Water quality monitoring in Massachusetts and Cape Cod Bays: April and May 1994

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FINAL

WATER QUALITY MONITORING IN MASSACHUSETTS AND CAPE COD BAYS: APRIL AND MAY 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
Aimee Keller
Robert Vaillancourt
Laura Reed
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 second 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 two surveys conducted during April and one survey conducted during May of 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 April survey was a combined farfield/nearfield survey that included sampling at an additional 25 stations throughout Massachusetts Bay and Cape Cod Bay, including two stations in Boston Harbor and three stations along the northeastern boundary with the Gulf of Maine that were new for 1994 water column monitoring. 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.

April - May 1994 was a period during which seasonal stratification of the water column fully developed at most locations in the Bays. Accompanying stratification was the normal set of conditions expected at the end of the winter-spring-bloom: low nutrient and chlorophyll concentrations in surface layers, with the presence of a subsurface chlorophyll maximum and higher nutrient concentrations in deep water.

At the regional scale (in early April), there were only minor variations in physical parameters within Massachusetts Bay or between Massachusetts and Cape Cod Bay. Even so, an inshore-offshore gradient in many water quality parameters was apparent from Boston Harbor seaward, as has been quite typically observed. Besides the gradient, perhaps the most interesting large-scale pattern was a temporal one. Between March and early April, the peak chlorophyll concentrations in the region had shifted from Cape Cod Bay stations to Massachusetts Bays stations.

Several key monitoring parameters — nutrients, dissolved oxygen (DO), chlorophyll, and phytoplankton (at the surface of one station, N10P) — were measured on each of the three surveys. During the farfield surveys in early April, additional key parameters — phytoplankton and zooplankton — were measured at 10 "BioProductivity" stations. Specific findings for each of the key parameters are summarized below:

- Nutrients — Aside from Boston Harbor and in its adjacent Bay receiving waters, nutrient concentrations generally were low in the warm surface layers above the thermocline. Below the thermocline, nutrients characteristically increased as a function of increasing water depth. For DIN, concentrations at depths > 45 m were often 5-10 μM and were thus similar to high DIN concentrations measured within Boston Harbor (up to 8 μM in early April). Dissolved nutrient concentration showed patterns in relation to salinity over time that reflected the seasonal transition from horizontal gradients to vertical gradients as stratification became more strongly developed.

- DO — A decline in DO concentrations in bottom waters of the nearfield was observed from April to May. This trend, and a shift from generally supersaturated to slightly undersaturated DO levels, has now been observed for each year during 1992-1994. The decline defines a distinct partitioning of metabolism of upper and lower layers of the water column as stratification proceeds.

- Chlorophyll — Temporal differences in chlorophyll concentrations between Cape Cod Bay and Massachusetts Bay were mentioned above. In early April, chlorophyll concentrations typically were higher in Massachusetts Bay than in Cape Cod Bay. One of the defining attributes of the period was the difference in vertical chlorophyll distributions between inshore and offshore waters. Typically, peak chlorophyll concentrations were usually found within the surface layer at nearshore stations, which were often weakly stratified or received nutrients from inshore sources. In contrast, offshore stations had a subsurface chlorophyll maximum (generally 2-6 $\mu g\ L^{-1}$) that in some cases was quite deep (>25 m). The highest chlorophyll concentration noted during the farfield survey (about 18 $\mu g\ L^{-1}$) was located in a mid-water layer (about 20 m) at station F27B in the deep basin east of Stellwagen Bank and therefore outside of Massachusetts Bay proper. During one survey (late April), a subsurface chlorophyll maximum in the nearfield ($>2.4\ \mu g\ L^{-1}$) commonly was found below the pycnocline; this deep feature may have represented some sinking cells. Later, in May, the subsurface chlorophyll maximum ($>4\ \mu g\ L^{-1}$) was found within the thermocline and may have represented development of a seasonal mid-depth community typical of stratified conditions.

- Phytoplankton — Total phytoplankton counts illustrated some of the same trends as chlorophyll, but in no samples from early April were counts as high as 1×10^6 cells L^{-1}. Counts in Cape Cod Bay were low $<0.3 \times 10^6$ cells L^{-1}, whereas counts at Massachusetts Bay stations (coastal and nearfield) were typically 0.3 to 0.8×10^6 cells L^{-1}. There were no sharp geographic differences in terms of a cell count-chlorophyll ratio or species composition. The phytoplankton community in early April was dominated by microflagellates, cryptomonads, and a variety of diatom species. Temporal trends in Massachusetts Bay at station N10P (a sentinel monitoring station examined at each April and May survey) generally indicated relatively low cell counts, some minor fluctuations in species, and low dinoflagellate presence throughout the April-May period .

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

- Zooplankton — Zooplankton counts were higher in Cape Cod Bay than in Massachusetts Bay, in spite of lower chlorophyll in Cape Cod Bay. This difference in relative abundance of phytoplankton and zooplankton may occur because of differences in timing and progression of winter-spring bloom events in Massachusetts and Cape Cod Bays. A primary reason for higher zooplankton abundances in Cape Cod Bay was a greater abundance of copepod nauplii. Geographic differences in zooplankton species composition were small. Dominant copepod species included *Oithona similis, Paracalanus parvus*, and *Calanus finmarchicus*. The appendicularian *Oikiopleura dioica* was ubiquitous and often present in high numbers.

- Metabolism — Primary production measurements were made in early April at two stations, one at the edge of Boston Harbor (station F23P) and another in the middle of the nearfield (station N16P). At station N16P, significant net production was occurring at the depth of the subsurface chlorophyll maximum and to the 1% light isolume. Integrated ^{14}C primary production rates averaged 1.66 g C m^{-2} d^{-1} (n=2) and 1.53 g C m^{-2} d^{-1} (n=2) at stations F23P and N16P, respectively. Although the integrated production rates at these stations were similar, the vertical profiles of volumetric production were different at the two stations, in part a consequence of different turbidity levels and photic zone depths. The result illustrates that a given level of integrated production can be attained under different environmental conditions. In addition to production measurements, dark respiration (by oxygen decline in bottle incubations) was estimated for samples from three depths at two stations (N20P and F19). A time-series approach was successful, with samples incubated at near ambient (*in situ*) temperatures for periods of several hours to about 6 days. Slopes of linear regressions of DO concentration over time revealed low rates of respiration of 0.003 to 0.007 mg O_2 L^{-1} h^{-1}, with no patterns over station or depth.

Finally, a brief discussion emphasizes some of the interannual variations that have been observed for this season from 1992 to 1994. There have been differences in both the timing and intensity of the winter-spring bloom, as well as its termination, in Massachusetts Bay. The principal constant observed over the three years for the February - May period has been the occurrence of a winter-spring phytoplankton bloom that generally starts earlier and attains higher peak chlorophyll levels in Cape Cod Bay than in Massachusetts Bay.

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: APRIL AND MAY 1994".

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

This report is the second 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 April and March; each of these surveys included sampling at 21 stations in the nearfield area. The early April survey was a combined farfield/nearfield survey 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 (early April farfield/nearfield survey, late April nearfield survey, May nearfield survey).

Section 6. Discussion of the late 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). The first periodic report for 1994 has been submitted (Kelly *et al.*, 1994e).

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 (West, 1994a,b; Dragos, 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 April and May 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 (early) April 5-10 (W9404), (late) April 27-28 (W9405), and May 22 (W9406).

1.4 Summary of Accomplishments: April and May 1994

For the combined farfield/nearfield surveys in early April (W9404), *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 (W9405,W9406), 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.

The last two days of the early April (W9404) farfield/nearfield survey and a second day of the late April nearfield survey were 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 archival) 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 April and May.

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

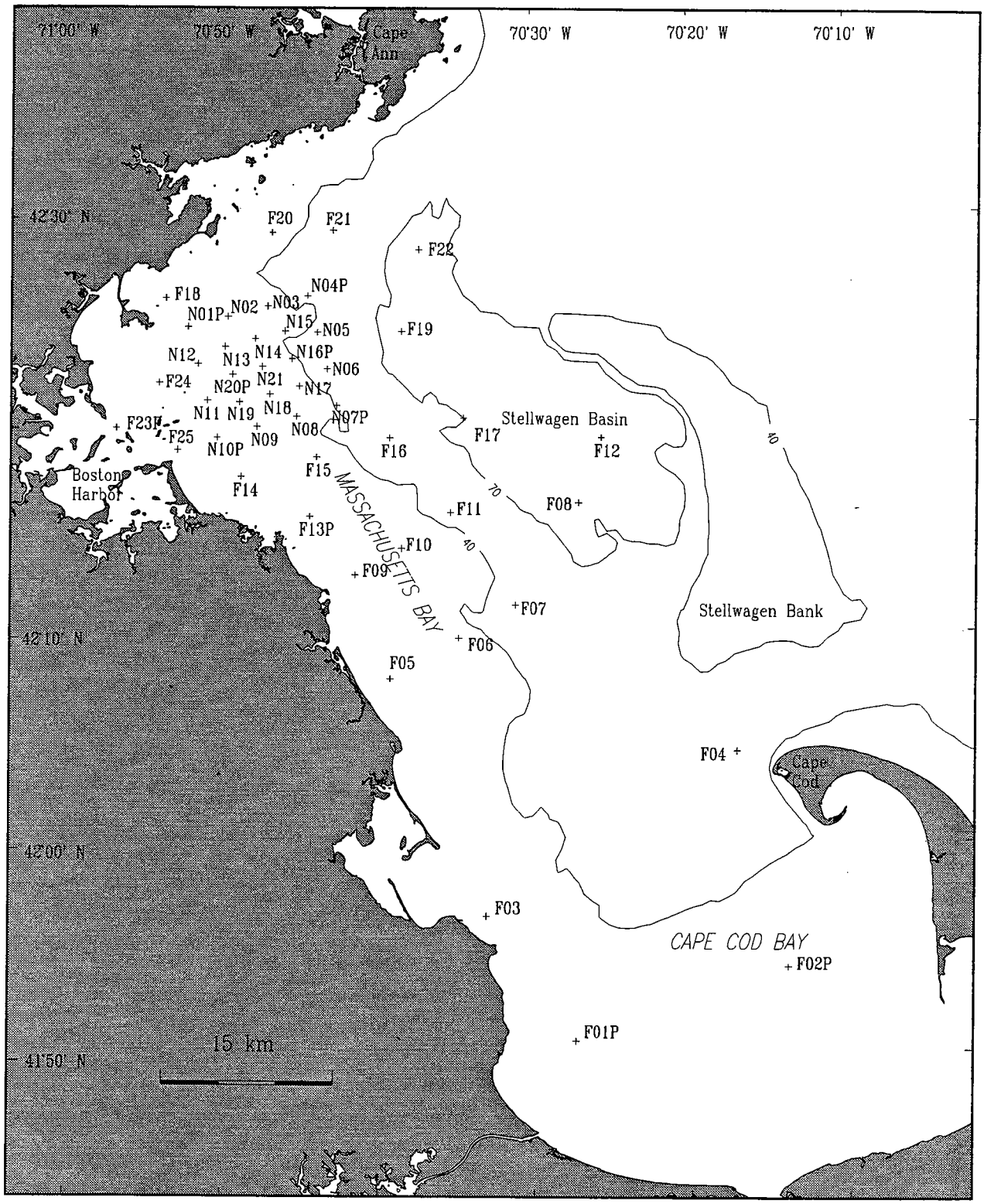


Figure 1-1. **Water quality sampling stations in Massachusetts and Cape Cod Bays. Station codes — F: Farfield, N: Nearfield, P: Biology/Productivity. Depth contours are in meters.**

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 1994 high-resolution surveys.

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, and include 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

In early April, a time-series incubation approach was implemented as a trial attempt to measure water column respiration rates. Previous efforts using only initial and final samples have been unsatisfactory because rates are low, and often there has been no statistically significant change in initial and final DO concentrations. Instead, initial samples were taken and a number of dark bottles were incubated, with replicate bottles serially being fixed at time periods up to 6 days. Results are presented in Appendix D. This sampling occurred at stations N20P and F19 and samples from three depths at each station were incubated.

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 trapped 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 reported in Kelly *et al.* (1994a), 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 D).

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 survey W9403.

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 $(\mu gC\ \mu gChl^{-1}\ hr^{-1})/(\mu E\ m^{-2}\ sec^{-1})$], calculated from I (light irradiance level, $\mu E\ m^{-2}\ sec^{-1}$) and P_{SB}.

In the CW/QAPP and in the first periodic report for 1993 (Kelly *et al.*, 1994a), 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 that this is not 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 that included 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 day-time primary production rates (g C m^{-2} d^{-1}) was made as described above for the individual incubation depth samples.

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 EARLY APRIL 1994 COMBINED FARFIELD/NEARFIELD SURVEY (W9404)

3.1 Farfield Survey

3.1.1 Horizontal Distribution of Surface Water Properties

Surface temperatures were between 3.3 and 5.5°C in the study area in early April 1994 (Figure 3-1). Shallow inshore locations in Boston Harbor were the warmest and there was an apparent warm (>4.6°C) plume extending southward from Nantasket Roads about 15 km along the coast. Much of the offshore surface water was <4°C and this cooler water seemed to extend into the northern part of Cape Cod Bay. Further south, in the central portion of Cape Cod Bay (stations F01P and F02P), the surface water was >4°C.

Spatial patterns for salinity are shown in Figure 3-2. Most of the Bays' surface water was between 31 and 32 PSU, although the salinity in an area of the southeastern nearfield ranged lower, between 30.8 and 30.9 PSU. Near Boston Harbor, salinities dropped to <31 PSU and at the entrance to the Inner Harbor (station F30B), a value of 28.1 PSU was measured. The highest salinity (and the coldest surface water) was measured at station F03, off Plymouth Harbor. Surface salinity increased only slightly from the northern boundary to the Massachusetts-Cape Cod Bay boundary (a line from Plymouth to Provincetown). The pattern suggests that the surface water at the northern boundary of Massachusetts Bay was not fresher than the main body of Massachusetts and Cape Cod Bays, and higher salinities were measured at the northern boundary stations than at locations 5 km outside Boston Harbor which, at the time of measurement, was a distinct source of fresh water. A well-defined flow from a spring freshet of northern rivers was, therefore, not distinctly observed at this time.

In most of the Bays' surface water, beam attenuation was in the range of 0.5 to 0.8 m^{-1}. The striking feature shown in Figure 3-3 is a gradient from high to lower turbidity, extending from Boston Harbor seaward. Turbidity was also relatively high along the coast north of Boston. The pattern for chlorophyll was similar to beam attenuation, as shown in Figure 3-4, which presents *in-situ* sensor data

nominally as chlorophyll *a* (see Appendix A). High concentrations of chlorophyll were detected in the Harbor, along the coast near the Harbor, and at the northeast corner of the nearfield. At all other locations, concentrations were mostly < 1.5 $\mu g\ L^{-1}$.

The patterns for dissolved inorganic nitrogen (DIN) concentrations were similar to those for turbidity and chlorophyll, and showed a sharply decreasing concentration gradient that radiated seaward from the Harbor, where DIN concentrations were > 6 μM (Figure 3-5). Except for the coastal stations near the Harbor, DIN was usually well below 1 μM and often near detection limits. A gradient away from the Harbor was observed for nitrate (NO_3; Figure 3-6) and ammonium (NH_4) concentrations.

Surface water phosphate (PO_4) concentrations were low (e.g., < 0.5 μM) everywhere (Figure 3-7). Concentrations were near zero (at detection limits) for most open water locations in the Bays and were slightly higher (0.2-0.5 μM) at some shallow nearshore stations from Boston Harbor southward to western Cape Cod Bay. Unlike DIN, no significant PO_4 enrichment was evident in surface water throughout Boston Harbor. In contrast, silicate (SiO_4) was enriched in Inner Boston Harbor ($> 6 \mu M$) and decreased sharply into western Massachusetts Bay, similar to the gradient noted for DIN (Figure 3-8). Except for enrichment at locations near the Harbor, silicate was virtually depleted (< 0.3 μM) throughout most of Massachusetts Bay. Surface concentrations of silicate were higher (0.8-1.6 μM) in Cape Cod Bay than in Massachusetts Bay and were similar to the tidally influenced coastal stations adjacent to Boston Harbor.

3.1.2 Water Properties Along Selected Vertical Sections

A set of standard transects for examining vertical sections was established for the 1994 series of water column periodic reports (Kelly *et al.*, 1994e). 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 (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.

The slightly warmer water in Boston Harbor and the similarity in surface temperature throughout most of the Bay (discussed above) are illustrated in Figure 3-10a. Waters were thermally stratified at all locations. Inshore, the stratification extended to the bottom, but beyond about 15-30 m water depth, there was a distinct surface layer with a sharp transition to a cold ($<2.5°C$) bottom layer. Interestingly, in some of the deepest Stellwagen Basin water (stations F22 and F17) the temperature rose again in near-bottom water. Salinity (Figure 3-10b) also showed vertical layering throughout the Bay, with some horizontal spread of fresher water from Boston Harbor. Density layering (σ_T, not shown) was similar to that for salinity (see Appendix B).

Contoured chlorophyll concentrations across the sections (Figure 3-10c) displayed patches of high chlorophyll (>4 μg Chl *a* L^{-1}) and low chlorophyll (<2 μg Chl *a* L^{-1}). In the Harbor or close to shore, the higher chlorophyll concentrations were often found near the surface or within the top 10 m. Offshore, the surface water was generally low in chlorophyll but a distinct subsurface chlorophyll maximum was regularly detected below 20 m. This mid-water, high-chlorophyll layer sometimes coincided with the bottom of the joint thermocline-halocline-pycnocline that marked the transition between surface and bottom water layers, but in many cases (e.g., stations F12, F16, F17; see Appendix B), the vertical profiles indicate that the subsurface chlorophyll maximum was 5-10 m below the pycnocline and, thus, well into the bottom water layer.

The relative enrichment of DIN in Boston Harbor was evident throughout the water column (Figure 3-10d) and DIN appeared to be dispersed at the surface several kilometers into the Bay, reaching the western side of the nearfield. In addition to this nutrient-enriched zone, waters throughout the surface layer and to the depth of the subsurface chlorophyll maximum (20-30 m) were low in DIN (<1.5 μM). In the bottom water layer below the thermocline, DIN concentrations characteristically increased to values >6 μM in the deepest waters sampled in Stellwagen Basin.

For the Boundary Transect (Figure 3-11), south (station F12, Stellwagen Basin) is positioned to the left and north (station F26, Cape Ann) is positioned to the right on the sections. Note that station F28 is positioned on Stellwagen Bank and station F27B is located in the deepwater basin seaward of a 40-50-m sill that forms a boundary between the northern tip of Stellwagen Bank and Cape Ann. At station F27 (outside the Bay), water at depths >30 m was warmer than inside the Bay and temperature actually increased to the bottom of profiles to approximate the surface temperature. At other stations, a 20-m layer of warmer surface water was found above a cold bottom layer. In deep water, salinity differences were slight, both inside and outside of the Bay, and vertical layering was similar across the transect. At all four stations of the transect, a subsurface chlorophyll maximum layer was present *below* the pycnocline, within the upper levels of the bottom water layer. In all cases, the chlorophyll maximum coincided with a turbidity maximum, and these features were found at or below the 1% light level (Appendix B). The highest chlorophyll concentrations (>12 $\mu g\ L^{-1}$) were found at station F27B outside of the Bay, but the elevated concentration detected at station F26 off Cape Ann was also high (>10 $\mu g\ L^{-1}$). In the deep basin water at station F27B, chlorophyll concentrations (and beam attenuation) were slightly elevated (>2 $\mu g\ L^{-1}$) in comparison to other background bottom water values. DIN concentrations were highly layered, being nearly depleted at the surface and increasing with depth. Bottom water in Stellwagen Basin (station F12) reached higher DIN concentrations than in the deeper basin outside the Bay (station F27B), but concentrations were similar to values near Cape Ann (station F26). Over Stellwagen Bank (station F28), DIN concentrations of all samples were <2 μM.

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 b. Individual station profiles are provided in Appendix C. Appendix C also includes separate scatter plots for groups of stations clustered by region defined in Figure 3-13.

The temperature-salinity plot in Figure 3-12a shows that there was a relatively narrow range in temperature over a broad range in salinity. That the points are relatively well constrained on the T-S plot suggests a broad uniformity in the development of vertical layering within the Bays, as was

apparent in section plots, and few regional distinctions other than those afforded by differences in overall water depth. Inspection of regional T-S scatter plots (Appendix C) revealed broad overlap of data points between adjacent regions, but generally increasing in salinity across the Harbor, coastal, nearfield, offshore, and boundary regions. The range in salinity was large, about 5 PSU. The sampling spanned a large range of locations and water types, from the inshore, estuarine water of inner Boston Harbor (<29 PSU) to deep Stellwagen Basin waters (>32 PSU) and to the high salinity bottom water 80-100 m deep at boundary station F27B (approaching 33 PSU), in the basin that lies east of Stellwagen Bank. As shown in Figure 3-11, the deepest waters at station F27B were slightly warmer than the deep water at Stellwagen Basin stations.

Moving out from the Harbor, beam attenuation (turbidity) decreased broadly between areas of low salinity and intermediate levels (31-32 PSU) to the high-salinity water of the deep boundary station; in very deep, high-salinity near-bottom waters, beam attenuation often increased. This geographic transition thus characterizes the overall pattern of beam attenuation and salinity (Figure 3-12a). At the offshore and boundary stations (see Appendix C), there was a broad linear relationship between turbidity and chlorophyll (Figure 3-12a). In the relatively clear water away from land and terrigenous sources of turbidity, chlorophyll has a strong influence on water clarity. A few observations of high turbidity in offshore water were not associated with high chlorophyll concentration and these observations diverge from the main linear trend shown in Figure 3-12a; these cases occurred in near-bottom waters and likely represent a bottom nepheloid layer of suspended sediment. There was also a trend of concomitantly increasing turbidity and chlorophyll for the Harbor stations but, compared to the offshore, the Harbor stations showed a sharper increase in turbidity per increase in chlorophyll, resulting in additional scatter at intermediate chlorophyll concentrations shown in the full data plot (Figure 3-12a). For the Harbor, some turbidity is not related to increasing chlorophyll; given the inverse relationship between turbidity and salinity in the Harbor, the more turbid water likely carries a terrigenous input of suspended solids.

In general, dissolved oxygen (DO) was supersaturated in the surface layer and approached 100% at lower depths. The general pattern thus mimics the vertical distribution of chlorophyll (Figure 3-12b). Chlorophyll concentrations were routinely >2 $\mu g\ L^{-1}$ in the surface layer; subsurface chlorophyll peaks between 4 and 12 $\mu g\ L^{-1}$ were noted at depths to 40 m.

At most regions, there was a similar amount of scatter in the DIN concentrations at any given depth and there was an overall trend towards an increasing concentration with depth (Figure 3-14a). Highest DIN concentrations reached at depth were 6-10 μM; highest concentrations were detected in at station F12 in Stellwagen Basin. The only regional distinction was that, at a few Harbor and coastal stations, DIN concentrations were high compared to other surface waters (0-10 m deep), and the highest concentrations were comparable to near-bottom water (6-8 μM). NH_4 and NO_3 patterns with depth were similar to DIN patterns. Both NH_4 and NO_3 were detected at depth in all regions. Some Harbor and coastal samples were enriched in NH_4, but Harbor samples were often more enriched in NO_3 than were coastal samples (Figure 3-14b). Although this observation has previously been made, it is, nonetheless, curious. If enhancement in the Harbor was simply due to high inputs of nitrate and ammonium, one might expect that nitrate (like ammonium) would also be enriched at some coastal locations as the Harbor water becomes dispersed in that region.

No distinct enrichments in PO_4 concentrations were noted in the Harbor (Figure 3-14c). Although a wide range of PO_4 concentrations was measured at each depth, there was still a general increase in concentration with depth. In contrast, SiO_4 concentrations in all samples except those collected from <50 m at the boundary stations, showed relatively small variability and no broad increase with depth. Most Boston Harbor samples were enriched in silicate relative to the Bays' surface waters, but unlike DIN, enrichments were not apparent in the coastal region.

A Harbor-coastal enrichment in N relative to P was apparent and there was significant variation in N/P ratios within the nearfield (Figure 3-15a). In contrast, a Harbor-coastal enrichment in N relative to Si was not observed when comparing either DIN or NO_3 to silicate (Figure 3-15b). In general, the N/Si ratio was high (>2:1) for the majority of samples, suggesting relative Si depletion through the Bays in general, presumably from the winter-spring bloom that included silicate-utilizing diatom species. In contrast to N/P patterns, we did not observe sharp differences in N/Si ratios within the nearfield during the course of the farfield and nearfield surveys.

DIN plotted as a function of salinity (Figure 3-16a) reveals a pattern previously observed in the spring. A descending arm of DIN concentration with increasing salinity to intermediate salinities (31-32 PSU),

followed by an ascending arm of DIN concentration rising with higher salinity above 32 PSU, even in the nearfield. This pattern signals development of physical and geochemical stratification, as well as the outflow of dissolved nutrients from Boston Harbor. The decrease in DIN at low to mid salinities reflects, in part, mixing of Harbor and Bay waters. The rise at high salinity reflects the simultaneous increase in salinity and DIN with increase in water depth. Between these "arms," are the data that represents the surface layer throughout most of the Bay, where DIN is relatively depleted. Early in the winter, the descending arm is prominent because there is no stratification and subsequent layering with depth. In contrast, during strong stratification in the summer, when nutrients are rapidly assimilated and the Harbor exports organic nitrogen (Kelly, 1994), the descending arm is not prominent but the ascending arm is highly pronounced. Thus, the strong presence of both "arms" indicates that this period is a biogeochemical transition point between winter and summer ecosystems.

In light of this understanding of the normal two-arm DIN-salinity pattern, the differences between NH_4 and NO_3 patterns with salinity (Figure 3-16b) may reveal something about differences in their sources, dynamics, and their potential as water mass diagnostics. For example, the Harbor is a strong source of NH_4, while there a modest increase in NH_4 in stratified bottom layers. In contrast, the Harbor is a more moderate source of NO_3, while a sharp increase with depth is indicated.

The SiO_4-salinity pattern was very similar to the NO_3-salinity pattern, and indicative of a Harbor source and a distinct increase in very deep waters (Figure 3-16c). The PO_4 relationship with salinity was similar to that for NO_3, but there was much more scatter and only a modest Harbor source, if any, was suggested. Note that regional distinctions within the Bays at a given salinity level are not readily apparent. Concentrations of N and Si were generally depleted in the surface layer (intermediate salinity). For P, however, concentrations in Bay surface waters often were as high as in the Harbor and at deepwater locations.

In general, concentrations of the combined forms of N (DIN + PON) and total N (TN) were high in Boston Harbor (Figure 3-17). Concentrations in Cape Cod Bay were low, but they fell within the range measured in the nearfield. Because sampling for these forms of N is conducted at the surface and subsurface chlorophyll maximum depths, the samples do not extend to the deepest waters sampled at a

station. Because so few deepwater samples were collected, the DIN+PON and TN versus salinity plots generally display only the characteristic descending arm of the DIN-salinity plot. This arm displays decreasing concentrations as a function of increasing salinity — a feature that generally reflects the mixing of Harbor water with Bay water and indicates the importance of the Harbor as a nutrient source to the surface layer in western Massachusetts Bay. However, because the chlorophyll maximum was deep at some nearfield stations (20-35 m) and at the boundary station (20 m), there are five samples with salinity >32 PSU in this sample set. The trend of increasing N with increasing salinity (and depth) may be suggested by these samples, particularly for the boundary station (F27B) where an intense bloom was present and the concentrations of combined N forms were high, in part, because biological particles had concentrated nutrients (probably from throughout the surface layers, followed by subsequent sinking). For these samples, the PON concentration was especially high (8 μM) and DIN concentrations were, in contrast, about 0.41 μM. Other samples that were high in PON included (1) the chlorophyll maximum sample from station N07P (PON ~5 μM at 35 m, a case of relatively high salinity, similar to F27B), (2) the surface sample from station N10P receiving export water just outside the southern Harbor (PON ~5 μM), and (3) at depths from ~ 1 to 5 m at both stations (F30B and F31B) within the Harbor (PON ~4.5 to 5.9 μM). Although the plots in Figure 3-17 suggest a general decrease in nutrient concentrations with a decrease in salinity, the scatter undoubtedly arises because the samples reflect various localized conditions where both biological and physical processes affect chemical distributions, but the balance between biological and physical controls varies.

3.1.4 Distribution of Chlorophyll and Phytoplankton

At the stations that were sampled, phytoplankton abundance was in the range of 0.1 to 0.85 million cells L^{-1} (Figure 3-18); this range is indicative of significant phytoplankton populations but not strong bloom conditions. Cell counts were low in Cape Cod Bay (particularly at station F01P), highest in the nearfield (stations N01P and N04P), and intermediate at coastal (F13P) and Harbor-edge (F23P, two occupations) stations. A roughly linear relationship between phytoplankton abundance and chlorophyll concentration can be seen in Figure 3-18, and there were no sharp geographic or depth-related differences in a cell count-chlorophyll ratio.

A comparison of surface and subsurface (chlorophyll maximum) counts (Figures 3-19, 3-20) indicates that there is not a striking difference between total cell counts as a function of depth. At both depths and at every station except station F01P in eastern Cape Cod Bay, diatoms were the dominant organisms. Variations in diatom counts accounted for the variation in total cell counts because the next dominant group, the microflagellates, was relatively constant across all samples. Dinoflagellates were a minor component of the total cell count.

Tables 3-1a and 3-1b identify the dominant taxa in both surface and subsurface samples, respectively. A full taxonomic listing of samples is included in Appendix E. Microflagellates, a multi-species grouping, were always among the main dominant organisms; cryptomonads, another multi-species grouping, were occasionally among the lesser dominants. Dominant individual species were virtually all diatoms. A variety of *Chaetoceros* species and *Thalassiossira* (cf) *gravida/rotula* were the main taxa in Massachusetts Bay. The community in Cape Cod Bay was slightly different than in Massachusetts Bay. In Cape Cod Bay, for example, *Thalassiossira* (cf) *gravida/rotula* was not a significant organism, but *Leptocylindrus minimus* was significant.

Screened phytoplankton samples (Tables 3-2 a and 3-2b) confirmed that there were small numbers (1's to 100's of cells L^{-1}) of dinoflagellates, although more than one dozen species was detected. No regional patterns were discernible.

3.1.5 Distribution of Zooplankton

Total zooplankton abundance showed geographic differences (Figure 3-21). Zooplankton numbers were high at both stations in Cape Cod Bay, both in comparison to other stations and relative to chlorophyll concentrations. On the other hand, cell numbers were low at station F23P at the edge of Boston Harbor.

Compositionally, there were also geographic differences (Figure 3-22). The difference in total numbers in Cape Cod Bay was due to a large abundance of copepod nauplii. At station F23P, the copepod fraction (adult and juveniles, as well as nauplii) was much lower. A group of stations (e.g., N10P, N01P,

and F13P) closest to the Harbor and within the influence of its exported water, also were relatively low in copepods; samples from these stations and station F23P were relatively high in barnacle nauplii counts.

A full taxonomic listing of the zooplankton in all samples in provided in Appendix F. A substantial fraction of the community at most stations was classified as the "other" category (Figure 3-22). In general, this fraction was comprised mostly of *Oikiopleura dioica*, an appendicularian often noted in the Bays, and which was relatively abundant at many stations (>7,000 individuals at station N04P) and ubiquitous during the early April 1994 survey. *Oithona similis* and *Paracalanus parvus*, both small-sized species that are usual dominants in samples from the Bays, and *Calanus finmarchicus*, a large form, were also numerically dominant. *C. finmarchicus*, which can be prey for whales, was present in high numbers ($>10^3$ m^{-3}) at the nearfield stations most distant from the Harbor (e.g., N20P, N16P, N07P, and N04P) and at station F01P in western Cape Cod Bay. Except for the fact that much higher numbers of copepod nauplii were found in Cape Cod Bay samples than in Massachusetts Bay, a preliminary review of the copepod taxa and abundance data does not reveal any other striking differences between the copepod communities of Massachusetts and Cape Cod Bays.

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. Note that all calculations used a survey-specific (rather than station- or day-specific) incident irradiance level so that variations in calculated production rates do not result from day-to-day fluctuations in irradiance. Calculations are presented for incubations of four samples from station F23P (at the edge of the Harbor) and station N16P (in the middle of the nearfield); incubations were performed on successive days (April 5 and 6).

The photic zone was deeper at station N16P (23.5-28.5 m) than at station F23P (18 m), a common finding. P_{max} or P_{sb} values ranged between 3.7 and 11.6 μg C (μg Chl)$^{-1}$ hr^{-1} and most curves were fit without a photoinhibition term in the model. The surfacemost incubation consistently yielded the highest

estimate of integrated water column production because P_{max} (or P_{sb}) and/or α were often the highest of a given series. The range of integrated production rates, based on individual samples, was 936 to 3975 mg C m^{-2} d^{-1}; this was also approximately the range at station N16P on April 5.

Using the calculation scheme described previously in Section 2 (methods) to combine results of the four incubations into a single estimate, we calculated rates of 1464 and 1855 mg C m^{-2} d^{-1} for station F23P on April 5 and 6, respectively. From the composite profile for station N16P, we calculated rates of 1746 and 1322 mg C m^{-2} d^{-1} on April 5 and 6, respectively. Thus, in spite of photic zone depth differences and some spatial and temporal variability in chlorophyll, the integrated production rates across stations and time were similar, within ~30-40% of each other.

3.1.7 Dark Respiration Measurements

Results of dark-bottle-incubation time series at stations N20P (middle of the nearfield) and F19 (east of the nearfield) are presented in Appendix D. In general, the time series approach was successful over 0-48 h and the strongest regressions of DO concentration over time were obtained with time series that extended to about 7 d. Slopes from all regressions indicated that rates were low (0.003 to 0.007 mg O_2 L^{-1} h^{-1}), and confirmed that time series are required to adequately characterize the rates. No depth-related or station-related patterns in respiration rate were noted.

3.2 Nearfield Survey

3.2.1 Distribution of Water Properties from Vertical Profiling

Scatter plots for a variety of parameters for the nearfield survey alone (April 8) are shown in Figure 3-23. Patterns and ranges may be compared to all stations in Figure 3-12, as well as to separate regions in Appendix C. Results for the nearfield survey of 21 stations show a strong coherence among stations with respect to T-S characteristics. The range in T is narrow (about 2°C) and the salinity range is from ~31 to 32.5 PSU; a decrease in temperature and concomitant increase in salinity represent

increasing depth of the sample. Spatial variations in temperature and salinity portray a T-S gradient from shore to sea, with T decreasing and S increasing slightly offshore (Outer Eastern Transect) and at increasing depth (Figures 3-24a and 3-24b). 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 temperature and salinity from the southwestern corner of the nearfield (station N10P).

Beam attenuation was slightly higher at lower salinity and also increased at high salinity (Figure 3-23a). The increase at high salinity was near the bottom of vertical profiles. Beam attenuation and chlorophyll were correlated (Figure 3-23a). Chlorophyll concentration peaks occurred at about 10 m for many profiles, but for others, a deeper peak near 40 m was evident (Figure 3-23b). Correspondingly, DO profiles generally showed conditions of supersaturation in the upper 20 m, with percent saturation decreasing below that depth; however, sometimes concentrations above saturation were detected as deep as 40 m (Figure 3-23b). From section plots in Figure 3-24c, a change in the vertical distribution of chlorophyll was noted as a function of distance from shore. Nearshore, along the Outer Western Track, especially the southwestern corner, chlorophyll concentrations were high in the surface 15 m. In the midfield, especially at station N20P, a subsurface peak occurred at about 20 m, which was the depth of a sharp pycnocline at the bottom of the surface water layer. At the offshore side of the nearfield, the subsurface chlorophyll maximum occurred within the bottom water layer and was found generally at 30-50 m water depth.

DIN concentrations were highest (>4 μM) in deepest water on the eastern side of the nearfield, where salinity was also high (Figure 3-24d). Except at station N11, DIN concentrations of surface water were <2 μM. In the middle of the field, DIN concentrations were generally <2 μM throughout the water column, whereas to both the east and west, bottom waters were enriched in DIN relative to surface water.

3.2.2 Water Quality Variability in the Nearfield

There were corresponding spatial trends in physico-chemical and biological parameters, expressed both vertically and horizontally and displayed in Figure 3-24. Perhaps most interesting was the variability in chlorophyll from inshore to offshore. Across this increase in water depth, the vertical position of chlorophyll concentration peaks graded from the surface layer to the bottom layer. Concomitantly, DIN concentrations were generally higher in surface layers inshore than in surface layers offshore. It is possible that the deepwater chlorophyll offshore reflects the sinking of cells and the collapse of a bloom no longer supported by a source of nutrients because vertical stratification has developed. In contrast, at the inshore waters, stratification was not as well developed and there was a strong source of nutrients (i.e., Boston Harbor). These inshore conditions are favorable to maintaining a phytoplankton population in an active growth phase rather than a senescent phase and therefore may allow development of surface-layer phytoplankton populations that cannot be maintained further offshore.

Comparisons of data for nearfield stations, occupied during the farfield survey and again on the nearfield survey, provide some indication of the temporal dynamics in the nearfield. The surface water at station N10P, for example, was lower in salinity and higher in temperature on April 5 than on April 8. This station is influenced by tidal dynamics, so it is not necessarily a good indicator for field-wide temporal trends. Other stations that are further offshore (e.g., N20P, N16P, and N07P) are less directly influenced by tidal processes. Although the thermal regime of these stations was similar on both April 5 (or 6) and April 8, salinity at these locations had increased significantly between April 5 and 8. Both higher salinity and cooler temperature were measured at station N04P on April 8. Among this group of four eastern nearfield stations, the pycnocline generally deepened over the few days between sampling events and, moreover, chlorophyll concentrations either decreased throughout the water column or peaks became more deeply distributed. The salinity change implies some advection and the distinct cooling at station N04P additionally could suggest advection from the north (cf. Figure 3-24a). Whatever the mechanism, the dynamics seemed to affect the physical layering of the upper water column and contribute to deepening of the subsurface chlorophyll maximum if it did

not also promote chlorophyll settling to deeper water. This medley of physical and biological events has been noted during this season in previous years (cf. Kelly *et al.*, 1993a, 1994b), although the mechanism promoting it is not known.

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

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Apr. 07	Apr. 05	Apr. 06	Apr. 06	Apr. 05	Apr. 05	Apr. 05	Apr. 05	Apr. 07	Apr. 07
CHAETOCEROS COMPRESSUS						0.014 (5)	0.011 (4)	0.016 (5)		
CHAETOCEROS DEBILIS	0.043 (3)	0.059 (4)	0.049 (4)	0.088 (3)	0.014 (4)	0.031 (4)		0.017 (4)		
CHAETOCEROS SOCIALIS	0.014 (5)	0.031 (5)							0.012 (3)	
CHAETOCEROS SPP. (10-20UM)			0.033 (5)	0.030 (5)	0.038 (3)		0.009 (5)			
CHAETOCEROS SPP.(<10UM)	0.204 (1)	0.102 (3)	0.370 (1)	0.395 (1)	0.014 (4)	0.061 (3)	0.017 (3)	0.066 (3)	0.004 (5)	0.008 (3)
CRYPTOMONADS									0.016 (2)	
CYLINDROTHECA CLOSTERIUM										0.003 (5)
GYRODINIUM SPIRALE										0.003 (5)
LEPTOCYLINDRUS MINIMUS									0.005 (4)	0.210 (1)
MICROFLAGELLATES	0.130 (2)	0.178 (1)	0.095 (2)	0.080 (4)	0.085 (2)	0.180 (1)	0.091 (1)	0.143 (1)	0.079 (1)	0.096 (2)
THALASSIONEMA NITZSCHIOIDES										0.005 (4)
THALASSIOSIRA (CF) CONSTRICTA						0.014 (5)				
THALASSIOSIRA (cf) GRAVIDA/ROTULA	0.031 (4)	0.147 (2)	0.085 (3)	0.155 (2)	0.116 (1)	0.118 (2)	0.080 (2)	0.087 (2)		
THALASSIOSIRA SPP.					0.007 (5)					
UNID. ATHECATE DINOFLAGELLATE										0.003 (5)

Units are millions of cells/L 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 April 1994.

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Apr. 07	Apr. 05	Apr. 06	Apr. 06	Apr. 05	Apr. 05	Apr. 05	Apr. 05	Apr. 07	Apr. 07
CHAETOCEROS COMPRESSUS						0.043 (4)				
CHAETOCEROS DEBILIS	0.042 (3)	0.059 (4)	0.068 (4)	0.088 (3)	0.008 (5)	0.042 (5)		0.020 (4)		
CHAETOCEROS SOCIALIS		0.039 (5)	0.024 (5)	0.029 (5)					0.007 (4)	
CHAETOCEROS SPP. (10-20UM)			0.024 (5)					0.014 (5)		
CHAETOCEROS SPP.(<10UM)	0.201 (1)	0.116 (1)	0.376 (1)	0.329 (1)	0.034 (3)	0.111 (2)	0.021 (3)	0.021 (3)	0.013 (2)	0.007 (3)
CRYPTOMONADS	0.016 (5)				0.008 (5)		0.010 (5)		0.010 (3)	
LEPTOCYLINDRUS MINIMUS									0.002 (5)	0.168 (1)
MICROFLAGELLATES	0.095 (2)	0.060 (3)	0.183 (2)	0.084 (4)	0.177 (2)	0.121 (1)	0.158 (1)	0.175 (1)	0.084 (1)	0.080 (2)
NAVICULOID DIATOMS										0.006 (4)
THALASSIONEMA NITZSCHIOIDES										0.004 (5)
THALASSIOSIRA (cf) GRAVIDA/ROTULA	0.032 (4)	0.089 (2)	0.085 (3)	0.115 (2)	0.284 (1)	0.102 (3)	0.143 (2)	0.115 (2)		
THALASSIOSIRA SPP.		0.059 (4)			0.009 (4)		0.011 (4)			

Units are millions of cells/L and rankings are given in parentheses.

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

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Apr. 07	Apr. 05	Apr. 06	Apr. 06	Apr. 05	Apr. 05	Apr. 05	Apr. 05	Apr. 07	Apr. 07
ALORICATE CILIATES	18	8	55	35	33	5	20	15	5	5
AMPHIDINIUM SPP.	0	0	0	3	0	0	3	0	0	0
CERATIUM FUSUS	0	0	3	0	3	0	0	0	0	0
CERATIUM LINEATUM	0	0	0	0	0	0	3	0	0	0
CERATIUM LONGIPES	8	0	3	5	10	0	5	3	8	10
DICTYOCHA FIBULA	0	0	3	0	0	0	0	0	0	0
DICTYOCHA SPECULUM	0	3	3	0	3	3	5	9	0	0
DINOPHYSIS ACUMINATA	0	0	0	0	0	0	0	0	0	3
DINOPHYSIS NORVEGICA	5	0	0	8	13	0	13	0	10	28
DINOPHYSIS SPP.	0	0	0	0	0	0	0	0	0	8
GYMNODINIUM SPP.	0	0	0	0	0	0	0	3	0	0
GYRODINIUM SPIRALE	25	13	28	18	10	28	5	17	13	8
GYRODINIUM SPP.	13	0	0	0	3	0	0	0	5	10
MESODINIUM RUBRUM	3	0	35	13	15	0	8	9	0	0
PEDIASTRUM SPP. COLONY	0	0	0	0	0	0	0	3	0	0
PROTOPERIDINIUM BIPES	8	0	3	3	3	3	0	3	3	0
PROTOPERIDINIUM BREVE	8	10	0	10	23	5	3	6	3	30
PROTOPERIDINIUM DENTICULATUM	8	0	3	5	15	3	0	0	0	0
PROTOPERIDINIUM DEPRESSUM	0	0	0	3	3	0	0	9	0	25
PROTOPERIDINIUM SPP.	105	28	60	128	85	43	53	46	40	153
SCENEDESMUS SPP.	0	3	0	0	0	0	0	0	0	0
SCRIPPSIELLA TROCHOIDEA	0	0	0	0	0	0	0	0	3	0
TINTINNIDS	48	78	228	43	33	65	28	113	25	20
UNID. ATHECATE DINOFLAGELLATE	3	0	15	0	20	0	3	9	0	3
UNID. THECATE DINOFLAGELLATES	0	0	0	0	0	0	0	9	0	0

Units are cells/L.

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

	Coastal Stations		Nearfield Stations						Cape Cod Bay Stations	
	F13P	F23P	N01P	N04P	N07P	N10P	N16P	N20P	F01P	F02P
	Apr. 07	Apr. 05	Apr. 06	Apr. 06	Apr. 05	Apr. 05	Apr. 05	Apr. 05	Apr. 07	Apr. 07
ALORICATE CILIATES	23	3	83	13	65	5	75	40	0	28
AMPHIDINIUM SPP.	0	0	3	0	0	0	0	0	3	0
CERATIUM LINEATUM	0	3	3	3	0	0	0	0	0	0
CERATIUM LONGIPES	3	0	0	5	0	0	3	0	5	8
DICTYOCHA SPECULUM	0	5	0	0	0	0	0	0	0	0
DINOPHYSIS ACUMINATA	3	0	0	0	0	0	0	0	0	0
DINOPHYSIS NORVEGICA	8	0	3	0	0	5	0	0	10	33
DINOPHYSIS SPP.	0	0	0	0	0	0	0	0	5	0
EUTREPTIA/EUTREPTIELLA SPP.	0	0	0	0	0	0	3	0	0	0
GYMNODINIUM SPP.	0	3	0	0	0	0	0	0	0	0
GYRODINIUM SPIRALE	15	15	30	13	45	8	78	33	20	15
MESODINIUM RUBRUM	0	0	13	15	18	0	25	28	30	0
PEDIASTRUM SPP. COLONY	0	0	0	0	0	0	0	0	0	0
PROTOPERIDINIUM BIPES	0	0	0	8	3	0	5	0	0	0
PROTOPERIDINIUM BREVE	5	5	15	20	0	0	3	10	5	53
PROTOPERIDINIUM DENTICULATUM	0	0	5	5	20	3	5	5	0	0
PROTOPERIDINIUM DEPRESSUM	0	5	8	0	0	0	3	3	25	18
PROTOPERIDINIUM PALLIDUM	0	0	0	0	0	5	0	0	0	0
PROTOPERIDINIUM SPP.	103	23	80	85	25	23	28	33	35	210
TINTINNIDS	95	70	8	15	13	15	20	15	13	15
UNID. ATHECATE DINOFLAGELLATE	8	5	8	5	8	3	10	10	0	0
UNID. THECATE DINOFLAGELLATES	0	0	18	0	0	0	0	0	0	0

Units are cells/L.

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

	F23P 05-APR-94				F23P 06-APR-94				N16P 05-APR-94				N16P 06-APR-94			
Water depth (m)	24.5				23.0				44.0				42.5			
$Z_{(0.5\%Io)}$ (m)	18.0				18.0				23.5				28.5			
Sample depth (m)	2.1	5.9	11.7	18.0	2.5	4.7	8.4	14.7	1.5	9.2	21.1	31.6	2.2	12.9	25.3	32.8
Rate (mg C $m^{-2}d^{-1}$)	1623	1614	1095	1024	2443	1576	2320	1192	3975	1352	1766	969	2091	1210	1464	936
Model[1]	P	W	W	W	W	W	W	P	W	W	W	W	W	W	W	W
P_{SB} or P_{MAX}[2]	7.12	6.59	4.52	3.85	9.24	7.76	11.57	7.21	10.66	4.69	4.89	3.73	5.34	6.24	5.15	4.11
α[3]	0.068	0.064	0.042	0.054	0.125	0.039	0.056	0.032	0.397	0.082	0.163	0.051	0.287	0.041	0.087	0.039
β[4]	0.001	-	-	-	-	-	-	0.002	-	-	-	-	-	-	-	-

[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.

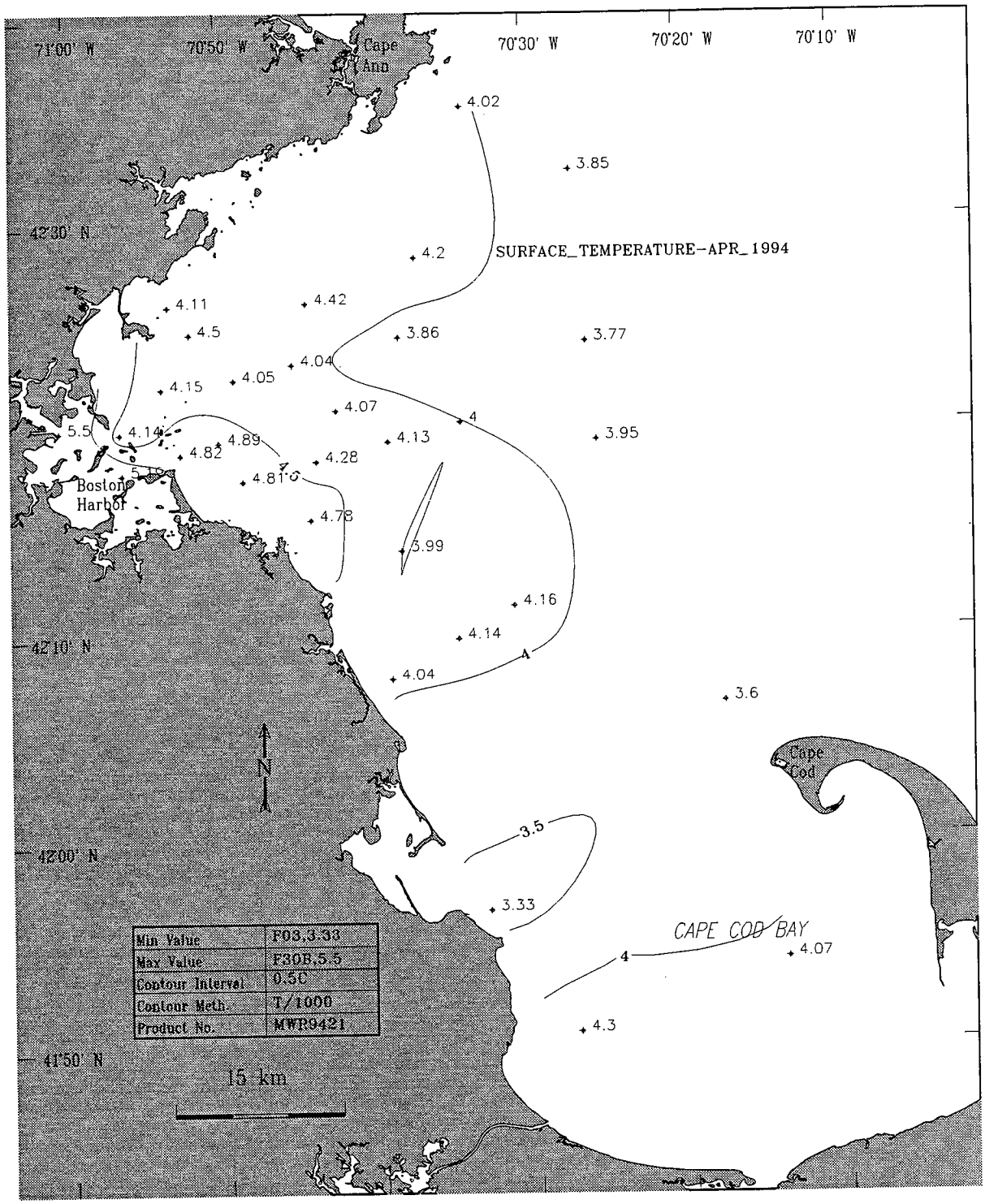


Figure 3-1. **Surface temperature (°C) in the study area in early April 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

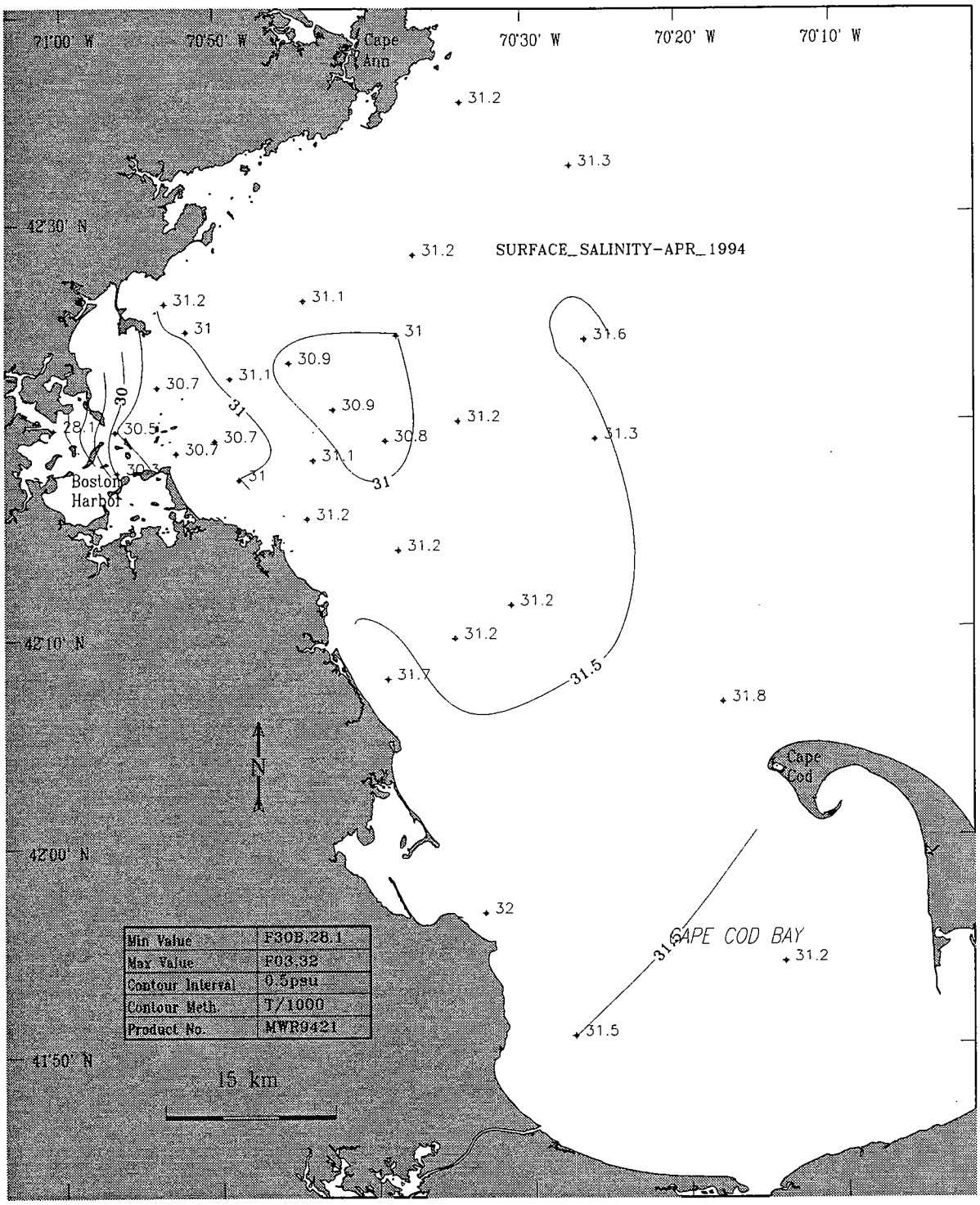


Figure 3-2. **Surface salinity (PSU) in the study area in early April 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

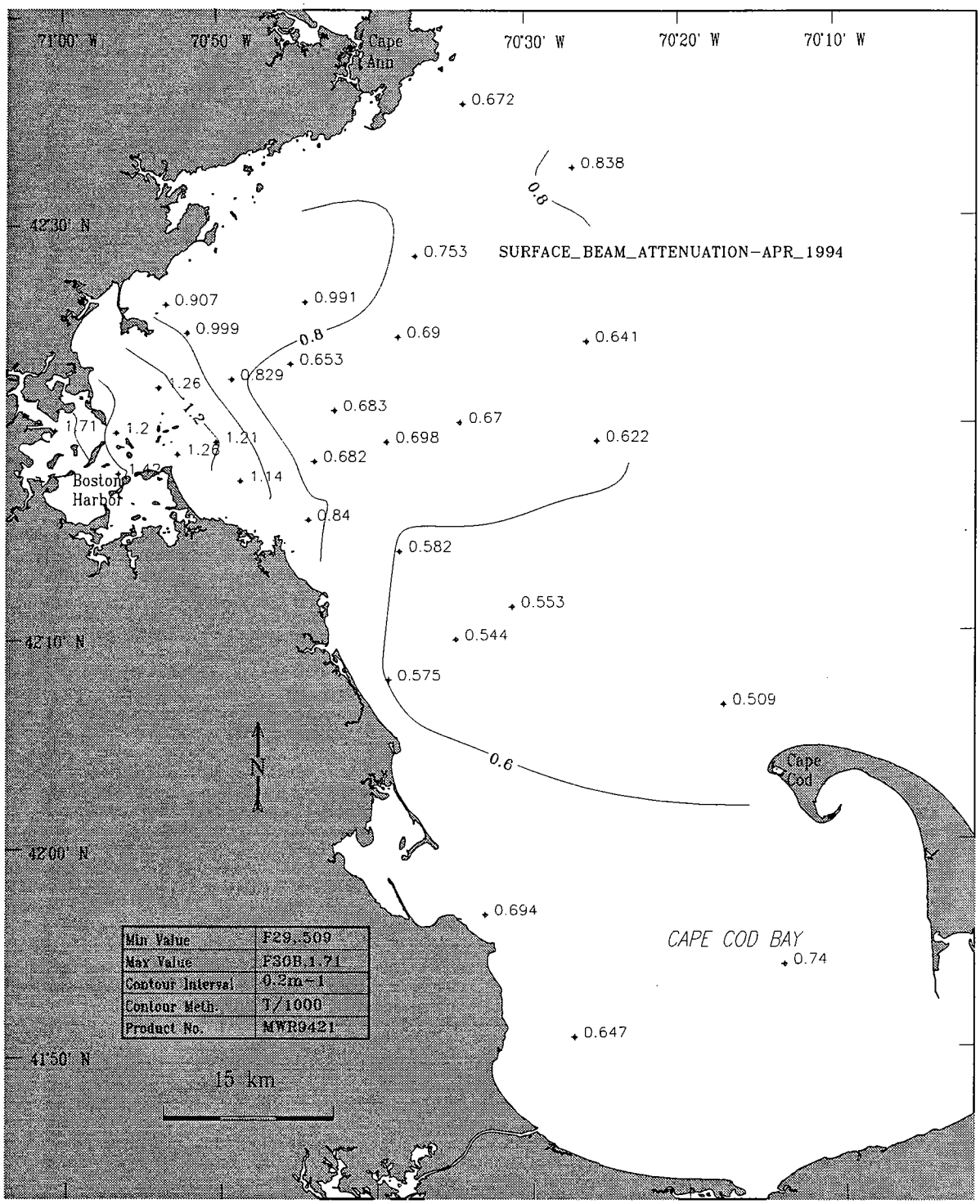


Figure 3-3. **Surface beam attenuation (m^{-1}) in the study area in early April 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

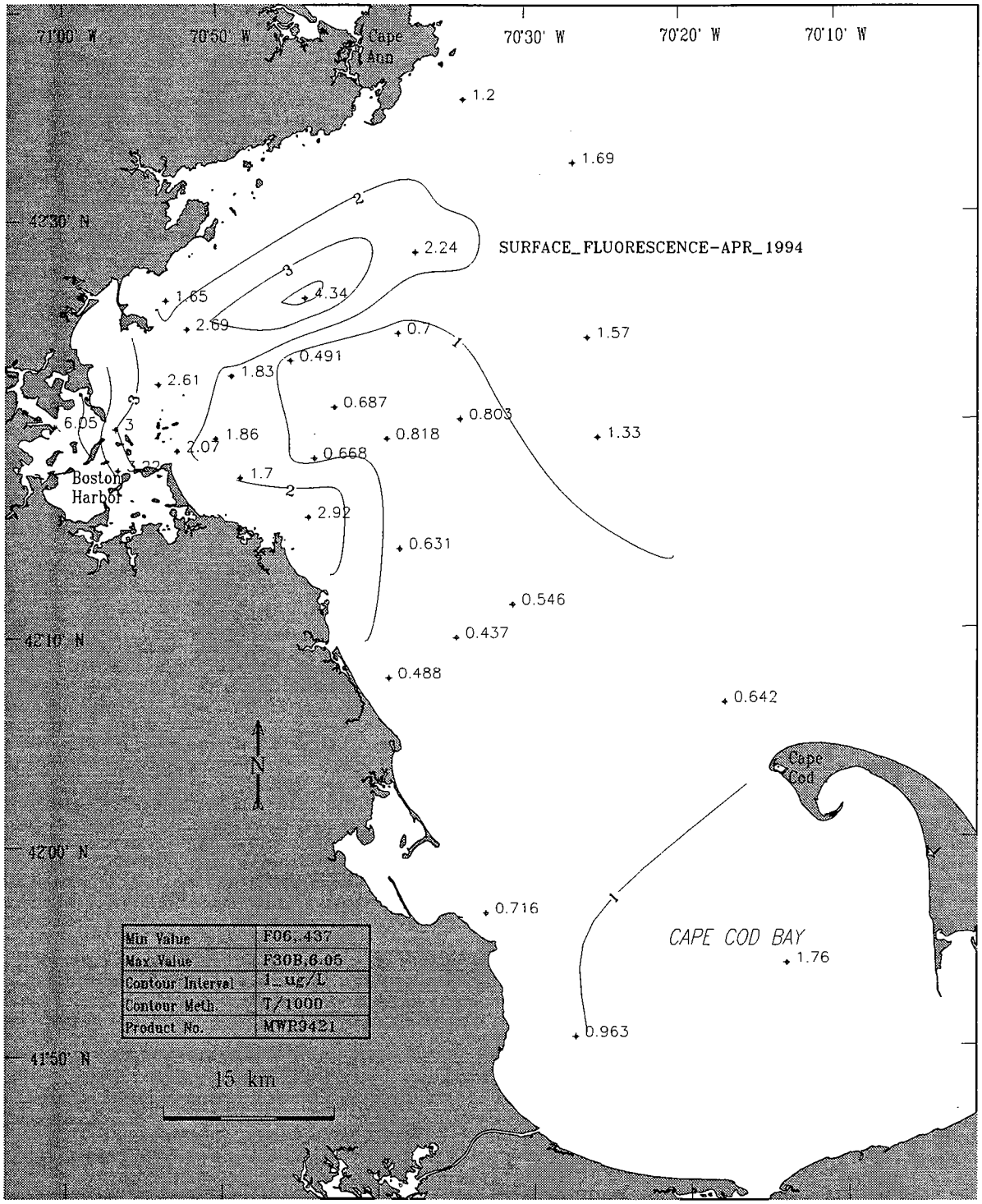


Figure 3-4. **Surface *in situ* fluorescence (as μg Chl L^{-1}) in the study area in early April 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

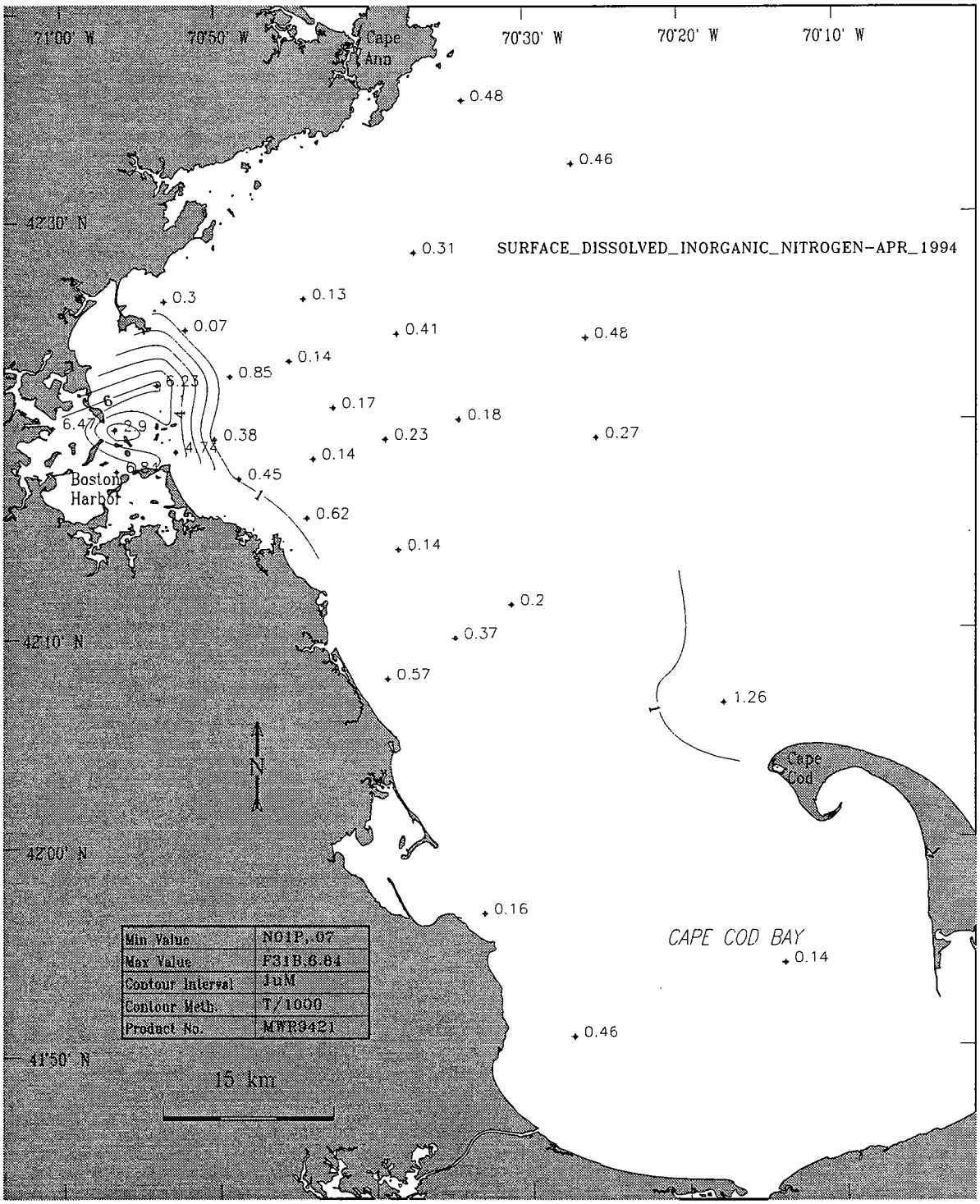


Figure 3-5. **Surface dissolved inorganic nitrogen (DIN, μM) in the study area in early April 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

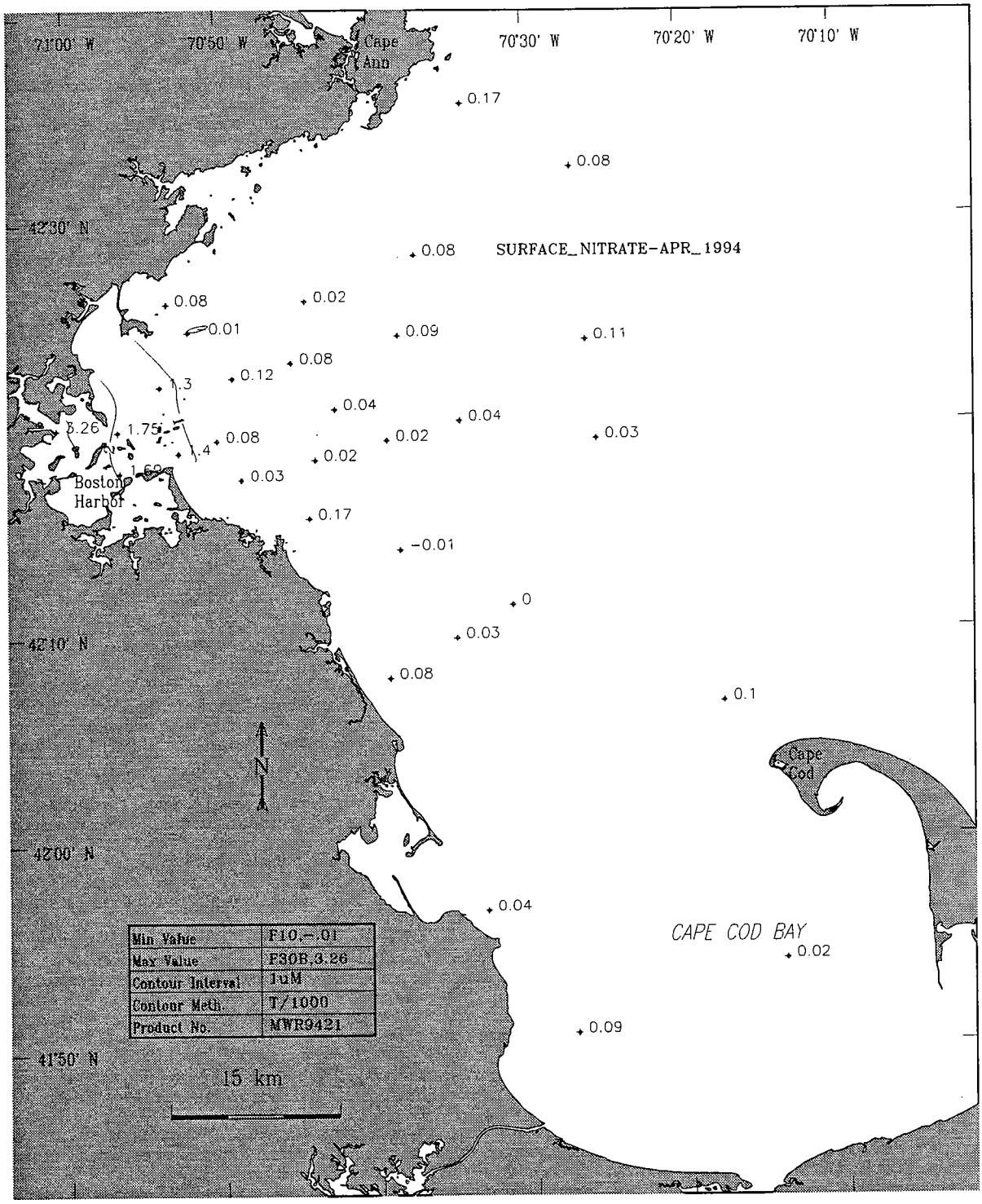


Figure 3-6. **Surface nitrate (NO_3, μM) in the study area in early April 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

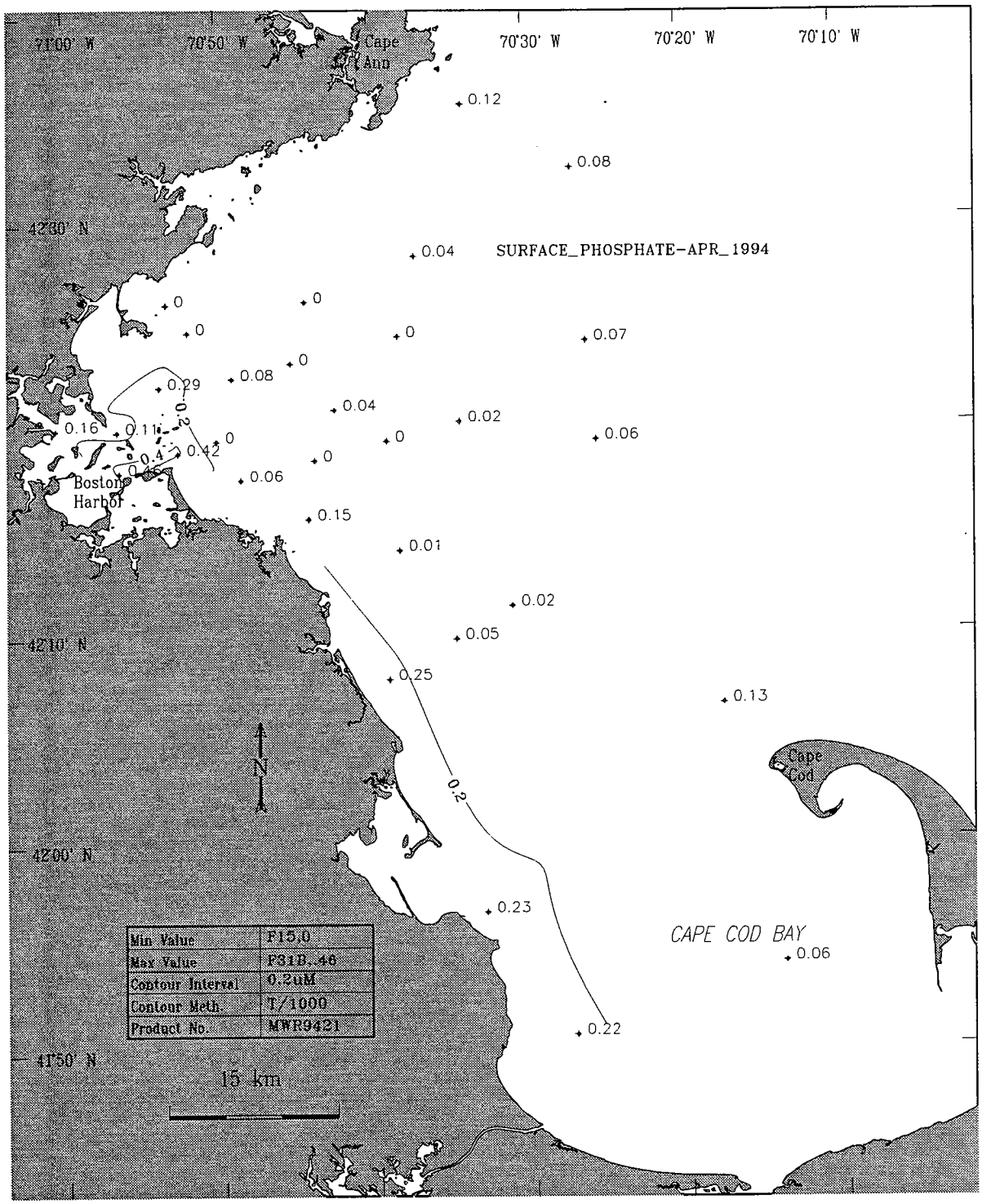


Figure 3-7. **Surface phosphate (PO_4, μM) in the study area in early April 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

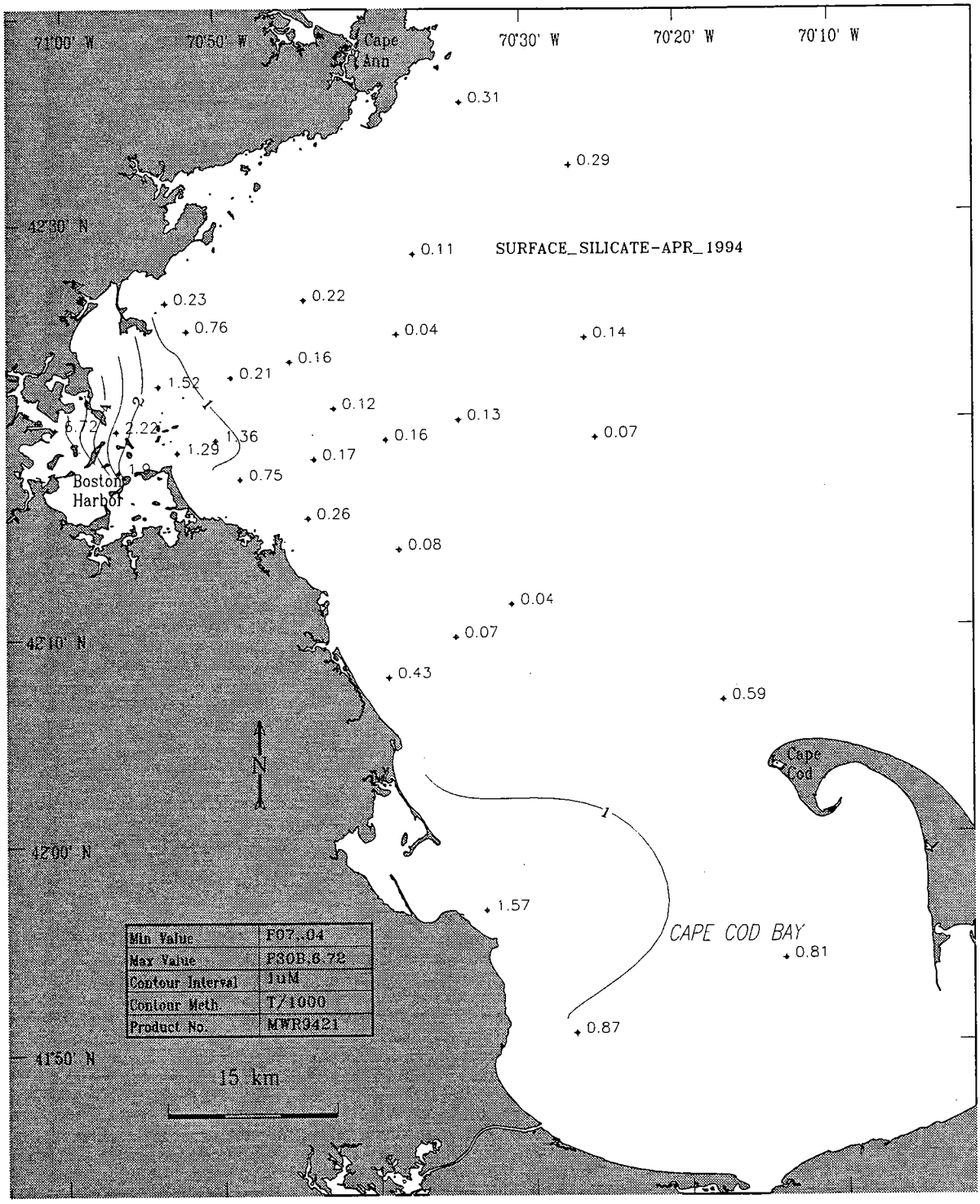


Figure 3-8. **Surface silicate (SiO_4, μM) in the study area in early April 1994. Data are from the surfacemost sample at all farfield survey stations, including the B/P stations within the nearfield grid (Appendix A).**

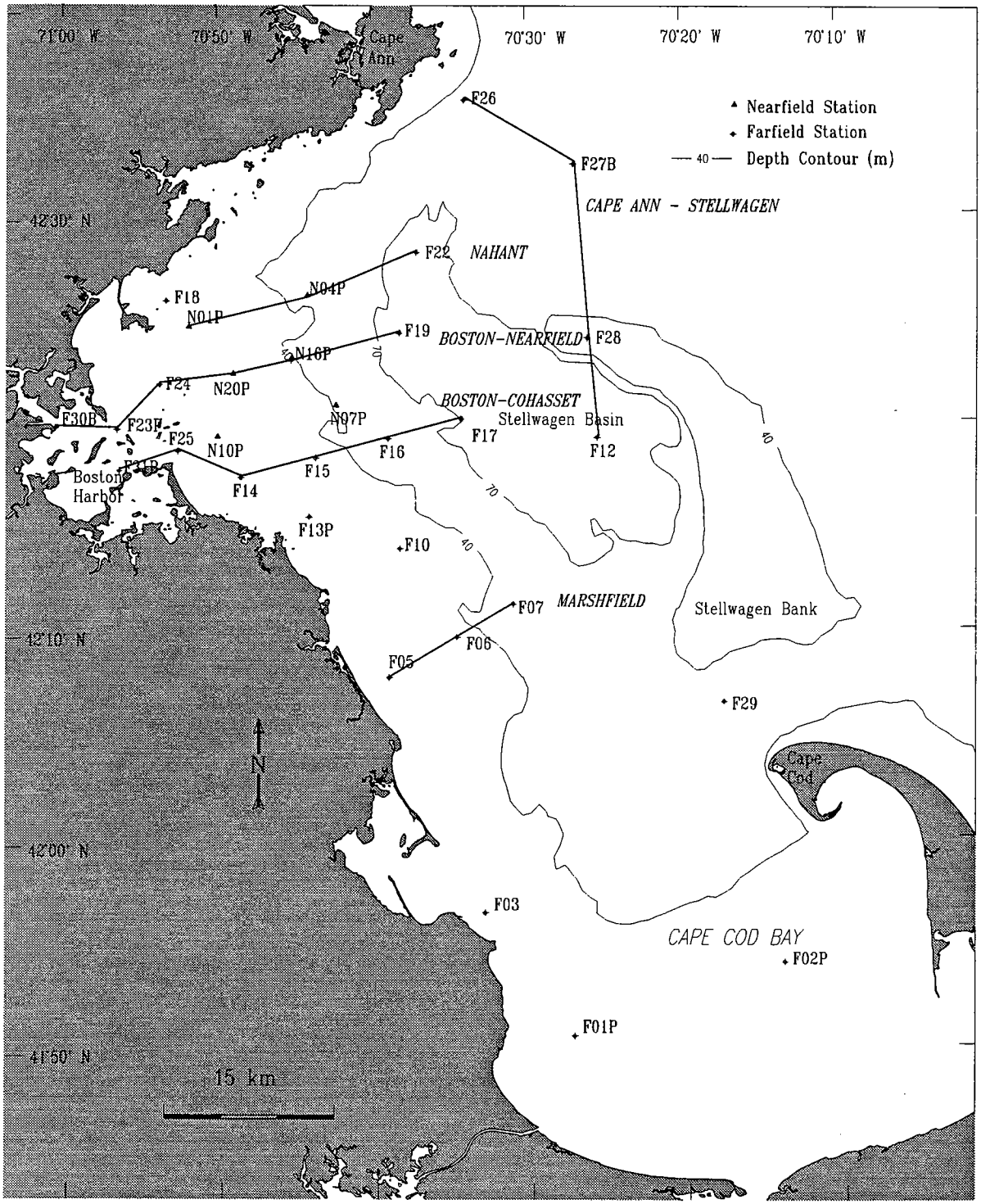


Figure 3-9. Map showing position of five standard transects for which vertical contour plots were produced in Figures 3-10 and 3-11.

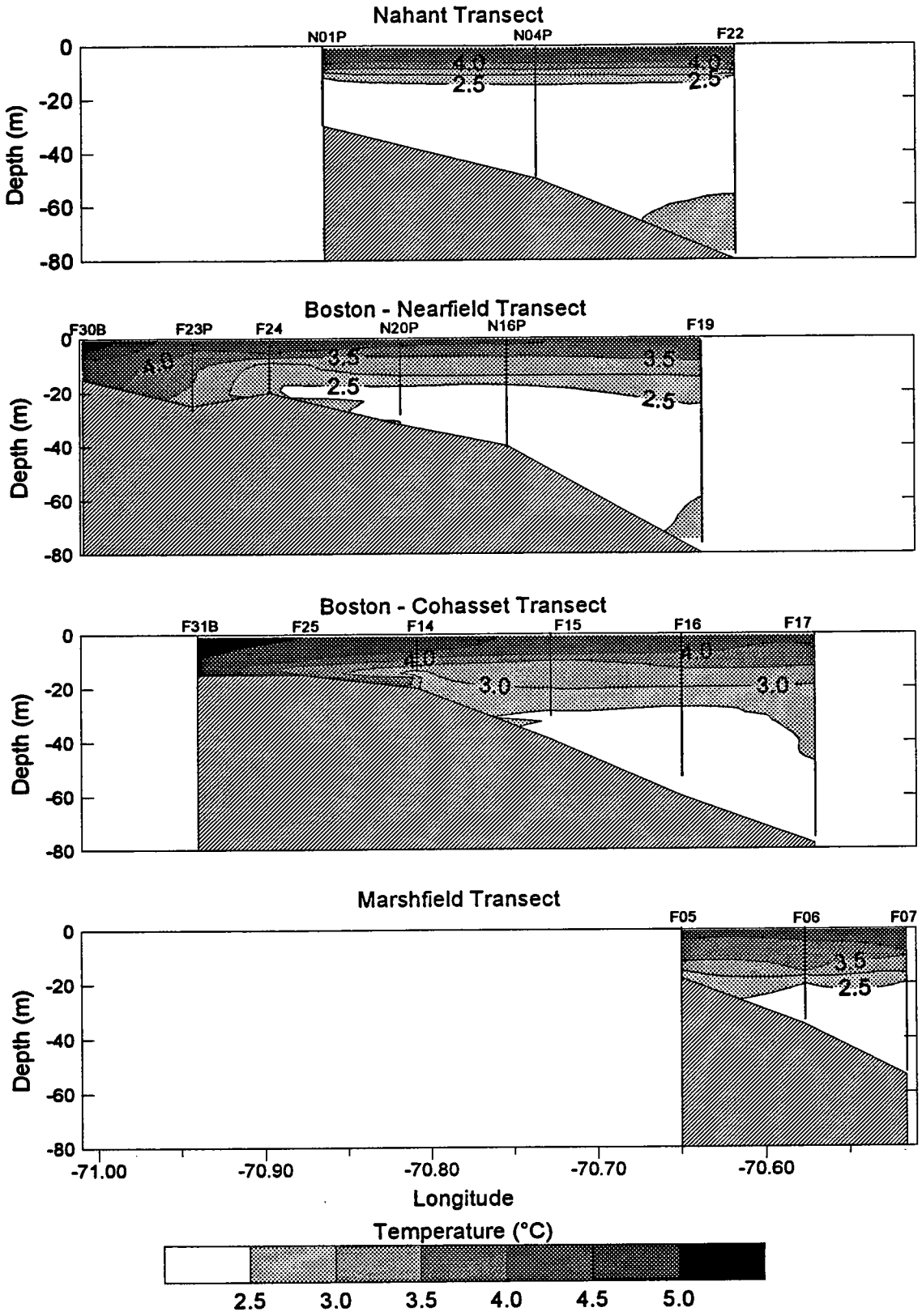


Figure 3-10a. Vertical section contours for standard transects (see Figure 3-9) on Survey W9404. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

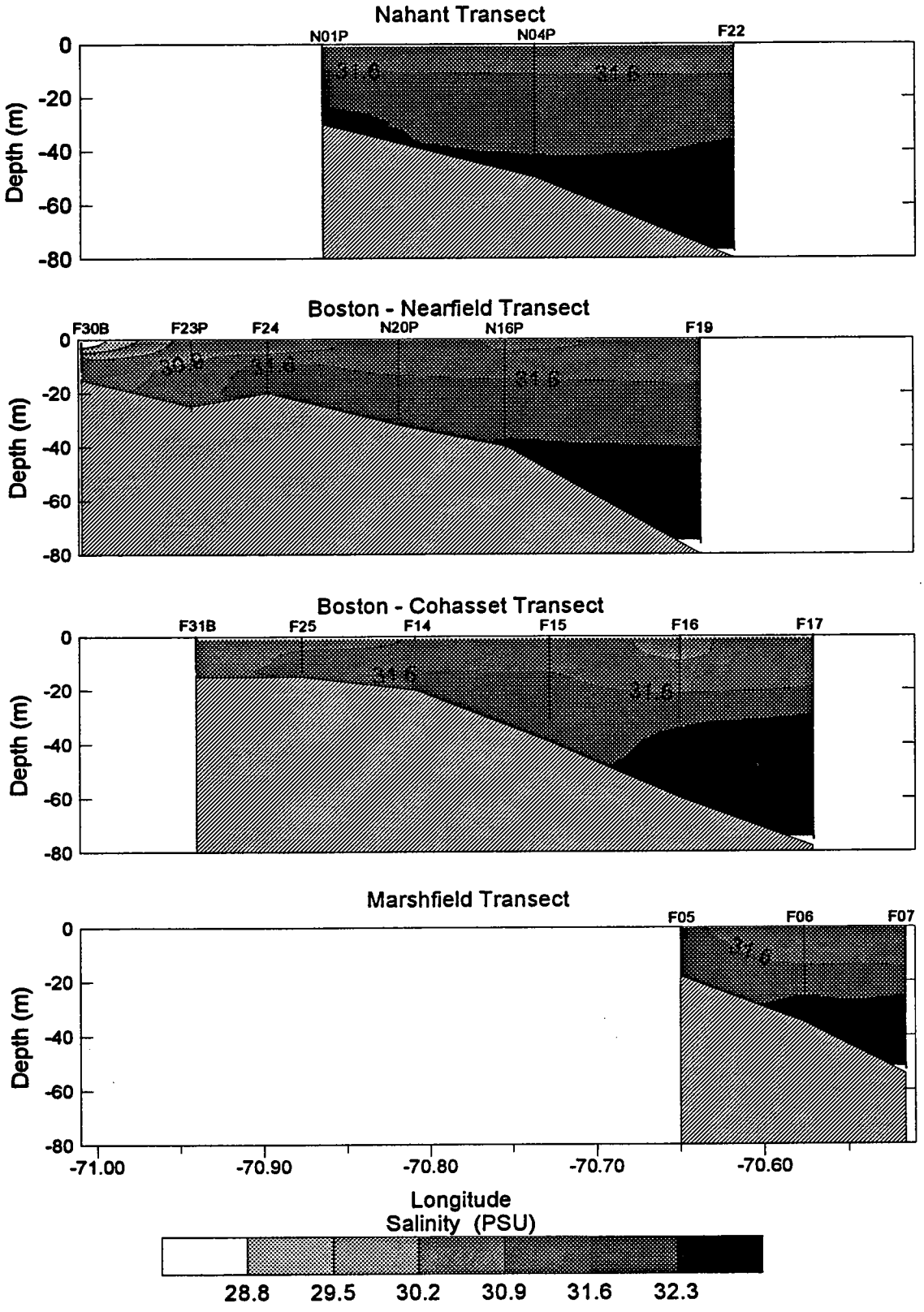


Figure 3-10b. Vertical section contours for standard transects (see Figure 3-9) on Survey W9404. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

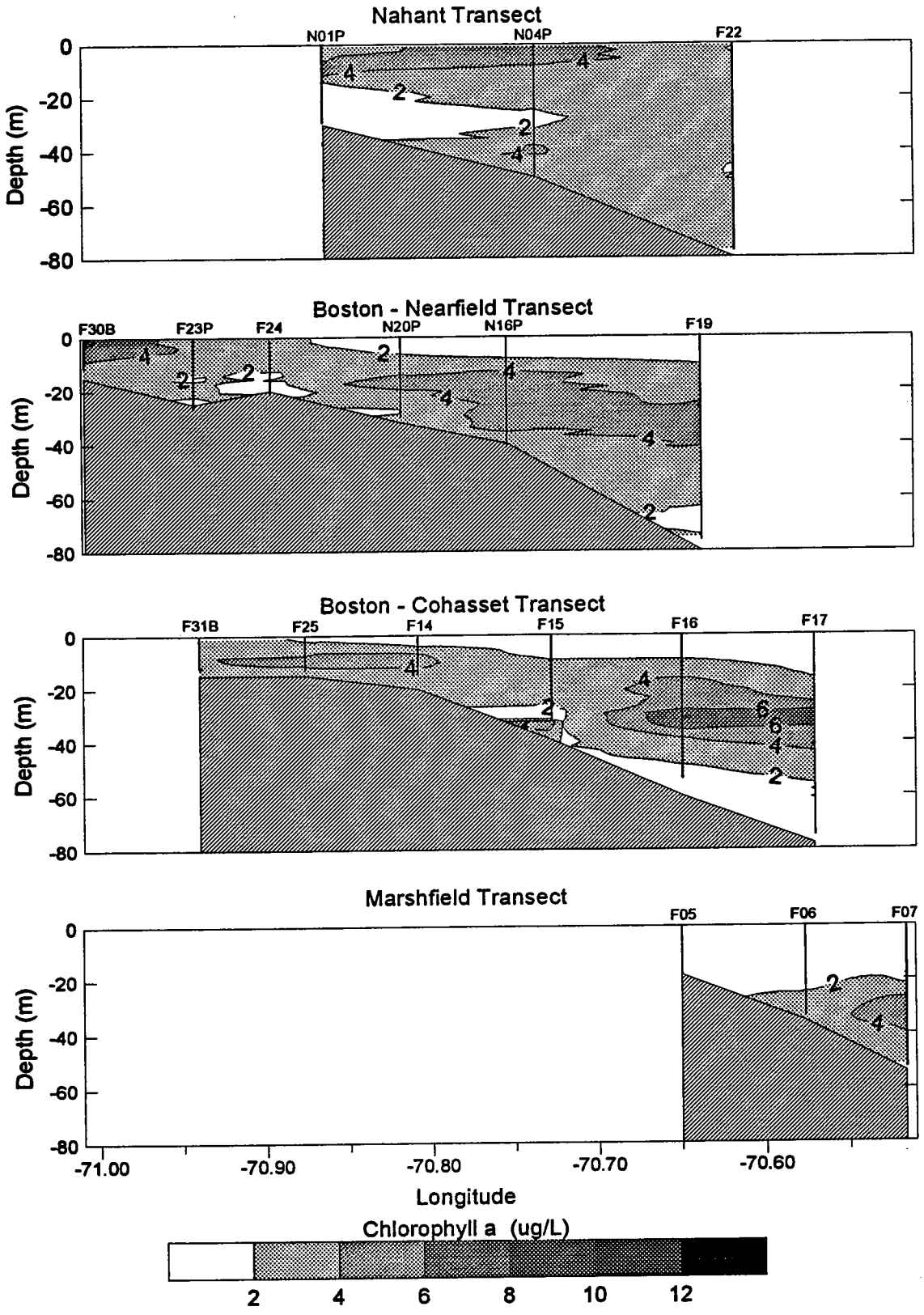


Figure 3-10c. Vertical section contours for standard transects (see Figure 3-9) on Survey W9404. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station.

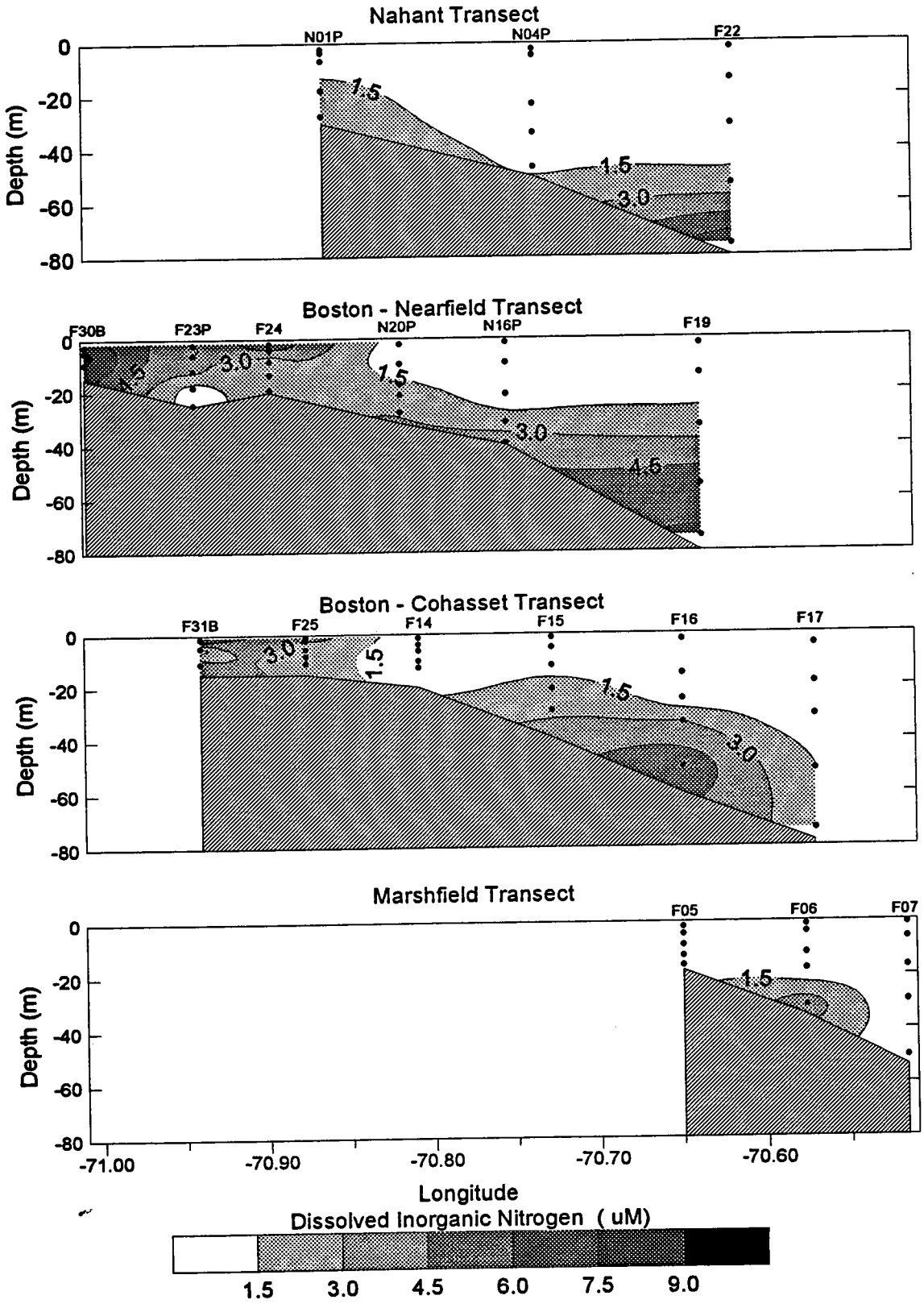


Figure 3-10d. Vertical section contours for standard transects (see Figure 3-9) on Survey W9404. The data used to produce the contours are from discrete bottle samples (Appendix A).

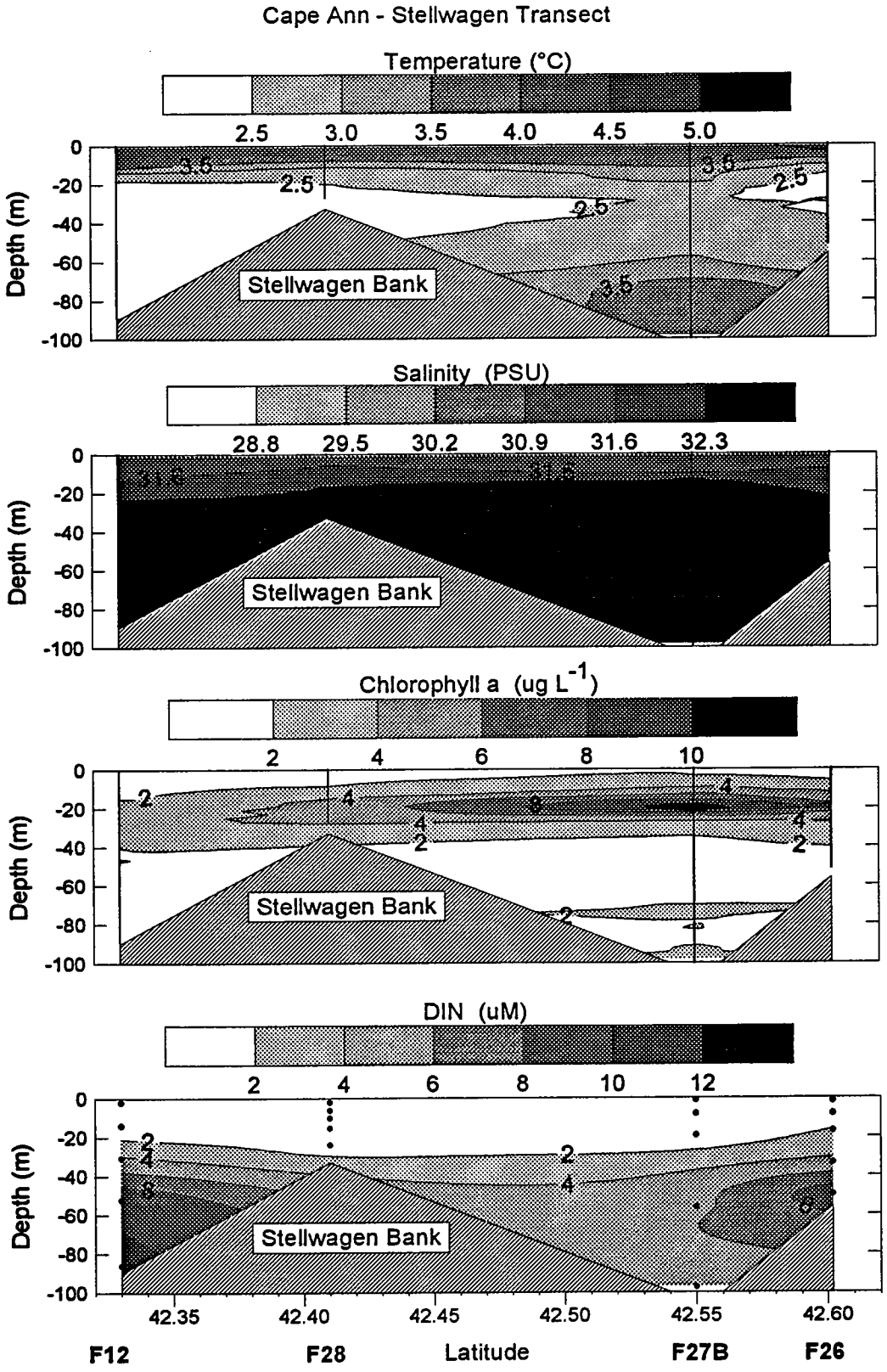


Figure 3-11. Vertical section contours for the Cape Ann - Stellwagen transect (see Figure 3-9) on Survey W9404. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station (temperature, salinity, and chlorophyll) and discrete bottle samples (DIN; Appendix A).

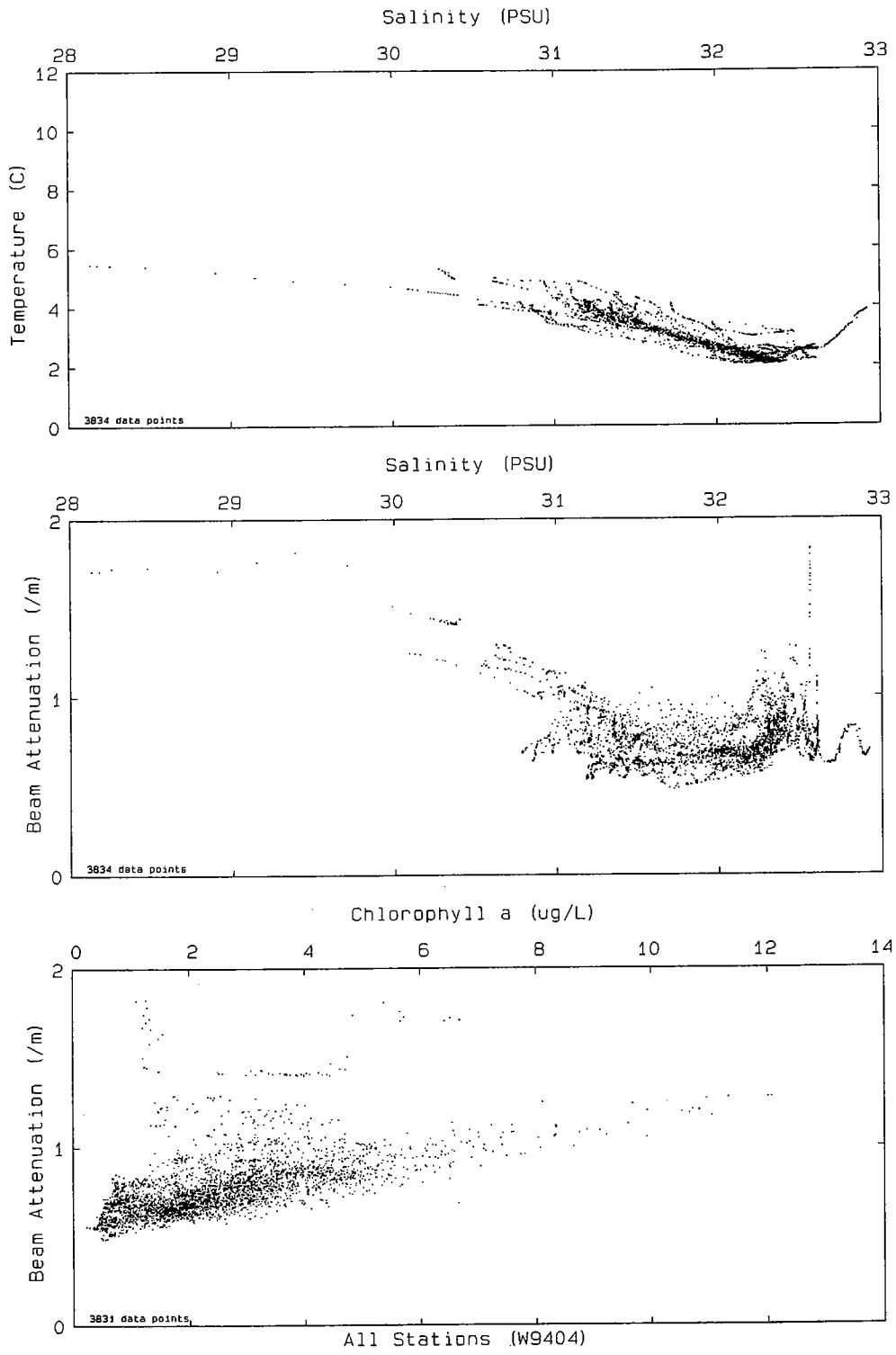


Figure 3-12a. Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in early April 1994. Chlorophyll is estimated from *in situ* fluorescence.

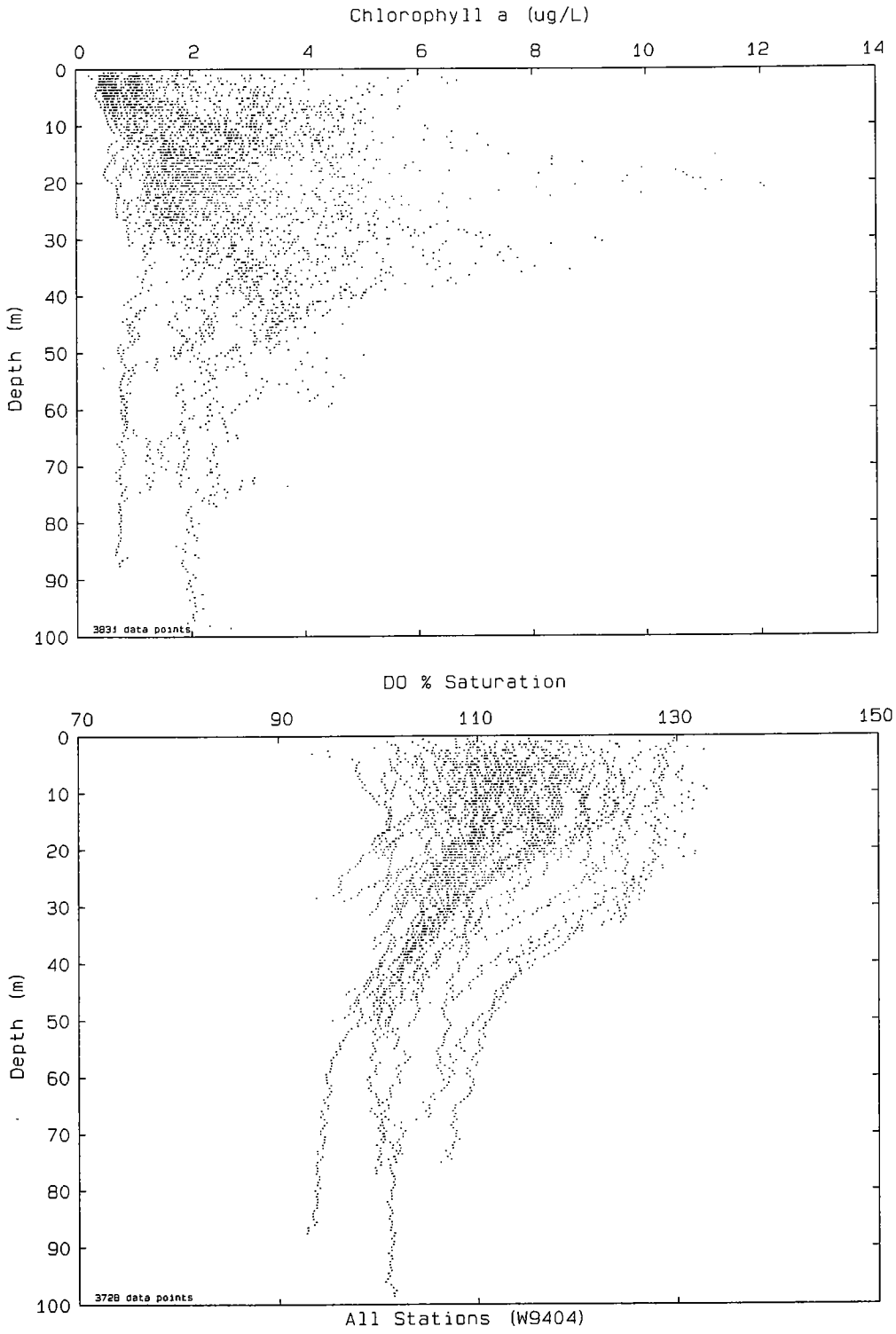


Figure 3-12b. Scatter plots of data acquired by *in situ* sensor package during vertical casts at all farfield and nearfield stations occupied in early April 1994. Chlorophyll is estimated from *in situ* fluorescence.

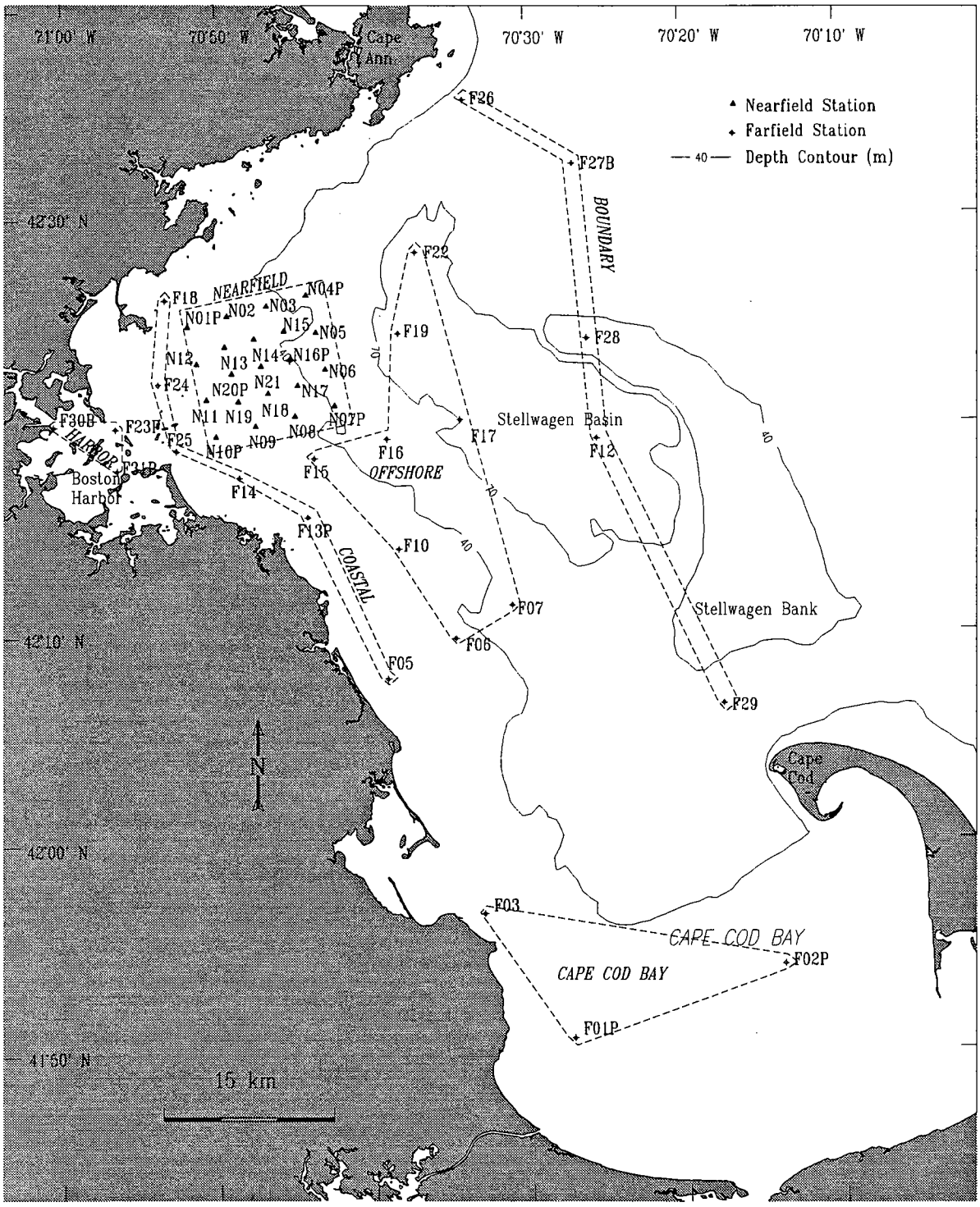


Figure 3-13. Map to show regional station groups designated in Figures 3-14 through 3-21.

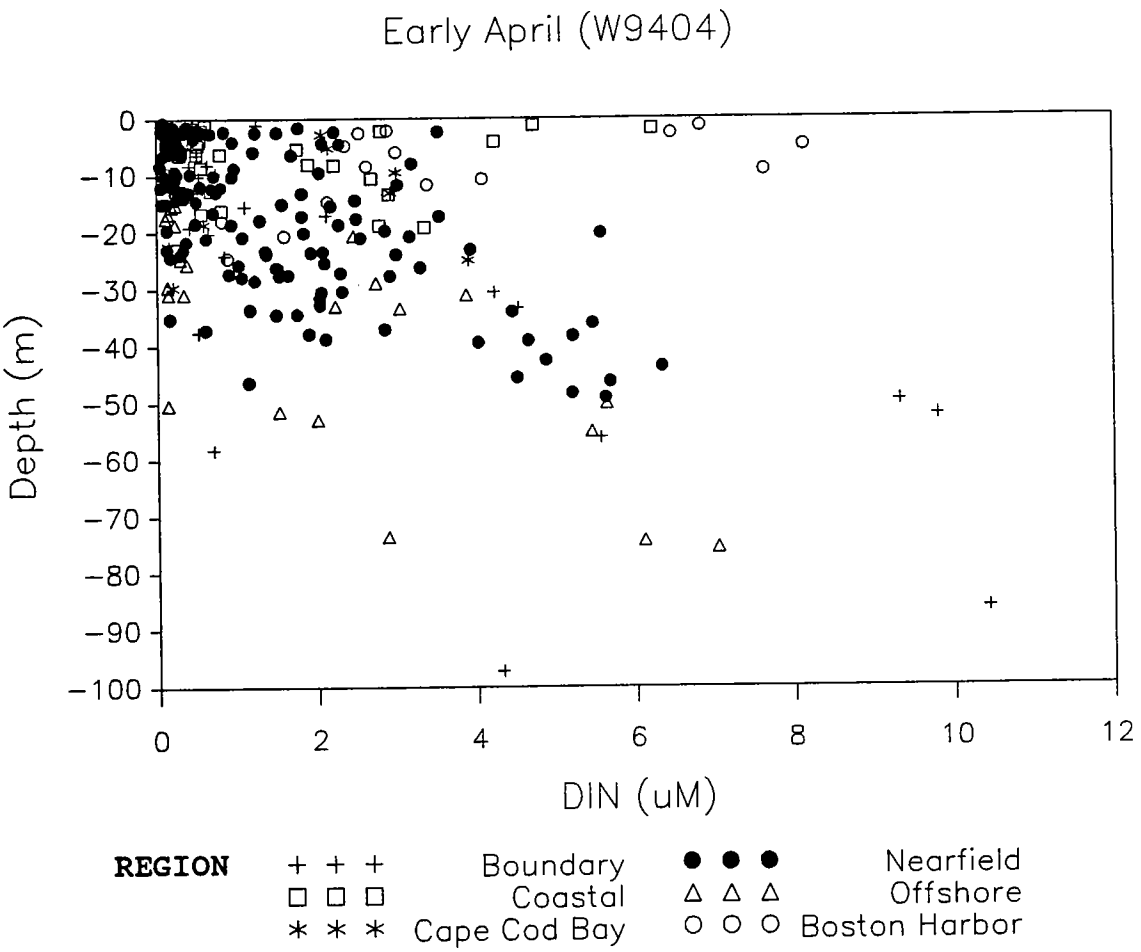
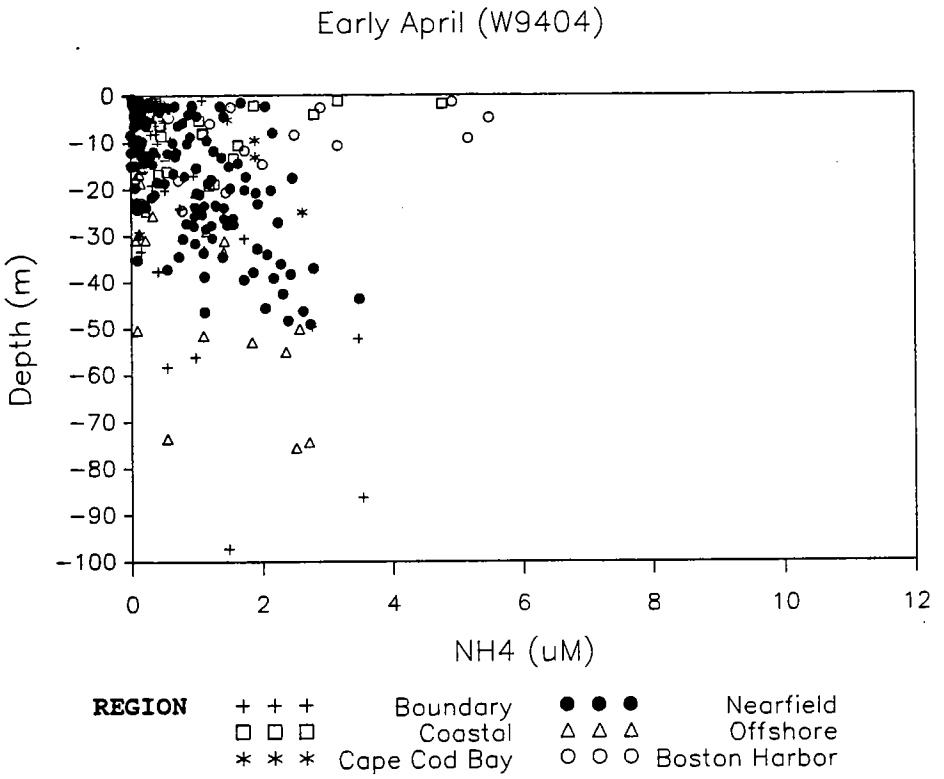


Figure 3-14a. DIN vs. depth in early April 1994.



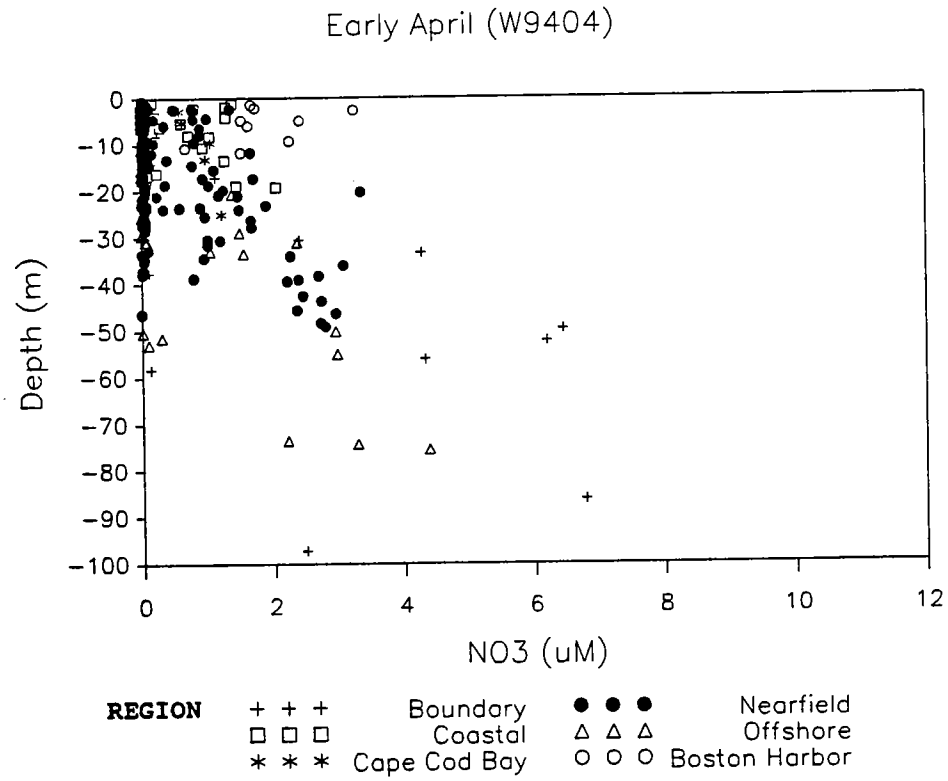


Figure 3-14b. NH_4 and NO_3 vs. depth in early April 1994.

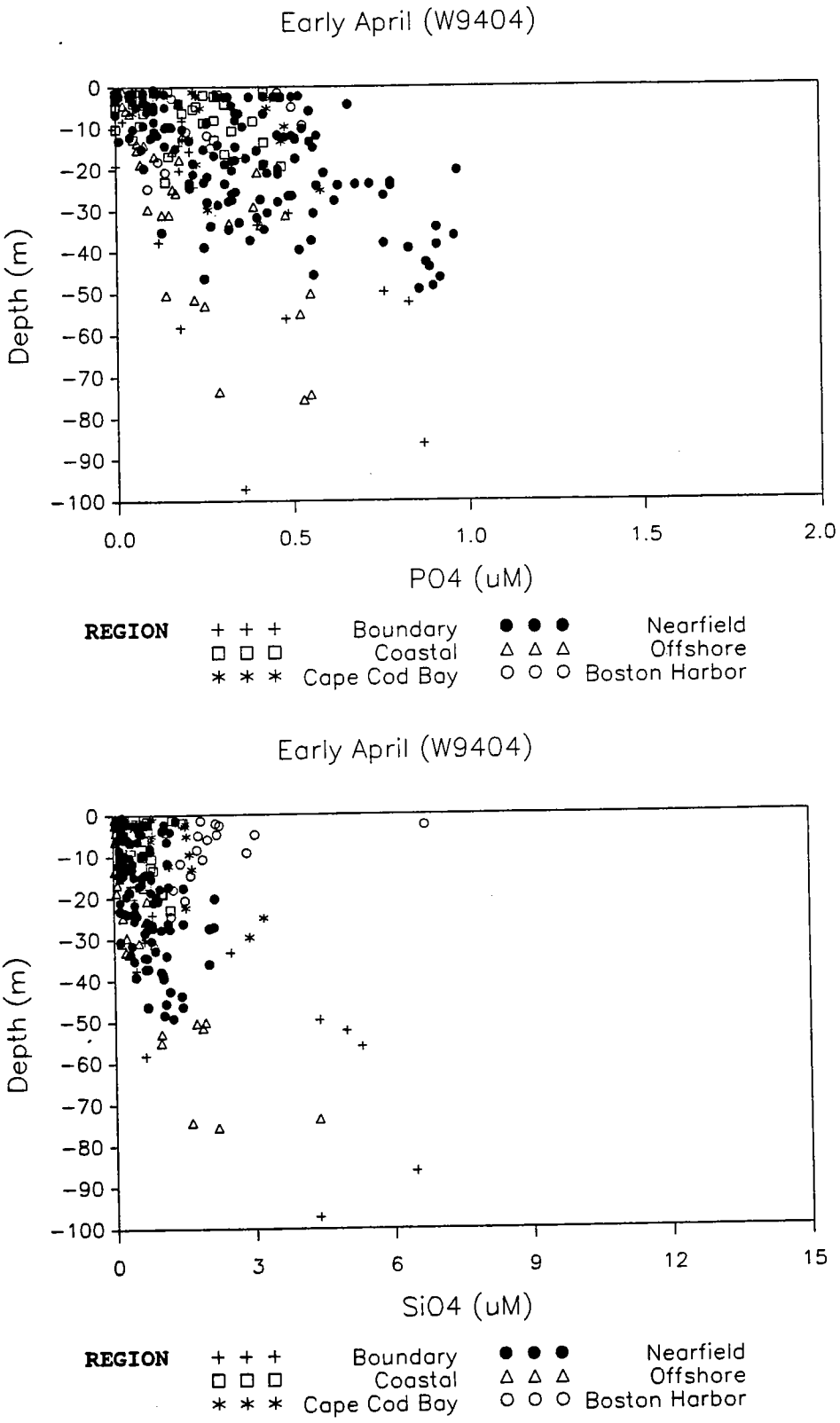
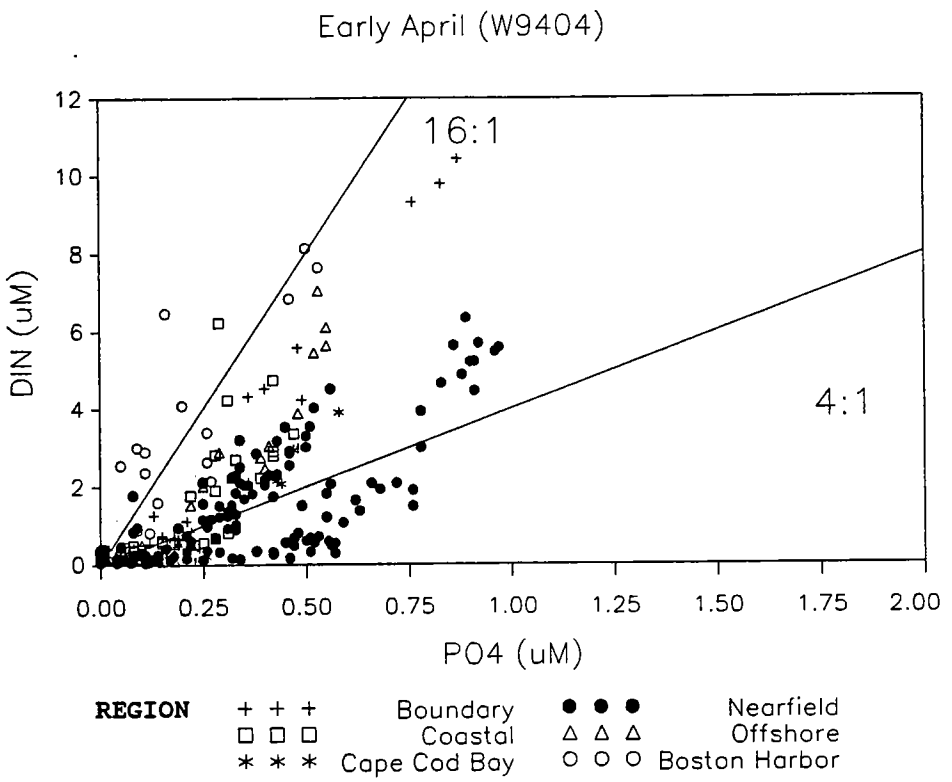


Figure 3-14c. PO_4 and SiO_4 vs. depth in early April 1994.



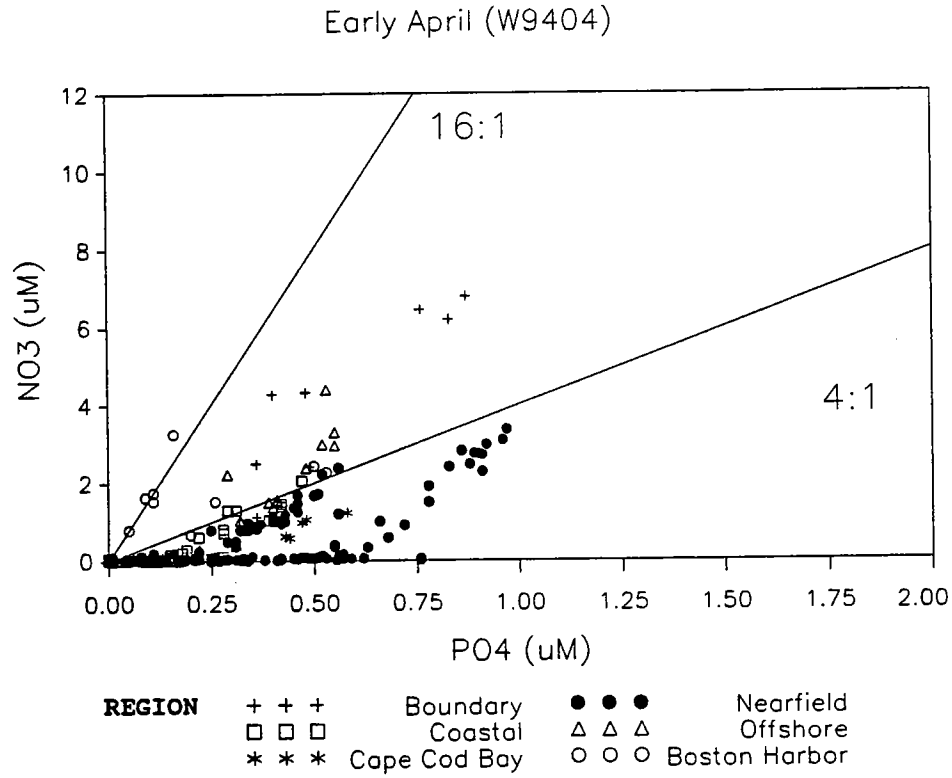
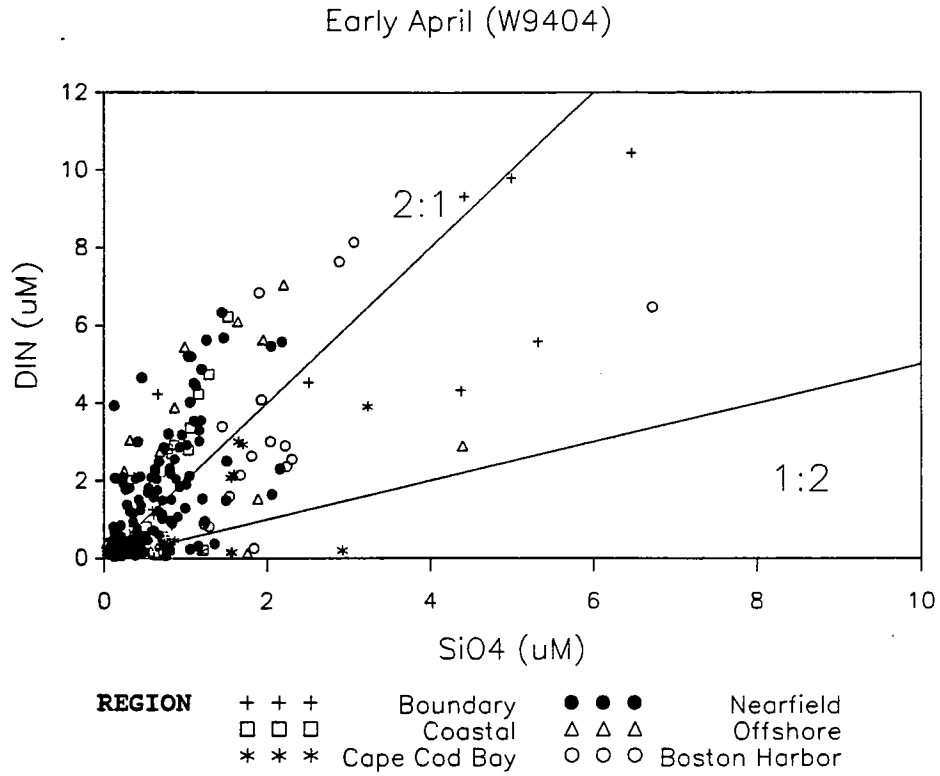


Figure 3-15a. Scatter plots of nitrogen forms vs. PO_4 in early April 1994. Lines show constant proportions of nitrogen relative to phosphorus.



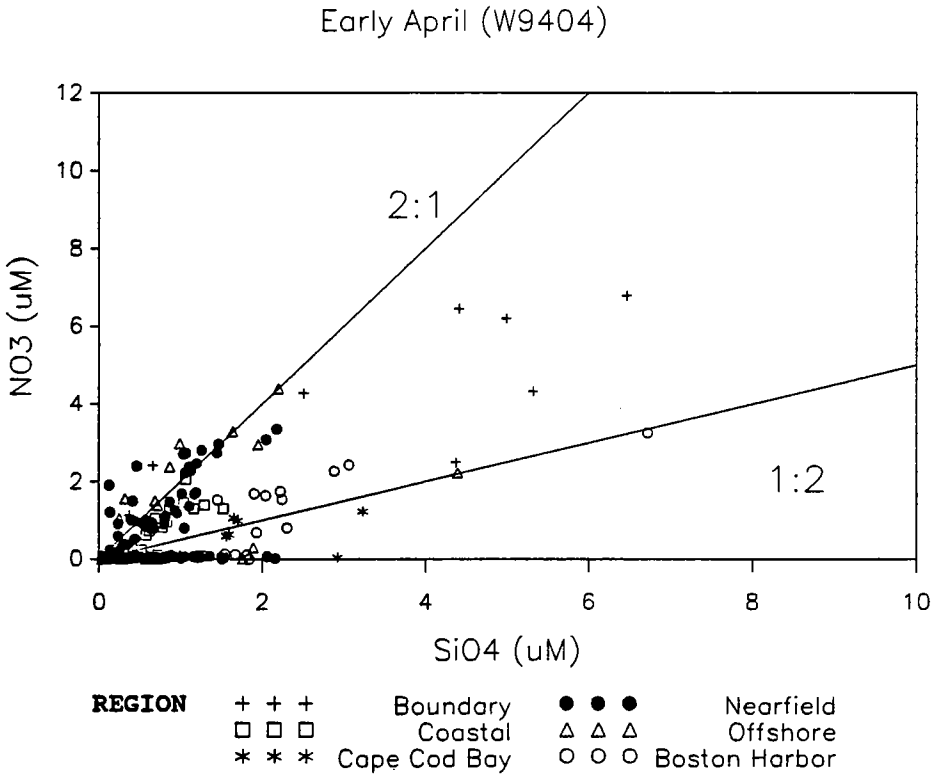


Figure 3-15b. Scatter plots of nitrogen forms vs. SiO_4 in early April 1994. Lines show constant proportions of nitrogen relative to silicate.

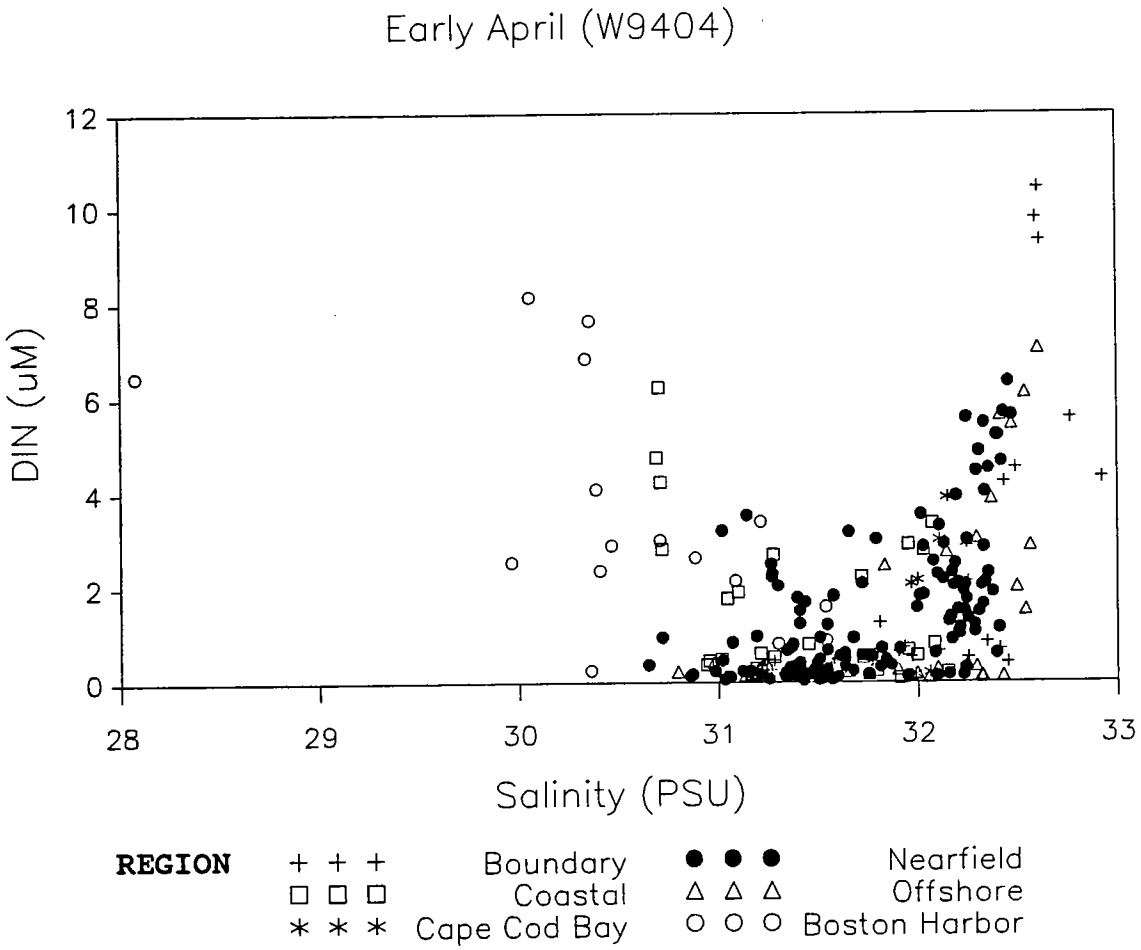


Figure 3-16a. DIN vs. salinity in early April 1994.

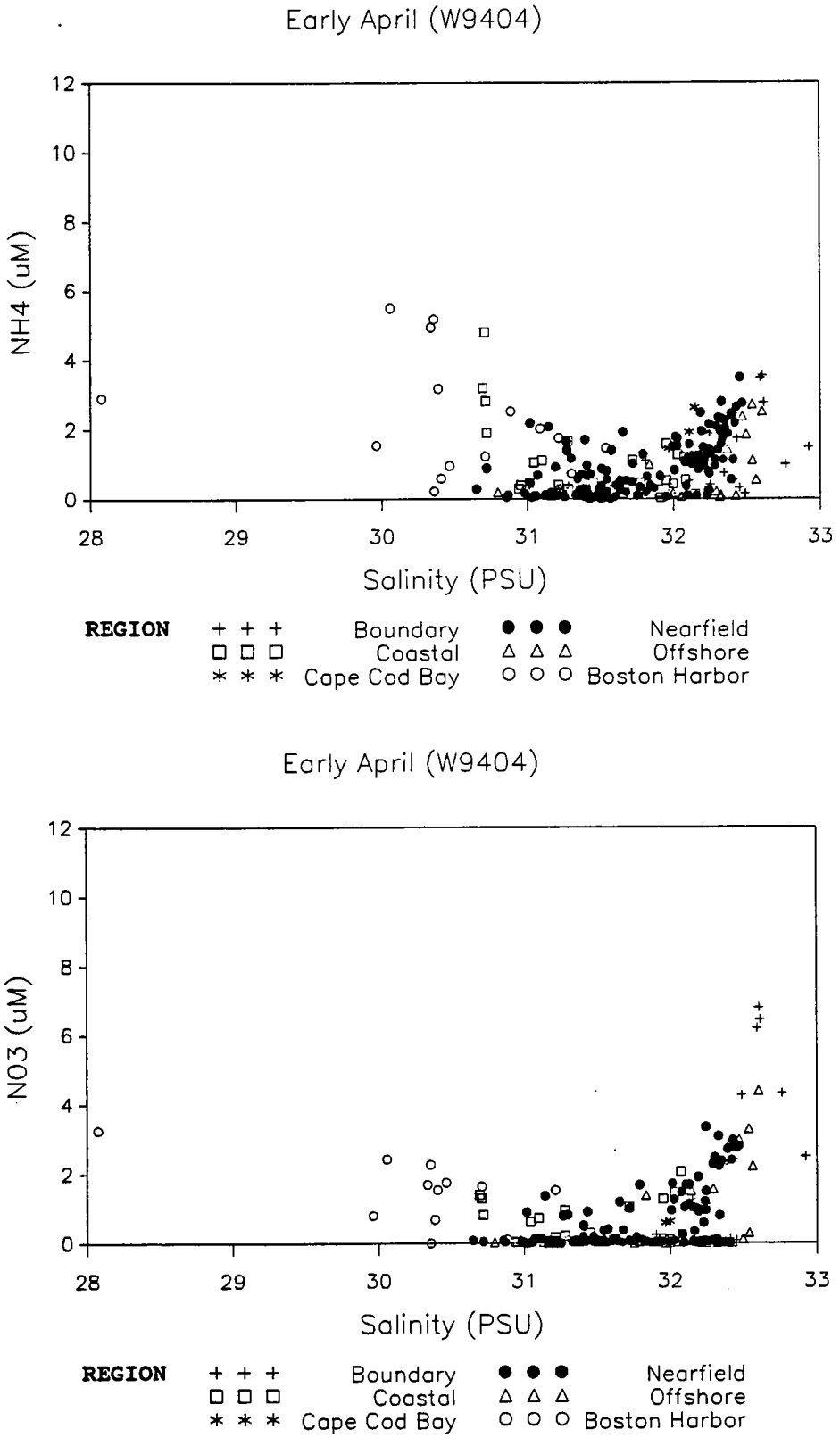
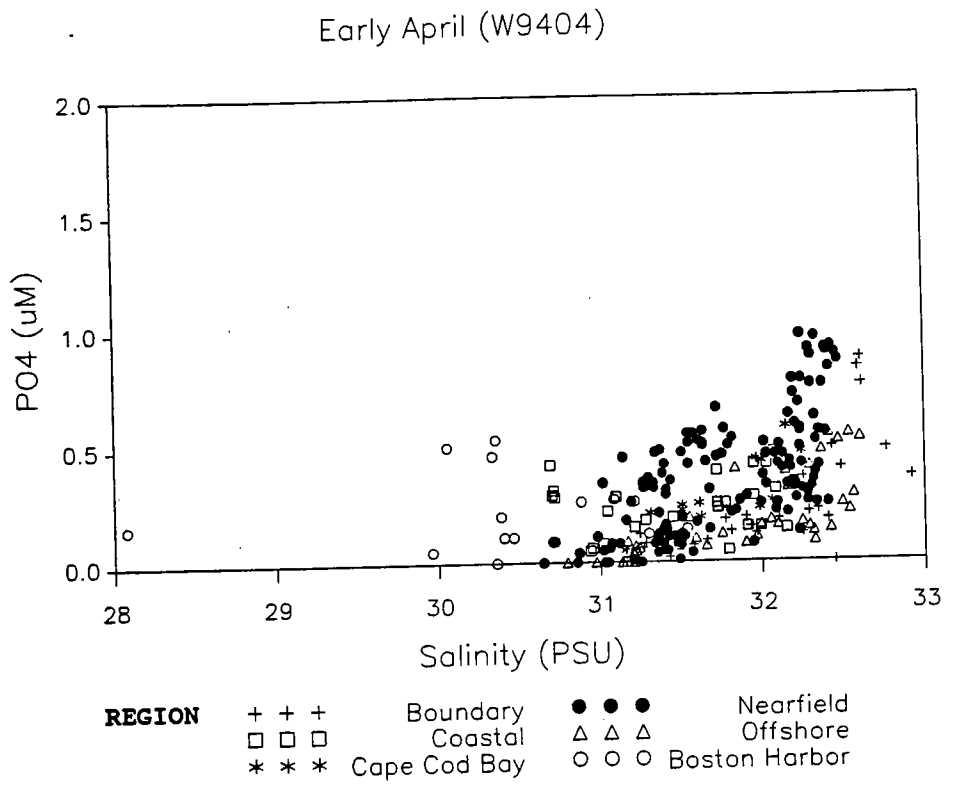


Figure 3-16b. NH_4 and NO_3 vs. salinity in early April 1994.



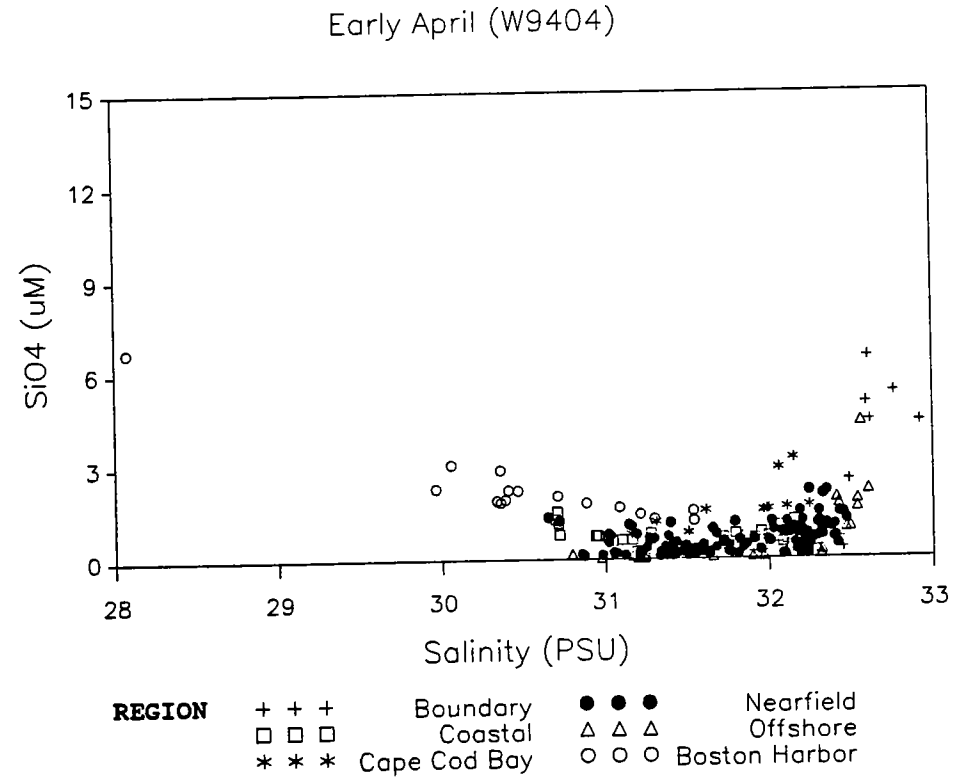


Figure 3-16c. PO_4 and SiO_4 vs. salinity in early April 1994.

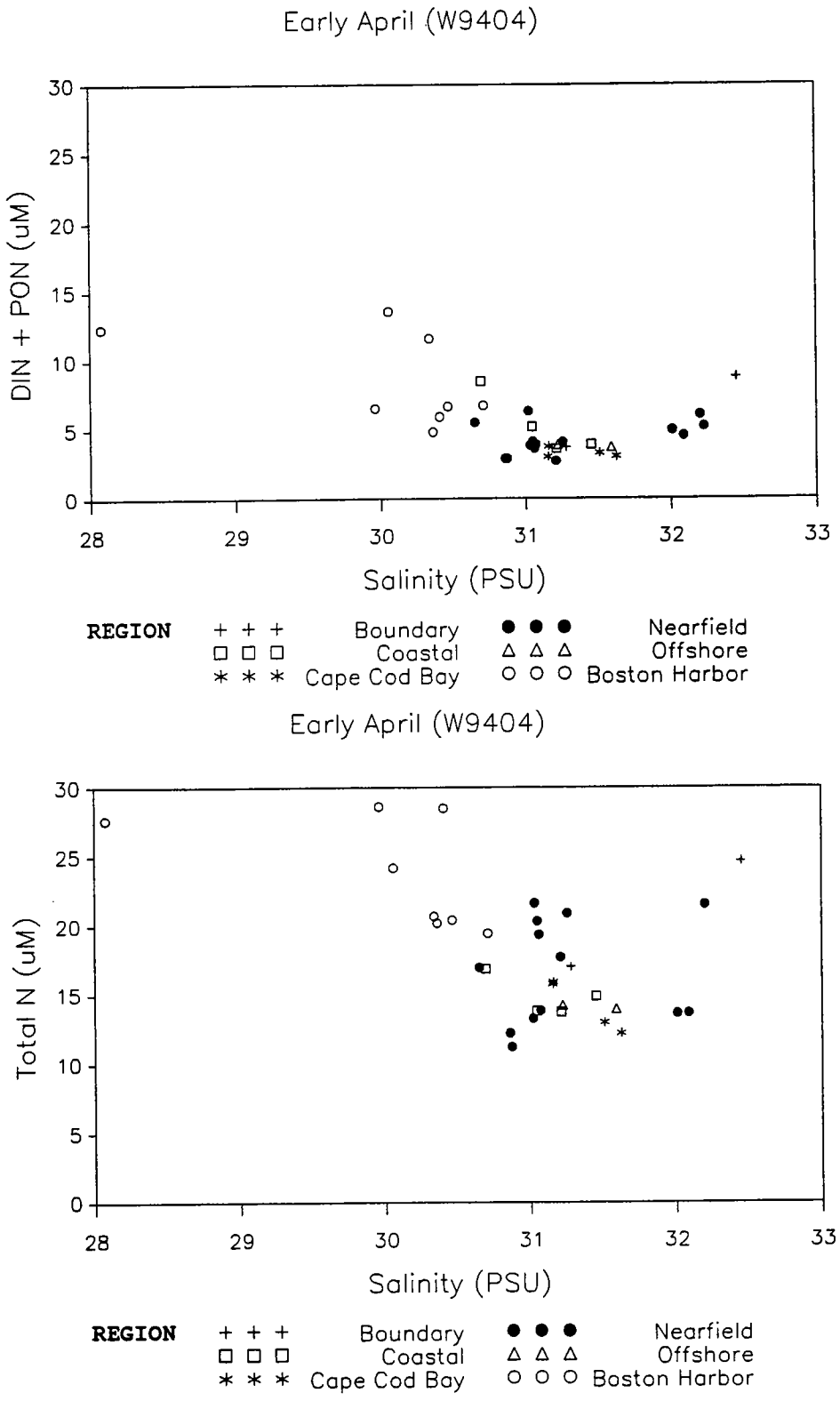


Figure 3-17. **Nitrogen forms vs. salinity in early April 1994. Data are from B/P stations and special stations (Appendix A). Dissolved inorganic nitrogen = DIN, Particulate organic nitrogen = PON, Total nitrogen (TN) = Total dissolved nitrogen (TDN) + PON.**

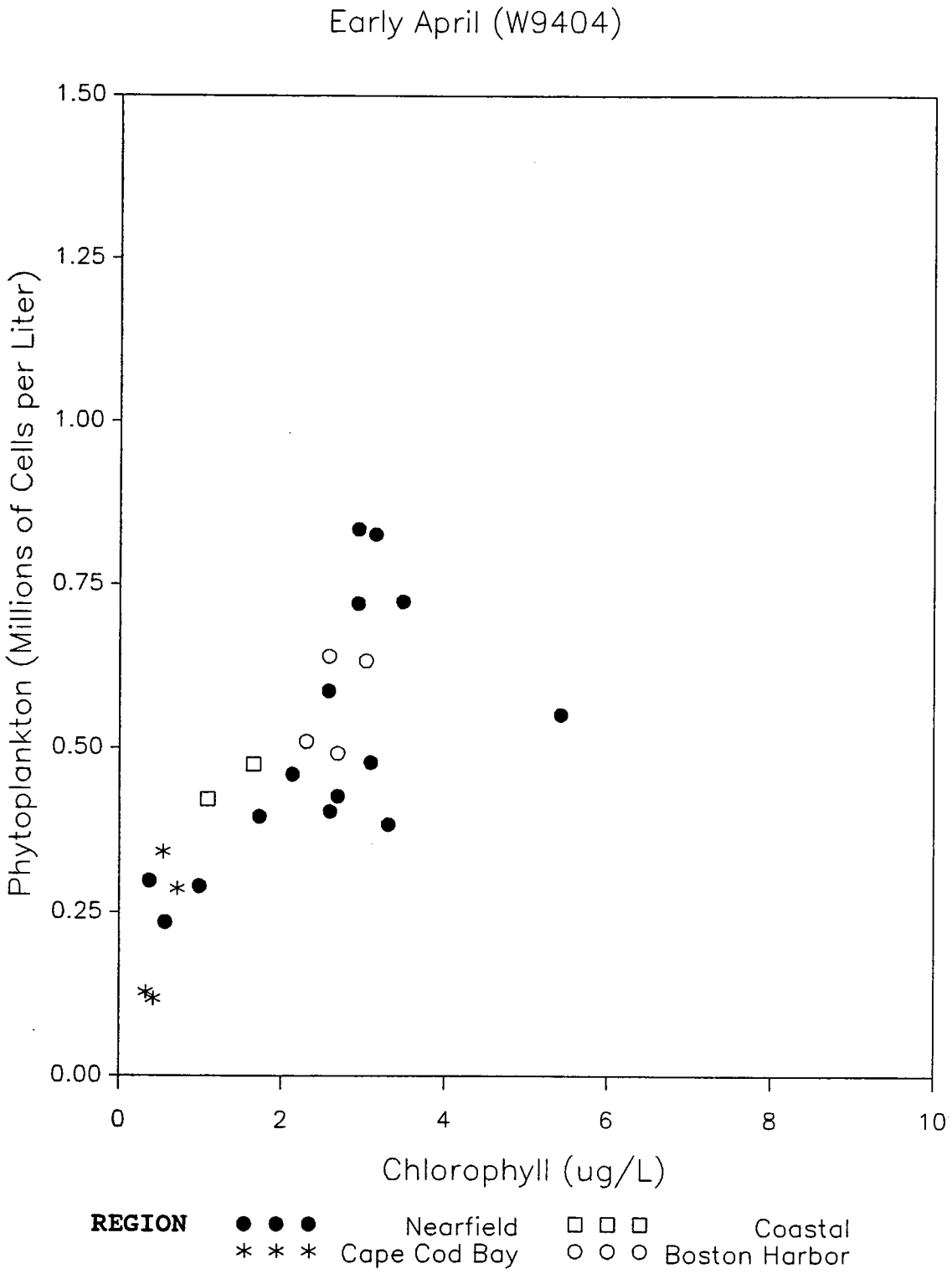


Figure 3-18. Total phytoplankton abundance vs. chlorophyll (extracted samples) at B/P stations in early April 1994.

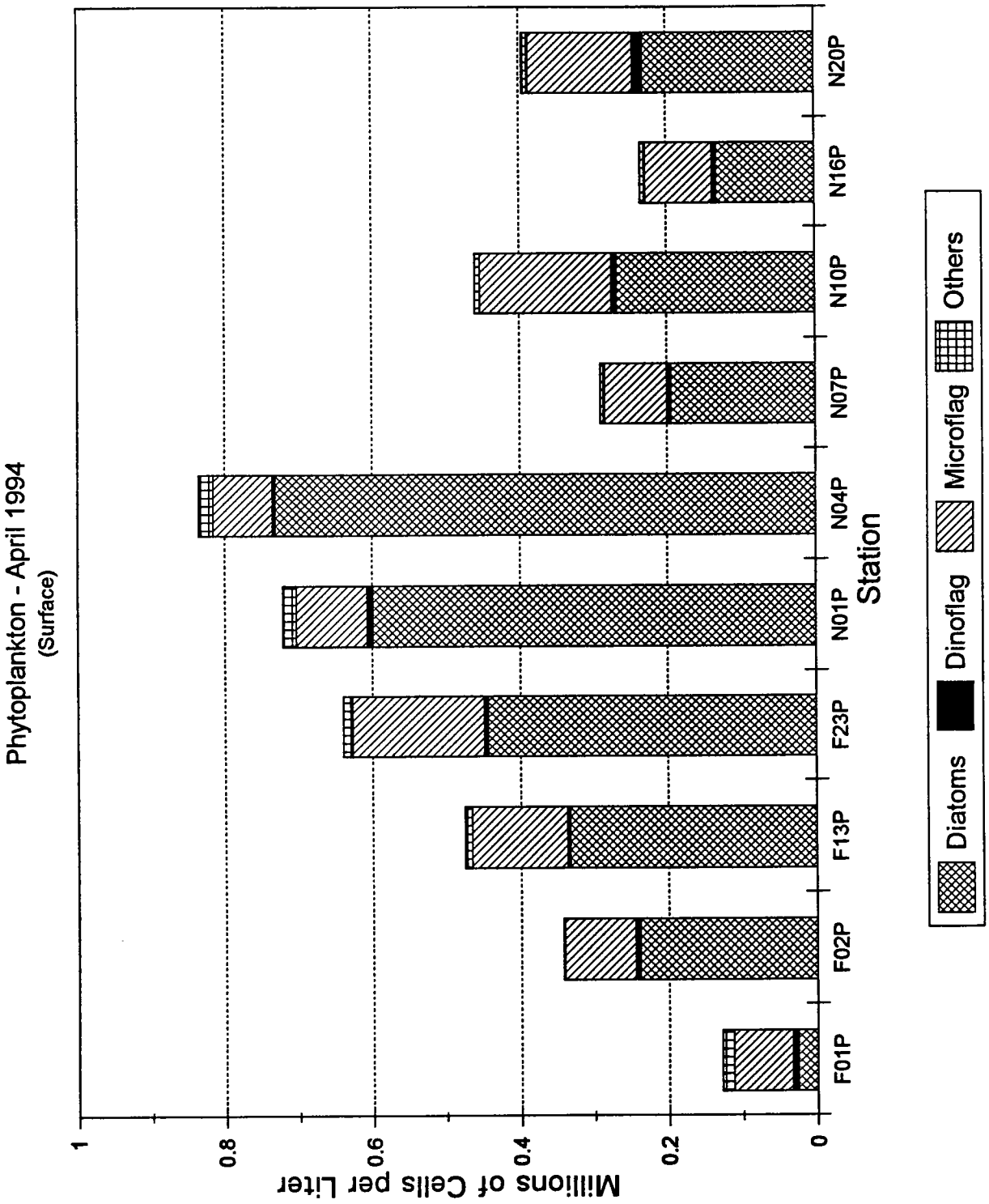


Figure 3-19. **Total phytoplankton abundance, by taxonomic group, near the surface of B/P stations in early April 1994.**

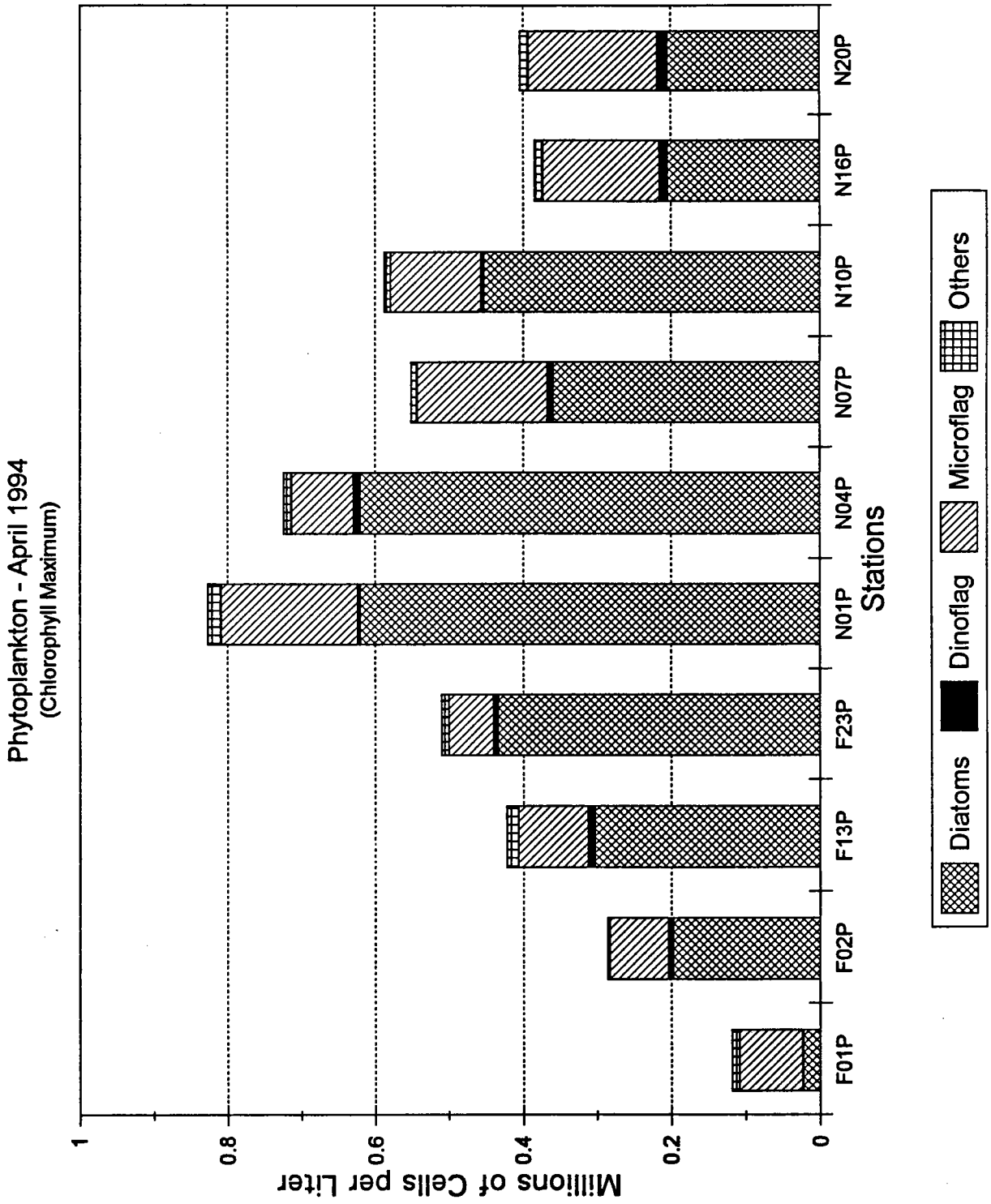


Figure 3-20. **Total phytoplankton abundance, by taxonomic group, near the chlorophyll maximum of B/P stations in early April 1994.**

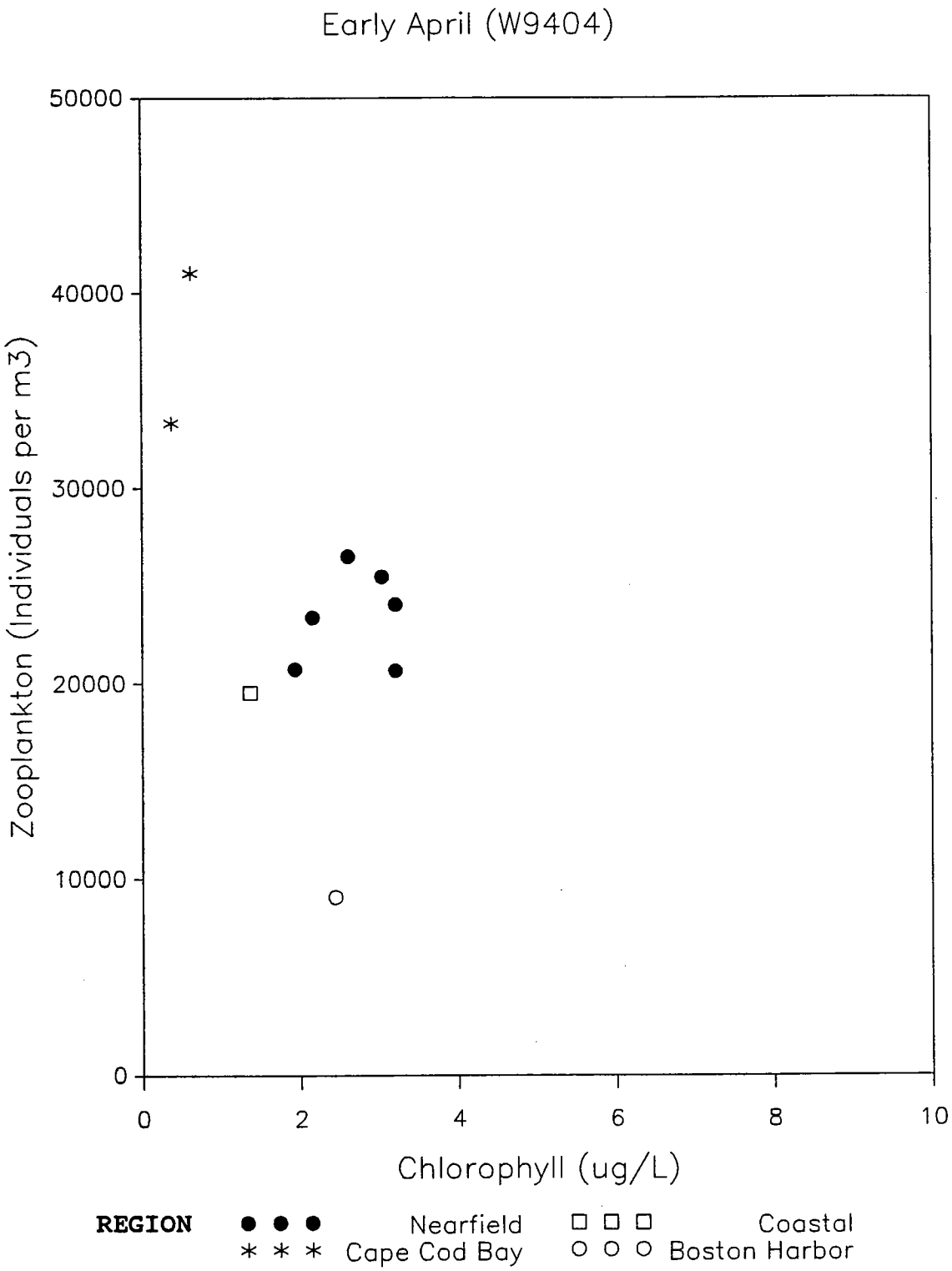


Figure 3-21. Zooplankton abundance vs. average chlorophyll concentration (extracted samples; n=4 per station) for early April 1994.

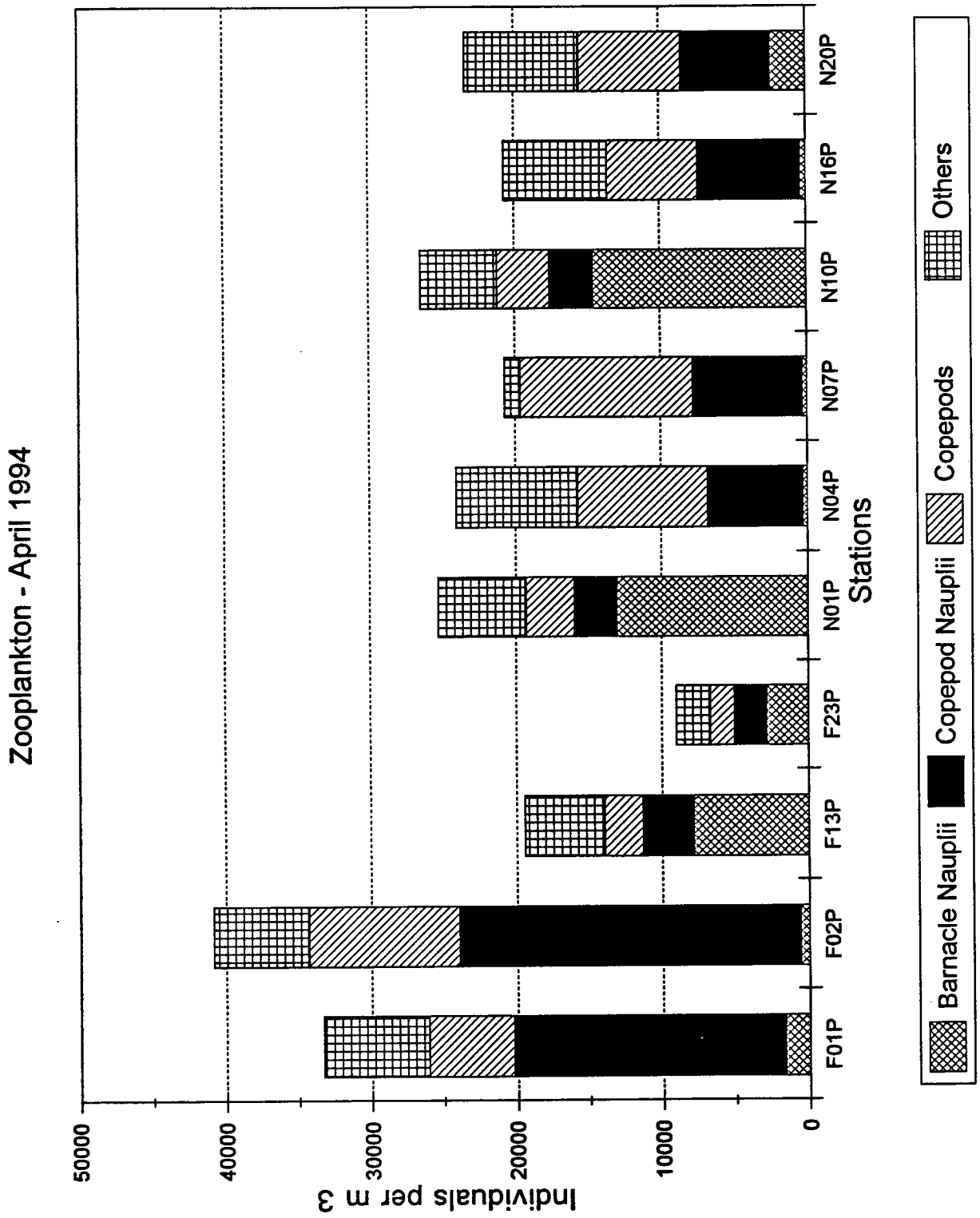


Figure 3-22. Zooplankton abundance, by groups, at B/P stations in early April 1994.

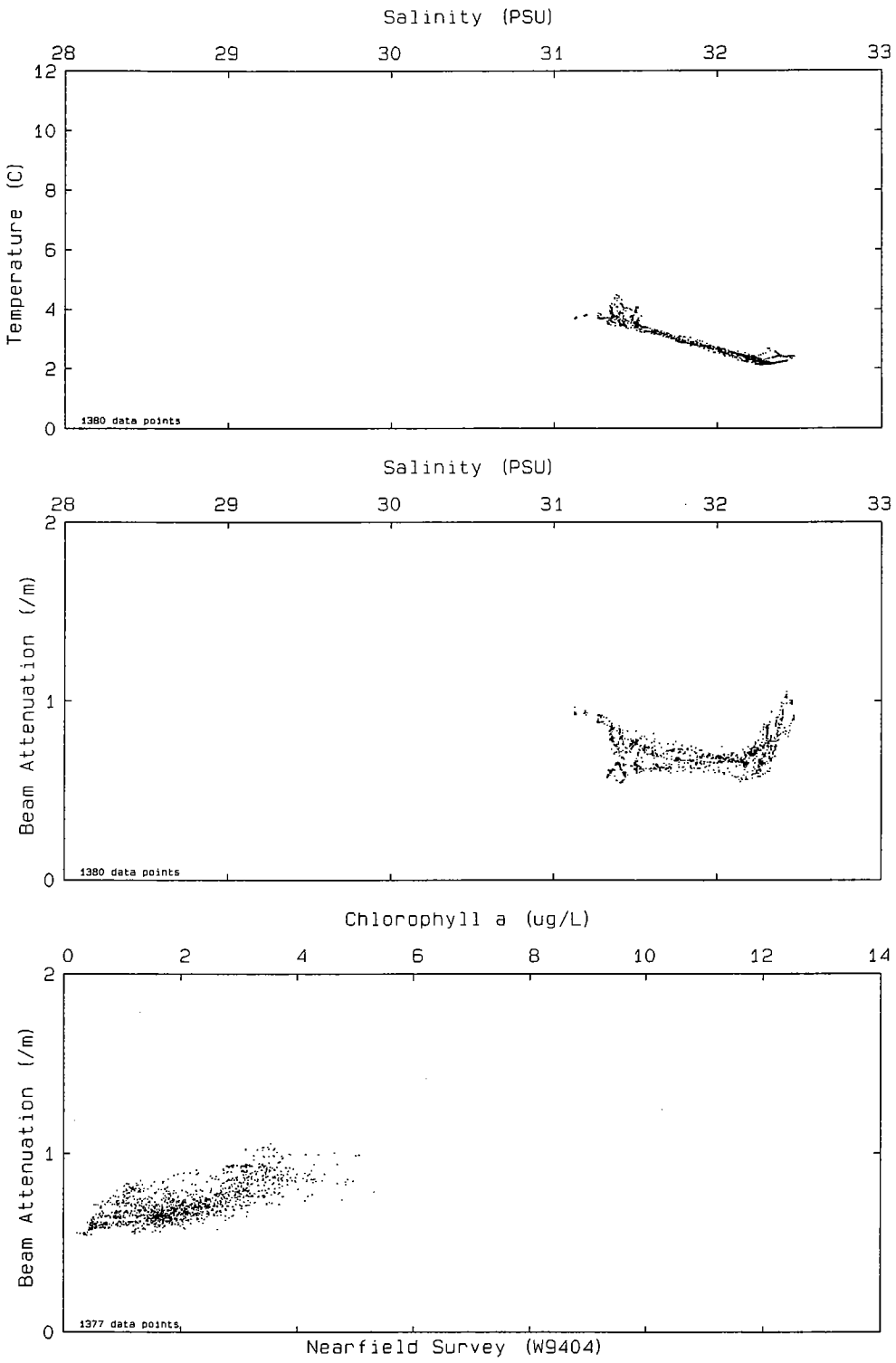


Figure 3-23a. Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in early April 1994. Chlorophyll is estimated from *in situ* fluorescence.

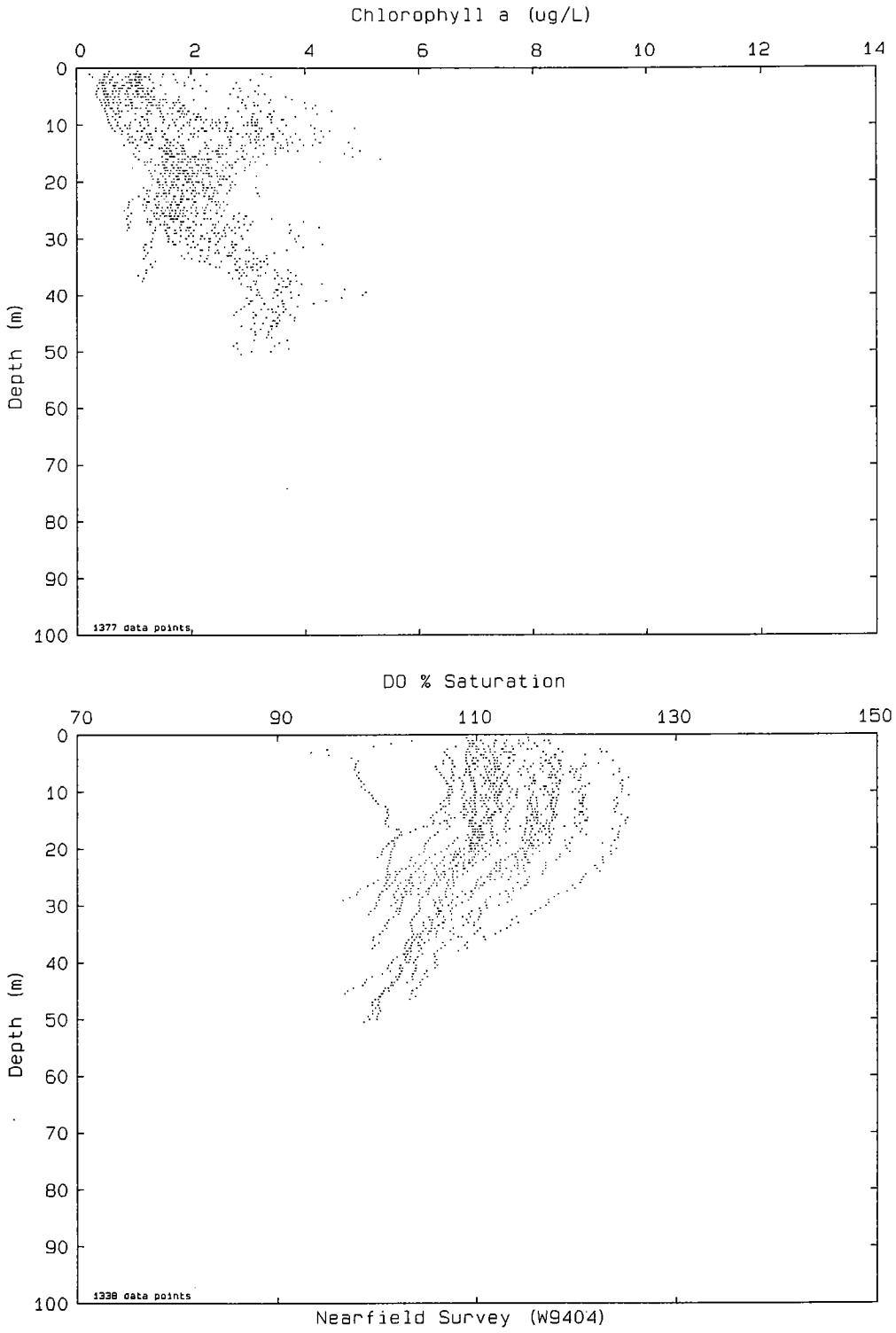


Figure 3-23b. Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in early April 1994. Chlorophyll is estimated from *in situ* fluorescence.

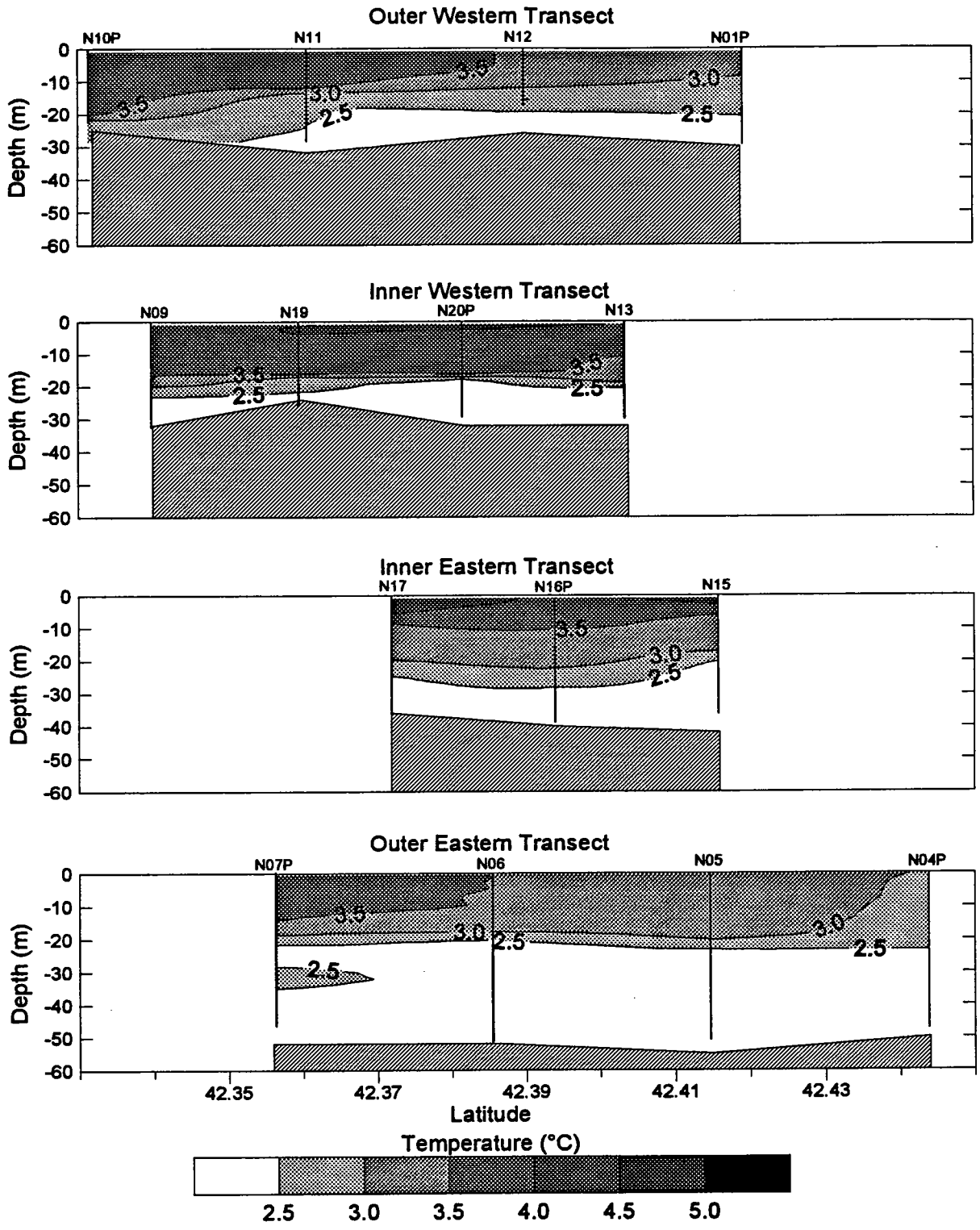


Figure 3-24a. **Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9404. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.**

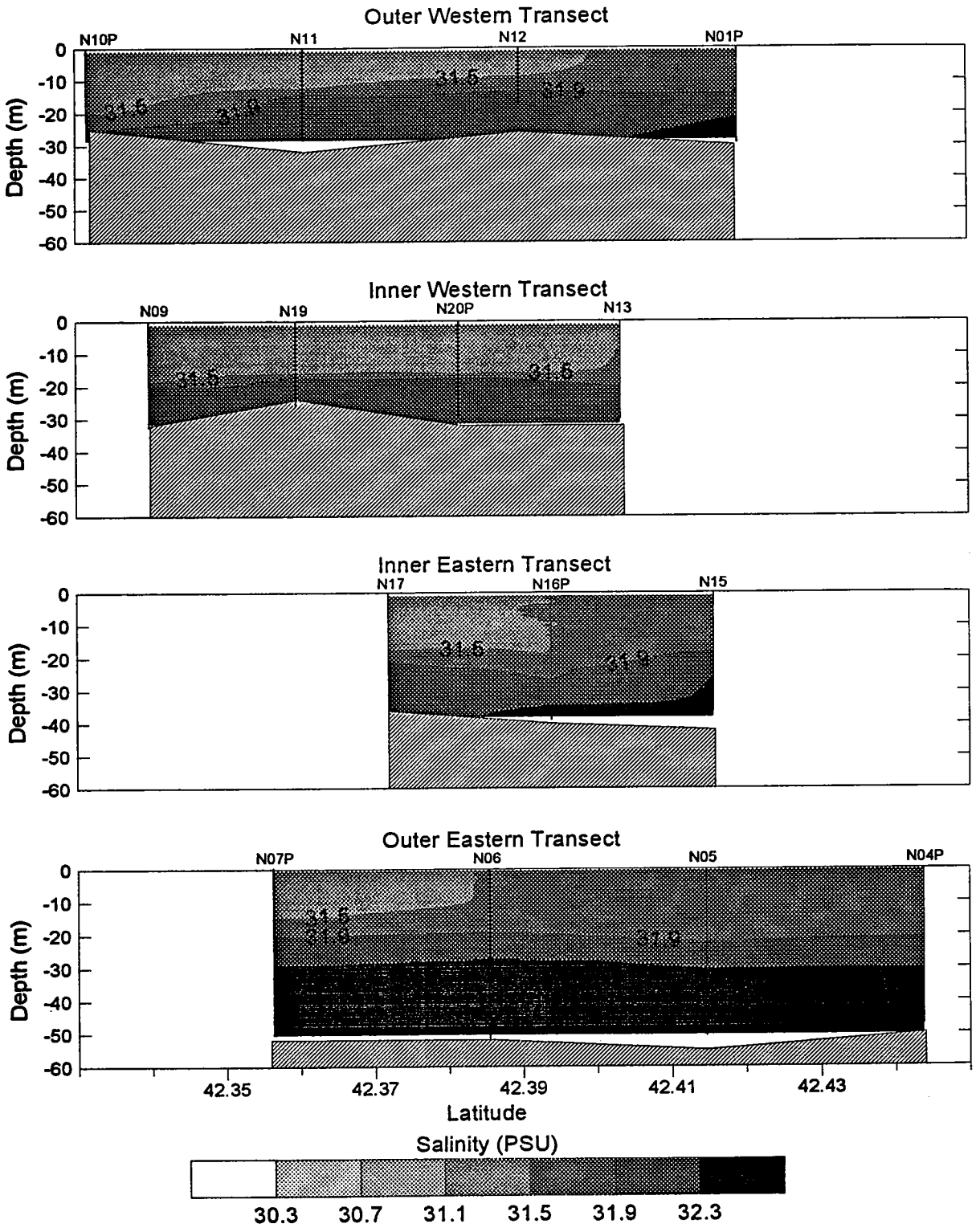


Figure 3-24b. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9404. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

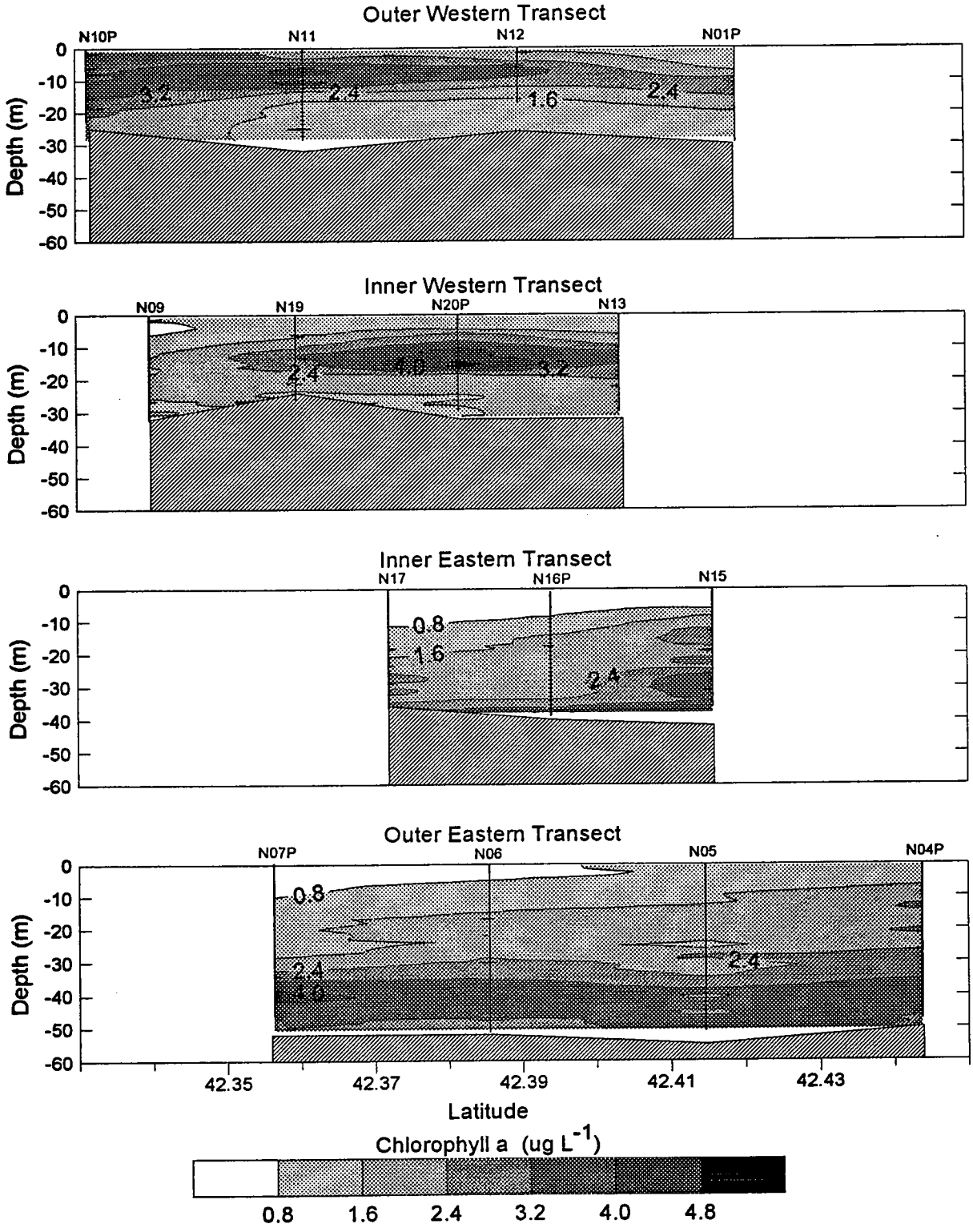


Figure 3-24c. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9404. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

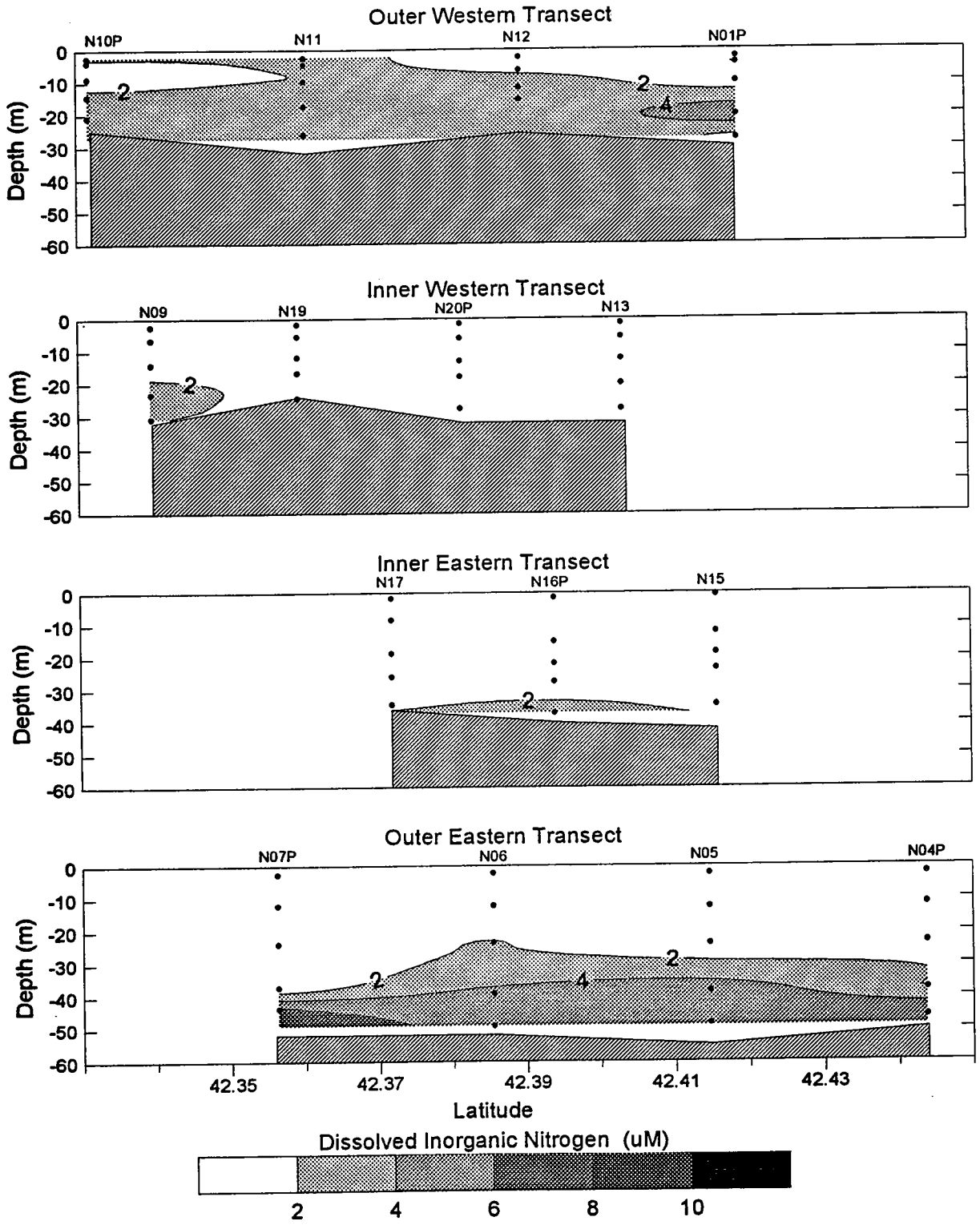


Figure 3-24d. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9404. The data used to produce the contours are from discrete bottle samples taken at each station during the nearfield sampling day (Appendix A).

4.0 RESULTS OF LATE APRIL 1994 NEARFIELD SURVEY (W9405)

4.1 Distribution of Water Properties from Vertical Profiles

Vertical profiles were obtained at all 21 nearfield stations on April 27 (Appendix B). Scatter plots of the *in-situ* sensor data are presented in Figure 4-1. The temperature range for the nearfield in late April (~3-7°C) had risen as well as broadened considerably from the range observed in early April (cf. Figure 4-1a and Figure 3-23a). Moreover, the salinity range had also broadened to include fresher conditions and now ranged from ~30.25 to 32.5 PSU. The freshening was concomitant with warming, and this type of water was found at the surface and undoubtedly represented continued input from spring runoff. Along with the increased range in T-S values, the strong T-S pattern coherence among station profiles that had earmarked the early April survey was disrupted in late April, an event that signals increased spatial heterogeneity in physical conditions across stations, particularly in upper layers of the water column. Indeed, review of vertical profiles in Appendix B indicated that sometimes a broad pycnocline (5-20 m) was present (e.g., station N01P), sometimes it was sharp (10-15 m, station N03), sometimes it was multi-layered rather than a single transition between upper and lower water masses (e.g., stations N17 and N20P), or sometimes it was nonexistent (e.g., station N10P). In general, it appeared that the conditions from west to east across the nearfield represented a transition from fairly well-mixed inshore water to more highly stratified offshore conditions.

Both beam attenuation and chlorophyll ranged narrowly (Figure 4-1a). As suggested in early April, there was often a slight increase in turbidity near the surface of low salinity water (inshore) and a near-bottom increase in deeper, more saline water (offshore). Chlorophyll concentrations were generally low, ranging between 0 and 2 $\mu g\ L^{-1}$, and poorly correlated with turbidity (Figure 4-1a). Profiles for a group of stations located on the eastern and northeastern side of the nearfield (stations N03 through N07P, see Appendix B, and Section plots discussed later), displayed chlorophyll concentrations that were 2-4 $\mu g\ L^{-1}$ (Figure 4-1b) at depths below 20 m. DO profiles usually dipped below 100% saturation in the deep waters at these locations, but DO was generally near saturation or slightly above saturation within the surface waters (Figure 4-1b).

Dissolved nutrient concentrations increased with water depth (Figure 4-2). DIN was not fully depleted at the surface and ranged from ~1 to 9 μM (Figure 4-2a), with the lower values generally at the surface and higher values at depth. Several near-surface samples, including two at station N10P which receives Harbor water, were as high in DIN concentration as bottom waters. NH_4 was usually low at the surface and increased with depth. The few surface-layer samples with DIN concentrations >5 μM were from stations N10P and N11 on the western side of the nearfield. NO_3 concentrations increased virtually linearly with depth and dominated DIN below 30 m (Figure 4-2b).

The distribution of phosphate throughout the water column was similar to DIN; concentrations of phosphate ranged from ~0.25 to 0.9 μM (Figure 4-2c). Silicate concentrations increased slightly with depth, but the concentration range was relatively narrow (~2-5 μM) so that N/Si ratios were generally higher at depth than in the surface layer.

The nutrient-salinity plots (Figure 4-3) showed only an ascending "arm" (see Section 3) with increasing concentrations as a function of increasing salinity, reflecting the dual increase in nutrients and salinity with increased water depth. The lack of a descending "arm" on the nutrient-salinity plots (cf. Section 3) is partially due to the lack of data from Harbor and coastal stations. However, the few anomalous samples with relatively high DIN (especially NH_4, a signal of Harbor water) and phosphate concentrations, which diverge from the main trend at salinities near 31.5 PSU, are from the southwestern corner of the nearfield (see Appendix A), so there is a small portion of a descending arm present. But this enrichment source occurred at intermediate salinity, rather than appearing as it typically does at low salinity because, at this time, salinity was lowest at the offshore, rather than the inshore, side of the nearfield. Thus, there was no low salinity nutrient source suggested for the nearfield at this time. Moreover, stratification causes the principal dissolved nutrient concentration gradient to occur in the vertical rather than the horizontal dimension for the nearfield area.

Several of the nutrient-salinity plots have a noticeable curvature. Often, in using such plots to deduce chemical behavior during mixing of fresh and saline water, a concave curve is used to suggest a non-conservative distribution and imply that there exists a sink for nutrients. In this case, the curvature results primarily, but not exclusively, from variations in the vertical dimension, where mixing, because of

stratification, is slightly restricted. The curvature, however, might suggest removal of nutrients by biological activity at mid-depths corresponding with subsurface chlorophyll maxima. While the nutrient-salinity plots and curvature show an interesting pattern to be explored further, there was also some horizontal variation in surface salinity and nutrient content across the field, so that a generic, field-level interpretation may be simplistic.

There was a distinct difference across nutrient types (N, P, Si) in the degree of curvature in nutrient-salinity plots. For example, DIN, NO_3 (especially), and SiO_4 all had significant curvature, whereas the curvature for NH_4 and PO_4 was slight, if present at all. Regardless of whether a biological sink is active during mixing or at a certain depth level, variation across elements and compounds in plots relative to salinity tells us that the biogeochemical dynamics of these forms were different.

4.2 Water Quality Variability in the Nearfield

Vertical contours of temperature, salinity, chlorophyll (as measured by fluorescence), and dissolved inorganic N are presented in Figure 4-4. The vertical profile data used to produce the contours were obtained over the course of a day: stations N10P (0645 EST) to N01P (0830 EST), stations N04P (1000 EST) to N07P (1200 EST), stations N09 (1330 EST) to N13 (1430 EST), and N15 (1700 EST) to N17 (1730 EST). The diurnal warming was suggested by higher temperature in a thin surface layer at stations in the middle of the field that were sampled in mid- to late afternoon (Figure 4-4a). Offshore waters in the surface 10 m generally were warmer than inshore waters, but it is not clear that this too was a diurnal effect. The presence of significantly less saline surface water (<30.7 PSU) over much of the northeastern corner of the nearfield (Figure 4-4b) instead suggests that there were different surface water masses that, to an extent, abutted in the middle of the field. This dynamic, along with some diurnal heating of surface waters, lead to the complex vertical profiles for physical variables that were described above.

Interestingly, the surface-water salinity distribution is the reverse of that typically observed because low salinity water was on the seaward side of the field, rather than on the shallow side directly influenced by

tidal exchange with Boston Harbor. This observation suggests that, at the time of the survey, the nearfield was dominated by a low salinity advection from the northwest that was a more important source of freshwater to the nearfield than Boston Harbor was.

The physical (T, S) transitions, inshore to offshore, did not markedly affect surface chlorophyll concentrations, which were uniformly low (Figure 4-4c). As observed in early April, a deep chlorophyll maximum was apparent in bottom water offshore.

In contrast to the lack of correspondence between surface chlorophyll and physical parameters, surface DIN concentrations more closely tracked salinity. For example, nutrient-depleted (<2 μM) surface waters were associated with the low offshore surface salinity (<31.1 PSU) water mass, whereas concentrations of DIN were regularly >4 μM in surface water with salinity >31.5 PSU. Therefore, a dominant freshwater flux, due to seaward advective processes that may be implied by the distributions, does not necessarily imply a concomitant dominant DIN flux from offshore, rather than inshore, sources.

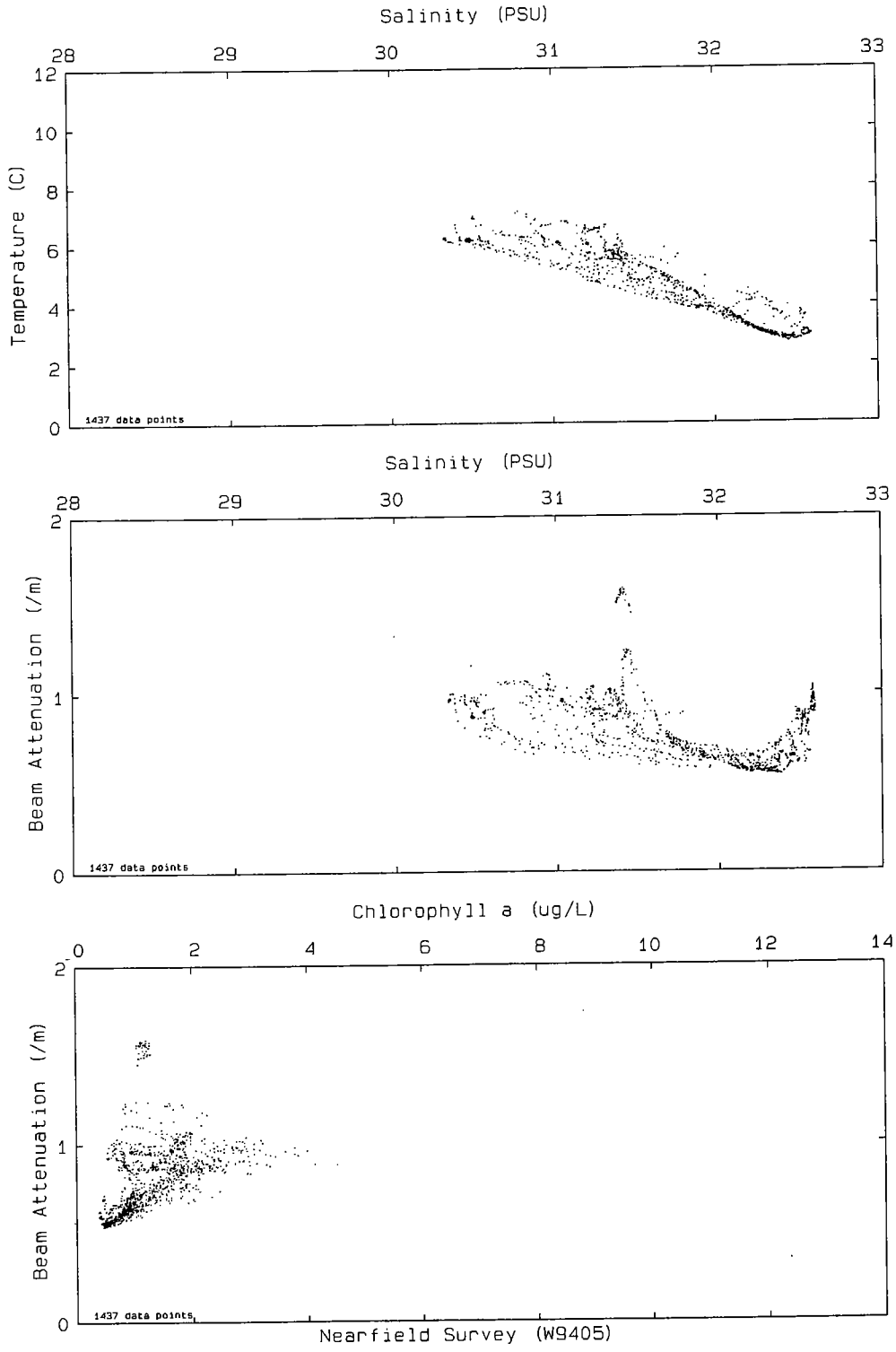


Figure 4-1a. **Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in late April 1994. Chlorophyll is estimated from *in situ* fluorescence.**

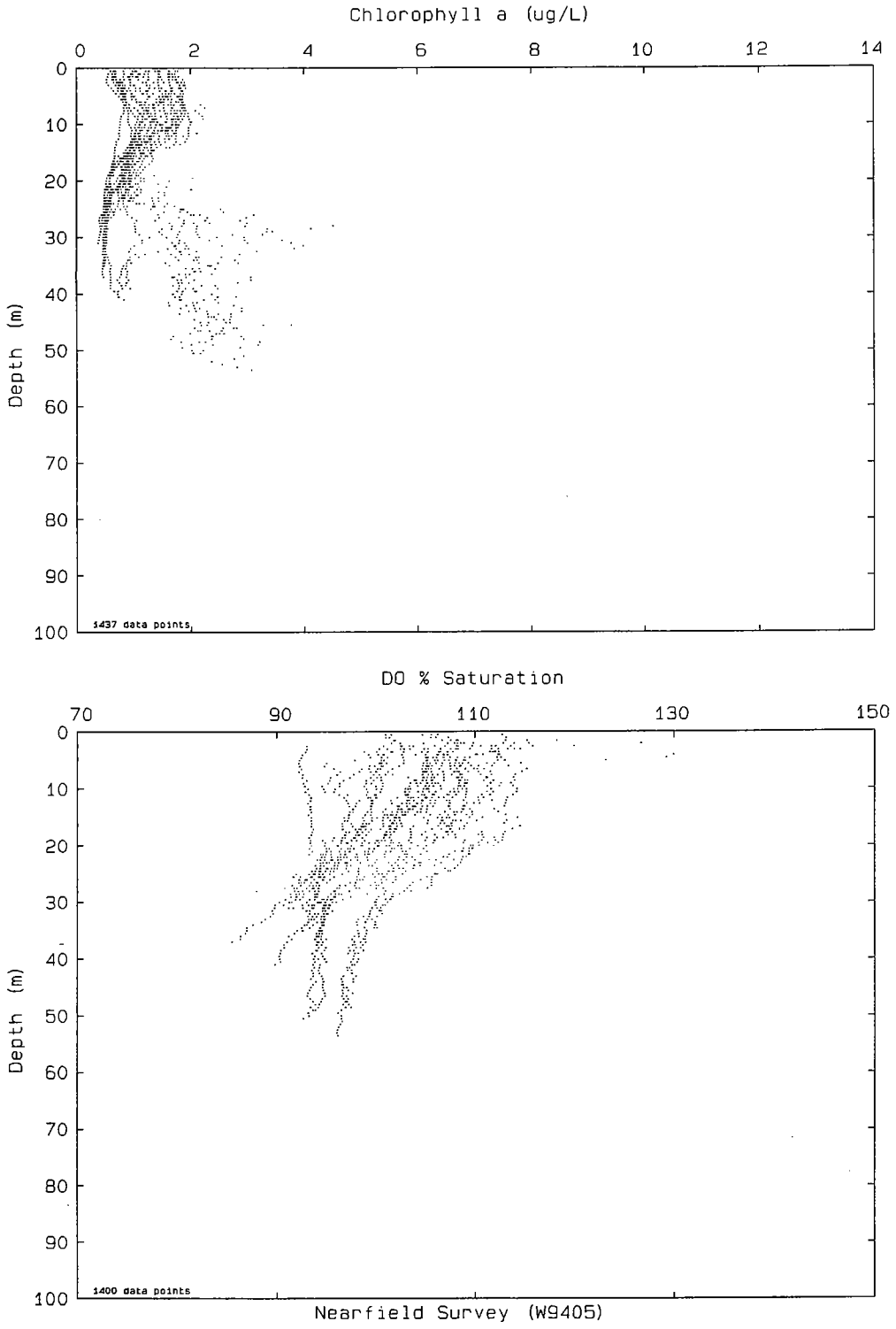


Figure 4-1b. Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in late April 1994. Chlorophyll is estimated from *in situ* fluorescence.

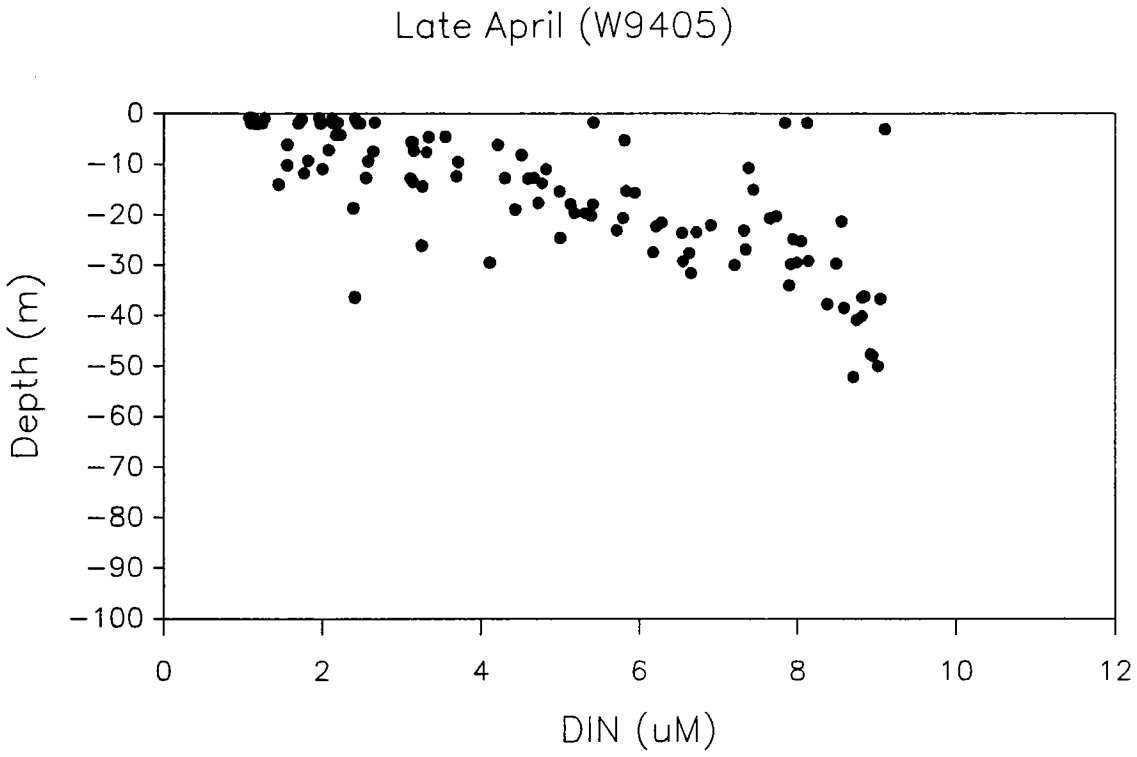


Figure 4-2a. DIN vs. depth in late April 1994.

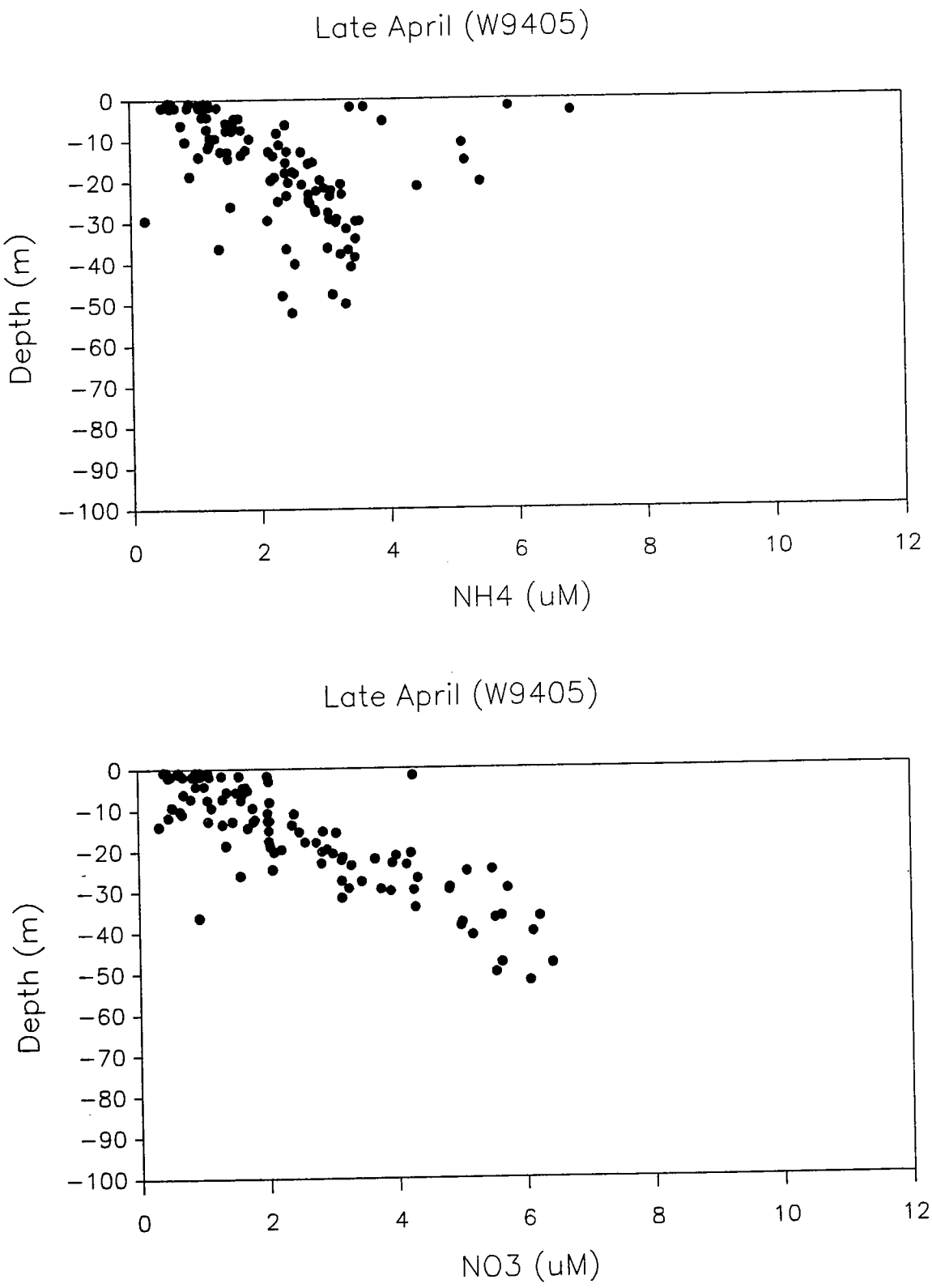
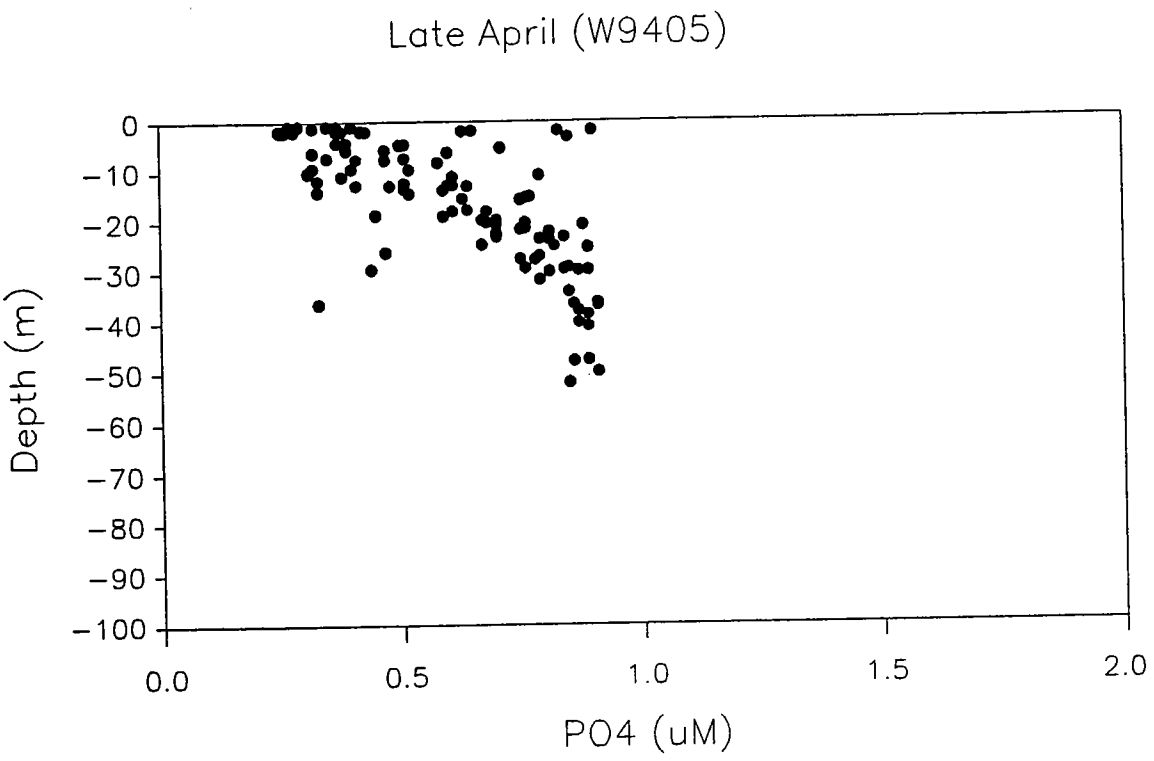


Figure 4-2b. NH_4 and NO_3 vs. depth in late April 1994.



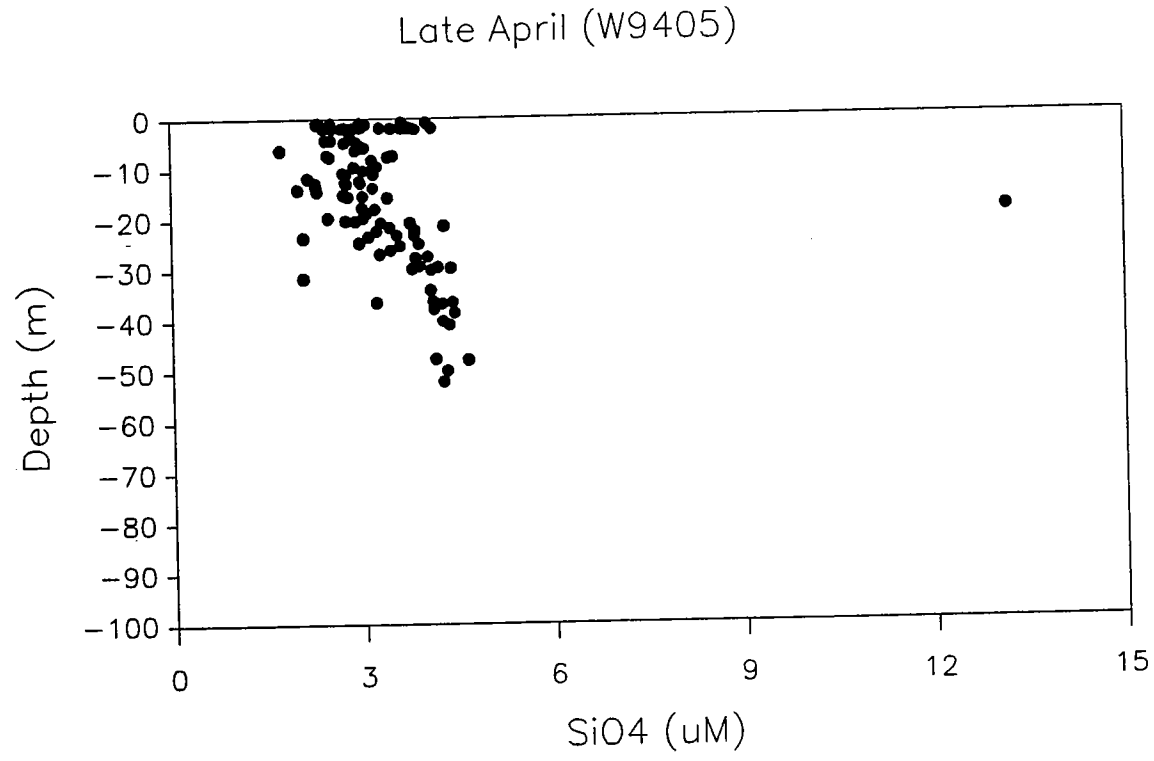


Figure 4-2c. PO_4 and SiO_4 vs. depth in late April 1994.

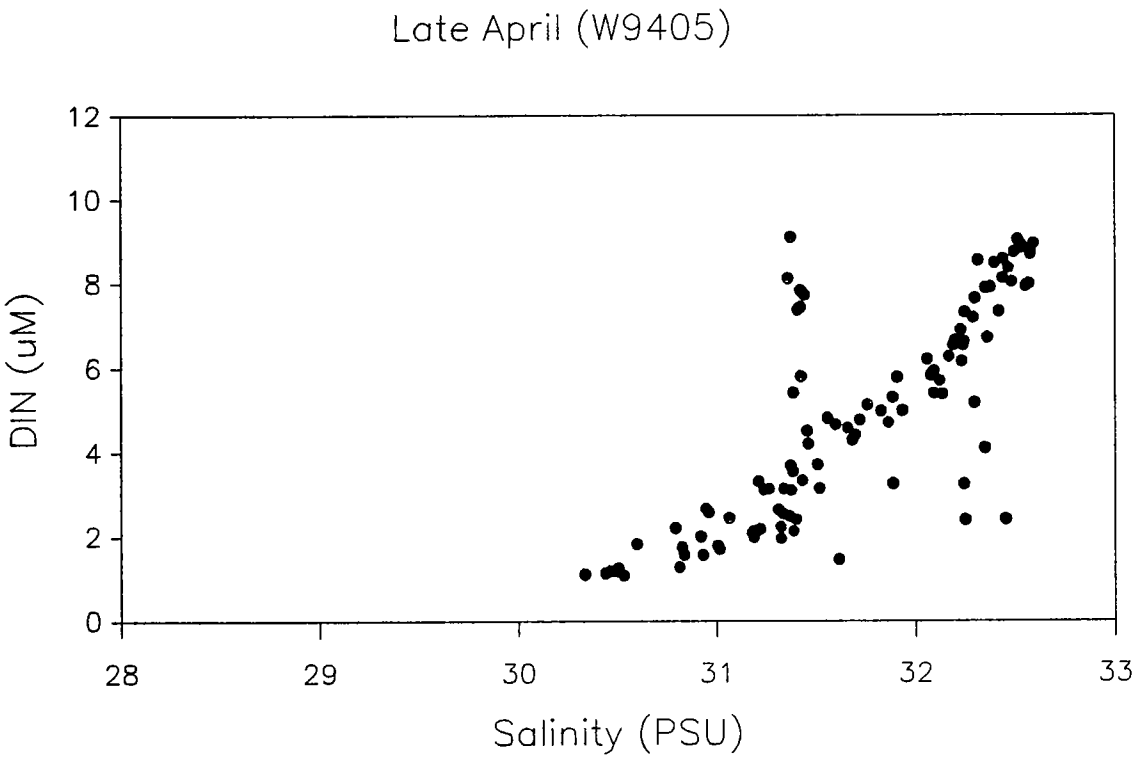
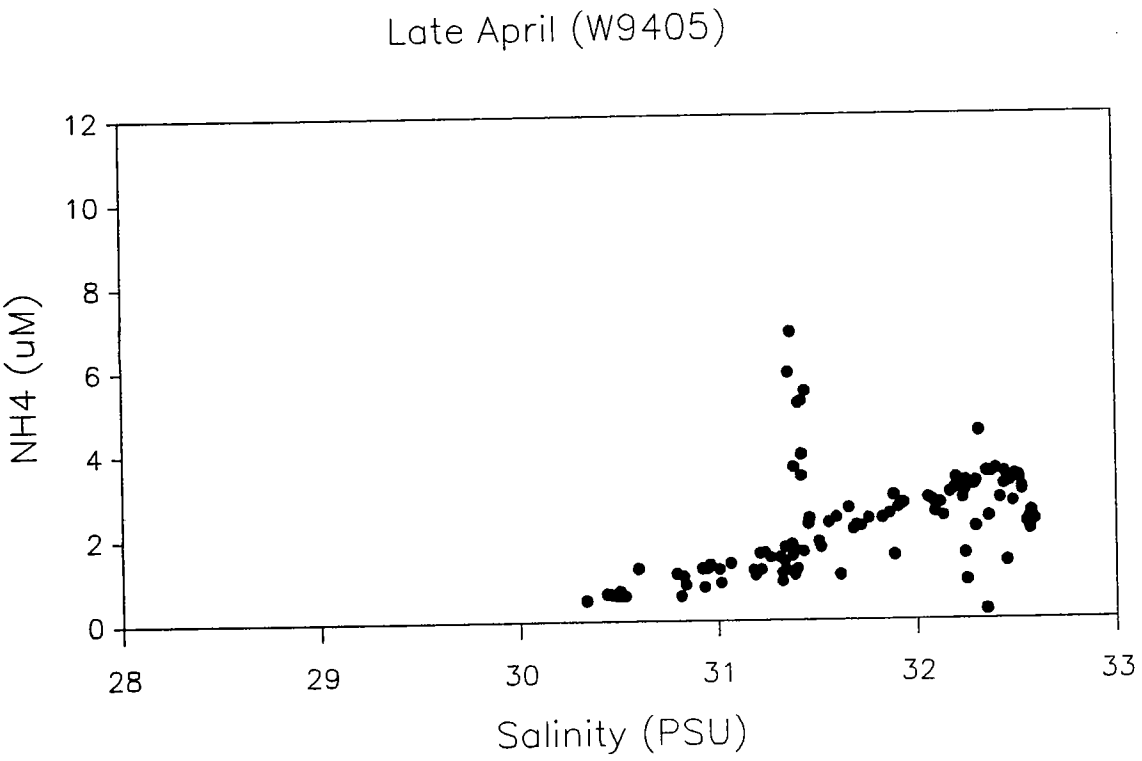


Figure 4-3a. DIN vs. salinity in late April 1994.



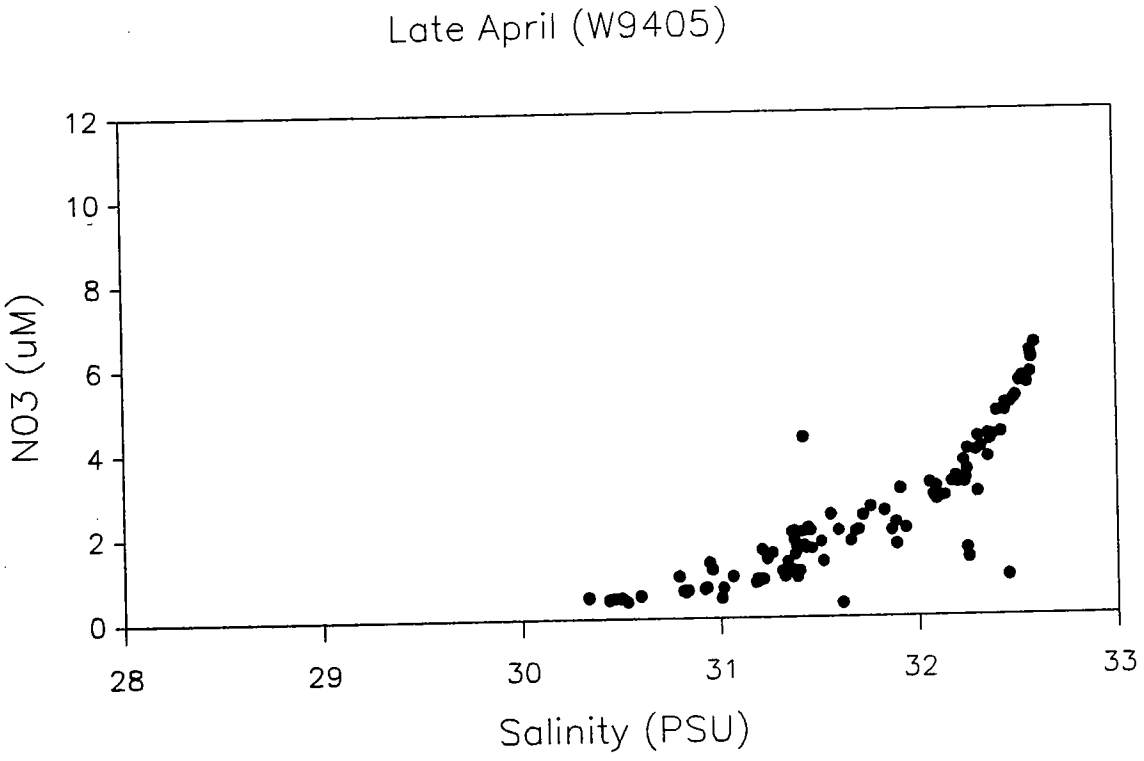
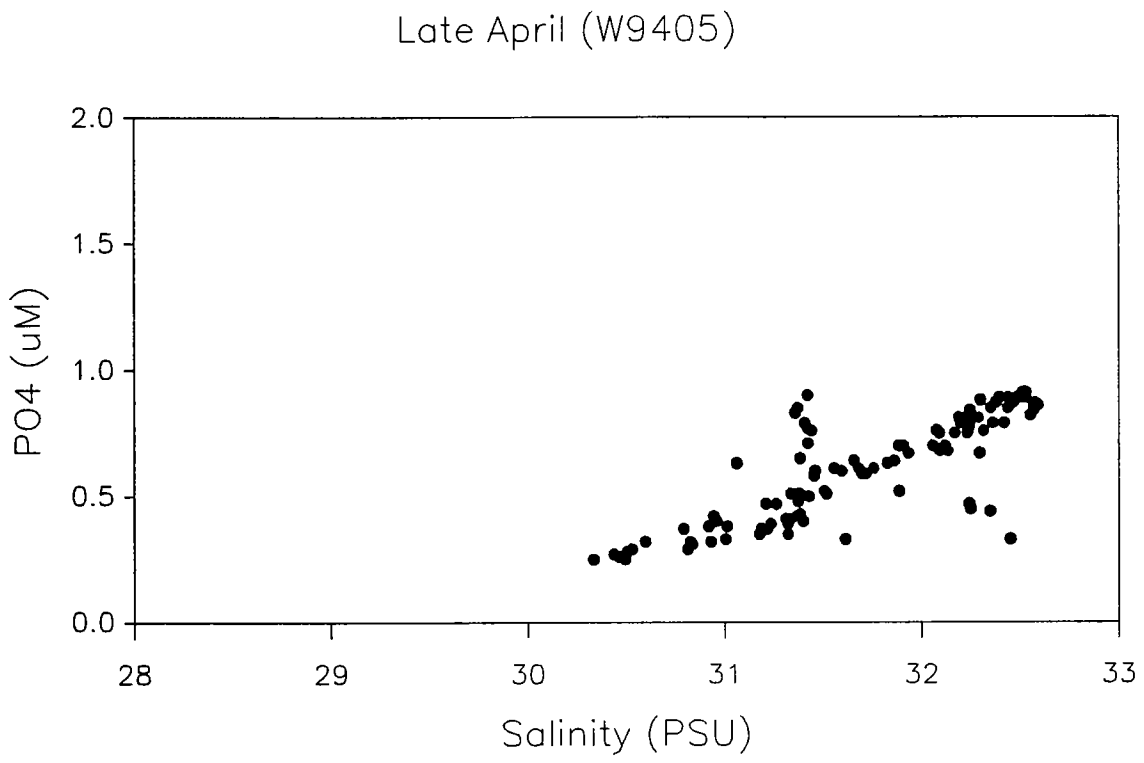


Figure 4-3b. NH_4 and NO_3 vs. salinity in late April 1994.



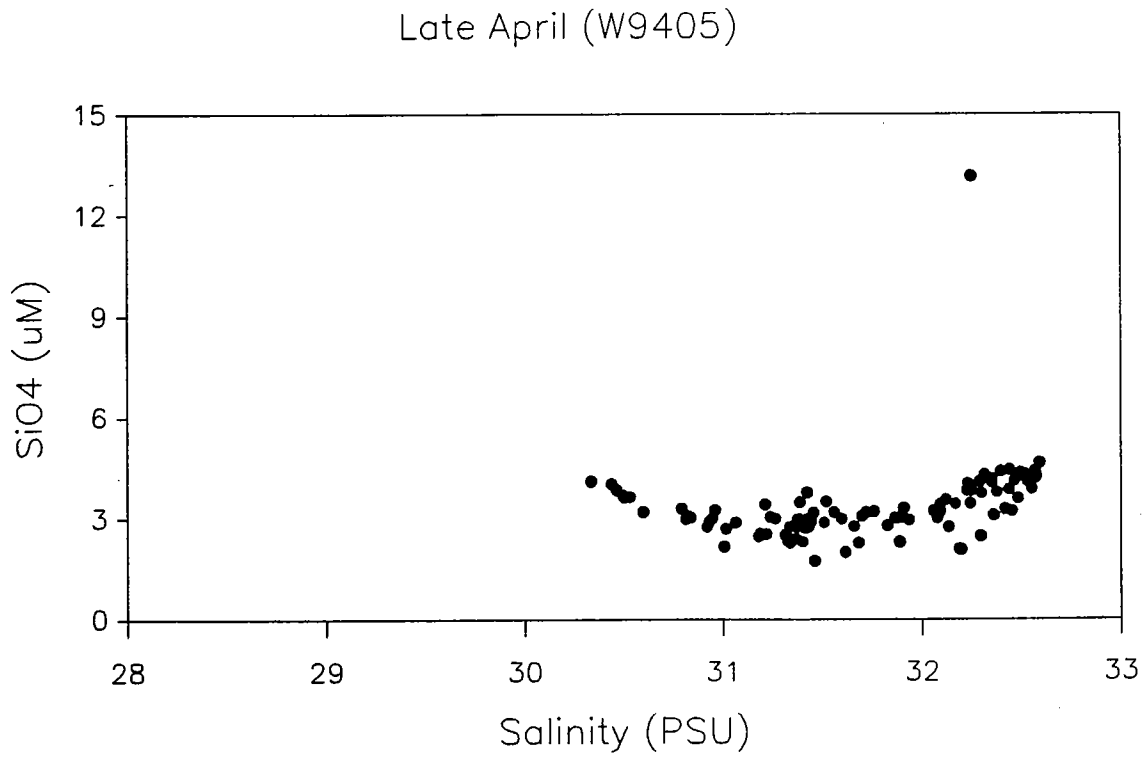


Figure 4-3c. PO_4 and SiO_4 vs. salinity in late April 1994.

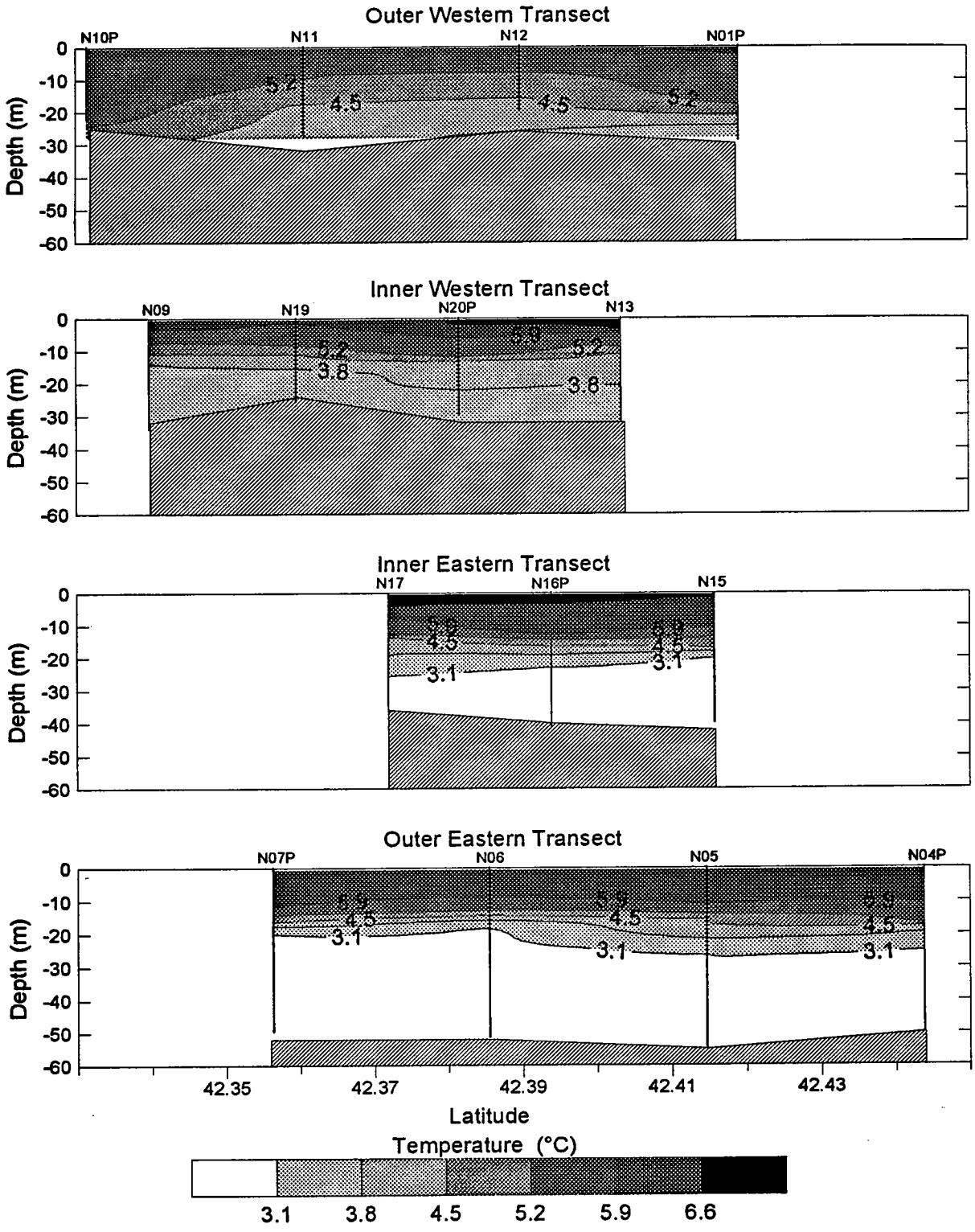


Figure 4-4a. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9405. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

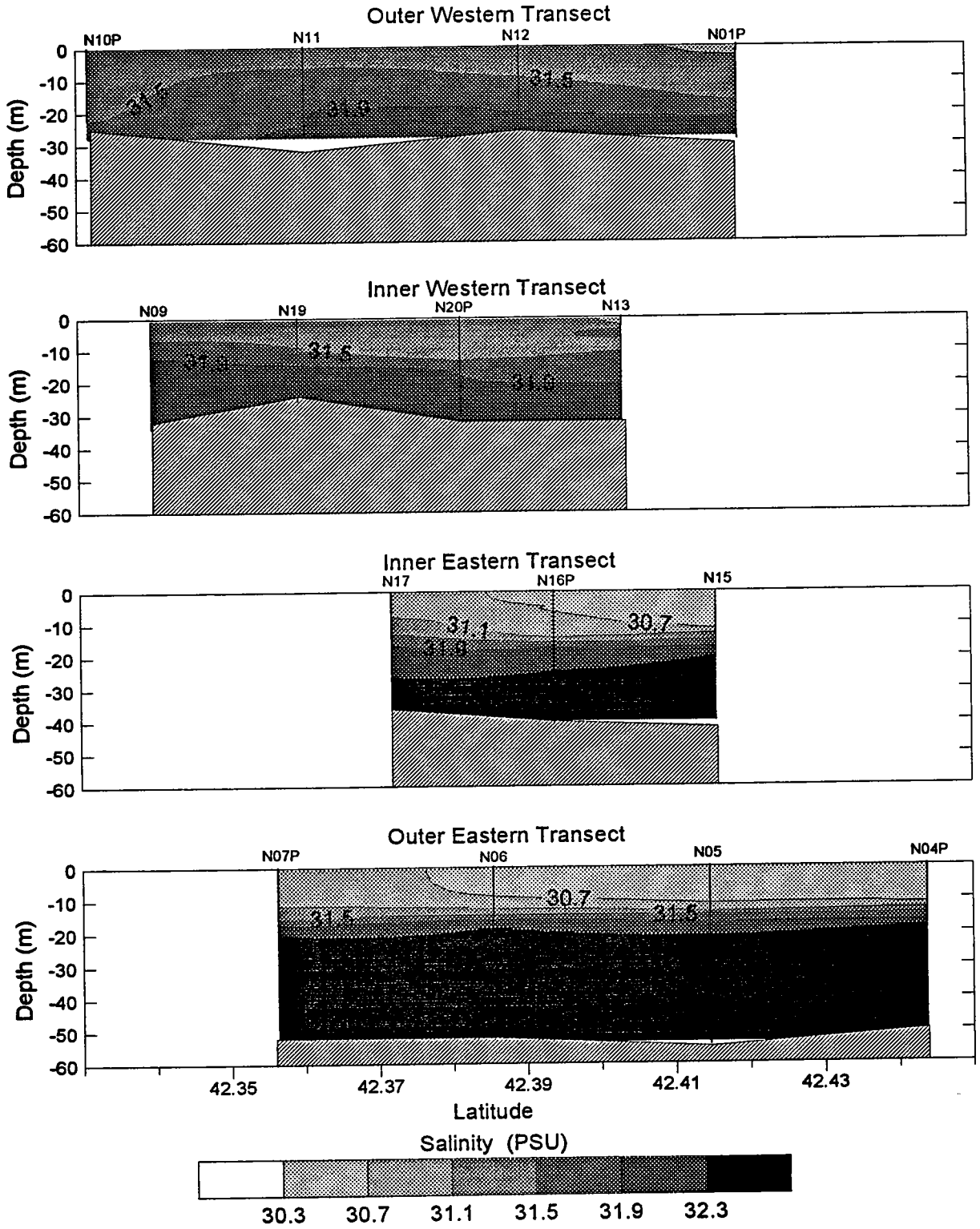


Figure 4-4b. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9405. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

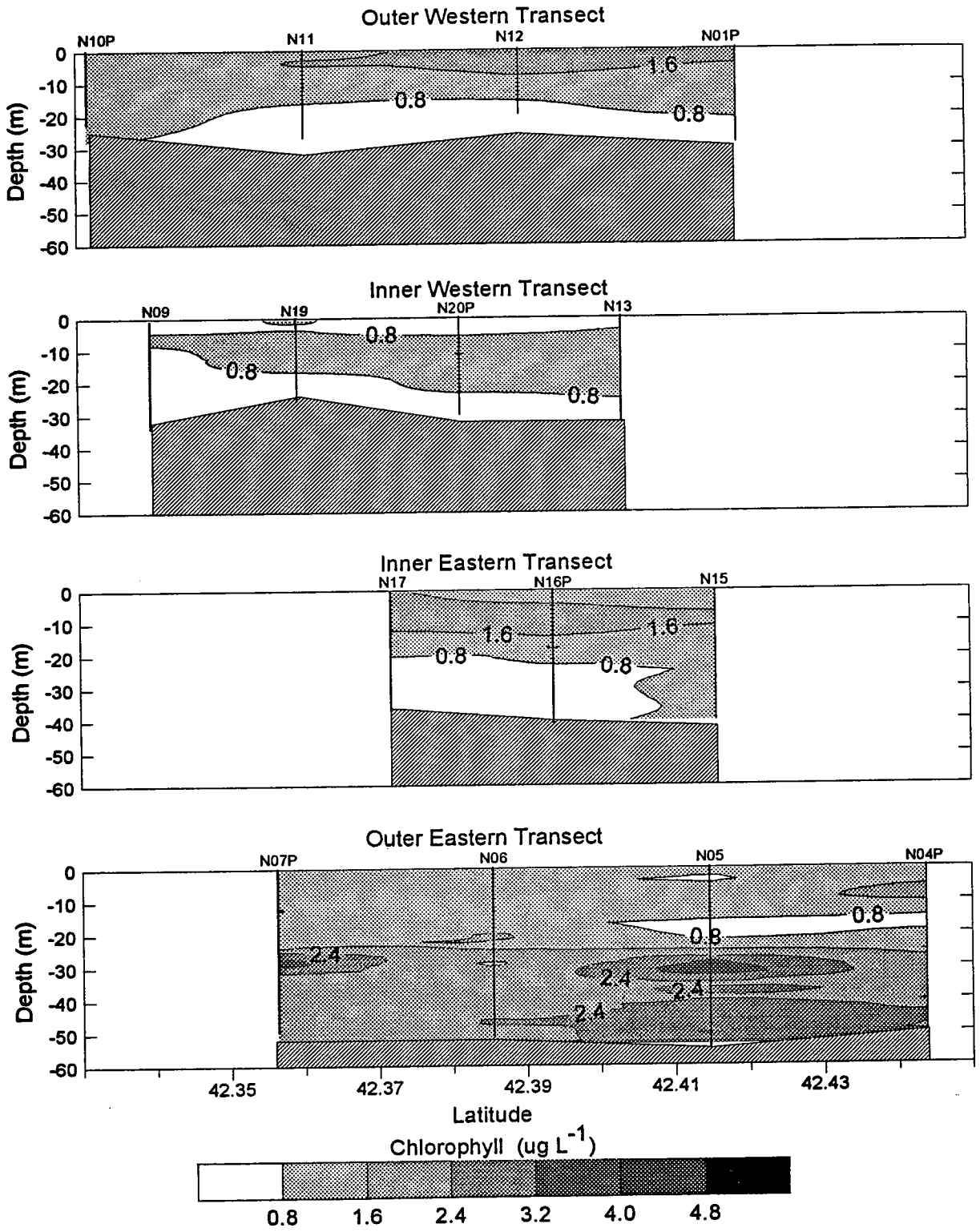


Figure 4-4c. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9405. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

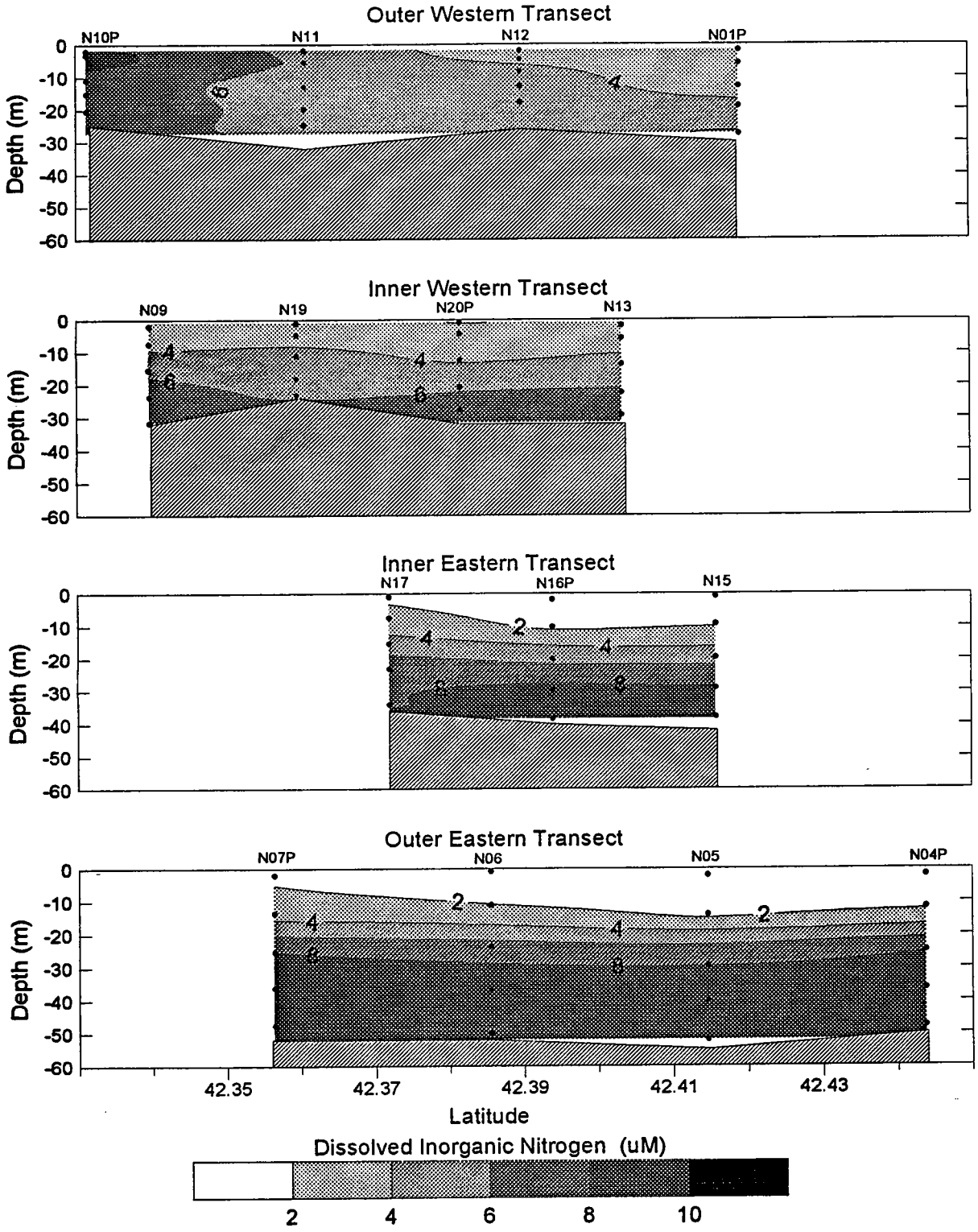


Figure 4-4d. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9405. The data used to produce the contours are from discrete bottle samples taken at each station during the nearfield sampling day (Appendix A).

5.0 RESULTS OF MAY 1994 NEARFIELD SURVEY (W9406)

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 show a strong coherence across stations in T-S signature for all bottom waters ($<8°C$ and >30.5 PSU). Some variation in the surface waters across the nearfield is noticeable as scatter at warmer temperature and lower salinity (Figure 5-1a). Some physical stratification was evident from all station profiles, although the magnitude of the gradient between surface and bottom water values (for T, S, and density) was generally slight along the inshore side of the nearfield. The depth of the surface layer varied across the field and the pycnocline was found from 5 m to >35 m, depending on location (Appendix B).

Beam attenuation was regularly higher in surface water; the pattern was generally a decrease in beam attenuation with increasing salinity (Figure 5-1a). Unlike the two surveys in April, a regular increase in near-bottom turbidity was not noted in May. Often, some turbidity enrichment ($> 1.0\ m^{-1}$) occurred without a significant increase in chlorophyll concentrations, so the overall correlation between turbidity and chlorophyll was poor. In part, this scatter between beam attenuation and chlorophyll reflected differences in their vertical distributions. As stated (and demonstrated in Appendix B), beam attenuation increased towards the surface, whereas maximum chlorophyll concentrations were regularly noted as subsurface features at depths from about 8 to 18 m (Figure 5-1b). Something other than bulk chlorophyll concentration in the surface water was apparently responsible for significant increase in turbidity. There are not sufficient data to identify the constituent.

DO saturation sometimes mimicked the vertical pattern of chlorophyll, exhibiting a slight subsurface maximum. Overall, DO saturation continued to be high within the surface layer. However, the DO concentrations dipped sharply, sometimes to $<90\%$ saturation in the bottom layer (Figure 5-1b).

As found in April, dissolved nutrient concentrations were related to depth, and the highest concentrations of all nutrients were found in the deeper (>25 m) offshore waters at stations at the eastern edge of the nearfield (Figure 5-2). Generally, surface DIN concentrations were nearly depleted, although the surface water in the region of stations N10P, N11, and N12 was again enriched in DIN (Figure 5-2a). This enrichment was apparent in both NH_4 and NO_3 concentrations (Figure 5-2b). DIN concentrations ranged from ~0 to 9 μM, similar to the range for late April. Between late April and the May survey, NH_4 concentrations at depth had increased by ~4 μM; by May, NH_4 and NO_3 contributed equally to the DIN concentration of the deep water in the nearfield.

Distributions of phosphate and silicate followed the typical pattern for stratified conditions and, thus, showed essentially the same distribution with depth as the nitrogen forms (Figure 5-2c). Neither phosphate nor silicate were as depleted as DIN in the surface waters, although surface phosphate concentrations were lower than they had been in late April. Surface SiO_4 concentrations were similar to those measured in late April but, at depth, concentrations of SiO_4 had increased significantly (4-5 μM) between late April and May, reaching concentrations equivalent to the maximum deepwater values (>9 μM).

The nutrient-salinity plots (Figure 5-3) reveal two features that differed from the late April pattern. The first feature was the re-emergence of the descending "arm" of nutrient concentrations as salinity increases from lowest values (near 30 PSU). This feature probably represents nutrient export from the Harbor because these samples were collected from stations in the southwestern corner of the nearfield where tidal interactions are strong (Kelly and Albro, 1994; Kelly, 1994). The appearance and disappearance of this descending arm may be as much a function of sampling times, relative to the stage of the tide, as it is to season, but it does require some high-nutrient freshwater flow to support the presence of lower salinity water.

The second feature in the plots was that no compounds exhibited an obvious curvature with salinity, as had been the case in late April (see Section 4). Instead, the typical plot exhibited a linear trend of nutrients with salinity. As discussed in Section 4, the proper interpretation of straight or curved nutrient-salinity plots in the milieu of the nearfield is not entirely clear, but the simplest interpretation

of linear trends observed in late April is that biological activity was reduced. This, of course, is also suggested by the generally low chlorophyll concentrations; strong physical layering implies minor vertical mixing by advective processes. The action of biological assimilation as a sink for dissolved nutrients across most of the nearfield (except the western edge) in May, therefore, may have been limited primarily to that supported by tidally pulsed nutrient flow from inshore (not evident at sampling) or the small fluxes of nutrients from bottom layers (due to diffusive processes across a chemical gradient; see Kelly, 1994). Note that a balance between the rate of nutrient diffusive flux from more saline water below and biological assimilation rates in less saline water above could result in a linear nutrient-salinity trend (i.e., indication of a "conservative" trend does not mean that there are no underlying transfers, just that they are generally balanced).

5.2 Water Quality Variability in the Nearfield

Vertical contours of temperature, salinity, chlorophyll (as measured by fluorescence), and dissolved inorganic N are presented in Figure 5-4. As indicated by some recent surveys during the spring 1994, a slight diurnal heating was suggested by the presence of a thin surface layer of warmer water ($>10.5°C$) at stations in the middle of the field, which were sampled in mid-afternoon (West, 1994b). Aside from this thin warm layer, there was a surface temperature gradient across the field, with slightly warmer temperatures at the inshore edge of the field (Outer Western Transect, Figure 5-4a) than at the offshore edge of the field (Outer Eastern Transect, Figure 5-4a). Only moderate thermal stratification was noted inshore, whereas a strong thermocline, relatively deep in the water column (25-50 m), was evident offshore.

Geographic trends for the halocline were similar to those for temperature (Figure 5-4b). For either temperature or salinity, trends in vertical stratification were pronounced in the east-west direction, but there were also weak north-south trends. However, there was a noticeable layer of low salinity (<30.3 PSU) water at stations in the southwestern corner of the nearfield. Such a feature has commonly indicated export of fresher Boston Harbor water (cf. Kelly and Albro, 1994).

As often observed, the vertical distribution of chlorophyll followed an inshore-offshore pattern (Figure 5-4c). A surface layer with generally higher chlorophyll concentrations (>3.2 $\mu g\ L^{-1}$) was found along the shallow inshore side of the nearfield. Transversing the field to the east, a subsurface chlorophyll maximum at 10-20 m depth became pronounced. The most intense subsurface maxima (>5 $\mu g\ L^{-1}$) were found in the middle of the field. In this mid-field area, the peak concentrations were usually associated with a pycnocline (Appendix B). In contrast, the peak subsurface chlorophyll concentrations offshore (e.g., stations N04P through N07P) were usually well above the deep pycnocline, a feature that occurred well below the 1% light level (see Appendix B).

Surface layers throughout most of the nearfield were low in DIN (Figure 5-4d) and there was not an obvious correspondence between chlorophyll and DIN distributions. However, it was clear than DIN concentrations related to salinity. Surface water concentrations of DIN were >2 μM (sometimes >6 μM) in the less-saline surface water identified in the southwestern corner of the nearfield. As suggested, this water was responsible for the reappearance of the descending arm on the DIN vs. salinity plot, and it indicates export of freshwater and nutrients from inshore to the nearfield.

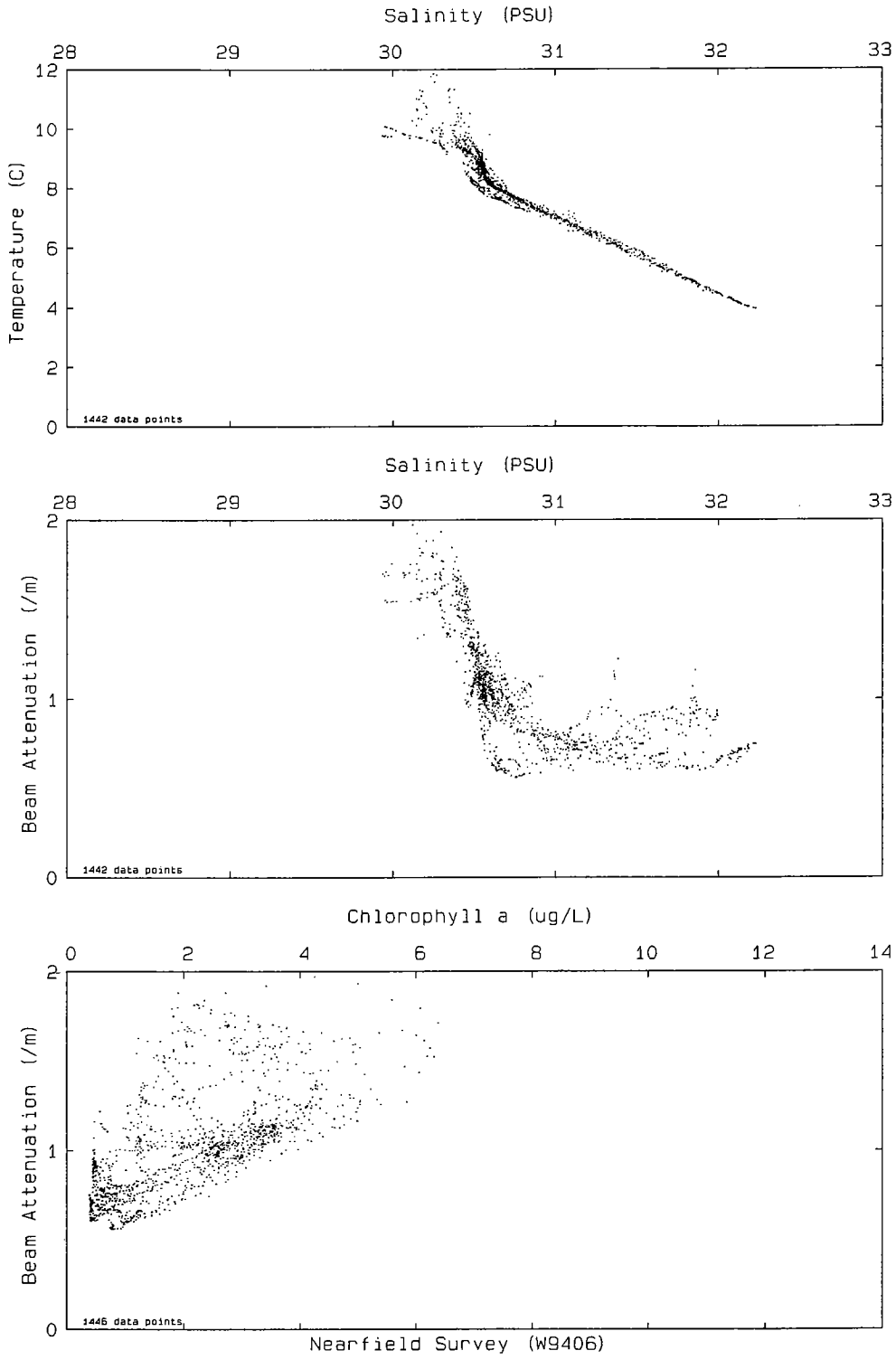


Figure 5-1a. Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in May 1994. Chlorophyll is estimated from *in situ* fluorescence.

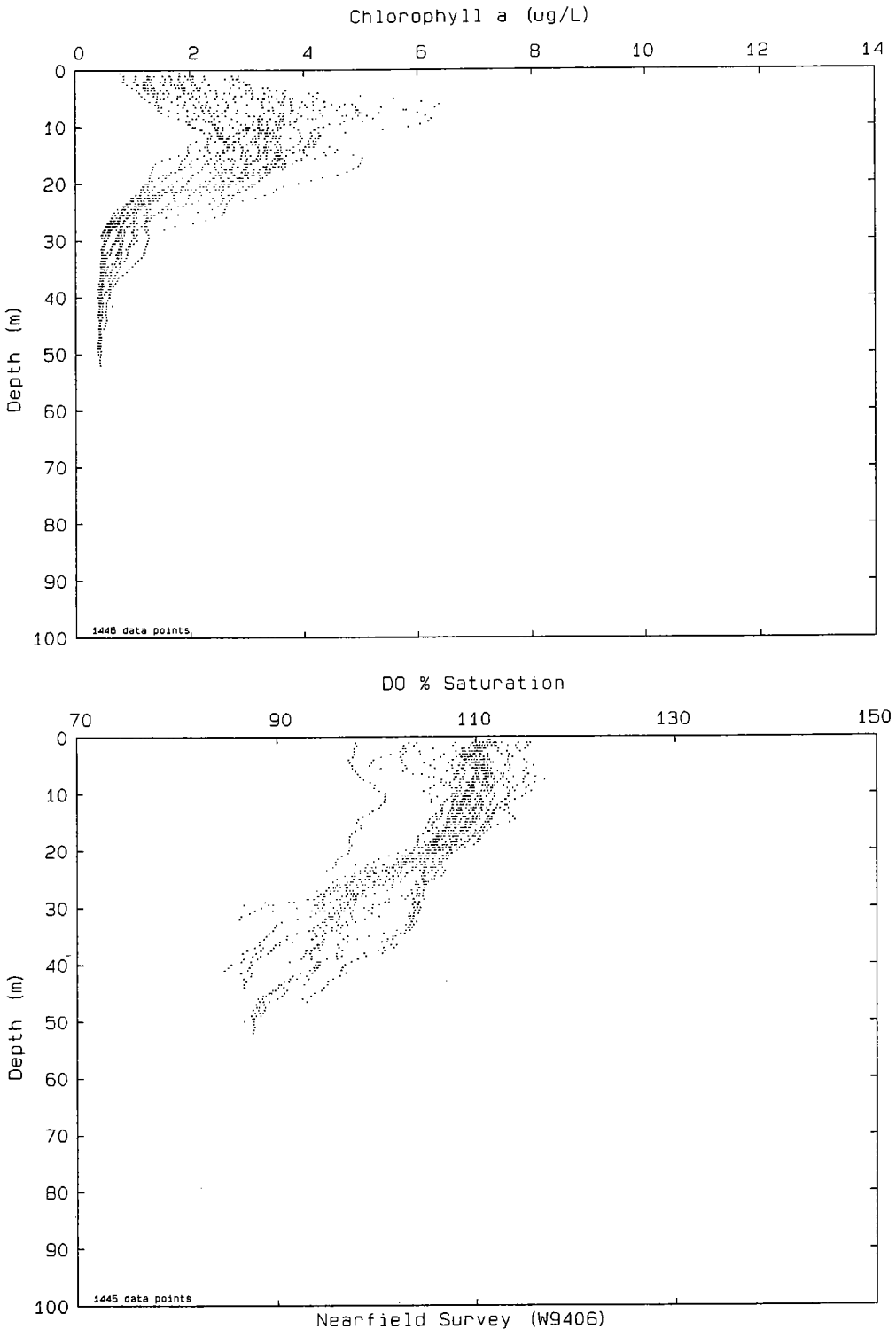


Figure 5-1b. Scatter plots of data acquired by *in situ* sensor package during vertical casts for nearfield survey in May 1994. Chlorophyll is estimated from *in situ* fluorescence.

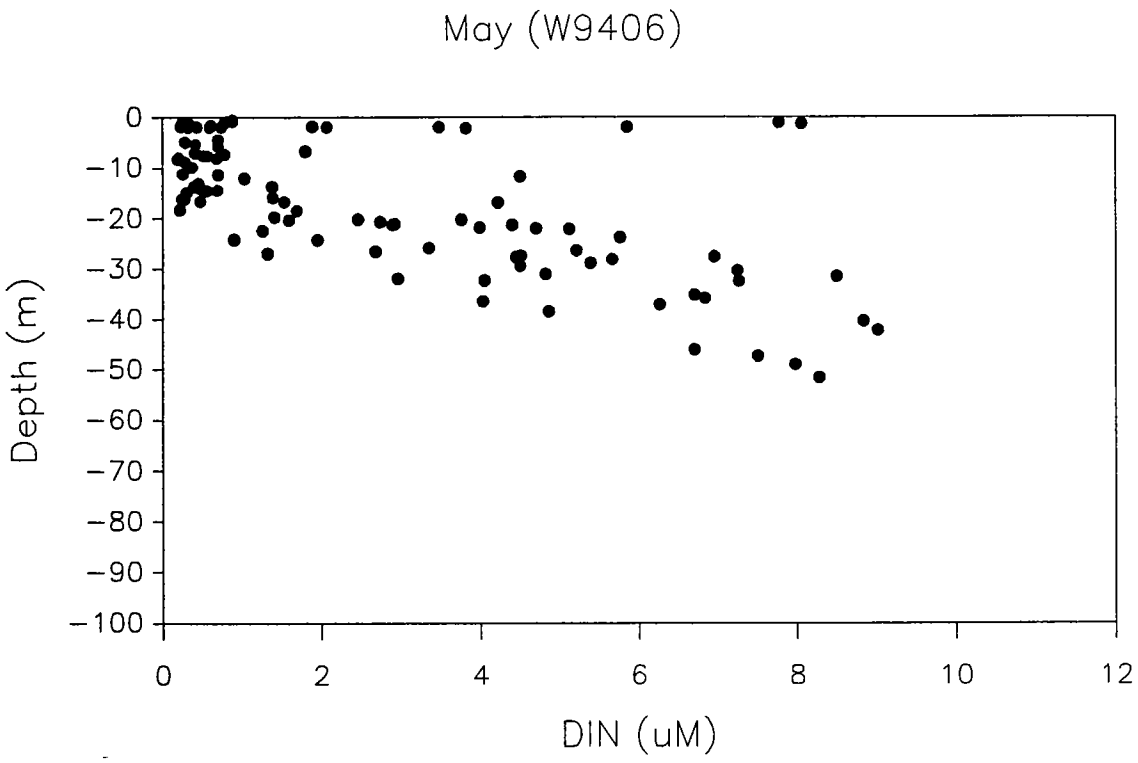


Figure 5-2a. DIN vs. depth in May 1994.

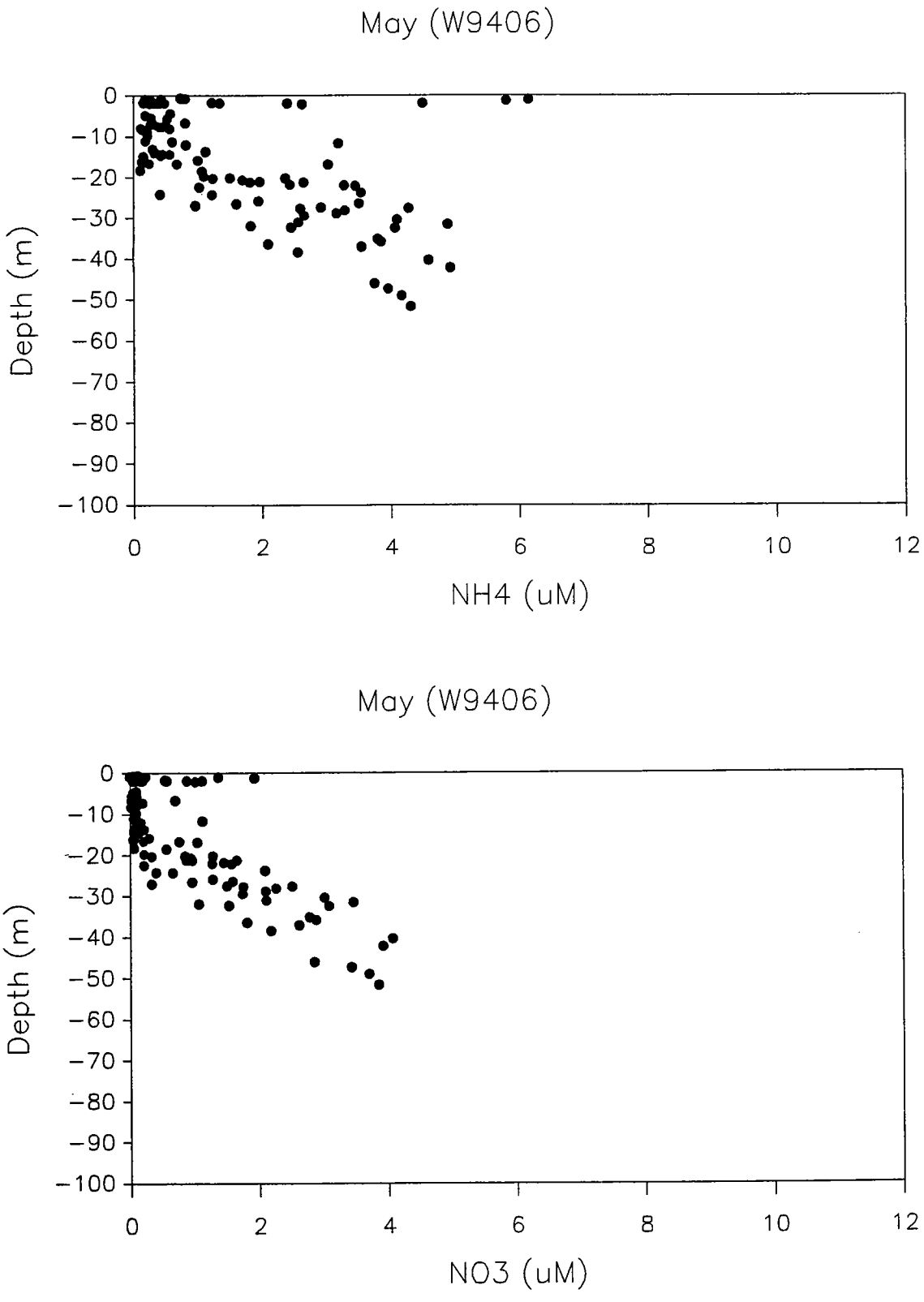
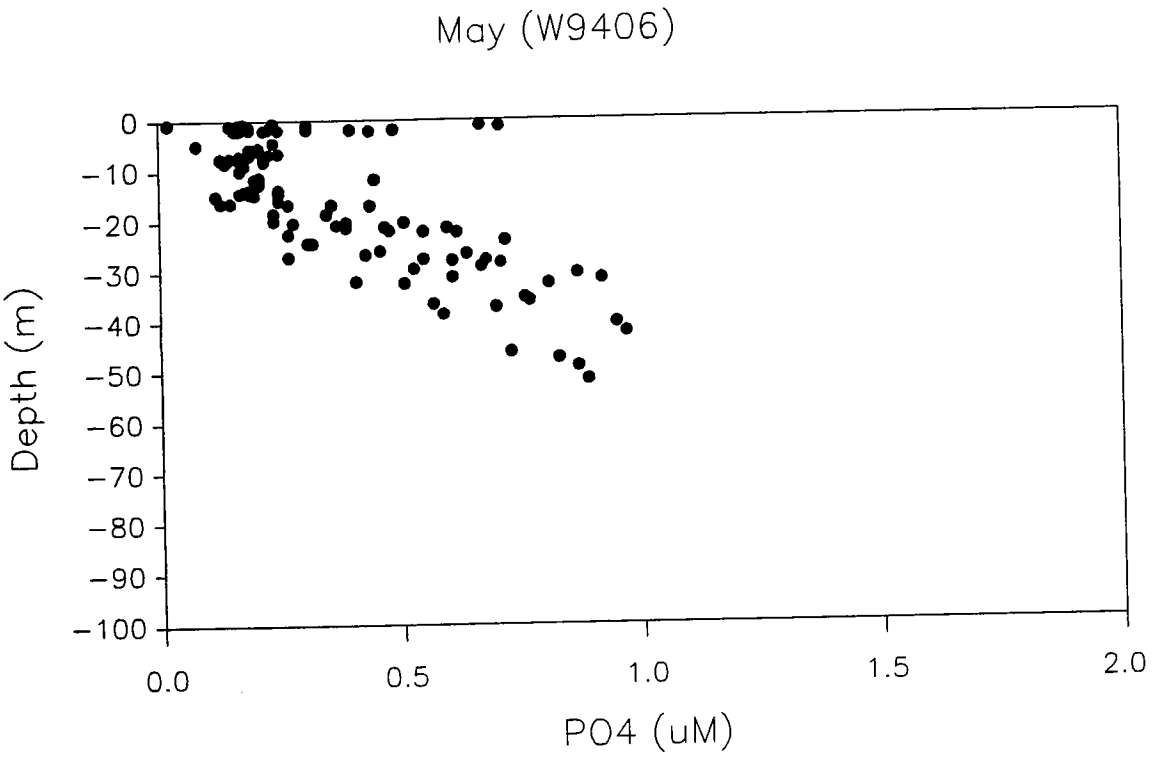


Figure 5-2b. NH_4 and NO_3 vs. depth in May 1994.



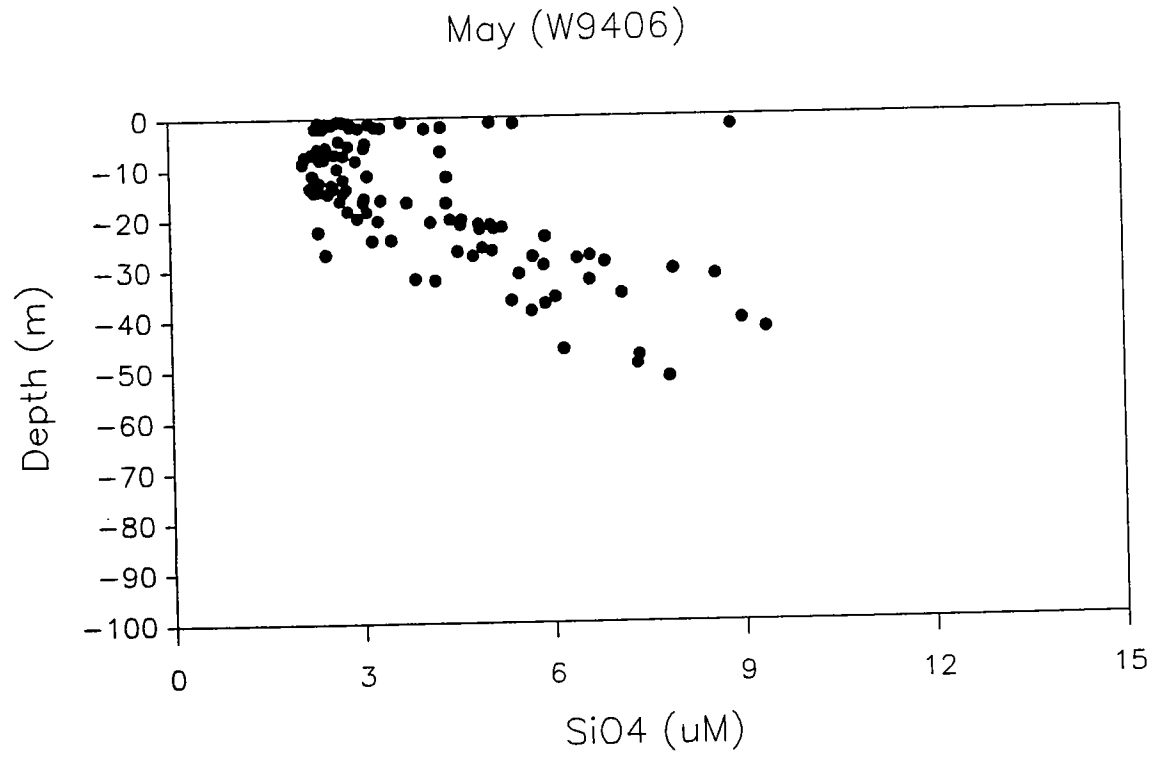


Figure 5-2c. PO_4 and SiO_4 vs. depth in May 1994.

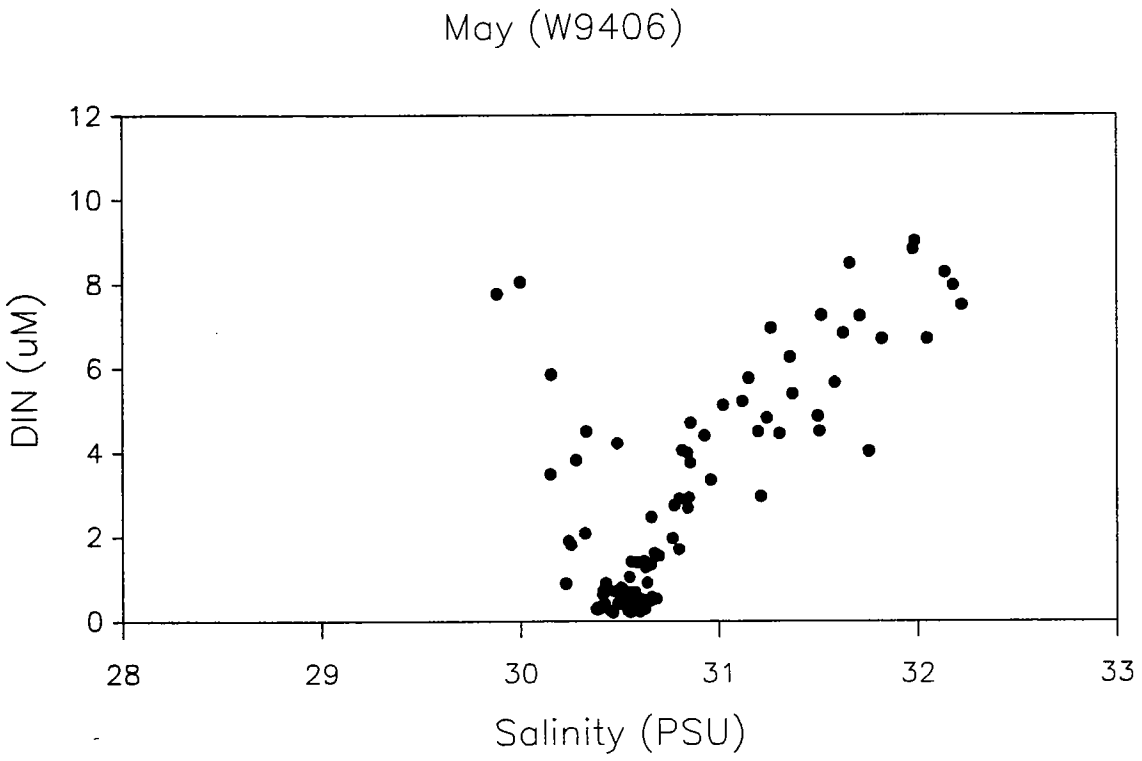
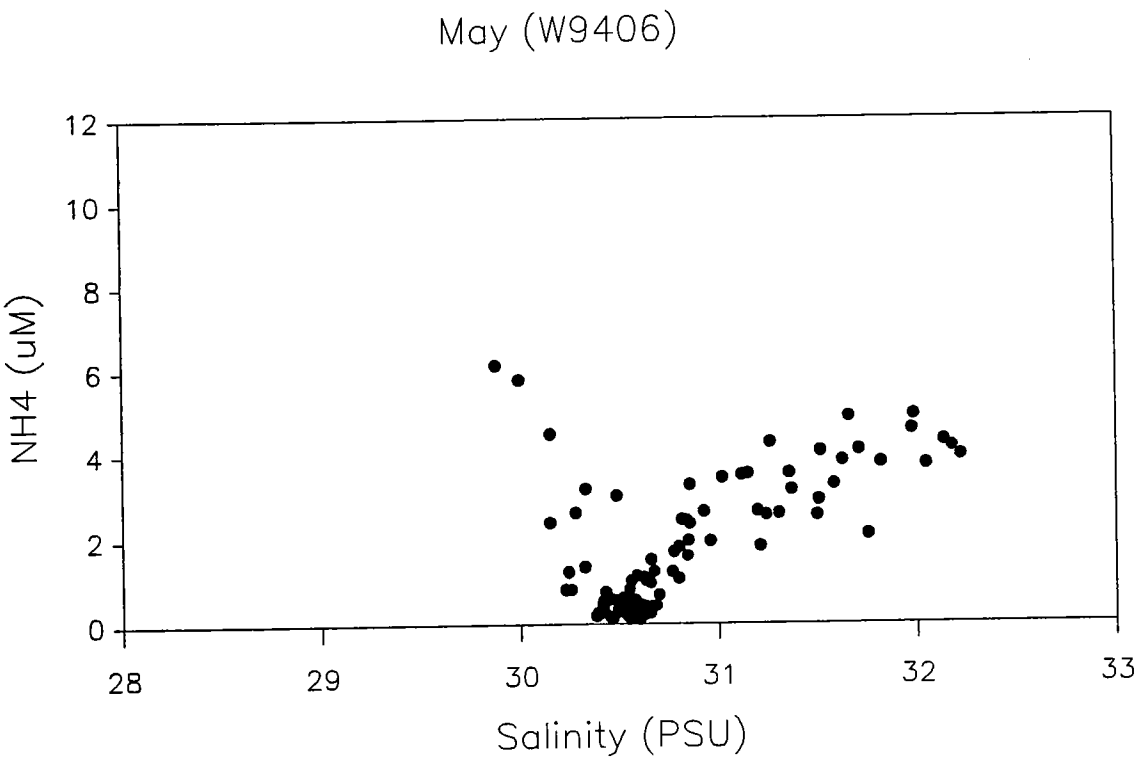


Figure 5-3a. DIN vs. salinity in May 1994.



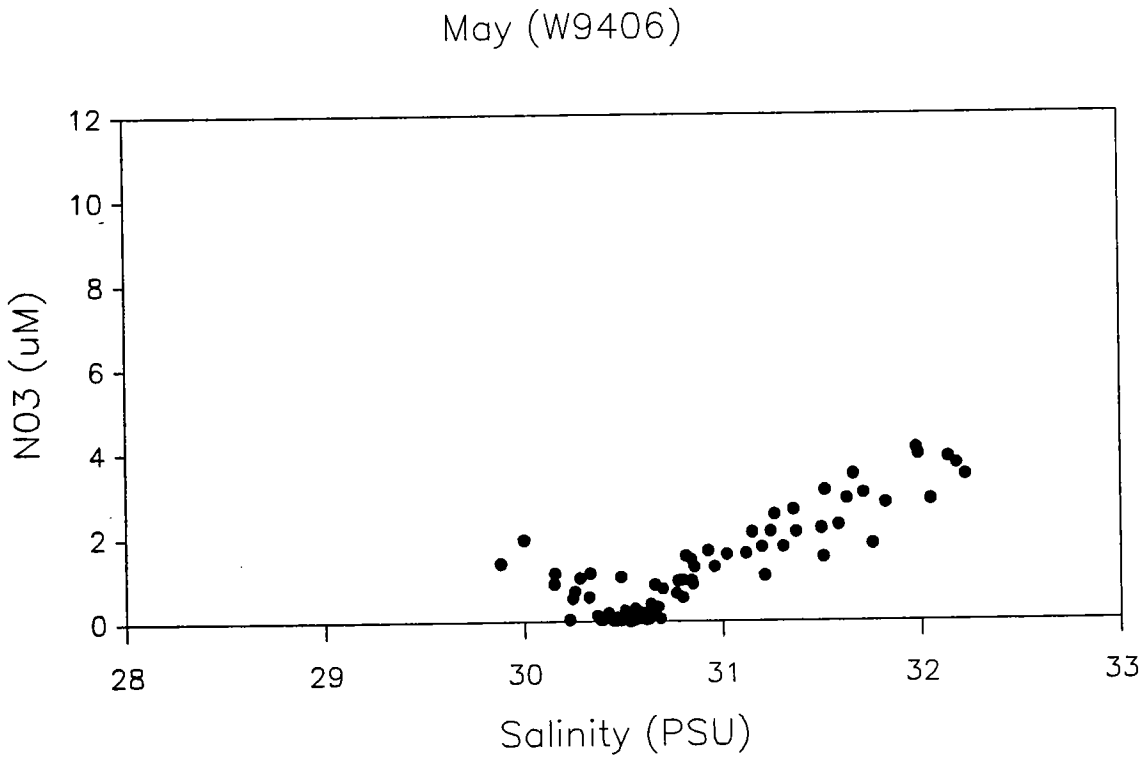
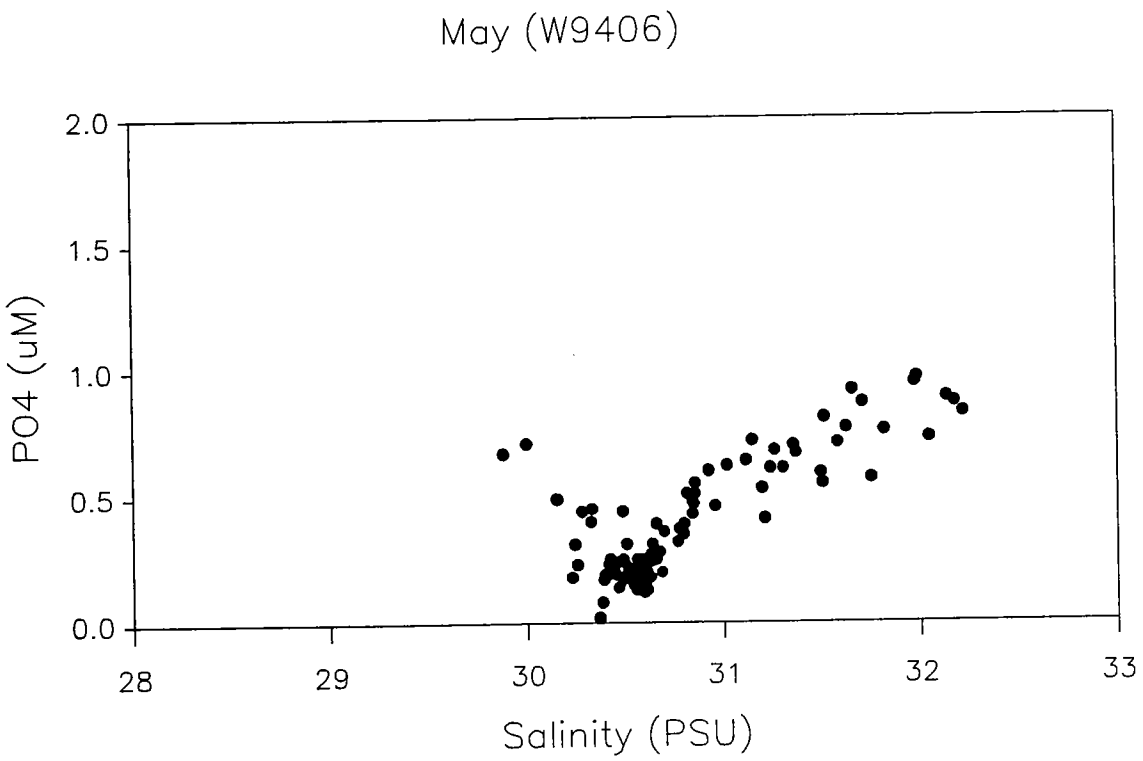


Figure 5-3b. NH_4 and NO_3 vs. salinity in May 1994.



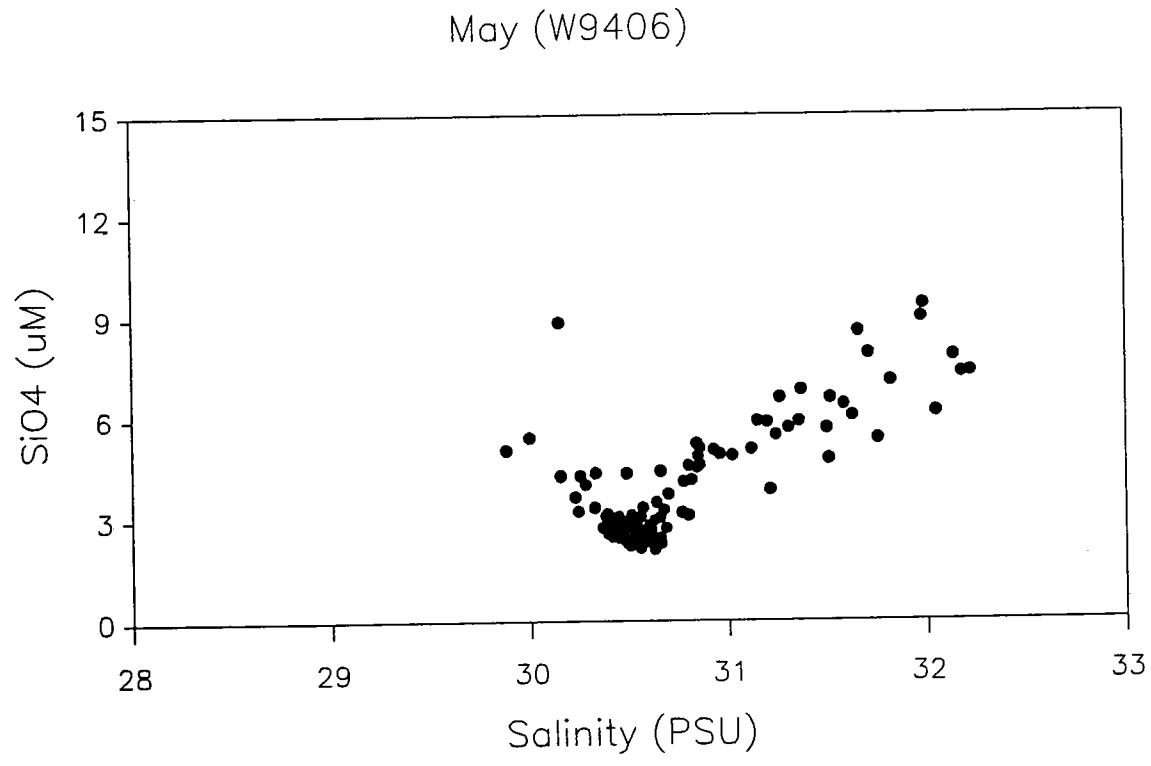


Figure 5-3c. PO_4 and SiO_4 vs. salinity in May 1994.

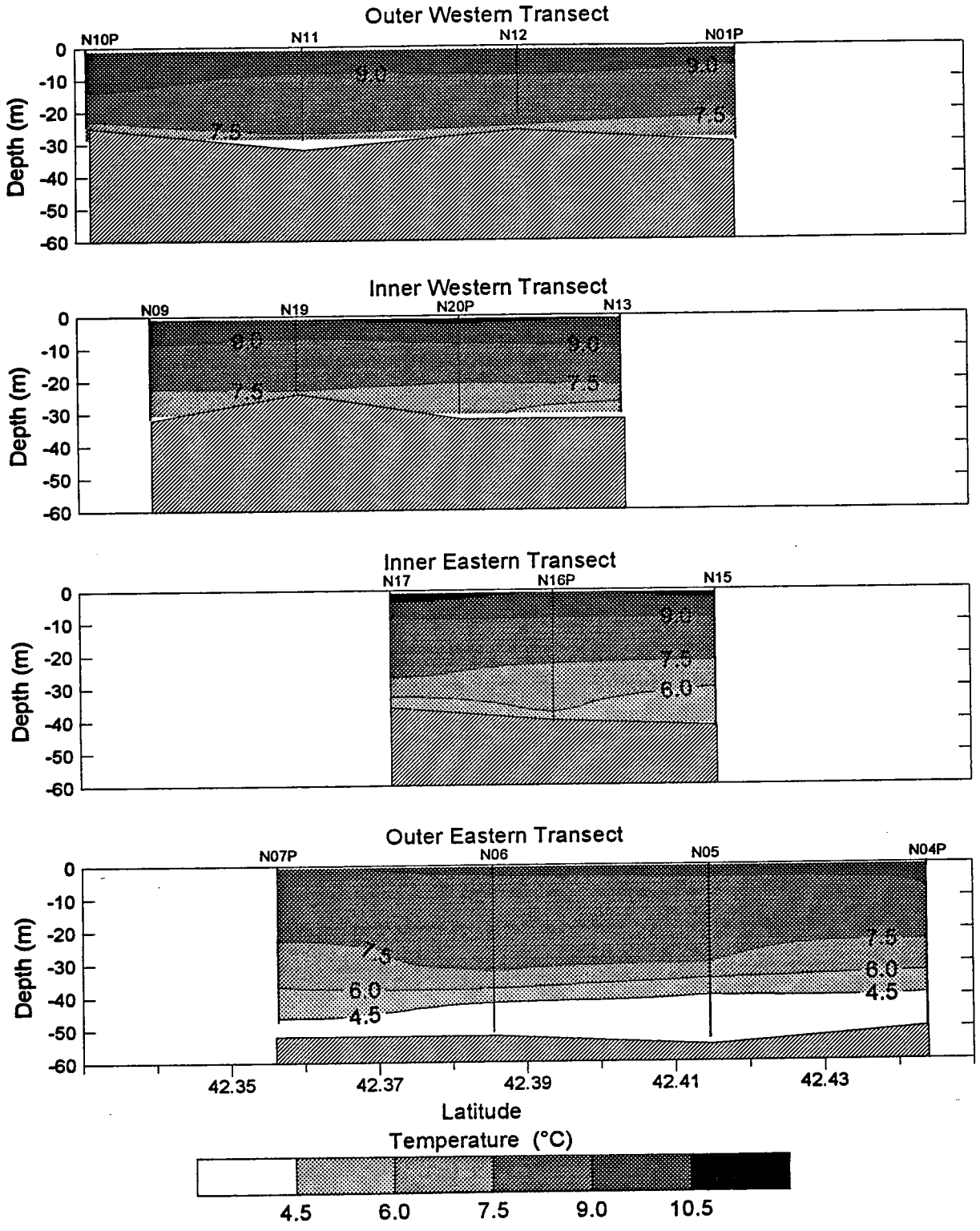


Figure 5-4a. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9406. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

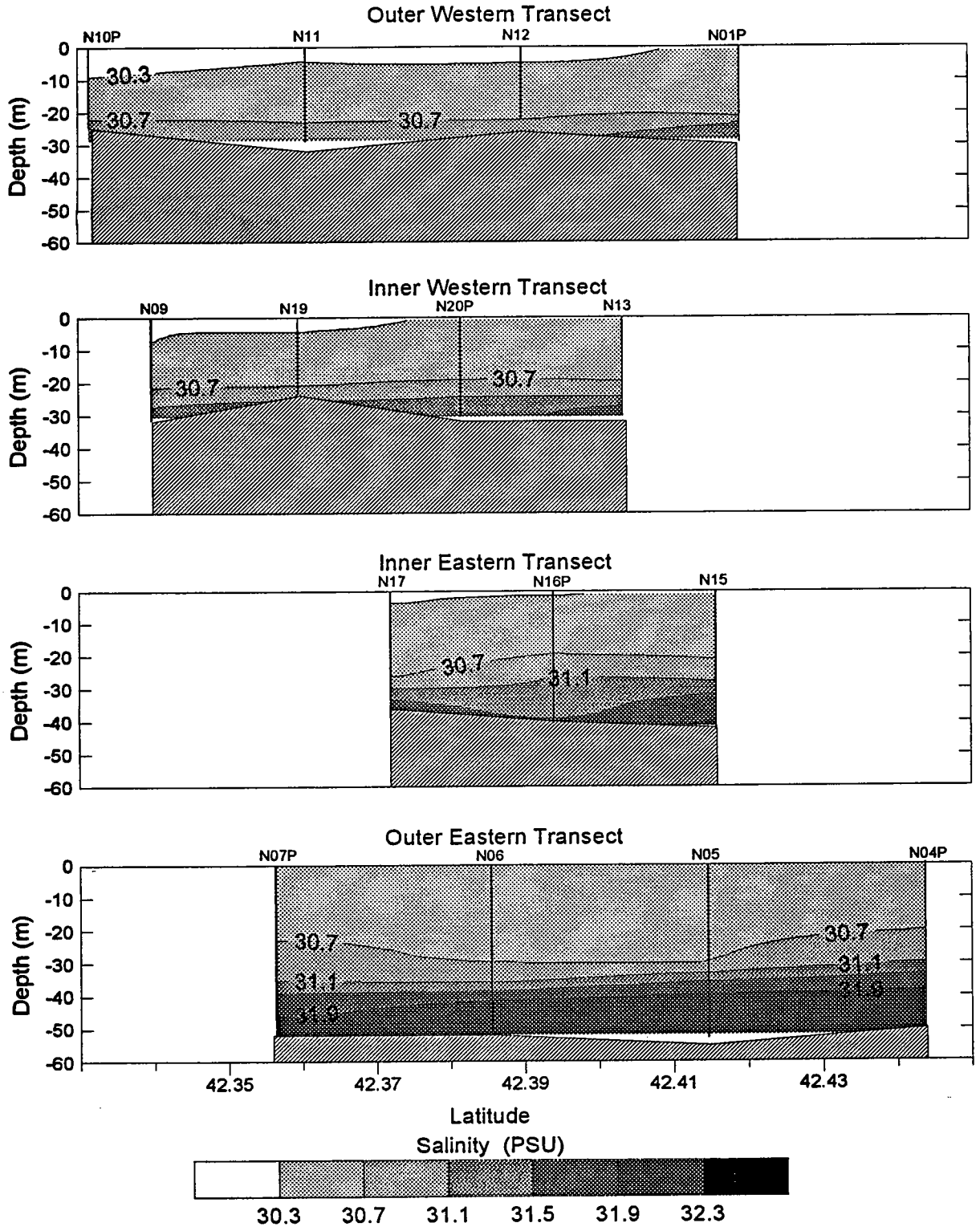


Figure 5-4b. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9406. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

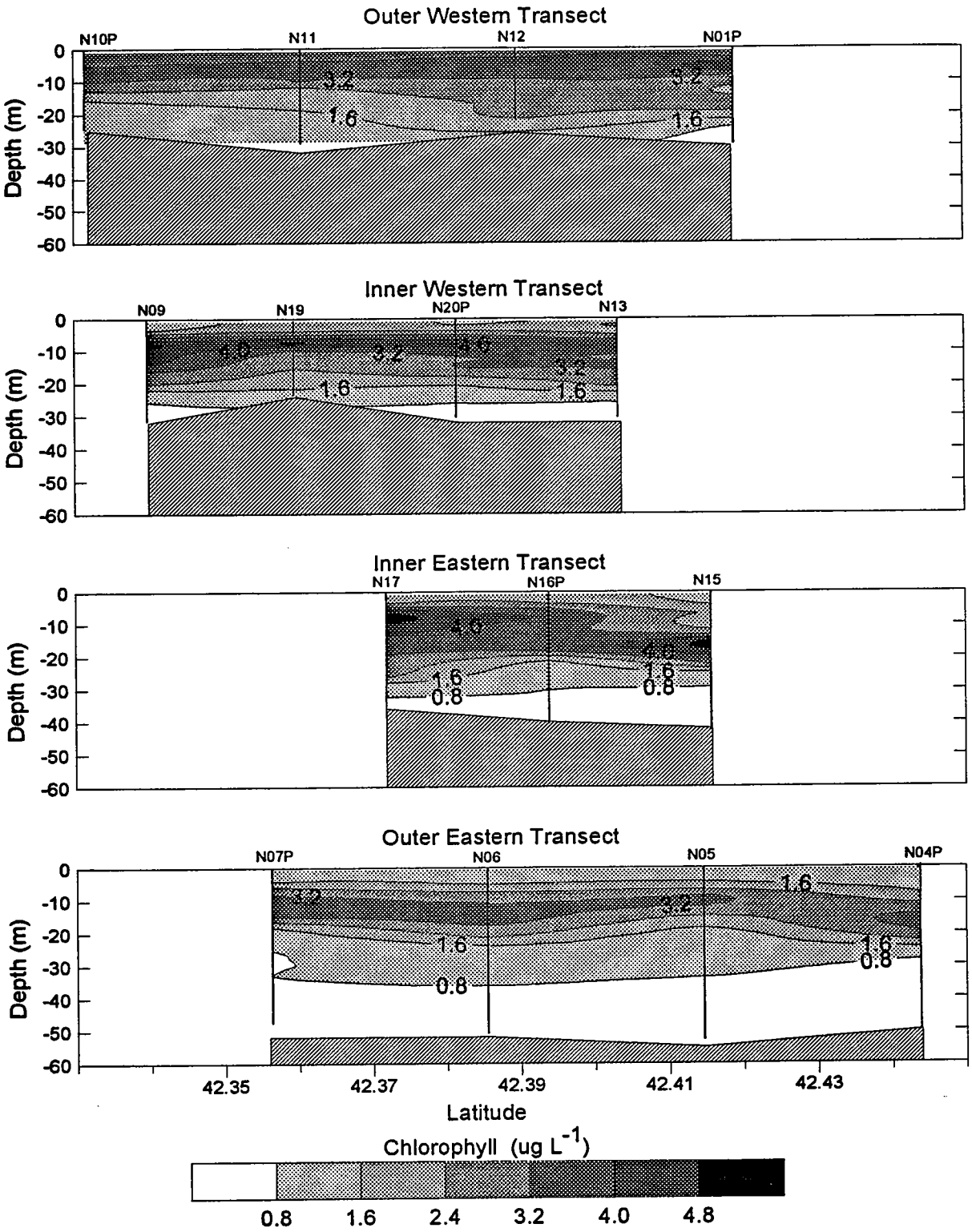


Figure 5-4c. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9406. The data used to produce the contours are from high-resolution continuous vertical profiles taken from the downcast at each station during the nearfield sampling day.

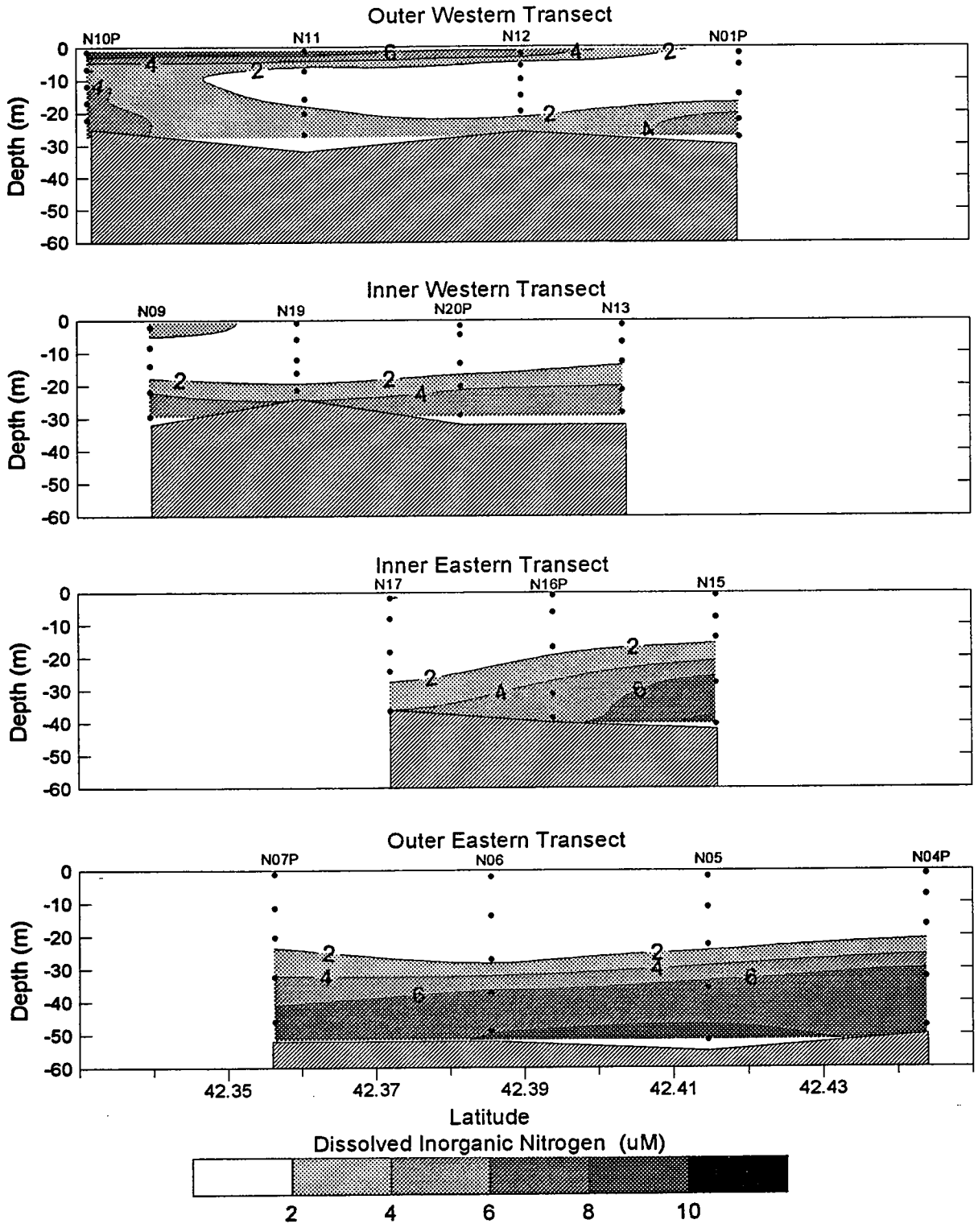


Figure 5-4d. Vertical section contours for nearfield standard transects (view towards Boston Harbor) on Survey W9406. The data used to produce the contours are from discrete bottle samples taken at each station during the nearfield sampling day (Appendix A).

6.0 DISCUSSION OF THE LATE SPRING PERIOD OF SURVEYS

6.1 Water Properties

6.1.1 Variability at the Regional Scale

During the months covered by this report, the regional scale was surveyed only once in early April (see Section 3), so temporal variability on the Bay-wide scale was not assessed within the late Spring period. Summary comments here relate to spatial variability.

Physical variations within the Bays were relatively minor, and principal differences in temperature and salinity occurred between Boston Harbor and Massachusetts Bay rather than between Massachusetts and Cap Cod Bays. In contrast to physical parameters, chlorophyll concentrations, especially in surface water, were higher at selected areas within Massachusetts Bay than they were at stations in Cape Cod Bay.

1994 surveys included water column monitoring stations 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 the late spring (early April) 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 within the range observed elsewhere in Massachusetts Bay. In terms of nutrients, the boundary station data were within the range of concentrations observed in surface and deep waters in Stellwagen Basin.

6.1.2 Variability in the Nearfield

Generally, the inshore side of the nearfield was weakly stratified in terms of temperature and salinity. In contrast, the offshore waters were more strongly stratified. On the eastern side of the nearfield, a

distinct, colder, and more saline bottom water layer persisted through April and May, although the depth of the thermocline/pycnocline varied over the period.

At each survey, less saline parcels of water were noted in the nearfield. In early April and May, these parcels were centered in the southwestern corner of the nearfield. In contrast, in late April, a less saline surface water mass was located at the northeastern corner of the field. We also noted repeatedly that some diurnal heating occurred in surface water during the course of the nearfield sampling.

The variations in salinity, temperature, and stratification define some of the physical dynamics occurring in the nearfield during this period. At short time scales (hours), tidal fluxes cause variability in surface water and probably vertical mixing in shallower waters, and solar radiation causes temporal variability in surface temperature (and also probably mixing of surface layers). At longer times scales, advection from inshore or from offshore leads to patchiness in physical attributes within surface waters of the nearfield.

6.1.3 Special Features: Comparison of 1994 with Previous Years

Figure 6-1 shows the surface temperature in the nearfield for all of 1993 and for 1994 through May. The thermal progression in winter-spring 1994 in nearfield surface waters was characterized by a continual and increasingly rapid warming. From early April to the middle of May, the average surface temperature increased ~5°C (from 4 to 9°C). The 1994 trend was relatively similar to that observed in 1992. In 1993, surface warming was a delayed until April, but warming into May was faster than in 1992 and 1994. Although only a minor difference, the initiation of seasonal water column warming and the development of the thermocline are important events, and may help regulate the expression and timing of the spring bloom, nutrient concentrations, and water quality in bottom waters later in the year.

At the end of the April-May 1994 period, DO concentrations in nearfield bottom waters reached ~9 mg L^{-1} (Figure 6-2). Thus, relative to concentrations earlier in the year, DO declined abruptly in late spring

as the stratified period commenced. A sharp decline during late spring has now been observed for each year of the monitoring program (1992 to 1994). Therefore, this decline is most likely part of the characteristic annual cycle in the nearfield. The decline in DO concentration in 1994 (Figure 6-2) represents a significant decrease in oxygen, from supersaturated to undersaturated levels. This trend defines a distinct separation of metabolism of surface and bottom waters that is initiated as the bottom layer begins a period of net heterotrophy following the concomitant developments of stratification, depletion of surface nutrients, and cessation of the winter-spring bloom. Organic matter, that has recently been produced within the photic zone and that has subsequently been transported below the pycnocline, is now being consumed. However, autotrophic and heterotrophic metabolism have become uncoupled by the physical (stratification) barrier to mixing of bottom waters with the lighted euphotic zone; DO cannot, therefore, be replenished by biological or physical re-aeration processes and the concentrations decline. Across years, it is possible that the bottom water DO in late spring may be an appropriate indicator of interannual variability in the level of primary production of the winter-spring period, but it should be an effective integrator of the relative amount of new organic matter that becomes transferred to bottom waters and metabolized within several months.

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. The profiles demonstrated that most stations were stratified by April and this stratification was uninterrupted through April and May. Nutrient concentrations over depth can also indicate the presence of mixed or stratified conditions. The transition between mixed and stratified conditions began in mid-March and rapidly produced a nutrient-poor surface layer that is generally typical of Massachusetts Bay during the stratified season. In general, nutrient-depth patterns were distinct throughout the Bay in April and May, with relative, if not absolute, depletion of nutrients in surface layers and increasing concentrations with depth.

6.2.2 Inshore-Offshore Gradients

The data indicated that nutrients followed typically described trends; higher nutrient concentrations (dissolved and total forms) were associated with less saline inshore waters, and lower nutrient concentrations were characteristic of more saline offshore waters. However, the typical presence of higher nutrient, lower salinity water at the western inshore side of the nearfield was punctuated by an absence of this characteristic water in late April. At that time, a low salinity, low nutrient water mass was detected at the eastern side of the nearfield. These represent geographic trends that are expressed and indicated by nutrient-salinity plots, and the progression of changes indicated by nutrient-salinity plots examined over the sequence of winter-spring surveys. During the late spring period, there is generally a transition from a mostly horizontal shore-to-sea nutrient distribution to one that is primarily vertical (surface-to-bottom), resulting from stratification. As this transition occurs, the inshore-offshore nutrient gradients become less distinct. Moreover, they are also more episodic because they may be regulated by pulsed, tidally mediated exports from Boston Harbor.

6.2.3 Special Features: Comparison of 1994 with Previous Years

In late March and early April 1994, surface water DIN concentrations represented the seasonal low in the nutrient cycle; higher values occurred later in the spring (Figure 6-3). In April and May 1994, the concentration range for DIN was wide, as observed during 1993. Higher values were consistently associated with less saline water near the Harbor. To some extent, the concentration range in the nearfield during the late spring period is dependent on sampling times, relative to tide and winds that enhance transport of nutrients from inshore to offshore. Also, the range of DIN concentrations in Figure 6-3 depends on the depth of the thermocline/pycnocline because the annual plot has historically included data from the top 20 m. For example, in late April, the thermocline was relatively shallow and many high-nutrient samples (>4 μM) were collected between 10 and 15 m, or within the pycnocline. Regardless of the elements (real and artifactual) that induce variability in the observed DIN concentration range in the nearfield area, a clear seasonal cycle has emerged from the 1992-1993 data. The finding is common for temperate zone coastal/shelf waters: high winter nutrient concentrations, followed by rapid

depletion in winter-spring as stratification is developing, and, thereafter, continued low levels of nutrients in the surface layer.

6.3 Biology in Relation to Water Properties and Nutrient Dynamics

6.3.1 Phytoplankton-Zooplankton Relationships

Figure 6-4 indicates that there was an inverse relationship between zooplankton and phytoplankton counts. Such a trend could derive from a lag in the development of zooplankton populations, compared to development of phytoplankton populations, especially at cold temperatures typical of the winter-spring period. Thus, higher zooplankton counts in Cape Cod Bay could be the result of the earlier winter-spring bloom in that area, and cessation of that bloom could result in high zooplankton but low phytoplankton counts. The differences between samples from Cape Cod Bay and Massachusetts Bay are not the only striking feature shown in Figure 6-4, nor the only geographic trend. Another interesting aspect illustrated by this plot is that the shallow coastal and Harbor zooplankton populations appeared to be low relative to the nearfield. Zooplankton counts at the Harbor-edge station (F23P) have often been relatively low during the 1992-1994 monitoring period, but the reason for a relative impoverishment of zooplankton at station F23P is not known.

6.3.2 Chlorophyll, Phytoplankton Species, and Water Properties

In Section 3, we described a general relationship between chlorophyll and cell counts in early April. For phytoplankton counts, there was a regional difference between Cape Cod Bay and Massachusetts Bay that differed between April and earlier in 1994. In February and March, for example, the Cape Cod Bay winter-spring bloom was in full "flower," while chlorophyll and cell counts throughout Massachusetts Bay were low. By early April, Cape Cod Bay was at the end of its seasonal bloom and phytoplankton counts had become quite low, whereas phytoplankton counts in Massachusetts Bay had increased.

Chlorophyll or cell counts were higher at many locations in the nearfield than at stations along the coast or within the Harbor, and the highest chlorophyll concentrations were often detected at nearfield stations deep in the water column (Figure 6-5). It is also noteworthy that the highest discrete-sample chlorophyll concentration measured in early April (~18 μg Chl *a* L^{-1}) was found at the subsurface maximum (about 20 m) at the boundary station (F27B), which is located over a basin that lies seaward of Massachusetts Bay. This concentration approaches the maximum concentration observed in discrete or continuous (fluorescence-calibrated) samples during all of 1992 and 1993. Samples for plankton were collected at this station, but they have been archived for future analysis.

In Cape Cod Bay, Massachusetts Bay, and Boston Harbor, the phytoplankton community in early April was dominated by a diatom assemblage and by microflagellates (see Section 3). For the late spring period, phytoplankton time trends in Massachusetts Bay were analyzed for nearfield station N10P. At this station, water quality fluctuated from survey to survey and the fluctuations, in part, reflect tidal events at the time of sampling. For example, DIN fluctuated from <2 to >8 μM during the period. Regardless, the dominants for each survey suggest that normal components of a winter-spring diatom successional community were present throughout April and May (Table 6-1). Table 6-2 additionally shows that dinoflagellates were only present in very low numbers through the entire period. A few more dinoflagellate species were present in May than in April, and May also marked the appearance of a few cells of *Alexandrium tamarense*, the agent of paralytical shellfish poisoning (PSP).

How did these regional differences relate to nutrients? Where total N (TN) concentrations were high, chlorophyll concentrations were generally also high and a trend of slightly increasing chlorophyll with increasing TN was apparent (Figure 6-6). At the boundary station where the chlorophyll concentration was near 18 µg Chl *a* L^{-1}, TN was high (25 µM) and PON was unusually high (about 8 µM). Excluding the boundary station, the suggested rise in chlorophyll per unit N was low compared to some previous sampling periods and compared to annual averages; the reason for this is not clear, but the trend could relate to light limitation or the lack of chlorophyll response to variations in TN when only a small portion of the TN variability is due to biologically available forms such as DIN (cf. Kelly, 1994).

6.3.3 Primary Production and Dark Respiration

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. Kelly *et al.* (1994e) presented a comparison of depth integration schemes and recommended that the composite profile scheme, as used in this report, be the standard for 1994.

Using the standard scheme, production rates at stations F23P and N16P in early April averaged 1660 and 1534 mg C m^{-2} d^{-1}, respectively. The ranges for the two measurements at these stations overlapped. These primary production rates are substantial, but not unusual and, in fact, are typical of winter-spring bloom rates (cf. Kelly, 1994). The similarity of the integrated water column rates at the two stations is particularly interesting because the depth distribution of production was distinctly different at the two stations (Figure 6-7). The photic zone was shallower (18 m) at station F23P and volumetric production was high (about 18-38 μg C L^{-1} h^{-1}) near the surface 10 m, but declined almost exponentially with depth. In contrast, light penetration at station N16P was deeper and the photic zone averaged about 25 m. Volumetric production rates near the surface at station N16P were about 5 μg C L^{-1} h^{-1}, but increased at mid-depth where peak chlorophyll concentrations were found each day. At mid-depth, rates peaked at about 8-18 μg C L^{-1} h^{-1} before declining at the bottom of the photic zone.

Dark respiration was measured at station N20P, near station N16P, and also east of the nearfield. Rates were low, and there were no patterns with depth or geographic location. Assuming the average respiration rate for six measurements (2-6 day incubations) applied to the nearfield, respiration was consuming 0.0045 mg O_2 L^{-1} h^{-1}. Converted to carbon, assuming a respiratory quotient (RQ = CO_2/O_2 atoms) of 1.0, implies a consumption of 1-2 μg C L^{-1} h^{-1}, which is low compared to production rates (Figure 6-7). Thus, the data suggest that ^{14}C production exceeded respiration throughout the photic zone at station N16P. Because the photic zone was deep (25 m in an overall water depth of about 44 m), the data suggest that the water column as whole had net production of organic carbon at this time near the end of the winter-spring bloom and, therefore, was still functioning as an autotrophic, rather than heterotrophic, system.

6.3.4 Special Features: Comparison of 1994 with Previous Years

Temporal trends for chlorophyll in nearfield surface waters during 1993 and early 1994 are shown in Figure 6-8. Water depths to 20 m are included, a layer that reaches the depth of the subsurface maximum noted in March 1994, and includes most, but not all, of the deep chlorophyll maxima observed in the nearfield during early April 1994 (e.g., Figure 6-5). The 1994 data generally showed a peak concentration (about 4 μg L-1) in March and lower average values during April and May. However, there was a similar range in nearfield surface layer concentrations between March and May. Trends in 1994 did not resemble those observed in 1993 during the early months of the year; in 1993, a significant increase in chlorophyll concentration was not noted until mid-April. The seasonal maxima in 1994 and 1992 were earlier than in 1993 (cf. Kelly *et al.*, 1993c; Libby *et al.*, 1994).

One significant aspect of the winter-spring season in the nearfield is that it appears to lack a distinct and highly elevated level of chlorophyll for a sustained period or widespread in nature. In the area of concern in western Massachusetts Bay, it is possible that "bloom" events are patchy and sporadic, and chlorophyll peaks may not always be detected by the regular two-week-interval sampling regime. In this context, however, chlorophyll *mass* in the water column, not necessarily peak concentrations, might be a better metric to assess the state of bloom events, and the data should be explored as time series of total chlorophyll m^{-2} for the nearfield. Regardless of such worthy data manipulations, it is noteworthy that the MWRA water column monitoring program has been successful in detecting a sustained, intense, and earlier winter-spring bloom in Cape Cod Bay in each winter-spring season between 1992 and 1994, even though the sampling is less frequent and involves fewer stations in Cape Cod Bay than in the nearfield. Moreover, it is also notable that in the three years of baseline monitoring, chlorophyll concentrations in the nearfield during the winter-spring period have not attained levels or spatial coverage comparable to those occurring in early fall (e.g., Figure 6-8). Again, comparisons can be made on the basis of mass rather than concentration, but the fall bloom often may involve a greater carbon flow than the winter-spring bloom in the nearfield.

6.4 Summary and Recommendations

The interannual comparisons can emphasize the intensity and regularity of seasonal and annual events in Massachusetts Bay. As data for the entire 1994 sampling year become available and are summarized in annual reports, these interannual comparisons will be reinforced.

It has been repeatedly emphasized that, from year to year, a distinct regional difference between Massachusetts and Cape Cod Bays is consistently noted. In early April, the Bays were again "out of phase," with Cape Cod Bay nearing the end of its bloom and Massachusetts Bay still in bloom (though less intense). Primary production measurements in Massachusetts Bay confirmed that substantial net production was still occurring even though stratification and subsurface chlorophyll maximum had developed, and surface-layer nutrients were at low levels.

Finally, a comment on sampling and measurement of water column respiration. In early April, a time-series approach to measuring low respiration rates was initiated in the monitoring program. Based on an initial review of the results of the dark respiration measurements, the time-series approach to characterizing DO respiration was recommended and adopted as the approach to continue using during surveys in June, August, and October 1994.

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

	N10P Apr. 05	N10P Apr. 08	N10P Apr. 27	N10P May 22
CHAETOCEROS COMPRESSUS	0.014 (5)	0.012 (5)		
CHAETOCEROS DEBILIS	0.031 (4)	0.047 (4)	0.098 (3)	
CHAETOCEROS SOCIALIS		0.012 (5)	0.035 (5)	
CHAETOCEROS SPP.(<10UM)	0.061 (3)	0.266 (1)	0.068 (4)	
CRYPTOMONADS			0.102 (2)	0.229 (1)
MICROFLAGELLATES	0.180 (1)	0.122 (2)	0.137 (1)	0.223 (2)
SKELETONEMA COSTATUM				0.193 (3)
THALASSIOSIRA (CF) CONSTRICTA	0.014 (5)			
THALASSIOSIRA (cf) GRAVIDA/ROTULA	0.118 (2)	0.088 (3)		0.099 (4)
THALASSIOSIRA SPP.				0.008 (5)

Units are millions of cells/L and rankings are given in parentheses.

Table 6-2. Abundance of all identified phytoplankton taxa in near-surface screened (20um) station N10P collected in April and May 1994.

STATION SAMPLE ID DATE	N10P W94040197 Apr. 05	N10P W94040530 Apr. 08	N10P W94050028 Apr. 27	N10P W94060041 May. 22
ALEXANDRIUM TAMARENSE	0	0	0	3
ALORICATE CILIATES	5	18	30	60
AMPHIDINIUM SPP.	0	0	0	0
CERATIUM FUSUS	0	0	0	0
CERATIUM LINEATUM	0	0	0	5
CERATIUM LONGIPES	0	0	0	25
DICTYOCHA FIBULA	0	0	0	0
DICTYOCHA SPECULUM	0	0	0	13
DINOPHYSIS ACUMINATA	0	0	0	0
DINOPHYSIS NORVEGICA	5	0	3	20
DINOPHYSIS SPP.	0	0	5	13
EUTREPTIA/EUTREPTIELLA SPP.	0	0	0	3
GYMNODINIUM SPP.	0	3	0	0
GYRODINIUM SPIRALE	8	5	5	0
GYRODINIUM SPP.	0	0	0	0
HETEROCAPSA TRIQUETRA	0	0	0	3
MESODINIUM RUBRUM	0	3	18	0
PEDIASTRUM SPP. COLONY	0	0	0	0
PROTOPERIDINIUM BIPES	0	0	0	0
PROTOPERIDINIUM BREVE	0	8	0	5
PROTOPERIDINIUM DENTICULATUM	3	0	0	0
PROTOPERIDINIUM DEPRESSUM	0	0	0	3
PROTOPERIDINIUM PALLIDUM	5	0	0	0
PROTOPERIDINIUM SPP.	23	63	30	38
SCENEDESMUS SPP.	0	0	0	0
SCRIPPSIELLA TROCHOIDEA	0	0	0	0
TINTINNIDS	15	40	48	70
UNID. ATHECATE DINOFLAGELLATE	3	5	0	0
UNID. THECATE DINOFLAGELLATES	0	0	0	0

Values are in Cells/L.

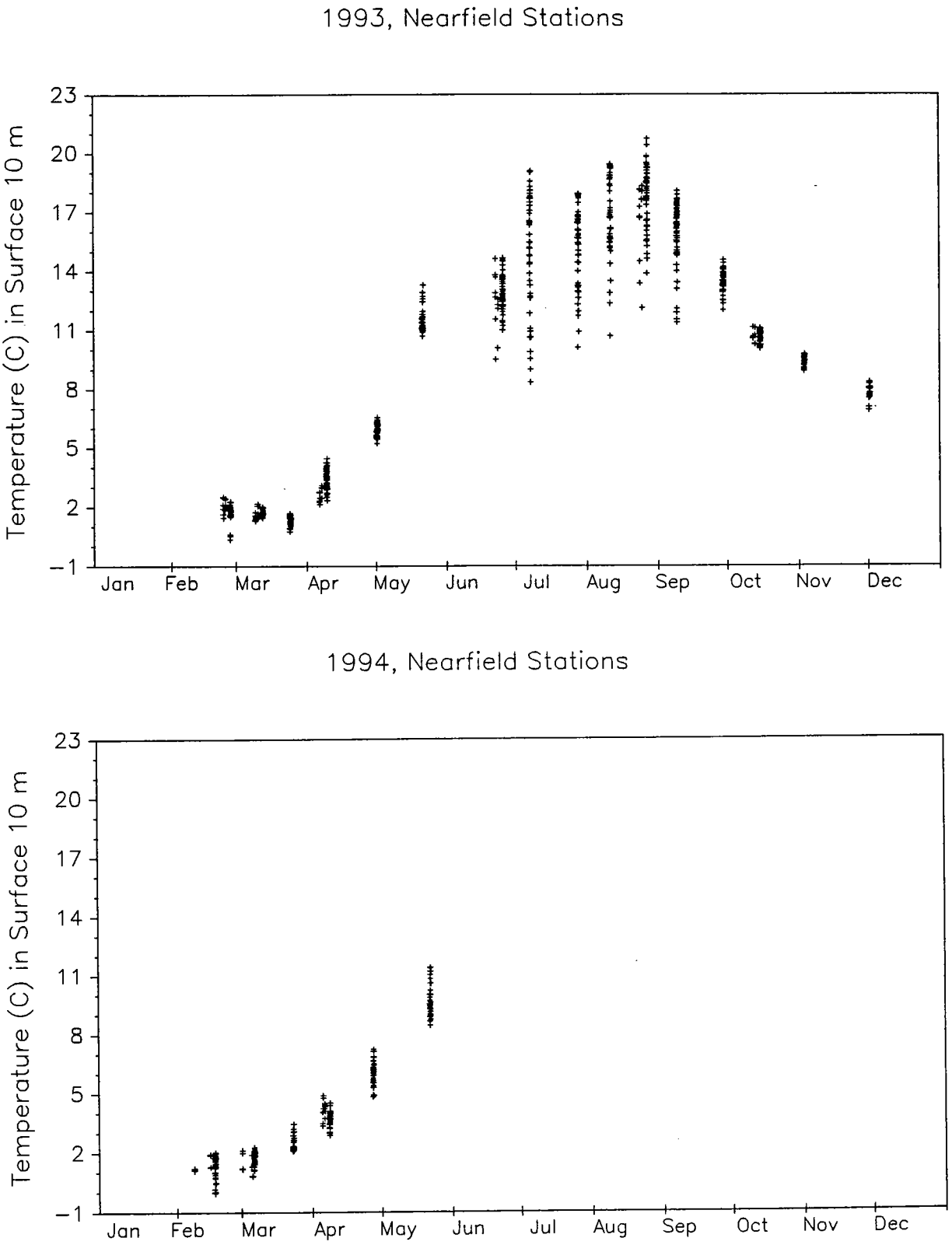


Figure 6-1. Comparison of the nearfield region in 1994 to the annual cycle of 1993: temperature (°C).

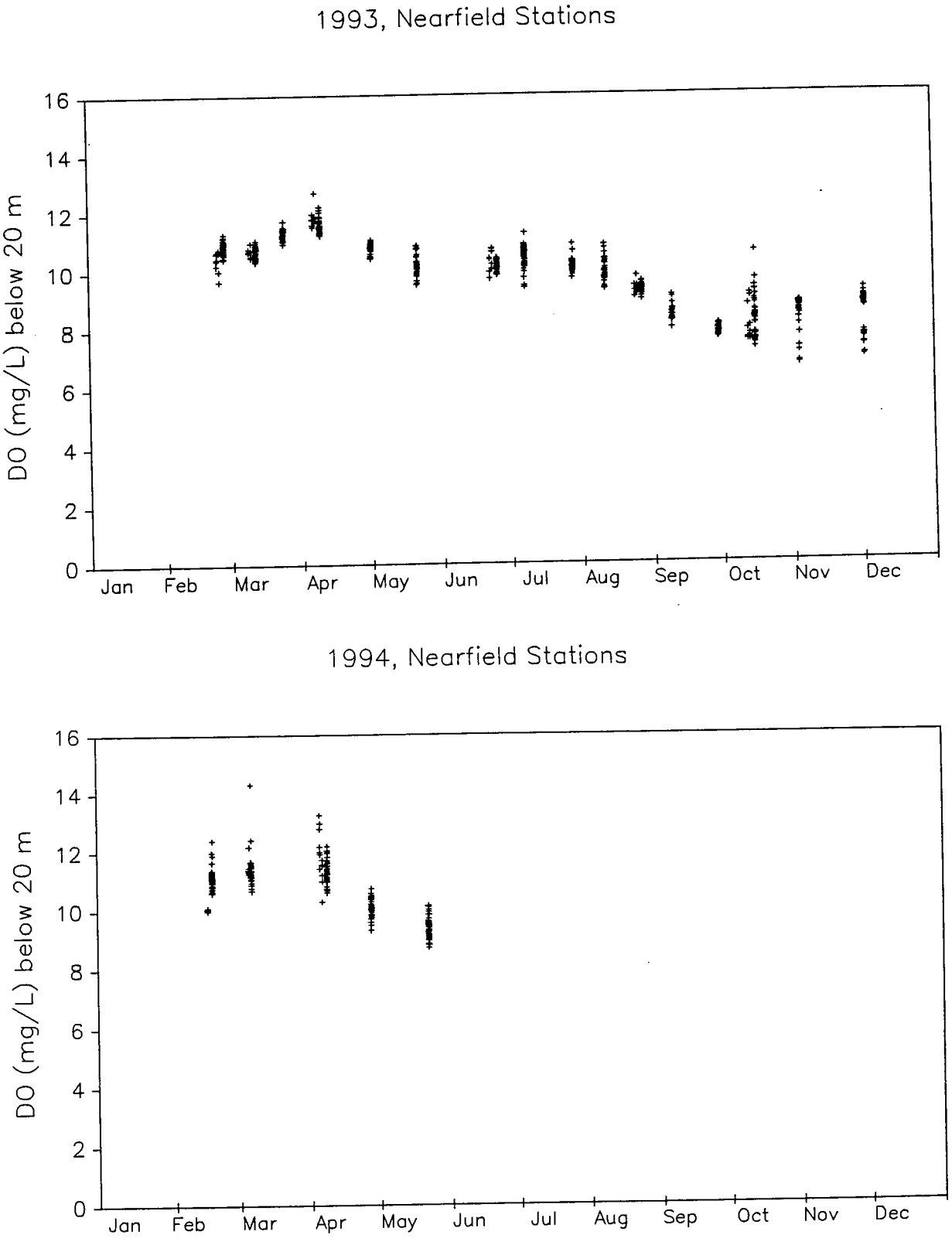


Figure 6-2. **Comparison of the nearfield region in 1994 to the annual cycle of 1993: dissolved oxygen (mg L^{-1}).**

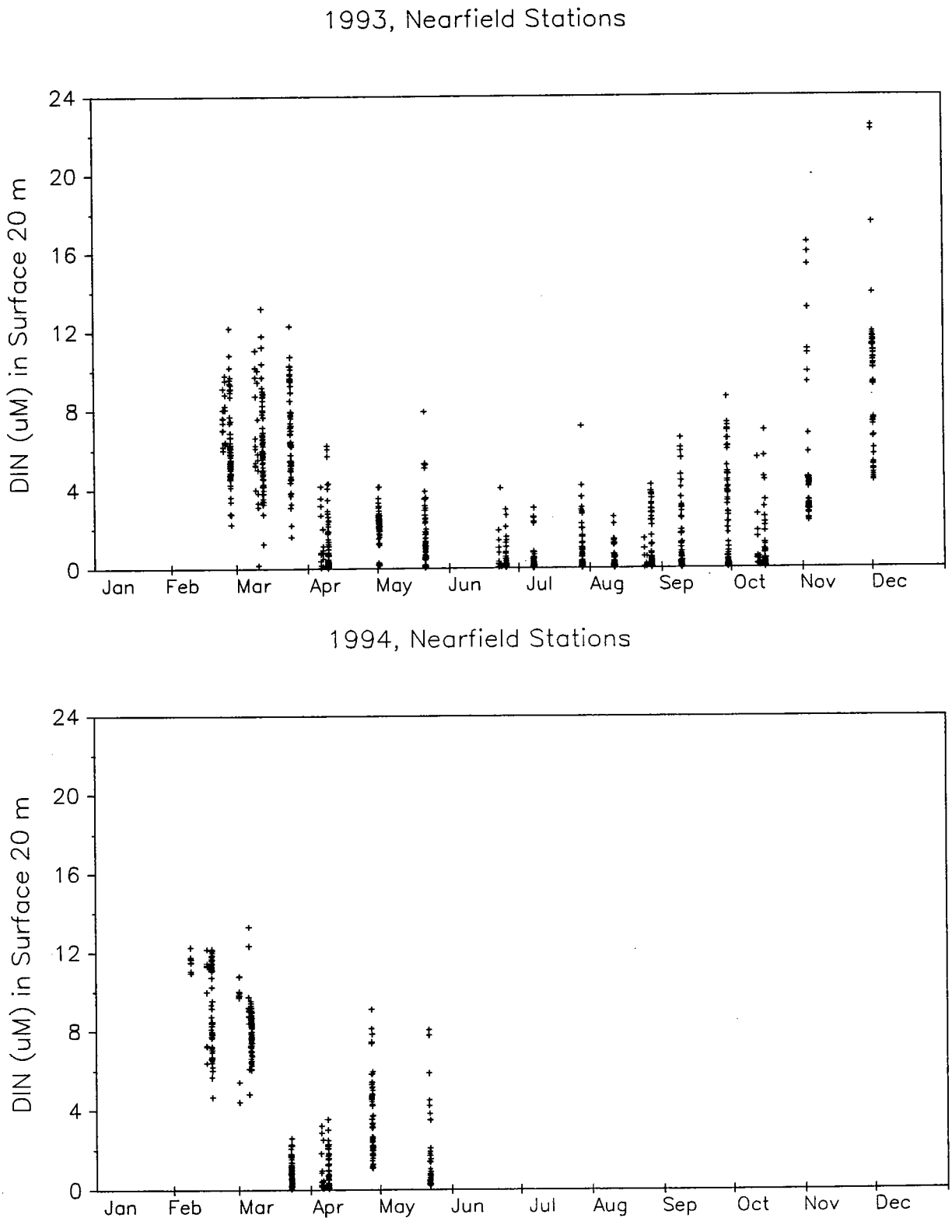


Figure 6-3. **Comparison of the nearfield region in 1994 to the annual cycle of 1993: dissolved inorganic nitrogen (μM).**

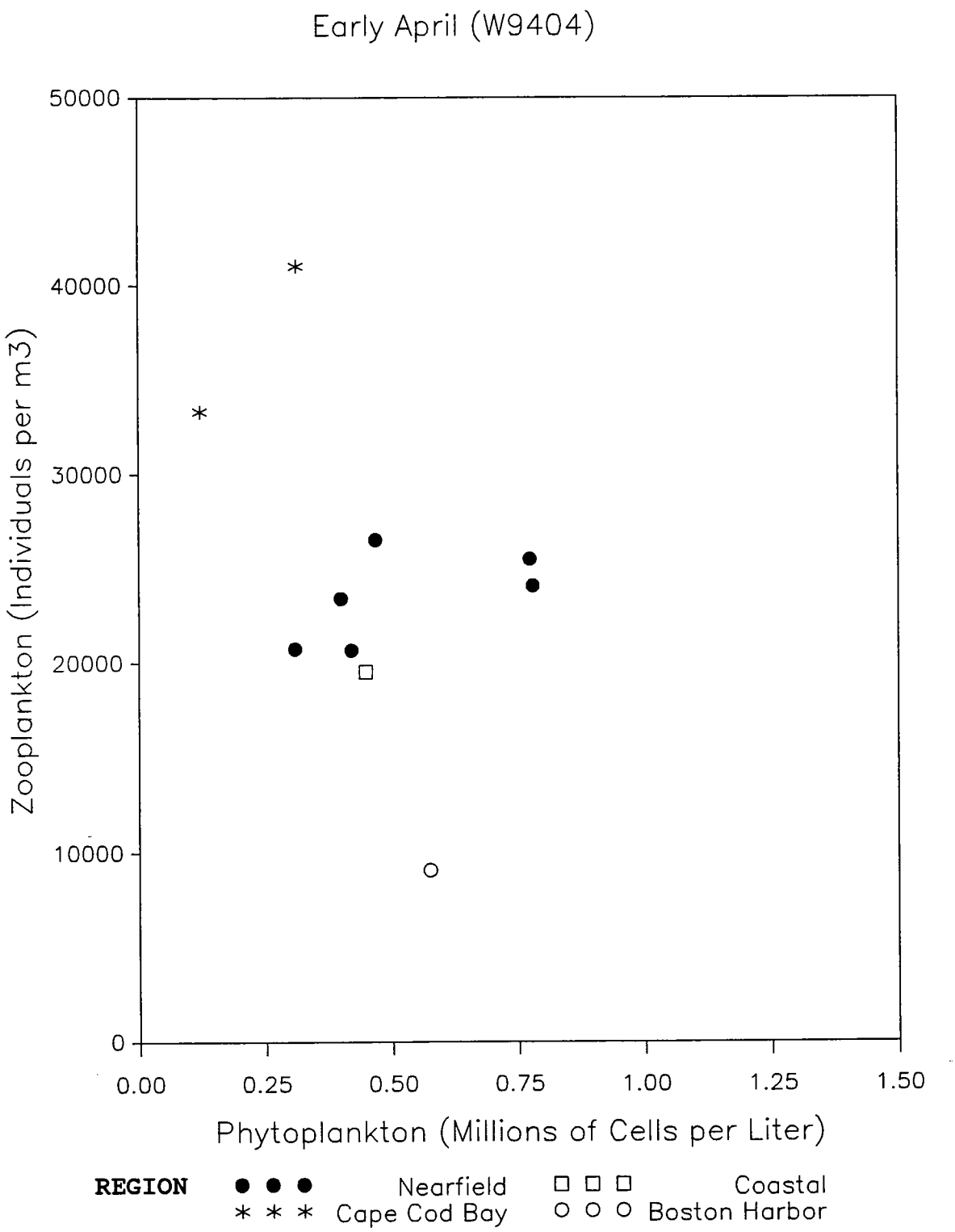


Figure 6-4. Zooplankton abundance vs. phytoplankton abundance for early April 1994.

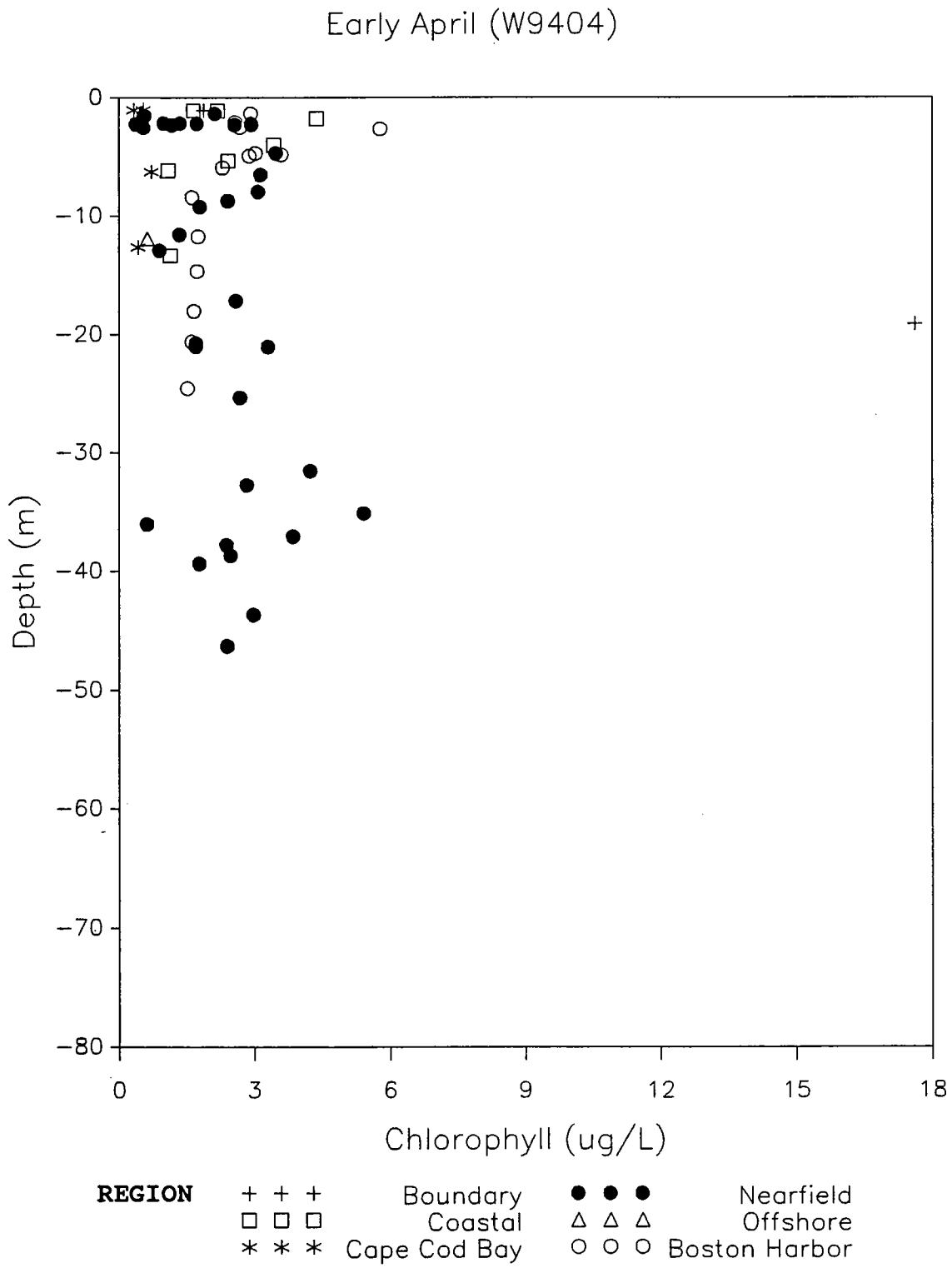


Figure 6-5. Chlorophyll (extracted) vs. depth for the study area in early April 1994.

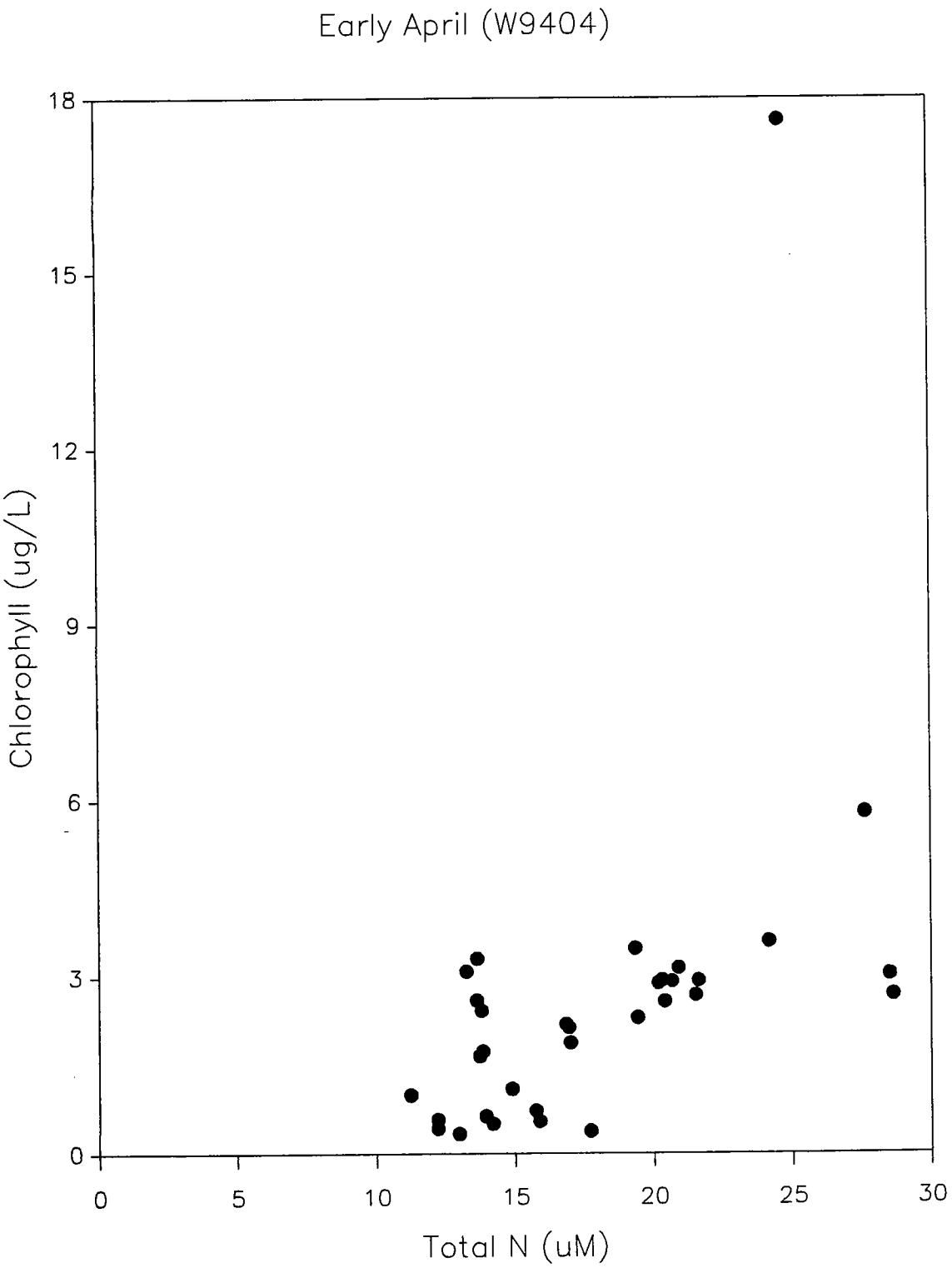


Figure 6-6. **Chlorophyll (extracted) vs. total nitrogen concentrations for the study area in early April 1994.**

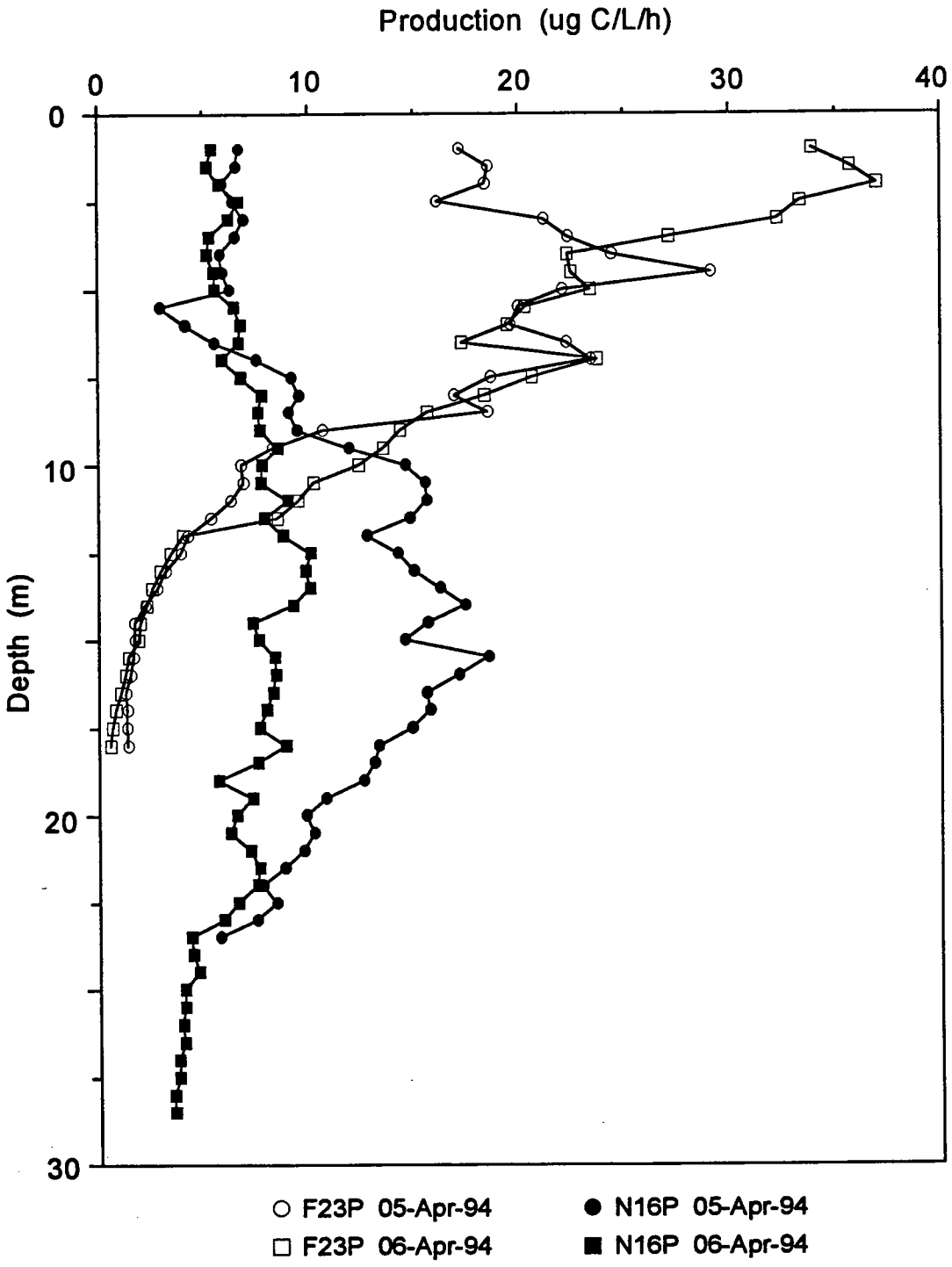


Figure 6-7. ^{14}C **production vs. depth at Bioproductivity stations F23P and N16P in early April 1994.**

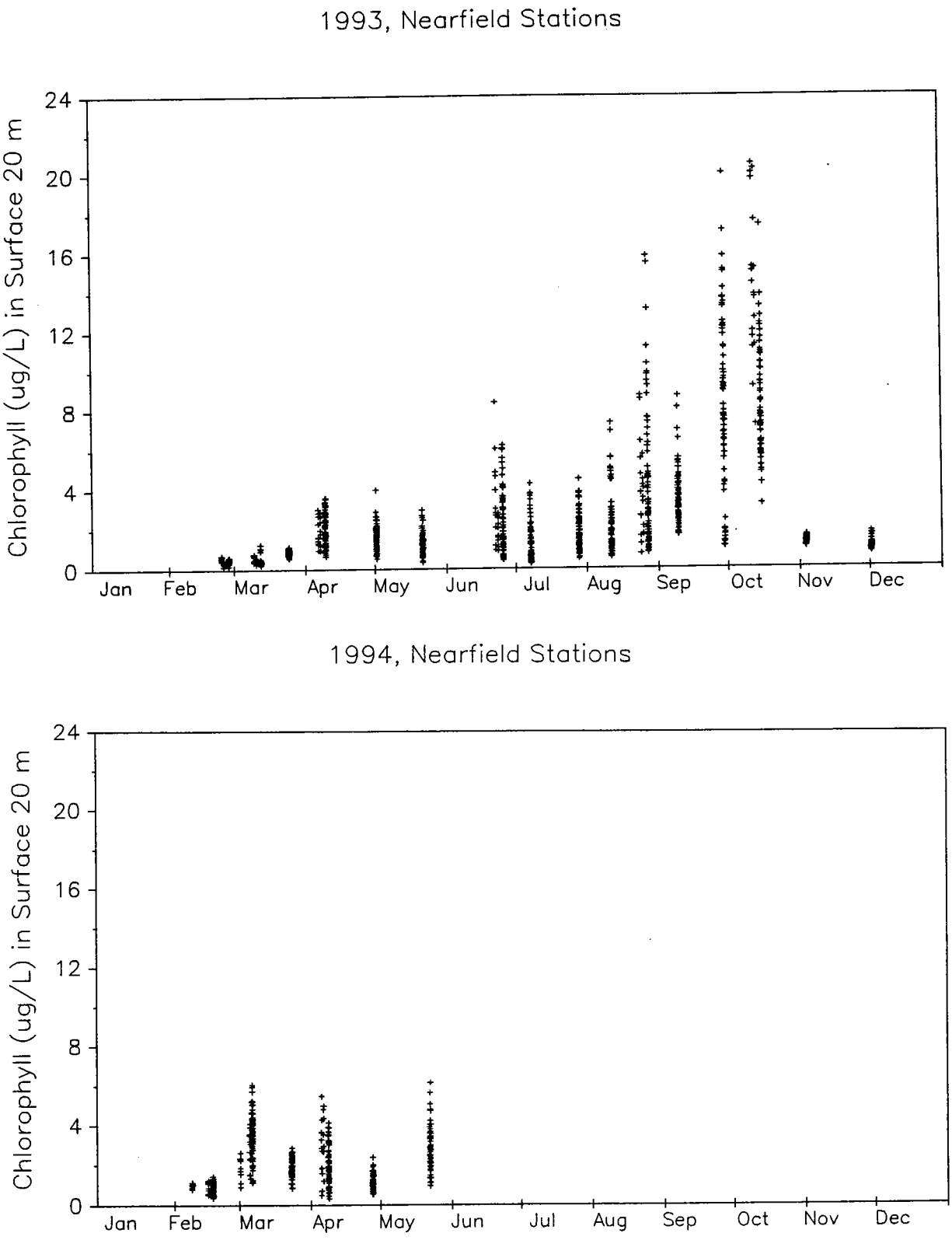


Figure 6-8. **Comparison of the nearfield region in 1993 to the annual cycle of 1994: chlorophyll ($\mu g\ L^{-1}$) as estimated from *in situ* fluorescence.**

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