshore gradient in DIN (and PO_4 and SiO_4, Appendix B) that was driven by higher nutrient concentrations in the deeper bottom water of the eastern nearfield stations (Figure 5-4d). Despite the higher nutrient concentrations at depth to the east, there was little regional variability in chlorophyll in the nearfield.

The distributions observed for the physical and chemical parameters suggest the initiation of seasonal stratification. There were clear vertical gradients in salinity (and density) and nutrients at the eastern nearfield stations. The diurnal heating of the surface waters observed over the course of the sampling day aids in the development of a thermocline and density stratification.

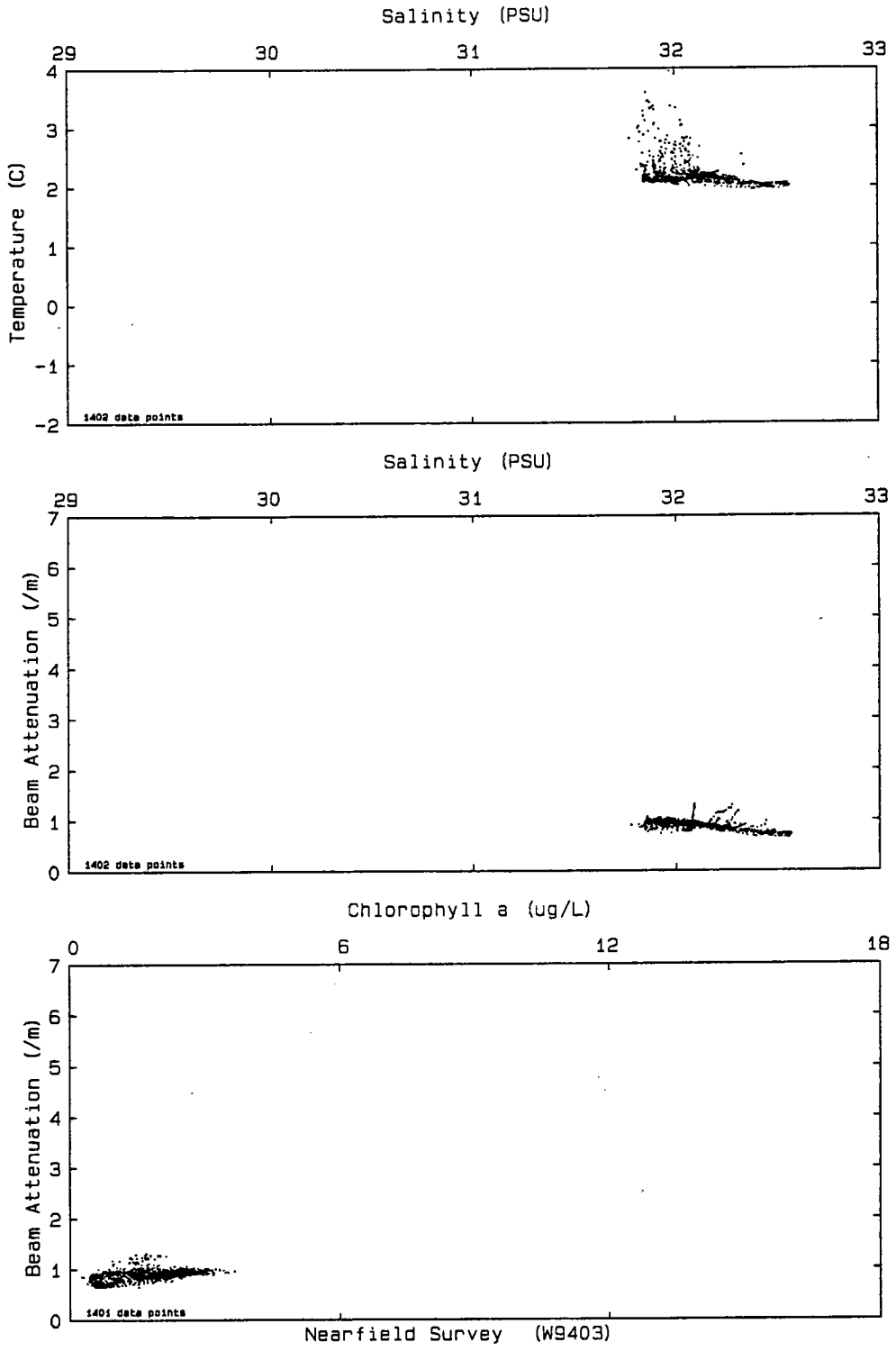


Figure 5-1a. **Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in late March 1994. Chlorophyll is estimated from *in situ* fluorescence.**

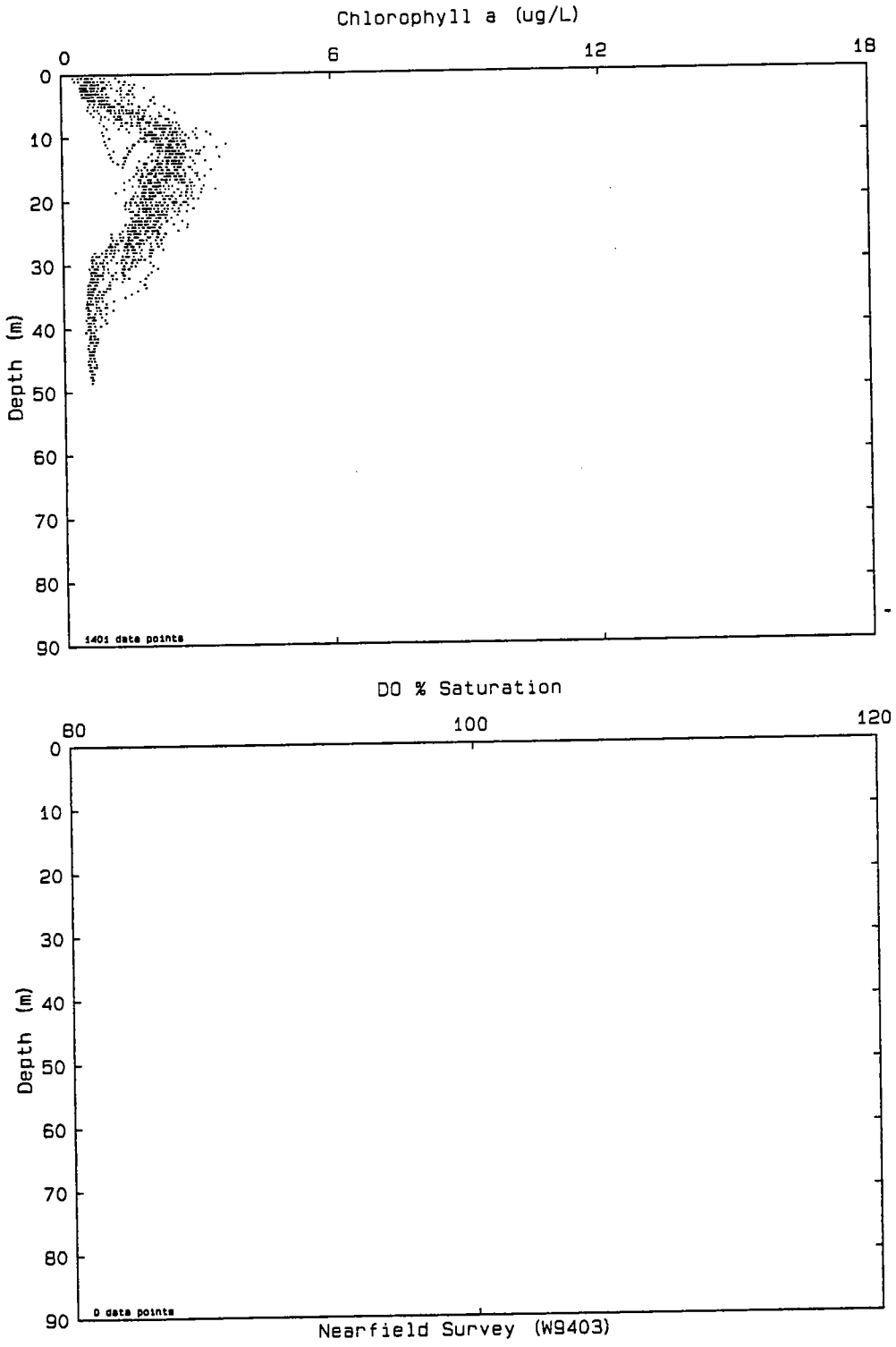


Figure 5-1b. **Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in late March 1994. Chlorophyll is estimated from *in situ* fluorescence.**

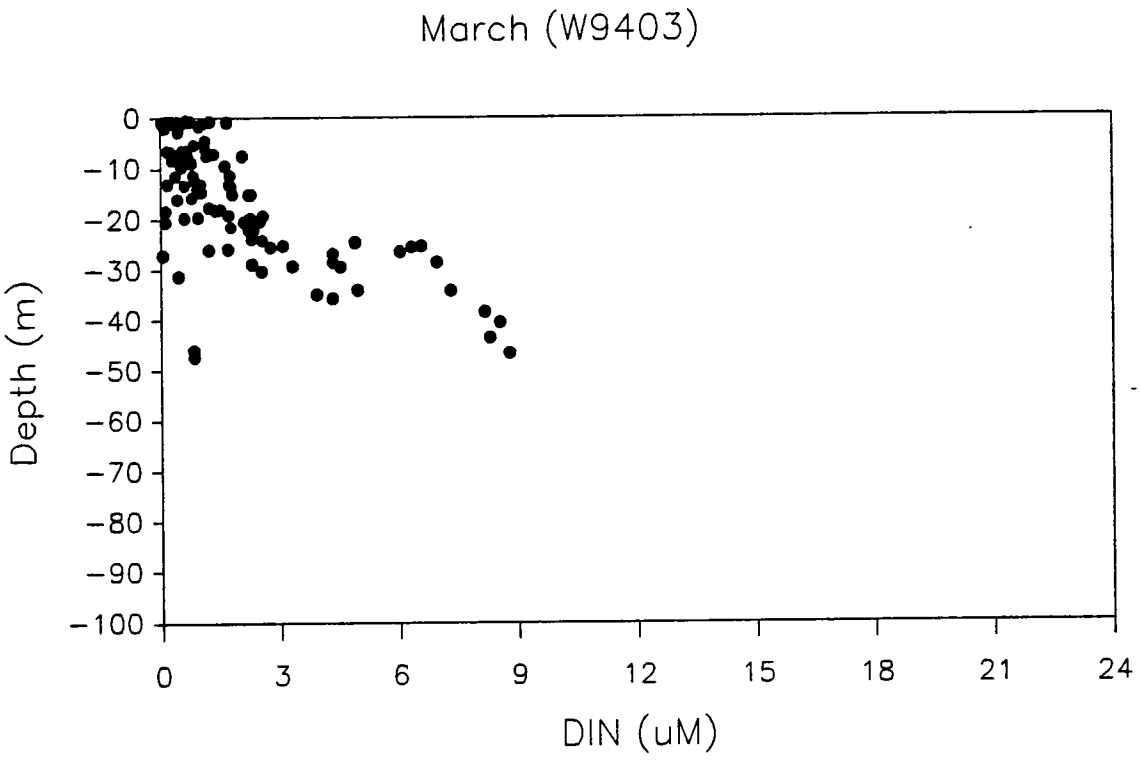
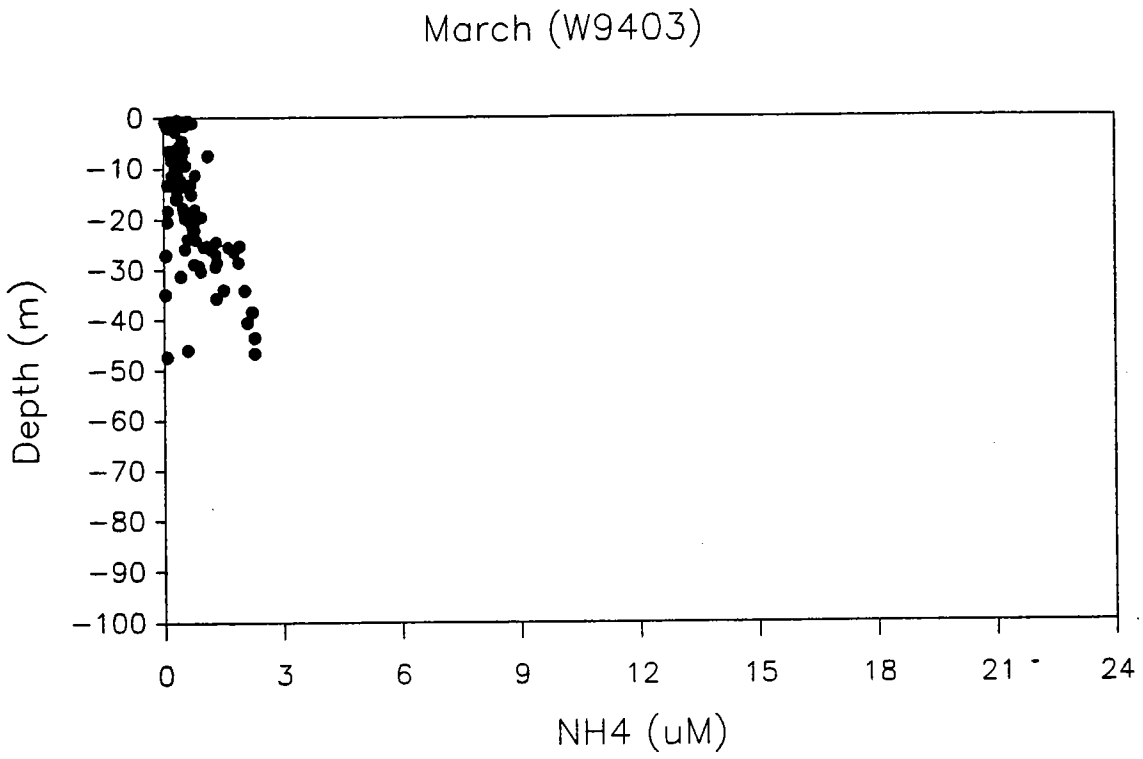


Figure 5-2a. DIN vs. depth in late March 1994.



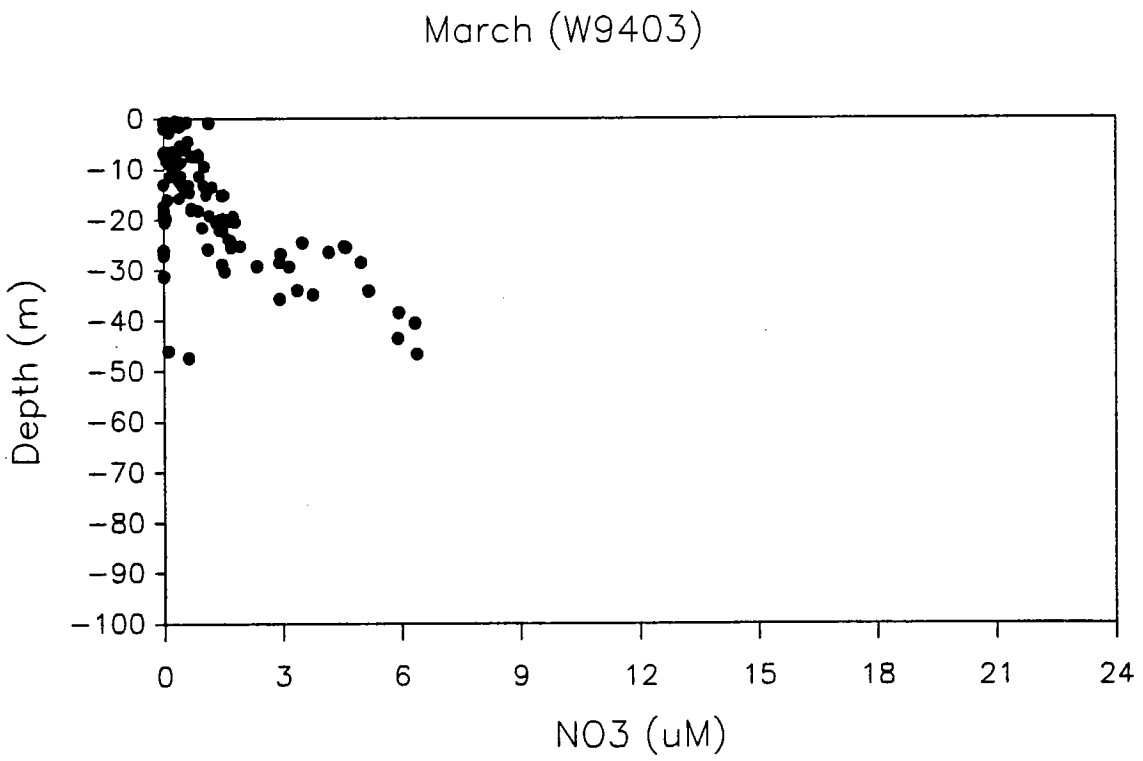
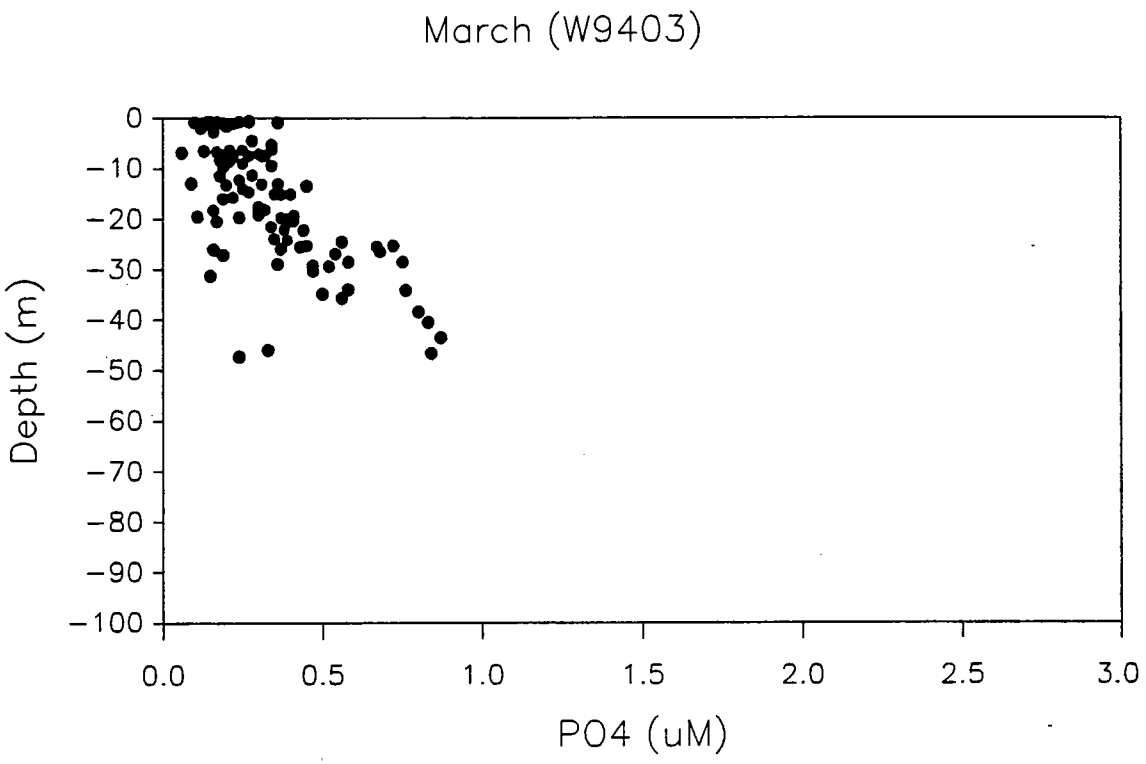


Figure 5-2b. NH_4 and NO_3 vs. depth in late March 1994.



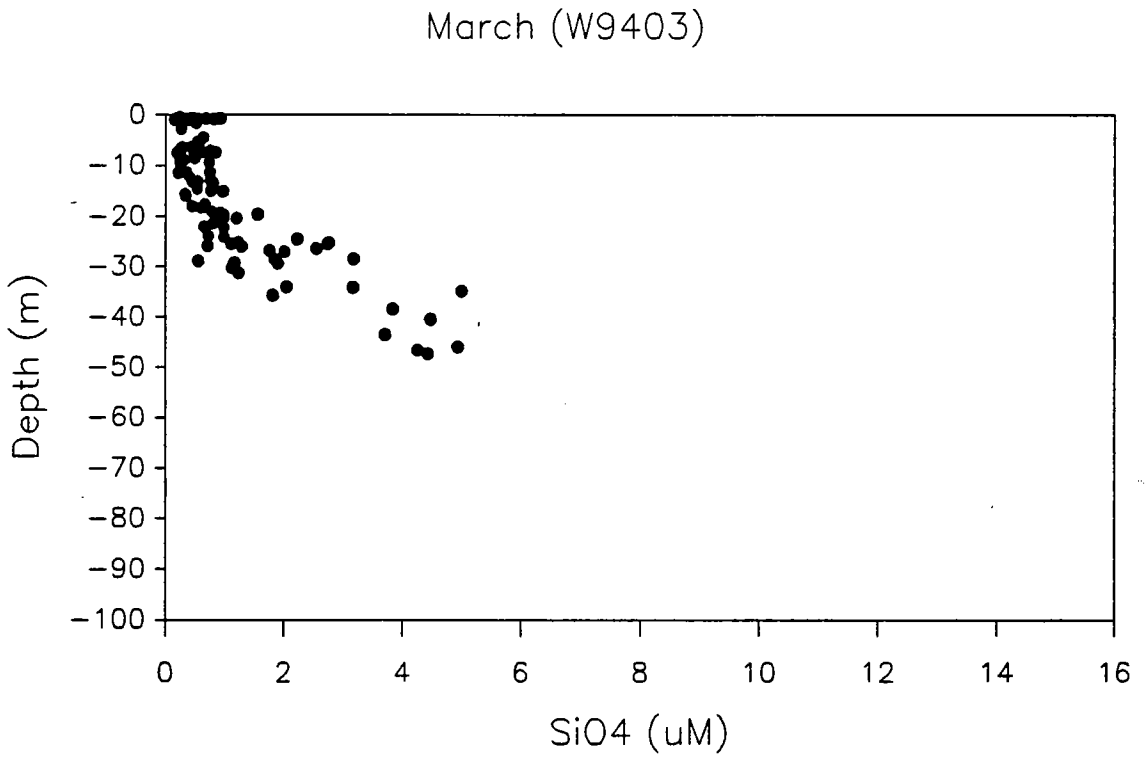


Figure 5-2c. **PO_4 and SiO_4 vs. depth in late March 1994.**

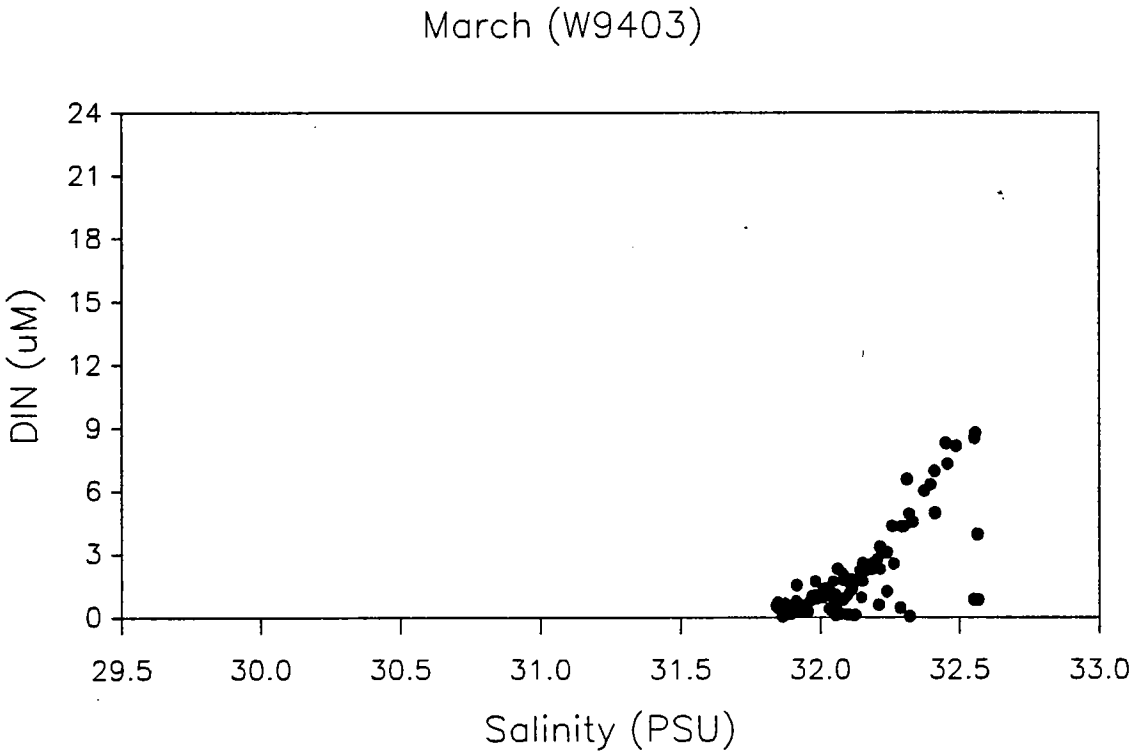
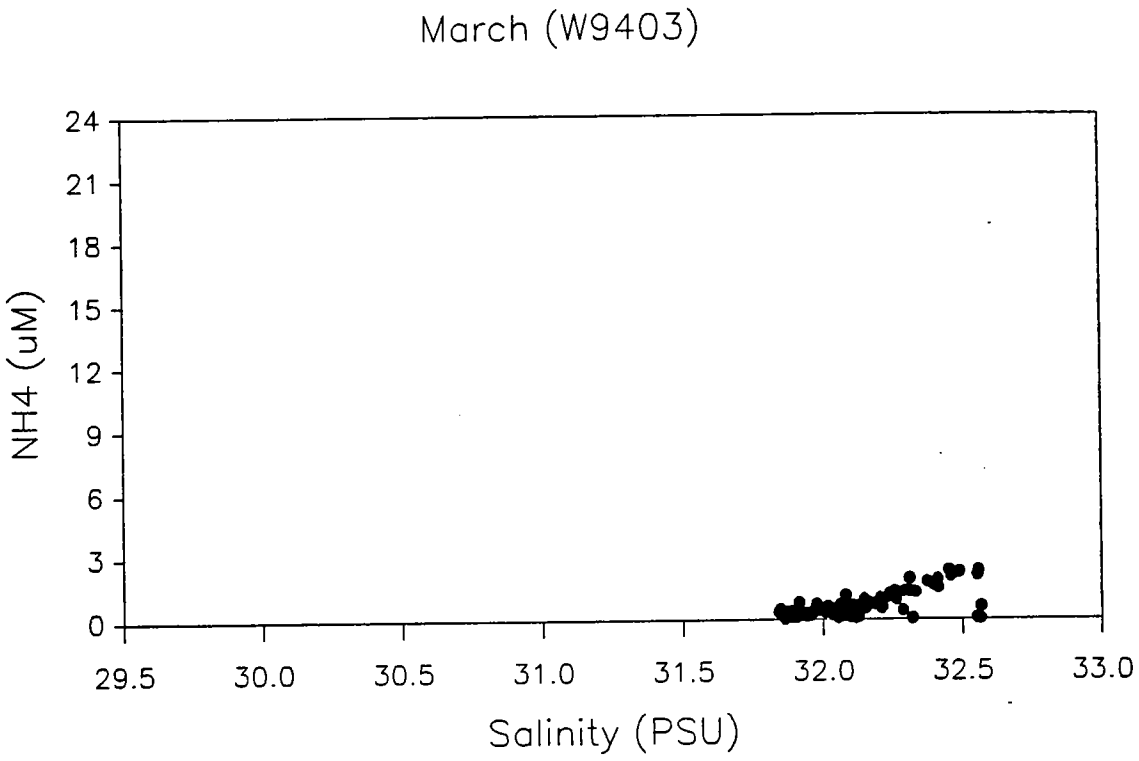


Figure 5-3a. DIN vs. salinity in late March 1994.



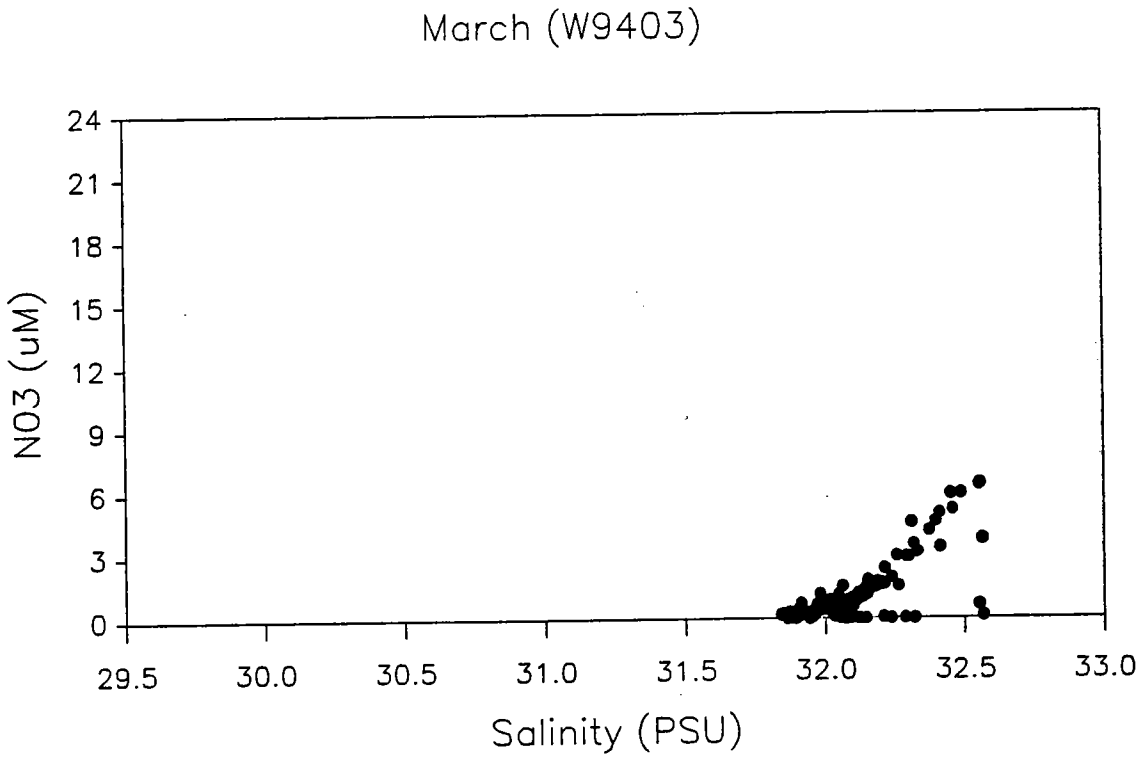
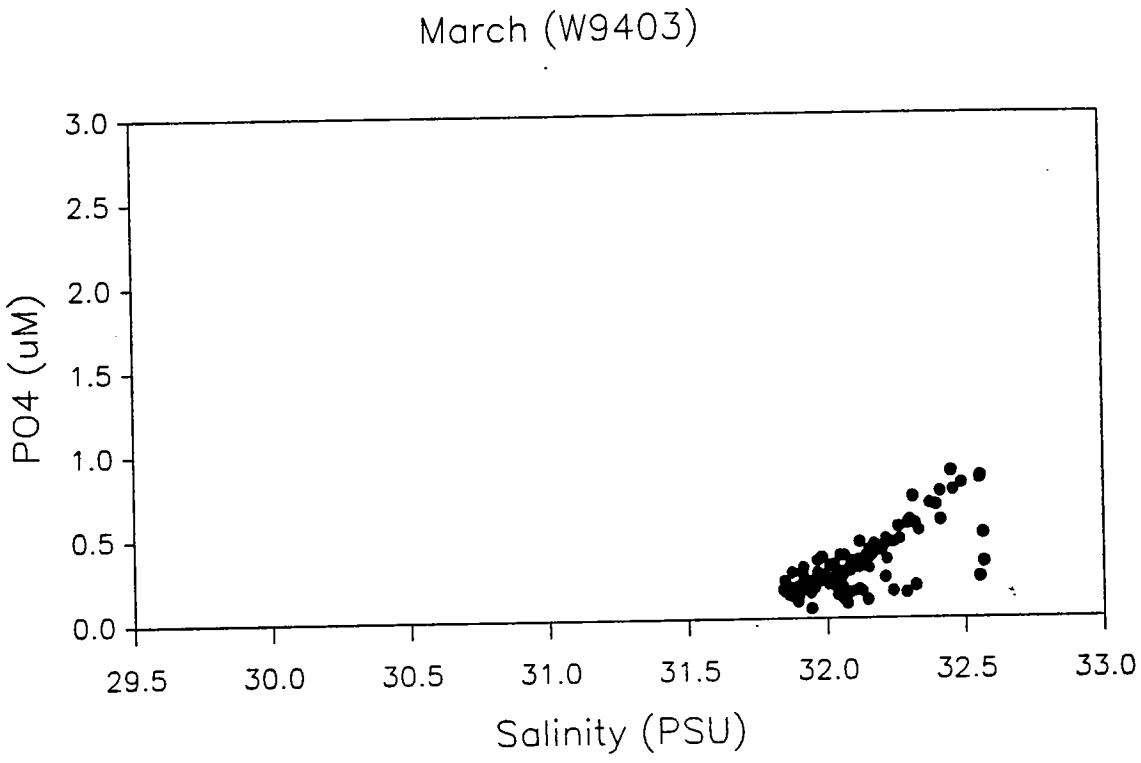


Figure 5-3b. **NH_4 and NO_3 vs. salinity in late March 1994.**



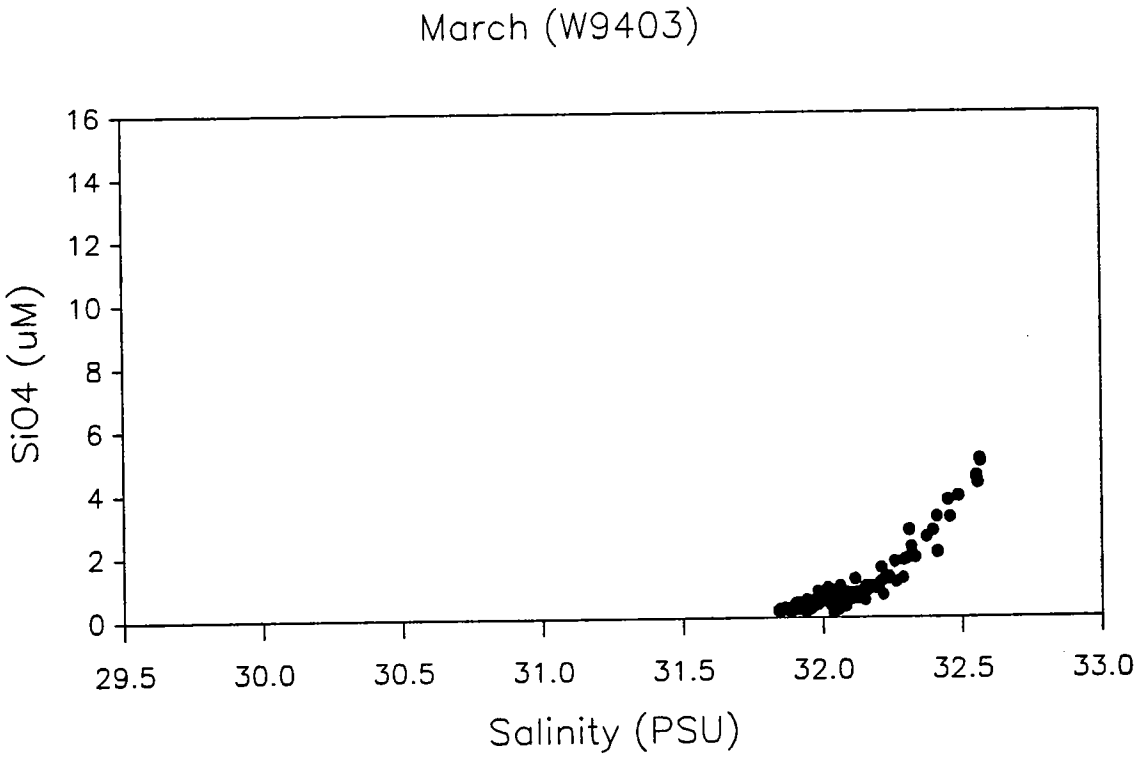


Figure 5-3c. **PO_4 and SiO_4 vs. salinity in late March 1994.**

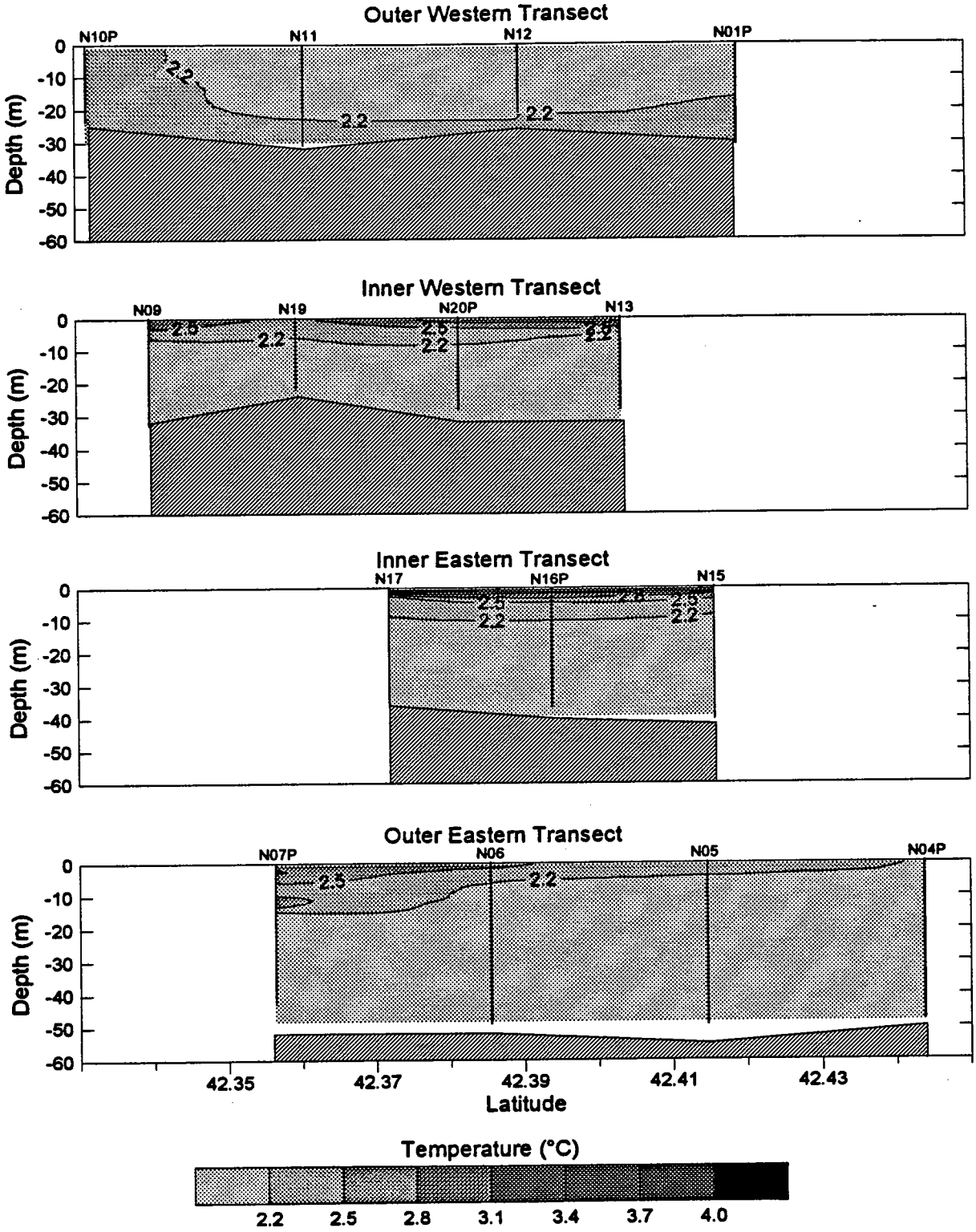


Figure 5-4a. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9403. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

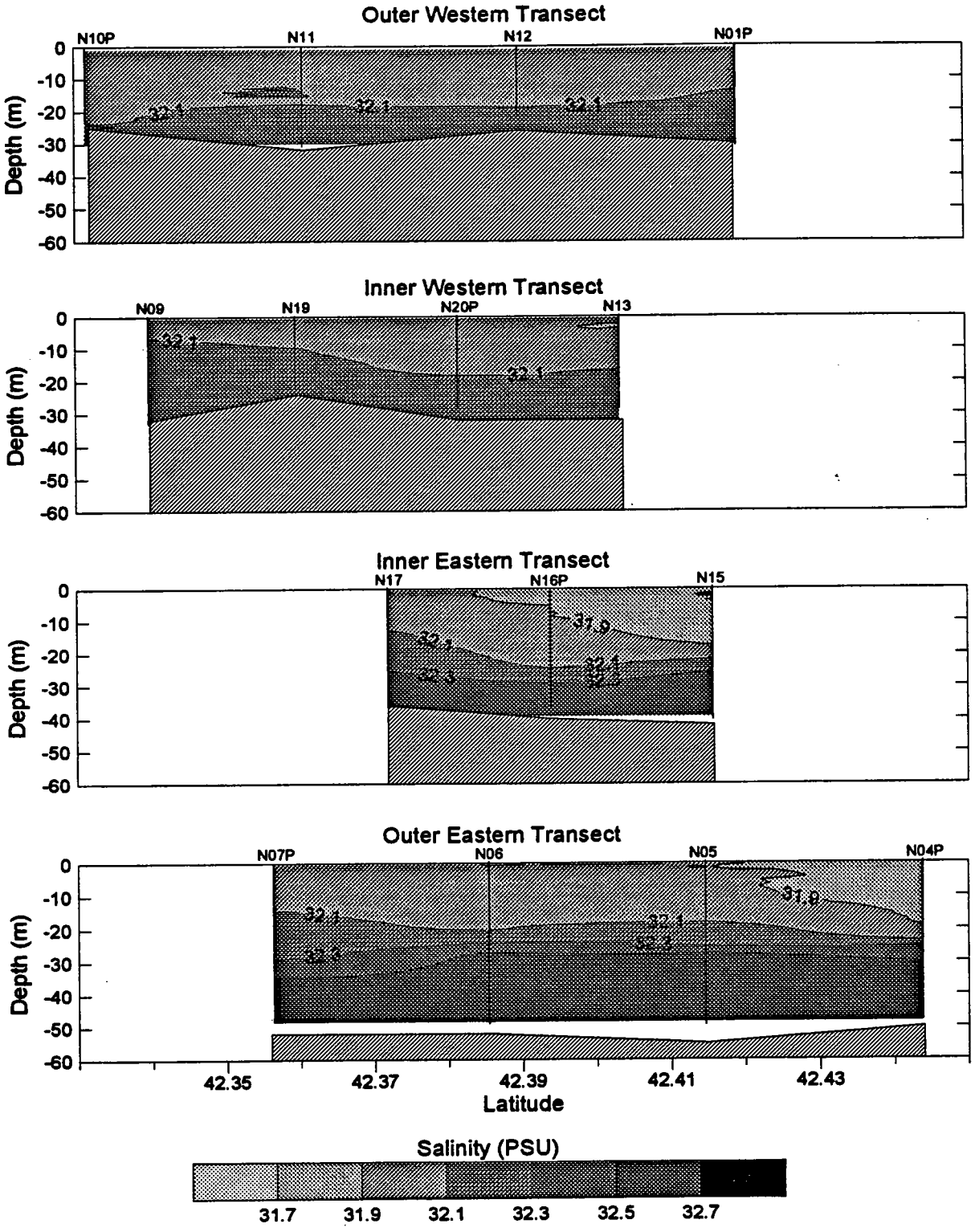


Figure 5-4b. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9403. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

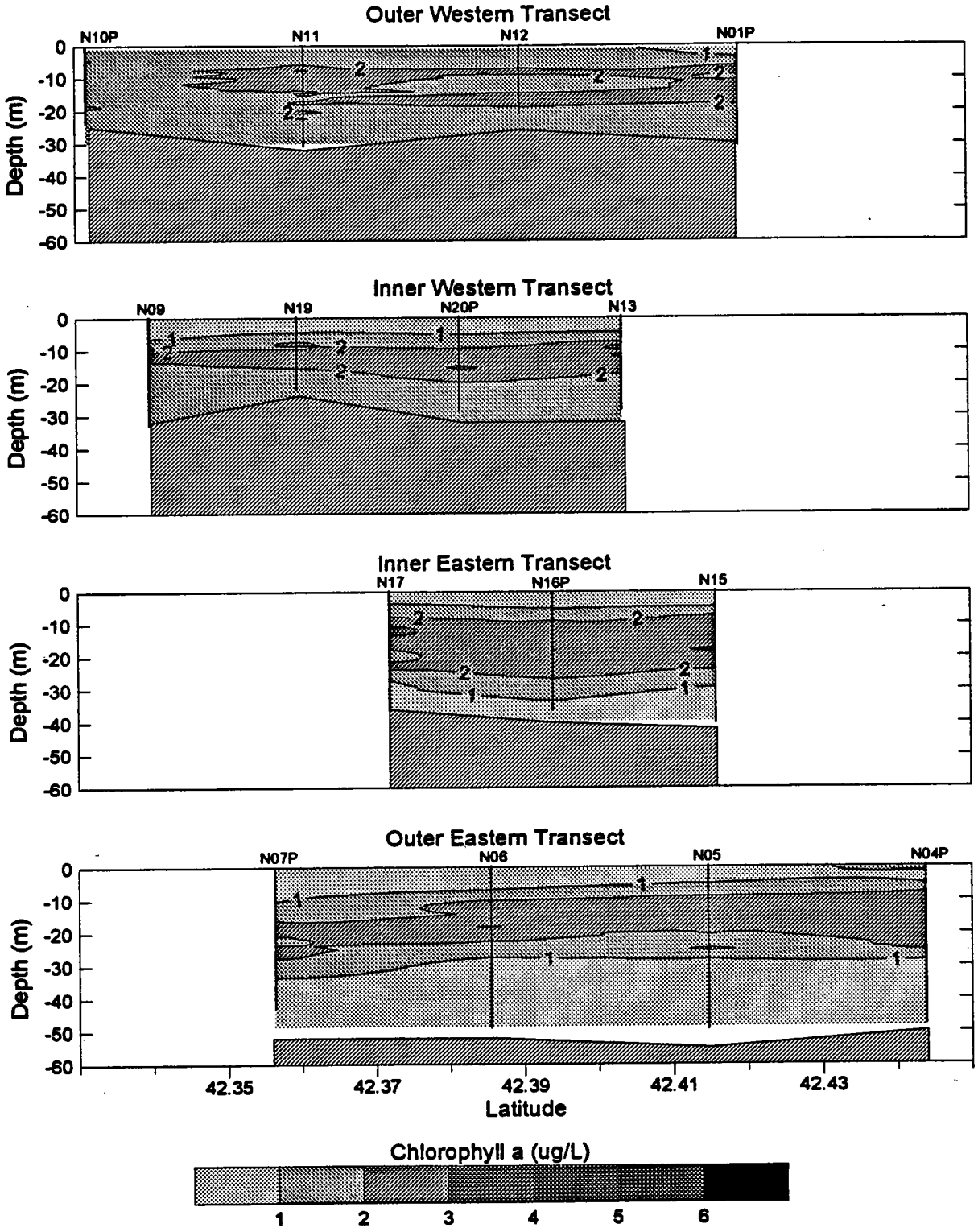


Figure 5-4c. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9403. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

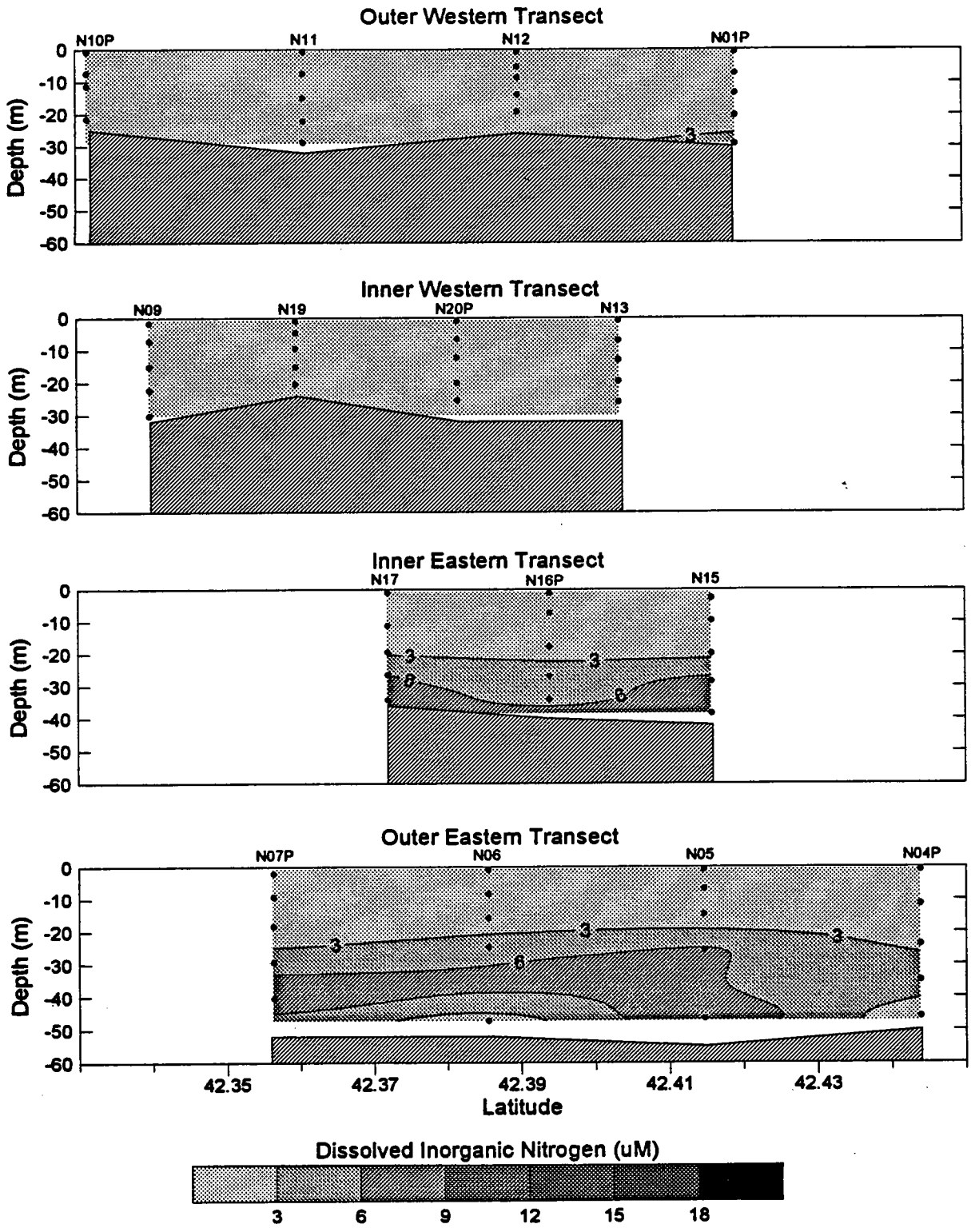


Figure 5-4d. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9403. The data used to produce the contours are from discrete bottle samples taken at each station during the nearfield sampling day (Appendix A).

6.0 DISCUSSION OF THE WINTER/EARLY SPRING PERIOD OF SURVEYS

6.1 Water Properties

6.1.1 Variability at the Regional Scale

The spatial pattern for most surface water quality parameters across the region was similar in February and early March. There were two persistent and notable features. The first was a distinction between the Massachusetts Bay region and Cape Cod Bay. In general, Cape Cod Bay was colder, less saline, and had higher turbidity, higher concentrations of chlorophyll, and lower concentrations of nutrients. The second feature was a general inshore-offshore gradient for many parameters; the gradient was most pronounced in western Massachusetts Bay adjacent to Boston Harbor. Inshore, especially at the Harbor, there was cooler, fresher, and more turbid water; unlike Cape Cod Bay, chlorophyll was not enhanced and nutrient concentrations were elevated rather than depleted.

The February and March 1994 surveys initiated a few changes in locations of MWRA monitoring stations, particularly the inclusion of several new across the northeastern boundary between Massachusetts Bay and the Gulf of Maine. Previously, the most seaward stations were in deep offshore water within Stellwagen Basin. During this winter/early spring period, only subtle distinctions were noted between boundary waters and their adjacent offshore waters. Physical conditions, as well as water quality, at the new boundary stations were generally similar to those observed elsewhere in Massachusetts Bay. In terms of nutrients, the boundary station data were often within the range of concentrations observed in the nearfield.

Changes in physical conditions in waters of the Bays between February and early March were not marked. In contrast, there were notable changes in turbidity and chlorophyll. For example, in Cape Cod Bay the phytoplankton bloom appeared to expand from its initiation on the eastern side in February to include the western side of the basin in March, and the bloom everywhere was accompanied by a progressive depletion of nutrients. In Massachusetts Bay, there was a temporal progression in the region between

Boston Harbor and the nearfield; both turbidity and chlorophyll increased from February to March. Interestingly, the increase in turbidity was noted over much of the Harbor-nearfield area, but the chlorophyll increase was more notable in the nearfield than in the Harbor. Offshore surface waters over Stellwagen Basin and Bank also increased in chlorophyll during the February-March period.

6.1.2 Variability in the Nearfield

Temperature-salinity gradients from shore were regularly noticeable as horizontal bands in contour plots, but until the third survey in late March, there was virtually no vertical density stratification in the nearfield. At that time, some diurnal heating at the water surface was noted; heating is a mechanism for developing or reinforcing a thermal stratification. Some salinity stratification was also evident. In general, density stratification was more strongly developed on the eastern side of the nearfield, in deeper waters less directly influenced by exchanges with Boston Harbor.

Temporal progressions in chlorophyll and nutrients in the nearfield are described below but, in general, peak chlorophyll values may have been reached prior to development of stratification. As this stage was reached in late March, surface nutrients, which had a wide range of concentrations in February and early March, fell rapidly and became more uniform across the nearfield.

6.1.3 Special Features: Comparison of 1994 with Previous Years

Figure 6-1 shows the surface temperature in the nearfield during 1993 and through March 1994. The February temperatures were very cold (<2 °C) in 1994, though within the range observed in 1993. Early March of both years was similar, but the main difference was that in 1994 a warming began in late March, whereas a cooling occurred in March 1993. The seasonal thermal trend in 1994 was more similar to 1992 than to 1993 (cf. Kelly *et al.*, 1992; 1994a) and the entire 1992-1993 nearfield station data set suggests that 1992 was a relatively mild winter, 1993 was cooler, and 1994 was the coldest.

Although the temperature range in February and early March was similar in 1993 and 1994, the temporal progression in 1994 was distinctly different from 1993 (but perhaps not 1992). Some warming was initiated in late March in 1994, where a continued cooling occurred in 1993. While some of this difference may relate to diurnal variability, there seem some real seasonal differences between the years, not just fine-scale transient features. Although seemingly a minor difference, the initiation of seasonal water column warming and the development of the thermocline is an important event, and may help regulate the expression and timing of the spring bloom, nutrient concentrations, and water quality in bottom waters later in the year. Cooling in 1993 appeared to delay the onset of stratification and influence the winter-spring bloom dynamics (Kelly *et al.* 1994a,b). Observations on seasonal bloom dynamics among years, some of which may correspond to physical trends, are discussed below.

During February and March of 1994, dissolved oxygen concentrations in bottom waters ranged between 10 and 14 mg L^{-1}. This in comparable to previous years, both 1993 (Figure 6-2) and 1992. Characteristically during this period, DO has been near or above saturation values.

6.2 Water Column Nutrient Dynamics

6.2.1 Vertical Structure

Vertical profiles of temperature, salinity, and density are indicators of water column stratification and/or mixing, and the profiles demonstrated that most stations were well-mixed until late March. Nutrient concentrations over depth can also indicate the presence of mixed or stratified conditions. In general, nutrients did not show strong patterns with depth throughout the Bay in February and early March. In late March, nearfield surface-layer nutrients were reduced (PO_4) or nearly depleted (DIN, SiO_4) compared to deeper waters. A depth-related increase in nutrient concentrations generally began at about 20 m and continued to 50 m. Where there was a pronounced pycnocline, it was indeed found at about 20 m. The transition between mixed and stratified conditions began in mid-March and rapidly produced a surface layer with low nutrient concentrations generally typical of the stratified season in Massachusetts Bay. Surveys during the remainder of the spring of 1994 will suggest whether the stratification was maintained

from late March onward into summer, or whether this early stratification was a transient phenomenon prior to the normal seasonal shift to fully stratified conditions. A consequence of the apparent early initiation of stratification was that bottom-layer nutrients had only decreased to about 6 μM (from highs of about 12 μM throughout the water column in February) on the east side of the nearfield as stratification developed. This suggests that in deeper water in particular in this year there was incomplete use, by phytoplankton, of the winter pool of N in the water column before stratification began to inhibit its availability to surface photic layers. In other years, 1993 for example, when development of stratification was prolonged, bottom water DIN reached lower concentrations before the seasonal stratification finally ensued.

6.2.2 Inshore-Offshore Gradients

The data indicated a typical inshore trend of higher nutrient (dissolved and total forms) concentrations with lower salinity, and showing a gradient to lower nutrients and higher salinity offshore. Over the period of surveys in 1994, the data also indicate a transition from horizontal banding of dissolved inorganic nutrients (concentration decreasing with distance from shore) to vertical layering of nutrients (concentrations increasing with depth below 20 m, the apparent depth of complete mixing at this time) in the Harbor-nearfield area.

6.2.3 Special Features: Comparison of 1994 with Previous Years

The range of DIN concentrations in February and early March was wide (Figure 6-3), as it has been in previous years, and this range (mostly 6-12 μM), in part, reflects the influence of the Harbor as it creates a decreasing concentration gradient from the western to eastern sides of the field. In February and early March, DIN concentrations were similar in 1993 and 1994, and in 1992 average DIN was lower. In the nearfield in 1994, surface DIN and other nutrients dropped rapidly in March, which was earlier than in 1993 (Figure 6-3), and more like the apparent progression in 1992 data (Libby *et al.*, 1994).

6.3 Biology in Relation to Water Properties and Nutrient Dynamics

6.3.1 Phytoplankton-Zooplankton Relationships

Although there appears to be some relationship between zooplankton and phytoplankton counts (Figure 6-4), the trend derives entirely from jointly higher abundances at Cape Cod Bay stations (one in February and two in March). Excluding the Cape Cod Bay stations, however, there was considerable variation in zooplankton counts without much variation in phytoplankton counts. While the bloom in Cape Cod Bay resulted in some of the highest zooplankton counts, the abundances were not high compared to some previous surveys conducted for the MWRA monitoring program (e.g., Libby *et al.*, 1994). Thus, overall there does not seem to be a very tight relationship between these autotrophic and heterotrophic components of the pelagic ecosystem in the Bays, or at least it was not a coupling strongly expressed during the time frame of the surveys covered by this report.

6.3.2 Chlorophyll, Phytoplankton Species, and Water Properties

Excluding Cape Cod Bay samples, no general relationship between chlorophyll and cell counts was evident, either within or across surveys during the period (Figure 6-5). The striking feature for phytoplankton was the regional difference between Cape Cod Bay and Massachusetts Bay. Also, within Massachusetts Bay, there was a difference between the Harbor-coastal area and the nearfield; this difference became more pronounced as the season progressed. Both the regional and temporal features are illustrated by chlorophyll concentrations for February and March (Figures 6-6a,b). In February, chlorophyll was only high in eastern Cape Cod Bay. In March, it was high at both Cape Cod Bay stations, although the peak concentration was now found in western Cape Cod Bay. At some nearfield stations, chlorophyll was as high as in eastern cape Cod Bay. The nearfield was, on average, higher than the Harbor and coastal stations; in fact, the ranges for nearfield and Harbor-coastal stations barely overlapped, suggesting that these regions were distinct. Finally, it was also noted that a subsurface chlorophyll maximum was typically found at about 10-20 m in late March, accompanying the onset of stratification,

but peak chlorophyll concentrations had dropped below those detected in early March prior to initiation of stratification.

In Cape Cod Bay, samples indicated the succession of a diatom bloom followed by a bloom of *Phaeocystis pouchetii*. However, in spite of sharp increases in chlorophyll in the nearfield in Massachusetts Bay during the period, total cell counts remained very low compared to Cape Cod Bay. *P. pouchetii,* although detected in Massachusetts Bay, was never prominent. As an example, phytoplankton temporal trends in Massachusetts Bay are presented for nearfield station N10P over the February-March period (Table 6-1). At this station, like others of the nearfield, DIN concentrations were relatively stable over the beginning of the period and then decreased in late March. In February, microflagellates and cryptomonads were dominant. Normal components of a winter-spring diatom successional community were present throughout March and diatom counts appeared to be increasing, but a strong near-surface diatom bloom, in terms of cell counts, was not really detected at station N10P in the southwest corner of the nearfield. Table 6-2 additionally shows that dinoflagellates were only present at very low levels through the entire period.

How did these regional differences relate to nutrients? There tended to be an inverse relationship between chlorophyll and nutrients. Where nutrients were consistently highest (near the Harbor), chlorophyll and plankton were never particularly high (Figure 6-7). Hypotheses concerning effects of light limitation rather than of nutrient limitation on chlorophyll concentrations have been discussed for both the winter-spring period in general and for the Harbor region in specific (cf. Kelly, 1994). The additional fact that high concentrations of chlorophyll were detected under conditions of low nutrient concentrations (e.g.,Cape Cod Bay) is a reminder of the strong influence of biology on nutrient cycles during the winter-spring period in cases where light is less limiting.

The succession of species in Cape Cod Bay was similar to that observed in 1992 when a Baywide bloom of *P. pouchetii* occurred. It appears that this organism can flourish when silicate becomes limiting due to intense diatom growth, a situation which then confers a competitive advantage to this species if N and P are still available because *P. pouchetii* does not require silicate. We have hypothesized that the successional sequence in 1992 affected water quality and the plankton community later in the year (Kelly et al., 1993c; Kelly, 1994). Once the 1994 data set becomes available, it will be useful to examine the full

sequence of biological events, nutrient concentrations, and nutrient ratios; we should be able to further develop understanding of these dynamics from the comparison of 1992 and 1994 events, relative to 1993.

6.3.3 Primary Production

The sampling strategy was designed to make comparisons between primary production rates at the Harbor-edge environment (station F23P) and the middle of the nearfield (station N16P), an environment that is normally less turbid than the Harbor and that is distant enough to be only weakly influenced by the outflow of Harbor water. The rate calculations indicate that primary production was lower at station F23P than at station N16P during both of the combined surveys (Figure 6-8). At station N16P, production rates increased significantly from February to early March. However, there was little change in the estimates of production at station F23P over the same time period. The increased production rates at station N16P were related to higher integrated chlorophyll biomass (Figure 6-8, based on the fluorescence profile for the entire photic zone) and also were coincident with very high P_{max} values (e.g., 11 to 26 μg C μg Chl^{-1} h^{-1} for March 5, 1994). Spatial and temporal trends in integrated production rates thus reflected the different concentrations and temporal trends in chlorophyll in the two areas, as described above, and additionally inferred from Figure 6-8.

In February, there was little variation and no apparent pattern in P-I model parameters as a function of depth (Table 3-3). This was also the case at station F23P during the early March survey. At station N16P in March, however, there was a very clear decrease in each of the P-I model parameters (P_{max} and α) as a function of increasing depth of sampling for the seawater used in the incubation (Table 4-3). The modeled production profiles for stations F23P and N16P on March 1, 1994 are shown in Figure 6-9. At each station, the light and chlorophyll (as measured by fluorescence) profiles used in calculating production rate profiles for each of the four incubations were identical. The differences in the production profiles shown in Figure 6-9, therefore, result solely from variations in the P-I model parameters of the incubations. Accordingly, for station F23P, where there was no systematic trend of P_{max} with depth, in comparison to station N16P where there *was* a systematic trend of P_{max} with depth, the production profiles reflect these station differences.

An appropriate way to calculate a single estimate of production for each station is to combine results of the four incubation samples as a composite profile, as outlined in Section 2. However, different integration schemes are possible and a comparison of three computational schemes for calculating integrated water column rates was made for the data from station N16P for March 5, 1994 (Figure 6-10). The first scheme uses the composite profile (Section 2), with production modeled for each 0.5-m depth interval, and relies on *in-situ* fluorescence data. The second and third schemes do not use a depth profile based on 0.5-m intervals; in contrast, a rate is calculated, using the P-I model for each incubation, for the light actually measured at the depth of the four depths of sampling in the field. In these schemes, the integrated water column estimate is then derived from a standard trapezoidal integration of the four points over depth, rather than a summation of all depth intervals as in the first scheme. The difference between the second and the third schemes is that the former uses *in-situ* fluorescence (post-chlorophyll calibration) for each depth and the latter uses the actual extracted chlorophyll data for each hydrocast bottle from which incubation sample water was taken. The trapezoidal integration of the data from each sample depth yielded estimates of 2962 mg C m^{-2} d^{-1} (extracted chlorophyll) and 3499 mg C m^{-2} d^{-1} (*in-situ* fluorescence). These estimates compare very well to the composite profile production rate estimate of 3186 mg C m^{-2} d^{-1} and the composite profile integration scheme will be used to estimate production for the remaining surveys in 1994.

6.3.4 Special Features: Comparison of 1994 with Previous Years

Chlorophyll temporal trends for surface waters in the nearfield in 1993 and early 1994 are shown in Figure 6-11. Water depths to 20 m are included, reaching the depth of subsurface maximum noted in March 1994. The 1994 trends were different from the 1993 trends during the early months of the year; in 1993, a significant increase in chlorophyll concentration was not noted until mid-April. In contrast, 1992 was similar to 1994 (cf. Kelly *et al.*, 1993c; Libby *et al.*, 1994). In late February 1992, the seasonal peak in chlorophyll was noted and, by mid-March, concentrations had generally decreased in 1992, just as in 1994.

There are other parallels that make the winter-early spring period of 1994 biologically more similar to 1992 than to 1993. This includes the presence of *Phaeocystis* in the Bay in 1992 and 1994 (but not 1993), although its precise expression in space and time may have differed between the years. For example, in 1992, a *Phaeocystis* bloom was documented Baywide, but in April not March. In early March 1994, farfield sampling showed that a *Phaeocystis* bloom had been limited (as yet) to Cape Cod Bay, with only a few cells present at a few selected Massachusetts Bay stations. Interestingly, the late March sampling at N10P (Table 6-1, Appendix E) only detected *Phaeocystis* at counts near the detection limits. Due to a possible mismatch in timing of surveys, relative to the growth of *Phaeocystis* in April, we may be unable to assess whether it spread throughout the Bay in 1994 as it did in 1992 (Kelly *et al.*, 1993a,c).

6.4 Summary and Recommendations

The interannual comparisons briefly described above are useful to begin to focus on some summary observations that serve as reminders, if not explicit recommendations, to the water quality monitoring program. The obvious one, which is almost trivial, is that annual cycles, as well as details of seasonal patterns, in chlorophyll and plankton biology fluctuate from year to year. This is the case even when effluent loads from the major discharge of nutrients to the Bay (via strong and rapid interaction with Boston Harbor) have not fluctuated to any substantial degree, and when the background (winter-early spring, pre-bloom season) concentrations of nutrients in the nearfield and other parts of the Bay have also been similar from year to year (e.g., Figure 6-3). For this reason, as well as others enumerated in this and other reports (e.g., Kelly, 1994), it is logical to presume that the fluctuations observed during the winter-early spring period most strongly relate to a factor(s) other than nutrients, such as light and climate, which can directly influence physical oceanographic processes.

Interestingly, the *constant* from year to year seems to be the existence of regional differences between Massachusetts and Cape Cod Bays in timing of bloom events. Assuming that, because the Bays are well-mixed for most water quality parameters, their background nutrient levels must also be similar, the persistent ecological difference suggests that there may be fundamentally different physical controlling factors for the two Bays' pelagic ecosystems during the early period of the year. If so, one could argue

that a similar climate (on the broad scale) can create different ecological expressions when the ecology is primarily structured by *in-situ* factors operating at more local (weather-like) scales, such as within a morphometrically defined basin. Obviously, monitoring and interpretation of annual patterns and trends, especially in response to anthropogenic changes, must recognize these notions, as well as one final caution.

The caution relates to the last summary observation on some apparent similarities between early seasonal dynamics in 1992 and 1994, similarities interrupted by different events in the same period in 1993. The limited interannual comparison serves to remind that, with an open pelagic ecosystem, calendar years can indeed be independent and distinct ecologically, because pelagic dynamics can be set in motion by a set of events occurring over preceding days, weeks, or months more than over preceding years. Moreover, if one arranged the order of these years differently, it would be possible to create "trends" in the data and to assume that a secular "change" was occurring, when, in any order, the data simply reflect the range of variability possible in nature under the basic set of environmental conditions that presently operate to define the character and dynamics of the ecosystem. Recognizing a degree of interannual independence and the high probability of creating some artificial annual trends in data sets with limited time series, one should be less tempted to interpret temporal trends based on data from only two or three annual cycles as a *response* to some intervention without strong information as to the probable cause.

Table 6-1. Abundance of top five dominant phytoplankton taxa in samples collected near the surface at station N10P in February and March 1994

	N10P	N10P	N10P	N10P
	Feb 17	Mar 05	Mar 06	Mar 23
CHAETOCEROS COMPRESSUS				0.034 (5)
CHAETOCEROS DEBILIS			0.007 (4)	0.048 (3)
CHAETOCEROS SPP.(<10UM)			0.006 (5)	0.152 (1)
CRYPTOMONADS	0.037 (2)			
MICROFLAGELLATES	0.160 (1)	0.012 (3)	0.015 (3)	0.040 (4)
NAVICULOID DIATOMS	0.004 (4)	0.007 (5)		
THALASSIONEMA NITZSCHOIDES	0.005 (3)	0.016 (2)	0.015 (3)	
THALASSIOSIRA (cf) GRAVIDA/ROTULA		0.071 (1)	0.122 (1)	0.075 (2)
THALASSIOSIRA SPP.		0.010 (4)	0.020 (2)	
UNID. CENTRALES	0.002 (5)			

Units are millions of cells L^{-1} and rankings are given in parentheses.

Table 6-2. Abundance of all identified taxa in screened (20μm) samples collected near the surface at station N10P in February and March 1994.

	N10P	N10P	N10P	N10P
	Feb 17	Mar 05	Mar 06	Mar 23
ALORICATE CILIATES	10		3	
CERATIUM LONGIPES	3			3
DICTYOCHA FIBULA	5	3	3	
DICTYOCHA SPECULUM	10	5		8
DINOPHYSIS NORVEGICA	3		3	5
GYRODINIUM SPIRALE				23
GYRODINIUM SPP.				3
MESODINIUM RUBRUM		3		
PROTOPERIDINIUM BREVE				8
PROTOPERIDINIUM DENTICULATUM				10
PROTOPERIDINIUM DEPRESSUM				3
PROTOPERIDINIUM SPP.			8	43
STAURASTRUM SPP.			3	
TINTINNIDS	35	18	3	5
UNID. ATHECATE DINOFLAGELLATE	3			5
UNID. THECATE DINOFLAGELLATES			3	23

Units are cells L^{-1}

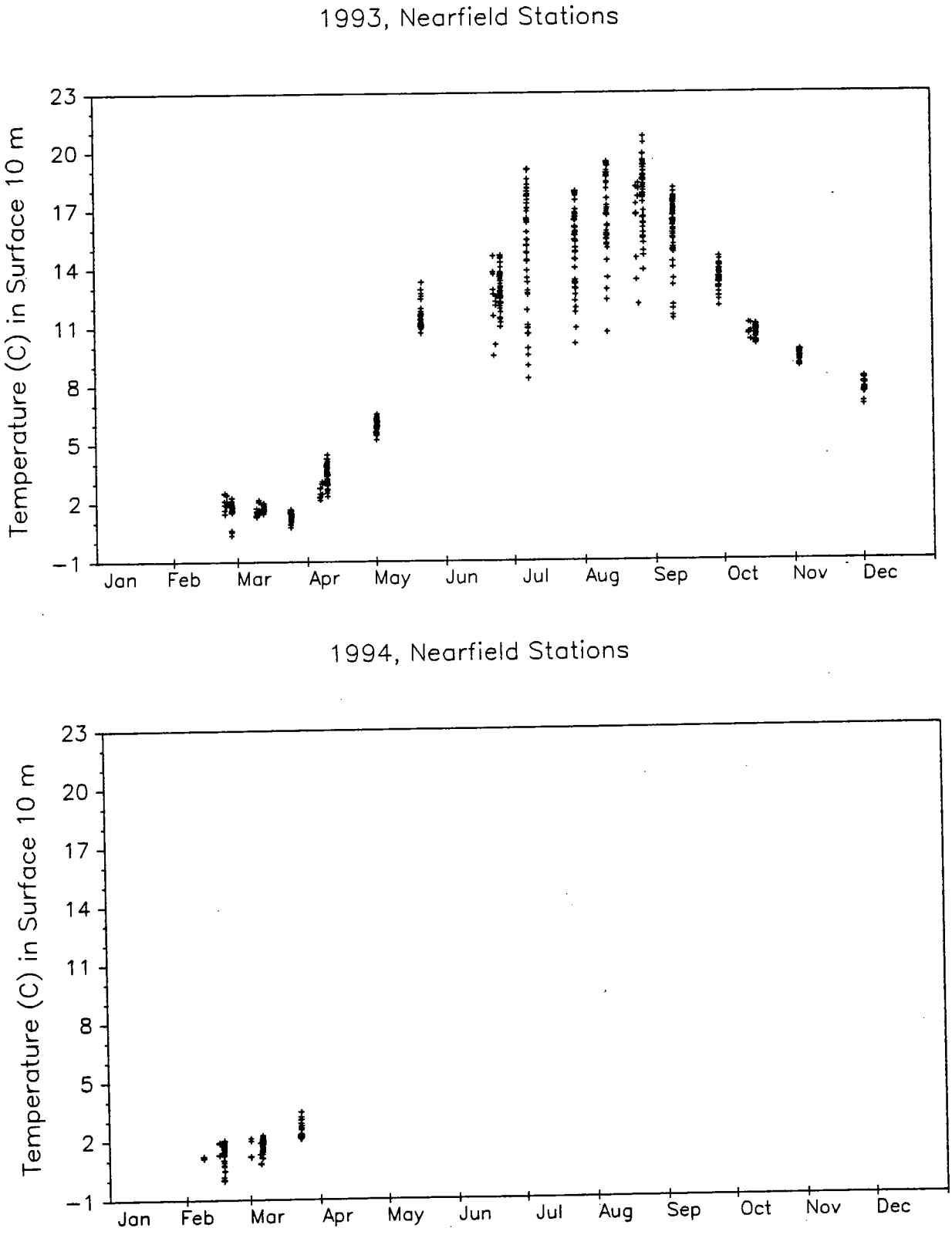


Figure 6-1. **Comparison of the nearfield region in 1994 to the annual cycle of 1993: temperature (°C).**

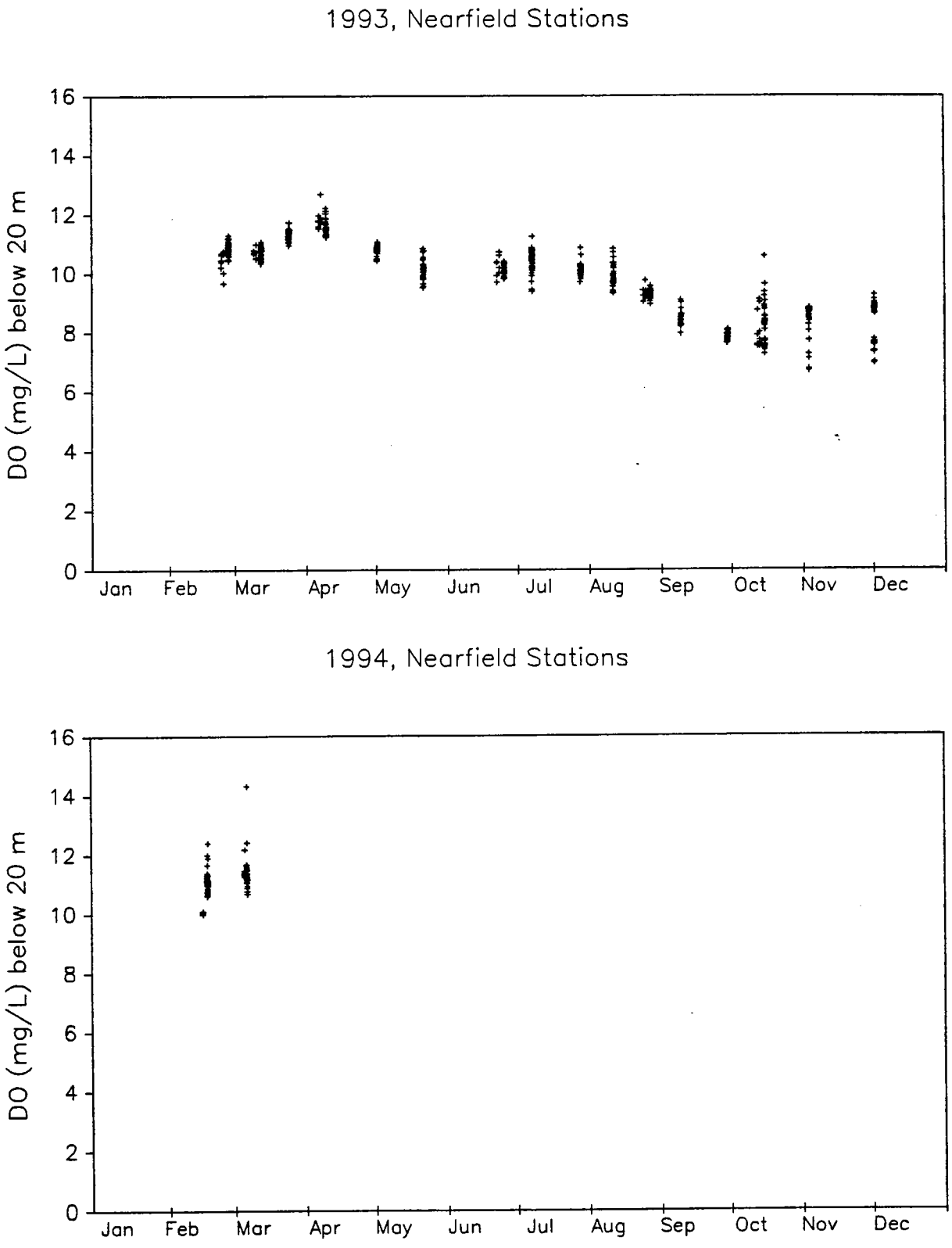


Figure 6-2. **Comparison of the nearfield region in 1994 to the annual cycle of 1993: dissolved oxygen (mg L^{-1}).**

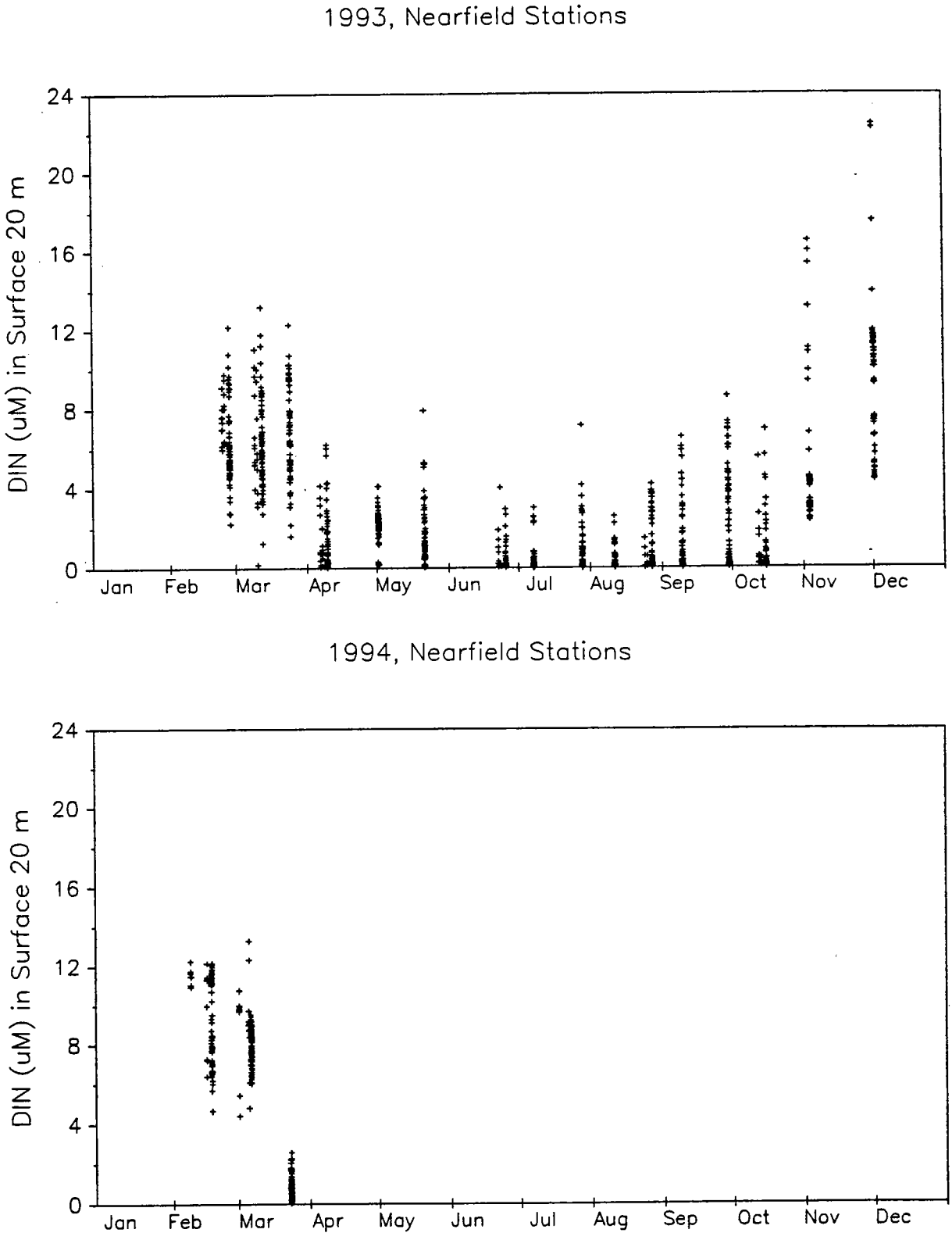


Figure 6-3. **Comparison of the nearfield region in 1994 to the annual cycle of 1993: dissolved inorganic nitrogen (μM).**

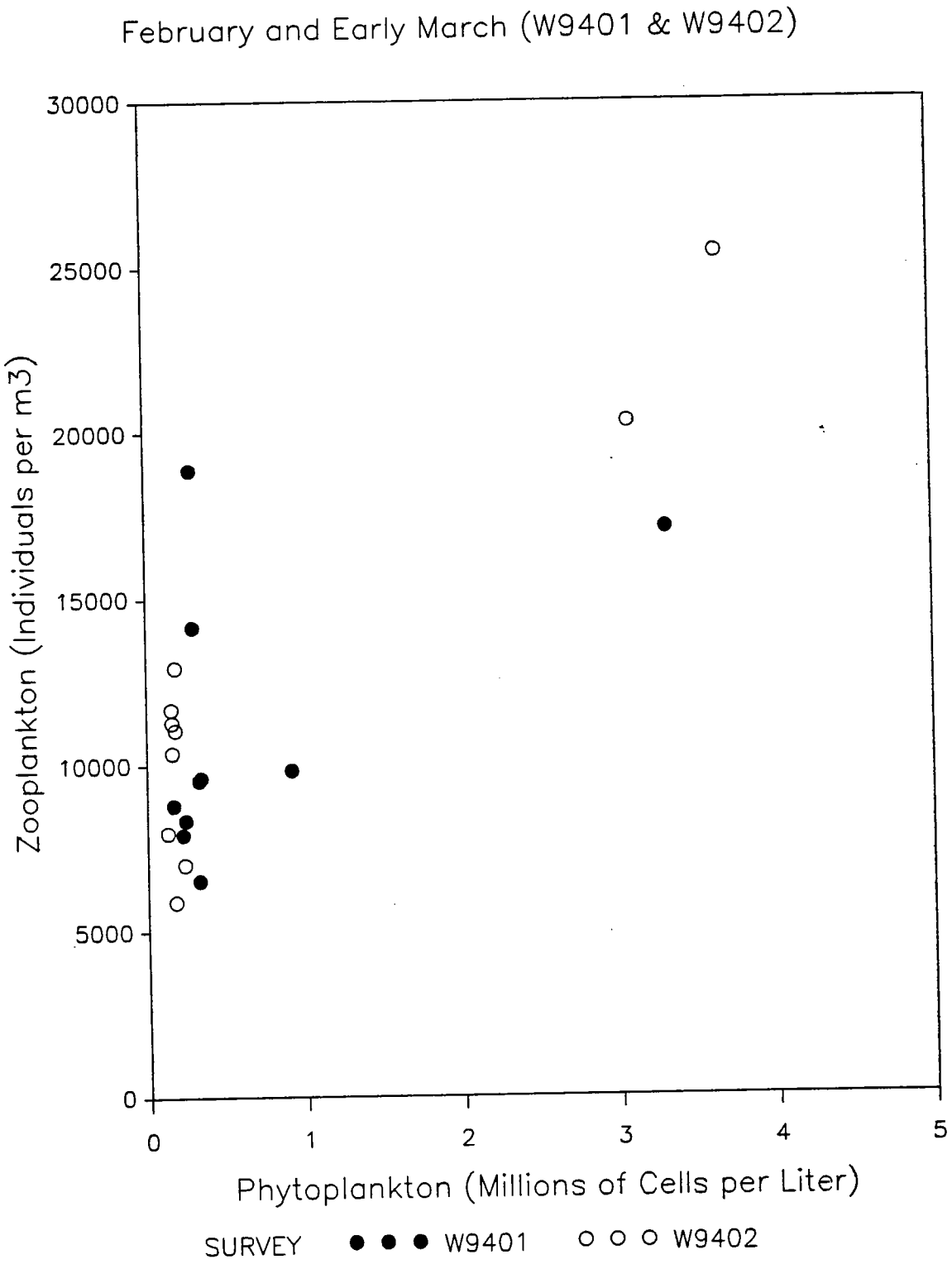


Figure 6-4. **Zooplankton abundance vs. phytoplankton abundance for February and early March 1994.**

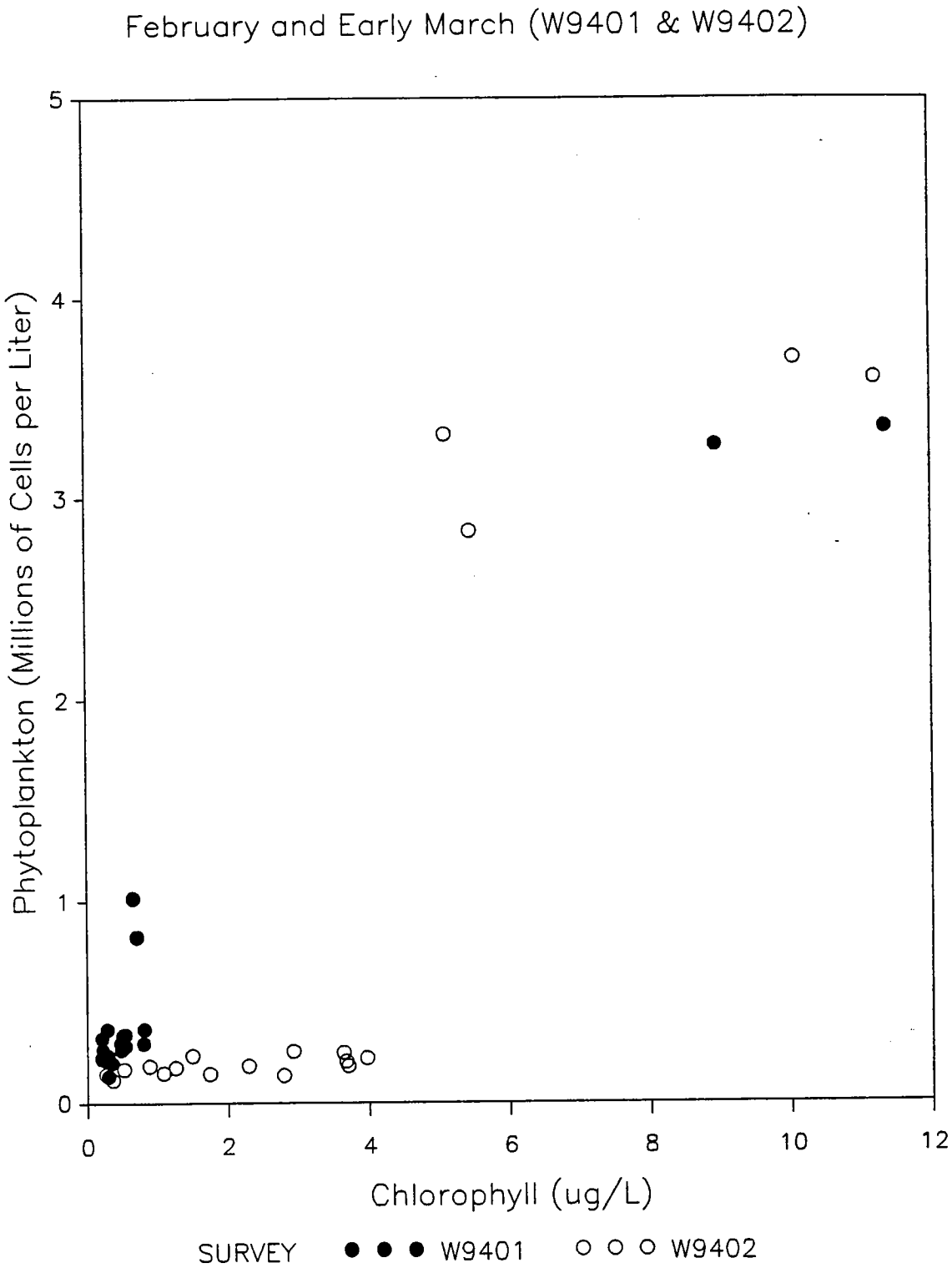


Figure 6-5. **Phytoplankton abundance compared to the average (extracted) chlorophyll concentration for February and early March 1994.**

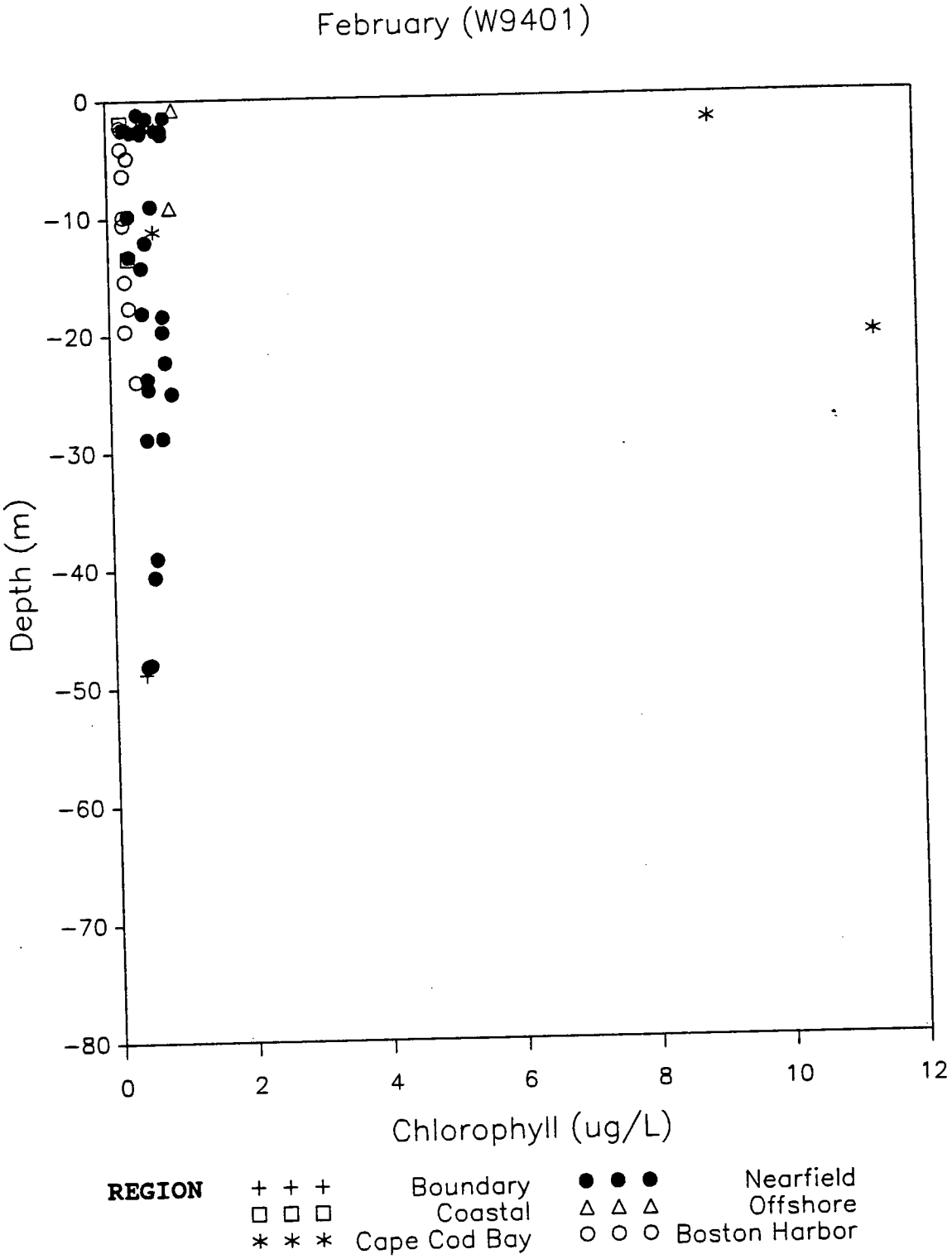


Figure 6-6a. Chlorophyll (extracted) vs. depth for the study area in February 1994.

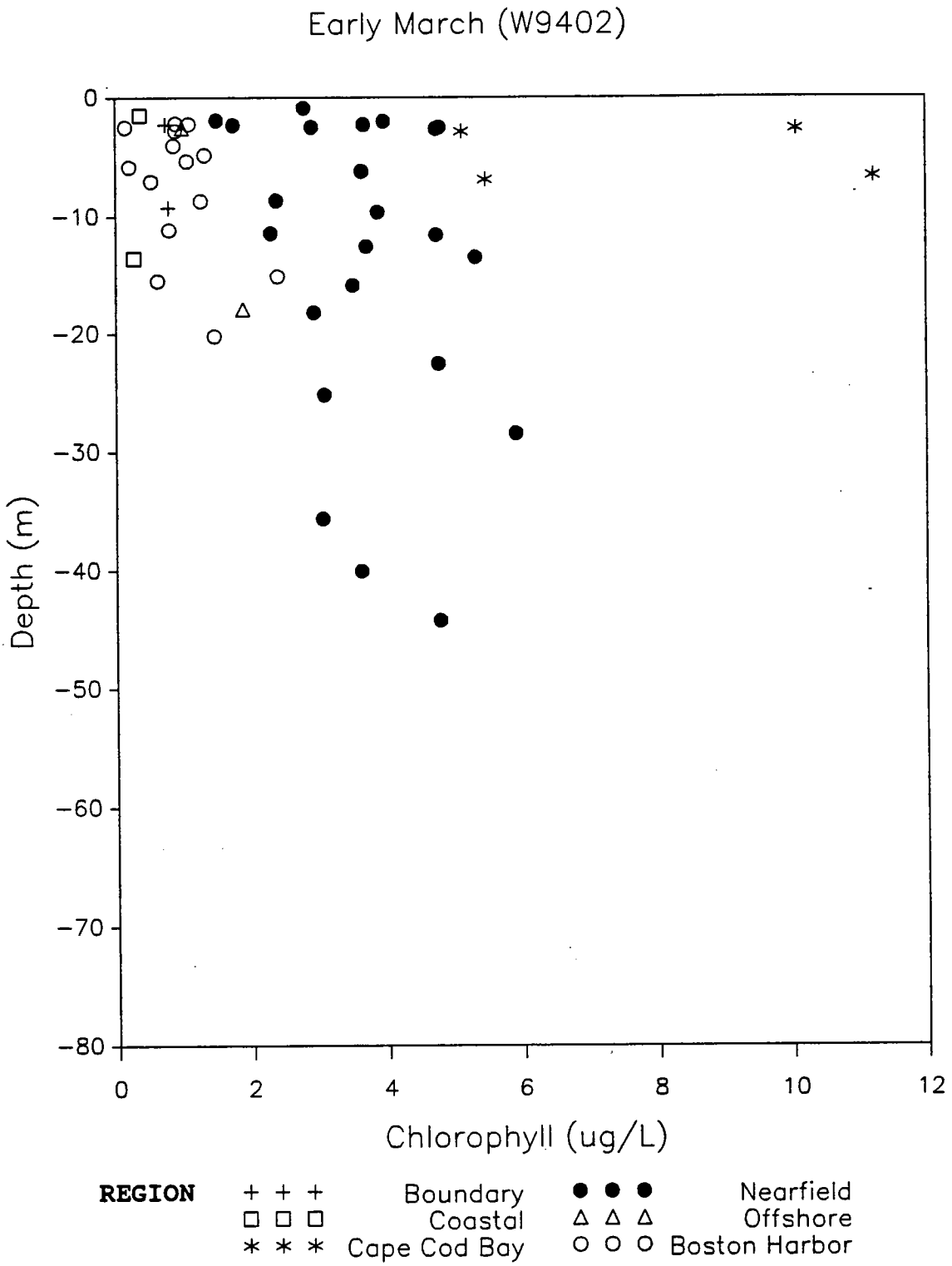


Figure 6-6b. Chlorophyll (extracted) vs. depth for the study area in early March 1994.

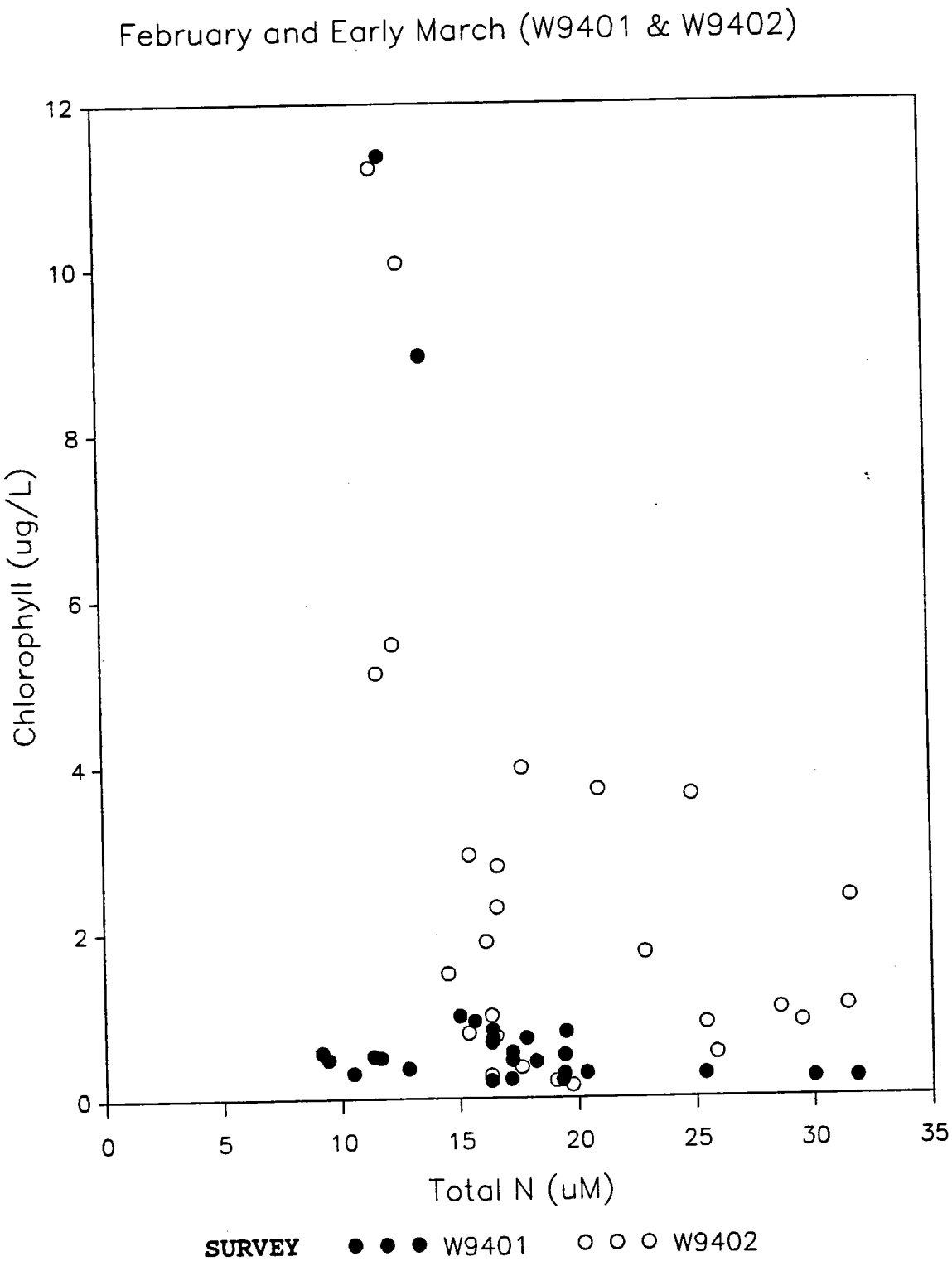


Figure 6-7 **Chlorophyll (extracted) vs. total nitrogen concentrations for the study area in February and early March 1994.**

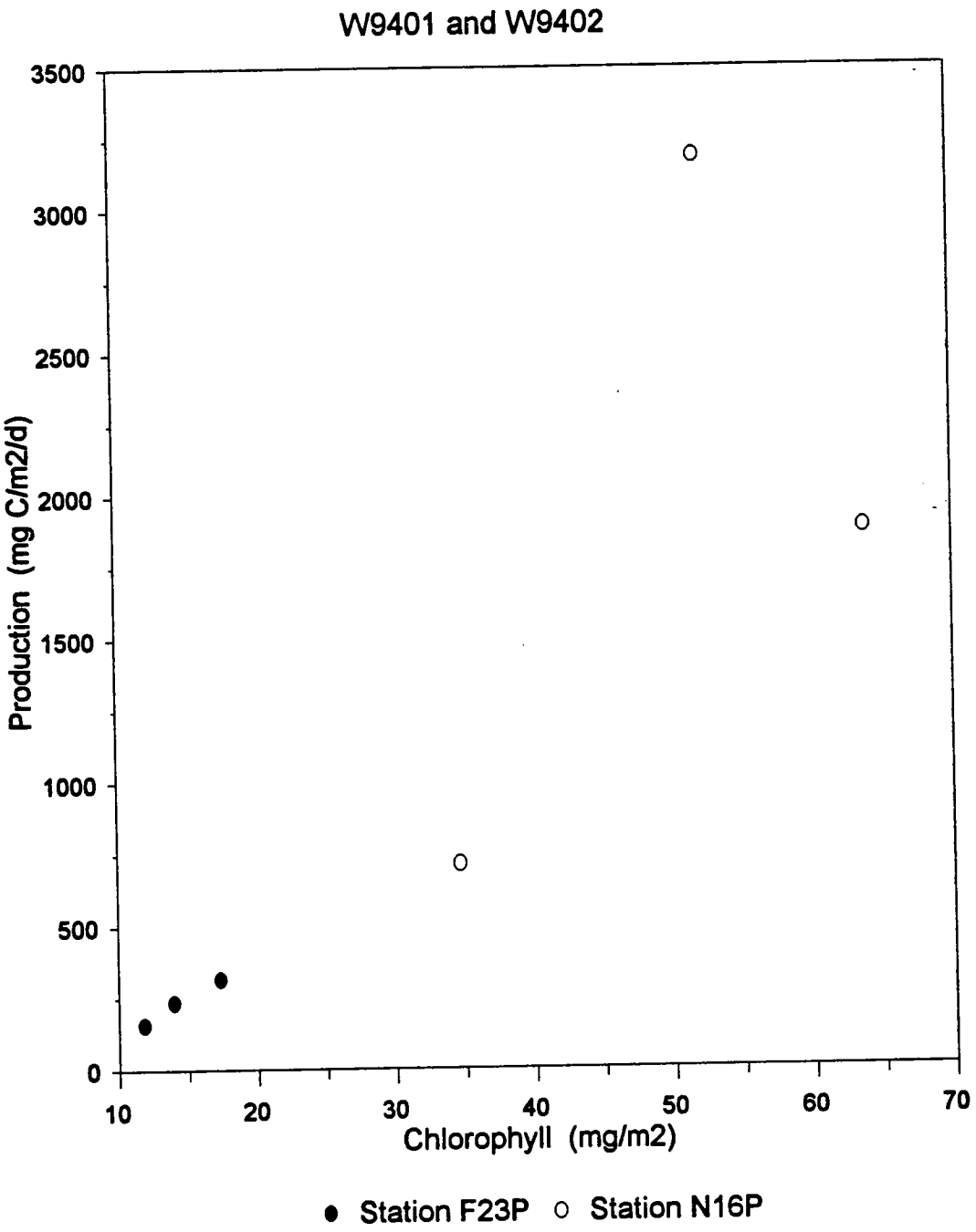


Figure 6-8. **Integrated water column ^{14}C production compared to integrated water column chlorophyll in February and early March 1994.**

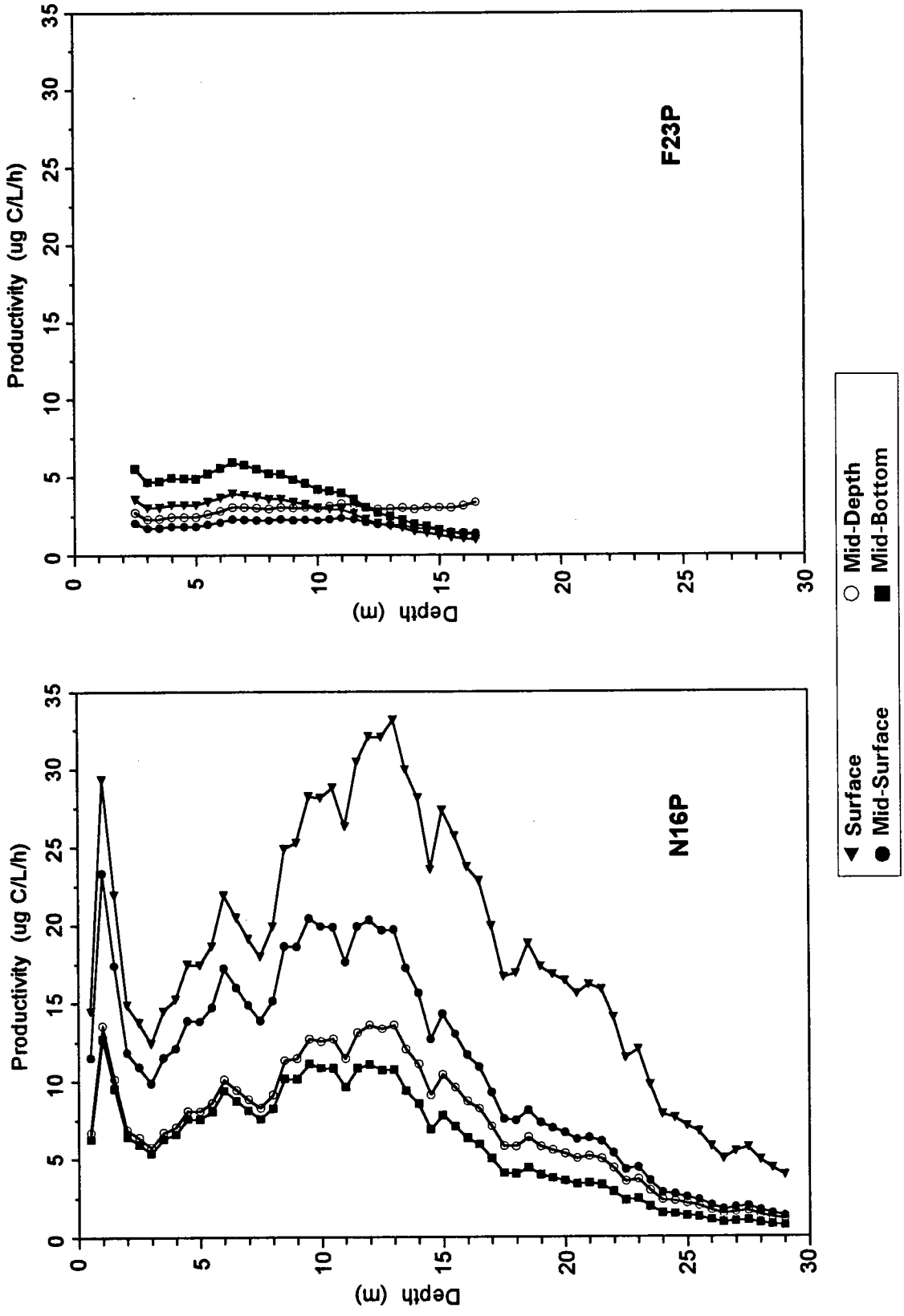


Figure 6-9. Comparison of ^{14}C production profiles with depth using data from four P-I incubations at stations N16P and F23P in March 1994 (see text).

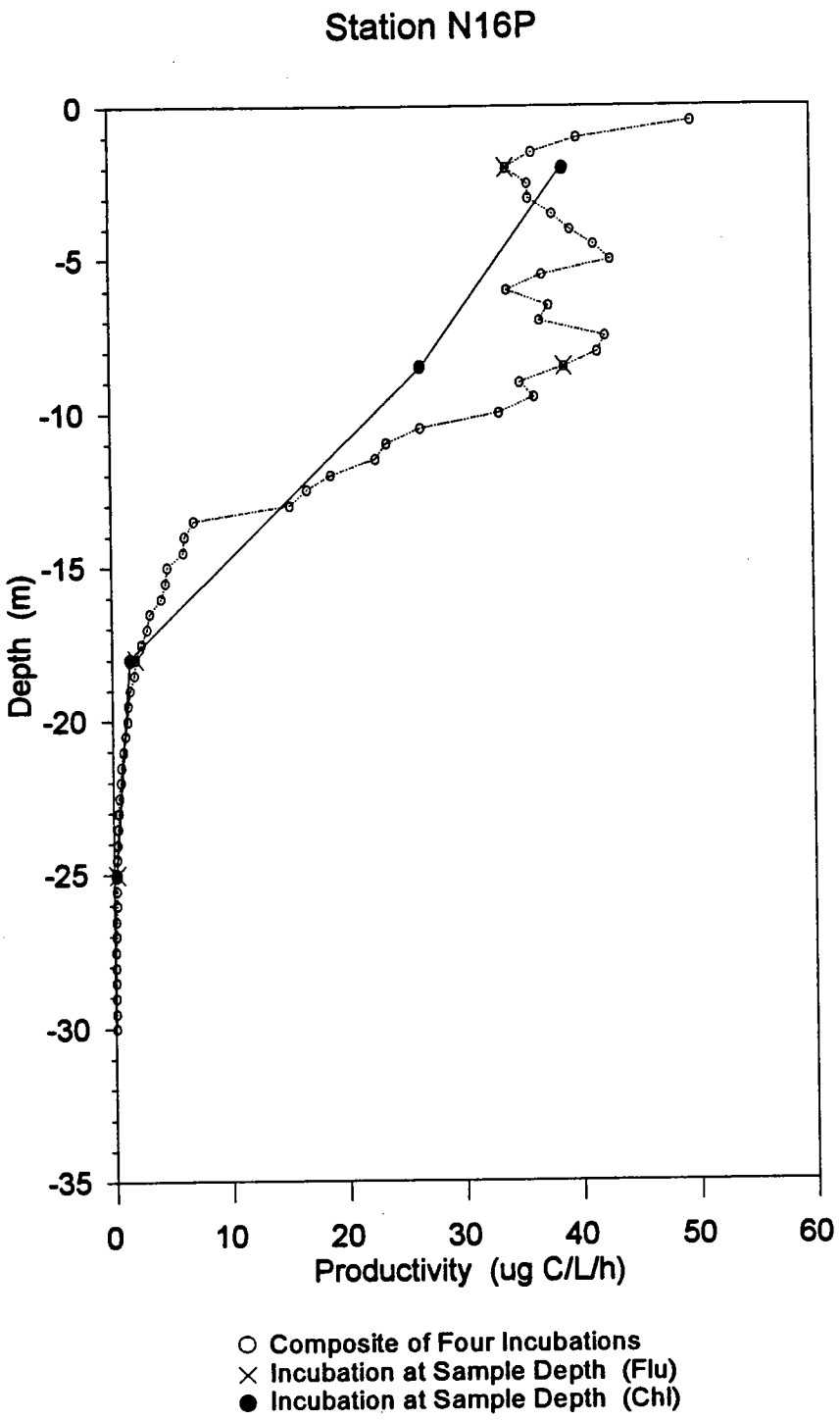


Figure 6-10. **Comparison of ^{14}C production using different calculation schemes to model integrated water column production (see text).**

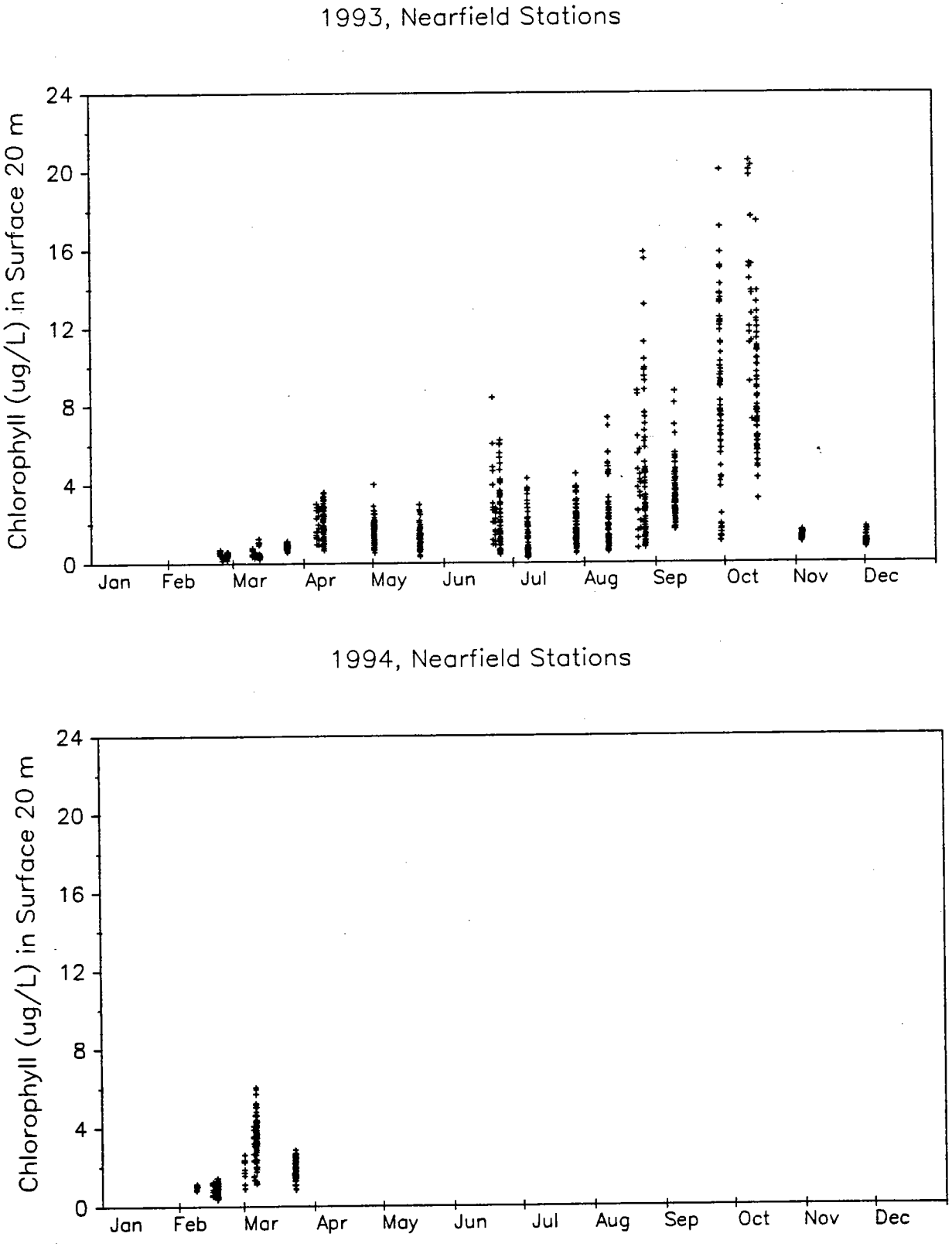


Figure 6-11. **Comparison of the nearfield region in 1993 to the annual cycle of 1994: chlorophyll ($\mu g\ L^{-1}$) as estimated from *in situ* fluorescence.**

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