High-resolution mapping studies of water quality in Boston Harbor and Massachusetts Bay during 1994

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High-Resolution Mapping Studies of Water Quality in Boston Harbor and Massachusetts Bay During 1994

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EXECUTIVE SUMMARY

During water quality monitoring surveys for the Massachusetts Water Resources Authority (MWRA) in 1994, a variety of intensive, high-resolution mapping studies were carried out. Twelve high-resolution surveys were conducted in February, March, April, June, July, August, September, and October 1994. High-resolution maps were developed from data collected by a suite of *in situ* sensors housed in a towfish that sampled continuously as it oscillated from near-surface to near-bottom at vessel speeds from ~4-7 kts.

A primary objective was to characterize the tidally-mediated interaction between Boston Harbor and adjacent western Massachusetts Bay, a region that will experience the largest water quality change when MWRA effluent is diverted to the Bay. Studies related to the interaction examined both major hydrological connections between the Harbor and the Bay, the northern one being President Roads off Deer Island and the southern one being Nantasket Roads off Hull. One survey in June used a series of six repeated tracks through President Roads to capture a entire 12 h tidal cycle; this exercise included an Acoustic Doppler Current Profiler (ADCP) with the suite of sensors and allowed comparison of water quality patterns with dynamical data. A secondary objective was to characterize variability in water quality conditions more broadly across Massachusetts Bay. Surveys in April (near spring runoff) and October (at fall destratification of the inshore water column) were conducted along a long triangle loop track running from western Massachusetts Bay northeasterly to Cape Ann, south across a deepwater basin outside the Bay, and then returning west across Stellwagen Bank and Basin almost to Boston Harbor. Specific results of the set of surveys conducted in 1994 are summarized below.

BAYWIDE

Surveys efficiently characterized a broad area and the data depicted both fine-scale and meso-scale structure across different regions of the Bay. Such broad surveys allow one to view local conditions (e.g., western Massachusetts Bay) in the context of their broader environmental setting.

The data for April provided water-quality diagnostics to distinguish water masses at the northern boundary of Massachusetts Bay. The data at this time strongly indicated that a portion of early spring coastal runoff advecting from the north of Massachusetts Bay did not enter the Bay, but skirted it east of Stellwagen Bank. South of Cape Ann within the Bay, the data showed some surface-water inflow to the Bay. The inflow was not continuous, but sporadic, and the fresher pools of surface water were depleted in chlorophyll relative to surrounding resident Bay water. The data suggest a strong degree of coupling in space and time between physical processes and plankton distributions, and could be further explored to examine this coupling.

The data for October demonstrated that variability in physical structure was a function of water depth. Inshore waters and the water column over Stellwagen Bank were vertically well-mixed. In waters deeper than about 25 m, there was a horizontal continuity of density stratification. The majority of the Bay was similarly layered — a lingering result of seasonal warming.

Concomitant with the vertical layering, a general depression of DO was observed in bottom waters during this fall period when, historically, annual bottom-water DO minimum have been observed. The 1994 DO minimum noted in most of the surveyed region of the Bay in mid-October 1994 was well below the state standard of 6.0 mg L^{-1}.

HARBOR—BAY INTERACTION

The surveys at different seasons covering all stages of the tidal cycle provided unprecedented characterization of waters in the region connecting the Harbor and the Bay. Data provide vivid graphical images depicting tidal fronts and areas of chlorophyll stimulation in the region of Harbor-Bay mixing. Specific surveys provided excellent "snapshots" of local conditions, and each survey could be examined in greater detail than attempted here. However, the principal and strong conclusion of our study was that the nature of the tidally-mediated interaction between the Harbor and the Bay varies seasonally.

Generalized conceptual models are presented to illustrate the seasonal variability in the Harbor's coupling with the Bay. The coupling is demonstrably influenced by variability in physical structure as well as differences in seasonal cycles of phytoplankton in inshore vs. offshore waters. During some periods the Harbor appears to import chlorophyll from the Bay and during other periods it exports chlorophyll to the Bay.

Our conceptual models were derived from changes in water properties at different stages of the tide and the inferred dynamics are founded on static data, even if the data are highly resolved in space. However, the concepts are generally consistent with dynamic information collected during a special velocity study in June 1994. Accordingly, the proposed hypotheses on seasonal exchange dynamics provide reasonable first-order paradigms and strengthen our fundamental conclusion of a seasonally variation in the physically-mediated coupling of Harbor and Bay ecology and biogeochemical cycles.

Another conclusion from our analyses is that different vertical layers of the Bay freely communicate with the Harbor at different seasons. For example, during summer stratification of the Bay, the pycnocline is a primary conduit for Harbor-Bay communication. A number of summer surveys, and the special velocity study in June, demonstrated a tidally- and bathymetrically-induced upwelling of water from within the pycnocline to the surface in the shallow western Bay region fringing the Harbor. Velocity measurements in June showed that the flood tide was initiated at depth, with a time lag in flow at the surface. There was also evidence for a weak estuarine circulation, with net outflow at the surface and net inflow near the bottom bathymetry. Calculations documented an internal tide that was likely induced by the abrupt bathymetric variation in western Massachusetts Bay near the Harbor entrance. The internal tide may be an important source of energy for vertical shears and it provides a physical mechanism for the observed upwelling near the channel leading into Boston Harbor from the Bay. These findings indicate some detailed features that need to be considered further in efforts to predict the ecological consequences of relocating the present MWRA effluent discharge to Massachusetts Bay.

Finally, an analyses was conducted to examine the potential export of chlorophyll from the Harbor and stimulation of chlorophyll growth in the Bay during summer conditions when the Harbor is generally enriched in chlorophyll relative to the Bay. Chlorophyll dispersion from the Harbor seems to occur by mixing and advection within a defined tidal mixing region that extends several kilometers into western Massachusetts Bay. Additionally, our analysis provided strong evidence that *in situ* chlorophyll stimulation and active growth occurred during the day at the seaward edge of the tidal excursion.

TABLE OF CONTENTS

List of Tables

List of Figures

List of Figures (Continued)

List of Figures (Continued)

List of Figures (Continued)

List of Figures (Continued)

Chapter 1 INTRODUCTION

Many studies of western Massachusetts Bay have depicted a continuum of changes in water quality from the shallow confines of Boston Harbor to the deeper waters in Massachusetts Bay (e.g, Pandan, 1977; Townsend *et al.*, 1991; Kelly, 1991, 1993). Trends observed regularly from the Harbor into the Bay include sharp decreases in concentrations of turbidity, chlorophyll, nutrients, as well as in salinity and temperature. Among other things these trends reflect that the Harbor is the strongest point source of nutrients into the Bay and is a weak source of freshwater. Gradients often extend 10-30 kilometers from shore before Bay "background" conditions are encountered. Moreover, a change in physical structure of the water is notable over this distance, changing from generally well-mixed conditions in the Harbor to density stratified conditions within the Bay.

Kelly (1991) focused attention on the Harbor as an inefficient sink for nutrients that are added by effluent discharges of the Massachusetts Water Resources Authority (MWRA). Subsequent studies have supported the notion that most of the input of nitrogen to the Harbor is exported to the Bay (e.g., Adams *et al.*, 1992; Giblin *et al.*, 1993; Kelly and Nowicki, 1993; Kelly, 1993). Almost concurrently, efforts of Signell and co-workers have been especially effective in elucidating many of the fundamental scales and physical mechanisms of Harbor-Bay exchanges and tidal interactions (e.g., Signell and Butman, 1992). Physical and water quality modeling studies have contributed to understanding of Harbor—Bay dynamics, generally supporting the notion of strong Harbor nutrient export. Such studies have also predicted some of the potential water quality effects of changes in effluent disposal practices (Signell *et al.*, 1995; HydroQual, 1995).

The Harbor—Bay gradient is one of the most striking features consistently apparent from the vast array of water quality monitoring conducted for MWRA in the past few years (cf. Kelly, 1993; Kelly and Turner, 1995a,b). Because high nutrient export supports the observed concentration gradient from shore and because conditions along this gradient will change markedly in the future when MWRA diverts effluent directly to a point about 15 km into the Bay, this region is of special interest. With effluent diversion, future changes in water quality should be pronounced as the Harbor "recovers" from present levels of inputs and the Bay "responds" to the new location for the major point source of nutrients to its western region.

In 1994 Battelle Ocean Sciences conducted for the MWRA a variety of intensive, high-resolution mapping studies to document conditions in the region from the Harbor to the point in the Bay where effluent will be discharged in the future. Surveys were conducted in February, March, April, June, July, August, September, and October of 1994. High-resolution maps were developed from data collected by a suite of *in situ* sensors housed in a towfish that sampled continuously as it oscillated from near-surface to near-bottom at vessel speeds from 4-7 kts.

A primary objective was to characterize the tidally-mediated interaction between Boston Harbor and adjacent western Massachusetts Bay. Studies related to this interaction examined both major hydrological connections between the Harbor and the Bay, the northern one being President

Roads off Deer Island and the southern on being Nantasket Roads off Hull. The 1994 studies provide fine-scale characterization of conditions in the region of expected future change and thus serve as a baseline against which to judge future change; moreover, these studies compliment ongoing predictive modeling efforts and elucidate important features or scales to be considered in predictive modeling.

A secondary objective during 1994 studies was to set the Harbor—Bay region in the broader context of conditions across Massachusetts Bay. Broad-scale surveys were conducted in April (near spring runoff) and October (at fall destratification of the inshore water column). For these, the survey was conducted along a long triangle loop track running from western Massachusetts Bay northeasterly to Cape Ann, south across a deepwater basin outside the Bay, and then returning west across Stellwagen Bank and Basin almost to Boston Harbor.

Chapter 2 METHODS

2.1 Surveys

In 1994, a total of 12 mapping surveys were conducted. Each survey was completed in one day and was done in conjunction with the standard water quality monitoring performed at fixed stations of the MWRA water quality monitoring program. Results of standard surveys have been reported in a series of periodic reports for 1994 and summarized in an annual report for 1994 (see Kelly and Turner, 1995b). Tables 2-1 and 2-2 give dates and general survey tracks for Harbor-Bay and Baywide surveys, respectively. The general tracklines for the nine Harbor-Bay and two Baywide surveys are given in Figure 2.1-1. For most of the Harbor-Bay studies, a survey consisted of data collection along two tracks, running either from the northern Harbor or southern Harbor. The seaward terminus of each transect was near station N16P, within the "Nearfield" region of the regular water column monitoring (Albro *et al.*, 1993; Kelly and Turner, 1995a, b). Station N16P is near the eastern terminus of the MWRA diffuser track which will, in the future, discharge wastewater effluent, as part of the court-mandated clean-up of Boston Harbor. Each of the two tracks generally was completed twice on a survey, with both the northern and southern transects sampled near high and low tide. Completion of one of the four "legs" of such a survey took about 2 h or more.

2.2 High-Resolution Survey Instrumentation and Technique

Over the past several years, Battelle Ocean Sciences has developed and used an instrument system that collects high-resolution data on *in situ* water quality in coastal environments. The Battelle Ocean Sampling System (BOSS) is a data acquisition system that combines position information with *in situ* sensor data. The system is modular, may be configured as a towfish housing with a multiple sensor array, as used in this study. BOSS towfish studies in Boston Harbor and western Massachusetts Bay have been conducted for the MWRA (e.g., McDowell *et al.*, 1991; Albro *et al.*, 1993; Kelly and Albro, 1994). Compared to tradition hydrocasts at stations separated by kilometers, the BOSS towfish sampling is efficient and provides higher (continuous) resolution that allows understanding on horizontal and vertical structure of the water column.

Methodological specifications and details on the instruments and procedures used for profiling water quality through the water column are provided in the water quality monitoring Combined Work/Quality Assurance Project Plan (CW/QAPP, Albro *et al.*, 1993). Methods are described only briefly below. High-resolution surveys in 1994 were conducted using these same procedures during 1992 and 1993, but those previous surveys were conducted exclusively in box-shaped tracks surrounding the location of the future MWRA offshore effluent diffuser. The previous studies had focused on characterization of the Nearfield sampling region, a roughly 10 X 10 km region (Figure 2.1-1). Results of previous high-resolution studies were included in periodic water quality monitoring reports for 1992 and 1993 sampling years; the interested reader can contact the MWRA for relevant reports.

For 1994 studies, the BOSS towfish was operated with a CTD sensor to make determinations of conductivity, temperature, and density; a beam transmissometer to determine light attenuation and estimate turbidity; a fluorometer to measure *in situ* fluorescence and indicate phytoplankton activity/biomass; and a DO sensor for dissolved oxygen. As the ship proceeded along the transect, the towfish continuously was oscillated in a V-shaped pattern from near-surface to near-bottom, completing a down-up cycle every 500 m. Because of the up-down pattern while being towed, this is termed a "tow-yo" survey. In the area of interest, the bottom bathymetry is highly variable and the towfish oscillation for the towfish must be performed with care to avoid landing the instrument. The depth of the towfish is indicated in real-time to the operator of the BOSS by a pressure sensor on the towfish and the bottom depth is simultaneously indicated by a dual-beam depthsounder fixed to the ship.

In June 1994, a special study was conducted (Table 2-1). High-resolution profiling was performed along the northern transect only, through President Roads and out a shipping channel into the Bay (Figure 2.2-1). This single track was repeated 6 times during a 12-h tidal cycle. An impetus for this effort was to characterize changes in water quality during tidal exchange of Harbor and Bay waters, and if possible use information on velocity to further understand the physical processes which shape water-quality changes during tidal mixing and dispersion. In addition to BOSS instrumentation an Acoustic Doppler current profiler (ADCP) was used on this survey to measure currents in this region (cf. Geyer and Signell, 1990; Geyer *et al.*, 1992; Signell and Butman, 1992). Details on methods related to the ADCP and associated study results are provided in a section of Chapter 5 contributed by W.R. Geyer.

2.3 Data Processing and Analyses

In this report we discuss results of all surveys except W9401, conducted in February 1994. This survey was a preliminary effort and differed in its design from the remainder of the studies. Moreover, water quality distinctions were not highly notable at this time (see Kelly *et al.* 1994a). The data for W9401, however, as for all the other 1994 surveys, has been compiled and conveyed into the MWRA Harbor and Outfall Monitoring Program database. Water-quality data from the BOSS sensors were averaged every 2 sec, with each data point being tied to a location in space (latitude, longitude, depth). Figure 2.3-1 displays a typical distribution of sampling points; sampling typically was performed to with 2-3 meters of the air-sea surface and within 5 m of the bottom bathymetry in western Massachusetts Bay.

For Harbor—Bay surveys, we generated contoured section plots for each leg of a survey, where a leg was defined as an east-west transect completed either from the Harbor to the Nearfield or vice versa. For visual display in this report and Appendix, the 2-sec-averaged sensor data along the V-shaped track of the towfish were then contoured (Surfer, 1994) as a vertical "slice" to display the water property profiles along the transect. Contoured sections were prepared for five parameters: temperature (T), salinity (S), density (σ_T), beam attenuation, and chlorophyll. Figures for parameters not discussed in the this text report are provided in the Appendix.

Table 2-1. Harbor—Bay High-Resolution Characterization Surveys in 1994.

SURVEY	DATE	TRACK
W9401	February 18	Repeated loop from Harbor to Bay, searching for Harbor outflow signature
W9402	March 7	Dual repeated Harbor—Bay transects, north and south channels of communication
W9403	March 22	Dual repeated Harbor—Bay transects, north and south channels of communication
W9404	April 9	Dual repeated Harbor—Bay transects, north and south channels of communication
W9405	April 28	Dual repeated Harbor—Bay transects, north and south channels of communication
W9407	June 25	Repeated north Harbor—Bay transect six times through a tidal cycle from low to low
W9409	July 28	Dual repeated Harbor—Bay transects, north and south channels of communication
W9411	Aug 22	Dual repeated Harbor—Bay transects, north and south channels of communication
W9412	September 12	Dual repeated Harbor—Bay transects, north and south channels of communication
W9413	September 29	Dual repeated Harbor—Bay transects, north and south channels of communication

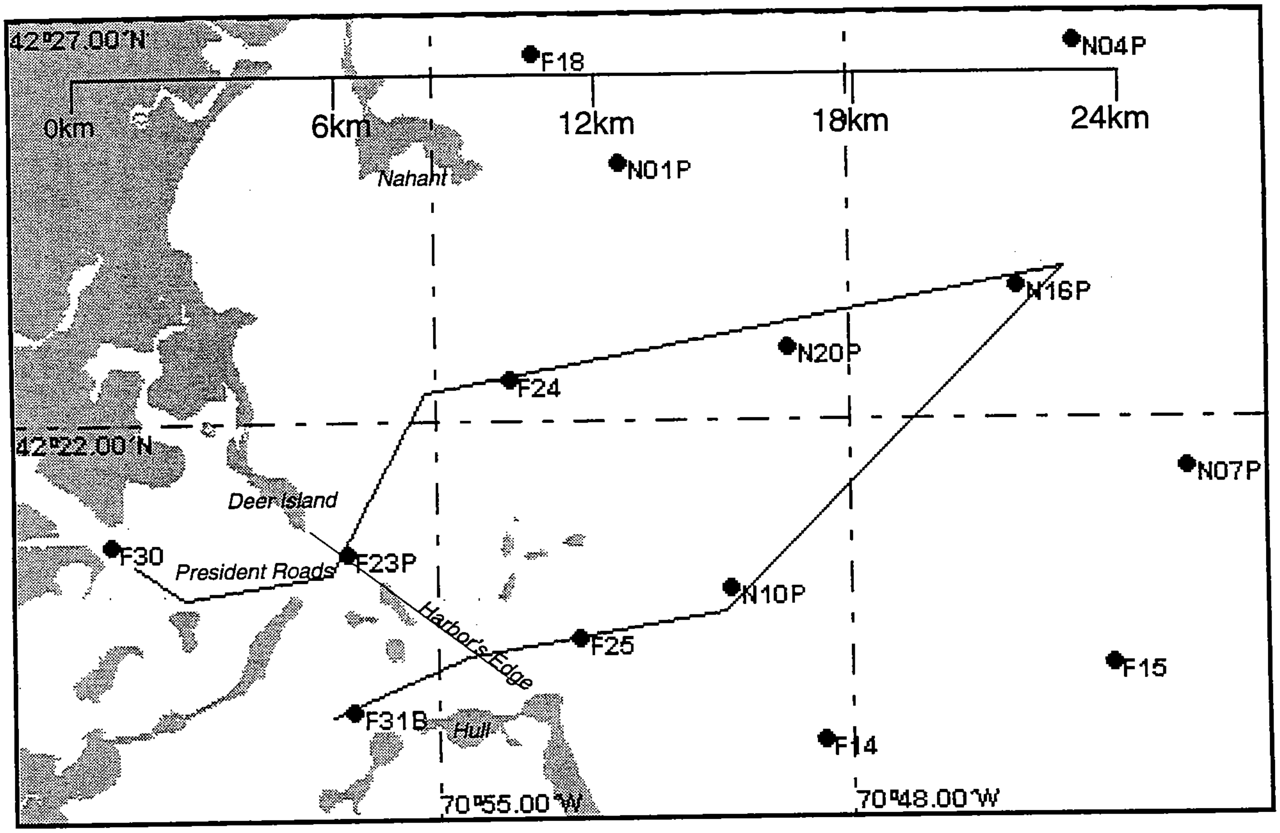
Table 2-2. Baywide High-Resolution Characterization Surveys in 1994.

SURVEY	DATE	TRACK
W9404	April 10	Nearfield—Cape Ann—Stellwagen Bank—Nearfield
W9414	October 15	Nearfield—Cape Ann—Stellwagen Bank—Nearfield

2.4 Terminology

The Chelsea *in situ* fluorometer in the BOSS sensor package measures fluorescence. We calibrated fluorescence readings to measured chlorophyll *a* concentrations, survey-by-survey (e.g. Albro *et al.* 1993). Specifics are presented in the Appendices to each of the five 1994 Water Quality Periodic Reports (consult Kelly and Turner, 1995b), which are available from the MWRA. The calibration, to a degree, imperfectly estimates chlorophyll *a* in individual samples. Nevertheless it provides a useful synoptic indicator and, for convenience, we use the term chlorophyll rather than "fluorescence, as calibrated to chlorophyll *a* concentrations" throughout this report.

Beam attenuation was measured with a SeaTech *in situ* transmissometer, which uses attenuation of a red-beam wavelength sensitive to attenuation by particles. Beam attenuation is an indicator of turbidity and may relate to suspended particulate matter (SPM) concentration; higher values of attenuation are associated with higher turbidity or SPM. For convenience in this report, we often use the term turbidity rather than beam attenuation to refer to transmissometer readings having units of m^{-1}.



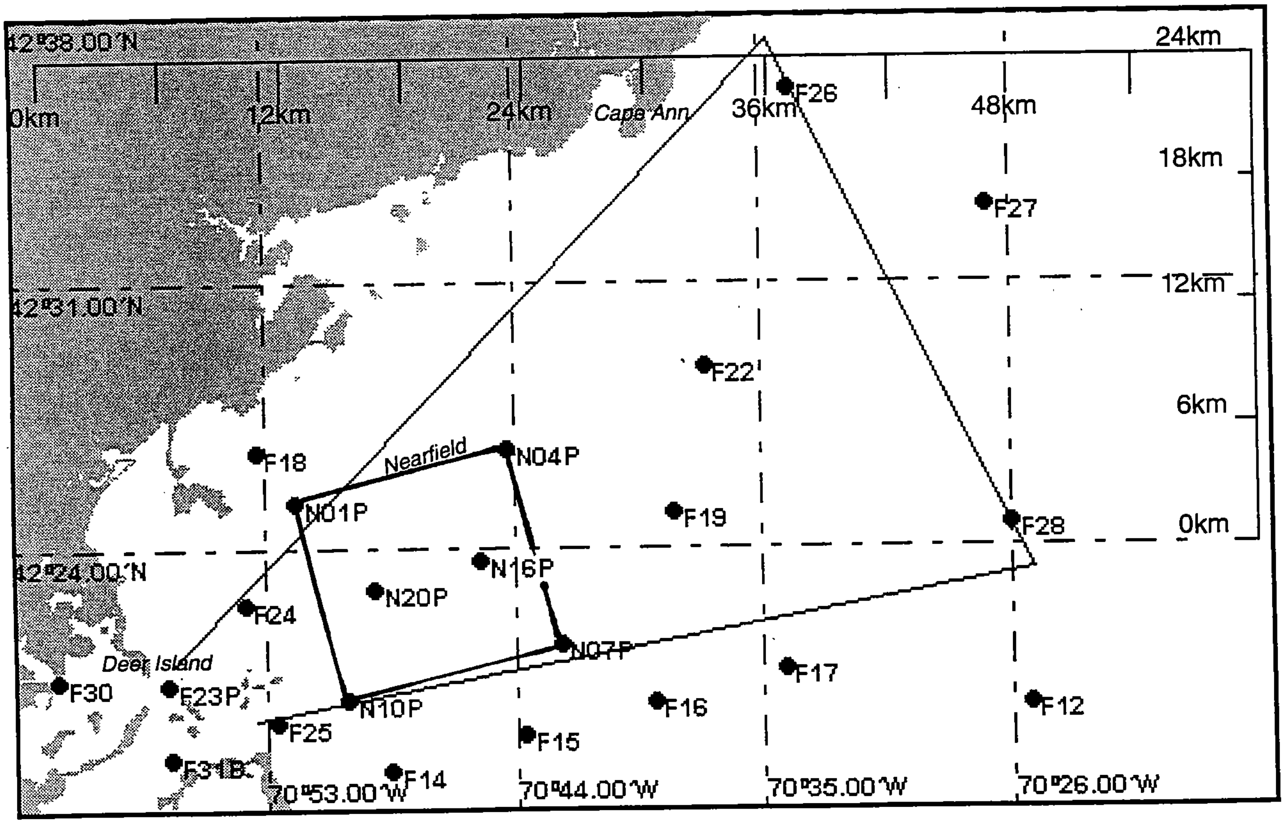


Figure 2.1-1. **Survey tracklines for Harbor-Bay dual, repeated tracks (top) and Baywide surveys (bottom). Stations of standard MWRA water column monitoring program are shown for reference.**

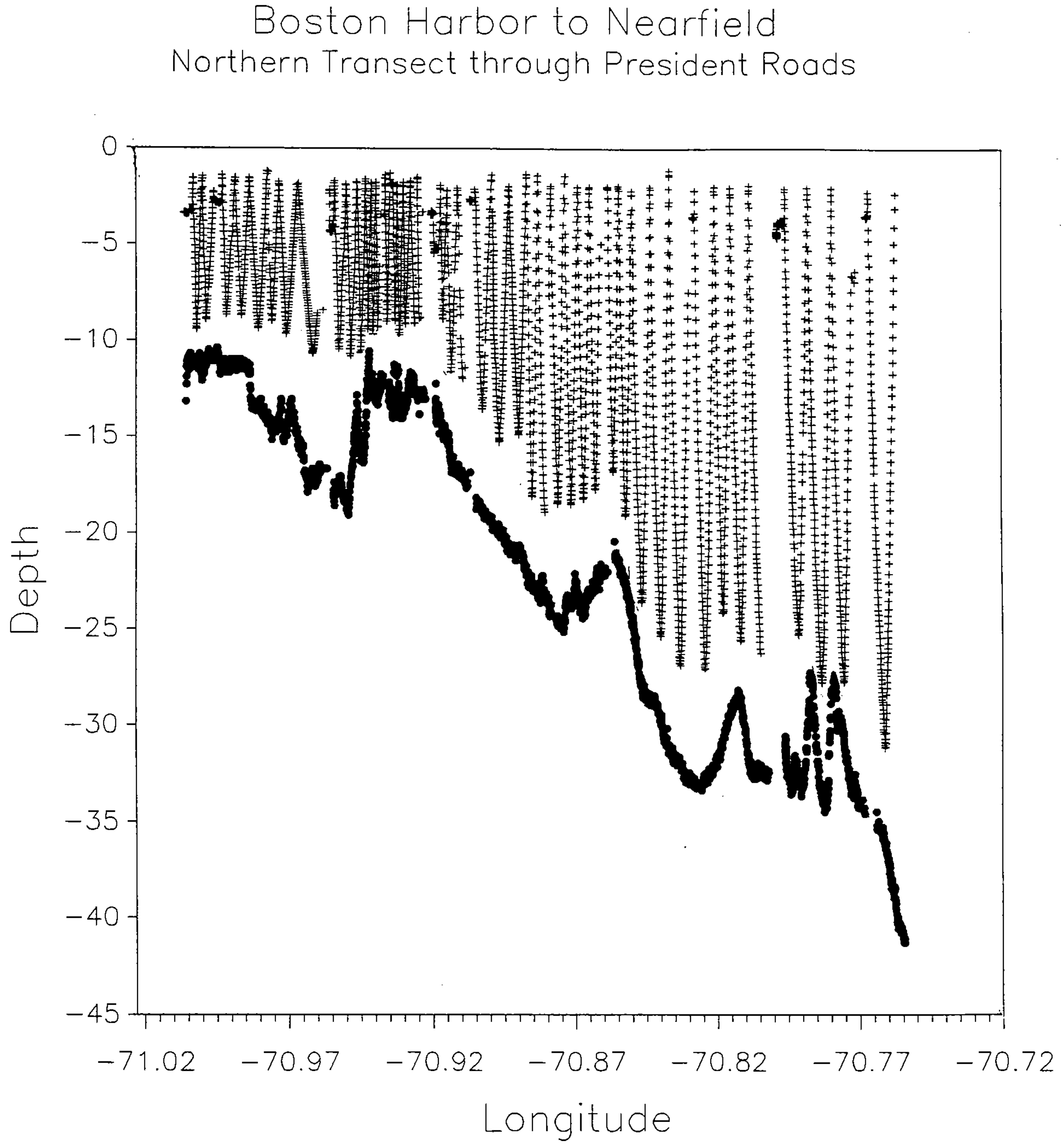


Figure 2.3-1. **Example of data collected on a "tow-yo" survey track. Actual bottom topography is shown along with 2-sec-averaged data points (+) throughout the water column. V-path of towfish is suggested.**

Chapter 3 DESCRIPTIVE RESULTS BY SURVEY

Our focus is on presentation of tidal and seasonal dynamics as depicted in the data. The descriptions below are not intended to be exhaustive, but to serve as examples of the kinds of features that can be documented and examined with the high-resolution data.

3.1 Harbor—Bay Transects

An example trackline for the dual repeated tracklines in and out of the Harbor was given in Figure 2.1-1. A day's towing typically covered more than 80 km. Contoured sections are presented by parameter (see Figure 3.1-1). For this style of graphic note that trackline legs 1-4 are indicated as headers on each panel; legs 1 and 3 cover the northern transect (towed from the Harbor to the Bay) and legs 2 and 4 cover the southern transect (towed from the Bay to the Harbor). Fixed monitoring station positions along the trackline are also indicated and these may be referenced to the trackline in Figure 2.1-1. Contours have been prepared and are displayed relative to a linear coordinate system running essentially along a line of latitude; note that distances along sections are referenced to distances as shown in Figure 2.1-1. The linear coordinate system is a simplification which "flattens" the bends in the actual track such as those at Harbor entry/exit (e.g., through the shipping channel between stations F23P and F24 of the northern transect (cf. Figure 2.1-1 and 3.1-1). The edge of the Harbor (the left side of each panel) is defined in Figure 2.1-1 and is located near station F23P of the northern Harbor transect and between stations F31B and F25 of the southern Harbor transect. Bathymetry measured during the survey is shown for each leg; one can see minor features of bathymetry vary on repeated legs. Also, note in Figure 3.1-1 that for each leg, the direction of sampling is indicated in the panel header. Moreover, a tidal height chart for the day is indicated as an insert. For each panel the time of sampling is indicated by a hatched bar, where the left side of the bar shows the start and the right side of the bar shows the end of the leg.

3.1.1 Winter-Spring (March through April)

March 7: Harbor-Nearfield. Salinity differences of about 1 PSU existed between the harbor mouths and the Nearfield. A tongue of fresher water protruded a few kilometers into surface waters in the Bay, the distance varying with tide and between the two exits to the Bay. Vertical density differences were slight, neither the Harbor nor the Bay were vertically layered at this time.

Notable was a gradient in turbidity (Figure 3.1-1). Beam attenuation changed from ~2.5-3 m^{-1} in the northern Harbor (President Roads) and ~2.0 in the southern Harbor (Nantasket Roads) to <1.5 m^{-1} in the Nearfield. For all legs, a tongue of higher attenuation spread into the Bay and thinned to a more dilute surface lens; this gradient appeared to coincide strongly with the salinity increase from the Harbor into the Bay. Comparing repeated transects, some tidal effects were noted. For example, the first leg out of President Roads started near high tide and the repeat (third) leg was conducted near low tide. The difference between these legs shows a low-tide, seaward advance of a turbidity maximum (>2.5 m^{-1}), which was centered at about 4000 m at high tide and apparently displaced to almost 8000 m by low tide. Comparing the two legs through Nantasket Roads (legs 2 and 4), one notices a near-bottom turbidity maximum that became prominent just after low tide; this feature suggests some bottom scour and sediment resuspension outside the Harbor (~12000 m mark) as the tide turned and flooded.

For all legs, chlorophyll levels were low (<2 μg L^{-1}) in the Harbor as well as in the tongue of lower salinity, higher turbidity water stretching out into the Bay (Figure 3.1-2). Chlorophyll was highest in the zone between the Harbor and the mid-Nearfield (~6000 to 18000 m). In this zone, concentrations were sometimes highest at mid-depth (~10-15 m) and other times close to the surface. Tidal dynamics seemed to affect vertical and horizontal distribution of chlorophyll. For example, near high tide a bottom-water layer with higher chlorophyll seemed to intrude to the Harbor ; in contrast, at low tide this higher chlorophyll layer was displaced a number of km seaward of the Harbor. Peak surface chlorophyll concentrations (5 to >6 μg L^{-1}) generally coincided with locations where turbidity levels dropped near or below 1.5 m^{-1} and Bay salinities (~32 PSU) were reached.

March 22: Harbor—Nearfield. Compared to the previous survey, a more pronounced, although still slight, salinity stratification was evident in the Bay (see Appendix). Salinities above 32 PSU were characteristic of water below about 10-15 m, and lower salinities occurred in almost all surface water. Salinities <29 PSU were noted in the northern Harbor at the low tide sampling (leg 3). In spite of vertical salinity patterns. density stratification was still slight in the Nearfield proper. Less dense water was (σ_T<25) was confined within the Harbor at sampling near high tide. At low tide density layering was evident, again as a protruding tongue shoaling seaward to the surface well past stations F24 and F25 and a distance about 6 km into the Bay from both northern and southern Harbor exits.

Like salinity and density, turbidity seemed to be dispersed further seaward from the Harbor at low tide sampling (Figure 3.1-3). Harbor turbidity was generally lower than in the previous survey (March 7) and only exceeded 2.0 m^{-1} within small patches. Perhaps slightly lowered turbidity lead to the increased chlorophyll levels observed within the Harbor at this time (Figure 3.1-4). Peak chlorophyll concentrations (>7 μg L^{-1}) were suggested within the northern Harbor as the tide was out (leg 3). Highest Bay levels were ~ 4 μg L^{-1}, except for small patches with chlorophyll >5 μg L^{-1} that were found at intermediate to near-bottom depths in areas with sharp bathymetric changes. For the southern transect, a patch with >5 μg Chl L^{-1} was located east of station N10P above a bathymetric depression west of the drumlins in the center of the Nearfield (leg 2). A remnant of this feature, located at almost the same position was detected on leg 4, which may indicate advection (N-S direction), dissipation of the patch, or that it was merely smaller than the trackline variation between legs 2 and 4.

Interestingly, the zone with lowest chlorophyll included the area of highest turbidity at the edge of the northern Harbor (>2.0 m^{-1}); this low chlorophyll region shifted with the tide and was also associated with the apparent movement of the density front between Harbor water and Bay water (cf. leg 1 and leg 3). The zone of low surface chlorophyll seemed to be compressed at low tide (leg 3) compared to high tide (leg 1). The resulting spatial pattern in surface water was characterized by: a) high chlorophyll within the Harbor, b) sharply reduced chlorophyll (<3 g L^{-1}) in the area where the tongue of fresher, lighter, and more turbid water extended from the Harbor-edge into the Bay, and c) increased chlorophyll (>4 $\mu g\ L^{-1}$) in most of the nearfield photic layer to a depth of ~15-20 m.

April 9: Harbor—Nearfield. A two-layered system with a thermocline was developing outside the Harbor and the Bay was mildly, but uniformly stratified. Temperature, salinity, and density sections all suggested that bottom water from the Bay slipped into the northern Harbor on the flood tide (e.g. Figure 3.1-5) Low salinities in the Harbor were <30 PSU and high salinities in bottom water in the Bay were >32 PSU.

Turbidity in the Harbor was further decreased from the late March survey and was generally <2.0 m^{-1}, with only patches above 1.5 m^{-1}. In surface water, there was decreasing turbidity from the edge of the Harbor to the Nearfield (Figure 3.1-6). For both northern and southern exits from the Harbor, there was slight seaward displacement of turbidity with tidal ebbing. Displacement was more strongly evident in the case of the southern Harbor due to the coincidence of sampling with the tidal cycle — the Harbor edge near Nantasket Roads was sampled very close to high and low tide on legs 2 and 4 respectively.

Chlorophyll was high (>5 $\mu g\ L^{-1}$) in the northern Harbor at the early flood stage flooding tide, but low near high tide (Figure 3.1-7). In the case of the northern Harbor, sampling likely detected seaward excursion of higher inner Harbor chlorophyll nearer low tide (leg 1), with that water mass being pushed back into the Harbor (out of the sampling area) during the high tide. This scenario is consistent with salinity data. In the case of the southern Harbor, chlorophyll was also generally higher at the Harbor-edge nearer low tide (leg 4) and flooding (leg 2) also may have pushed higher-chlorophyll water back into the Harbor "out of view" of sampling. Again, more seaward excursion of lower salinity occurred when chlorophyll was high and the same dynamic tidal scenario as envisioned for the northern Harbor is consistent with the data.

In the case of all four legs, a patch of high chlorophyll at mid-depth was seen near 16000 m along the transect. Each patch occurred at turbidity <1.0 m^{-1}, but was not coincident with a sharp drop in turbidity as had been noted in early March. Each patch was centered at the depth of a common isocline (~ $\sigma_T = 25$) and often was near the seaward extension of a lower salinity (<31 PSU) wedge or fragmented surface pool of water. However, while associated with some vertical layering features, the patches were seaward of and apparently not associated with any noticeable tidal fronts (horizontally-banded physical features. Given the proximity of the two tracks at this location (see Figure 2.1-1 tracklines), the identified chlorophyll patches on each transect may have been virtually continuous from north to south across the western side of the Nearfield. The patch detected along the northern transect appeared fairly stationary between the early-flood (leg 1) and near-high (leg 3) sampling times, also evidence that it was significantly seaward of the main Harbor-Bay mixing zone. For the southern transect, the mid-depth chlorophyll maximum patch near 16000 m was close to the bottom and at a point where the bottom bathymetry begins to fall off sharply. Interestingly, near low tide (leg 4), a wedge of high chlorophyll water from the Harbor seemed nearly to fuse with the patch which had been nearly isolated (at least in the east-west direction, along the section) near the high tide sampling (leg 2). A low-tide linkage of inshore and offshore patches of chlorophyll along the southern transect was not notable along the northern transect. Sampling times relative to tide were not optimum for detecting such a feature along the northern transect, but at the sampling closest to low tide (leg 1), inshore and offshore chlorophyll patches were, although still isolated, more closely linked than at high tide (leg 3).

April 28: Harbor—Nearfield. Thermal stratification had developed at depths >15 m outside the Harbor (Figure 3.1-8). The Harbor was still well mixed. Temperature within the Harbor and in all Bay surface water was >6 °C, whereas bottom water below ~25 m was <4 °C. Minimum salinity in the Harbor was slight below 31 PSU, the same as most surface water in the nearfield. Within the area of active tidal mixing for both the northern and southern Harbor exits, surface salinities were between 31 and 32 PSU, or similar to mid-depth water in the thermocline/pycnocline of the stratified Bay system.

Turbidity in the Harbor was as high as ~2.5 m^{-1} and distinct from Bay surface water 1-1.5 m^{-1} and Bay bottom water <1.0 m^{-1} (Figure 3.1-9). Comparing legs 1 and 3 and legs 2 and 4 in Figure 3.1-9, it is evident that the higher turbidity characteristic of the Harbor (>1.5 m^{-1}) was displaced seaward ~4-6 km on the ebb tide. Turbidity displacement was consistent with the salinity displacement that was evident for the northern channel, but not so clearly seen for the southern channel. At low freshwater flow, turbidity may be a fairly sensitive indicator of movement of Harbor water and its interaction with the Bay via tidal ebb-flow cycles.

Chlorophyll concentrations throughout the region of sampling was relatively low at this survey, mostly 1-2 $\mu g\ L^{-1}$ (Figure 3.1-10). Levels were distinctly reduced from early April/late March and signal that cessation of the winter-spring bloom in both the Harbor and the Nearfield. There was mild chlorophyll enrichment within the thermocline/pycnocline throughout most of the Bay. There may have been slightly higher concentrations in the Inner Harbor, for the highest chlorophyll concentration in the Harbor was noted near low tide when Inner Harbor water characteristically is displaced seaward and thus observed within the sampling region. Chlorophyll concentrations suggested only minor dynamic response with respect to Harbor-Bay tidal interaction; there was a generic but small enrichment in surface water chlorophyll near low tide as shown by changes from <1 to >1 mg L^{-1} for both northern and southern transects (Figure 3.1-10).

3.1.2 Early Summer (Special Study)

On June 25, 1994 a survey repeatedly measured conditions along a single transect from inside Boston Harbor to the Nearfield through President Roads, the northern channel of communication between the Harbor and the Bay. A series of six legs, each close to 2h in duration, were conducted from about dawn to early evening. The series started near low tide and measurements were continued through a complete flood-ebb cycle, ending at the next low tide. The Bay was thermally stratified at this time, whereas in general, the Harbor was well-mixed vertically

(Figure 3.1-11). Only minor variations (~1 PSU) in salinity were noted over time or space. Figure 3.1-11 shows that as the tide began to flood, water from within the thermocline in the Bay began to surge towards the Harbor and lift over a bathymetric feature representing the rising slope to the ship channel into the Harbor. By high tide, a protrusion of this mid-depth, 10-12 °C water was then found within the deeper basin at the entrance of the Harbor. As the tide receded, the 12 °C isotherm, which had risen to the surface near the ship channel at the turn of the tide, then deepened to again become a mid-depth feature. Also as the tide ebbed, isolated small pools of <12 °C water were left as remnants in bottom waters within the Harbor.

The associated dynamics for turbidity along the six legs is shown in Figure 3.1-12. The Harbor was more turbid than the Bay, as usual, and a characteristic tongue of surface turbidity extending to the Bay is apparent at low tide (legs 1 and 6). As cooler water uplifted and flooded into the Harbor (legs 2, 3), intrusion of clearer Bay water occurred and cooler water had penetrated the basin in the Harbor by high tide. Note, additionally, that the sharp tidal turbidity front at the seaward edge of Harbor water extension moved shoreward about 2 km by this time (legs 3-4 vs. leg 1). As the tide receded and the thermocline was pushed outside the Harbor again at low tide, so was turbidity. Concomitant tidal ebb and flood effects on chlorophyll patches at the tidal front region are indicated in Figure 3.1-13. Analysis of the dynamics of the infusion of pycnocline-layer water of the Bay into the Harbor and the relation of these dynamics to water quality are presented as an extended discussion of this special study in Chapter 5.

3.1.3 Late Summer (July and August)

July 28: Harbor—Nearfield. Thermal stratification was noted throughout the entire sampling region (Figure 3.1-14). Peak surface-water temperatures were in excess of 16 °C in the Harbor and the Bay. Bottom water in the Harbor was usually 12-14 °C. Bottom water in the Nearfield at 20-30 m was <8 °C. The distinction between Harbor and Bay water with respect to salinity was minimal. A small patch of Harbor water noted at low tide was <31 PSU, most water in the sampling region was 31-32 PSU, and deep water (20-30 in the Bay was ≤32 PSU. As typical during summer, density patterns and vertical layering basically was driven by thermal stratification.

Figure 3.1-15 shows turbidity for the transects. As usual, the Harbor was distinguished for high turbidity. Harbor values >2.5 m^{-1} were characteristic at this time and values above 4.0 m^{-1} were recorded. The pattern across transects generally suggested turbidity dilution into surface waters in the Bay; yet differences at different stages of the tide may suggest complex, heterogeneous processes. For example, transects near low tide (leg 1, northern; leg 2, southern) exhibit a somewhat smooth decrease of turbidity into the Bay. Especially in the case of leg 1, data show a characteristic protruding tongue of turbid water, progressively diluting and thinning towards the surface and far into the Nearfield. In contrast, other transects at flooding tide (leg 3) or close to high tide on early ebb (leg 4), display a discontinuous distribution of turbidity, where one or more patches of high turbidity (>2.0 m^{-1}) are clearly observable in the background of the Bay water (~1.5 m^{-1}). Comparing the distribution of high turbidity patches to temperature (Figure 3.1-14), one notes a similar discontinuity near the surface. Especially on leg 3, the pattern for temperature suggests an upwelling of thermocline/pycnocline-level water to the surface; the rise in isotherms at 6000 to 12000 m along this section appears to parallel the rise in bathymetric from the Bay towards the Harbor. The temperature and turbidity data here are consistent with a flood-tide physical process that isolates surface-water parcels of high turbidity, Harbor-origin water and perhaps releases them from entrainment within the ebb-flow cycle of tidal exchange.

Chlorophyll patterns (Figure 3.1-16) generally followed turbidity, an observation which supports the notion advanced above. But unlike turbidity, chlorophyll may offer insight on additional dynamics. For example, chlorophyll levels in the Bay at the edge of the tidal excursion appeared to be enhanced relative to turbidity, suggesting growth as well as dilution. Enhanced chlorophyll relative to turbidity was a characteristic of isolated surface water parcels (noted above). For both transects, sampling later in the day showed higher chlorophyll in the region of the seaward edge of tidal dynamics (12000 to 18000 m). Chlorophyll stimulation and diurnal growth are the subjects of further analyses and discussion in Chapter 5.

August 27: Harbor—Nearfield. Temperature and density patterns, in space and with time relative to tide were similar to the previous survey in late July. As in June and July, there appeared to be a lifting of mid-depth isothermal bands near the bathymetric rise outside the Harbor (Figure 3.1-17) the feature is evident on leg 3 and was sampled after the tide turned and began to flood. Leg 4 (compared to leg 2) also showed a bottom-water advance upslope towards the Harbor near the southern exit.

Salinity was as low as <30 PSU in the Harbor, thus being fresher than in July. Otherwise, patterns were fairly similar to late July.

Turbidity again stretched from generally high values in the Harbor to low values in the Bay (Figure 3.1-18). There was some patchiness to the distribution, but it was not as discontinuous as shown in late July. Sampling was not at optimum times relative to the tide to fully detect water mass isolation and release to the Bay, as speculated above.

Chlorophyll was generally higher at the edge of the southern Harbor than in northern Harbor, a feature not often seen (Figure 3.1-19). In the Bay at 12000 to 18000 m on each transect, patches of very high chlorophyll (even >10 $\mu g\ L^{-1}$) were noted. These were just outside of the 31 PSU isopleth that approximated the seaward extension of Harbor-water excursion. In part, this chlorophyll created increased turbidity at this location that seemed unrelated to advected/diluted turbidity from Harbor-Bay tidal mixing; we suspect this high chlorophyll contributed to the appearance of the discontinuous turbidity distribution described above. In the aforementioned patches, chlorophyll concentrations, as well the patch size, increased during the day.

3.1.4 Early Fall (September)

September 7: Harbor—Nearfield. In early September the depth of the thermocline in the Bay had deepened. The surface layer (~14-16 °C) extended generally to about 25 m and a thermocline was only apparent at water depths >25 m. Salinity was virtually uniform between

31-32 PSU; only in the northern Harbor near full ebb (leg 1) was a significant parcel of water with salinity <31 PSU encountered. Density sections (Figure 3.1-20) displayed the major distinguishing physical features at this time. These included 1) less dense water in the Harbor compared to the surface layer of the Bay and 2) a deep, near-bottom pycnocline in the Bay detected sporadically at depths below ~25 m. Also, in the mid-Nearfield on all legs, an upwelling of the 23.5 σ_T isopleth to the surface (or almost) was noted; this feature appeared to physically separate inshore and offshore waters within the Nearfield at this time.

The usual Harbor-Bay distinction in turbidity was once again pronounced (Figure 3.1-21). There was little variation as a function of tidal stage, but for all transects there was a semi-progressive decrease in turbidity from inside the Harbor to about 6-10 km into the Bay, with a horizontal turbidity gradient extending furthest near the surface. The trend indicates dilution/dispersion into the Bay. Interestingly, on both legs 1 and 2, which were sampled on a flooding tide, there was considerable near-bottom turbidity (>1.5 m^{-1}) at depths from about 20-30 m. We can not ascertain whether near-bottom turbidity is from bottom-sediment resuspension, but the concept is consistent with an inflowing tidal current meeting an upsloping bathymetry and developing drag and turbulence as a consequence.

Most notable about the chlorophyll distribution in early September was that concentrations were low where turbidity was high (e.g, the Harbor) (Figure 3.1-22). The notion brought forth by this pattern is that turbidity (affecting light) might be, in part, limiting chlorophyll development. This notion is tenable because chlorophyll became higher (2-3 $\mu g\ L^{-1}$) almost immediately out into the Bay where turbidity dropped below about 1.5 m^{-1}. With respect to chlorophyll, as for other parameters, no tidal-related dynamics were striking other than the general chlorophyll reduction shoreward of the tidal turbidity front. No intense patches of chlorophyll were noted in the Bay, in contrast to the previous survey. In general, a broad mid-depth chlorophyll maximum was evident in the Bay, with peak concentrations at 10-15 m, well above the suggested deep pycnocline.

September 29: Harbor—Nearfield. The last Harbor-Bay transect survey of the year was conducted in late September. Similar to three weeks prior, there was a relatively deep surface mixed layer and a pycnocline near the bottom (~25-30 m) was suggested (Figure 3.1-23). In contrast to early September, lower salinities (<30 PSU) were regularly observed in the Harbor and the subsequent surface outflow of less dense Harbor water was distinctly suggested along each transect.

In contrast, a strong turbidity gradient from the Harbor was not observed (Figure 3.1-24). The turbidity signal in the surface layer was confounded in part because intense and sizeable patches of chlorophyll (Figure 3.1-25) were present near the seaward extension of less dense Harbor water (cf. Figure 3.1-25 vs. 3.1-23). Chlorophyll concentrations in these patches were high enough (7-10 $\mu g\ L^{-1}$) to influence turbidity significantly. With respect to near-bottom turbidity increases around bathymetric hummocks, no concomitant rise in chlorophyll was noted and this set of observations is consistent with the notion of bottom-turbulence and resuspension in patches influenced by bathymetry.

For chlorophyll itself, three spatial features are noted; together these suggest motion and growth of chlorophyll during the day. First, it is possible that kilometers-long patches indicated along each transect were continuous from one transect to the other (north-south). The tracklines where peak chlorophyll concentrations occurred are only a few kilometers apart, i.e. less distant from one to another than the east-west length of the chlorophyll patch along a transect. Second, comparing northern and southern transects at their two respective samplings, it is apparent that the patches were displaced only slightly during the day. The southern transect suggested more displacement over time — the center of the patch being perhaps two kilometers shoreward at mid-flood (leg 4) compared to near-low (leg 2). The sampling being offset by only half a tidal cycle, relatively small displacements may be expected. Third, in the case of both the northern and the southern transects, the second sampling later in the day had increased chlorophyll concentrations, and roughly assessed, looked to have higher total mass in the patch. As suggested during summer surveys (e.g., late July, late August), growth of chlorophyll during daylight is implied from enhanced levels at the second sampling. Moreover, this implied growth appears to be a feature at least occasionally recognizable over and above physically-driven dynamics, including those regulated by tidal cycles. A section in Chapter 5 further assesses plankton growth and production in frontal patches moving with tidal actions in western Massachusetts Bay.

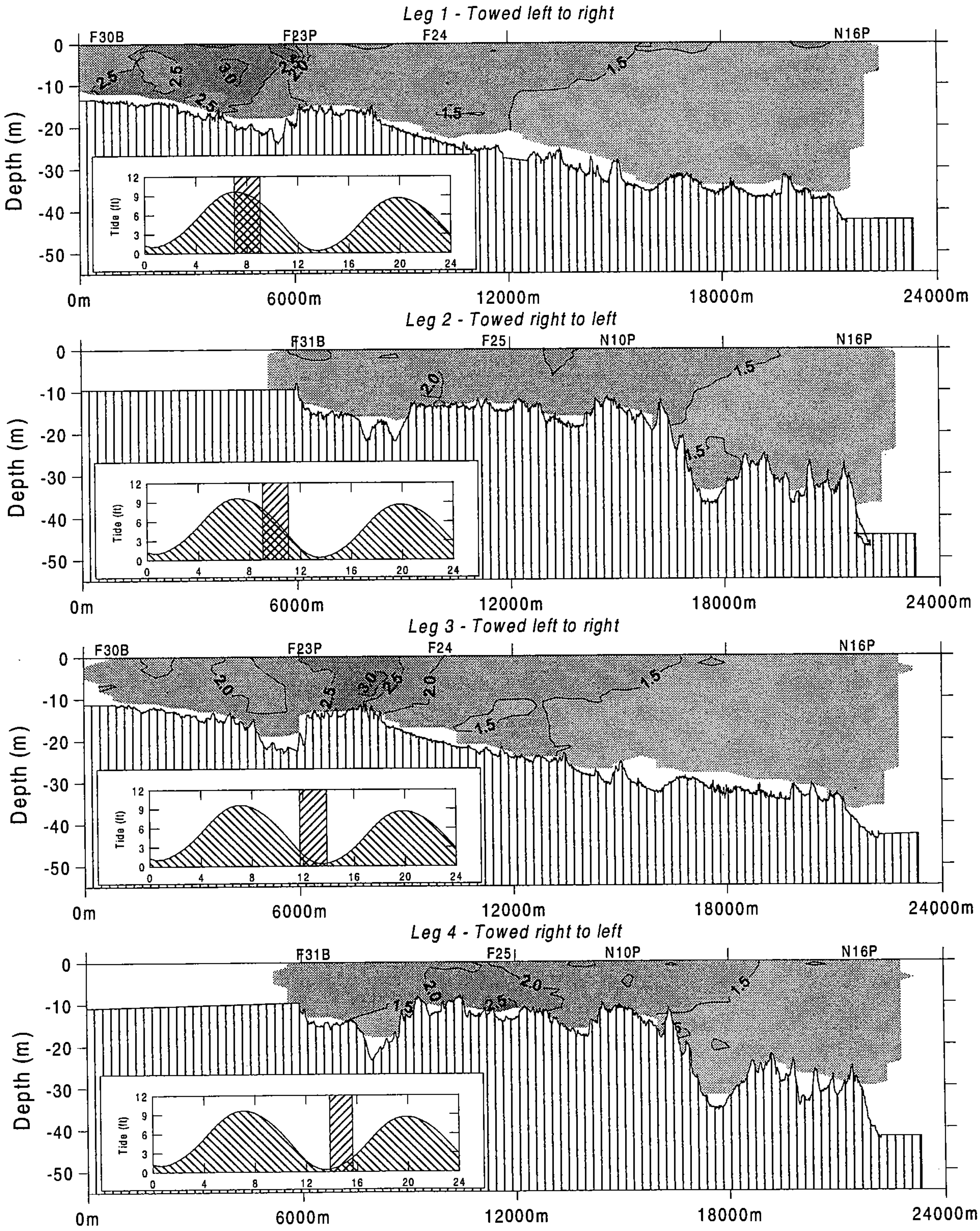


Figure 3.1-1. **Beam attenuation (m^{-1}) for Survey W9402 on March 7, 1994.**

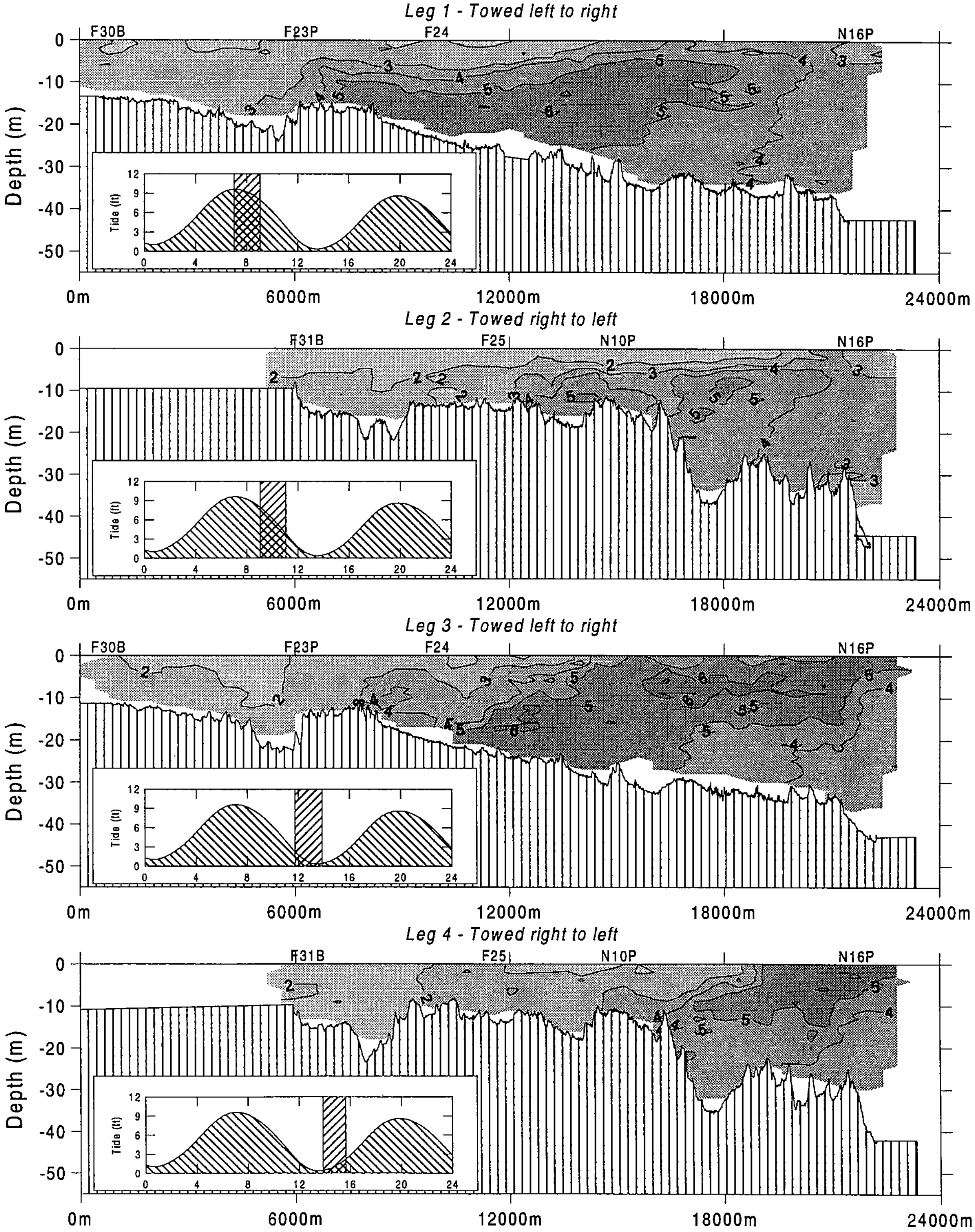


Figure 3.1-2. Chlorophyll a (μg L^{-1}) for Survey W9402 on March 7, 1994.

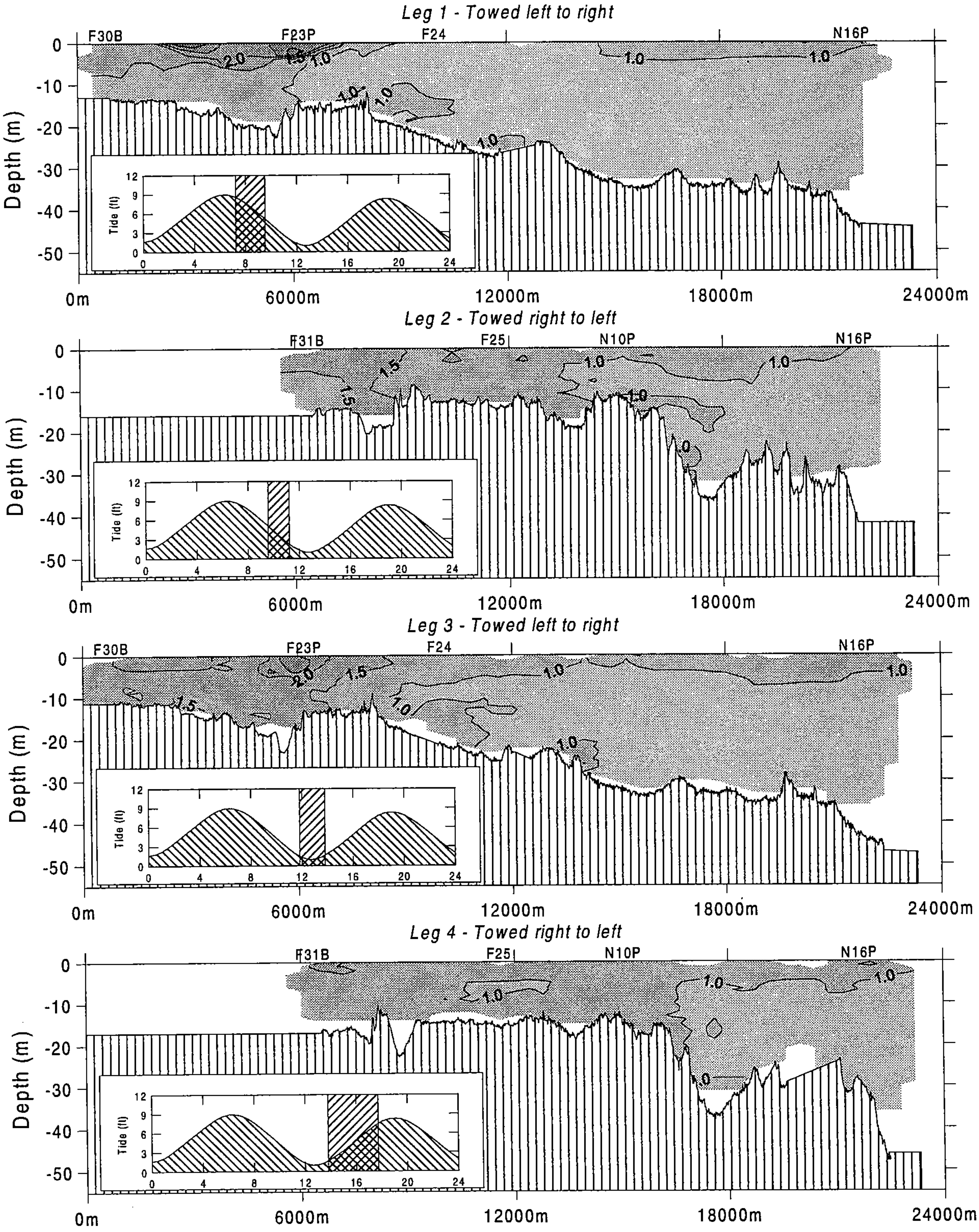


Figure 3.1-3. Beam attenuation (m^{-1}) for Survey W9403 on March 22, 1994.

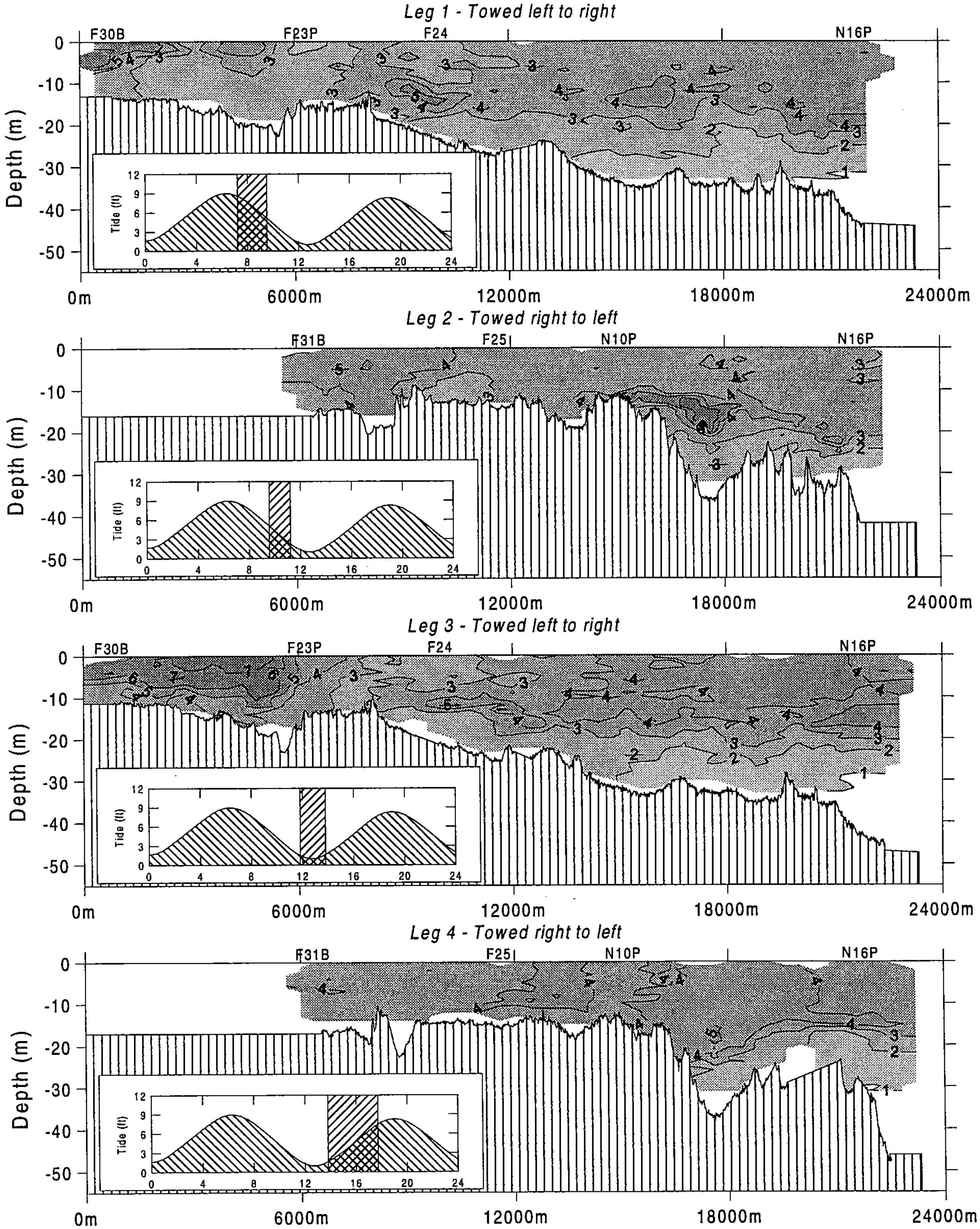


Figure 3.1-4. **Chlorophyll a (μg L^{-1}) for Survey W9403 on March 22, 1994.**

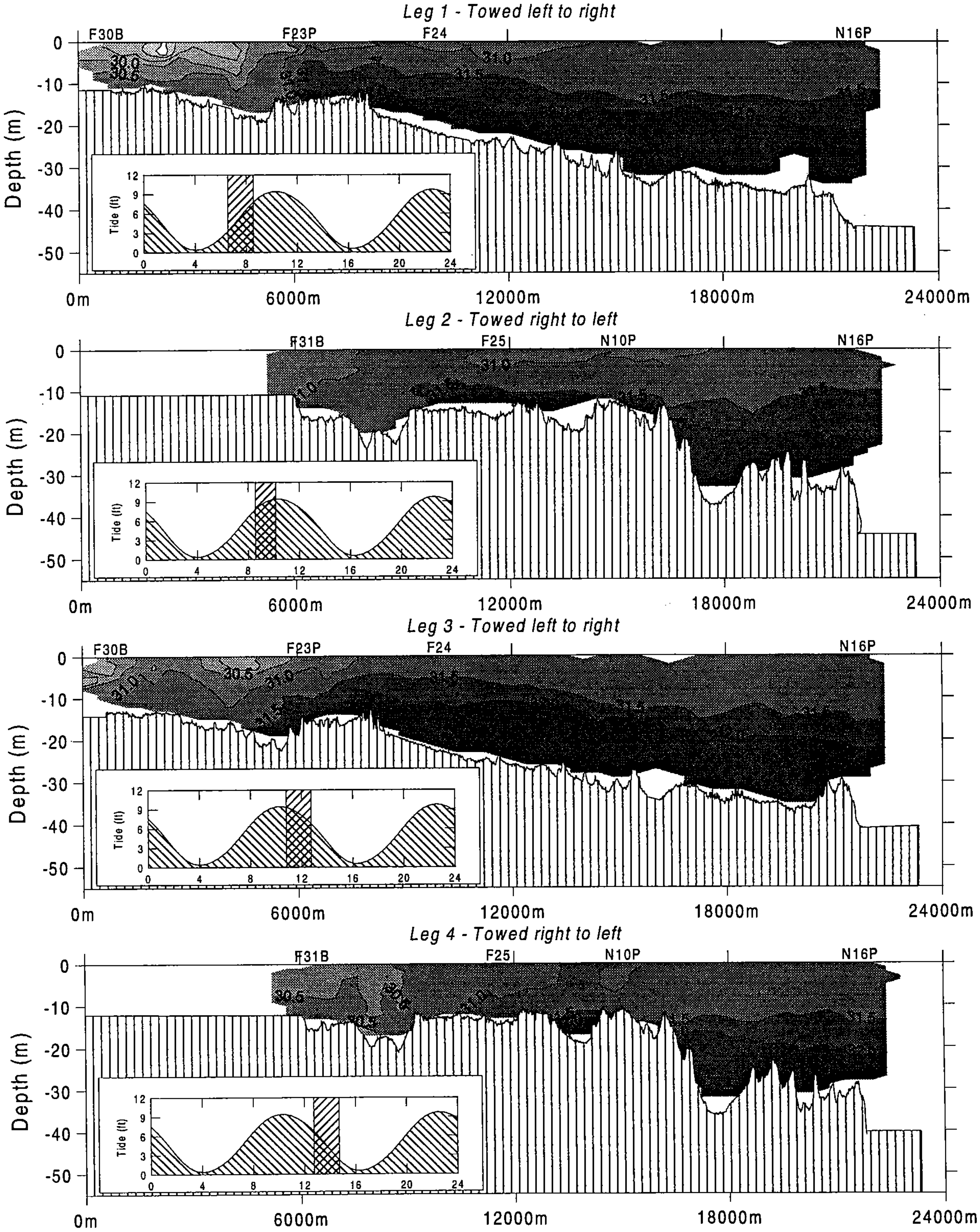


Figure 3.1-5. Salinity (PSU) for Survey W9404 on April 9, 1994.

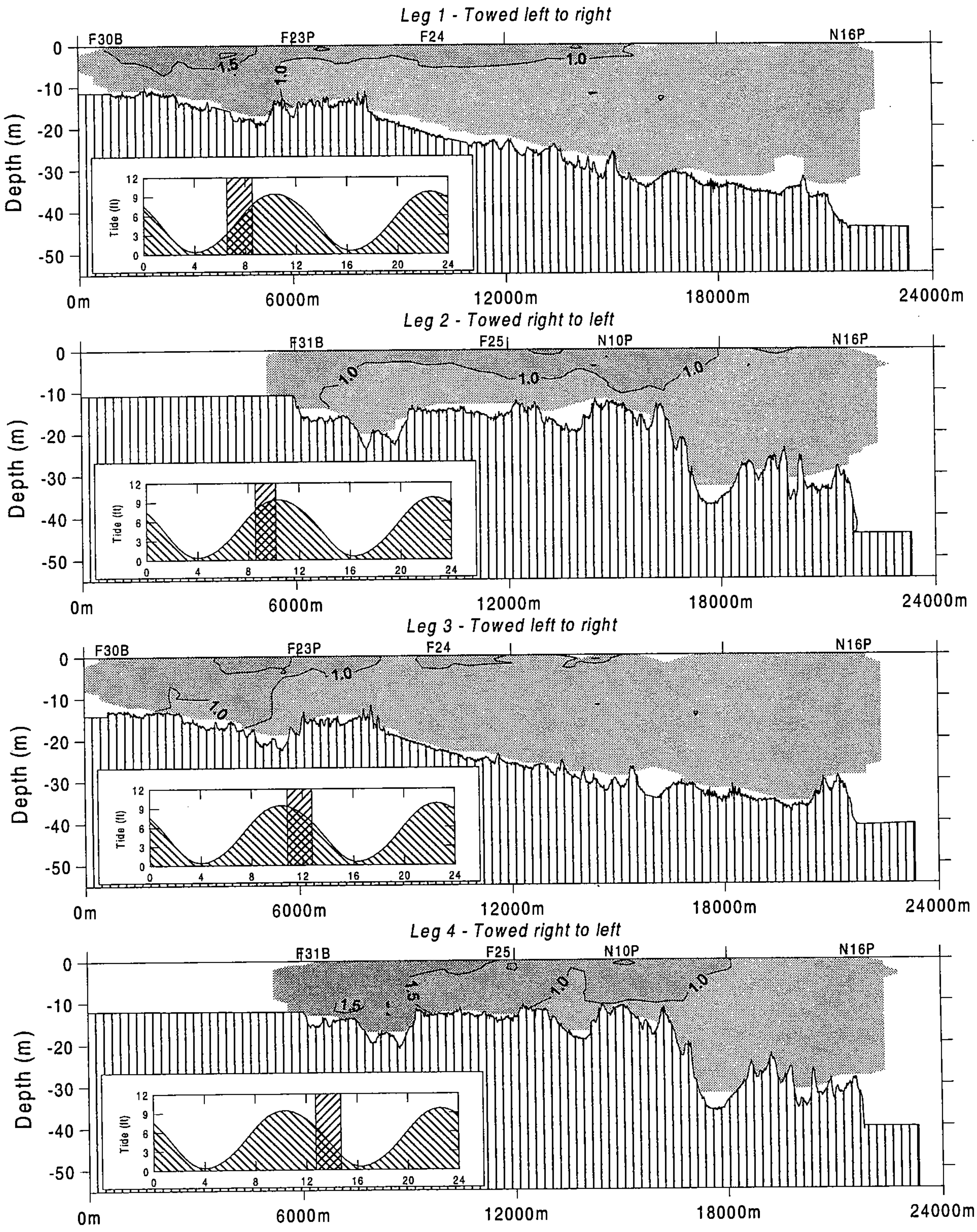


Figure 3.1-6. **Beam attenuation (m^{-1}) for Survey W9404 on April 9, 1994.**

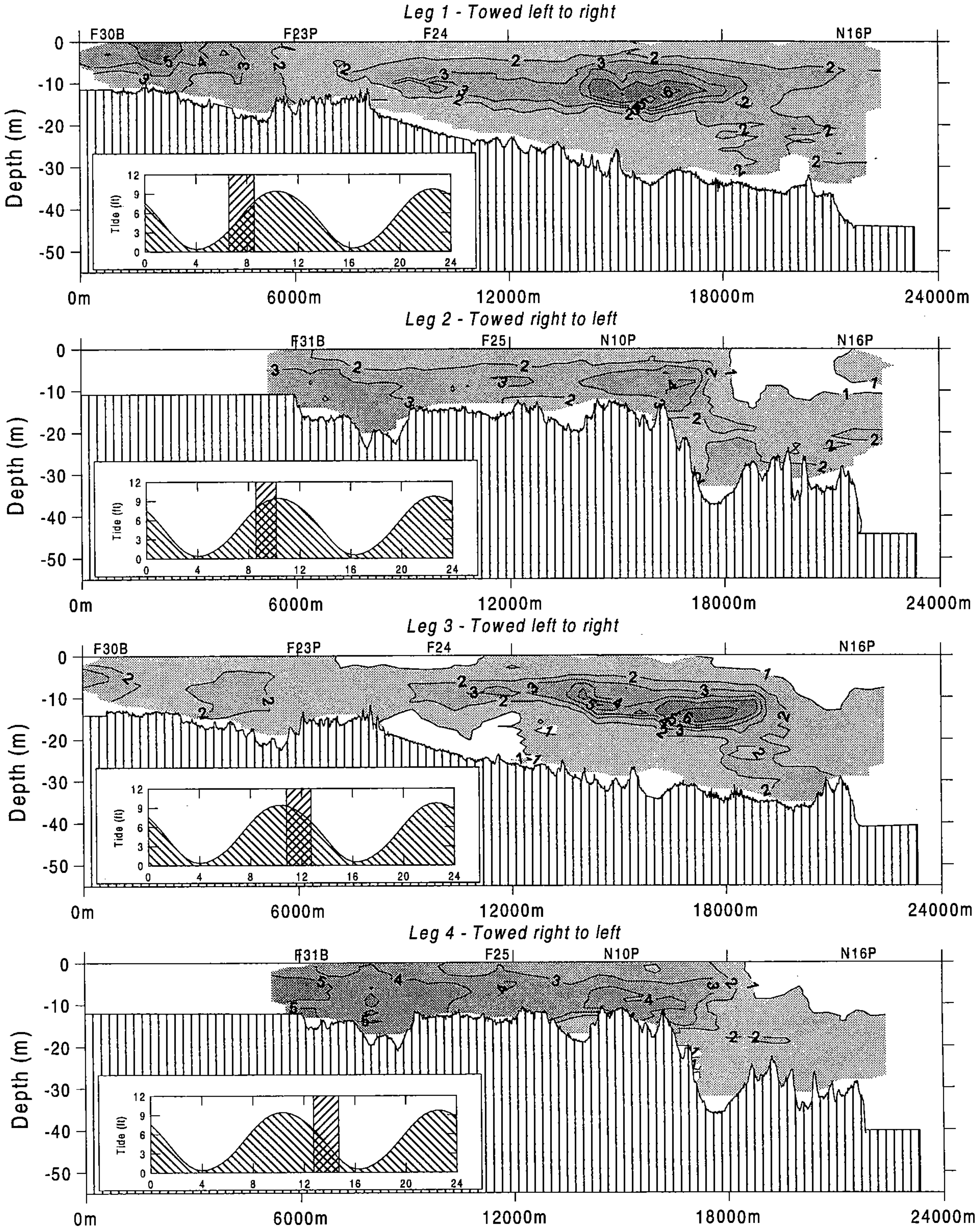


Figure 3.1-7. Chlorophyll ($\mu g\ L^{-1}$) for Survey W9404 on April 9, 1994.

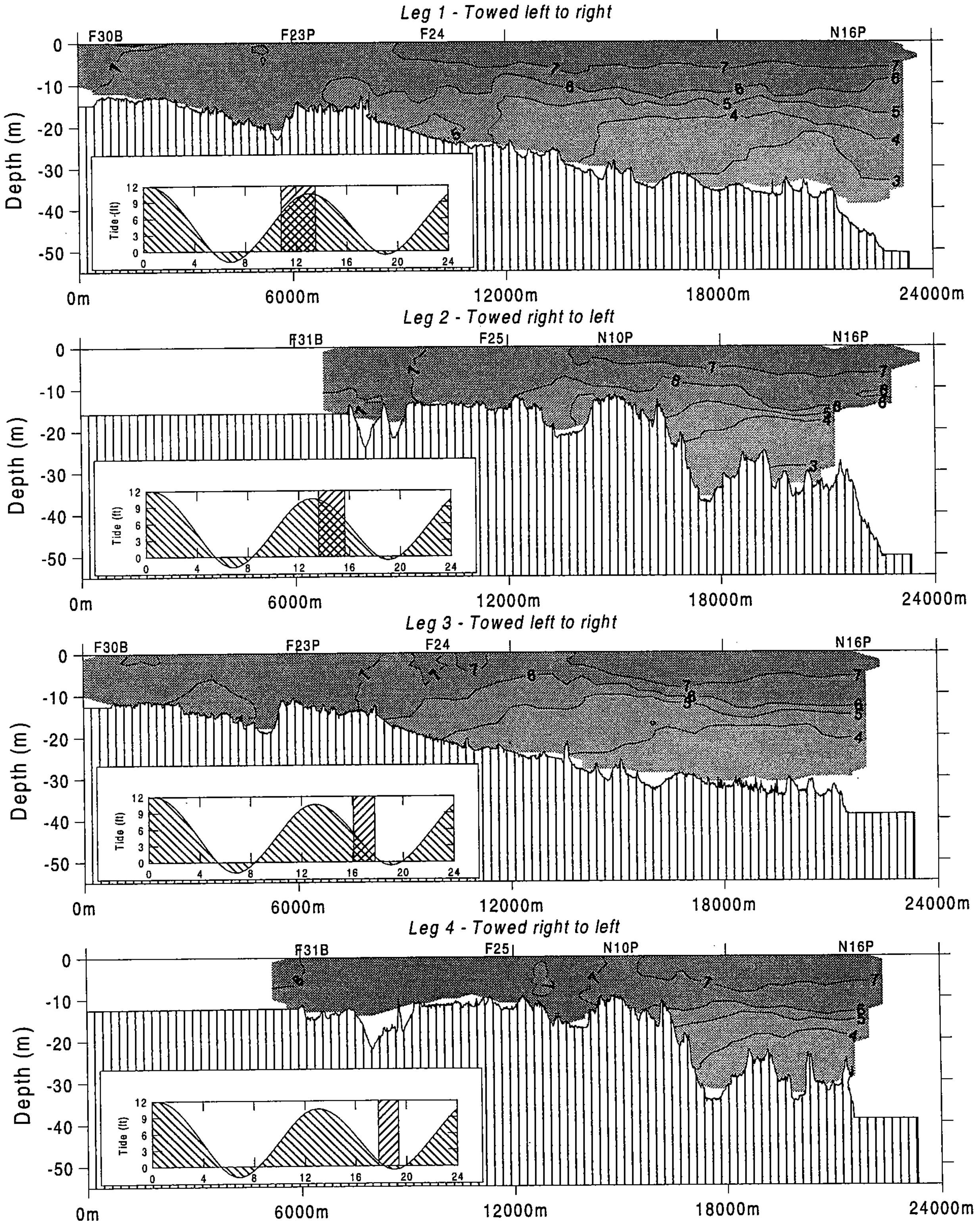


Figure 3.1-8. Temperature (°C) for Survey W9405 on April 28, 1994.

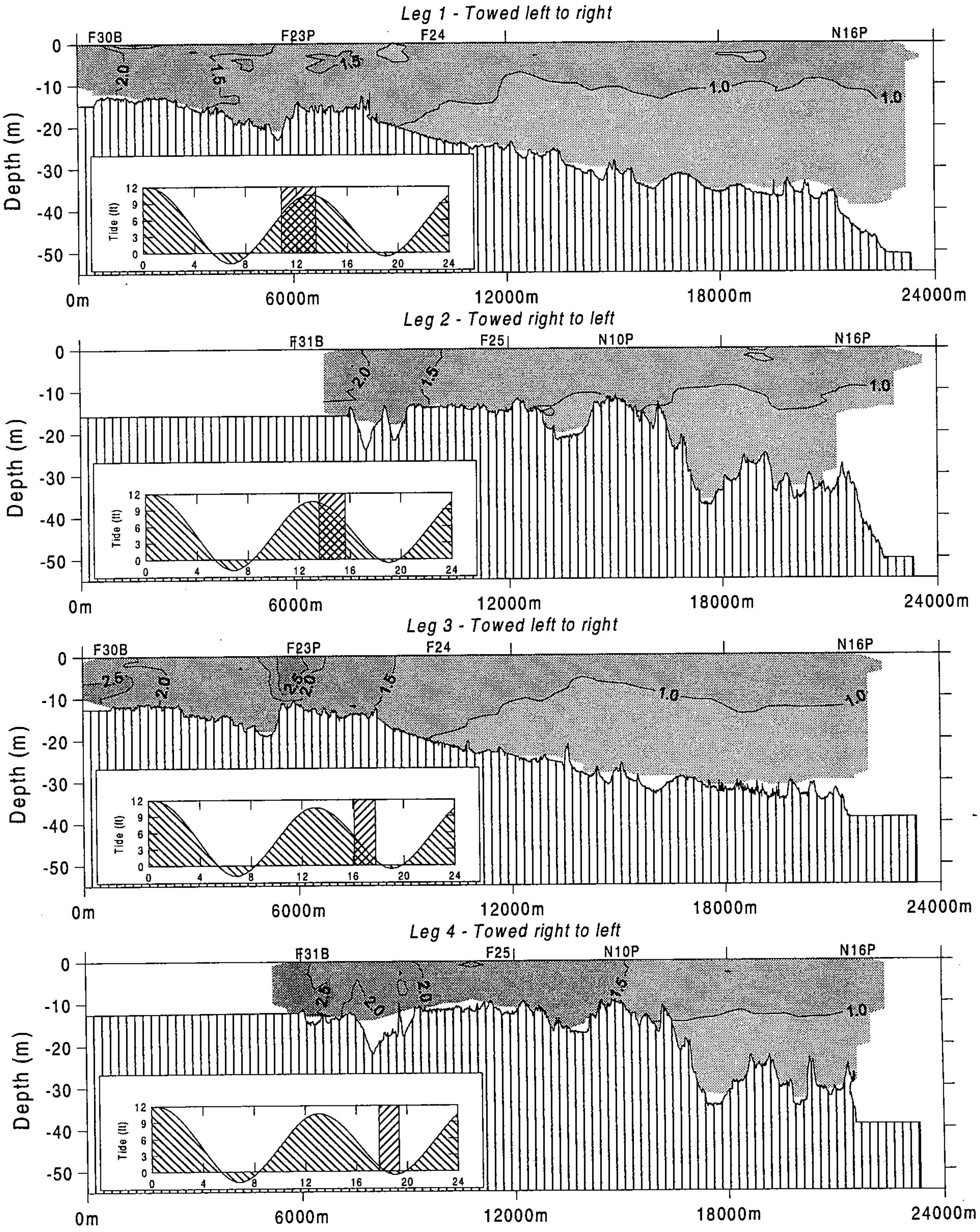


Figure 3.1-9. Beam attenuation (m^{-1}) for Survey W9405 on April 28, 1994.

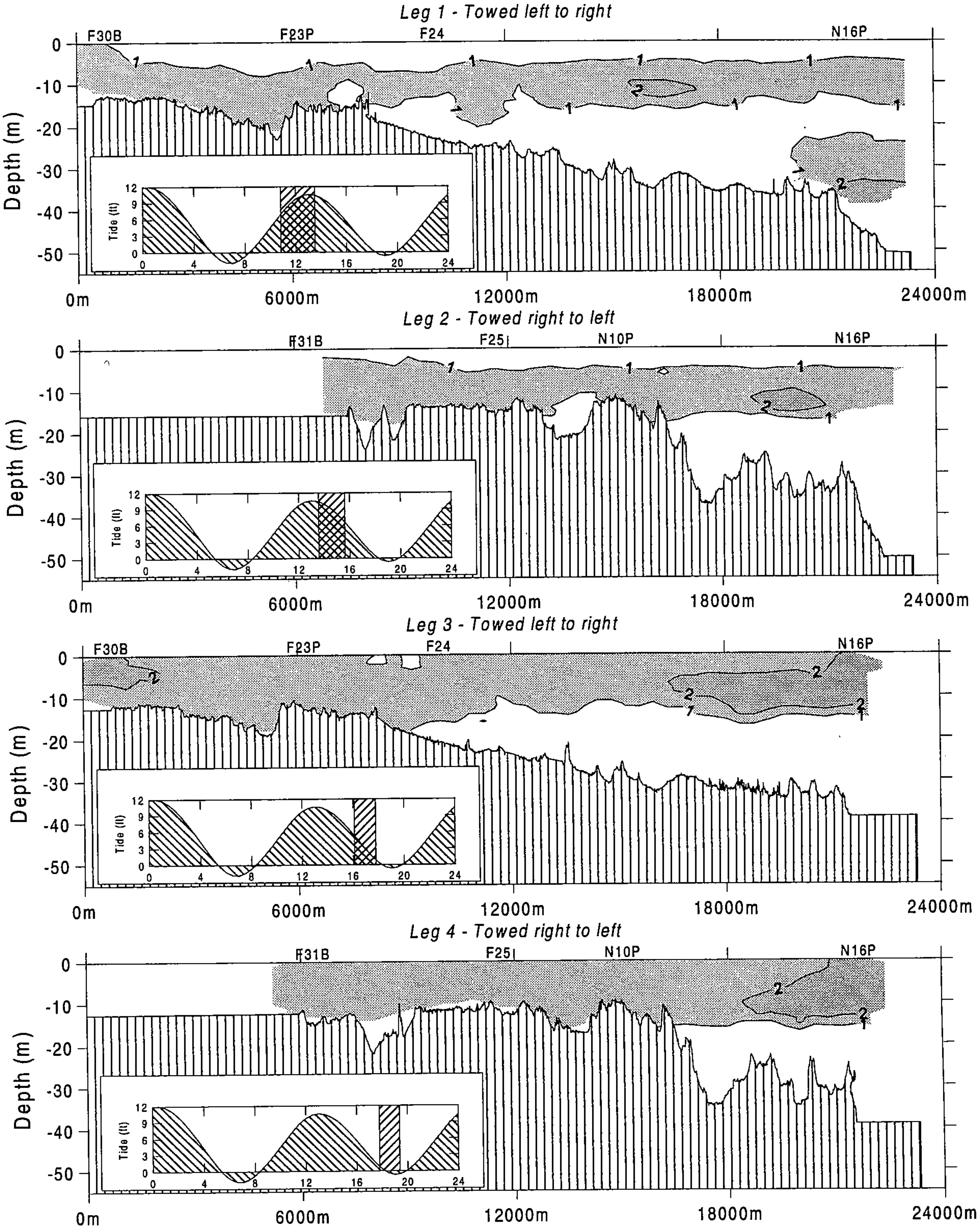


Figure 3.1-10. Chlorophyll (μg L^{-1}) for Survey W9405 on April 28, 1994.

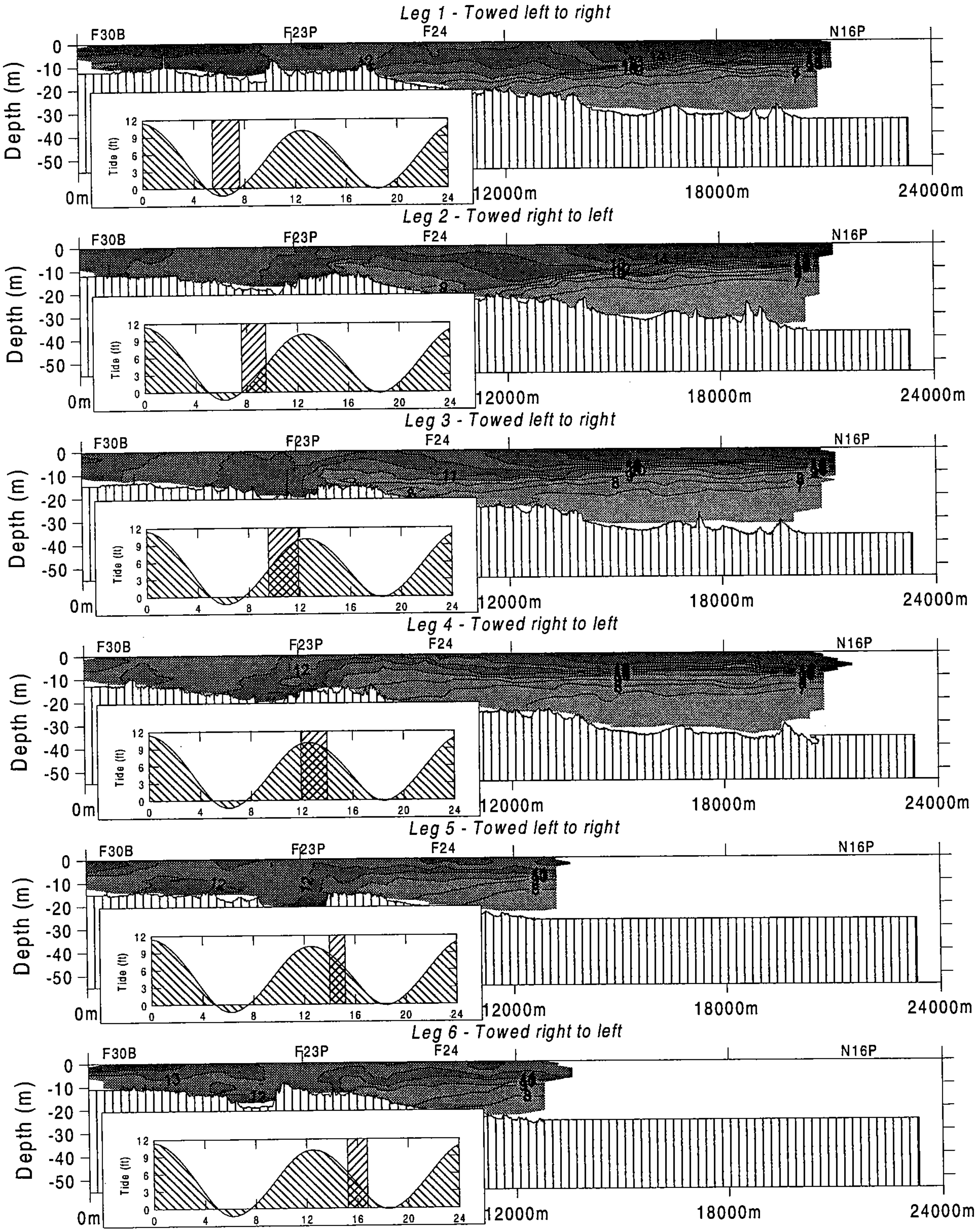


Figure 3.1-11. **Temperature (°C) for Survey W9407 on June 25, 1994.**

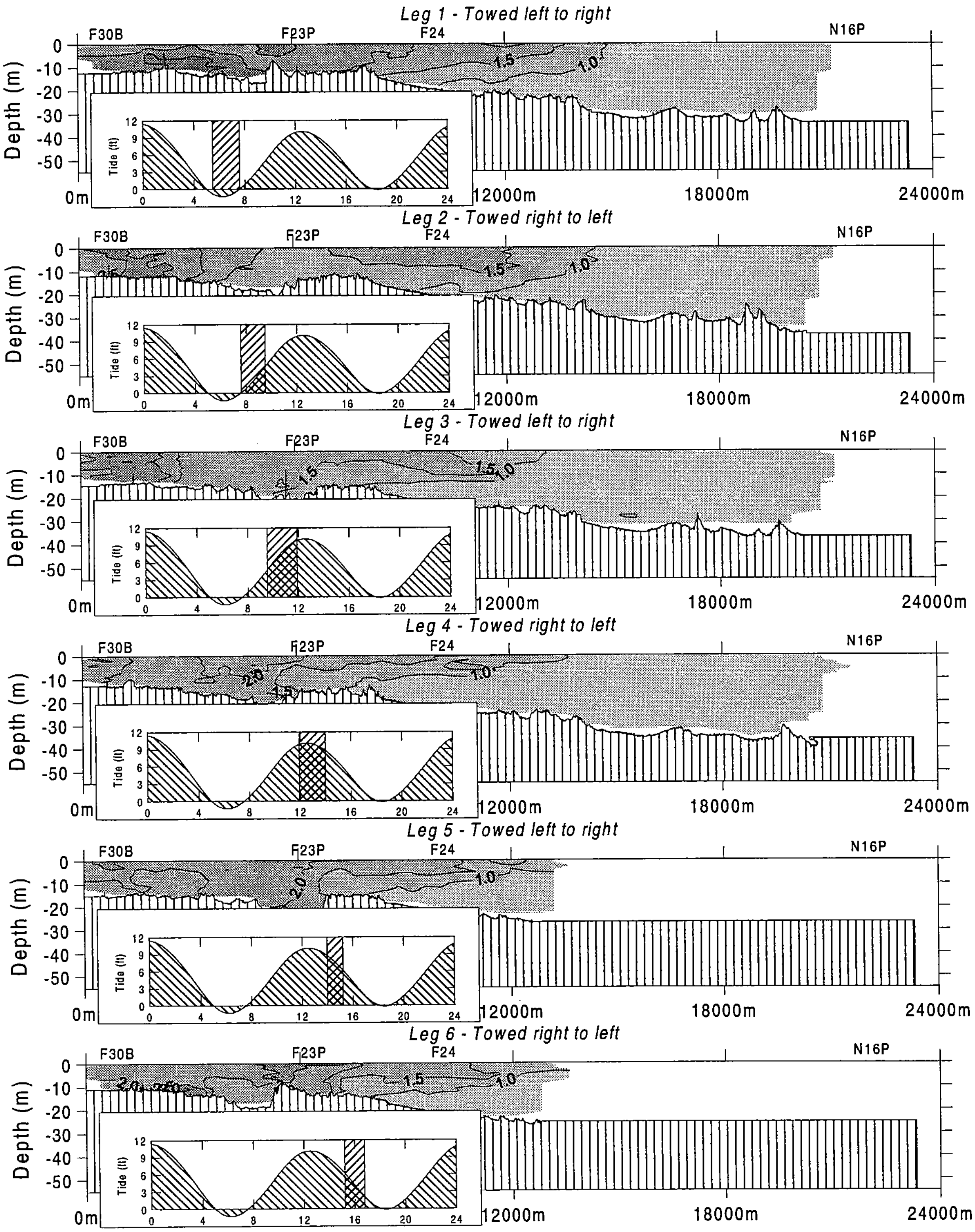


Figure 3.1-12. Beam attenuation (m^{-1}) for Survey W9407 on June 25, 1994.

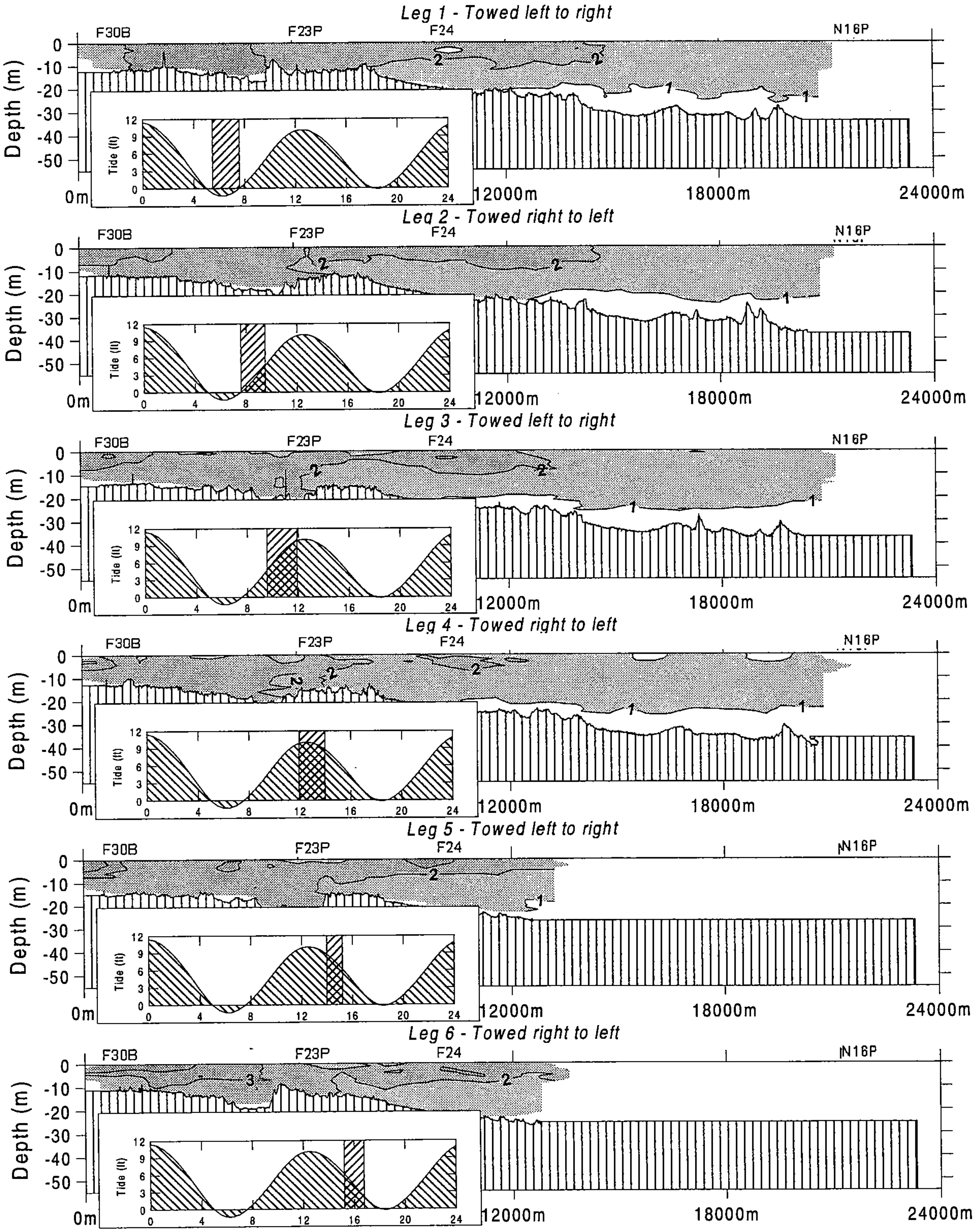


Figure 3.1-13. Chlorophyll (μg L^{-1}) for Survey W9407 on June 25, 1994.

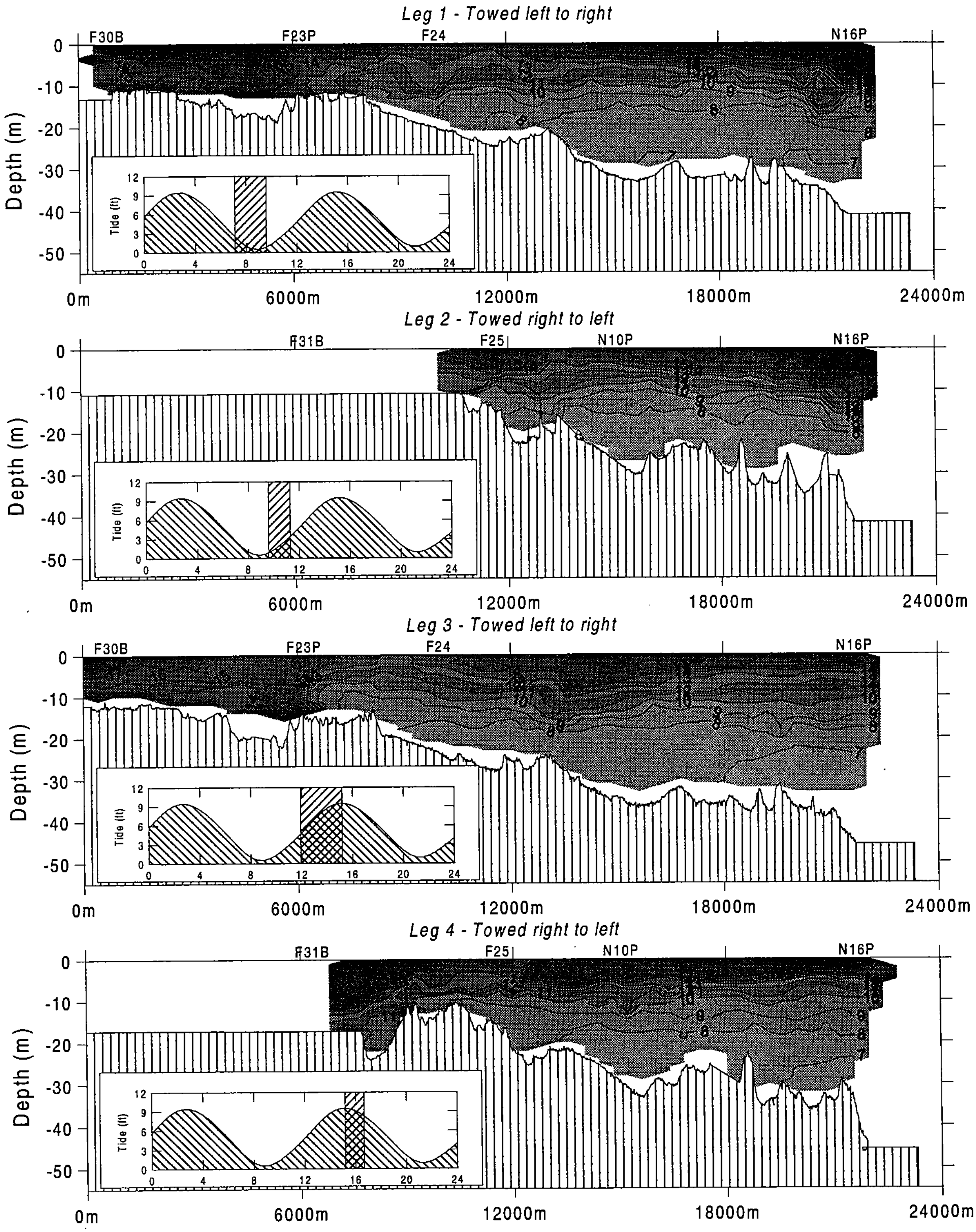


Figure 3.1-14. Temperature (°C) for Survey W9409 on July 28, 1994.

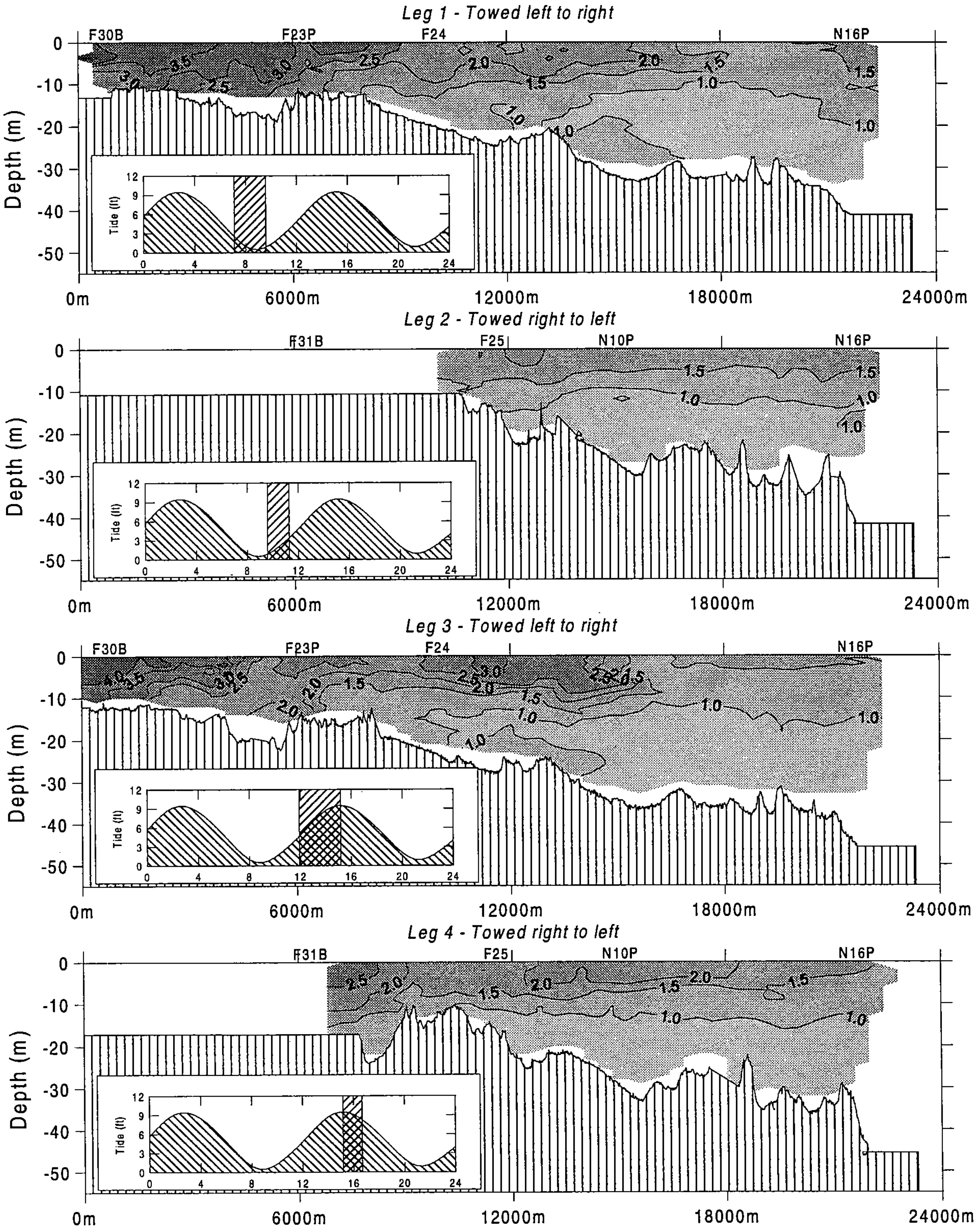


Figure 3.1-15. **Beam attenuation (m^{-1}) for Survey W9409 on July 28, 1994.**

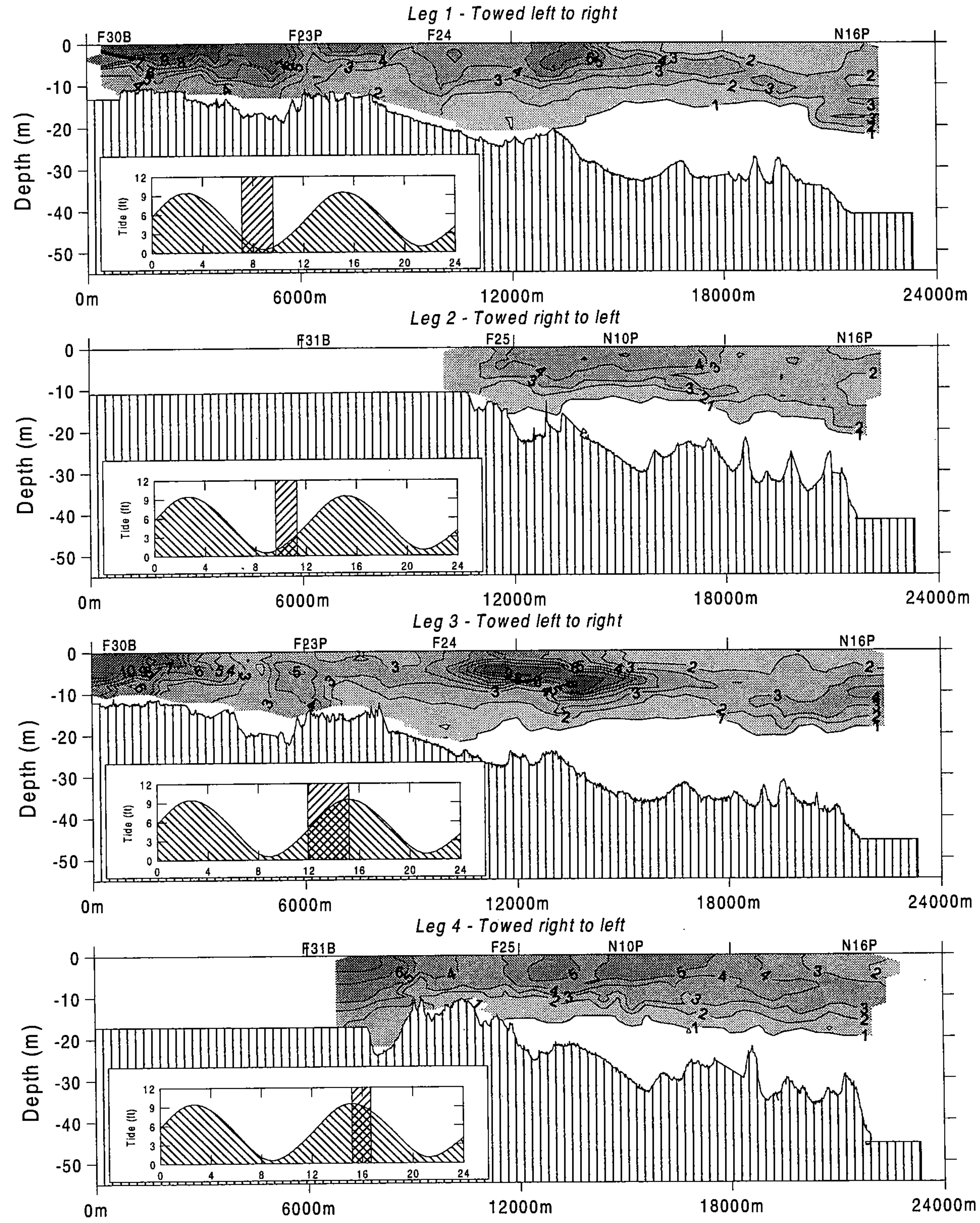


Figure 3.1-16. Chlorophyll (μg L^{-1}) for Survey W9409 on June 28, 1994.

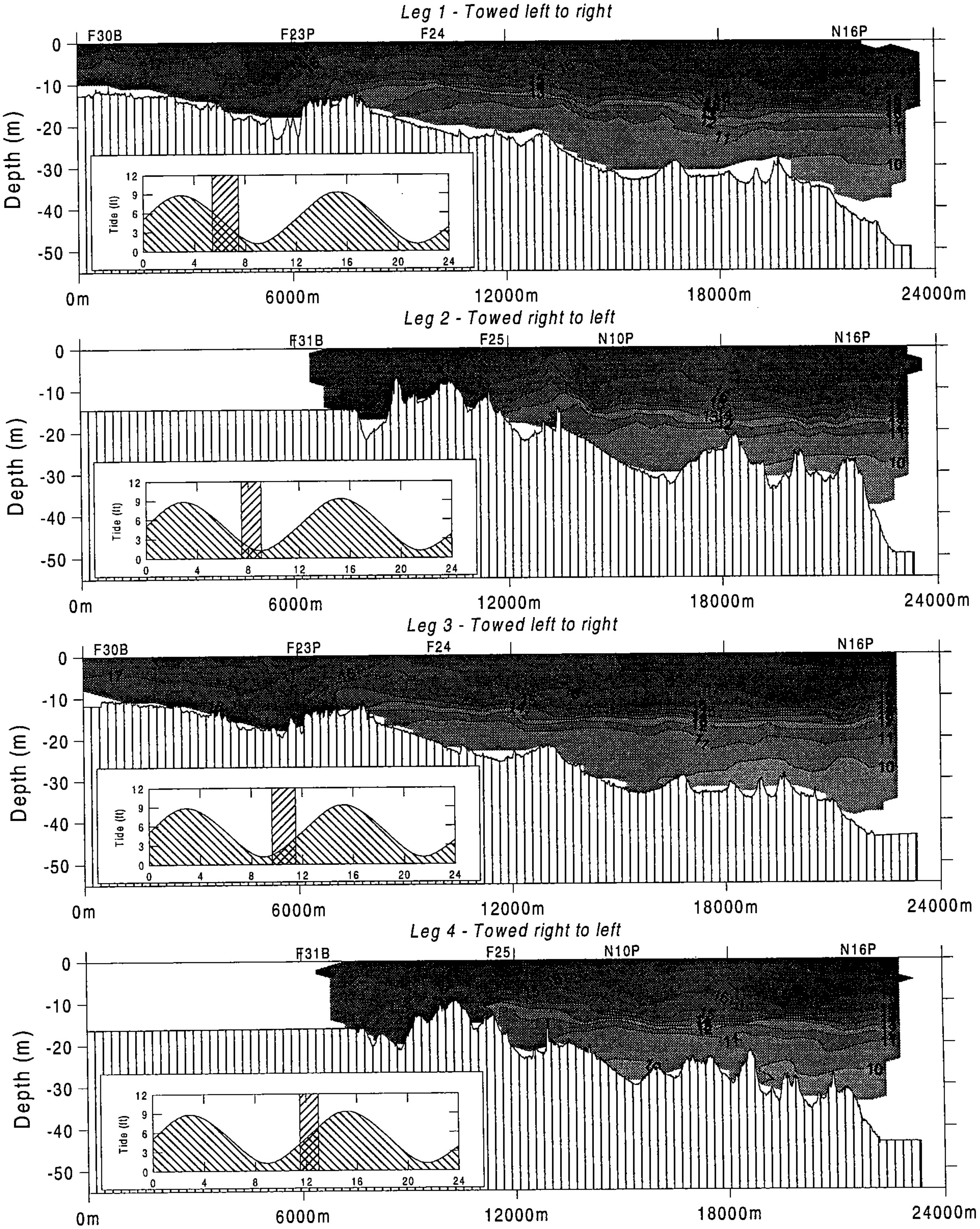


Figure 3.1-17. Temperature (°C) for Survey W9411 on August 27, 1994.

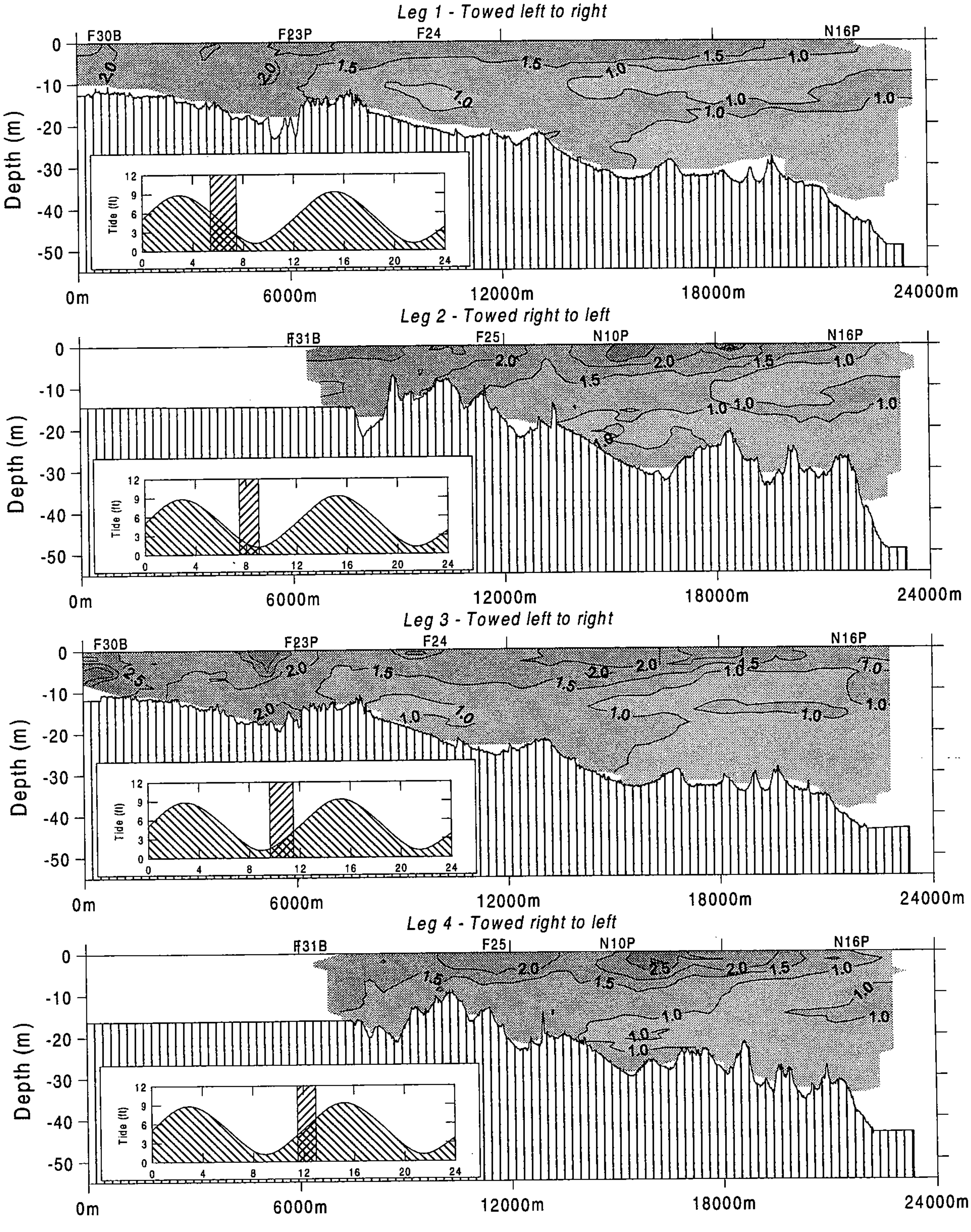


Figure 3.1-18. Beam attenuation (m^{-1}) for Survey W9411 on August 27, 1994.

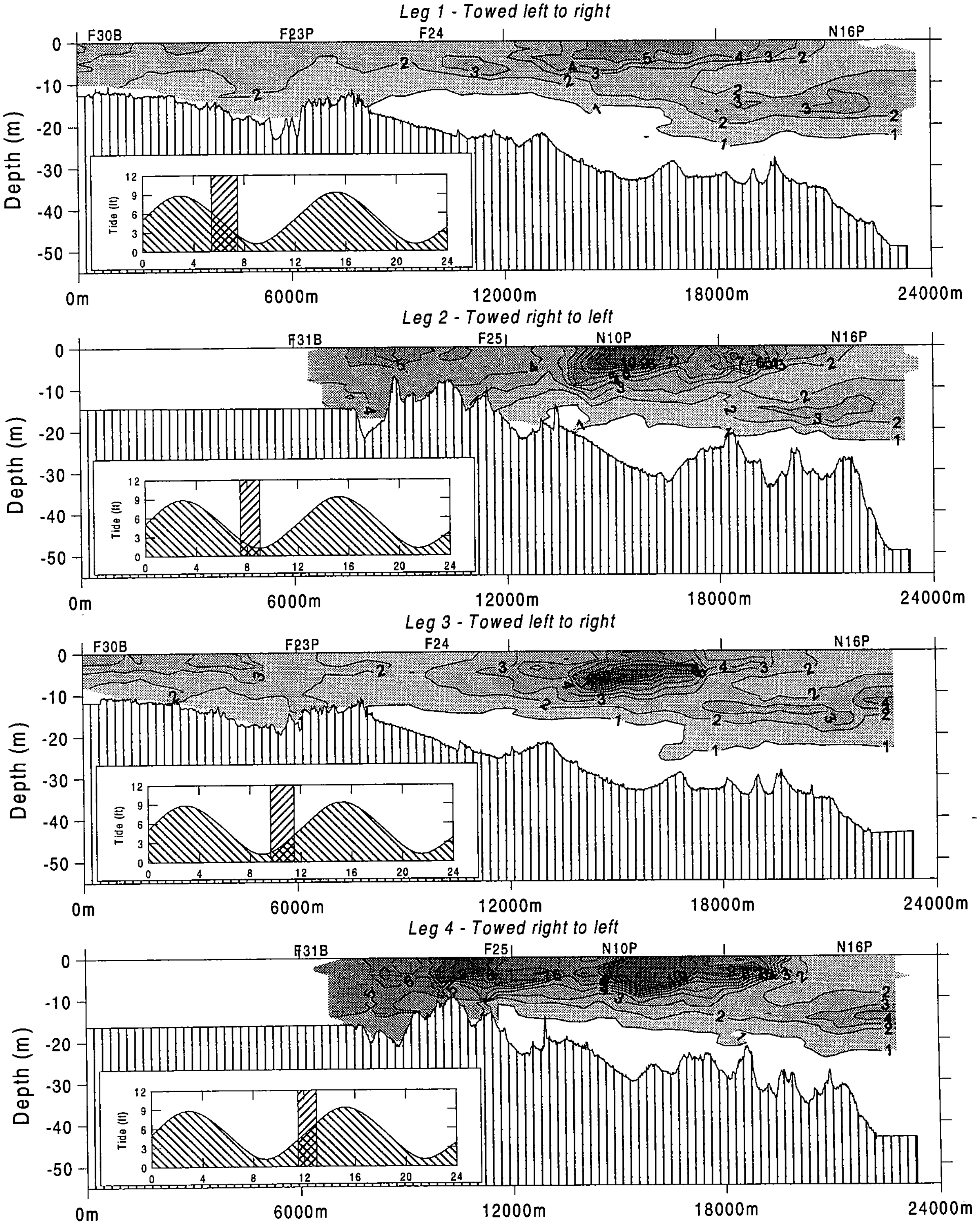


Figure 3.1-19. Chlorophyll (μg L^{-1}) for Survey W9411 on August 27, 1994.

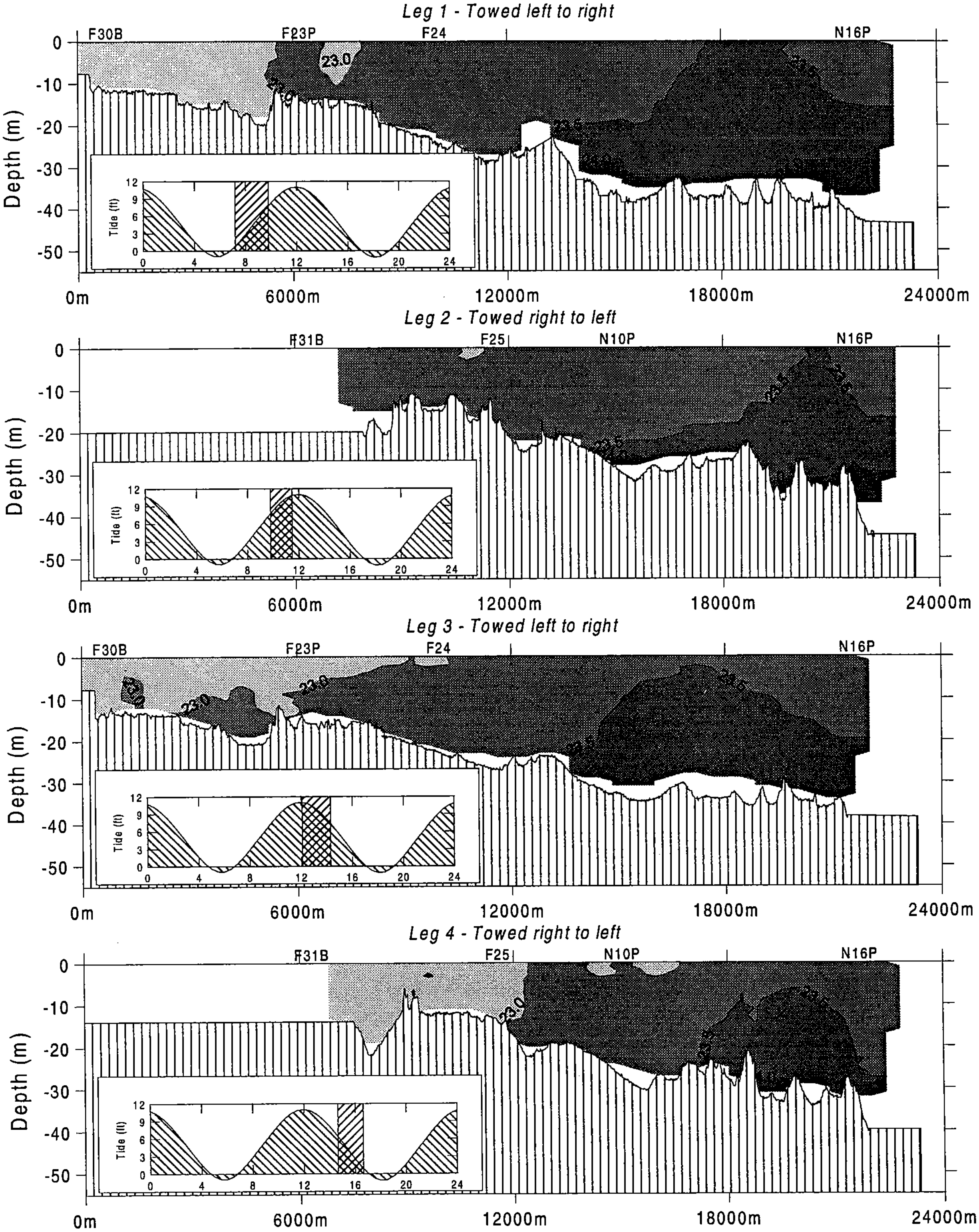
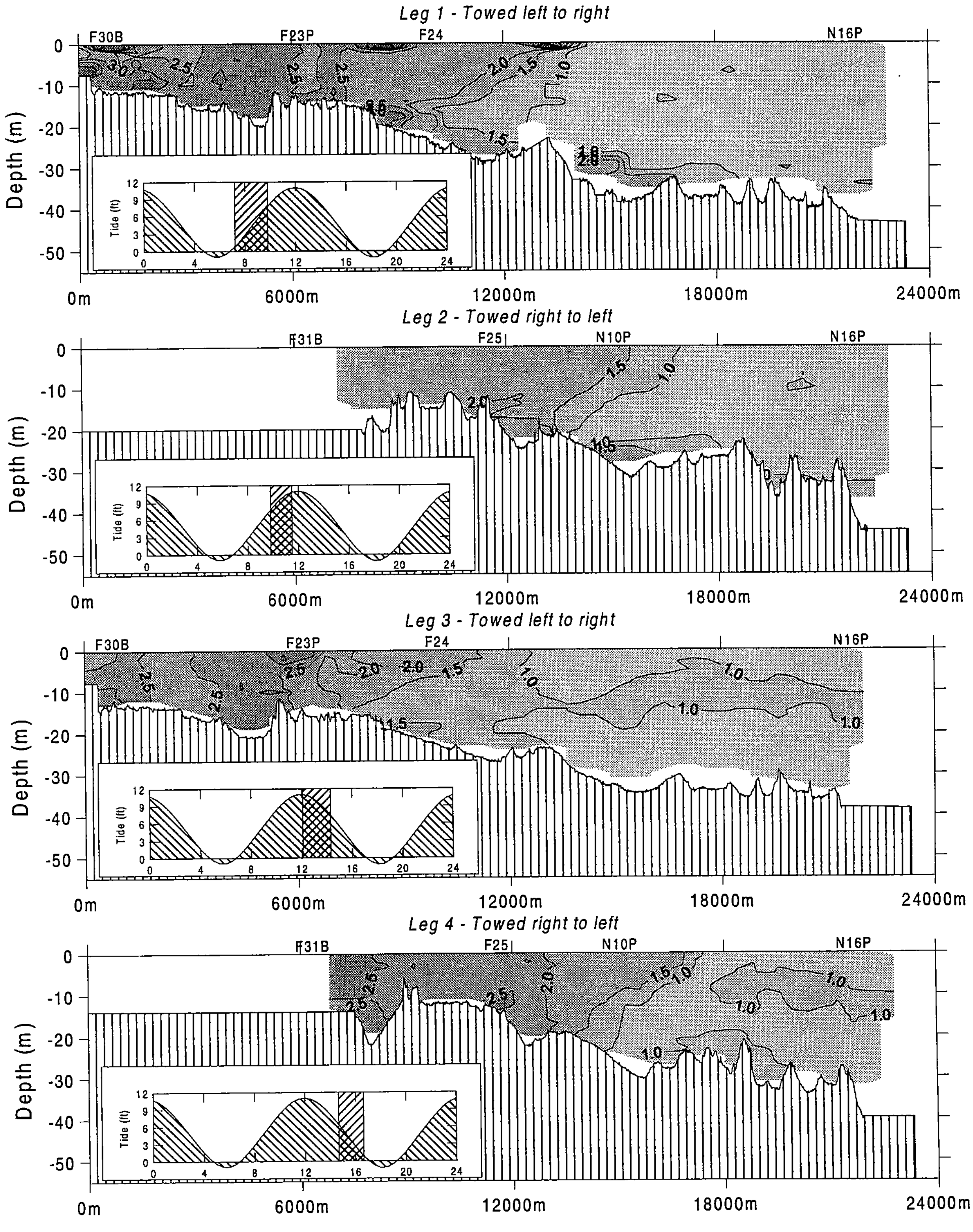


Figure 3.1-20. Density (σ_T) for Survey W9412 on September 7, 1994.



Leg 1 - Towed left to right

Leg 2 - Towed right to left

Leg 3 - Towed left to right

Leg 4 - Towed right to left

Figure 3.1-21. **Beam attenuation (m^{-1}) for Survey W9412 on September 7, 1994.**

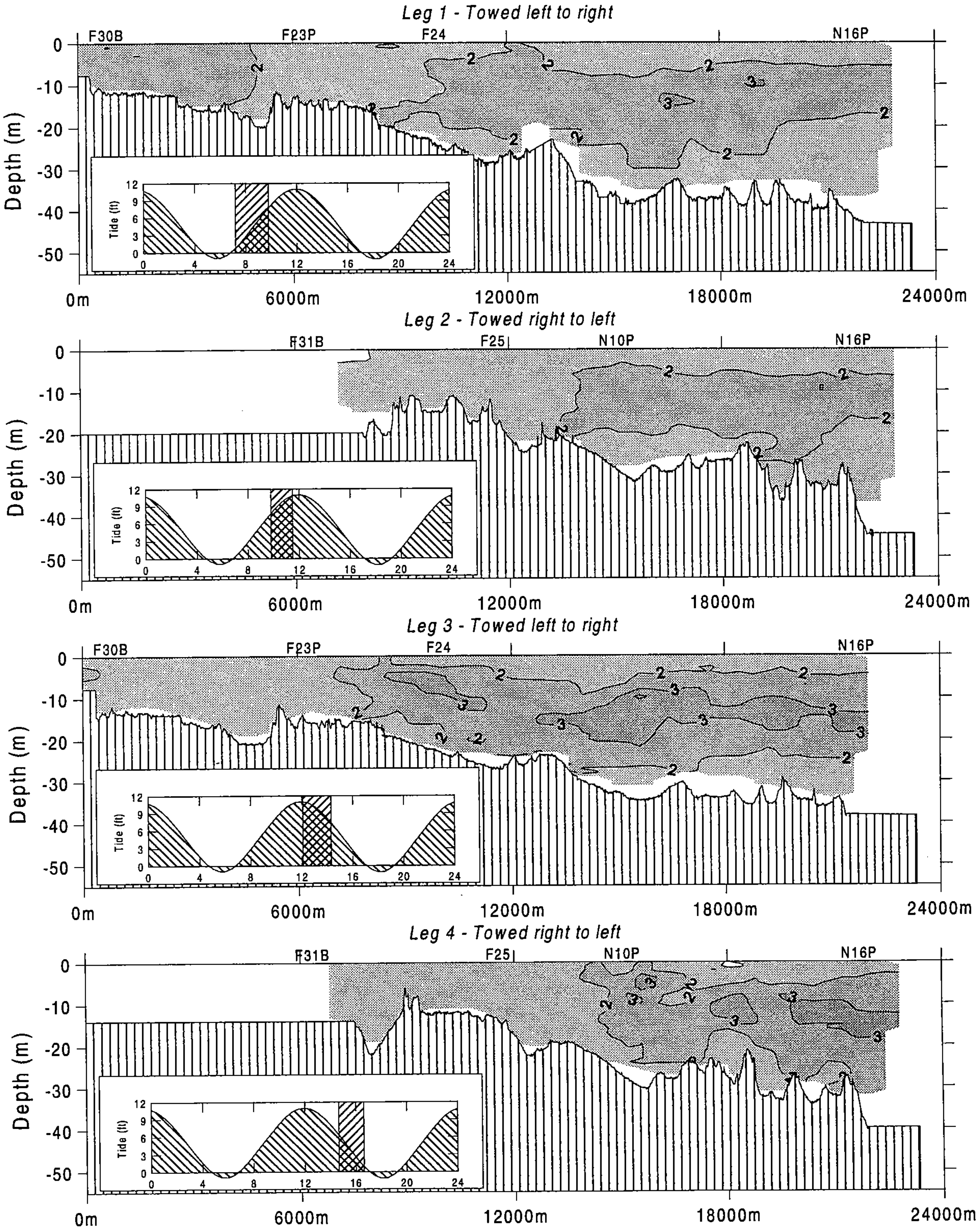


Figure 3.1-22. **Chlorophyll (μg L^{-1}) for Survey W9412 on September 7, 1994.**

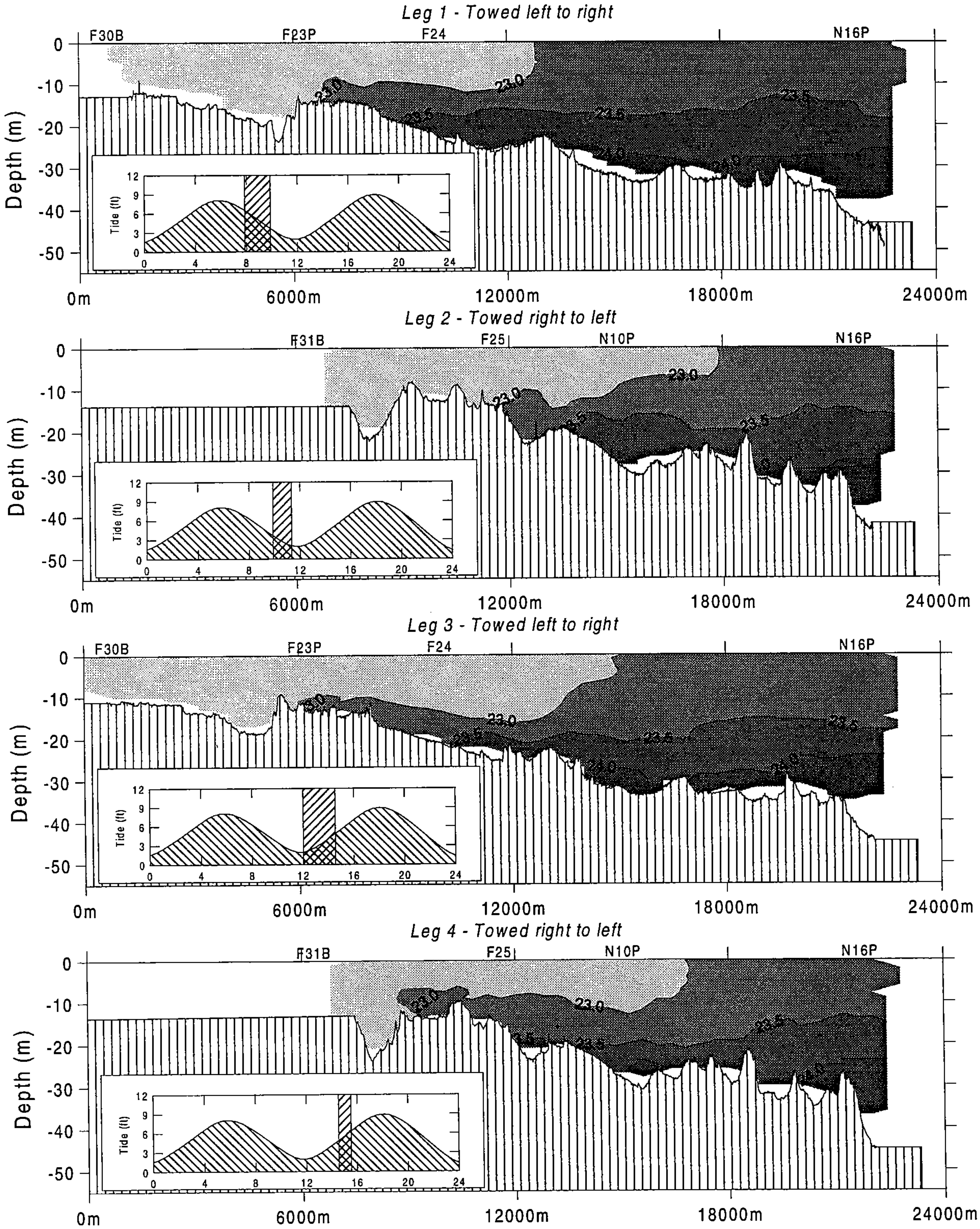


Figure 3.1-23. **Density (σ_T) for Survey W9413 on September 29, 1994.**

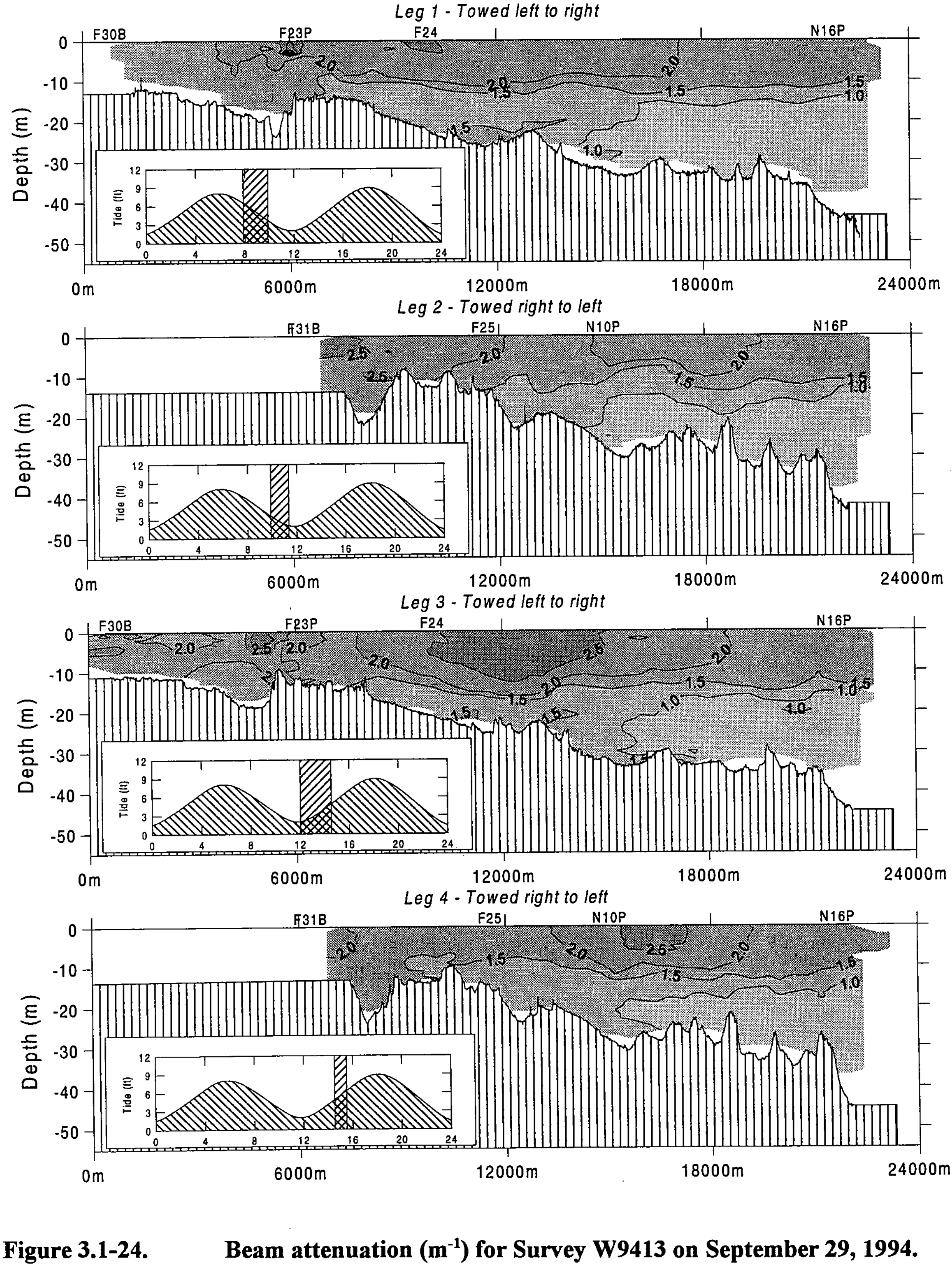


Figure 3.1-24. **Beam attenuation (m^{-1}) for Survey W9413 on September 29, 1994.**

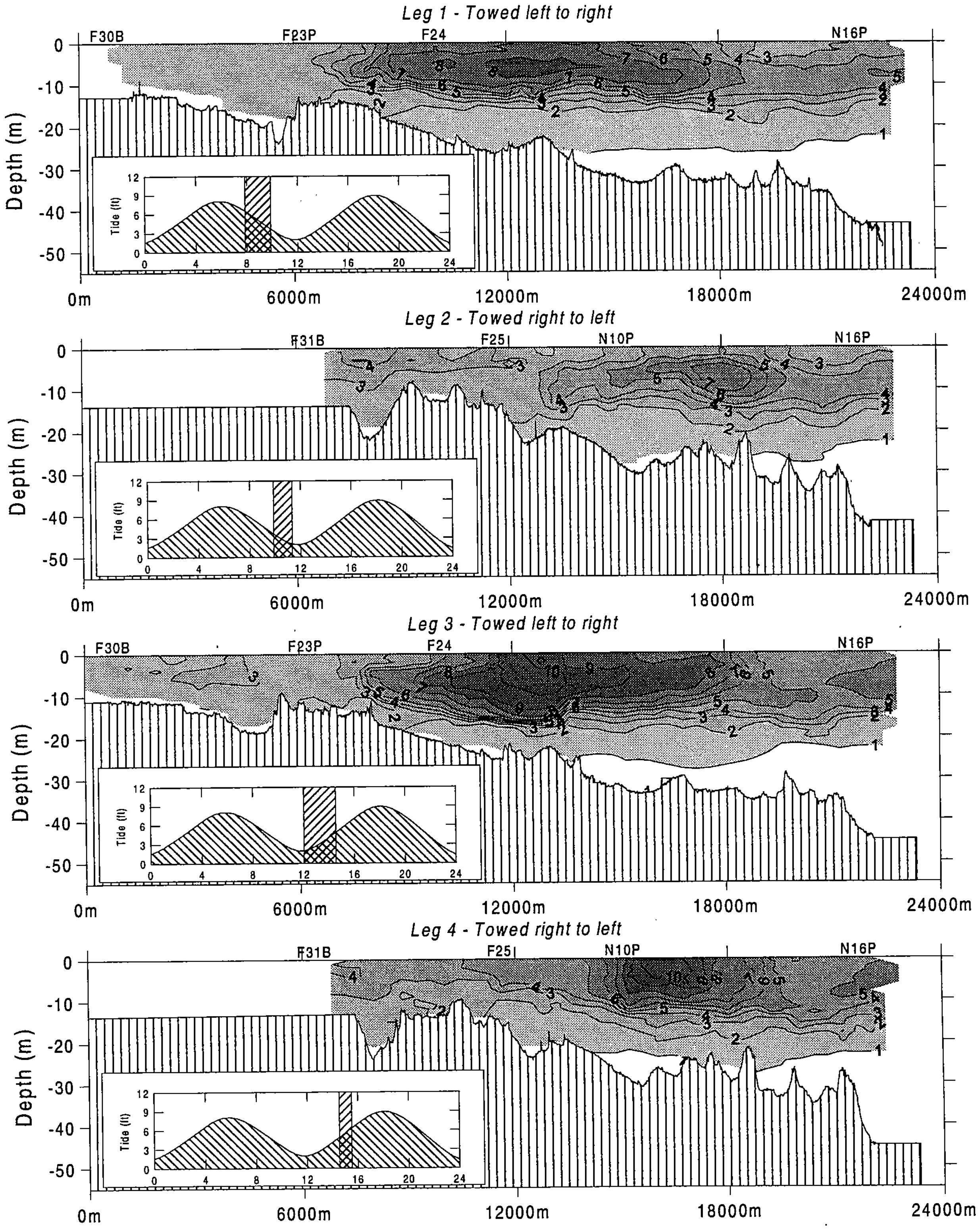


Figure 3.1-25. Chlorophyll (μg L^{-1}) for Survey W9413 on September 29, 1994.

3.2 Western Massachusetts Bay—Cape Ann—Stellwagen Bank Loop Surveys

An example trackline for these larger-scale Bay-wide surveys is given in Figure 2.1-1. A day's towing covered roughly 100 km of trackline. The coordinate system was linear (~latitudinal for leg 1 and 3 and ~longitudinal for leg 2) and is shown along with the distance scales in Figure 2.1-1. Those distances are referenced, along with major shoreline geographic features, on the contour plots presented in this section. It will be noted that contoured data generally extend to about 40 m, which is the achievable towfish depth for the cable length and normal vessel speed (~ 7 kts) used on these surveys. In one case (October survey), the vessel was slowed for several kilometers to briefly allow several oscillations of the towfish to a depth of about 60 m within a segment of water overlying Stellwagen Basin.

3.2.1 April 10 Nearfield—Cape Ann—Stellwagen Bank Loop

For this survey, the trackline extended from near Deer Island across the northwestern corner of the Nearfield on a line past Cape Ann to include part of a deeper basin northeast of Massachusetts Bay (leg 1, Figure 3.2-1). Leg 2 crossed southeast over a slight bathymetric rise before transiting a very deep basin (~ 100 m bottom depth) outside the Bay east of Stellwagen Bank. The last leg of the triangle, leg 3, crossed the Bank and Stellwagen Basin (maximum depth about 90 m) on the way towards Boston Harbor, cutting near stations N07P and N10P along the southern edge of the Nearfield.

Within a day, there were only small changes in Harbor-Bay transects as indicated by comparison to sampling on the day previous to this trackline (see April 9 survey, Section 3.1-1). Thus, one may regard data as virtually unqualified by tidal-scale, diurnal variability and the ~ 100 km covered can be examined as a semi-synoptic, continuous series across a variety of regions inside and outside the Bay.

For turbidity (Figure 3.2-1) and chlorophyll (Figure 3.2-2), similar broad regional patterns were evident. These patterns included *enriched* concentrations: a) near Boston (both legs 1 and 3), b) in surface and mid-depth patches within 5-15 km or so either side of Cape Ann, c) at mid-depth over the deep basin outside the Bay (leg 2), and d) minor patches at depth in Stellwagen Basin. Of the two measures, chlorophyll appeared to present much greater fine-scale heterogeneity in its distribution.

The highest chlorophyll concentrations were observed in rather large mid-water patches located primarily outside the Bay. Concentrations peaking at >7 $\mu g\ L^{-1}$ occurred northeast of Cape Ann (leg 1) and were nearly continuous with the large patch of very high chlorophyll at about 20 m water depth over the basin east of Stellwagen Bank (leg 2). Another patch of high chlorophyll was observed within the Bay, about 10 km southwest from Cape Ann (leg 1); in general this was the center of a 15-20 km length segment of the transect with much convolution in the contours of chlorophyll, suggestive of a complex physical oceanography in this region.

We conducted the broad-scale survey at this time in hopes of catching a southward flowing plume from spring runoff that might influence the northeastern boundary of the Bay. Such a feature was indeed found in the vicinity of Cape Ann (legs 1, 2) where the lowest surface salinities (< 31 PSU, lower than in western Massachusetts Bay) occurred (Figure 3.2.3). In this region, the surface lens of lower salinity also had higher temperature (>4 °C) than surrounding offshore water, but was similar to inshore surface water near Boston Harbor (Figure 3.2-4). The density data in Figure 3.2.5 furthermore suggest a *distinct and continuous* surface lens of lighter water existing *outside of the Bay*, i.e. seaward of a ~30 m sill at Cape Ann (leg 1). Along leg 1 from Cape Ann towards Boston and thus *inside the Bay*, there appeared also this same signature surface water (cf. Figures 3.2-3 to 3.2-5). However, in contrast to the smooth continuous distribution shown outside the Bay, data along this leg inside the Bay showed marked waviness in the pattern of density contours and a *discontinuous* surface distribution, with a patch of surface water bearing a characteristic northern boundary water mass signature from about the 25000 to 31000 m marks. At about the 18000 m mark, there was an additional surface water lens with physical and biological characteristics more like the patch of water close to the Harbor (about the 12000 m mark, leg 1) than the water outside Cape Ann.

The physical patterns suggest southward flow of water *outside* the Bay. The waviness and the appearance of separated surface lenses suggests a flow *into* the Bay that was pulsed, eddy-like, or parcelized, but certainly not continuous along the track. Speculating, bottom bathymetry and flow around the headland of Cape Ann might each contribute to complex and interrupted flow dynamics.

Each parcel of lighter, warmer, fresher water noted at the surface — whether inside or outside the Bay — characteristically had lower, rather than higher, concentrations of chlorophyll compared (horizontally or vertically) to surrounding local conditions (legs 1 and 2, Figure 3.3-2). Within the northeastern section of the Bay, patchiness in surface-water chlorophyll conditions may relate to sporadic advection of low-chlorophyll water parcels. Interestingly, the patterns of chlorophyll (Figure 3.3-2) suggest that water flowing like a river or as an isolated pool on the surface may concentrate chlorophyll at the leading (southward) edge. Perhaps as lighter water slides over existing water layers, it concentrates or creates a mid-water chlorophyll maximum.

The set of observations from this survey provides two significant conclusions relative to inputs and flow from the north (cf. Kelly, 1993 and HydroQual, 1995). First, the data provide firm evidence to suggest that some boundary flow will skirt the edge of the Bay, and not become entrained within it. Clearly, only a portion of the mass of southward coastal current flow functions as input to the Bay. Second, in this specific case, the implied flow from the north does not carry high chlorophyll into the Bay (or even southward outside the Bay). Previously, we noted that dissolved inorganic nitrogen (DIN) concentrations were low in the surface water at stations near Cape Ann (similar to the rest of the Bay surface) (Kelly *et al.*, 1994b). Given approximately equivalent DIN and probably lower particulate nitrogen, we therefore have no reason to believe that the low salinity water seemingly flowing south at this time is *elevated* in total nutrients (dissolved and particulate) compared to concentrations in the surface water resident in the Bay. More likely, it was nutrient-depleted compared to the offshore Bay surface waters. As less-enriched water from the north moves in and pushes out the (more enriched) resident Bay water, a consequential effect would be to decrease *in situ* Bay concentrations. Such an effect would likely be small and is dependent on the input volume, but it would be a decrease nonetheless; note that such an effect may be counterintuitive to the mindset that any mass of nutrient loading to an open system will enrich the system. Concentration changes in a substantial volume of flow across the northern boundary into the Bay can affect background concentrations within the Bay — an obvious effect demonstrated by recent Baywide modeling (e.g. HydroQual, 1995) — but we may not yet know enough about the actual concentrations and pulses of flow into the Bay across this boundary to determine the boundary's real influence on variability and concentrations of water-quality parameters within the Bay.

3.2.2 October Survey

The trackline for this survey differed slightly from the one in April in that it did not extend *past* Cape Ann into deep water (cf. leg 1, Figures 3.2-5 and 3.2-6). However, leg 2, like in April, crossed from Cape Ann southeast over the deep basin ($\sim$100 m bottom depth) east of the Bay on the way to Stellwagen Bank. On leg 2 in October (at $\sim$ 12000 m), the towfish was oscillated briefly to nearly 60 m depth (Figure 3.2-6).

A main purpose of conducting the large-scale survey at this time of the year was to examine broad-scale patterns in vertical physical structure. Of specific interest was whether regions were similarly stratified and to what degree there was a continuity of horizontal layering. Differences in salinity throughout the entire sampled region were very slight ($\sim$ 1 PSU) and most of the density stratification (Figure 3.2-6) resulted from thermal stratification. The nature of thermal layering was related to water depth, as expected for this season. Generally, surface water was a maximum of 13-14 °C and bottom water was $<$11 to $\sim$13 °C. The lower bottom-water temperatures were detected in deep water below about 30-40 m in the northeastern section of the Bay on leg 1 and leg 2. Surrounding the Nearfield (legs 1 and 3), a thermocline existed where the depth was greater than $\sim$25 m and here the bottom-water temperature was characteristically about $>$12 °C. The shallowest waters (including Stellwagen Bank and western Massachusetts Bay) were virtually unstratified.

The broad-scale distribution chlorophyll (Figure 3.2-7) showed a significant fall bloom (generally $>$3-4 ug L^{-1}) through the surface layer everywhere in the sampling region. Lower values $\leq$3 ug L^{-1} were characteristic of the completely mixed water columns over Stellwagen Bank (leg 3) and nearest Boston Harbor (legs 1 and 3). The most intense bloom of chlorophyll hung over the area surrounding the nearfield (leg 1 and 3, near 15000 m marks). The vertical extent of this bloom was crisply defined, coinciding approximately with the 24.5 σ_T isopleth, which was found near bottom sediments. The sharp shore to sea increase in chlorophyll in western Massachusetts Bay was also seen in the Harbor-Bay transect conducted about two weeks earlier (29 September, see Section 3.1)

Under conditions where water column stratification persists during this season, a particular concern and interest is concentration of DO in bottom waters (e.g., Kelly, 1991). The annual DO minimum is regularly documented at this time in western Massachusetts Bay. The minimum DO concentration measured during monitoring of standard hydrographic stations in 1994 occurred days prior to this towing survey. In 1994, this DO minimum was substantially lower than in previous years (Kelly and Turner, 1995b). For this reason, we also examined and contoured DO concentrations for this high-resolution survey (Figure 3.2-8). We present this data with a strong caution: one cannot have full confidence in the absolute levels of DO in Figure 3.2-8 because the DO sensor has a slow response to temperature changes and in rapidly sampling a sharp thermocline the towfish sensor does not have adequate time for a full, equilibrated response. With this caveat, the patterns suggested similar levels of (low) DO across a broad expanse of deeper water — from about 30 m depth to the deepest regions sampled inside the Bay and outside the Bay at depths of 40-60 m. A association of DO distribution with vertical stratification was noted. Interestingly, there was a great deal of near-bottom DO variability at the depth of the nearfield where there is an irregular bathymetry (see leg 3 at ~15000 to 24000 m marks). In comparison to absolute concentrations shown in Figure 3.2-8, we had observed bottom-water DO of 5-6 mg L^{-1} at a few nearfield stations in October sampling and a value of 4.8 mg L^{-1} at one station (Kelly and Turner, 1995b). Therefore, values detected in both standard hydrocasts and tow-yo sampling were broadly below the state standard of 6 mg L^{-1}. For further discussion of the DO topic see Kelly and Turner (1995b) and Kelly and Doering (1995).

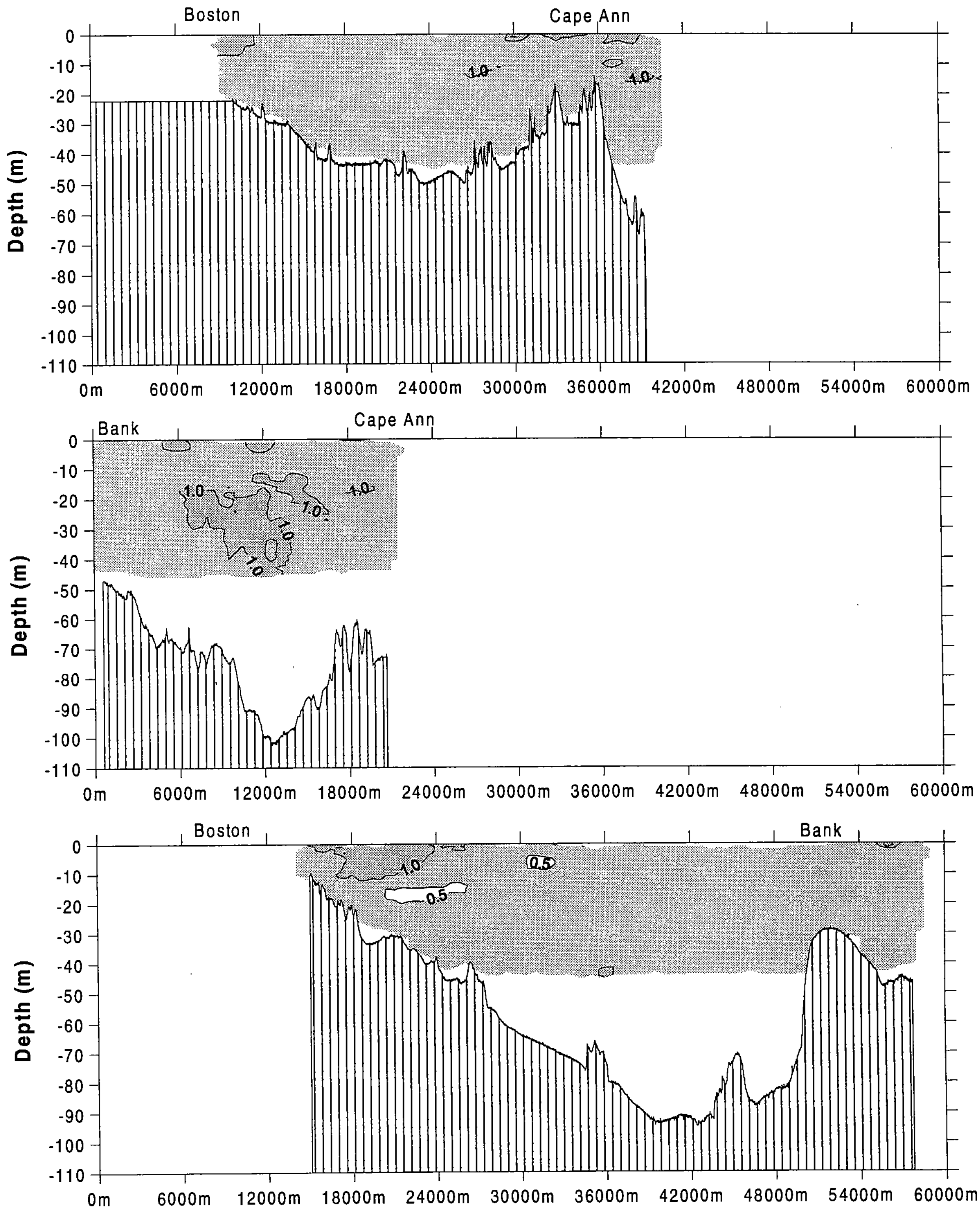


Figure 3.2-1. **Beam attenuation (m^{-1}) for Survey W9404 on April 10, 1994.**

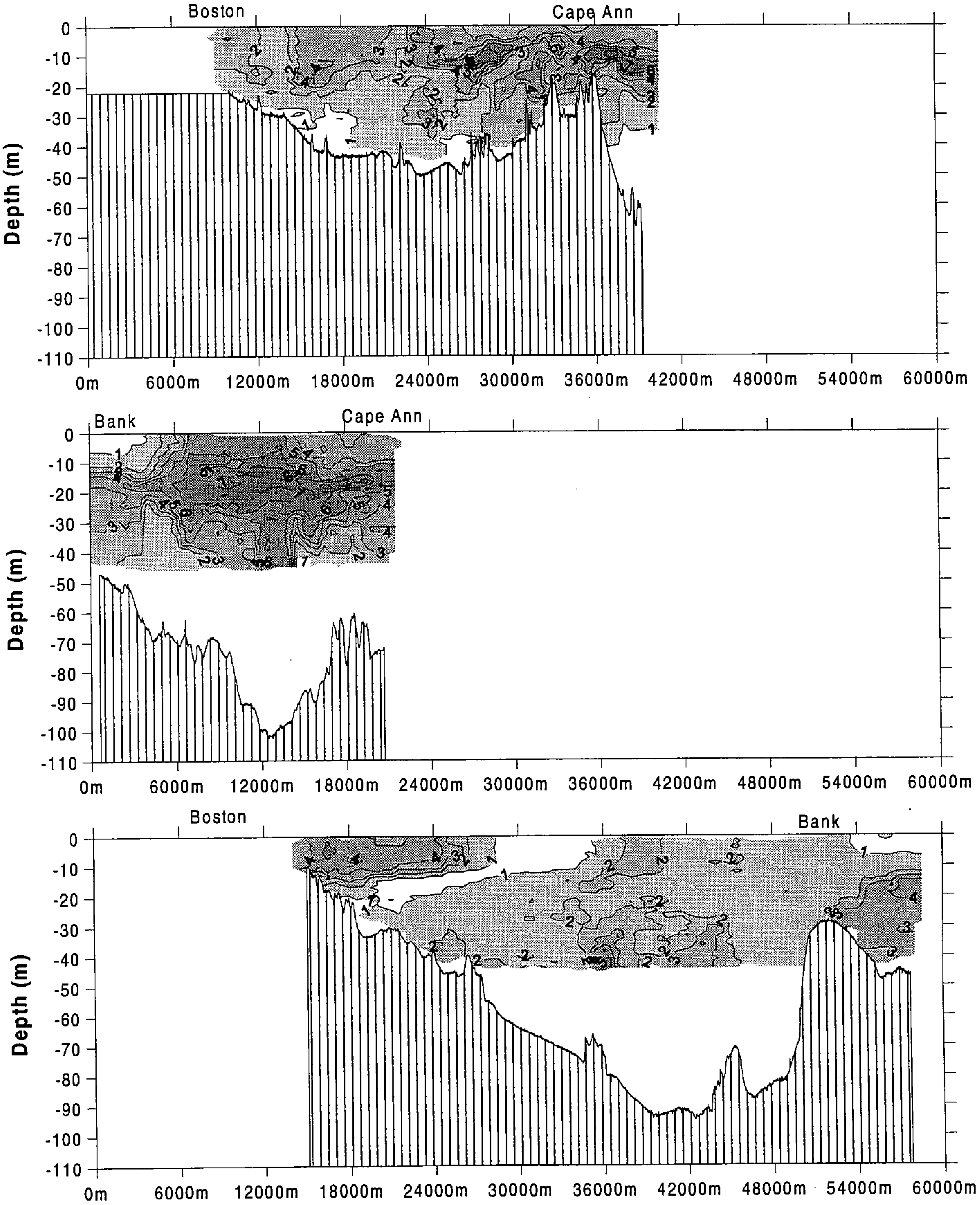


Figure 3.2-2. **Chlorophyll (μg L^{-1}) for Survey W9404 on April 10, 1994.**

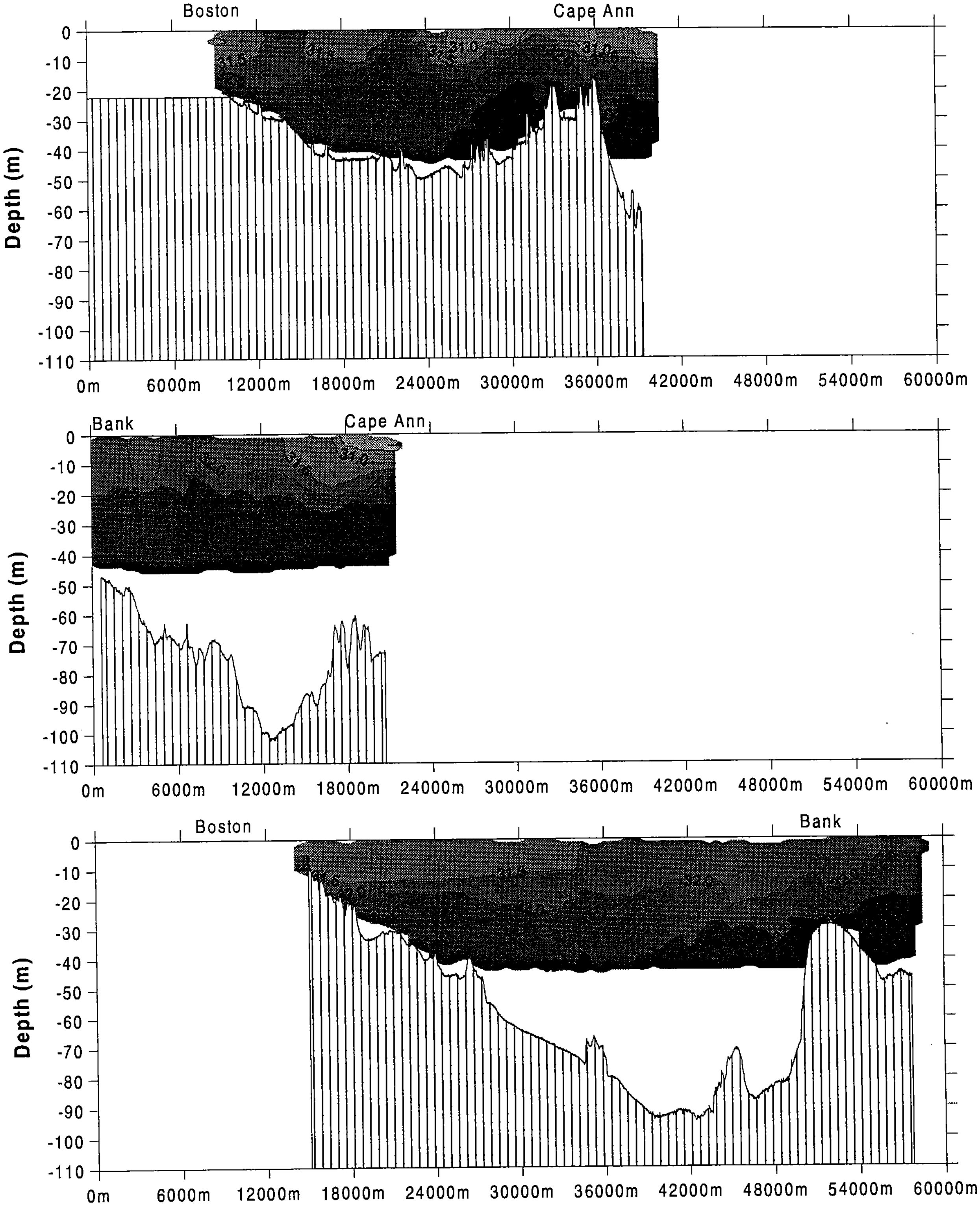


Figure 3.2-3. Salinity (PSU) for Survey W9404 on April 10, 1994.

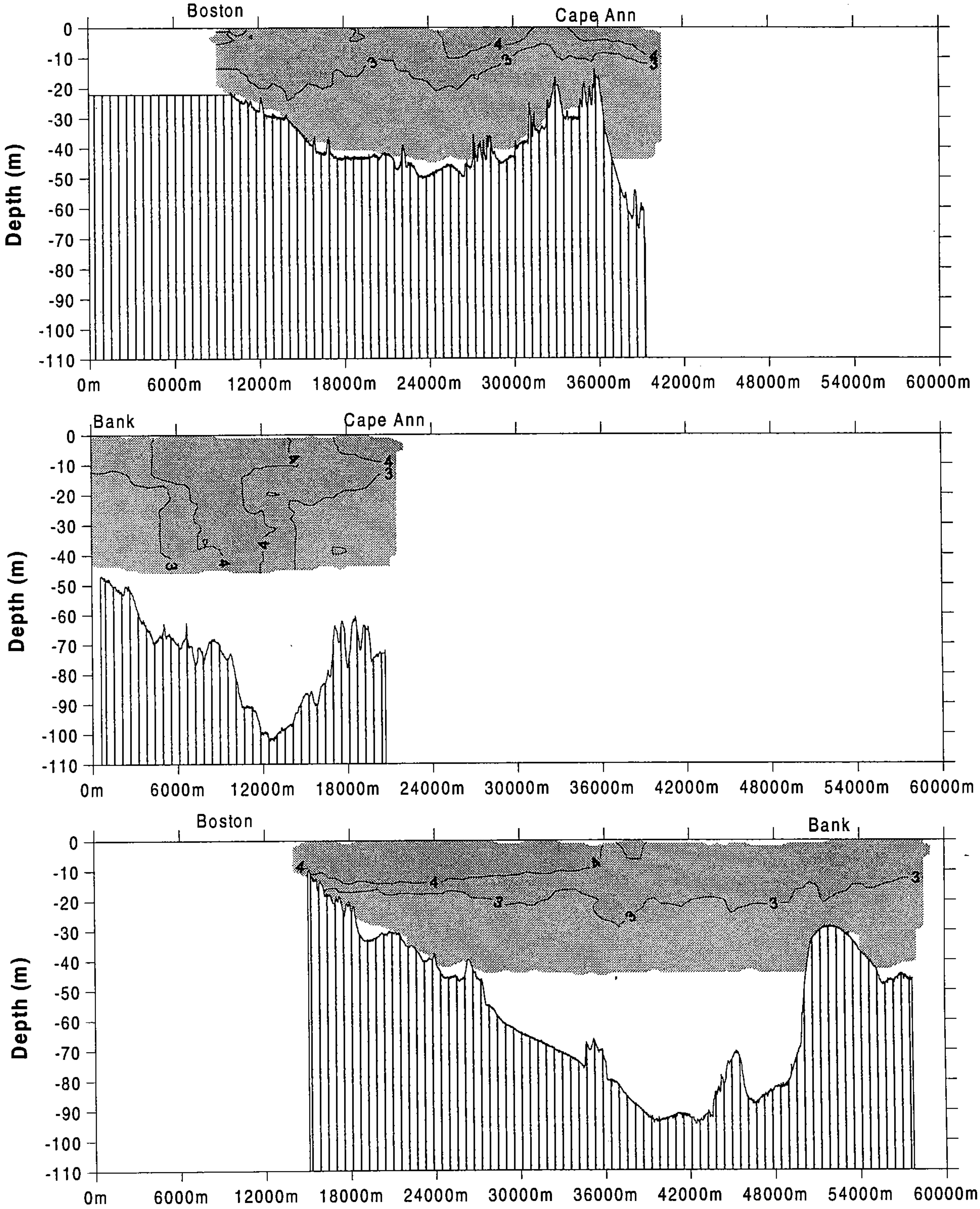


Figure 3.2-4. Temperature (°C) for Survey W9404 on April 10, 1994.

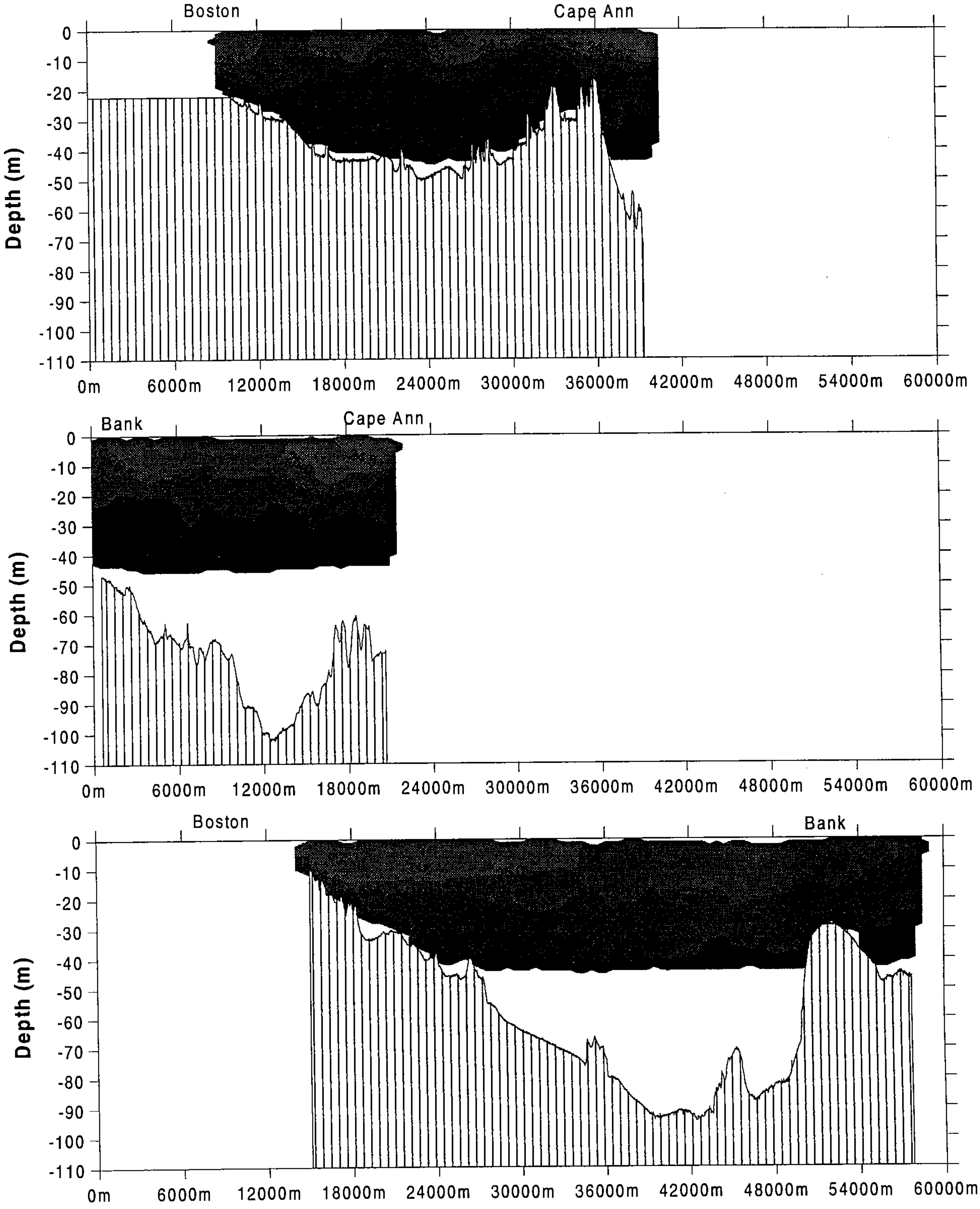


Figure 3.2-5. **Density (σ_T) for Survey W9404 on April 10, 1994.**

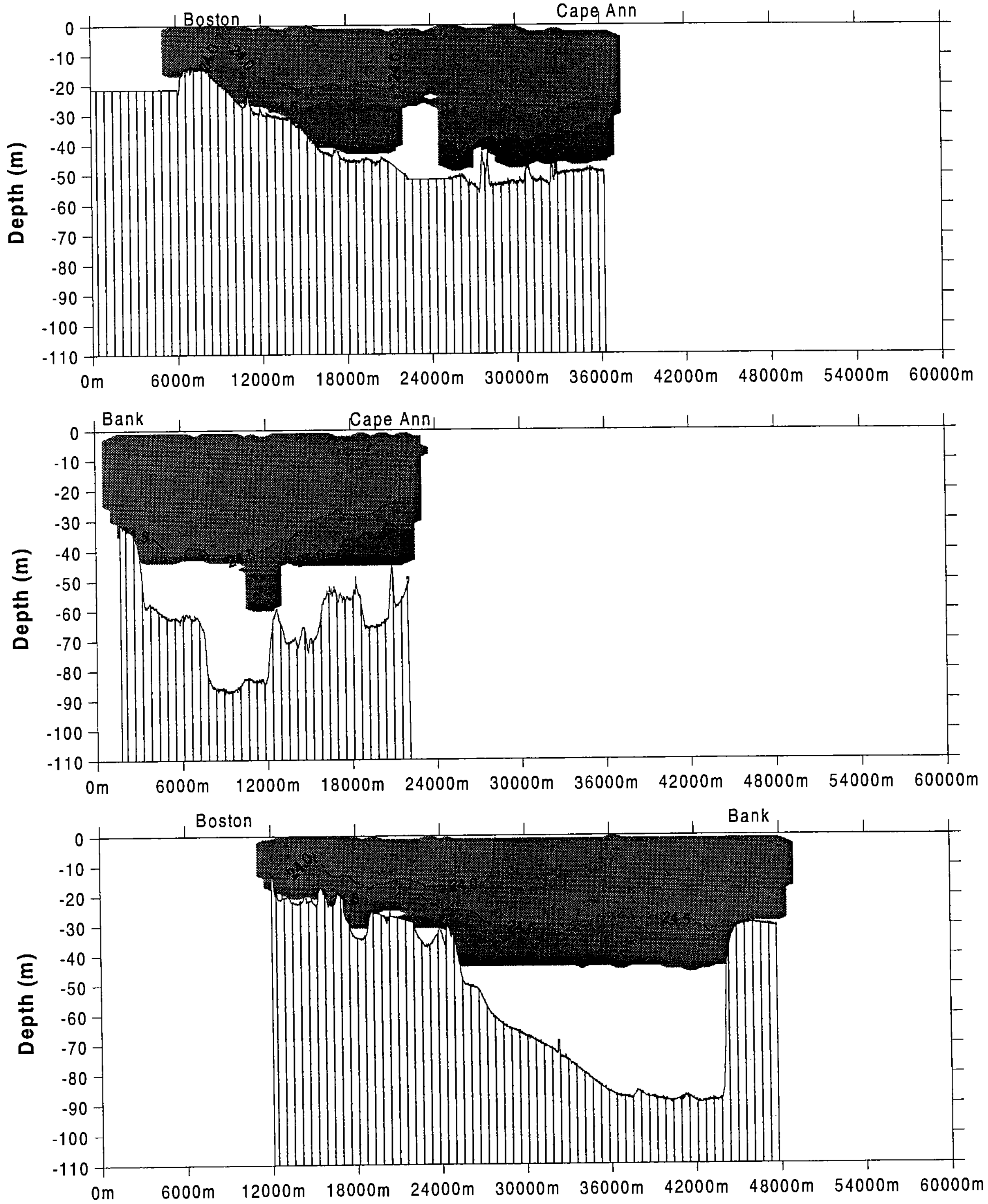


Figure 3.2-6. Density (σ_T) for Survey W9414 on October 15, 1994.

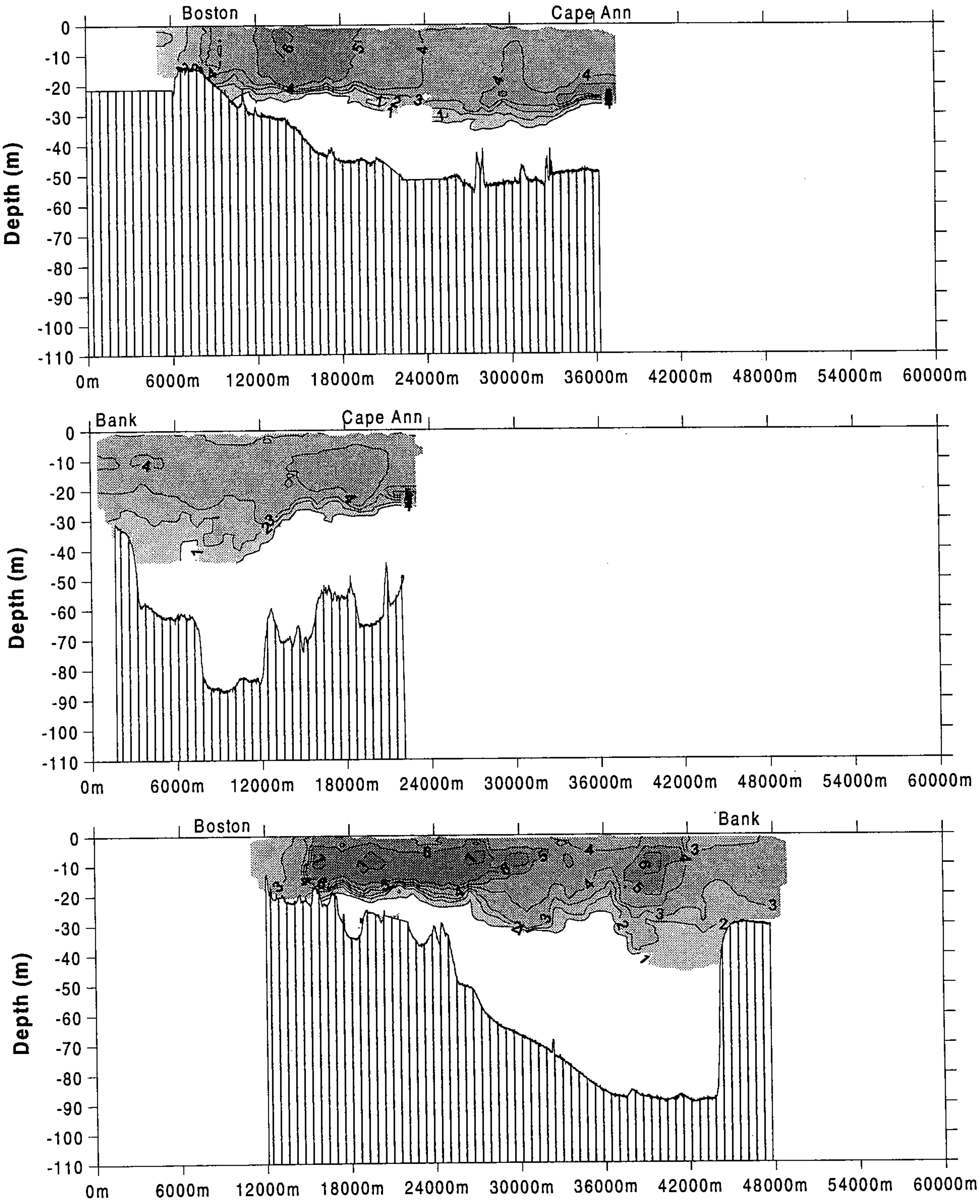


Figure 3.2-7. Chlorophyll (μg L^{-1}) for Survey W9414 on October 15, 1994.

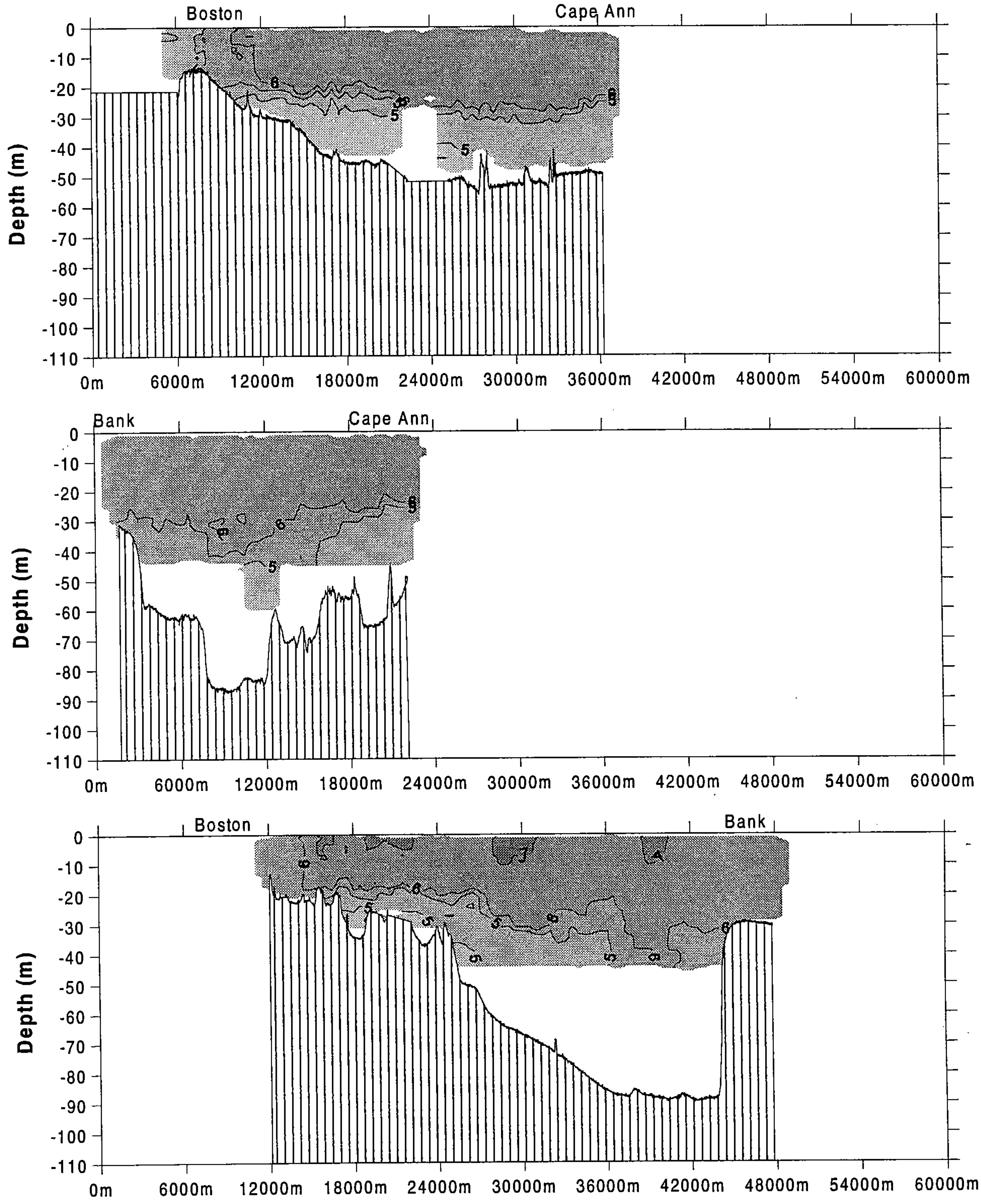


Figure 3.2-8. Dissolved oxygen (mg L^{-1}) for Survey W9414 on October 15, 1994.

Chapter 4 EMERGENT CONCEPTS OF HARBOR—BAY INTERACTION

In this discussion we emphasize features that have been revealed by the high-resolution tow-yo series that would not otherwise be evident in standard vertical profiles at a collection of stations separated by kilometers. We stress observations and hypotheses that add significantly to understanding and discussion of a geographical region with strong concentration gradients in the Bay, and which holds interest for its ecological dynamics and complexity, as well as for its significance to environmental management.

4.1 Seasonal Variability in the Nature of Harbor—Bay Coupling

A majority of the high-resolution survey effort in 1994 was expended to characterize the transect from within northern Boston Harbor to station N16P in the nearfield region of western Massachusetts Bay, a point just east of the easternmost extension of the MWRA effluent diffuser track into the Bay. Encompassing the existing gradient of conditions from inshore to offshore, surveys were intended to provide a legacy baseline characterization that will be invaluable for consultation when post-diversion assessments of water quality are conducted. The repetition of the northern Harbor-Bay transect throughout much of 1994 provides a rather unique opportunity to contrast water-quality conditions of the present and future effluent receiving areas with respect to seasonal cycles. Harbor-Bay contrasts have been made previously with more limited station profile data (e.g., Kelly and Turner, 1995a,b), but the towing data give an unprecedented degree of resolution and fidelity regarding the spatial connections of the Harbor and the Bay.

In Figures 4.1-1 through 4.1-5, we compiled data for each of nine surveys in 1994 (early March to late September). We included the legs from each survey that were conducted closest to low tide, providing cross-survey images that are tidally-normalized to the extent possible. The figures largely speak for themselves and the reader is invited to appreciate many differences in temperature, salinity, density stratification and physical layering of water masses (Figures 4.1-1 through 4.1-3). One relative constant through the year was a higher level of turbidity within the Harbor, compared to the Bay (Figure 4.1-4). Virtually independent of season, the transects documented that turbid surface water extended a number of kilometers into the Bay; the transition to clearer Bay waters was sometimes rather gradual (e.g., more like a dilution/dispersion gradient) and other times was abrupt (e.g., more like an inshore-offshore tidal front).

An interesting seasonal-scale contrast was apparent for chlorophyll (Figure 4.1-5) and it raises the notion of the seasonal variability in Harbor-Bay interaction with respect to biogeochemical cycles. Fundamentally, Harbor and Bay cycles for chlorophyll are somewhat out of phase. For example, high chlorophyll concentrations in the Bay in early Match signal an ongoing winter-spring bloom not yet expressed in the Harbor. Chlorophyll concentrations became enriched in the Harbor during summer stratification (starting in June); sporadic patches of higher chlorophyll concentrations in the Bay may be related to outflow from the Harbor. The most intense kilometers-scale chlorophyll patch in the western Bay was observed in late August, after the summer chlorophyll peak (July) in the Harbor had waned. Later in the season (late September), the Bay then experienced a broad-scale and pronounced fall chlorophyll bloom that was coincident with initiation of thermal destratification in shallower water of the Bay.

Seasonal disjunction of Harbor and Bay chlorophyll cycles suggests that there is seasonal variability in the basic nature of Harbor-Bay coupling mediated through tidal exchange. In principle, coupling can be characterized using a simple concept: mixing of a more enriched reservoir into a less enriched reservoir provides a *gross* input to the latter. Whether a *net* input is realized as the outcome is determined by the details of mixing, advection, and biogeochemical transformations within a receiving reservoir; nevertheless, the simple concept provides a first-order tool to characterize coupling.

Three sampling periods illustrate fundamental seasonal variations in exchange. 1) In early March chlorophyll concentrations in the Bay >> Harbor. In theory, simple tidal exchange and mixing could produce an import of chlorophyll to the Harbor. 2) In summer the situation appears somewhat reversed because chlorophyll concentrations in the Harbor >> Bay. This situation implies an export of chlorophyll (and thus some organic matter produced within the Harbor) to the Bay during tidal exchange. 3) In fall (starting in late September) the situation reverted to a March-like condition where chlorophyll concentrations in the Bay >> Harbor and in principle, chlorophyll influx to the Harbor may again be implied. This simplistic presentation demonstrates how material interaction between the Harbor and the Bay may change dramatically with season. With this as backdrop, discussion naturally leads to examination of tidal-scale exchange, wherein processes are nested within the broader seasonal-scale variability of Harbor and Bay cycles.

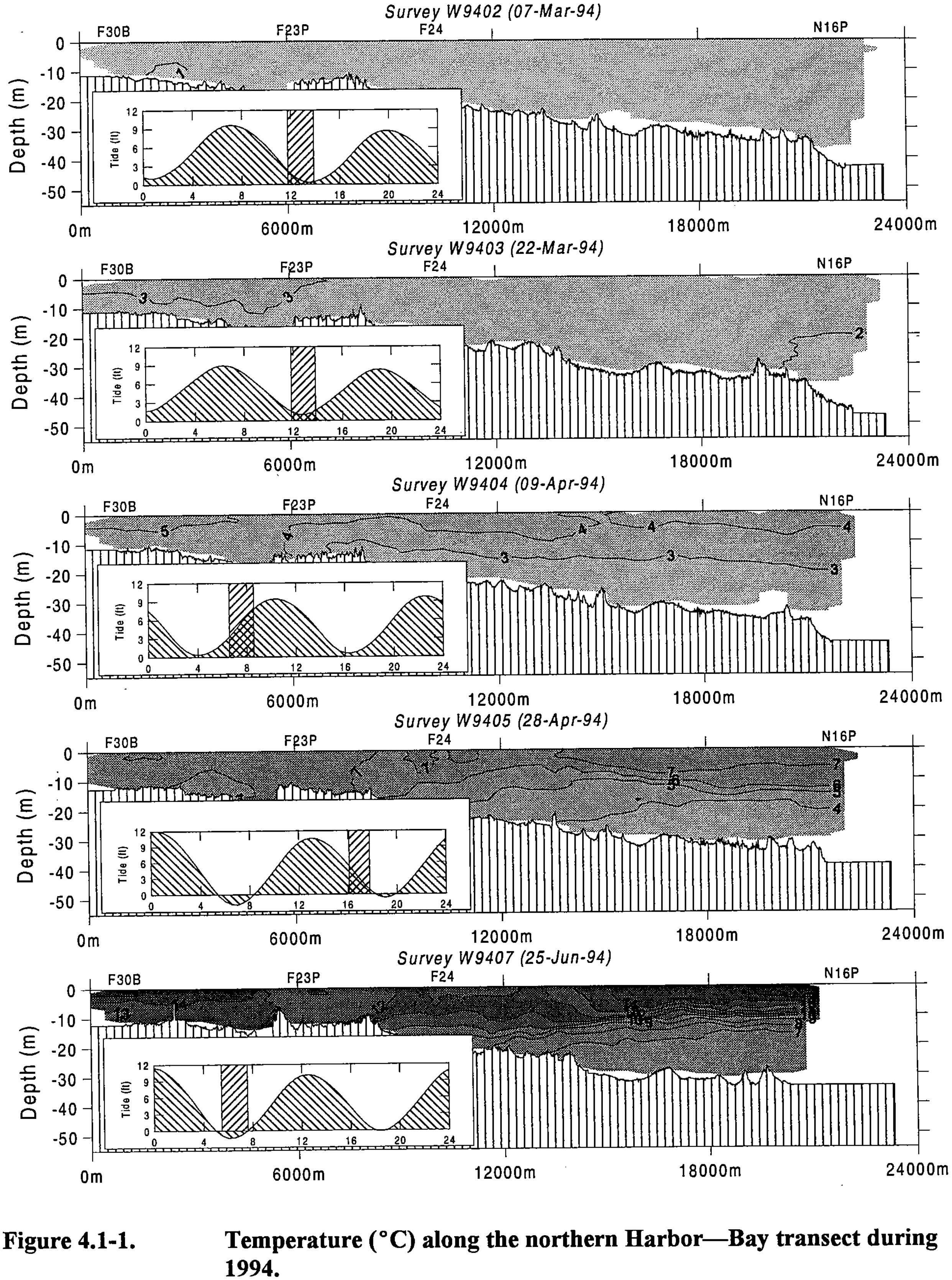


Figure 4.1-1. Temperature (°C) along the northern Harbor—Bay transect during 1994.

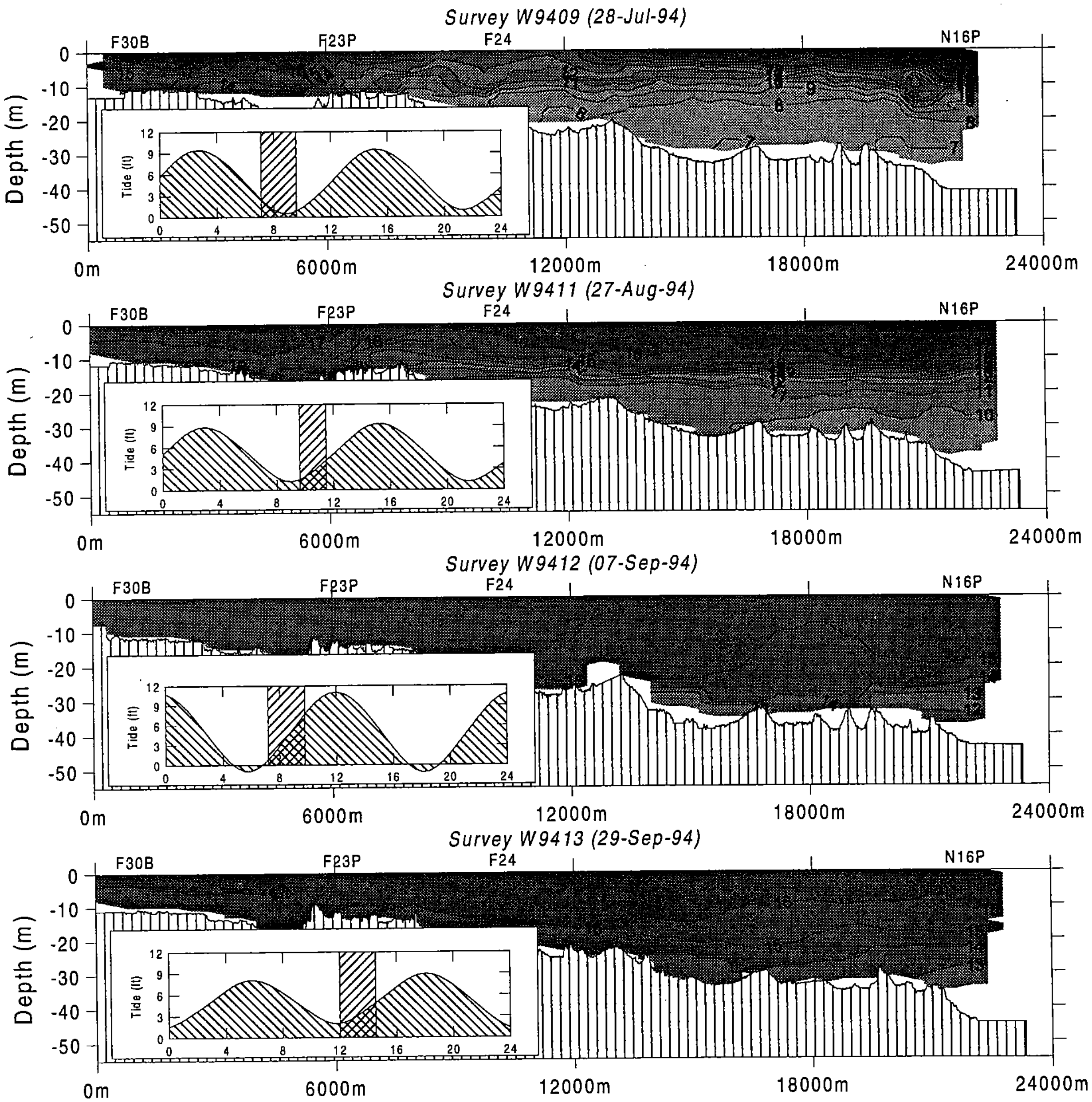


Figure 4.1-1 (cont.). Temperature (°C) along the northern Harbor—Bay transect during 1994.

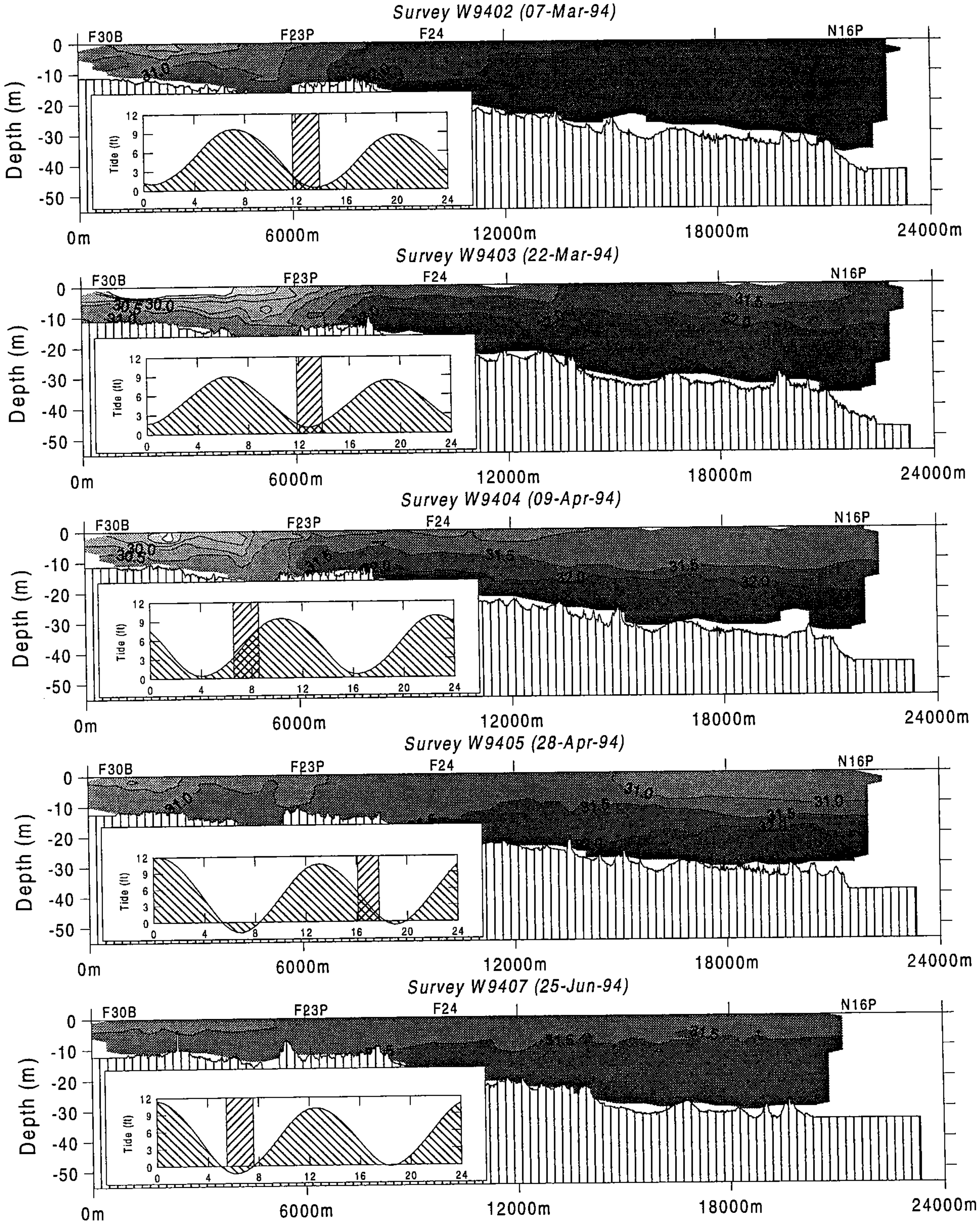


Figure 4.1-2. Salinity (PSU) along the northern Harbor—Bay transect during 1994.

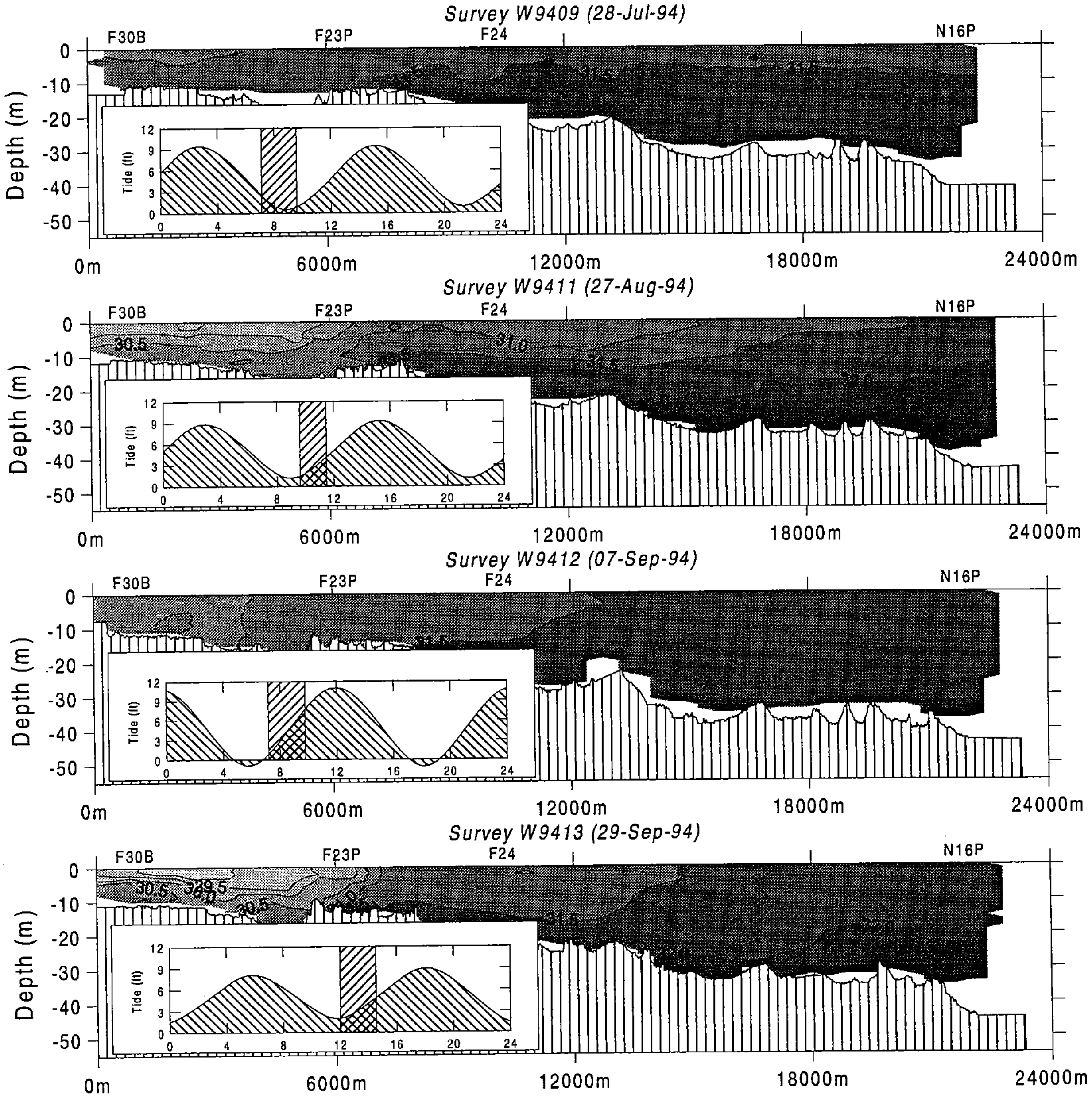
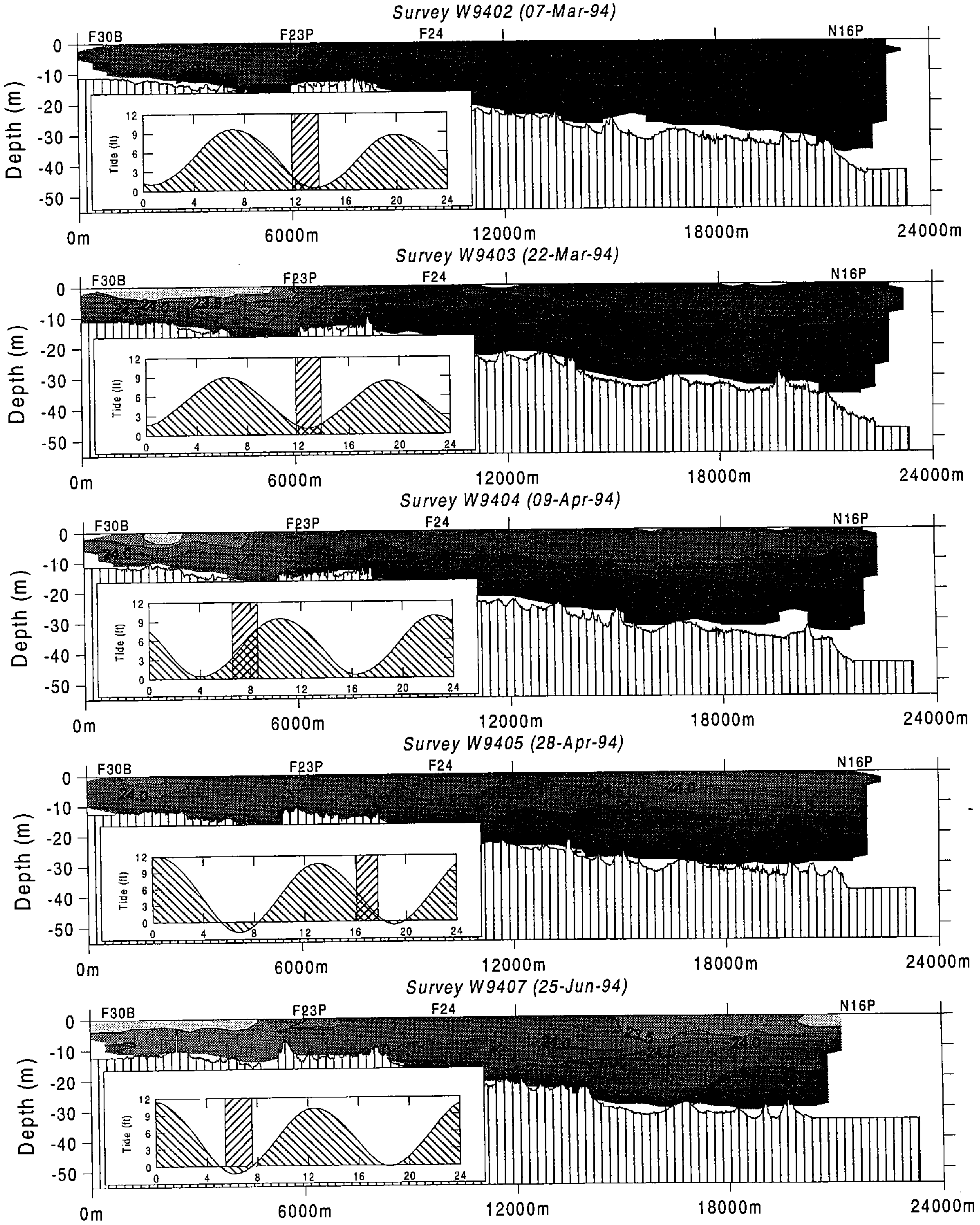


Figure 4.1-2 (cont.). Salinity (PSU) along the northern Harbor—Bay transect during 1994.



Survey W9402 (07-Mar-94)

Survey W9403 (22-Mar-94)

Survey W9404 (09-Apr-94)

Survey W9405 (28-Apr-94)

Survey W9407 (25-Jun-94)

Figure 4.1-3. Density (σ_T) along the northern Harbor—Bay transect during 1994.

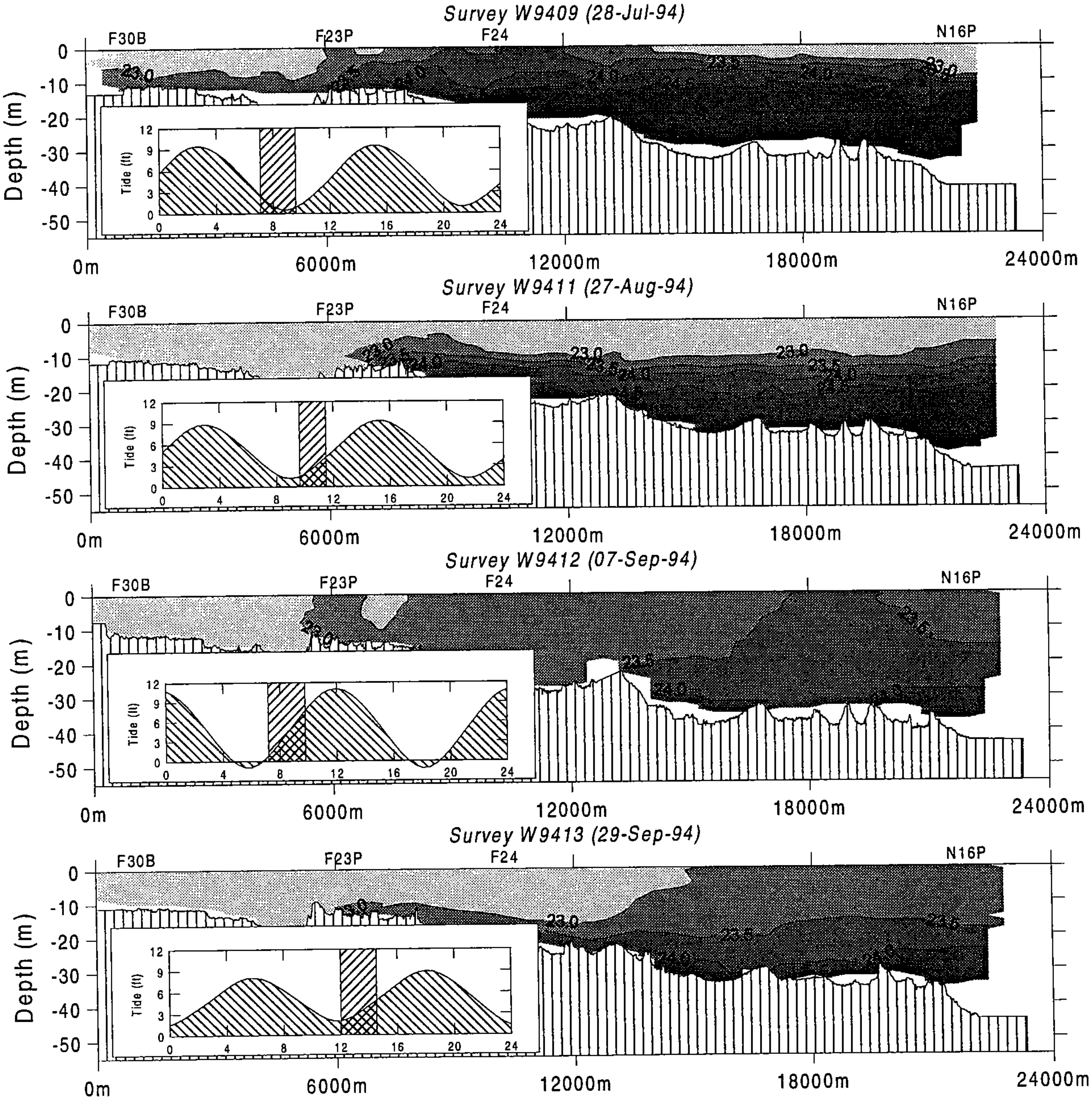
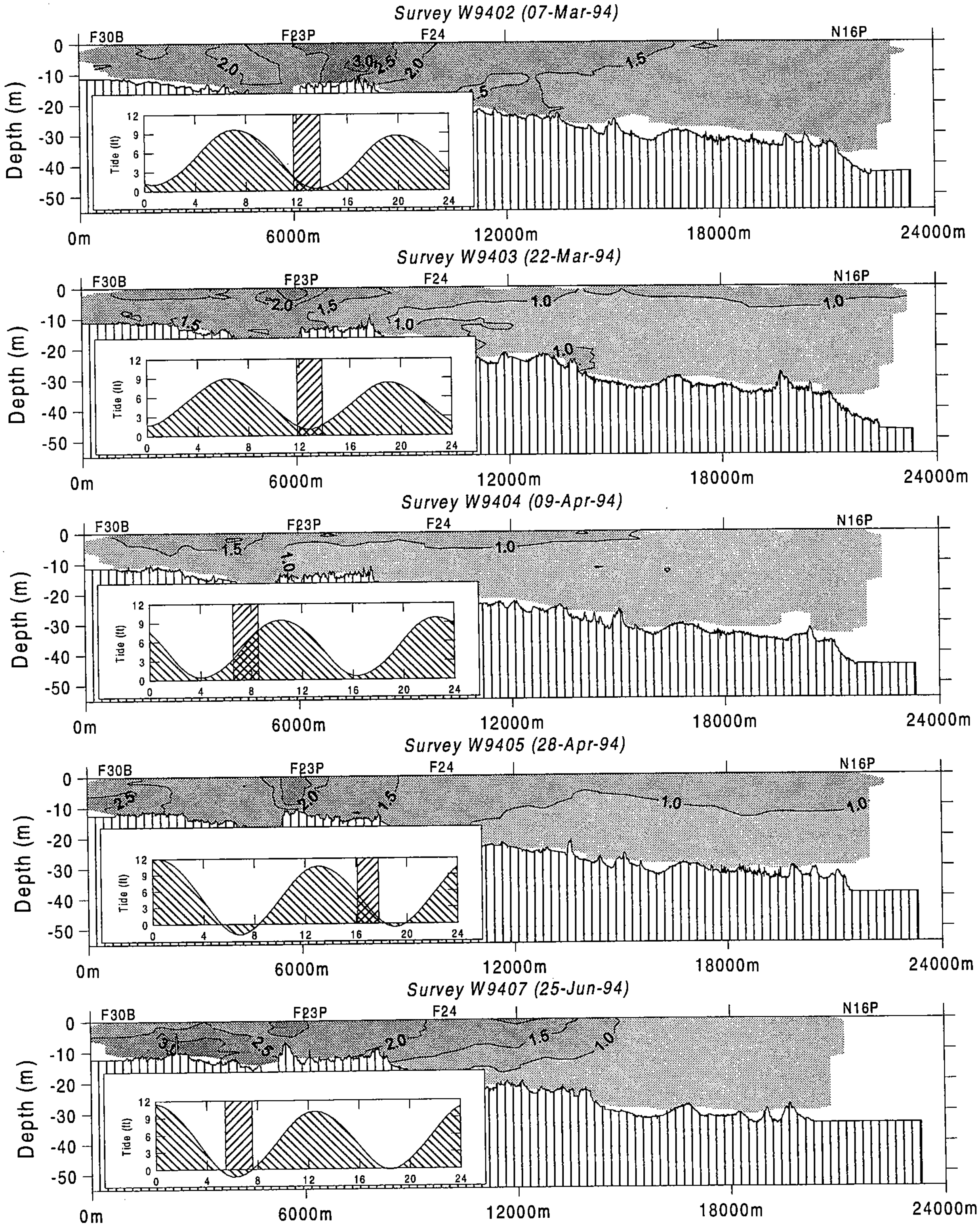


Figure 4.1-3 (cont.). Density (σ_T) along the northern Harbor—Bay transect during 1994.



Survey W9402 (07-Mar-94)

Survey W9403 (22-Mar-94)

Survey W9404 (09-Apr-94)

Survey W9405 (28-Apr-94)

Survey W9407 (25-Jun-94)

Figure 4.1-4. **Beam attenuation (m^{-1}) along the northern Harbor—Bay transect during 1994.**

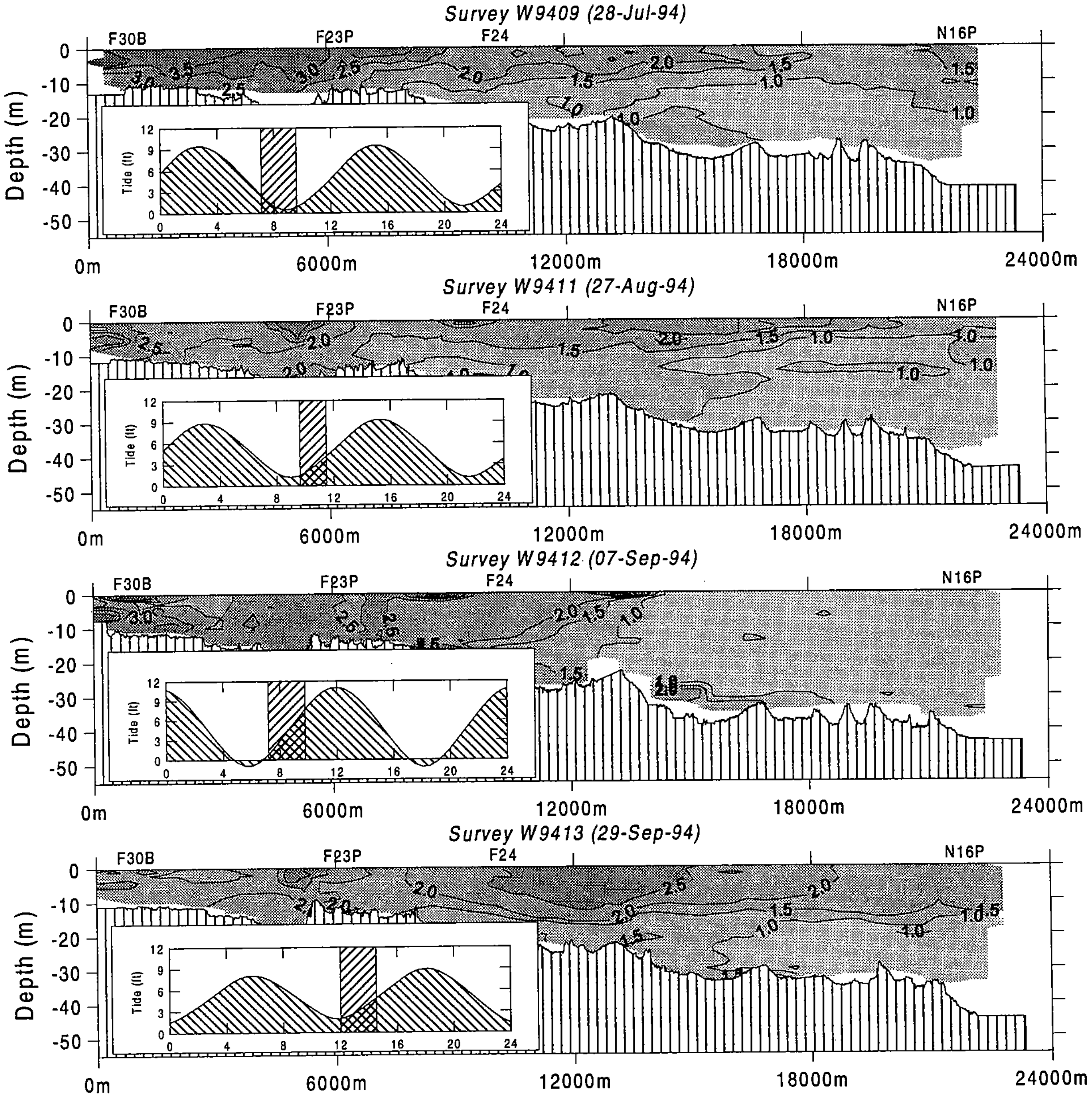
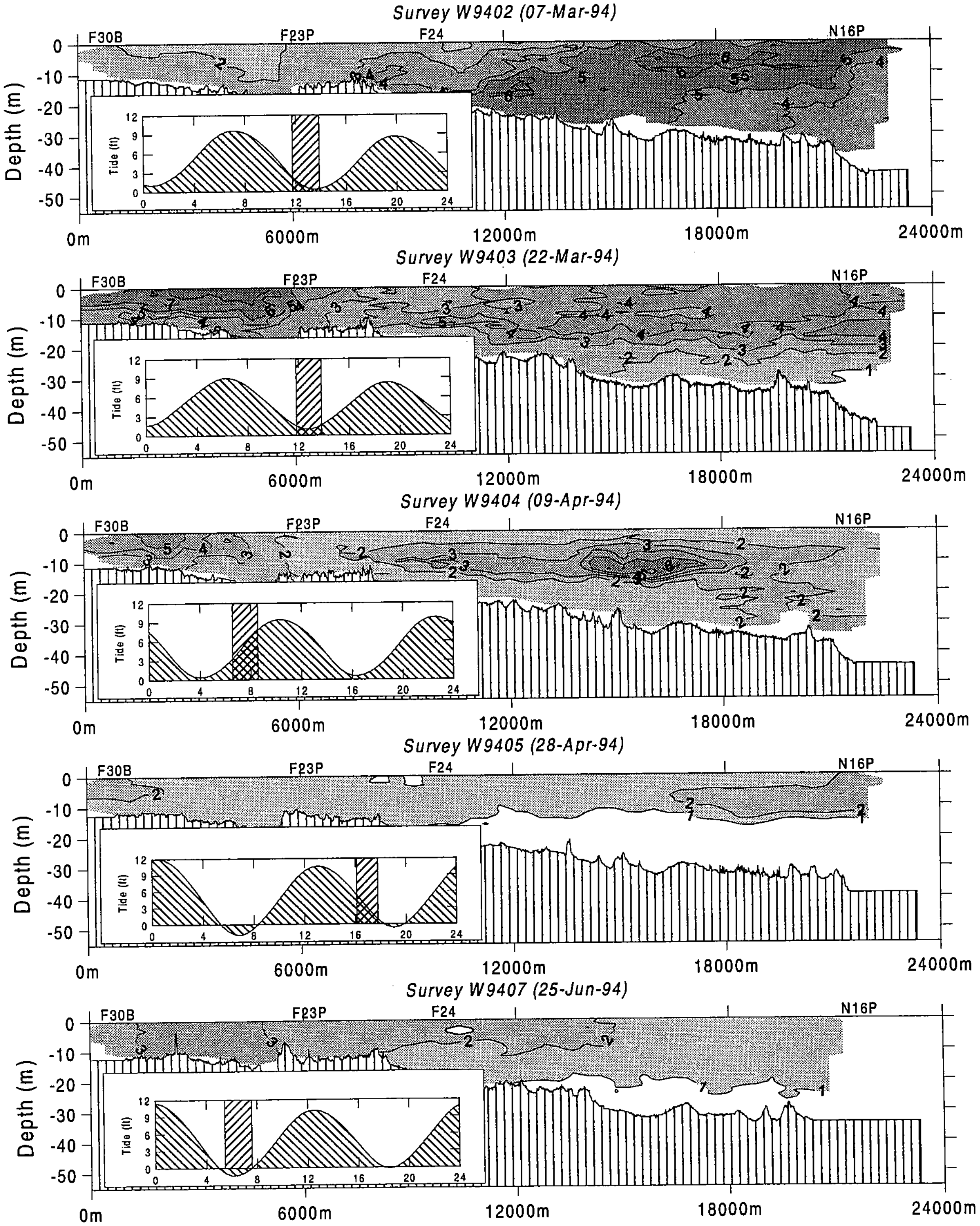


Figure 4.1-4 (cont.). Beam attenuation (m^{-1}) along the northern Harbor—Bay transect during 1994.



Survey W9402 (07-Mar-94)

Survey W9403 (22-Mar-94)

Survey W9404 (09-Apr-94)

Survey W9405 (28-Apr-94)

Survey W9407 (25-Jun-94)

Figure 4.1-5. **Chlorophyll (μg L^{-1}) along the northern Harbor—Bay transect during 1994.**

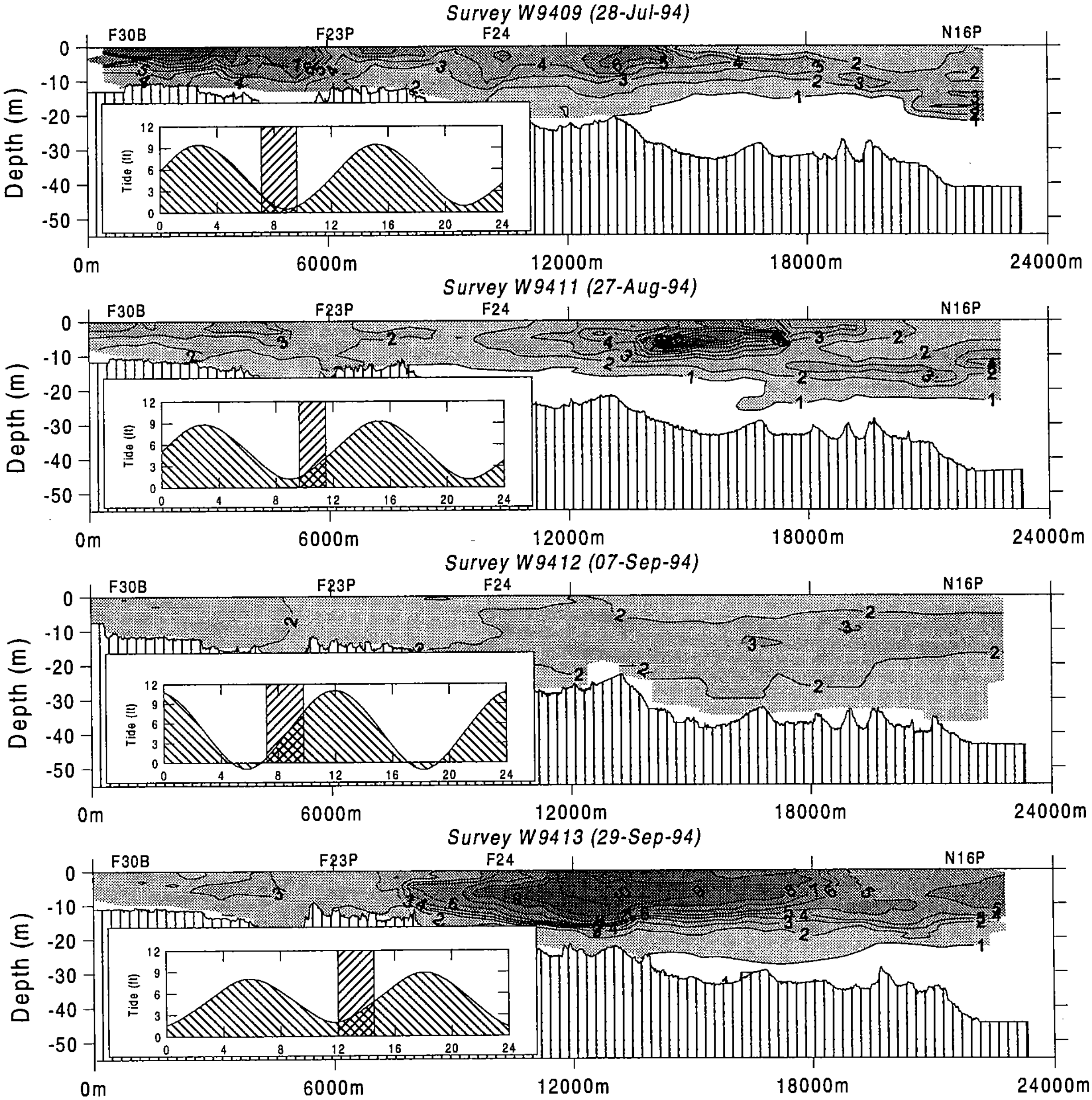


Figure 4.1-5 (cont.). Chlorophyll (μg L^{-1}) along the northern Harbor—Bay transect during 1994.

4.2 Harbor—Bay Exchange as Influenced by Seasonally-Varying Physical Constraints

For each survey we reviewed changes (especially temperature, salinity, and density) between repeated transects at different tidal stages for the transect in and out of the northern Harbor. Although our comments focus upon the northern Harbor transect, casual observations suggest that phenomenon were fairly similar and generically applicable to the southern Harbor entrance. From the data review, we offer conceptual models for the dynamics of Harbor-Bay exchange at tidal scales. These notions are intended as a guide — a qualitative basis for discussion spurring additional study — not a complete quantitative analyses.

From review of the surveys, we suggest three fundamental (seasonal) cases where differing sets of physical conditions regulate tidal interactions in an ecologically-significant manner. These cases emphasize different modes for communication of Harbor and Bay waters and periods between them are transitional, when a variety of interactions may occur. Basic observations on typical conditions for each of the three cases are synopsized next.

Case 1: The Bay surface receives Harbor outflow and the Harbor receives Bay bottom water inflow.

Conditions. A type example is the March 7 survey, when the Harbor was mildly stratified (by salinity) and the Bay was not stratified. There was less dense water throughout the Harbor, but especially at the surface.

Description. There appears a strong surface outflow with a surface lens extending into the Bay almost 10 km, as measured by the salinity signal (Figure 4.2-1). There is a noted inflow of denser Bay water (σ_T >25.5, salinity > 32 PSU) into the Harbor with the flood tide. Figure 4.2-1 suggests a two-layer estuarine tidal circulation with surface wedge outflow and bottom water inflow.

Additional considerations or modifiers. This pattern should be enhanced by increased freshwater flow, winds from the west, and with stronger (spring) tides.

Case 2: The Bay surface receives Harbor outflow, sometimes modulated, and the Harbor may receive Bay intrusion from mid-depth at the level of the pycnocline.

Conditions. The Bay is mildly or strongly stratified and in general the Harbor is mildly stratified or well mixed. Harbor water is generally less dense due to slightly lower salinity and sometimes warmer temperature. These conditions were more or less present beginning with mild stratification in the Bay in late March and continuing through about late August.

Description. Surface waters are fairly similar density and actively communicate — a slight lower salinity wedge extends into the Bay with ebb tides. Typically a flood-tide surge of water up the bathymetric slope from the Bay to the Harbor spills over into the channel and into the Harbor. Typically, the water at this depth (~15 m) is within the pycnocline. With the surge, isopycnals tend to rise at the channel's seaward edge and sometimes the rise to near-surface may produce an upwelling between stations F23P and F24 (Figure 4.2-2).

Additional considerations or modifiers. It is unclear whether upwelling is strong enough to produce a convection from within the pycnocline to the surface that then becomes carried seaward with ebb flow. Wind direction and strength might modify the pattern with respect to convection. Additional freshwater flow might restriction upwelling/convection. Regardless, we can suggest that the flood surge and pycnocline rise can act to modulate the surface outflow from the Harbor, particularly by interrupting and "parcelizing" output. This process may thus promote advection of discrete small parcels of water of Harbor origin into the coastal circulation within western Massachusetts Bay. On the other hand, there is clear evidence for advection from within the pycnocline into the Harbor. Tidal strength will in part determine the extent of this flow.

Case 3: The Bay surface receives Harbor outflow and inflow from the Bay is restricted to water from within the surface layer.

Conditions. This case occurs when there is a very deep pycnocline in the Bay, as exemplified by the two September surveys, September 7 and 29. Lighter Harbor water is distinct from that within the Bay surface layer and can spread over the surface in the Bay.

Description. With this case, the surface mixed layer and the pycnocline are deep enough that the flood tide excursion does not surge up the bathymetric rise far enough to reach the depth of the channel into the Harbor (Figure 4.2-3). Depending on the level of freshwater flow from the Harbor, there may or may not be significant inflow on the flood tide, of water from the surface layer of the Bay. For example, on September 29 (Figure 4.2-3) the Harbor salinity decreased significantly from September 7 (<30 PSU vs. >31 PSU). The wedge of light Harbor water ($\sigma_T < 23$) extended to the bottom sediments to the Harbor's channel-edge (past station F23P) at mid-high tide and was fully to the seaward side of the channel at low tide. In this way, Harbor water may effectively expand to cover the entire region of the channel and part of Broad Sound as an extended buffer zone; excursion of this entire body of water with the tides may occur with net outflow as surface release to the Bay, but with little inflow to the Harbor because of the bathymetric restriction at the seaward edge of the channel to the Harbor.

> Additional considerations or modifiers. As suggested, this pattern may be modified by changes in freshwater flow. Whereas increased freshwater flow may tend to restrict two-layer inflow-outflow, winds from the west and stronger (spring) tides may tend to promote more of a two-layer circulation.

The primary physical factors that appear influential in regulating the present interaction between the Harbor and the Bay are summarized in Table 4-1. Of the factors in the list, the principal advancement offered by results of our high-resolution studies is the impact of variability in the depth of the seasonal thermocline in the Bay. Recent previous efforts on Harbor and Bay physical circulation and modeling (e.g., Signell and Butman, 1992; Signell *et al.*, 1995; Geyer *et al.*, 1992; Adams *et al.*, 1992) have emphasized the other factors in the table.

Table 4-1. Suggested Physical Features Causing Significant Variability in the Nature of Harbor-Bay Interaction Mediated by Tides.

FEATURE	MECHANISM OF INFLUENCE	SUGGESTED EFFECT ON INTERACTION
Depth of thermocline/ pycnocline in Bay	Controls the depth and layer of Bay water that flood into the Harbor	Communication between surface and bottom layers in Harbor and Bay
Tidal height (e.g., spring vs neap tide volumes)	Interacts with depth of thermocline to regulate quality of flooding water	Communication between surface and bottom layers in Harbor and Bay; degree of tidal pumping at inlets
Freshwater flow volume	Alters density differences between Harbor and Bay, as well as vertical layering	Strength of export flow and degree of two-layer estuarine circulation
Meteorological conditions (e.g. wind speed, direction, variability)	Modifies surface flow	Modulates two-layer flow; affects upwelling vs. downwelling phenomenon

It is useful to further discuss how variations in physical aspects of tidally-mediated exchange link with notions for chlorophyll exchange as simply outlined in Section 4.1.

Case 1. In the wintertime conditions, there is a period when the winter-spring bloom has been initiated in the Bay but not yet in the Harbor. As indicated, during tidal exchange, there must be an import of chlorophyll to the Harbor. From detailed examination of physical variation with the tide, it appears that chlorophyll input may occur in bottom water inflow, since there is general freshwater outflow suggested at the surface at this time. Using salinity as a conservative tracer, Kelly (1993) suggested that there is substantial Harbor export of dissolved nutrient forms in surface water at this time. The Case 1 hypothesis is that Harbor-Bay coupling therefore appears to involve export of dissolved nutrients from the Harbor and import of a portion of organic matter produced within the Bay, and which in part is supported by the dissolved nutrient export (Figure 4.2-4).

Case 2. The nature of the coupling is qualitatively reversed in the summer, when chlorophyll concentrations generally in the Harbor exceed the Bay. The situation implies an export of chlorophyll (and thus some organic matter produced within the Harbor) to the Bay during tidal exchange. The general chlorophyll gradients depicted from inshore to offshore during summer (Figure 4.1-5), although often being a patchy distribution, are broadly characteristic of the region (cf. Kelly 1991, 1993) and indicative of export of chlorophyll to the Bay in near-surface waters. Dissolved nutrients, although slightly enriched within the Harbor, are generally low throughout the region at this time. Kelly (1993) provided strong evidence that primary surface-water export from the Harbor to the Bay during summer stratification occurs in organic and particulate nutrient forms, including plankton biomass (indicated by chlorophyll). As the basic Case 2 hypothesis from the set of observation, however, we suggest there is chlorophyll (and organic matter) export in surface water and dissolved import from the Bay in water from within the pycnocline (Figure 4.2-5). Whether dissolved nutrients from depth in the Bay offer a feedback conduit to Harbor-Bay cycles or are strongly involved tidal exchange processes may depend on the precise meteorological and tidal phase conditions. For example, Signell and Butman (1992) suggested the morphometry of the Harbor entrances may promote an phenomenon of "tidal pumping" (Stommel and Farmer, 1952; see also Geyer and Signell, 1992) and one would expect greater dispelling of export into the Bay on spring tides. The previous studies did not have the benefit of detailed understanding of the vertical structure of the water column offered by our observations. Here we additionally suggest that, while "pumping" seems a reasonable concept and fairly apt descriptor, it is also possible that bathymetric-induced upwelling, also a function of tidal phase and current strength, (Figure 4.2-5) may act to interrupt outflow such that tidal cycles produce discrete or semi-discrete parcels which then advect with Bay circulation and mixing. Seeing as how these parcels, during summer, are characteristically laden with turbidity and chlorophyll compared to the receiving Bay water, we think the term "tidal puffing" to be appropriately descriptive term for the hypothesis. This case and associated dynamics are further explored in Section 5.

Case 3. In fall (late September) chlorophyll concentrations again are characteristically higher in the Bay than in the Harbor. In that sense this case has some similarity to case 1 conditions. However, the cases differs from the first case because chlorophyll influx to the Harbor in late fall may occur only when waters *within or above* the pycnocline are exchanged during tidal processes and deep stratification precludes bottom-water exchanges (Figure 4.2-6). Probably the more ecologically significant feature of the interaction at this time relates to surface output. Nutrient concentrations are typically higher in the Harbor at this time (e.g., Kelly and Turner, 1995a,b). In this case, our hypothesis is that nutrient export helps stimulate and feed the fall bloom in the Bay at the seaward edge of the tidal front.

These three case hypotheses raise two main topics. The first relates to physical mechanisms for Harbor-Bay coupling and future effluent discharge conditions. The second relates to ecological effects of the present coupling, viewed from the perspective of the receiving system.

With respect to the first topic, a firm conclusion is that there is variability in the fundamental nature of communication between the Harbor and the Bay. We believe this range of variability is not fully included in any water-quality modeling projections to date (cf. Signell *et al.*, 1995; HydroQual, 1995).

The full range of variability and complexity of Harbor-Bay exchange is useful to keep in mind for continuing efforts to predict and monitor the changes in water quality from the future outfall diversion. For example, we suggest that when the Bay's water column is fully mixed, there can occur (at present) communication of bottom water in the Bay with the Harbor. This is postulated as a consequence of two-layered circulation established in part by the strength and character of freshwater flow. Note that freshwater flow will be somewhat diminished with effluent diversion, which may moderate the conditions that presently seem to promote bottom water intrusion. Secondly, during stratification, when it is expected that an offshore outfall effluent plume will rise towards the pycnocline, it appears to be water *from within the pycnocline* in the western Bay which communicates with water of the Harbor. In both these cases, we expect effluent to be greatly diluted compared to present conditions. Moreover, the strength of infusion of water with any level of diluted effluent depends on horizontal excursion rates, because the nearest diffuser of the future outfall is located some distance from the location of water hypothesized to communication with the Harbor based on our observations. Given the very strong layering during stratification, and the greater apparent rate of horizontal vs. vertical dispersions at the pycnocline as determined by recent dye studies (Geyer and Ledwell, 1994), the possibility exists of communication of diluted effluent through the pycnocline as a conduit back into the Harbor.

Related to the second topic — ecological effects — is one simple question. Is export from the Harbor during summer stratification purely advective and dispersive or does it stimulate ecological events in the receiving system? This topic has interest because it has been suggested from observations and calculations (cf., Kelly, 1993) that presently, export from the Harbor does support *in situ* production of chlorophyll biomass in western Massachusetts Bay and within the Nearfield region. Predictions of future conditions of effluent diversion have suggested that production in the surface layer of western Massachusetts Bay may therefore decrease with a dilute effluent trapped below the surface photic layer (Kelly, 1991, 1993; HydroQual, 1995).

Hypotheses on physical mechanisms and ecological responses are not independent of each other. Both topics are further explored in the next chapter. But before that, some final cautions. One problem with the concepts, notions, and hypotheses suggested above is that they are perhaps too empirical and therefore subject to local, and not fully characterized, conditions at the time of measurement. That is one reason they are posed as concepts, notions, and hypotheses to be further examined, rather than a substantiated theory. A second issue is that even though derived from spatially high-resolved measurements, the measurements in time are not frequent relative to the time scales of physical forcing. Moreover, measurements are not fully synoptic, for the tracks themselves are conducted over about 2 h or more and thus cover a third or more of a flood or ebb portion of a semi-diurnal tide. Additionally, repeated track measurements offer strong clues to dynamics, but are nonetheless based totally on static, not dynamic properties. Related to this, we recognize that interpreting changes over repeated lines as movement along the transect is imperfect, for cross-track motions also must be considered. Finally, although dominant tidal motions are semi-aligned with the survey tracks from Harbor to Bay, the possibility of cross-track flow exists and this is not possible to assess from data along a linear transect. Related to these issues of dynamics, one discussion theme in the next chapter focuses on the occasion in June 1994 when we had the opportunity to make simultaneous measurements of current velocity along the transect sections. This special study allows perspective on a number of issues of interpretation from static properties.

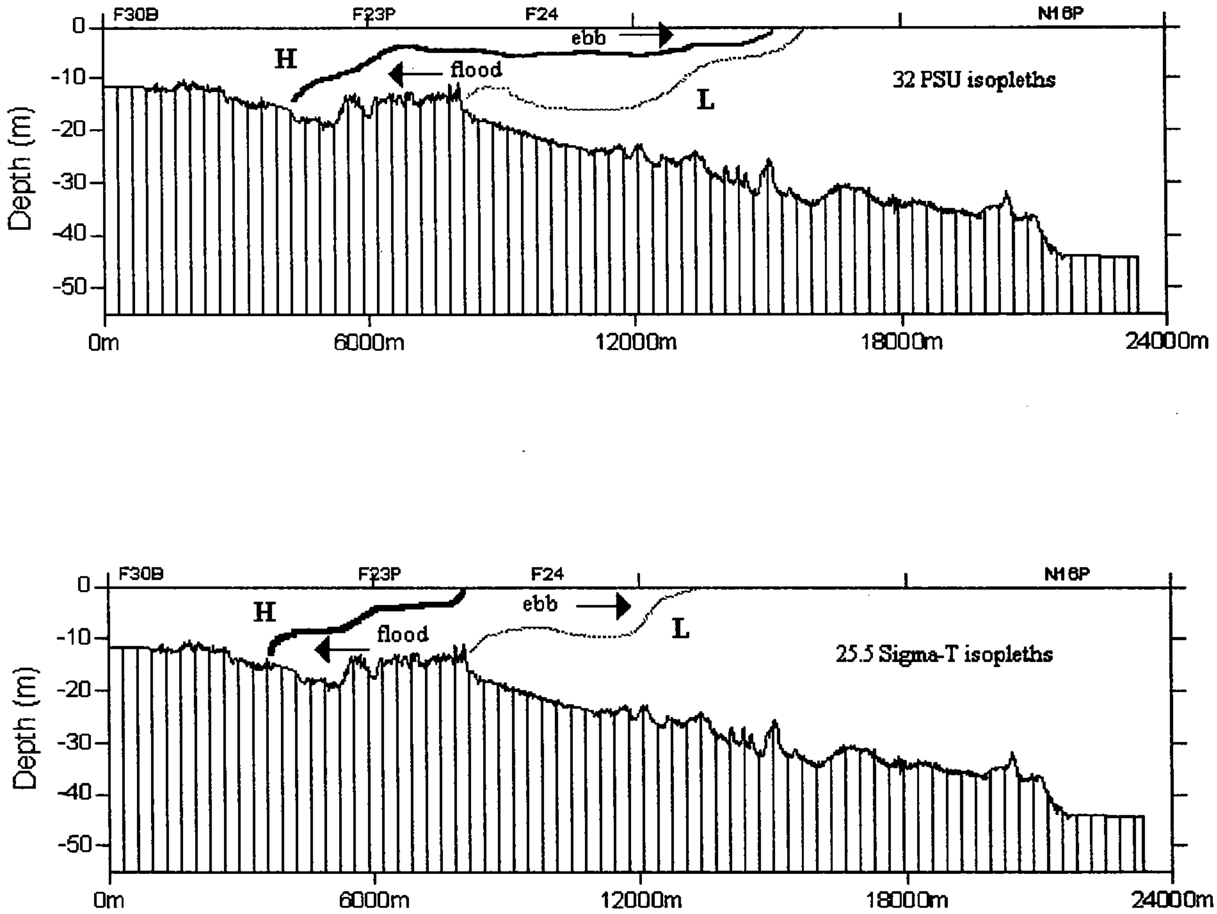


Figure 4.2-1. **Physical exchange scenario based on winter-spring conditions. Top shows salinity and bottom shows density isopleth movements with high and low tide, based on March 7 survey.**

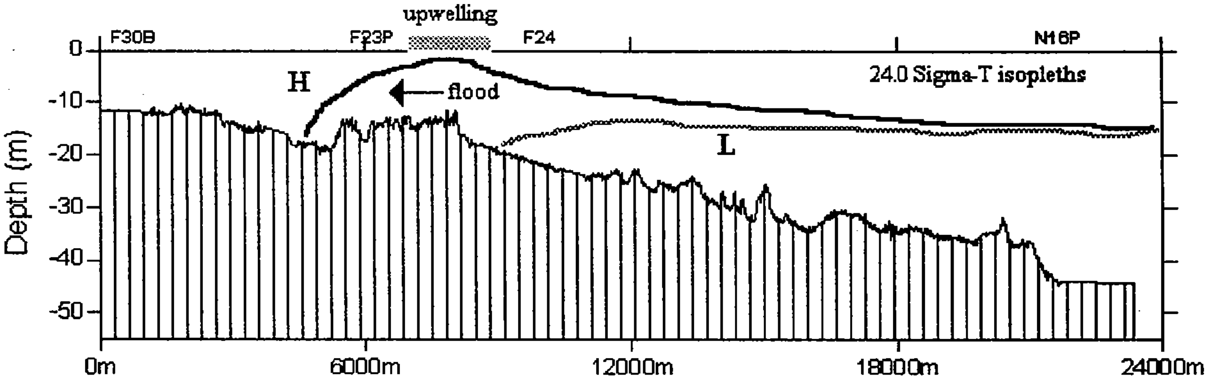


Figure 4.2-2. Physical exchange scenario based on summer conditions. Density isopleth movements are shown with tidal motion, based on June 25 survey.

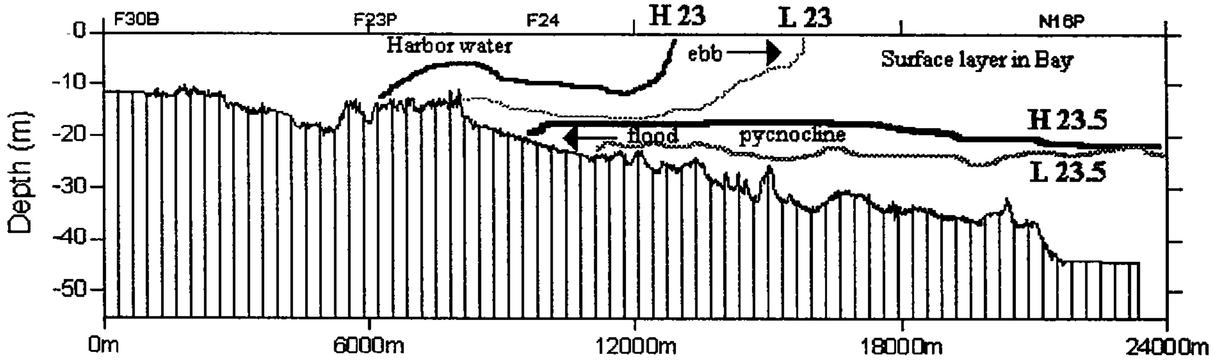


Figure 4.2-3. Physical exchange scenario based on fall conditions. Density isopleth movements are shown with tidal motion, based on June 25 survey. The 23.0 isopleth indicates Harbor water and the 23.5 isopleth indicates the position of the deep pycnocline in the Bay.

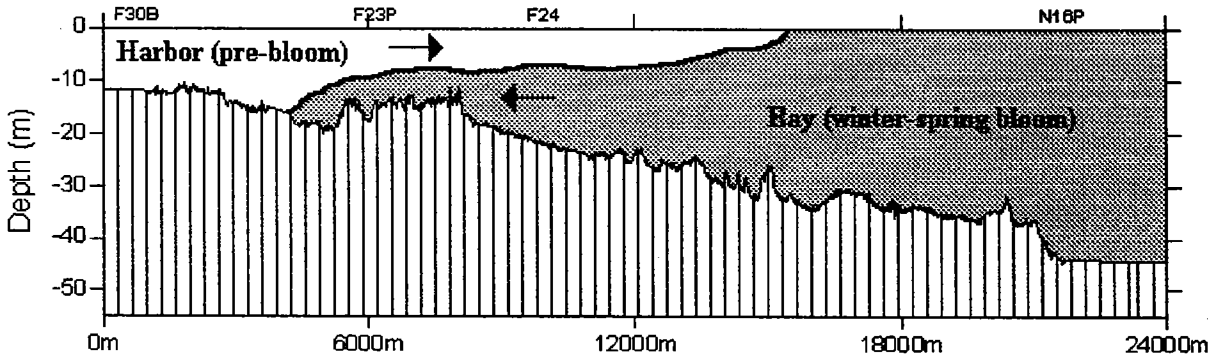


Figure 4.2-4. Case 1 conceptualized diagram of the ecological interaction of Harbor and Bay. There appears to be chlorophyll (and thus particulate organic) input to the Harbor with bottom water and dissolved nutrient export to the Bay in surface water.

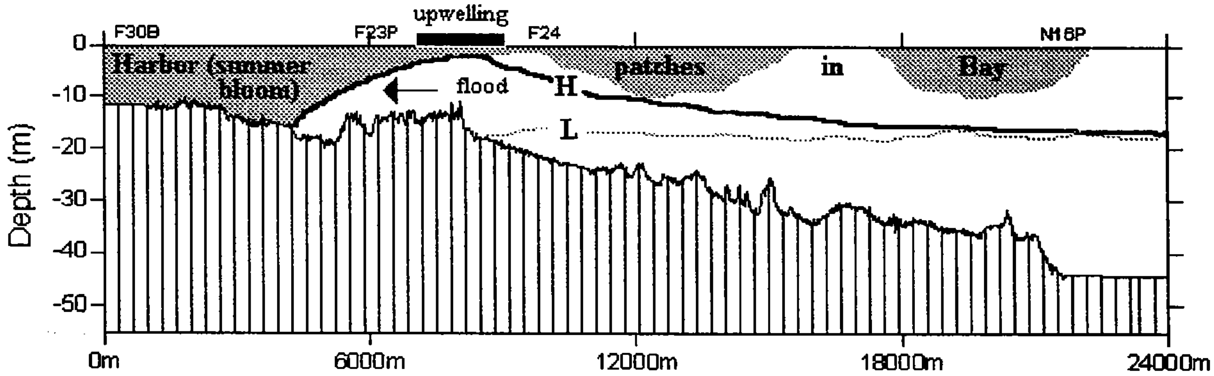


Figure 4.2-5. Case 2 conceptualized diagram of the ecological interaction of Harbor and Bay. Inflow to Harbor may depend on the phase of the tide and meteorological conditions. It seems possible to have chlorophyll and dissolved nutrient input from the Harbor to the Bay, through exchange from within the pycnocline, not the Bay's bottom water. Tidally-regulated upwelling may interrupt and "parcelize" a strong export of chlorophyll to the Bay in surface water.

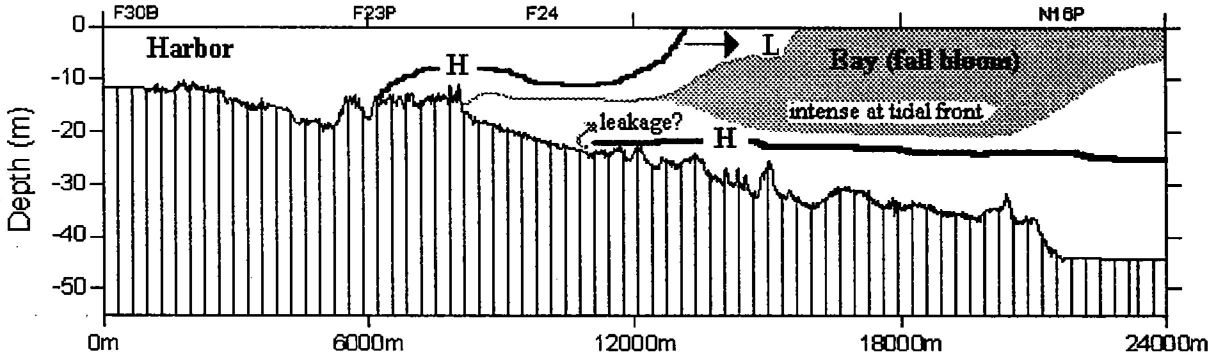


Figure 4.2-6. Case 3 conceptualized diagram of the ecological interaction of Harbor and Bay. Dissolved output from the Harbor may again be exported to the Bay and there contribute to chlorophyll growth in the Bay's receiving water. It is possible that leakage of bottom-water nutrients occurs where the bathymetry interacts with tides to disrupt the pycnocline. Inflow to the Harbor of the Bay's surface mixed layer may occur, but this may be inhibited by density differences between Harbor and Bay water.

Chapter 5 SPECIAL TOPICS DISCUSSION

There were many facets of Harbor-Bay interaction and Bay-wide patterns revealed by these studies, as suggested in survey descriptions. Comprehensive quantitative examination is far beyond the scope of this report. However, in this chapter, we address two selected topics in greater detail:

> *Topic 1: Detailed dynamics of tidal exchange with respect to velocity distributions and physical mechanisms to explain water quality distributions in time and space during tidal cycles* (Section 5.1), and
>
> *Topic 2: Harbor export during summer and ecological responses with the receiving system* (Section 5.2).

5.1 Western Massachusetts Bay Velocity Survey in June 1994
(Contributed by W. Rockwell Geyer)

5.1.1 Introduction

The BOSS high-resolution surveys provide detailed information about water properties, but they lack information about velocities. A shipboard acoustic Doppler current profiler (ADCP) can provide the velocity structure to complement the water-properties data obtained by BOSS. This section presents the results of a survey was conducted in June, 1994, with these objectives:

1. Documenting the tidal velocity structure;
2. Determining the magnitude and variation of estuarine circulation;
3. Identifying convergence zones and fronts;
4. Interpreting time-variations of water properties;
5. Assessing the feasibility of future monitoring activities with combined use of the ADCP and BOSS.

5.1.2 Methods

A survey was conducted on June 25, 1994, between Boston Inner Harbor and western Massachusetts Bay (Figure 5.1-1) on the R/V Marlin. The seaward end of the track coincides with the new MWRA sewage outfall. A 1200 kHz ADCP (manufactured by RD Instruments) was mounted to the side of the vessel, with its transducers approximately 1.3-m below the water surface. Velocity data were obtained at 1-m depth intervals (or "bins"). The uppermost velocity bin was centered at 2.3-m depth. The maximum depth of velocity resolution for 1200 kHz units is about 30 m. In waters less than 30-m, the lowest 15% of the water column are not resolved due to interference of the bottom echo. The velocity of the ship is determined by the bottom echo. The precision of the measurements for 30 second averages is ±1 cm s^{-1}, and the accuracy is ±5 cm s^{-1} (Geyer and Signell, 1990). The ship speed averaged 3 m s^{-1} (or 6 kts). The raw data were averaged into horizontal bins of 100-m length, for a total of 206 bins between the Inner Harbor and the end of the line. This corresponds to approximately 30 seconds per bin, or 70 pings of the ADCP. Position information was provided by a differential GPS system as part of the BOSS data acquisition system.

Errors in bottom tracking were identified by comparison with the navigation system. Comparison of the ship speed based on navigation with that from bottom tracking showed excellent performance of the bottom tracking system (rms error < .5%). However, there were errors associated with the rotation of the velocity vector that are due to a problem in the firmware of the instrument. These errors were identified by regression analysis between the ship velocity and water velocity and were corrected.

5.1.3 Results

The tidal conditions were intermediate between springs and neaps (3.2 m range; 10% greater than average). High water occurred at 1329 EDT (all times are reported in local time, EDT). The weather was overcast, with easterly winds estimated at 10–15 kts. The Boston meteorological buoy was not reporting winds at this time.

Sampling commenced at 0630 and was completed at 1745. Three round-trips were performed, yielding six transects[1]. The last two were shortened due to time constraints. The portion of the track that was covered by all six transects was subject to tidal analysis to determine the magnitude of the tidal and "mean" or non-tidal velocity over the sampling period. The ship tracks in the vicinity of the Harbor entrance varied in lateral position, due to navigational constraints with unusually heavy ship traffic. This produced variations in velocity between lines that do not reflect temporal changes but rather spatial variations of the flow. These variations in position degraded the tidal analysis in the vicinity of the Harbor entrance.

Spatial structure of the flow. The spatial variability of the flow is evident in maps of near-surface velocity vectors (Figure 5.1-2). These plots indicate the magnitude and direction of the current at the shallowest depth bin (2.3-m depth). Every 10th sample was plotted (corresponding to 5 minutes or roughly 1 km). At the beginning of the first line (Figure 5.1-2a), the tide is still ebbing in the Harbor, with speeds of up to 40 cm s^{-1}, but it is beginning to flood by the end of the line. Tidal analysis reveal that this change in flow is not due to spatial variation but rather to the finite time (almost 2 hours) required to complete one transect. The abrupt reversal just south of Deer Island is likely due to an eddy (see Signell and Butman, 1992, for detailed observations and modeling of the flow in President Roads). The second line (Figure 5.1-2b) shows an

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[1] Note that in this section, transects are referred to as "lines" rather than "legs", the terminology used through the rest of the report.

increase in flooding velocity, with a maximum inflow velocity of 88 cm s^{-1} at the Harbor entrance. The third line (Figure 5.1-2c) shows a continuation of strong flood conditions at the Harbor entrance, and weak currents in the Bay. The fourth line (Figure 5.1-2d) starts at slack high water at the seaward end of the line and reaches the Harbor entrance during the early ebb. There are complex cross-flows at the Harbor entrance during this phase of the tide. The fifth line (Figure 5.1-2e) shows early ebb conditions, with outflows of around 30 cm s^{-1} at the mouth. The sixth line occurs during strong ebb conditions, with more than 80 cm s^{-1} outflow to the east of the Harbor entrance. The weak and irregular flows in the Harbor entrance result from the ship track moving out of the main channel to avoid vessel traffic.

Vertical structure. The eastward (roughly along-channel, rotated to an orientation of 75°) component of velocity is shown as a function of depth and distance in Figure 5.1-3. The horizontal coordinate is referenced to the tip of Deer Island at the Harbor entrance, with distance measured relative to a coordinate system oriented at 75°. The geographical position of the transects can be referenced to Figure 5.1-1. During the first line (Figure 5.1-3a), there is an apparent convergence at km 0 in the Harbor entrance. However the vector velocity data (Figure 5.1-2a) suggest that it is due to a horizontal eddy. Just seaward of the Harbor entrance (km 4–6), the near-bottom flow is flooding while the surface flow is still ebbing. During the second line (Figure 5.1-3b), again there are abrupt convergences near the Harbor entrance that result from the three-dimensionality of the flow. There is significant vertical structure in the inflow, with stronger inflow at depth and weak flow near the surface. As will be shown later this variation is due to both a mean, estuarine circulation and an internal tide. During the third line (Figure 5.1-3c), the flow through the Harbor entrance is relatively uniform in the vertical, but there are vertical variations in velocity throughout the seaward portion of the transect. The fourth line (Figure 5.1-3d) also shows considerable vertical variation in the flow in the seaward portion, with flood continuing at depth after the surface has started to ebb. The fifth line (Figure 5.1-3e) takes place during strong ebb. The large variations in the flow near the Harbor entrance (km -2–2) are related to crossing in and out of eddies at the edge of the navigation channel. The sixth line (Figure 5.1-3f) continues through the strong ebb. Again there are large variations due to crossing in and out of the navigation channel.

Tidal analysis. A least-squares tidal analysis was performed for each horizontal and vertical bin, using a mean and semi-diurnal (12.42 hour period) oscillation to fit the observations according to the relationship

$$u(x,z,t) = U_{mean}(x,z) + U_{M2}(x,z)\cos(\omega t - \Phi(x,z))$$

where $U_{mean}(x,z)$ is the tidally averaged velocity, U_{M2} is the amplitude of the semi-diurnal velocity in the EW direction and Φ is the phase in degrees. The phase is referenced to the time of high water in Boston. A phase shift of -28° would indicate that the current starts to ebb 1 hour before high water.

The results of this analysis are shown in Figure 5.1-4. The amplitude of the semi-diurnal velocity reaches a maximum of more than 80 cm s^{-1} at the Harbor mouth, and it decreases rapidly in either direction. Note that the analysis does not extend over the entire line, since it is limited to the portion of the survey for which there are 6 transects. The phase of the semi-diurnal current (Figure 5.1-4b) shows uniform vertical structure within the Harbor, but there is a pronounced phase shift with depth in the vicinity of the Harbor entrance. This phase shift indicates that the currents start to flood approximately 2 hours earlier at depth than they do at the surface. Such a phase shift is too great to be explained by frictional effects; it must be due to an internal tide (see Section 5.1.4). The variations in vertical structure associated with the internal tide are also evident in vertical profiles of E-W velocity (Figure 5.1-5). The large shears between 5 and 10-m depth correspond to the pycnocline.

Mean velocity. The estimation of the mean velocity is crude, due to the limited number of transects and the large amount of variation in position between lines. The analysis is particularly suspect in the vicinity of the Harbor entrance, where the large tidal velocities dominate over the residual. Further seaward, where the tidal velocities are weaker and the ship track is more consistent, the mean velocity estimates are reasonable. The mean velocity vectors in the region seaward of the Harbor entrance are shown in Figure 5.1-6. They show an estuarine-like circulation in the deeper water (km 4 to 8), with deep water moving landward and surface water moving seaward.

Temperature measurements. A description of the water quality (BOSS) results is found in Section 3.1.2, but a brief comparison of the water properties observations to the currents is warranted here. Figure 5.1-7 shows temperature contours for the 6 transects. A strong thermocline is evident during the first two lines. It slopes down in the landward direction from 10- to 20-m depth, where it intersects the bottom. A surface front is evident at 10-km. This feature is associated with the velocity convergence (Figure 5.1-3a). The intersection of these water masses probably results in downwelling of the 12°C water under the warm layer. The bottom front intrudes across the sill at 2 km during line 3, bringing 10°C water up into the mouth region. The intrusion of cold water continues in line 4, as evidenced by an increase in thickness of the cold layer between 2 and 8 km. The velocity observations at the same time show a lingering inflow between 10 and 20-m depth. The 5th and 6th lines show the influence of the strong ebb flow in pushing the cold water back out of the Harbor.

Salinity. Salinity data for lines 1 and 4 are shown in Figure 5.1-8. The water in the Harbor is slightly fresher than that immediately offshore, but the surface salinity decreases again moving seaward. Low-salinity water is often observed in western Massachusetts Bay, apparently as a result of non-local inputs from the rivers of the Gulf of Maine (see Geyer *et al.*, 1992).

Density. The density data (Figure 5.1-9) reflect the combined influence of temperature and salinity. The bottom front is evident during line 1. Note that there is no significant horizontal density gradient in the surface waters, indicating the relatively weak forcing of the estuarine circulation.

Light Transmission. Measurements of light transmission (as beam attenuation, in m^{-1}) are shown in Figure 5.1-10. They show a clear distinction between the relatively clear, Bay water and the turbid Harbor water. The motion of the front is evident, although it is not at clear as in the temperature record.

5.1.4 Discussion

Comparison with other observations. The magnitude of the tidal currents at the mouth of the Harbor are larger than the 60 cm s^{-1} tidal currents observed during a survey in 1990 (see Signell and Butman, 1992). Those observations were made during neap tides (2.5 m range), explaining the difference in tidal velocities. Detailed comparison between the observations and the model results of Signell and Butman (1992) is difficult without a dedicated model run for the conditions of the field observations. A casual comparison suggests that the model results and data are consistent. However, the vertical structure revealed by the measurements is an important ingredient in the exchange that is not included in the two-dimensional, vertically integrated model.

Internal Tide. An internal tide is a vertically varying tidal fluctuation that is caused by vertical variations of a density interface, i.e., internal waves, which occur at the tidal frequency. Internal tides are generated when tidal currents occur in a stratified water column in the vicinity of abrupt bathymetric variations. Although internal tides are normally less energetic than surface, or barotropic tides, their contribution to vertical mixing may be significant in some environments. Observations of vertical shears by Geyer and Ledwell (1994) as part of a vertical mixing study indicate that the internal tide may be an important source of energy for horizontal dispersion and vertical mixing. At the Harbor entrance, the vertical shears and upwelling associated with the internal tide provide a means of transporting dense, Bay water into the Harbor entrance, where it is mixed with Harbor water and exposed to the near-surface waters. This may be an important conduit of nutrient-rich water from the outfall into the euphotic zone. This upwelling process is probably more intense at the Harbor entrance than elsewhere, due to the stronger tidal currents at this location. The tide-induced upwelling process probably operates around the perimeter of the Bay, with varying intensity depending on the local strength of the barotropic (vertically averaged) tidal velocities.

Estuarine Circulation. The mean velocities suggest an estuarine circulation pattern at the Harbor mouth, with surface outflow of less dense water and inflow of more dense water. The density distribution (Figure 5.1-9) shows a longitudinal density gradient at the Harbor mouth, which provides the driving force for the estuarine circulation. The reversal of the density gradient further offshore (due to reduced surface salinity) weakens the forcing for the estuarine circulation. In addition, wind-driven upwelling and downwelling may overshadow the influence of the estuarine circulation during periods of strong wind forcing. Upwelling motions (due to southerly winds) will augment the estuarine circulation, and downwelling will retard it. The estuarine circulation may work in concert with the internal tide and wind-induced upwelling to carry nutrient-rich water from the new outfall into the surface waters near the Harbor mouth.

5.1.5 Future Efforts

This survey clearly indicates the effectiveness of combining the ADCP with a "tow-yo" profiler for detailed surveys of water properties. The ADCP did not hinder ship operations at all, and it provided valuable information about the dynamics of the Harbor–Bay system. The use of an ADCP would be particularly valuable in plume tracking surveys after inception of the new outfall. The presence of energetic but highly variable internal tides in western Massachusetts Bay renders standard tidal current prediction nearly useless. Therefore, estimates of the influence of currents on the trajectory of the plume will require direct measurements. An ADCP can provide the spatial coverage necessary to document the influence of internal tides as well as atmospherically forced motions in the Bay.

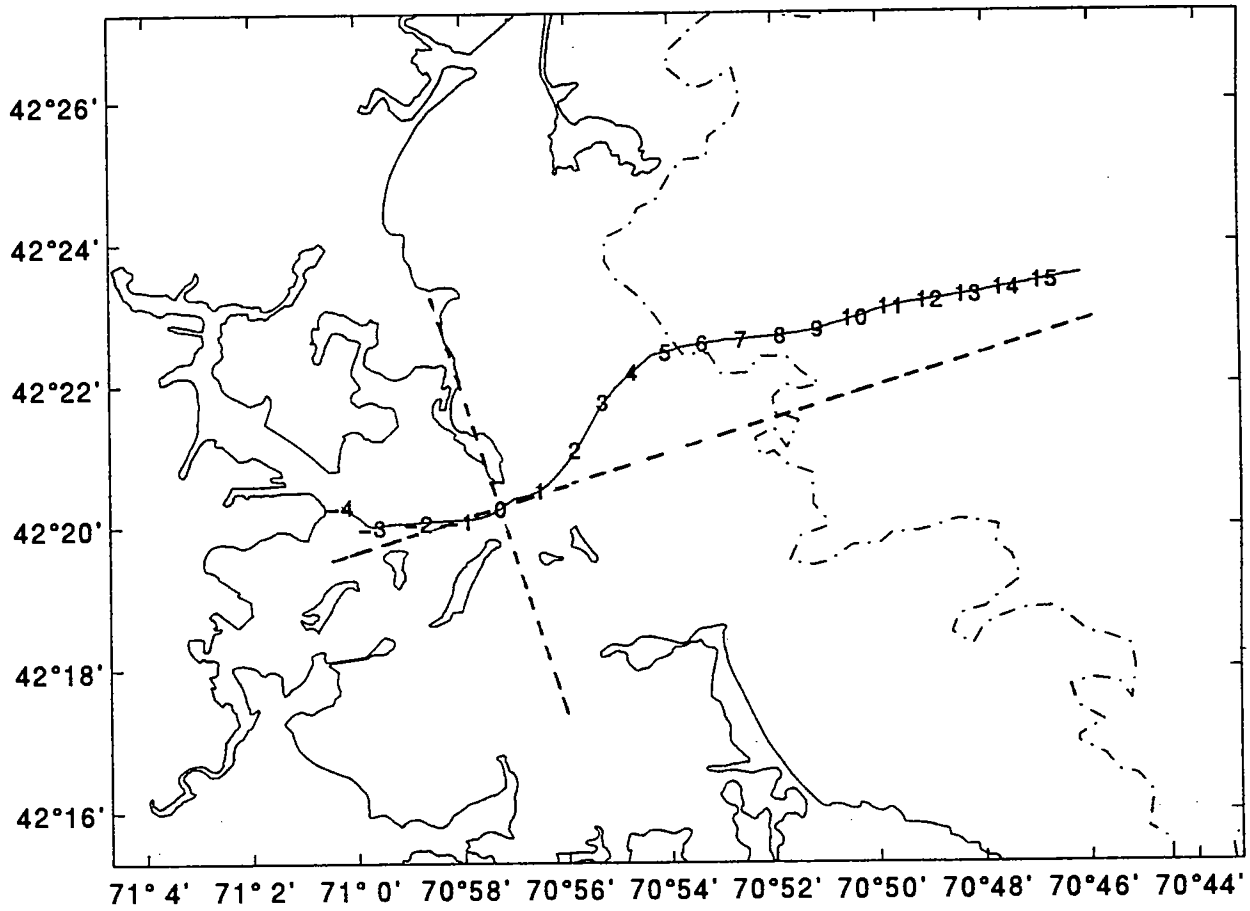
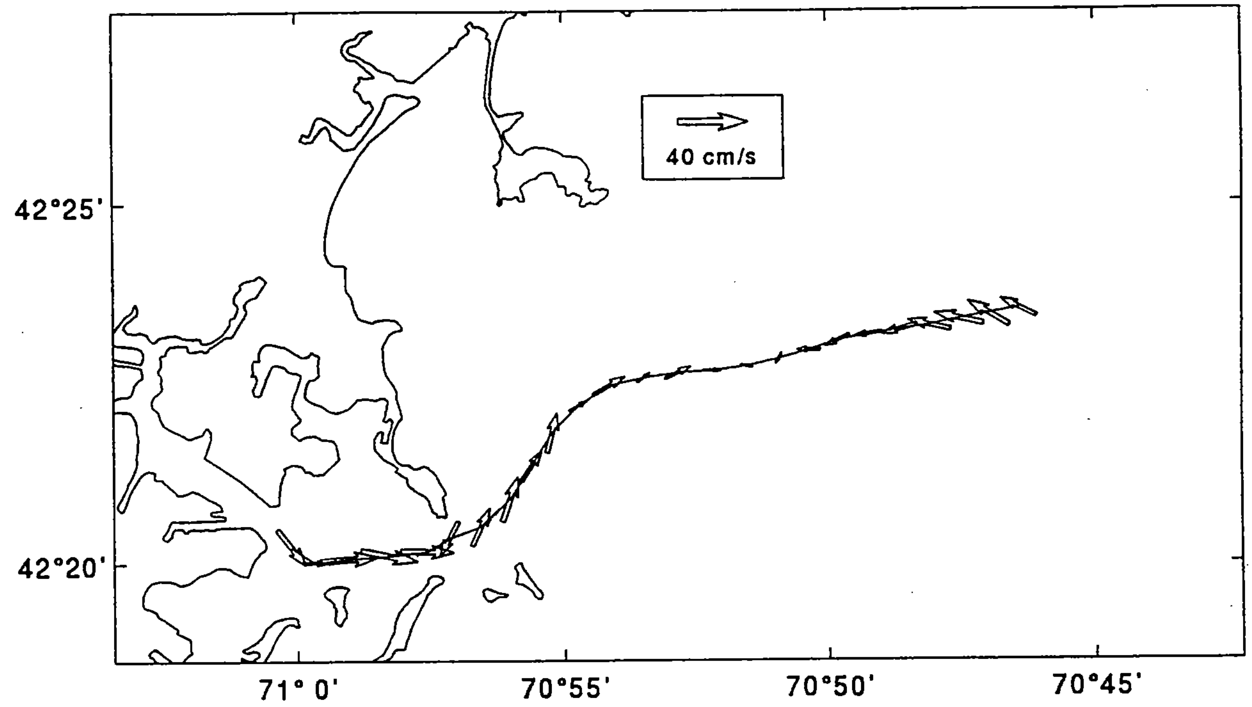


Figure 5.1-1. **Map of Boston Harbor and western Massachusetts Bay, showing the survey line. The line was repeated six times during a 12-hour period on June 25, 1994. The numbers indicate kilometers with respect to a coordinate system oriented at 75° (shown by dashed lines). The origin is in President Roads at the site of the present outfall. The new outfall is located beneath the survey track between 13 and 15 km.**

Near-surface velocity, line 1, 0621 - 0831



Near-surface velocity, line 2, 0836 - 1027

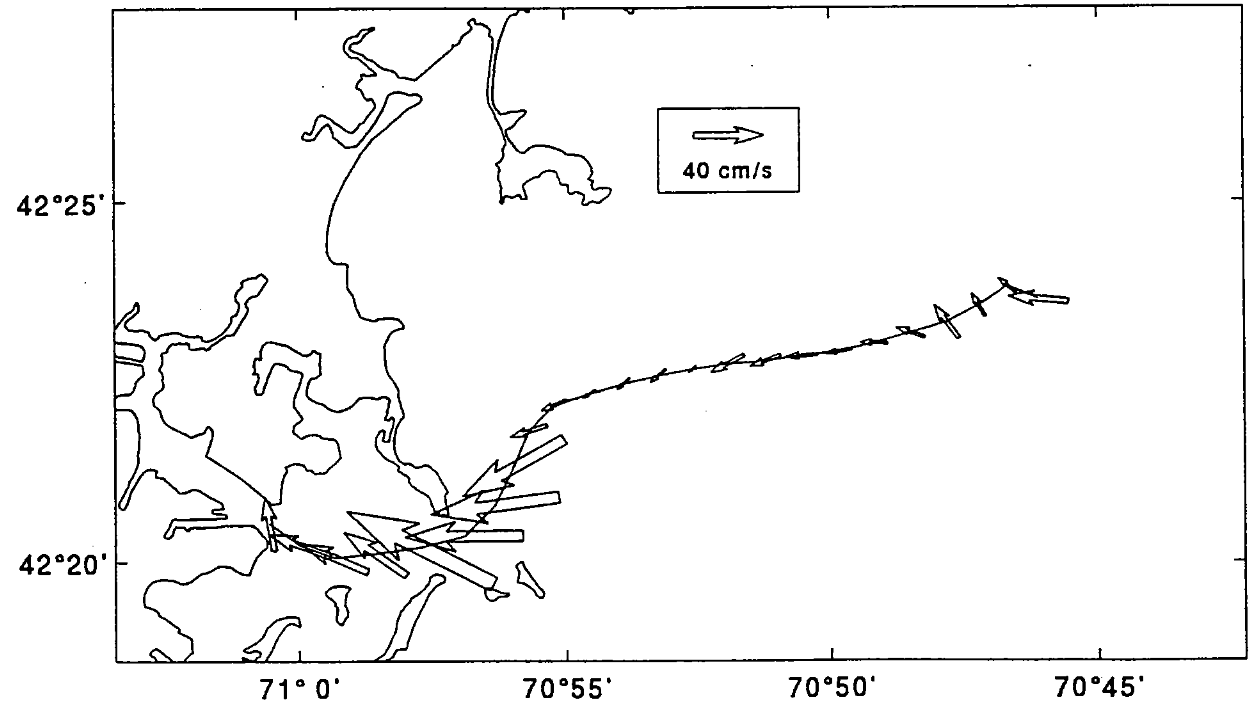


Figure 5.1-2 (a, b). **Vector velocity at 2.3-m depth during lines 1 and 2. Local time is indicated on the headers. Line 1 (heading seaward) corresponds to the end of ebb and the beginning of flood. Line 2 (heading landward) is increasing flood.**

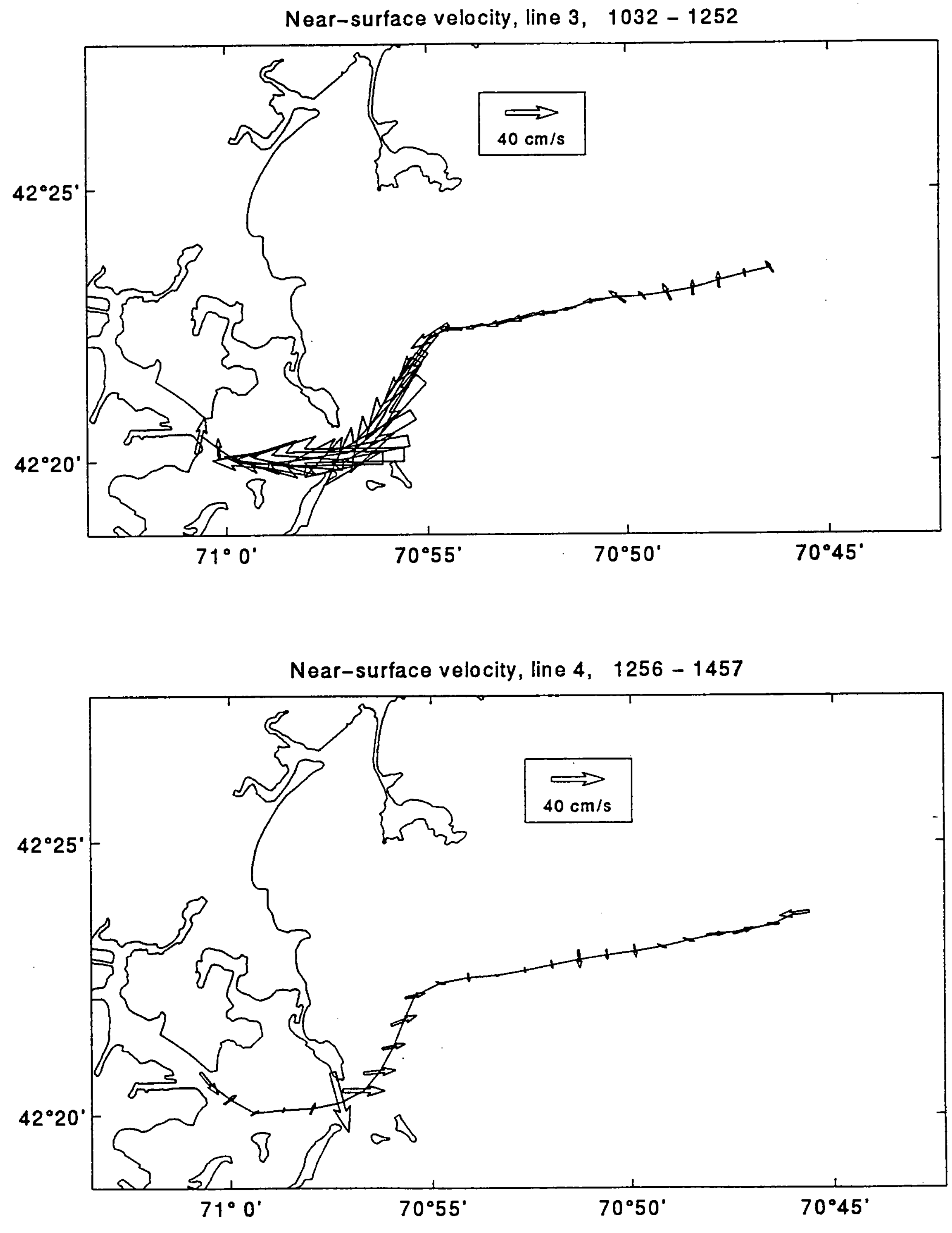


Figure 5.1-2 (c, d). Vector velocity at 2.3-m depth during lines 3 and 4. Line 3 (heading seaward) is during the late flood, and line 4 (heading landward) is early ebb.

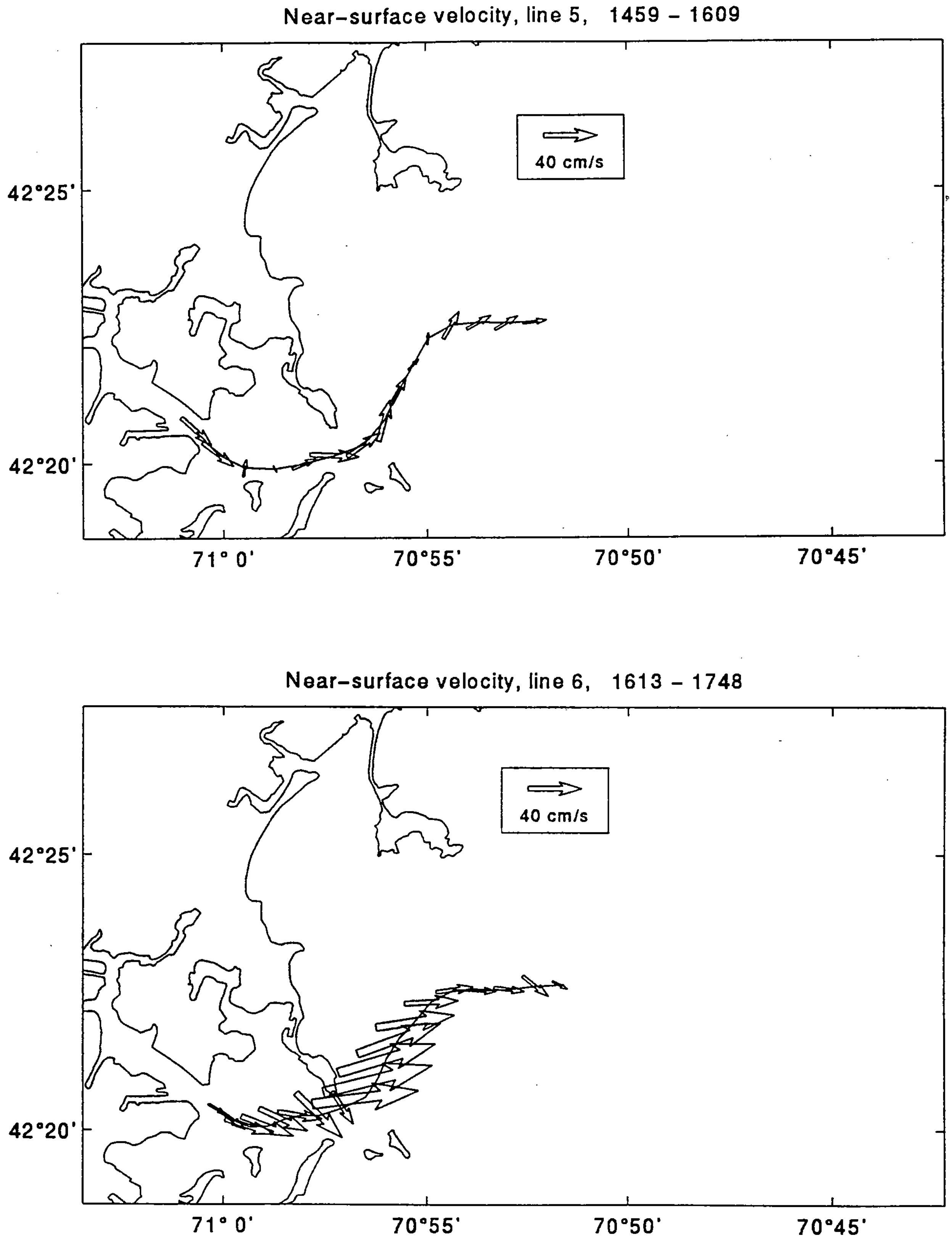


Figure 5.1-2 (e, f). Vector velocity at 2.3-m depth during lines 5 and 6. These lines were truncated due to time limitations. Line 5 (heading seaward) is during early ebb.

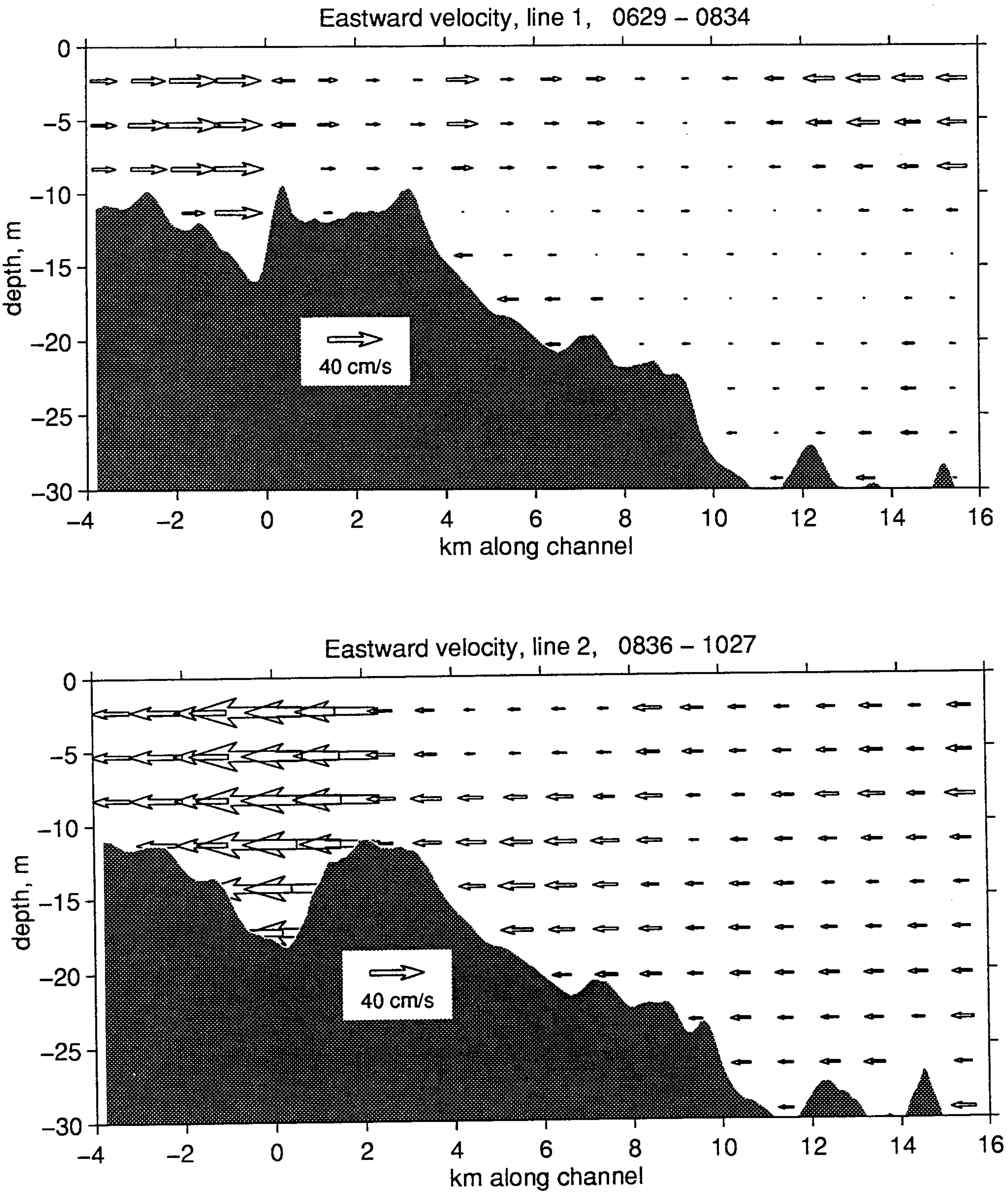
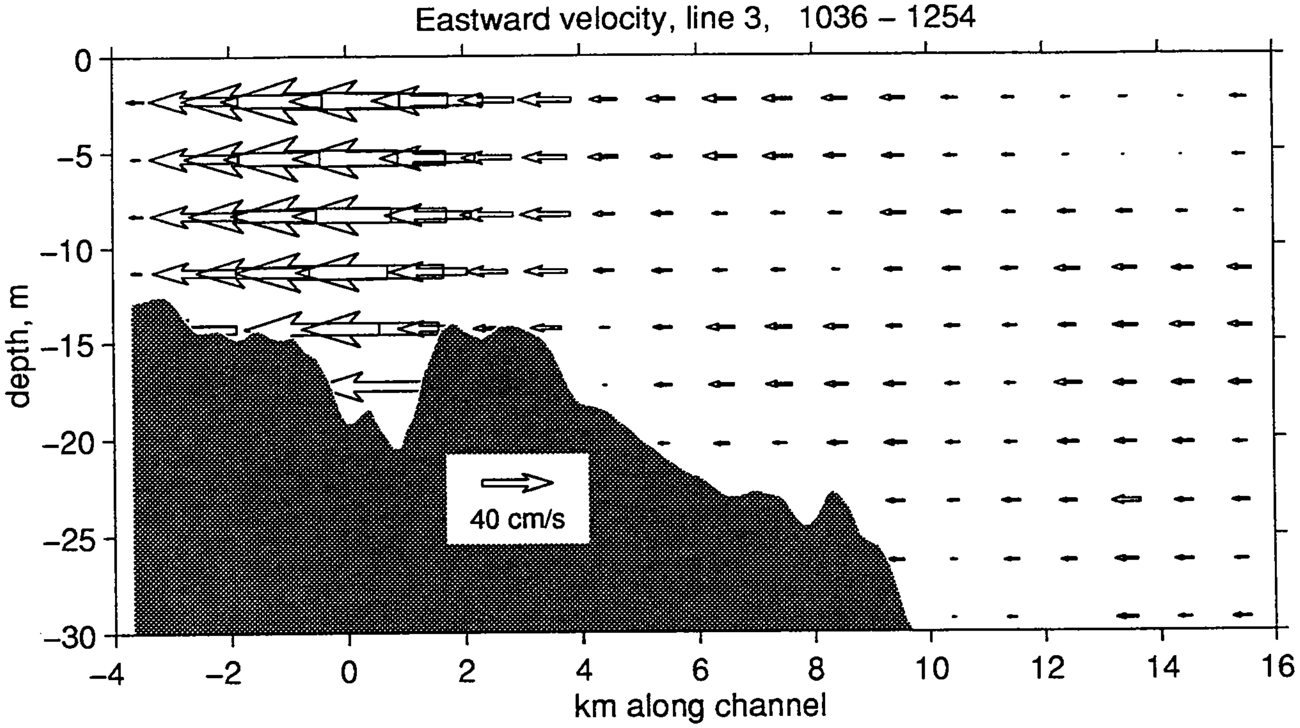


Figure 5.1-3 (a, b). Cross-shore velocity (oriented at 75°) during lines 1 and 2. Local time is indicated on the headers. Line 1 (heading seaward) corresponds to the end of ebb and the beginning of flood. Line 2 (heading landward) is increasing flood.



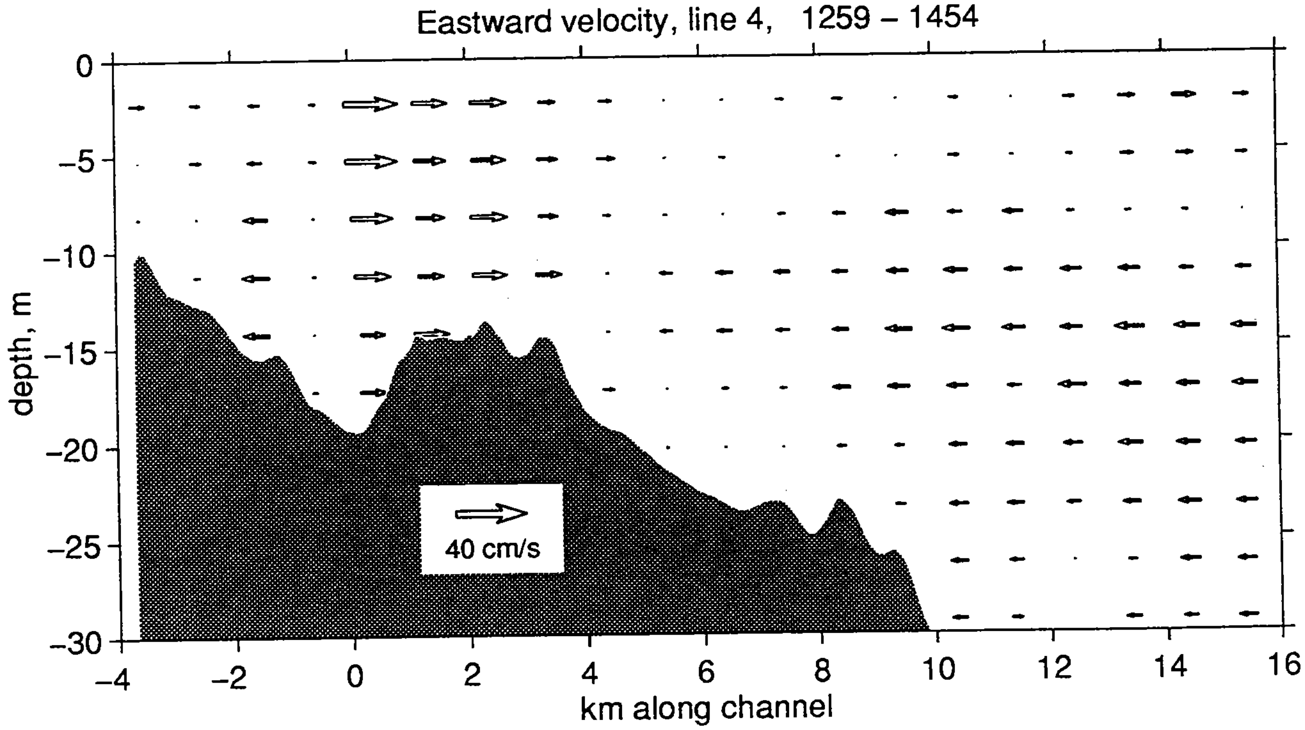


Figure 5.1-3 (c, d). Cross-shore velocity during lines 3 and 4. Line 3 (heading seaward) is during the late flood, and line 4 (heading landward) is early ebb.

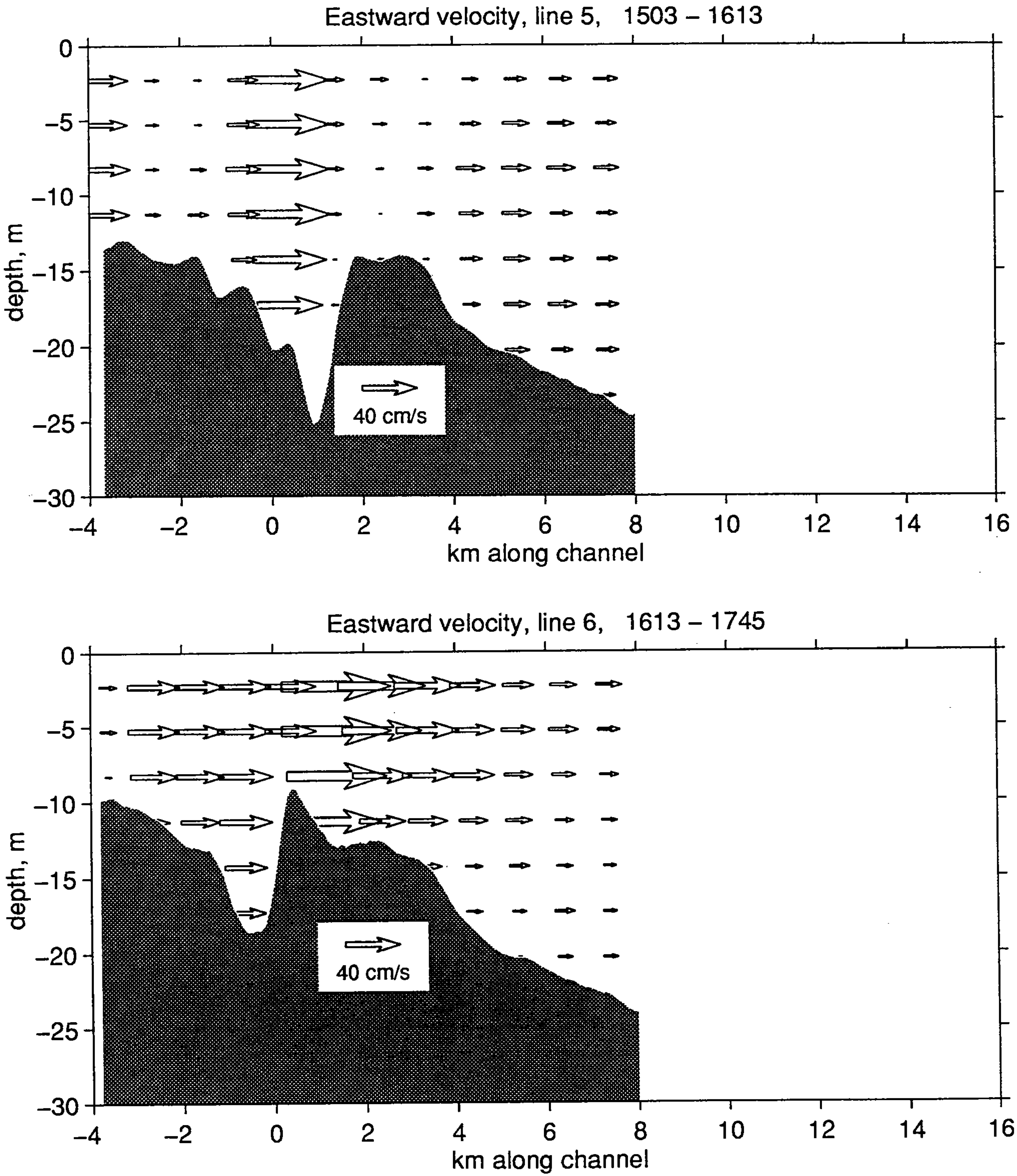


Figure 5.1-3 (e, f). Cross-shore velocity during lines 5 and 6. These lines were truncated due to time limitations. Line 5 (heading seaward) is during early ebb. Note that the large variations in velocity between km 0 and 4 are due in part to variations in ship position in and out of the channel. Line 6 (heading landward) is during mid-ebb.

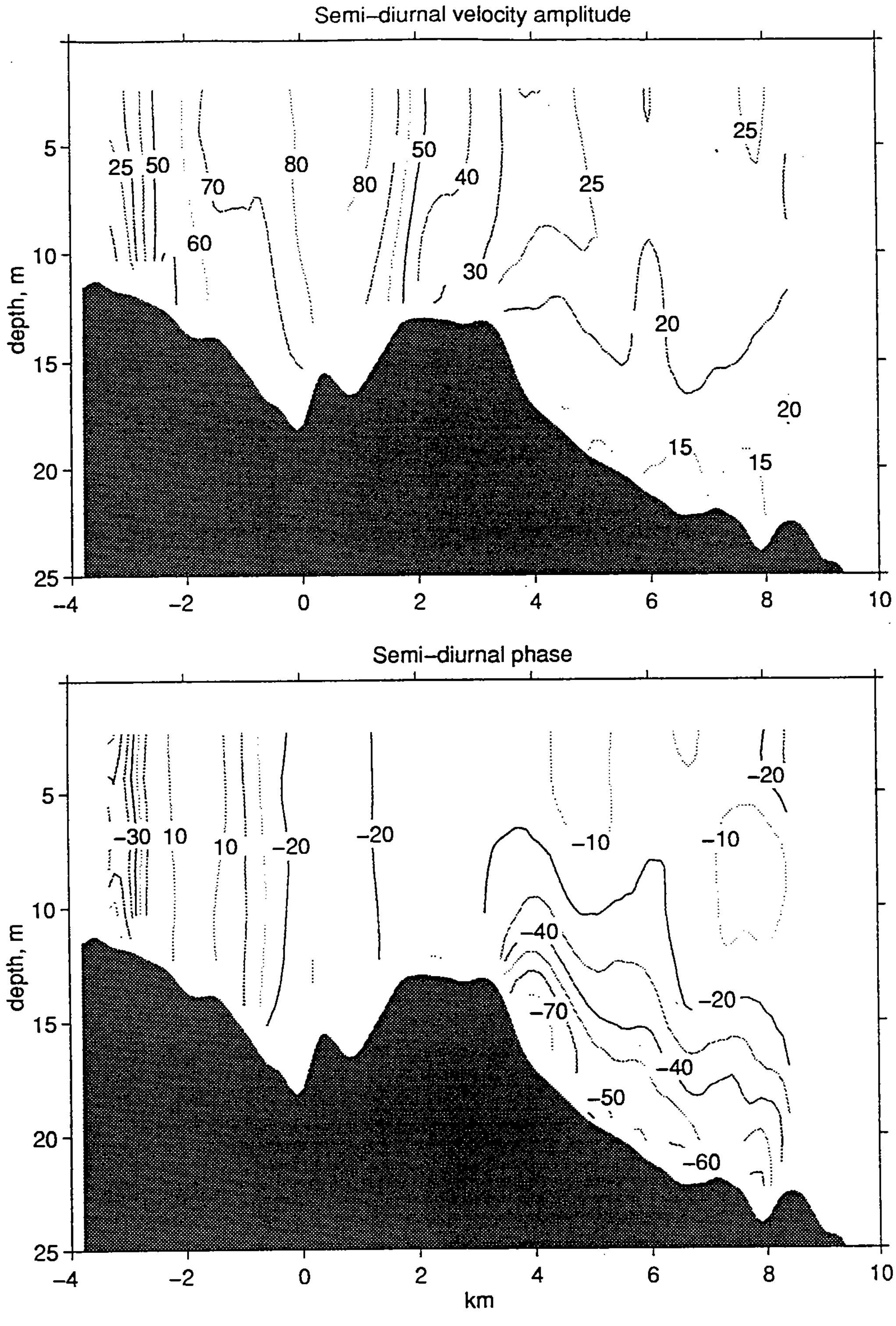


Figure 5.1-4. Semi-diurnal tidal amplitude and phase estimated by harmonic analysis of the six survey lines. The outer 6 km could not be analyzed due to truncation of the last two lines. High velocities are observed in the constriction near km 0. These velocities decrease to around 25 cm s^{-1} further offshore. Other observations (e.g., Geyer *et al.*, 1992), indicate that the tidal amplitude continues to decrease to around 15 cm s^{-1} at the end of the survey line. The variations in phase between 4 and 8 km are evidence of an internal tide.

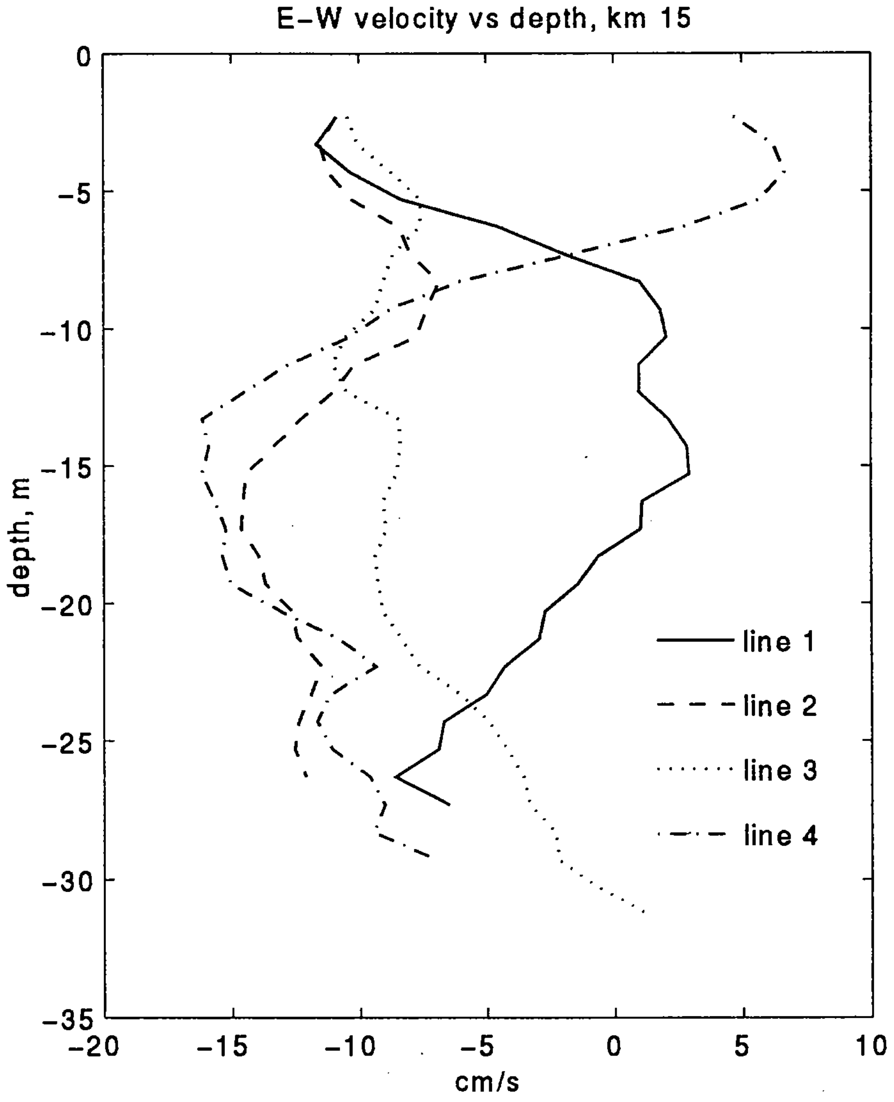


Figure 5.1-5. Variations in velocity with depth for the first 4 lines, close to the end of the survey track (km 15). Large, time-dependent, vertical fluctuations are evidence of the energetic internal tide in this area.

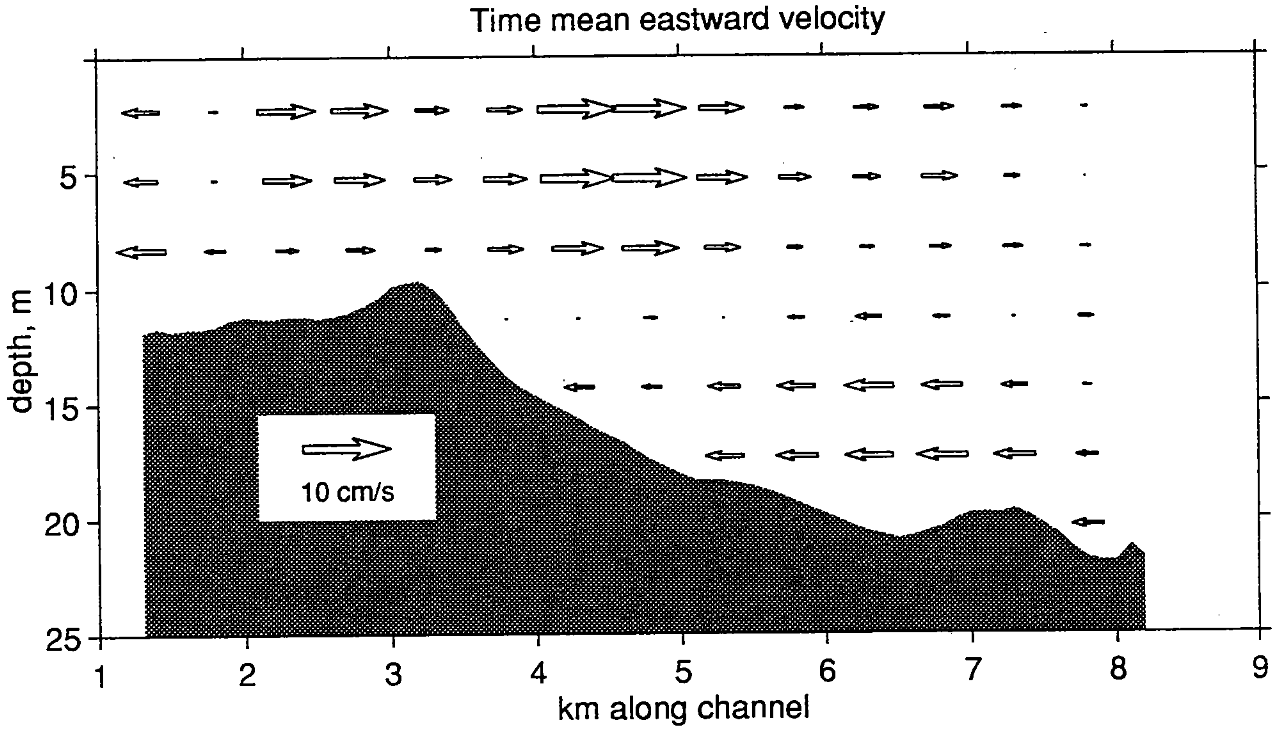
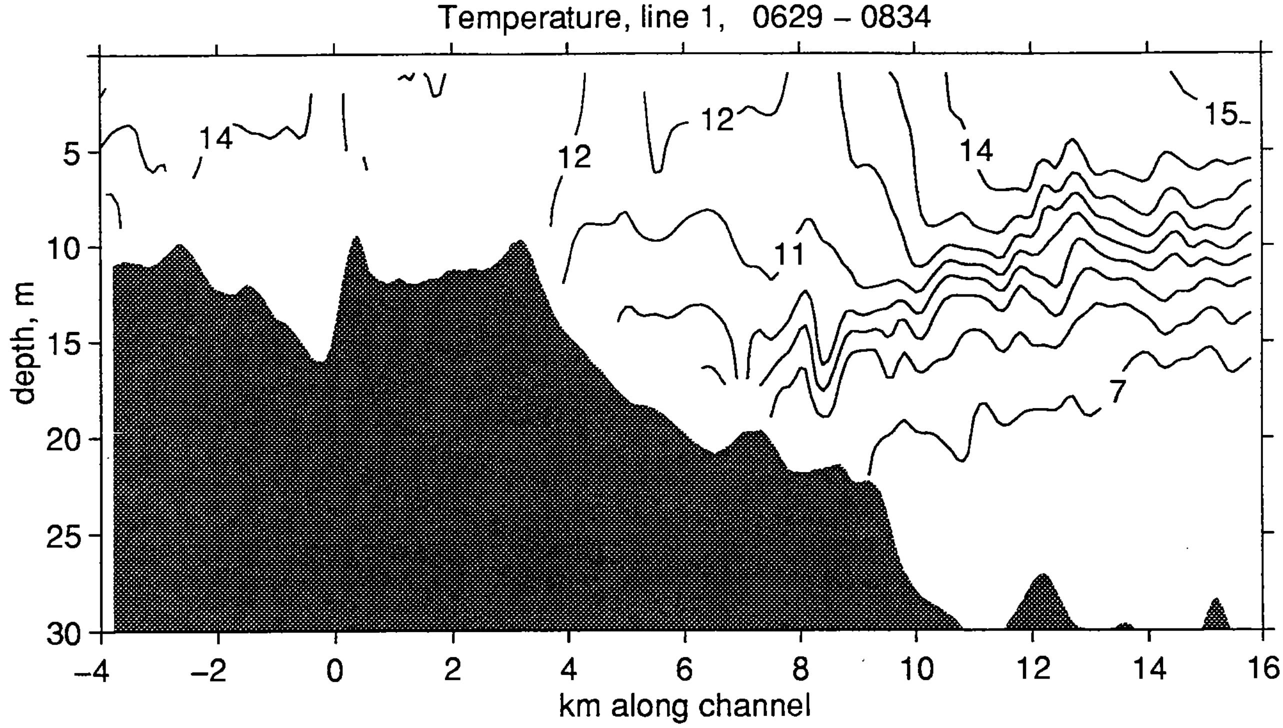


Figure 5.1-6. Time-average flow in the vicinity of the harbor entrance. This 7-km segment in which the tidal analysis was robust enough to estimate the time means. An estuarine-like circulation is evident, with outflow at the surface and inflow at depth. Typical velocities are 5–7 cm s^{-1}. Although these velocities are much smaller than the tidal velocities, they are important for exchange due to their persistence.



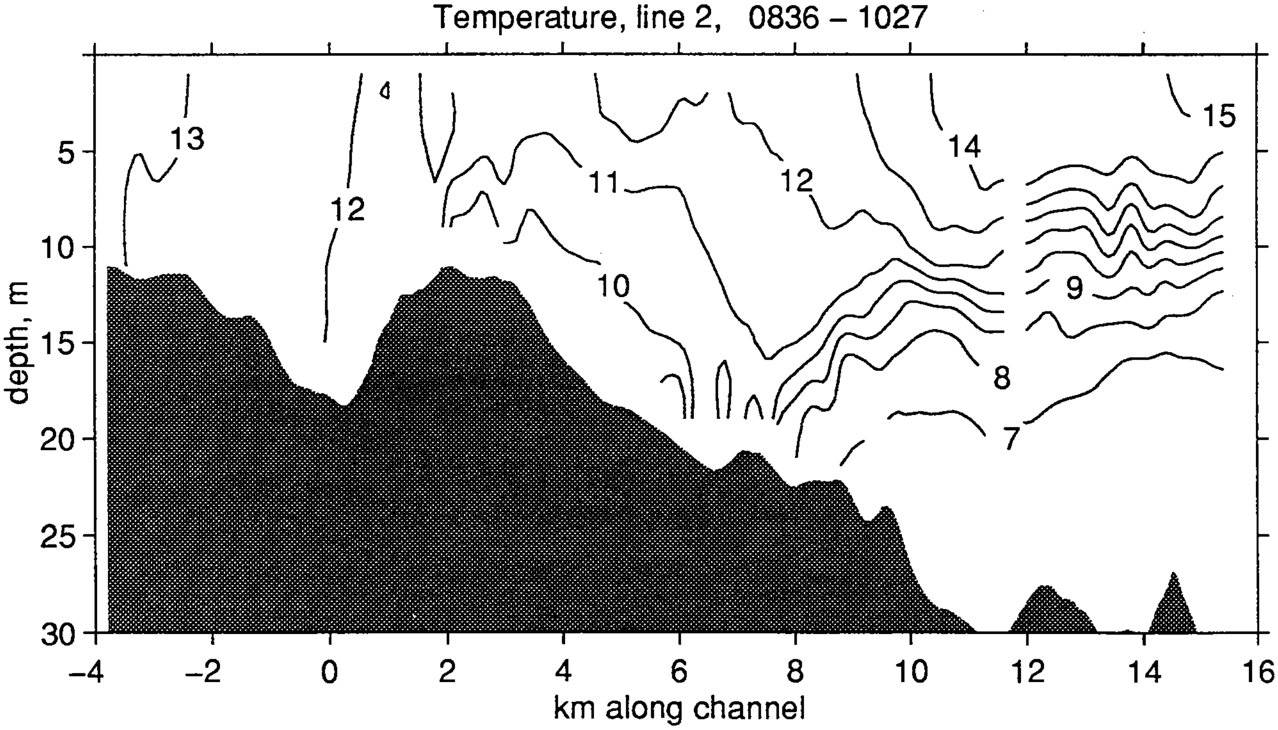


Figure 5.1-7 (a, b). **Temperature data from BOSS during lines 1 and 2 (end of ebb and early flood). A strong bottom front is evident around km 8, where the thermocline intersects the bottom.**

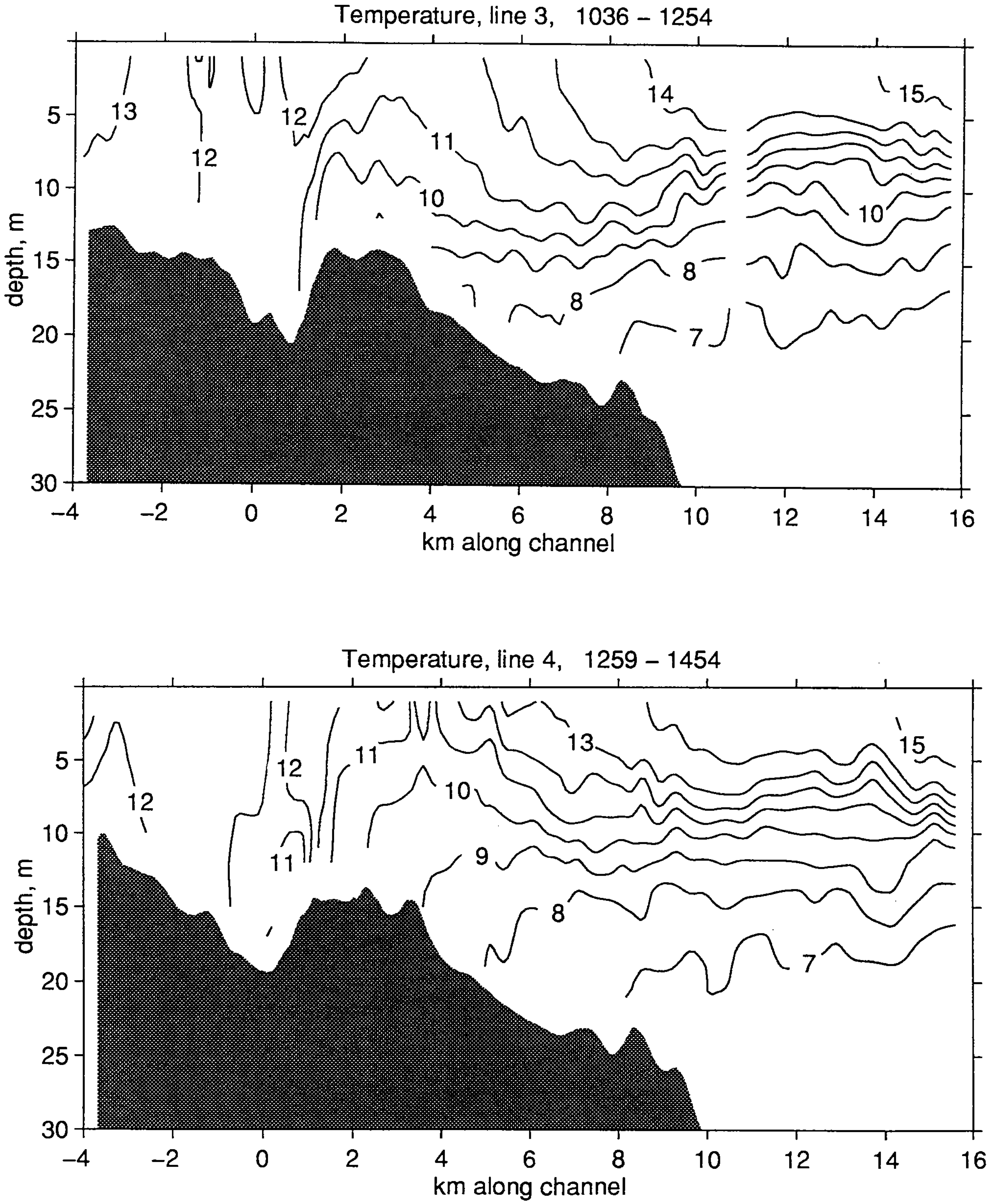
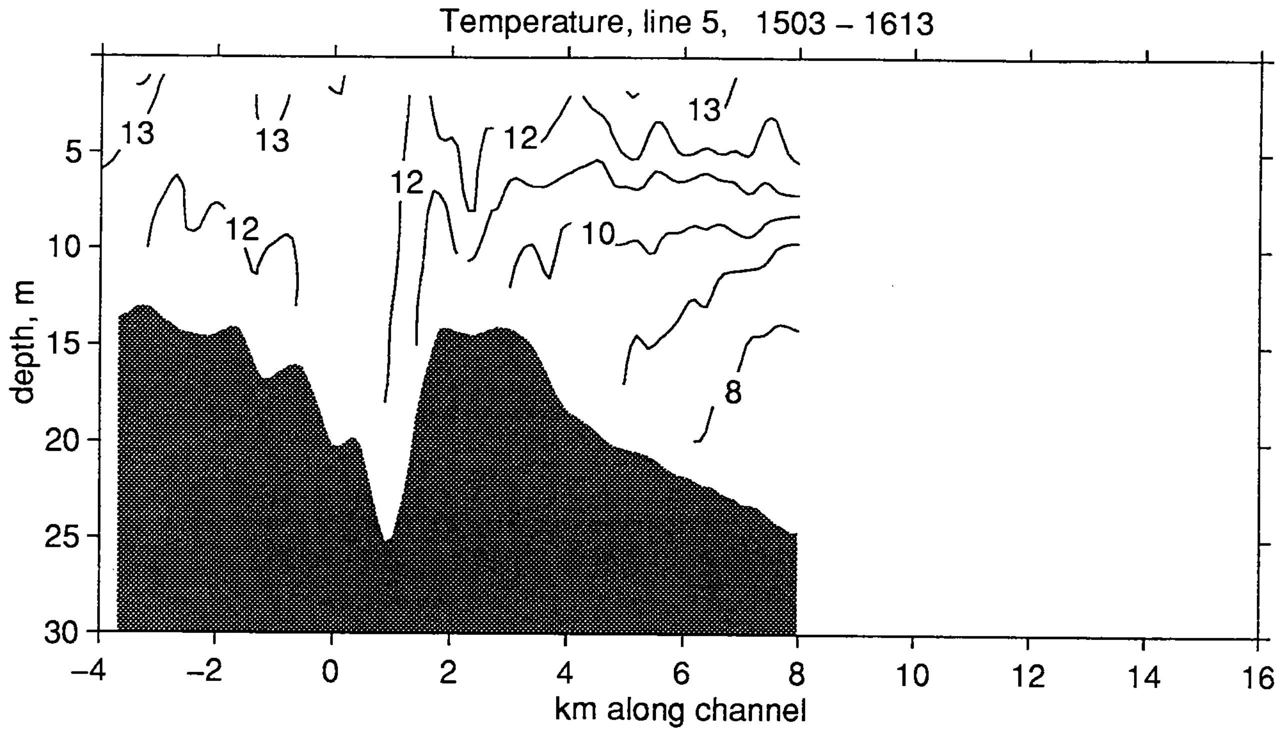


Figure 5.1-7 (c, d). Temperature data from BOSS during lines 3 and 4 (late flood and early ebb). The temperature front has advected into the harbor entrance. The thermocline is spreading vertically.



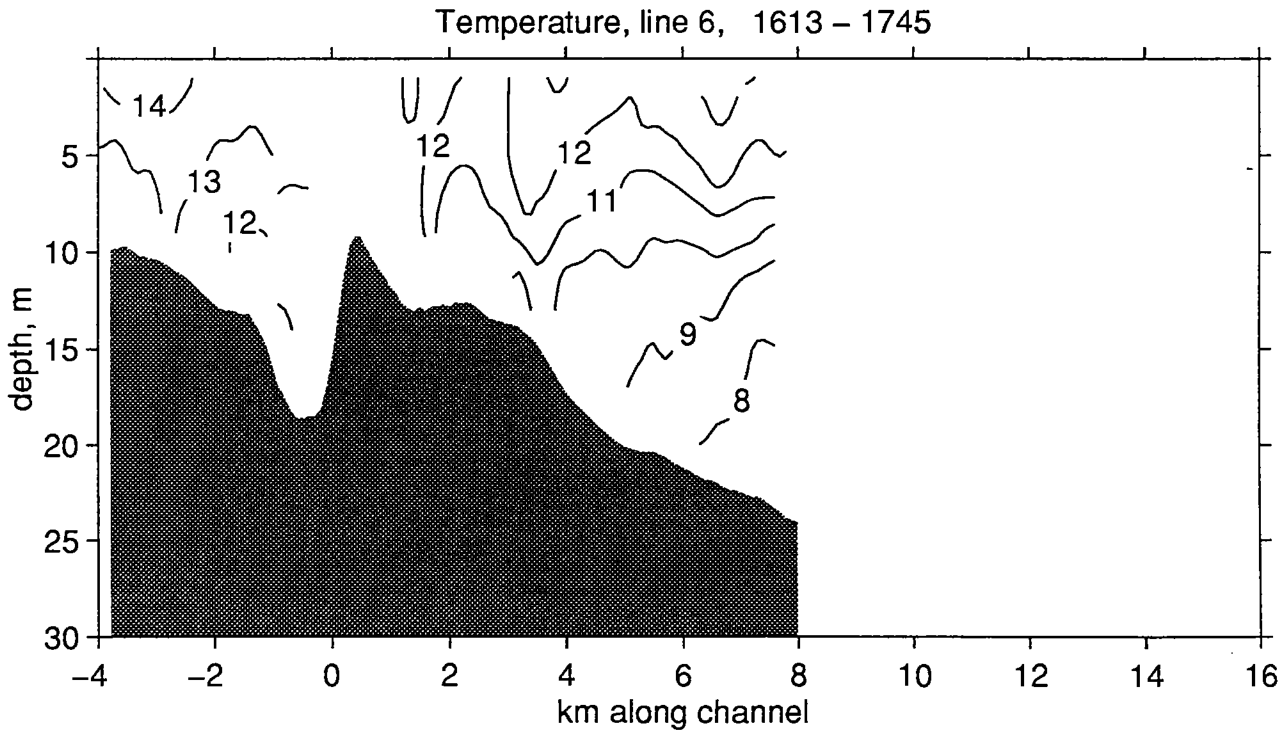


Figure 5.1-7 (e, f). **Temperature data from BOSS during lines 5 and 6 (early and mid-ebb). The temperature front is becoming spread out due to mixing.**

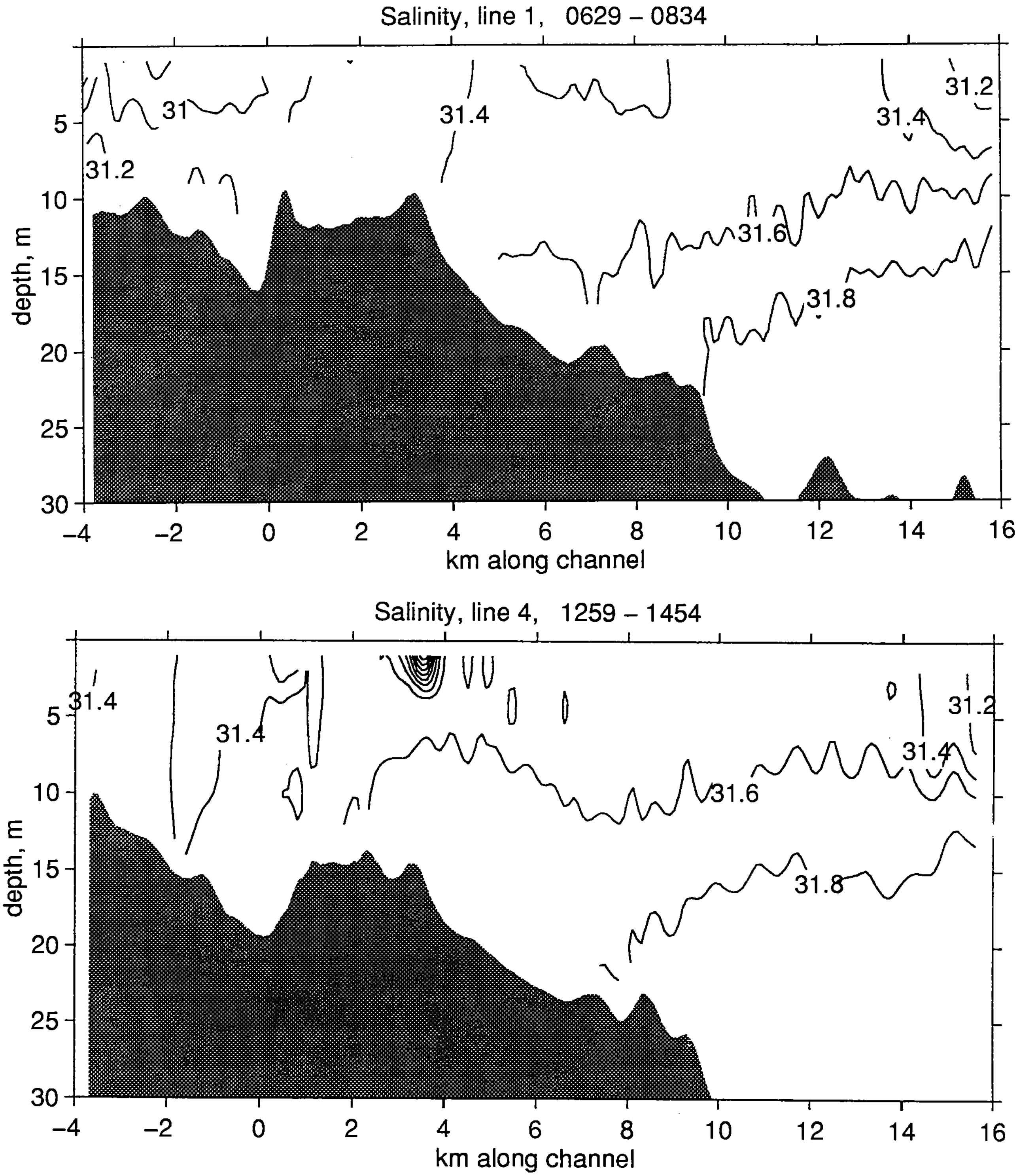


Figure 5.1-8. **Salinity data from BOSS during lines 1 and 4. The blob of very low salinity water at km 4 during line 4 may be due to surfacing of the BOSS sensor.**

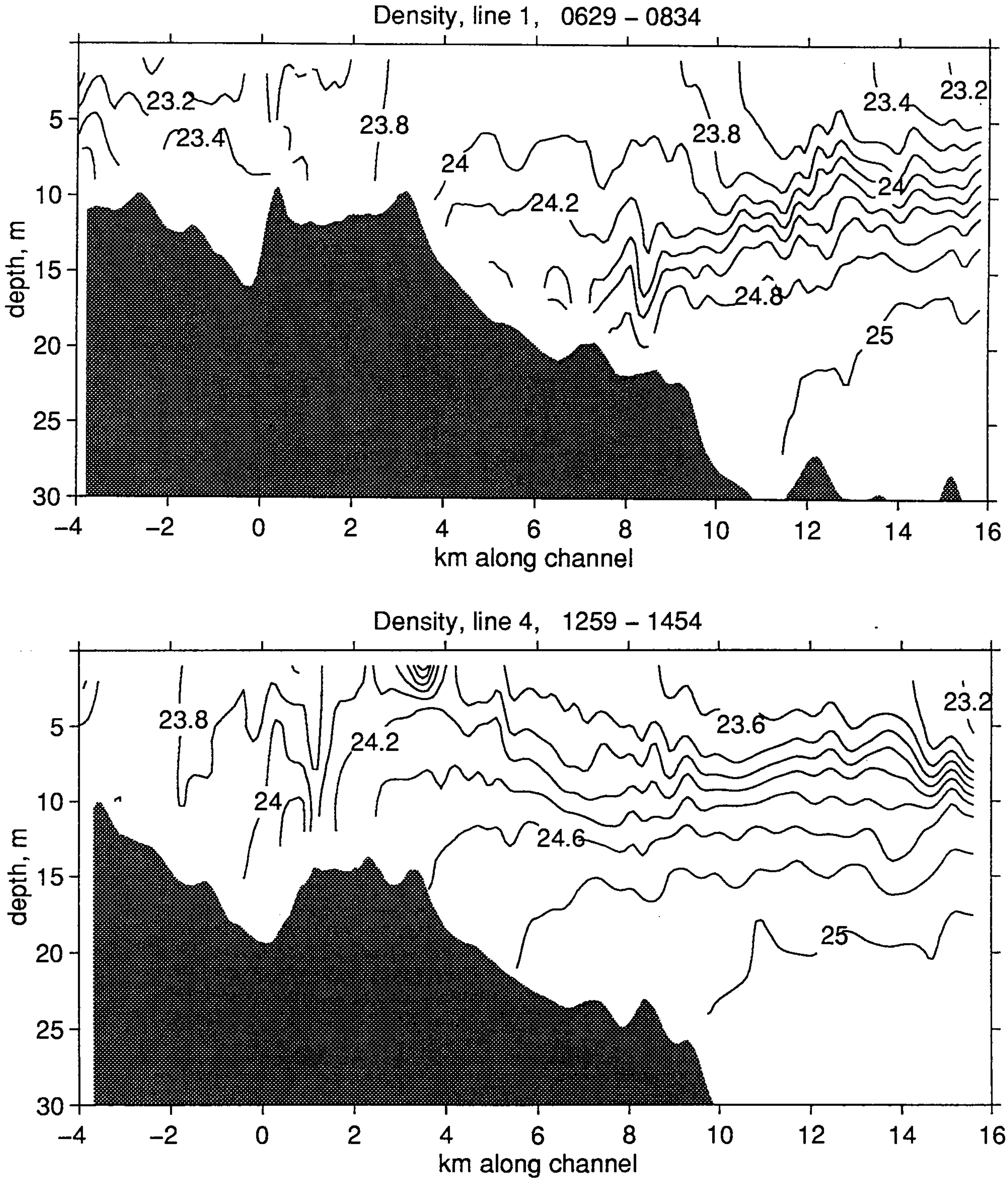


Figure 5.1-9. **Density data from BOSS during lines 1 and 4.**

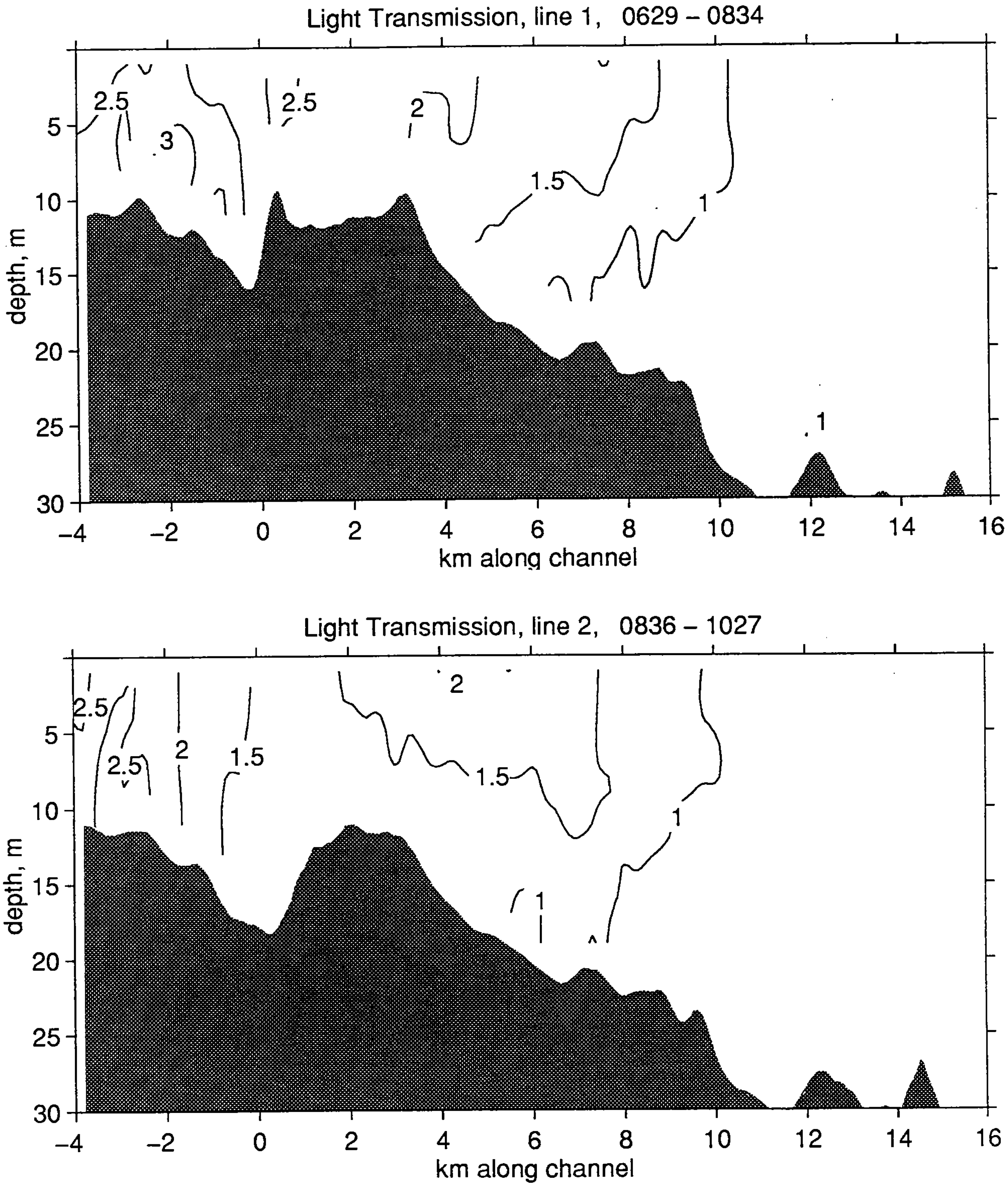


Figure 5.1-10 (a, b). **Light transmission (as attenuation, m^{-1}) during lines 1 and 2. The high values between -3 and 0 km are likely due to the Deer Island outfall. The bay water is considerably clearer, with values generally less than 1.**

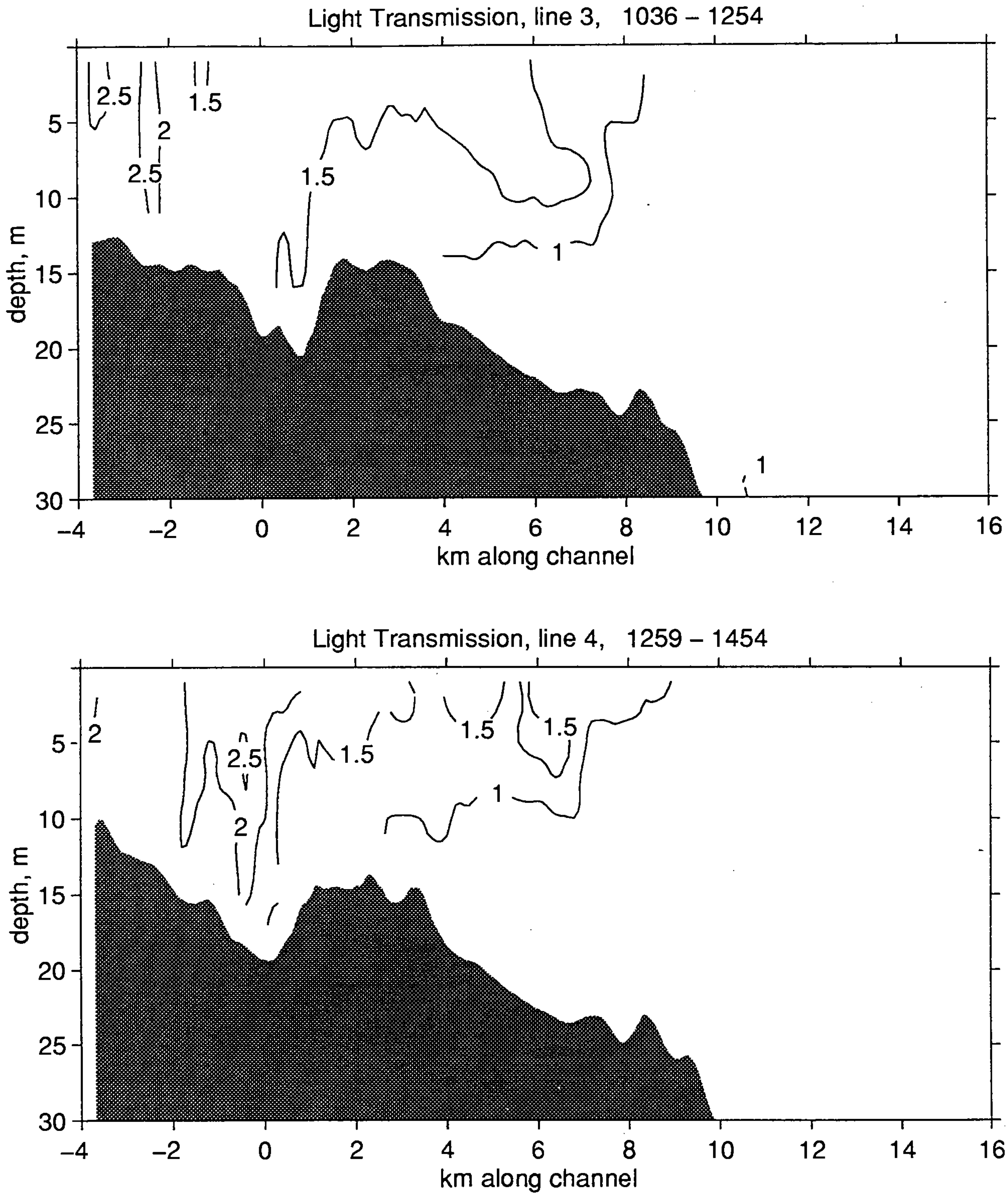


Figure 5.1-10 (c, d). **Light transmission (as attenuation, m^{-1}) during lines 3 and 4. The clear, bay water is penetrating beneath the turbid plume.**

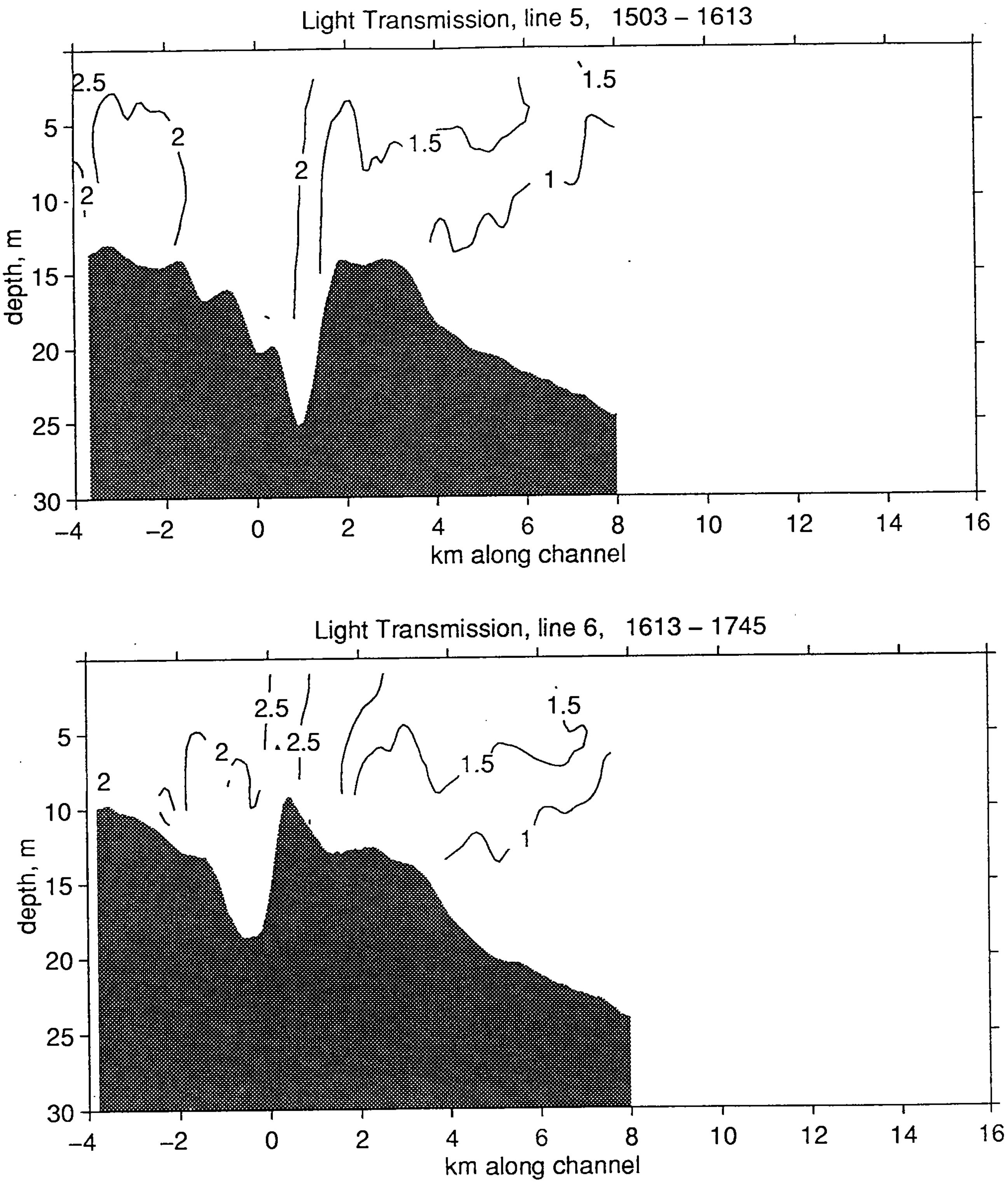


Figure 5.1-10 (e, f). **Light transmission (as attenuation, m^{-1}) during lines 5 and 6. Turbid water is being advected out by the ebb.**

5.2 Summer Chlorophyll Export: Effects Within the Bay Receiving Area

Kelly and Albro (1994) were able to show that fluorescence in the region of active Harbor-Bay mixing could not be produced by conservative mixing of surveyed waters, and had to result from *in situ* growth (or less likely, advection into the sampling field). The presumption was that *in situ* growth was related in some way to mixing processes, possibly involving changes in light availability because non-chlorophyll turbidity decreased with dispersion of the high-turbidity water into the Bay. For the interested reader, Kelly (1993, 1995), Kelly and Turner (1995a,b) and Kelly and Doering (1995) have explored facets of the interaction of light and phytoplankton along the gradient from the Harbor to the nearfield sampling region in the Bay.

Here, we wanted to examine further the question: *what is the effect of tidal motion and the interaction of Harbor and Bay waters on phytoplankton biomass distribution and growth as indicated by chlorophyll?* We conducted an analysis of the survey data for July 1994 to address our question. The July survey was chosen for several reasons: 1) to evaluate a different month than previously examined (June) by Kelly and Albro (1994), 2) because the survey provided tracklines for both Harbor exits to the Bay, 3) because observed conditions included a summertime chlorophyll peak in the Harbor distinguishing it from the Bay, and 4) because there also appeared to be chlorophyll increase in the day (suggestive of growth) in the Bay receiving areas outside both exits.

Legs 1 and 3 of this survey extended through President Roads in the northern Harbor to station N16P in the middle of the Nearfield. Legs 2 and 4 surveyed the transect through Nantasket Roads in the southern Harbor to station N16P. We coded the data by regions along the survey leg, as indicated in Figure 5.2-1. In this figure for the northern Harbor transect, we display the location (longitude, depth) of *in situ* sensor data points, each point representing a 2-sec average of a sensor reading. Data collected west of longitude -70.945°, which includes a small basin off Deer Island, were considered to be inside Boston Harbor (see Figure 5.2-1). From that point to the eastward end of the shipping channel (longitude -70.915°) the trackline bent northward; because the axis used in this presentation is longitude, it (artifactually) appears that data from V-oscillations are more closely spaced in this channel. We classified waters seaward of the edge of the channel (eastward of longitude -70.915°) as within the Bay proper. For the southern Harbor-Bay entrance, we used longitude readings of -70.88° and -70.83° to classify the Harbor and Bay regions, respectively, with the region in between being termed "channel."

5.2.1 Results

Northern Harbor (legs 1 and 3). Figure 5.2-2 shows chlorophyll and turbidity (beam attenuation) concentrations as a function of salinity on leg 1. The body of points for both parameters showed a nearly inverse relationship, with higher values at low salinity in the Harbor and lower values at higher salinity in the channel and in the Bay. A similar trend was evident for chlorophyll and turbidity as a function of density (Figure 5.2-3). For chlorophyll, one anomalous cluster of points from the Bay had high chlorophyll at intermediate values of the associated physical properties (e.g., salinity near 31.4 PSU and σ_T near 23.5; Figures 5.2-2 and

5.2-3). The high chlorophyll data are from near-surface water located slightly east of the channel near the edge of the tidal excursion. A second cluster of points from the Bay had unusually low chlorophyll values, again at intermediate values of physical parameters (Figures 5.2-2 and 5.2-3); these data were for surface water at the eastern end of the track in the Nearfield. A final small cluster of points within the channel had unusually low chlorophyll concentrations with respect to salinity (Figure 5.2-2) but this feature was less distinct with respect to density (Figure 5.2-3); these data were from a small parcel of surface water just outside the edge of the Harbor, which we suspect represents diluted MWRA effluent discharge near Deer Island (see below). For turbidity, a cluster of points with high values is not apparent, but a cluster with low values was evident in the Bay and represented surface water at the eastern end of the track. An increase in turbidity at the highest salinity and density suggests bottom sediment resuspension (Figures 5.2-2 and 5.2-3). Note that the high chlorophyll occurred without concomitant turbidity increase (Figure 5.2-4, top); the Bay's surface water slightly east of the channel had this anomalously high chlorophyll at intermediate turbidity (beam attenuation ~2-2.5 m^{-1}).

Related to our research question, the data of this survey clearly exhibited a major feature (high chlorophyll) that we wished to explore. The pattern of chlorophyll with salinity, density and turbidity confirm that the high chlorophyll was not produced by simple mixing of waters that were sampled on leg 1. The high chlorophyll could only result from advection (i.e., the data represent drift of a different water mass) or from *in situ* growth.

A question of chlorophyll advection vs. growth may be partially addressed by comparing low tide with high tide (Figures 5.2-4 through 5.2-6). Low tide (leg 1) samples were gathered from about 7-9 AM, in contrast to high tide (leg 3) samples, which were collected from ~noon to 3 PM. At high tide, an anomalously high chlorophyll was again observed (Figure 5.2-4) for samples from the surface layer in the region slightly outside the channel; peak values were higher than measured at low tide earlier in the day. At high tide, there was a slight enhancement of turbidity within the area of elevated chlorophyll (Figure 5.2-5 and 5.2-6). Enriched conditions (chlorophyll and turbidity) were centered at a salinity near 31.6 PSU and density near 23.5 at high tide. At low tide, the enriched (chlorophyll) conditions were centered at perhaps slightly lower values, but within 0.2 units of both salinity and density near 23.5 at low tide. For the high tide data (Figures 5.2-4 through 5.2-6), we also noted where some Harbor or channel data were relatively low. These data, with lower than ambient chlorophyll and turbidity, but low salinity and relatively low density, represent a sampling of distinctly different water. We believe we sampled some diluted MWRA effluent discharge in the Harbor and channel.

The tidal comparison data certainly support a hypothesis of *in situ* growth during the day in the Bay. Physical mechanisms cannot be fully ruled out, however, so we also re-examined physical properties. Figure 5.2-7a presents density sections for the survey. Figures 5.2-7b and c display T-S plots by survey leg. The T-S plots illustrate a number of features. Considering the northern transect, the low tide data suggest a fairly smooth mixing curve between the Harbor, channel, and mid-deep water of the Bay. A spur of low temperature water in the channel, as discussed above, may represent effluent. Most notable is that the Bay surface just east of the Harbor-Bay tidal front has a distinctly different signature and seems not to mix actively with the channel water. The same Bay-channel water distinction was maintained at high tide (Figure 5.2-7b, bottom). At high tide, the suspected effluent was identified. There were two main lines of Harbor points indicating mixing within the Harbor, but the Harbor T-S signal was offset, and partially separated, from the channel data. The highest temperatures in the channel do not appear to result from a mixing process, but rather from upwelling to the surface visible in Figure 5.2-7a. An overall interpretation is that on the ebb tide there was some Harbor-channel-Bay mixing, but this mixing with the Bay was with more with mid-depth waters than with the resident high temperature water mass just east of the tidal front. The data suggest an ebb-tide subduction and gradual mixing of inshore water into the Bay at mid-depth. On the flood, there was some mixing into the Harbor from the channel, but the immediate effect of upwelling was perhaps more a segregating, than a mixing, process. Interpretation of these data reinforce physical notions presented in Chapter 4 and are consistent with tidal dynamics captured by velocity studies (Section 5.1).

Chlorophyll distributions were examined as a function of density, and we noted that the unusual T-S water in Figure 5.2-7 was the region with high chlorophyll. The surface layer across the transect was generally characterized by $\sigma_T < 23.5$ (Figure 5.2-7). Essentially *all* Harbor water was <23.5 and this density layer extended to a maximum depth of about 10 m in the Bay. In the Bay, water between $\sigma_T = 23.0$ and 23.5 was the uppermost boundary of the pycnocline. Water of density 24.0 marked the upper-mid pycnocline in the Bay and this layer upwelled to within about 5 m of the surface near the eastern edge of the channel with the flood tide (Figure 5.2-7). Using discrete layers, one with $\sigma_T < 23.5$ and one with $23.5 < \sigma_T < 24.0$, we present the along-track distribution of chlorophyll concentrations in Figure 5.2-8. The region of chlorophyll stimulation in the Bay is evident in both layers. Chlorophyll variations in the Harbor-channel generally decrease seaward and seem mostly explainable by mixing processes.

Figure 5.2-9 compares the data from high and low tide samplings for each layer. A shoreward shift is evident with the flood tide. A shift of ~0.03° longitude (several kilometers) was evident for the Harbor-channel region, the location where chlorophyll concentrations generally mixed with salinity (e.g., Figure 5.2-2). A similar small shoreward shift was suggested for the location of peak chlorophyll concentrations within the Bay itself (seaward of station F24, Figure 5.2-10). Recognizing the shoreward shift, comparison of high and low tide chlorophyll concentrations show an increase in both density layers at high tide (mid-afternoon). Cross-track advection of both layers seems unlikely and not indicated by the data, so we believe a case is made for *in situ* growth in the Bay during the day.

Reviewing the density and chlorophyll sections (Figures 5.2-7 and 5.2-10), chlorophyll growth was not indicated in the location of strong pycnocline upwelling (at high tide) between stations F23P and F24, where the 23.5 isopleth reaches the surface. Rather, growth occurred seaward of the bathymetric-induced upwelling. Growth occurred at the point where the stratification was well defined, i.e. the seaward side of the tidally-migrating front marking the tidal mixing zone, which (from T-S, above) seemed isolated from tidal mixing processes. Note that the depth of the 24.0 σ_T isopleth rose slightly, perhaps 1-2 meters, in the region of peak chlorophyll growth.

The two density layers in question cover about the top 10 m of the water column in the region of active growth. Estimating that the change in chlorophyll over this column averaged roughly 3 μgChl *a* L^{-1} in about 4 hours, we calculate[2] that this represents, at a minimum, a net production of 4.5 μgC L^{-1} h^{-1}. Expanding to the entire day and the 10 m column[3], the chlorophyll growth could represent about 3.2 gC m^{-2} for the day. The estimate based on an observed chlorophyll change would underestimate net C production by missing losses due to grazing, sinking (and advection, although perhaps not relevant here). Even so, the rough estimate is at the high end of the range of measured and modeled net carbon production rates for the western Massachusetts Bay-Boston Harbor region during 1992-1994 (Kelly and Doering, 1995). Thus, we suggest that the localized region of high chlorophyll represents a significant location for primary production. High-production patches may only be a few kilometers or less in size and easily could be missed by sampling techniques other than high-resolution profiling. For example, in Figure 5.2-10 note the position of traditional (vertical hydrocast profile) sampling station F24 (cf. Kelly and Turner, 1995b). At the time of this survey station F24 was located between high chlorophyll concentrations characteristic of the Harbor and the frontal patch in the Bay, both at high and low tide. In contrast, a station located at the 12000 m mark would have missed the high chlorophyll patch at low tide, yet sampled the heart of it at high tide.

Southern Harbor (legs 2 and 4). Sampling on leg 2 barely reached into the Harbor and the salinity range was slight, making Harbor-Bay comparisons difficult. However, in contrast to the northern transect, the T-S plots (Figure 5.2-7c) suggest simple mixing between the Harbor, "channel", and Bay at low tide. At high tide, a slight separation of some of the Bay and channel data is shown, so a slight frontal water mass in the Bay may be indicated as well as upwelling in the channel.

Highest chlorophyll values were detected in the Harbor at high tide (leg 4). Otherwise, peak chlorophyll concentrations occurred in the channel-Bay regions, which included the area between stations F25 and N10P (the southwestern corner of the nearfield). Previous observations (e.g. Kelly *et al.*, 1992; Kelly and Albro, 1994) frequently have noted a tidal influence. Export from the Harbor often extends past station N10P at low tide, yet not reach N10P at high tide. Peak channel-Bay chlorophyll concentrations were associated with σ_T values of about ~23.5. At high tide (mid-afternoon), the chlorophyll-salinity plot (Figure 5.2-11) suggested values in the channel and Bay were elevated compared to an implied chlorophyll-salinity mixing line for the Harbor data. At this region at the high tide sampling, there was only the slightest suggestion that chlorophyll was elevated relative to turbidity (Figure 5.2-11), in spite of the fact that turbidity within the sampled southern Harbor region did not reach levels as high as in the northern Harbor.

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[2] A representative assimilation number is 6 μgC μgChl a^{-1} h^{-1} (Kelly and Doering, 1995).

[3] See Kelly and Doering (1995) for standard conversions from volumetric and hourly rates to areal and daytime rates.

The southern Harbor exit has a sharply sloping bathymetry (seaward of station F25) like the northern Harbor exit. Figure 5.2-7a suggests that, like the case of the northern exit, there was upwelling of the pycnocline (σ_T 23.5 to 24.0) to the surface at high tide (leg 4) near station F25, whereas it was relaxed at low tide (leg 2). As for the northern track, peak chlorophyll concentrations in the Bay were seaward of this upwelling (Figure 5.2-10). Sampling later in the day detected only mildly elevated peak chlorophyll concentrations for the same two density layers described for the northern track (Figure 5.2-12). A shoreward shift in density or chlorophyll was not noticeable for the southern track as observed for the northern track.

5.2.2 Interpretation

Basic characteristics of Harbor-Bay concentration gradients and the apparent changes with the stage of the tide were similar, but not identical along the two tracks in and out of the northern and southern Harbor. In summer, the northern Harbor-Bay connection seems to be the more active region of export and stimulation of chlorophyll. The major aspects of Harbor-Bay interaction from analysis of the survey data are summarized as:

- Within the Harbor and in the channel region of the Bay closest to the Harbor, there is strong mixing, indicated by the T-S plot and by relatively linear relation between salinity and turbidity and chlorophyll. For the northern Harbor transect, the location of active mixing region is identified in Figures 5.2-8 and 9. Observations imply active dilution of fresher water (land discharge) with more saline water of the Bay without a strong loss or gain in chlorophyll or turbidity, in the tidal mixing region.

- Slightly east of the channel mixing area, i.e., within the Bay, and at the seaward side of the tidal front, chlorophyll levels were higher than could be produced by simple mixing of any water within the sampling region. Stimulation of *in situ* chlorophyll is suggested. The repeated track surveys at low and high tide illustrated kilometers-scale excursion of surface water during tidal ebb and flood cycles. Within the high chlorophyll patches in the Bay, *in situ* growth of chlorophyll was suggested from low to high tide samplings, or from morning to mid-afternoon. Increases in chlorophyll occurred at the surface and within the upper pycnocline, which was slightly closer to the surface at high tide in the afternoon. Growth within the high chlorophyll patches was far more pronounced at the frontal region of the northern Harbor track than the southern Harbor track.

- Mid-Nearfield surface water had its own character, and relative to the mixing and receiving region of the Bay, had lower chlorophyll. The most intense accumulation of chlorophyll in this deeper-water region was found within the pycnocline. The regional spatial patterns for chlorophyll were similar to those reported for June 1993 by Kelly and Albro (1994).

- Physically, the data on density, as well as salinity and temperature suggest that surface waters of the Harbor, channel, and Bay communicate during low tide. Density layers are fairly continuous as surface waters appear to be exported into the highly stratified Bay.

> The surface-water communication and export of inshore water appears to be interrupted, for both Harbor-Bay connections, by upwelling at high tide. This dynamic, similar to that described above by Geyer (Section 5.1) for June 1994, brings water within the pycnocline to the surface and promotes a discontinuous distribution, supporting the notion of tidal pumping or puffing as conceptualized in Chapter 4. However, there is evidence that the surface water just beyond the seaward extension of diluted Harbor water advects with the tidal excursion but does not mix with inshore surface water. Interestingly, it is this seaward region in which active chlorophyll growth occurs in the upper layers of the stratified Bay waters. On ebbing tides, surface water in the channel and westernmost Bay may subduct and mix more easily with mid-depth Bay waters than across waters at the surface.

Note that in reference to our posed question, we have interpreted the data to indicate a variety of physical mechanisms. We suggest roles for *dilution* of Harbor chlorophyll and turbidity and *mixing* within the tidal excursion zone; *advection* of mixed, diluted water parcels that may be segregated each flood cycle by physical upwelling; and chlorophyll *stimulation* in the Bay outside the tidal mixing zone, with enhanced growth therein.

A lingering question is, why does chlorophyll stimulation occur where it does? Is it due to decreased turbidity and removal of light limitation? Is it nutrient stimulation from the Harbor outflow? We cannot resolve these questions with the data, but believe both factors are involved. With respect to lowered turbidity stimulating chlorophyll, it is curious that the region with high tide upwelling contains less turbid water, but chlorophyll does not actively develop there. We have established that light can play a very significant role (Kelly and Doering, 1995) in chlorophyll and primary production in the Harbor-Bay area, especially at the timescales of concern in this study. One significant mechanism related to light may be the slight uplift of the upper pycnocline in the stratified, high chlorophyll region. Tidal upwelling of just several meters may bring plankton to less light-limiting conditions within the upper pycnocline. We also suspect that in the upwelling region, in spite of clearer water, that the physical dynamics are too fast to allow an *in situ* plankton response. In contrast, within the more stably stratified water at the edge of the front, physical dynamics may be slow enough for population maintenance and growth to occur. Stability and a relatively shallow surface layer in this particular region may be coupled with conditions where both light and enhanced nutrient supplies are jointly maximal. Higher total nutrient concentrations often exist in the northern Harbor (where effluent is discharged) compared to the southern Harbor. Higher nutrient supply would be a mechanism to explain the more pronounced growth along the northern track during the day. However, if a factor, the physical data suggest that nutrient transfer from inshore to the high chlorophyll region in our survey might not be a simple mixing or advective process.

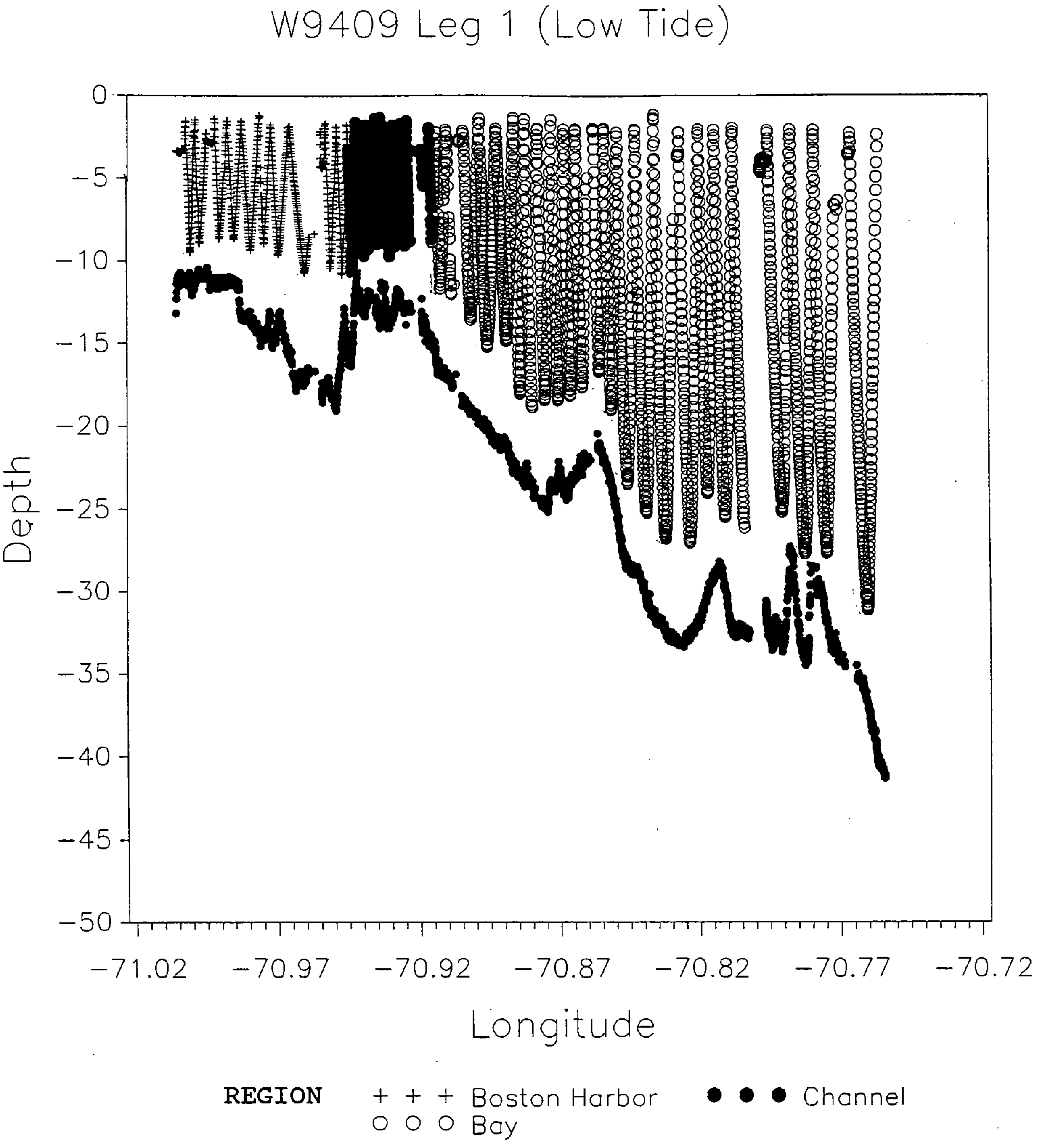


Figure 5.2-1. **Classification of data sampled in three regions along the northern Harbor transect. Actual bottom topography is shown along with 2-sec-averaged data points throughout the water column, suggesting the V-path of the towfish. Symbols indicate the regional classification (by longitude) used for following figures in Section 5.2.**

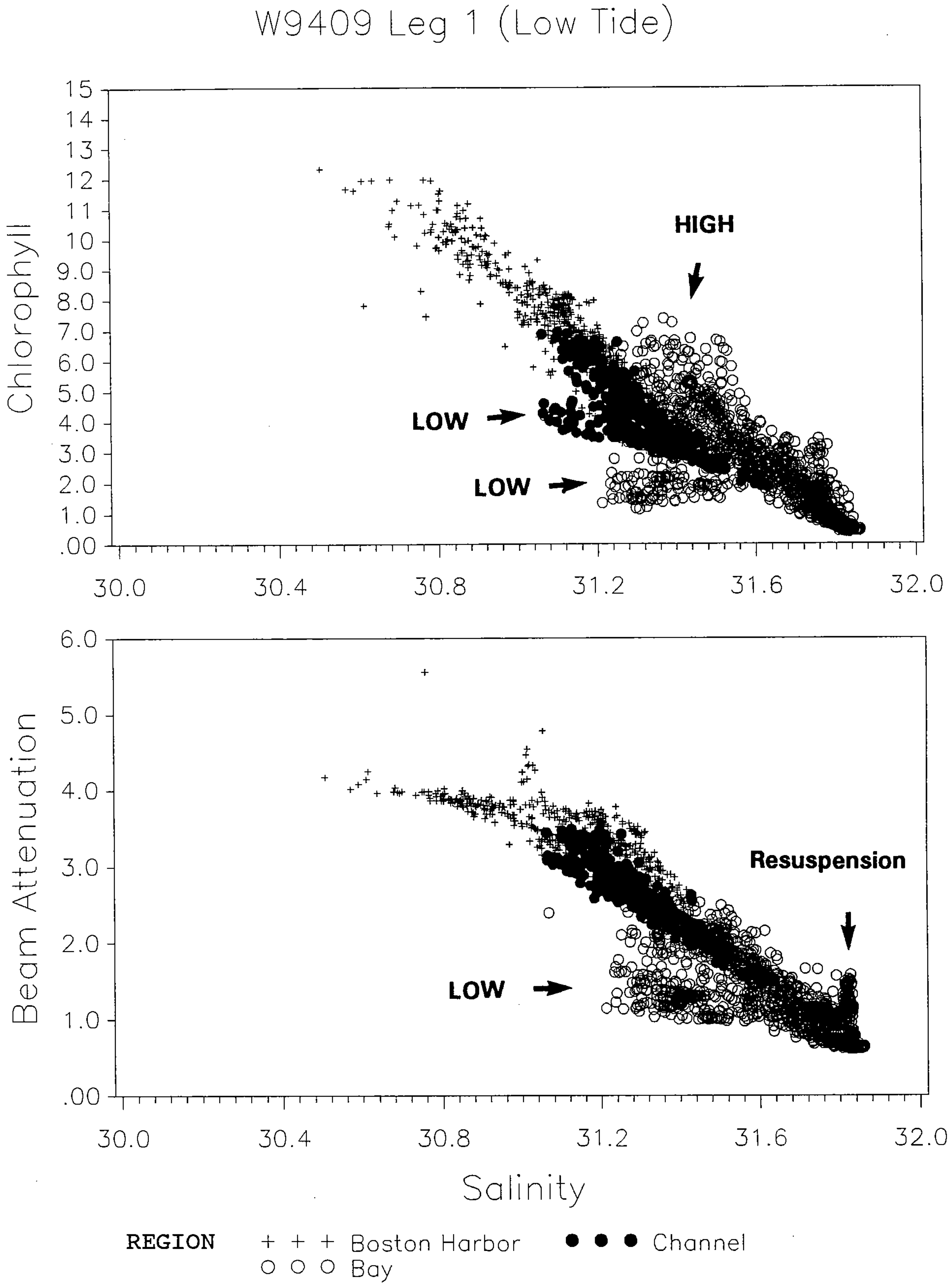


Figure 5.2-2. **Chlorophyll (μg L^{-1}) and turbidity (m^{-1}) vs. salinity (PSU) along the northern Harbor transect at low tide on July 28, 1994. Arrows point out features that depart from the main trend and are described in text.**

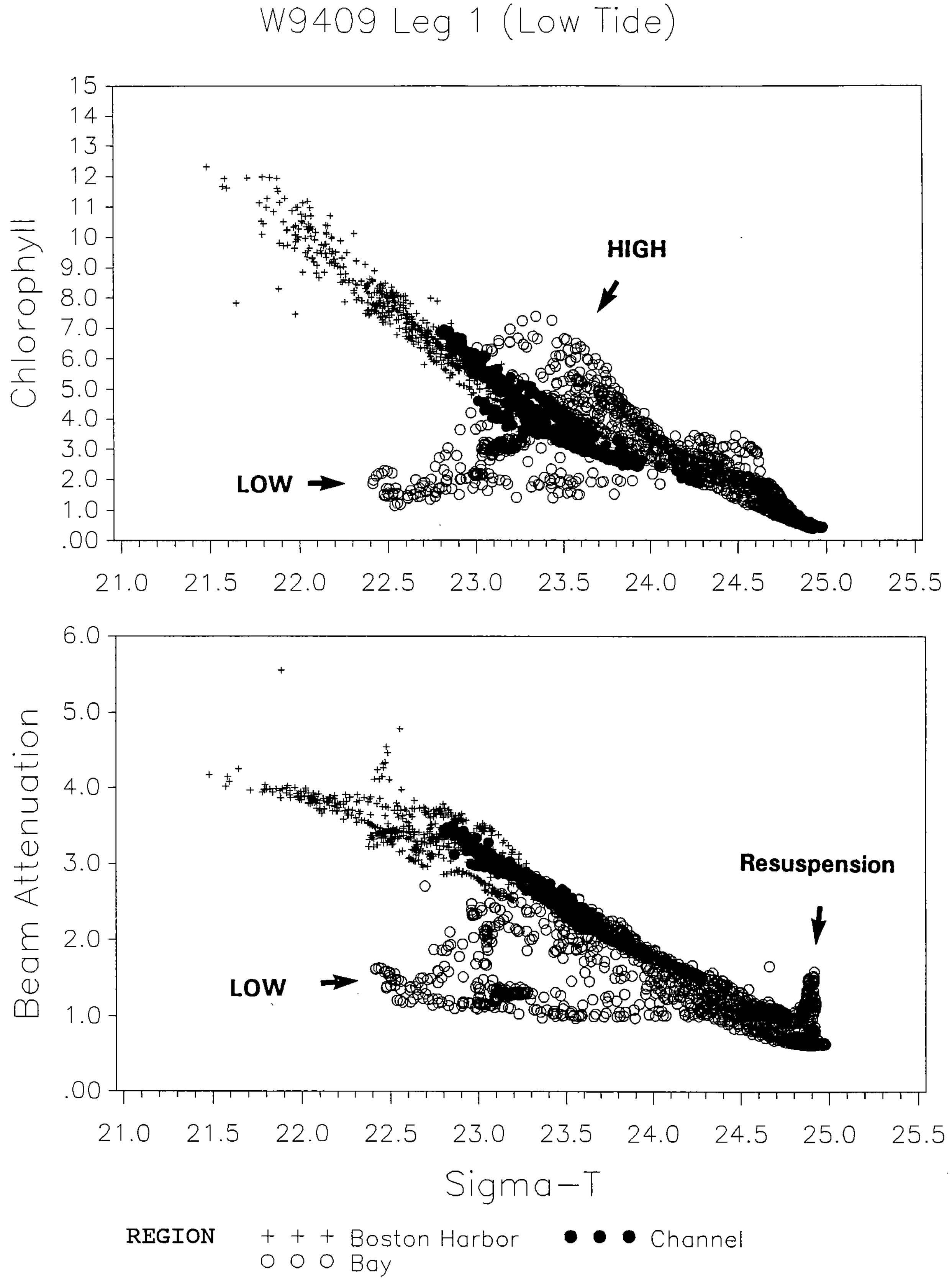


Figure 5.2-3. **Chlorophyll (μg L^{-1}) and turbidity (m^{-1}) vs. density (σ_T) along the northern Harbor transect at low tide on July 28, 1994. Arrows point out features that depart from the main trend and are described in text.**

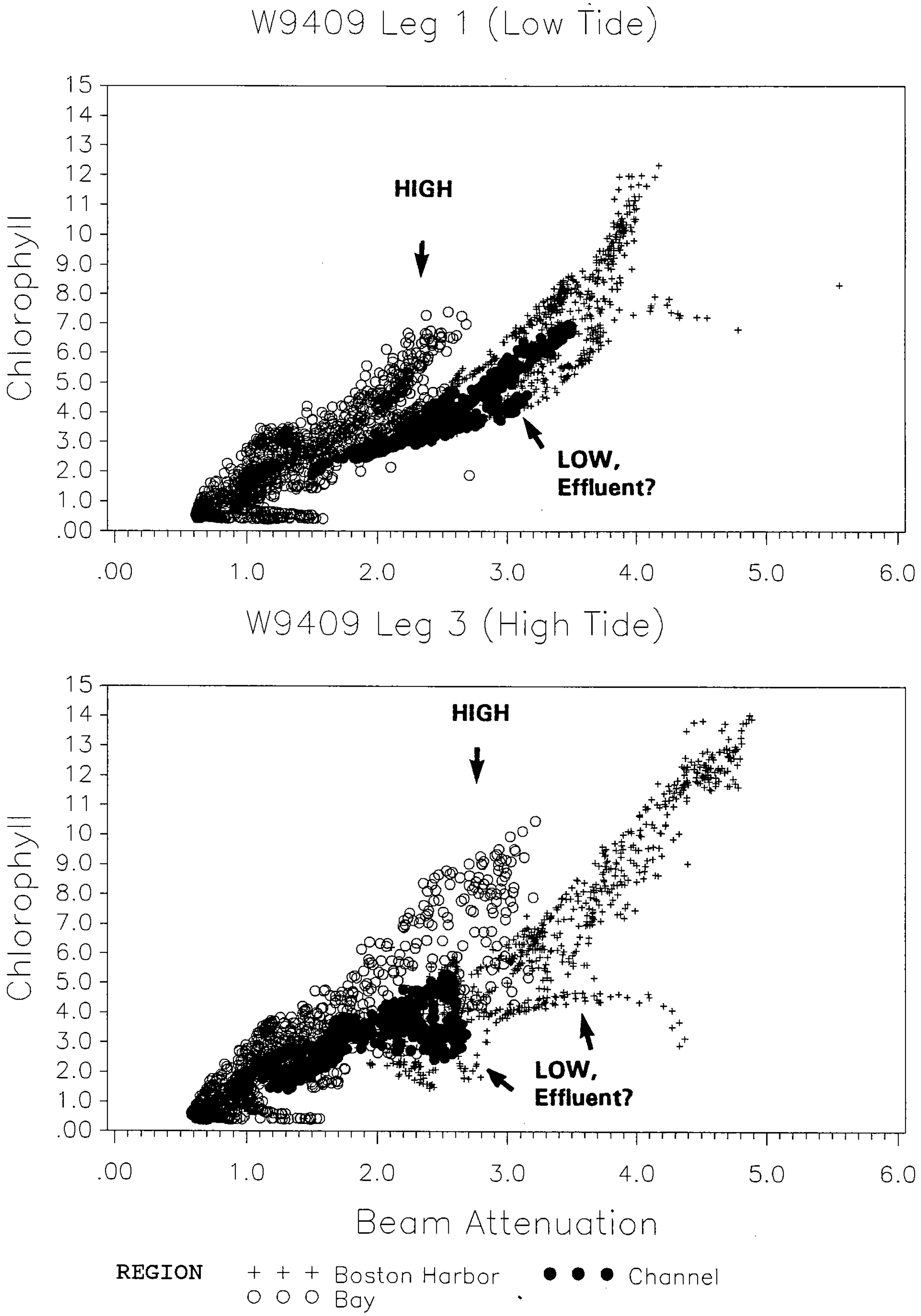


Figure 5.2-4. **Chlorophyll (μg L^{-1}) vs. turbidity (m^{-1}) along the northern Harbor transect at high and low tide on July 28, 1994. Arrows point out features that depart from the main trend and are described in text.**

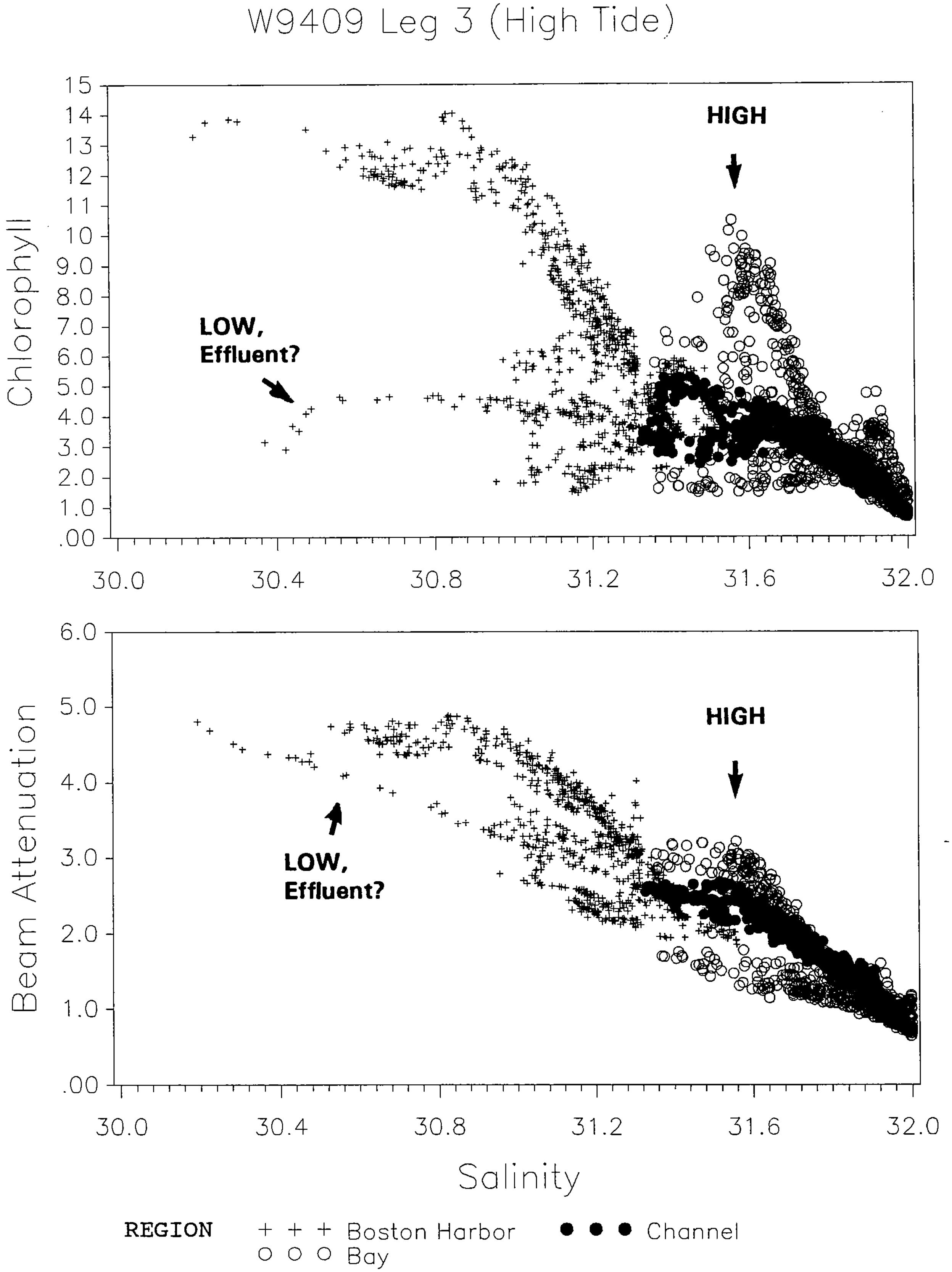


Figure 5.2-5. **Chlorophyll (μg L^{-1}) and turbidity (m^{-1}) vs. salinity (PSU) along the northern Harbor transect at high tide on July 28, 1994. Arrows point out features that depart from the main trend and are described in text.**

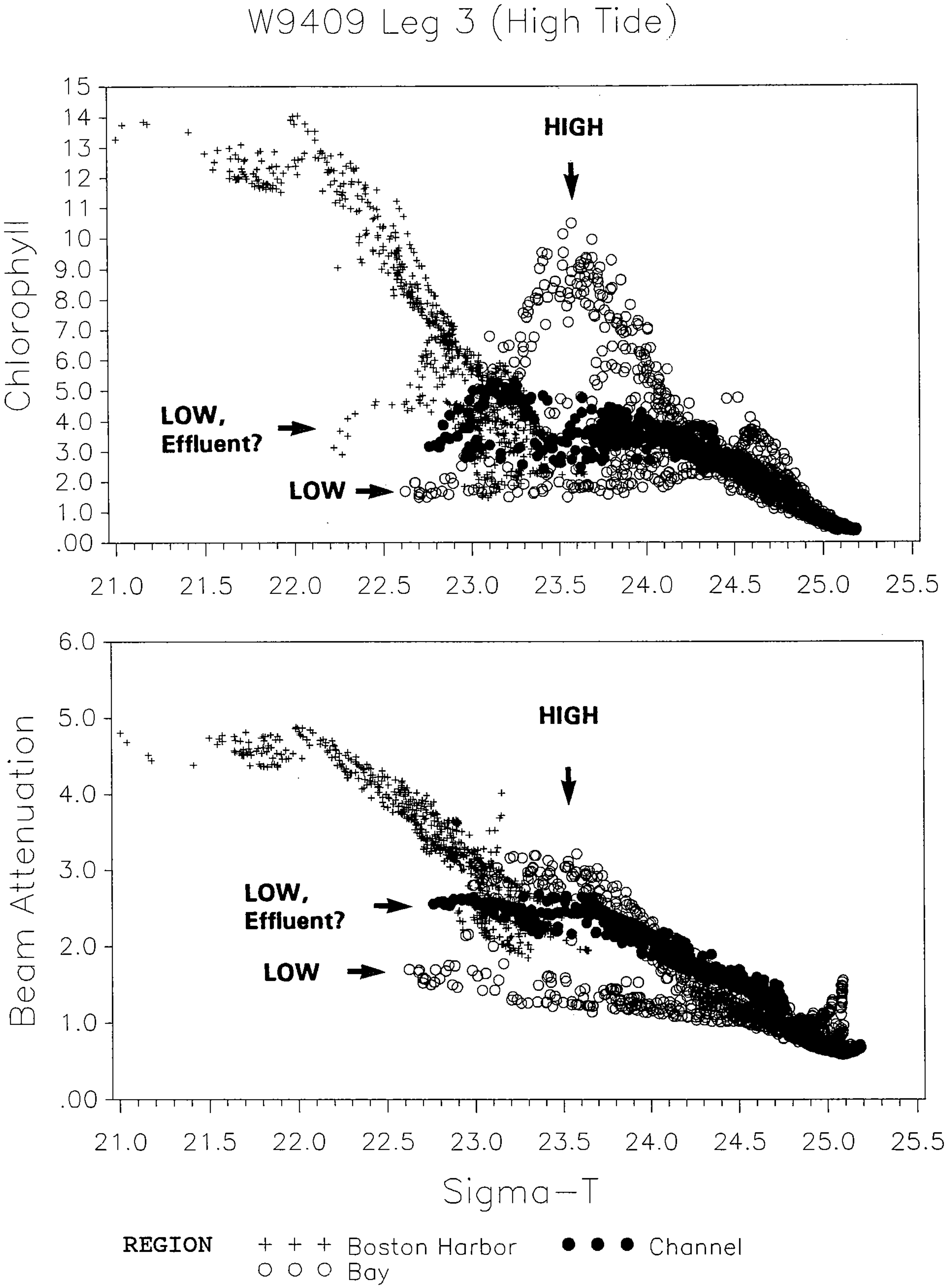
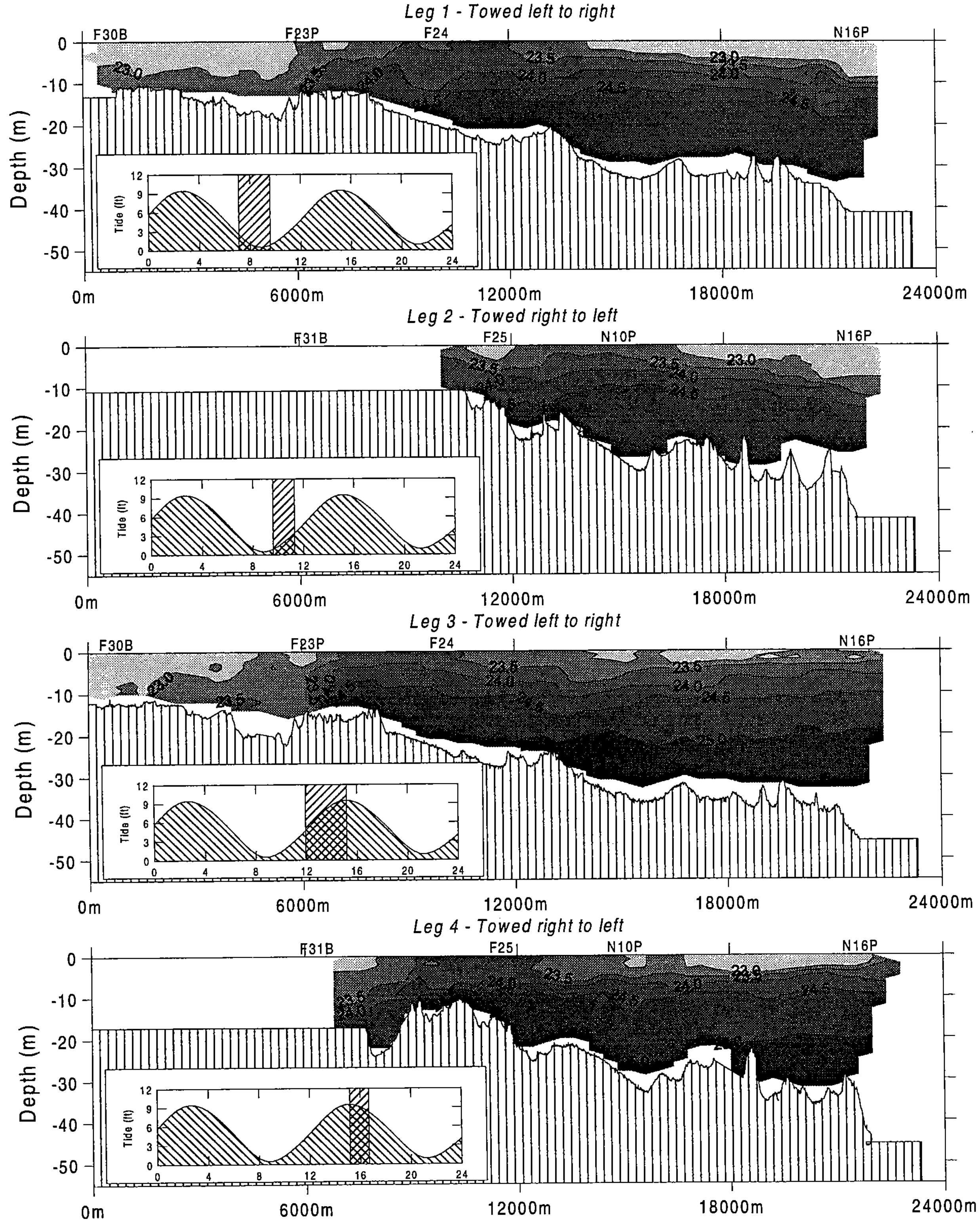


Figure 5.2-6. **Chlorophyll (μg L^{-1}) and turbidity (m^{-1}) vs. density (σ_T) along the northern Harbor transect at high tide on July 28, 1994. Arrows point out features that depart from the main trend and are described in text.**



Leg 1 - Towed left to right

Leg 2 - Towed right to left

Leg 3 - Towed left to right

Leg 4 - Towed right to left

Figure 5.2-7a. Density (σ_T) for Survey W9409 on July 28, 1994.

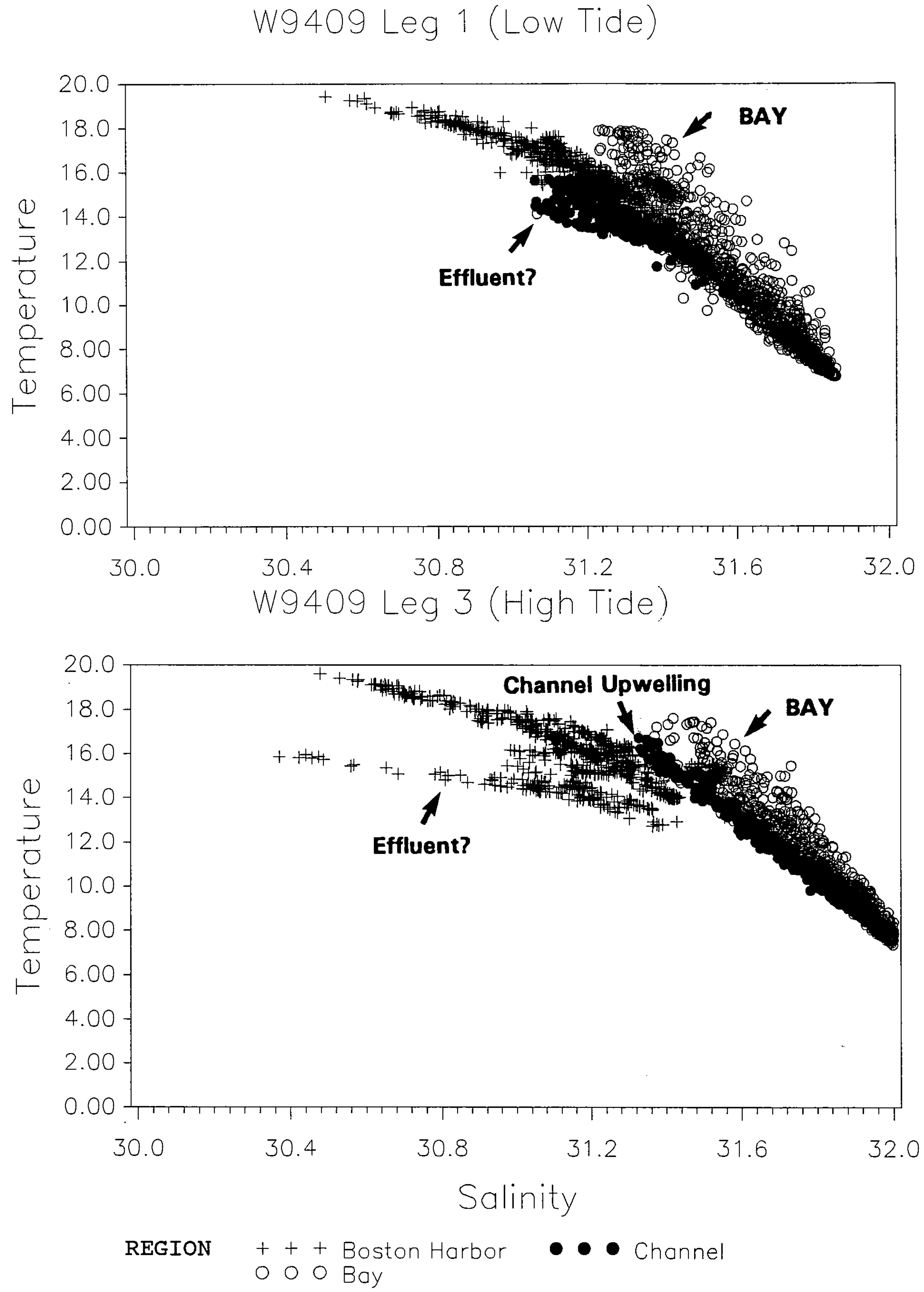


Figure 5.2-7b. **T-S plots for the northern Harbor transect on July 28, 1994. Arrows point out features that depart from the main trend and are described in text.**

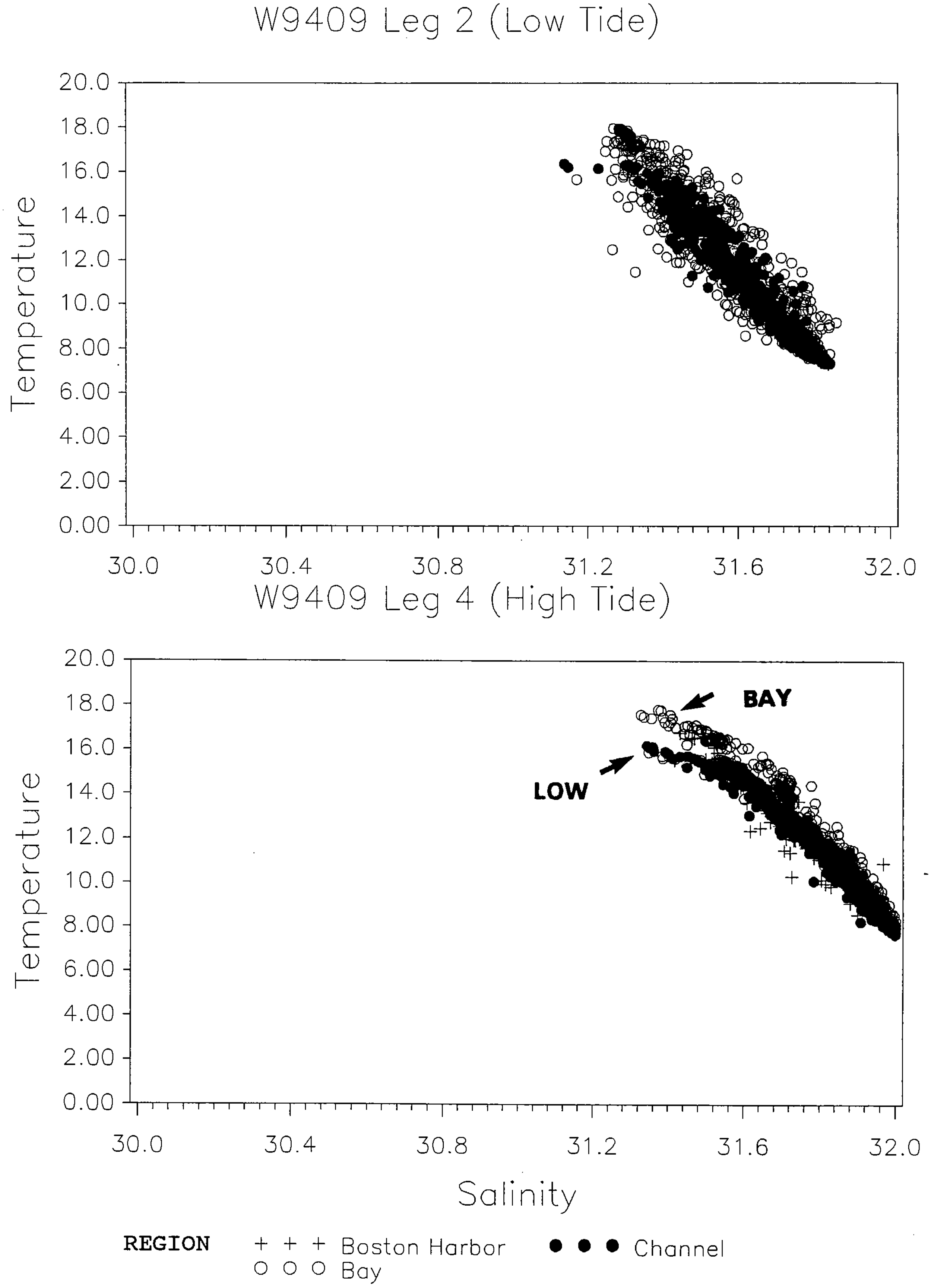


Figure 5.2-7c. **T-S plots for the southern Harbor transect on July 28, 1994. Arrows point out features that depart from the main trend and are described in text.**

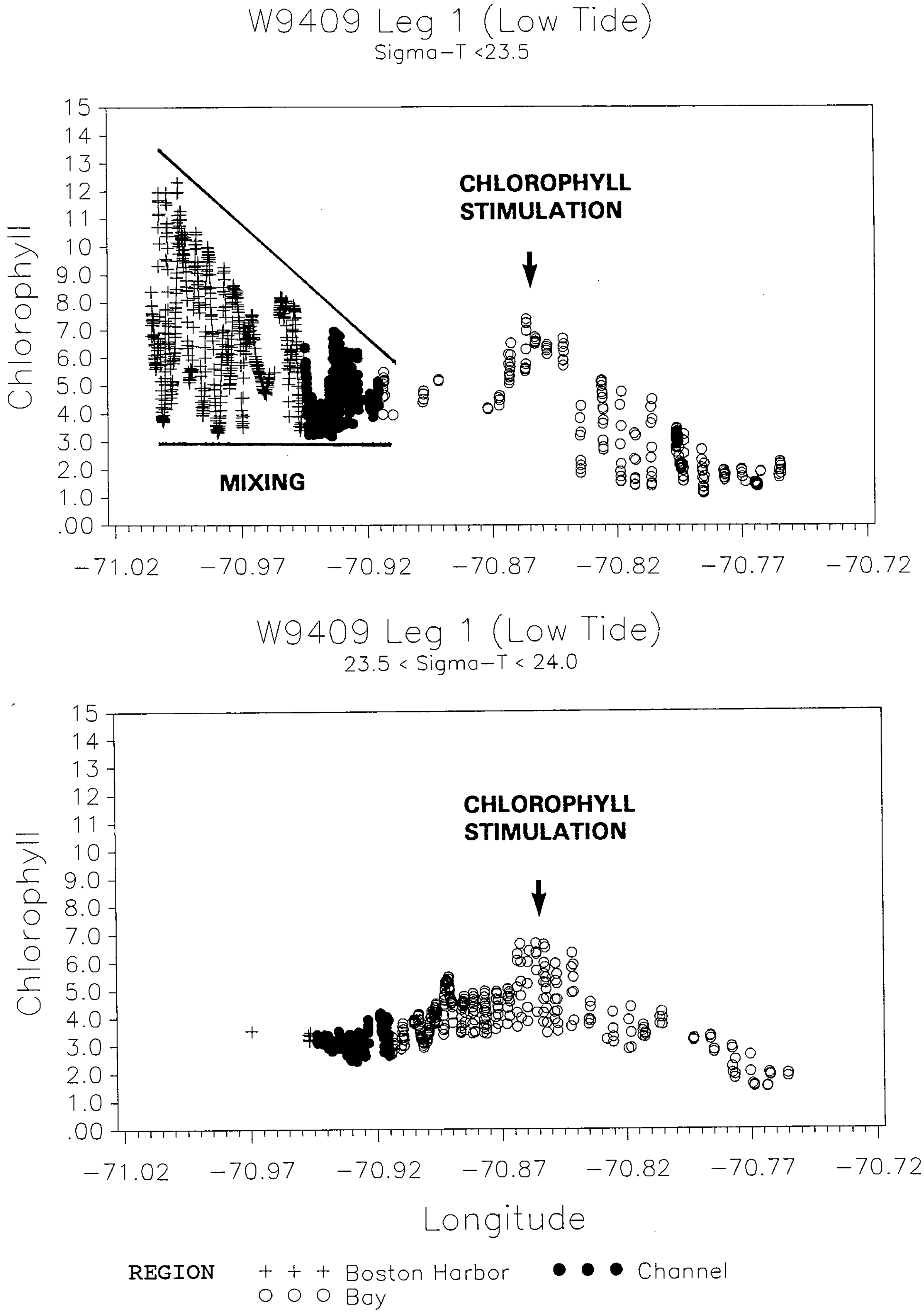


Figure 5.2-8. **Chlorophyll (μg L^{-1}) vs. longitude along the northern Harbor transect at high tide on July 28, 1994. Top shows surface water with density (σ_T) <23.5 and bottom shows pycnocline-level water where 23.5 < σ_T < 24.0.**

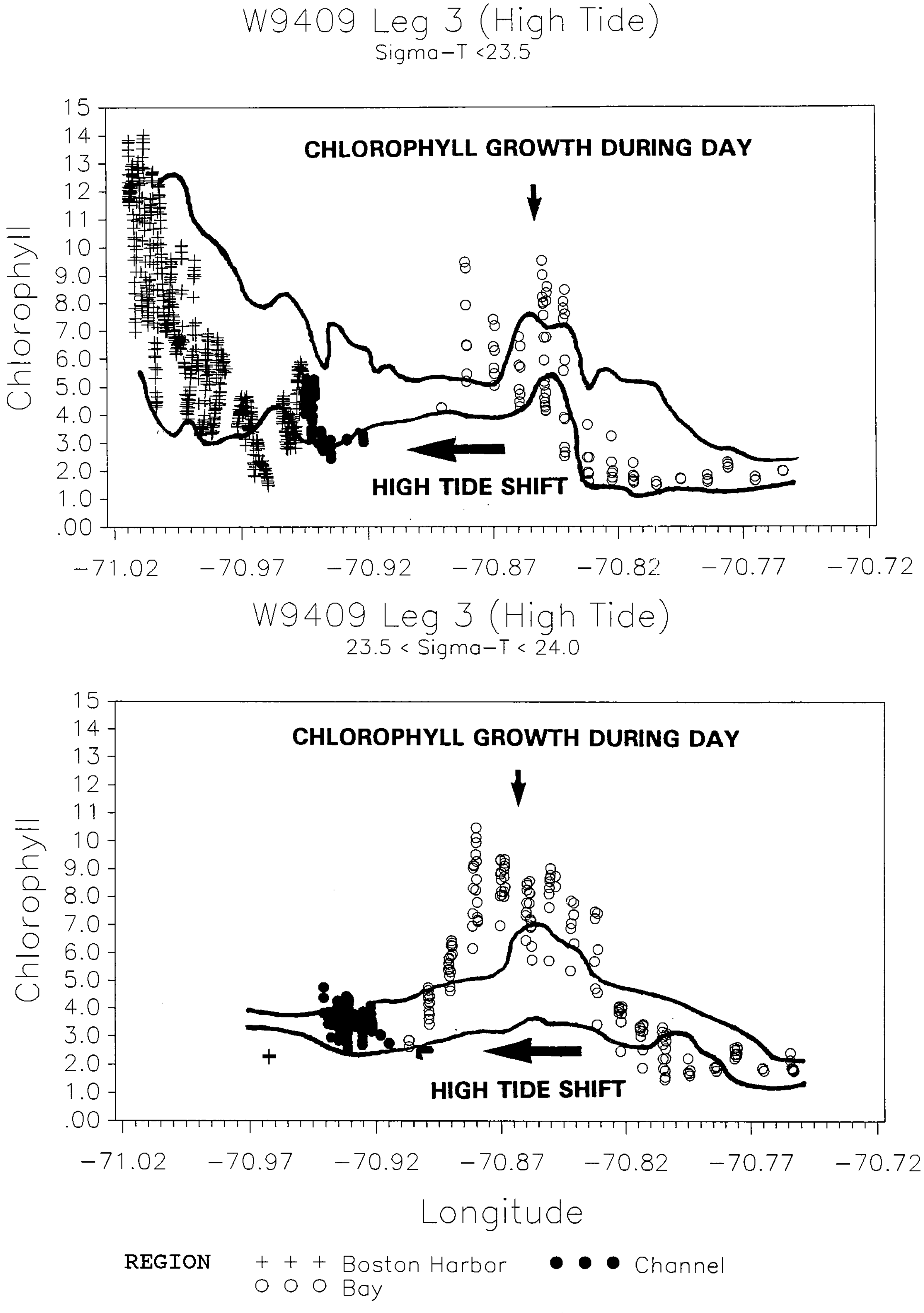


Figure 5.2-9. **Comparison of chlorophyll (μg L^{-1}) vs. longitude along the northern Harbor transect at low tide and high tide (see Figure 5.2-8) on July 28, 1994. The plotted data are from high tide; the envelope shows the range for low tide data as shown in Figure 5.2-8.**

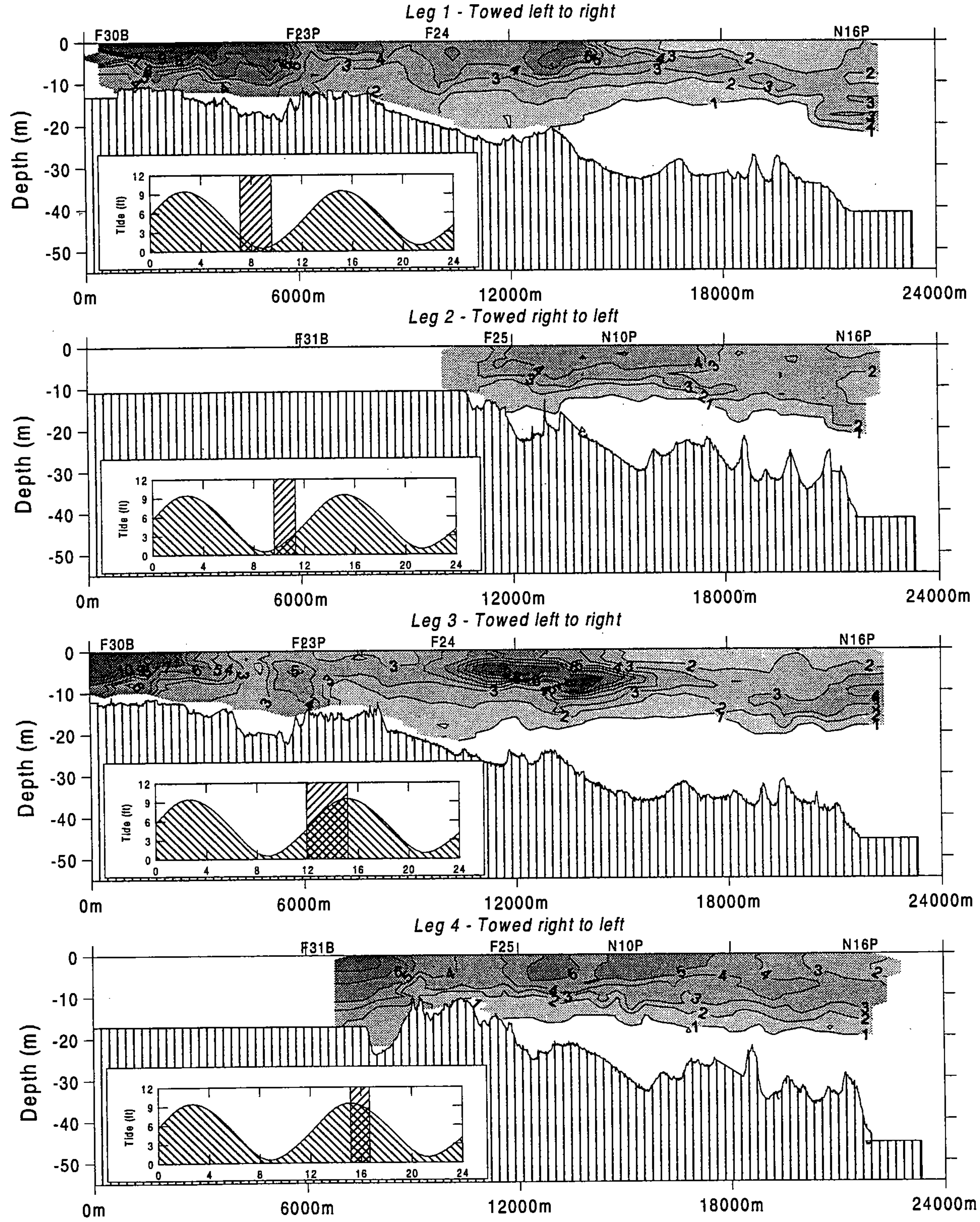


Figure 5.2-10. Chlorophyll (μg L^{-1}) for Survey W9409 on June 28, 1994.

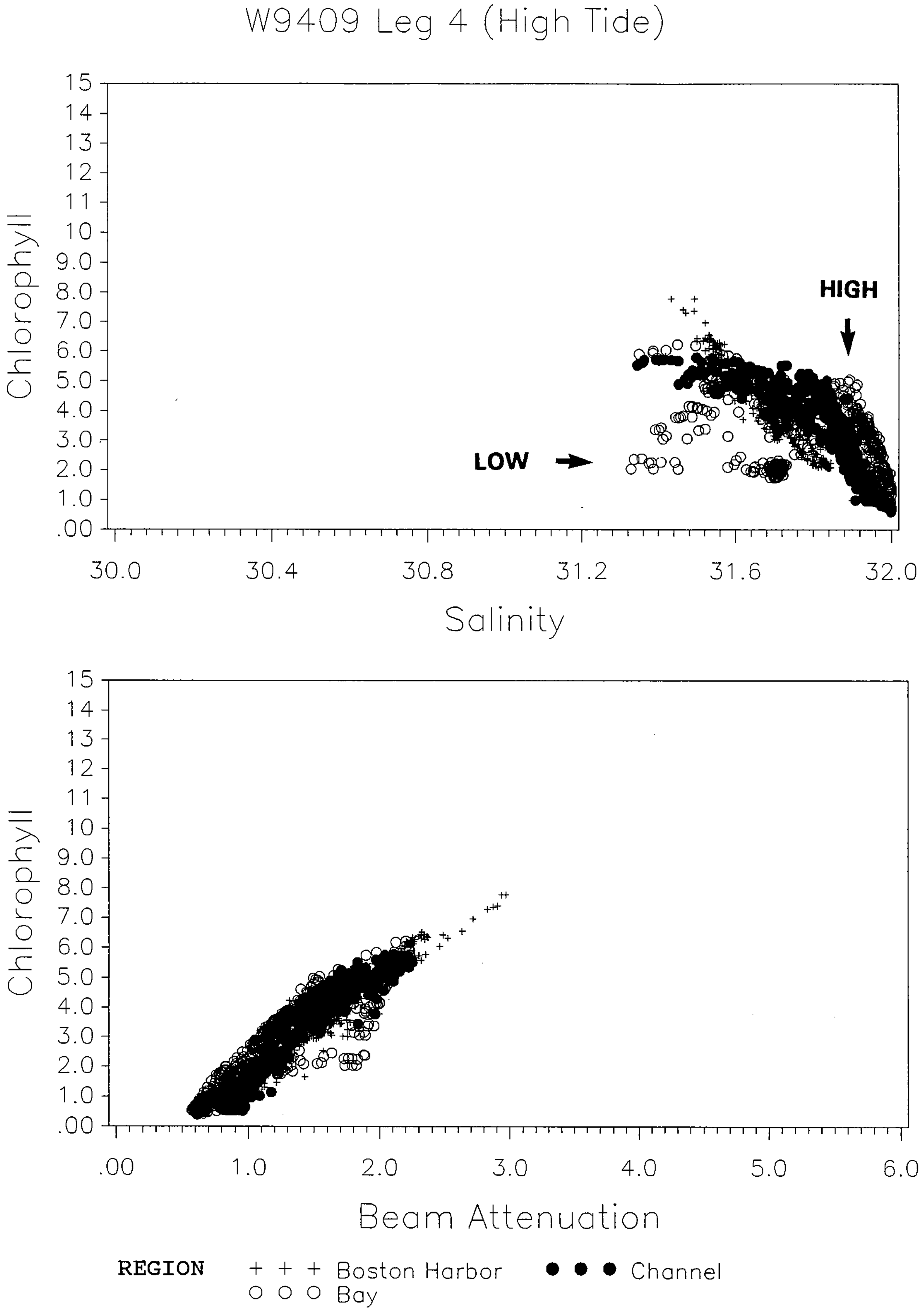


Figure 5.2-11. **Chlorophyll (μg L^{-1}) vs. salinity (PSU) (top) and turbidity (m^{-1}) (bottom) along the southern Harbor transect at high tide on July 28, 1994. Arrows point out features that depart from the main trend and are described in text.**

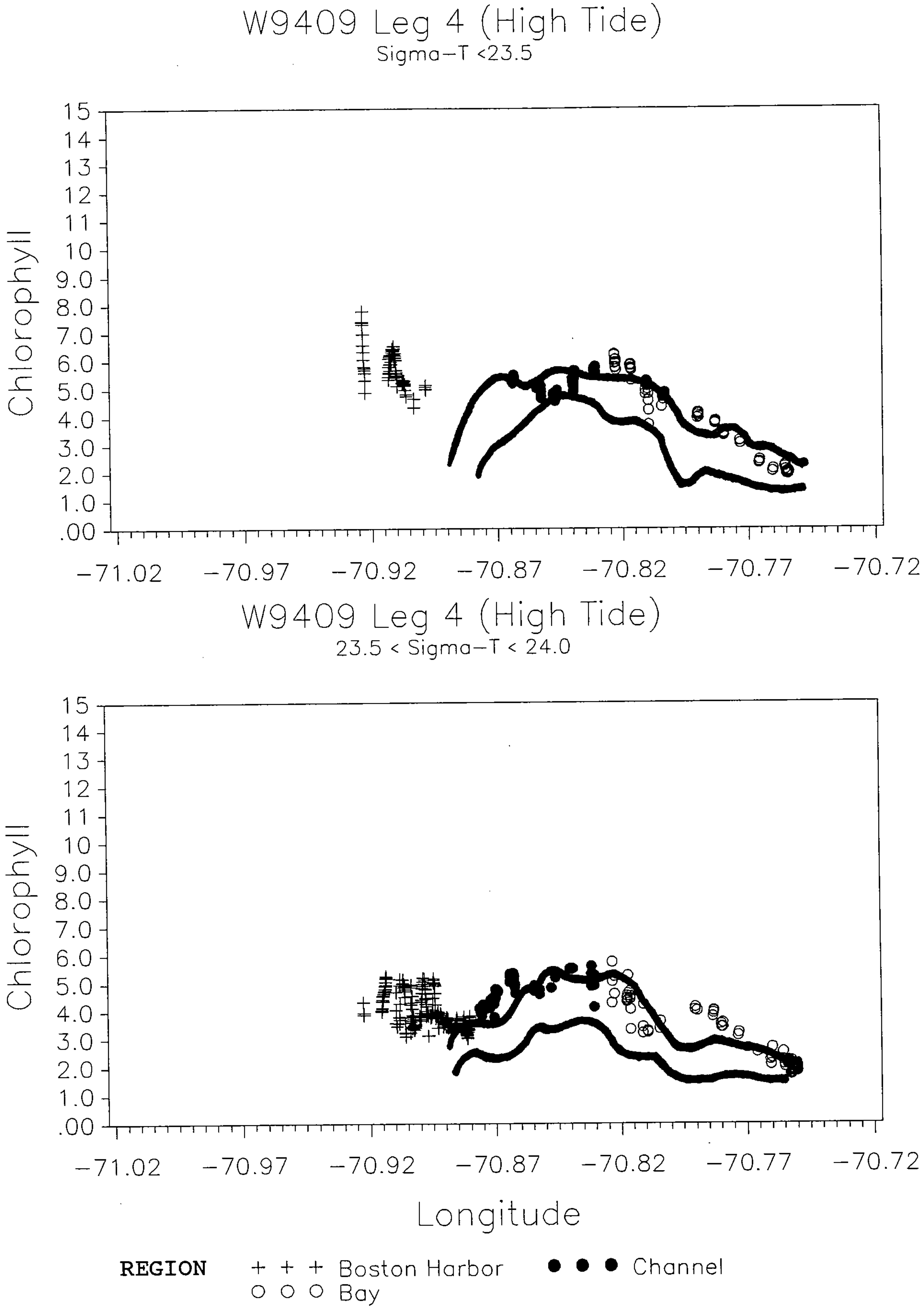


Figure 5.2-12. **Comparison of chlorophyll (μg L^{-1}) vs. longitude along the southern Harbor transect at low tide and high tide on July 28, 1994. The plotted data are from high tide; the envelope shows the range for low tide data.**

Chapter 6 CONCLUSIONS

The twelve surveys described in this report give an unprecedented degree of resolution and fidelity for a number of water quality features. Results illuminate some new facets of tidal interaction and they significantly refine understanding of the nature of the spatial connections of the Boston Harbor and Massachusetts Bay. Specific conclusions from the two categories of surveys conducted in 1994 are summarized below.

6.1 BAYWIDE

Surveys efficiently characterized a broad area and the data depicted both fine-scale and meso-scale structure across different regions of the Bay. Such broad surveys allow one to view local conditions (e.g., western Massachusetts Bay) in the context of their broader environmental setting.

The data for April provided water-quality diagnostics to distinguish water masses at the northern boundary of Massachusetts Bay. The data at this time strongly indicated that a portion of early spring coastal runoff advecting from the north of Massachusetts Bay did not enter the Bay, but skirted it east of Stellwagen Bank. South of Cape Ann within the Bay, the data showed some surface-water inflow to the Bay. The inflow was not continuous, but sporadic, and the fresher pools of surface water were depleted in chlorophyll relative to surrounding resident Bay water. The data suggest a strong degree of coupling in space and time between physical processes and plankton distributions, and could be further explored to examine this coupling.

The data for October demonstrated that variability in physical structure was a function of water depth. Inshore waters and the water column over Stellwagen Bank were vertically well-mixed. In waters deeper than about 25 m, there was a horizontal continuity of density stratification. The majority of the Bay was similarly layered — a lingering result of seasonal warming. Concomitant with the vertical layering, a general depression of DO was observed in bottom waters during this fall period when, historically, annual bottom-water DO minimum have been observed. The 1994 DO minimum noted in most of the surveyed region of the Bay in mid-October 1994 was well below the state standard of 6.0 mg L^{-1}.

6.2 HARBOR—BAY

Data along tracklines between the Harbor and the Bay indicated tidal motions and a number of physical and ecological processes related to the present interaction of waters within the Harbor and the Bay. Specific surveys provided excellent "snapshots" of local conditions, and each survey could be examined in greater detail than attempted here. However, the principal and strong conclusion of our study was that the nature of the tidally-mediated interaction between the Harbor and the Bay varies seasonally.

We have presented generalized conceptual models of the seasonal variability in the Harbor's coupling with the Bay. The coupling is demonstrably influenced by variability in physical structure as well as differences in seasonal cycles of phytoplankton in inshore vs. offshore waters. During some periods the Harbor appears to import chlorophyll from the Bay and during other periods it exports chlorophyll to the Bay.

Our conceptual models were derived from changes in water properties at different stages of the tide and the inferred dynamics are founded on static data, even if the data are highly resolved in space. However, the concepts are generally consistent with dynamic information collected during a special velocity study in June 1994. Accordingly, the proposed hypotheses on seasonal exchange dynamics provide reasonable first-order paradigms and strengthen our fundamental conclusion of a seasonally variation in the physically-mediated coupling of Harbor and Bay ecology and biogeochemical cycles.

Another conclusion from our analyses is that different vertical layers of the Bay freely communicate with the Harbor at different seasons. For example, during summer stratification of the Bay, the pycnocline is a primary conduit for Harbor-Bay communication. A number of summer surveys, and the special velocity study in June, demonstrated a tidally- and bathymetrically-induced upwelling of water from within the pycnocline to the surface in the shallow western Bay region fringing the Harbor. Velocity measurements in June showed that the flood tide was initiated at depth, with a time lag in flow at the surface. There was also evidence for a weak estuarine circulation, with net outflow at the surface and net inflow near the bottom bathymetry. Calculations documented an internal tide that was likely induced by the abrupt bathymetric variation in western Massachusetts Bay near the Harbor entrance. The internal tide may be an important source of energy for vertical shears and it provides a physical mechanism for the observed upwelling near the channel leading into Boston Harbor from the Bay. These findings indicate some detailed features that need to be considered further in efforts to predict the ecological consequences of relocating the present MWRA effluent discharge to Massachusetts Bay.

Finally, an analyses was conducted to examine the potential export of chlorophyll from the Harbor and stimulation of chlorophyll growth in the Bay during summer conditions when the Harbor is generally enriched in chlorophyll relative to the Bay. Chlorophyll dispersion from the Harbor seems to occur by mixing and advection within a defined tidal mixing region that extends several kilometers into western Massachusetts Bay. Additionally, though, our analysis provided strong evidence that *in situ* chlorophyll stimulation and active growth occurred during the day at the seaward edge of the tidal excursion.

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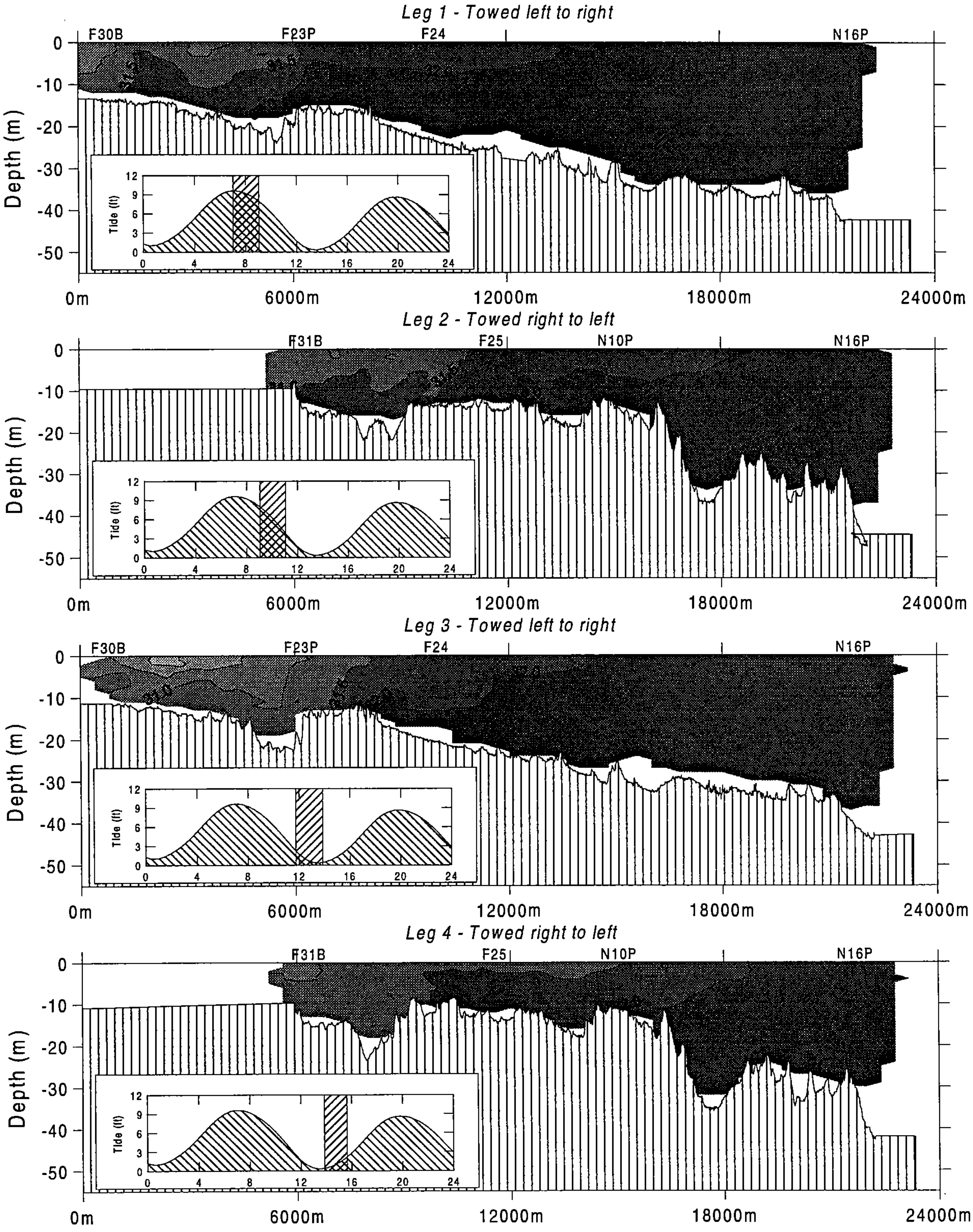
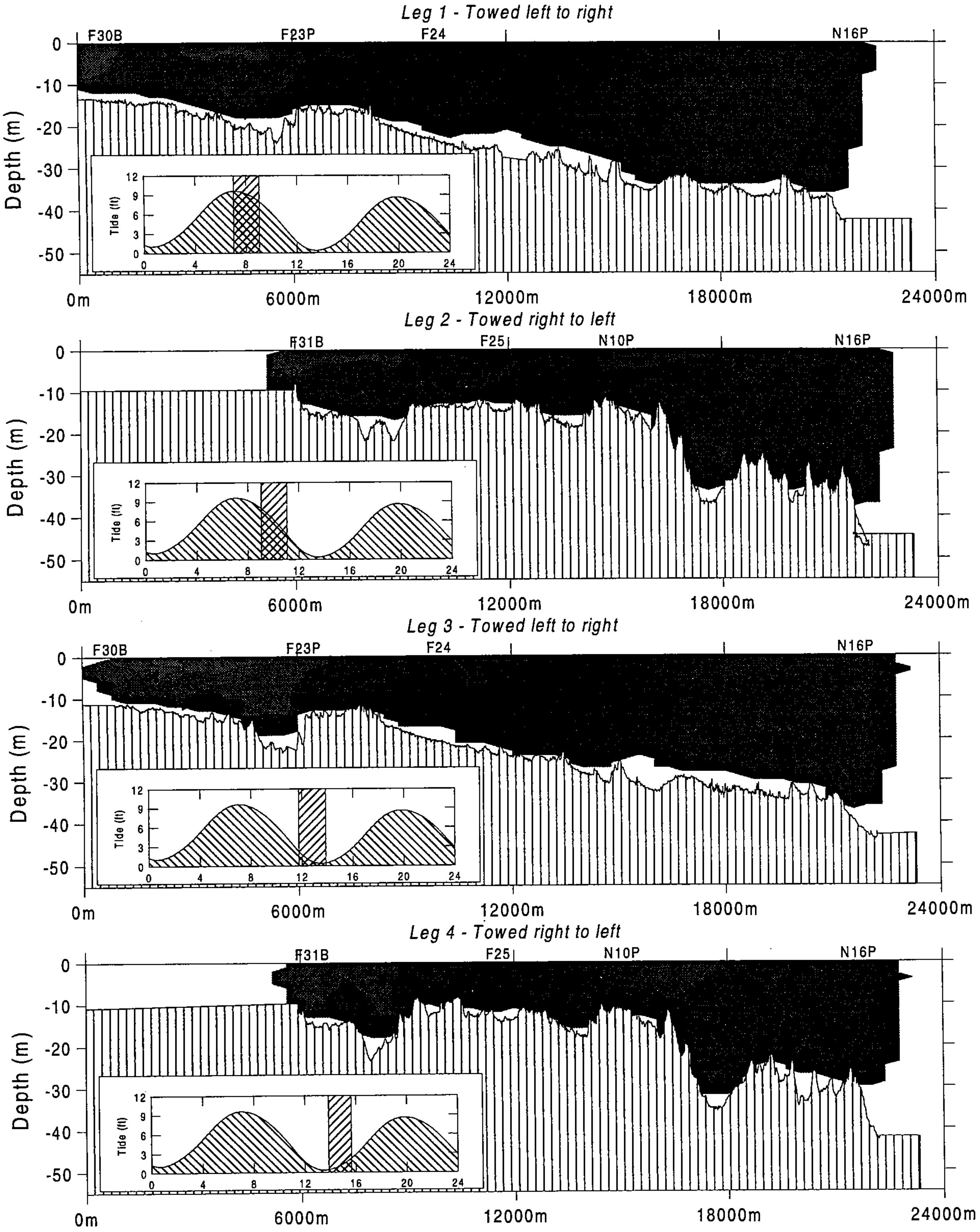
APPENDIX

For visual display, the 2-sec-averaged sensor data along the V-shaped track of the towfish during each survey were contoured as a vertical "slice" to display the water property profiles along the transect, using Surfer (1994). Contoured sections were prepared for five parameters: temperature (T), salinity (S), density (σ_T), beam attenuation, and chlorophyll. In this Appendix, plots are provided for parameters not displayed in the main report. Survey identifications and date of sampling are identified on each of the following figures.



Salinity (PSU) during Survey W9402 (07-Mar-94)



Leg 1 - Towed left to right

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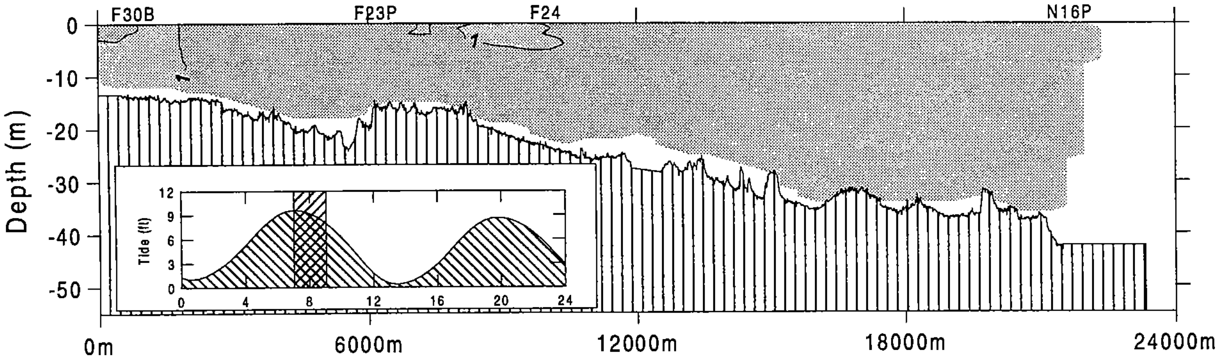
Leg 4 - Towed right to left

Sigma-T during Survey W9402 (07-Mar-94)

Leg 1 - Towed left to right



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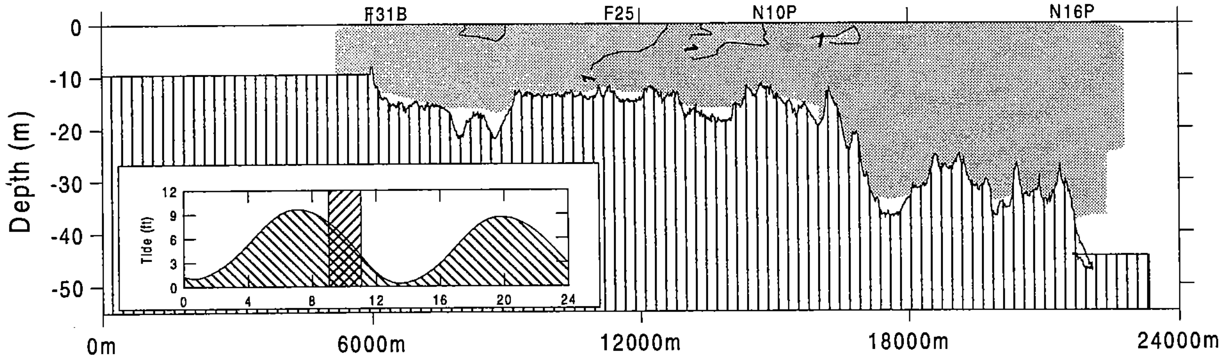

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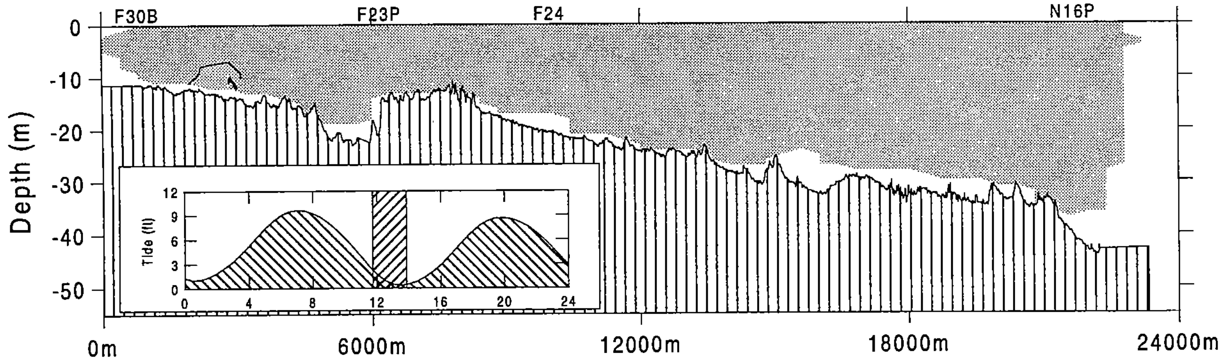

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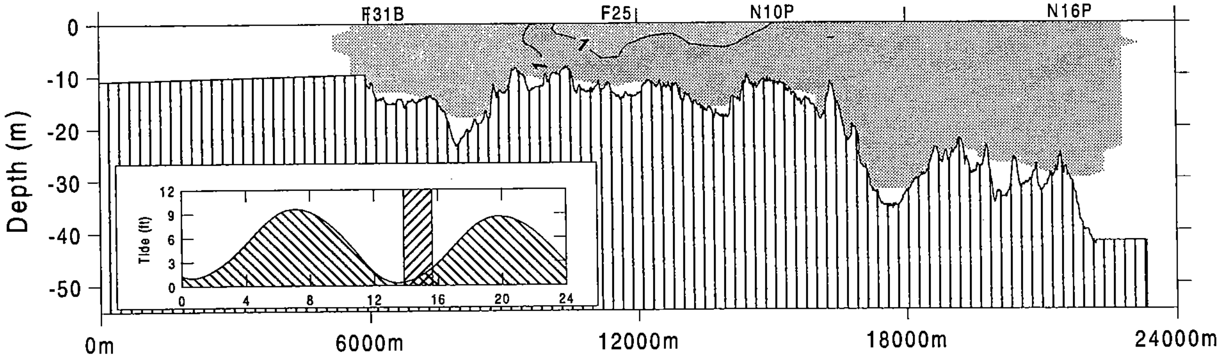
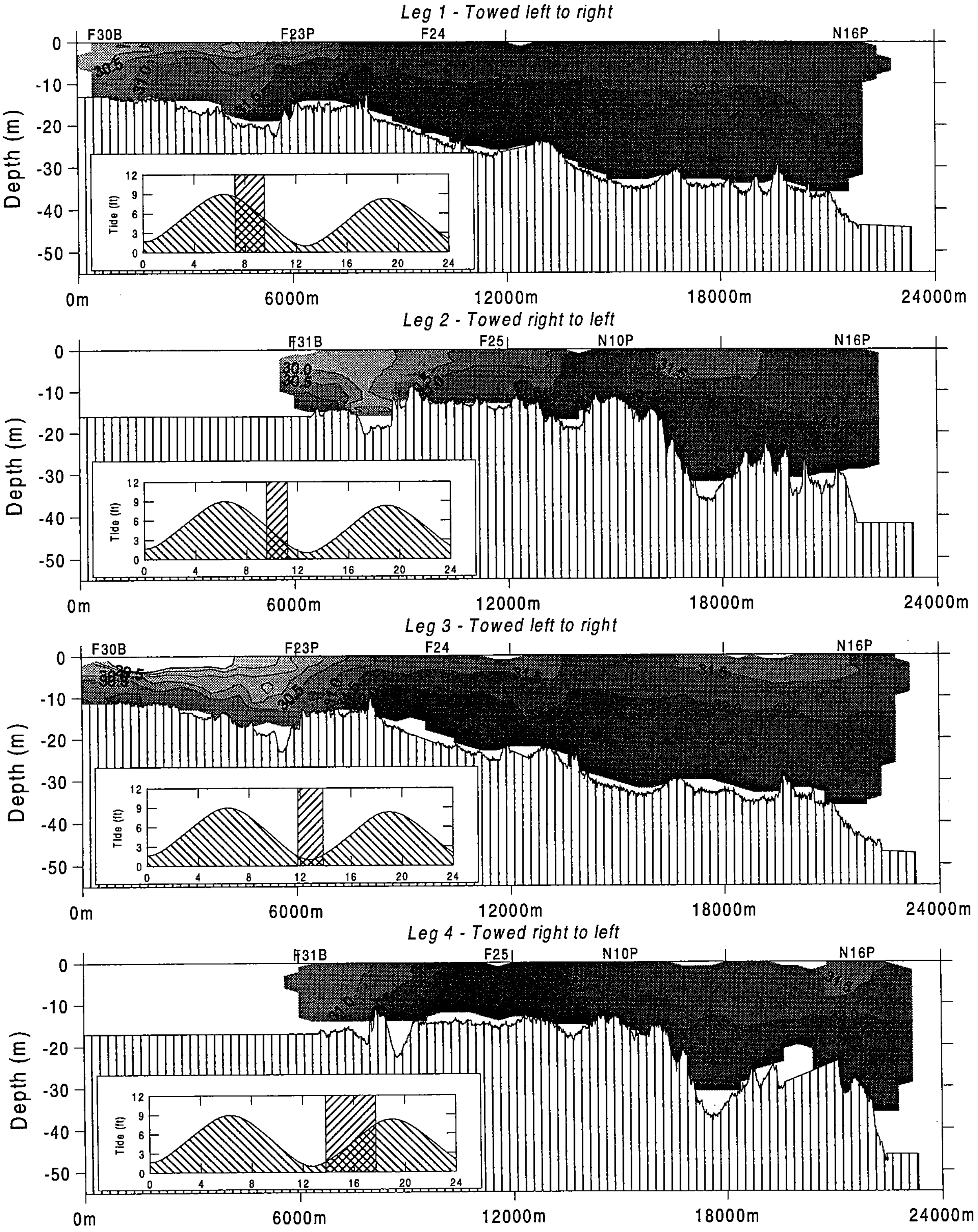


Temperature (°C) during Survey W9402 (07-Mar-94)



Salinity (PSU) during Survey W9403 (22-Mar-94)

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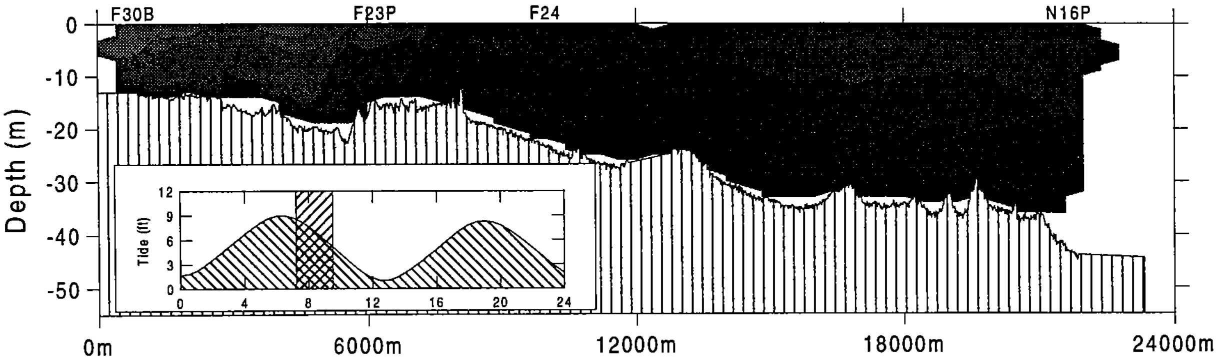

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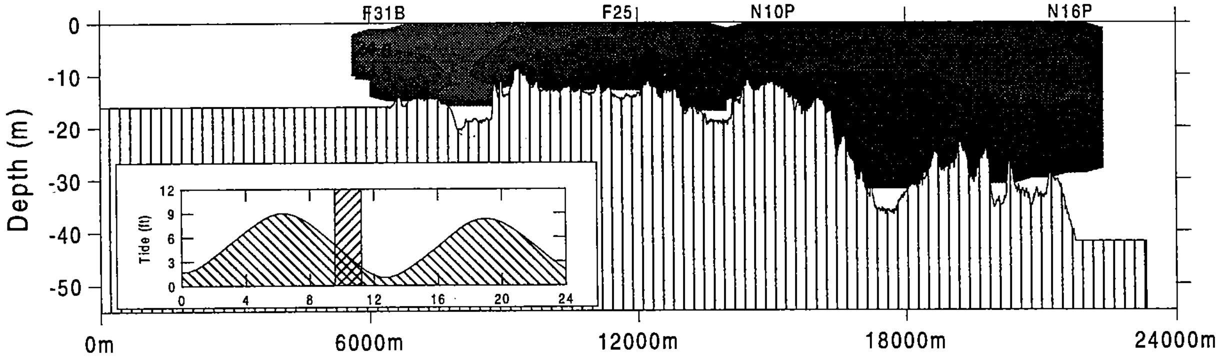

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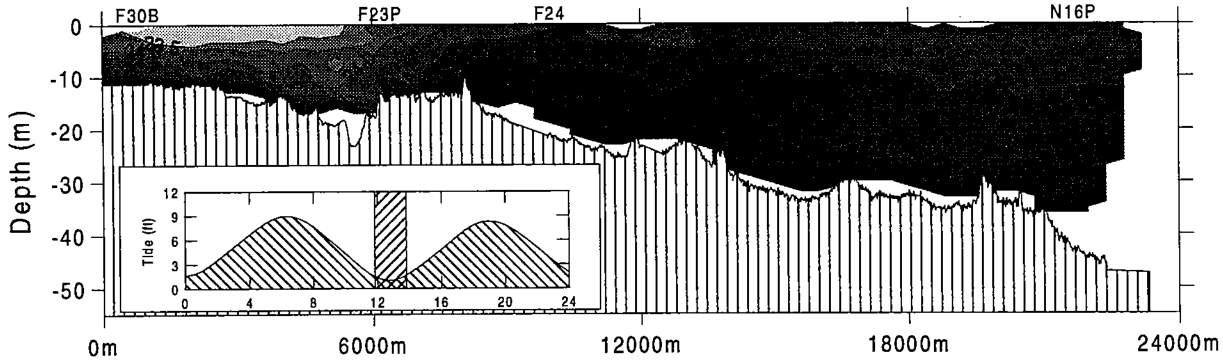

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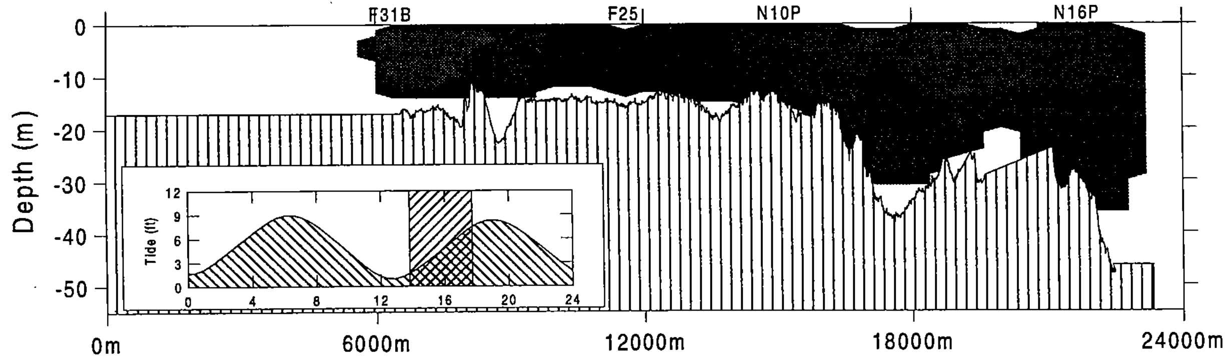
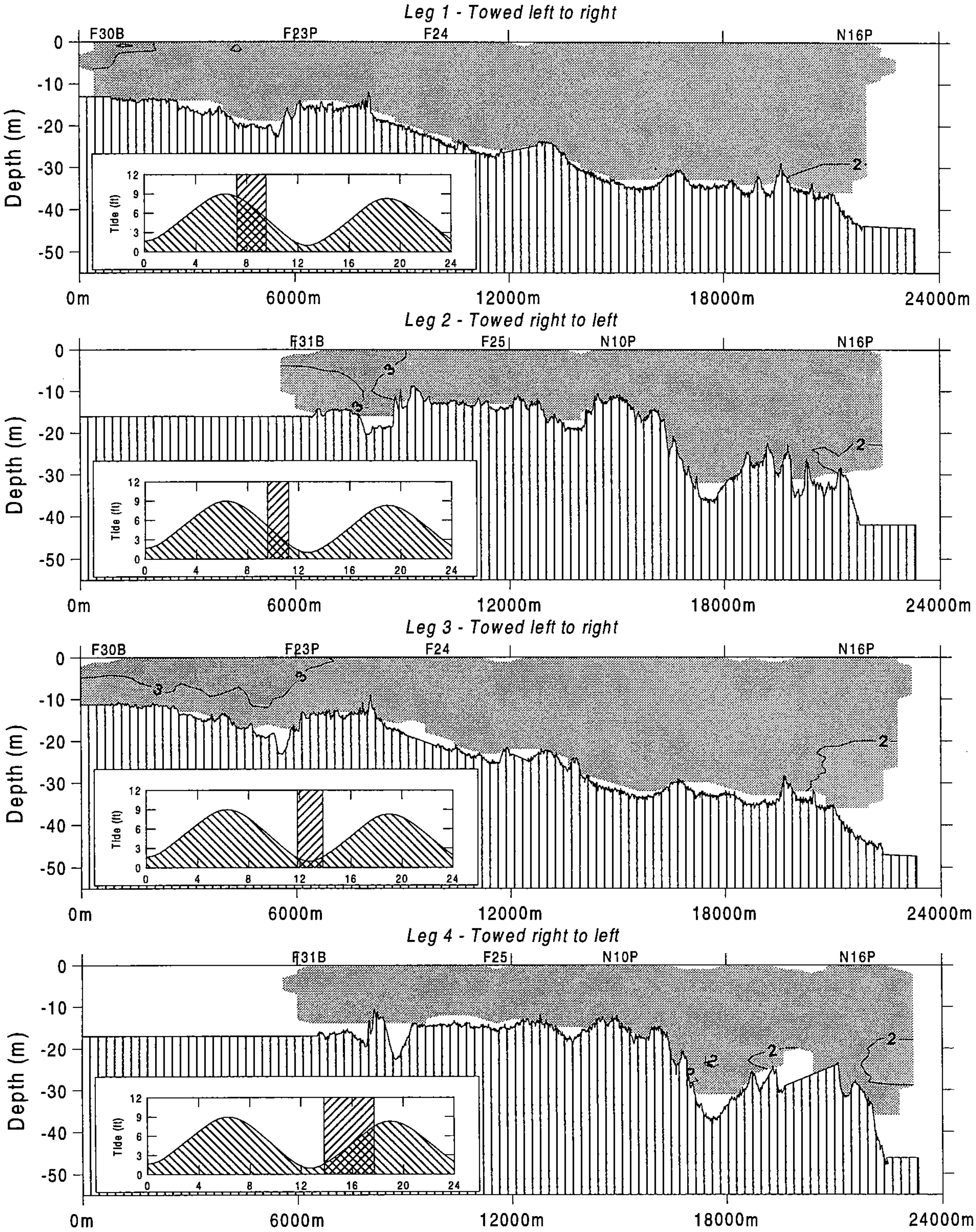


Sigma-T during Survey W9403 (22-Mar-94)



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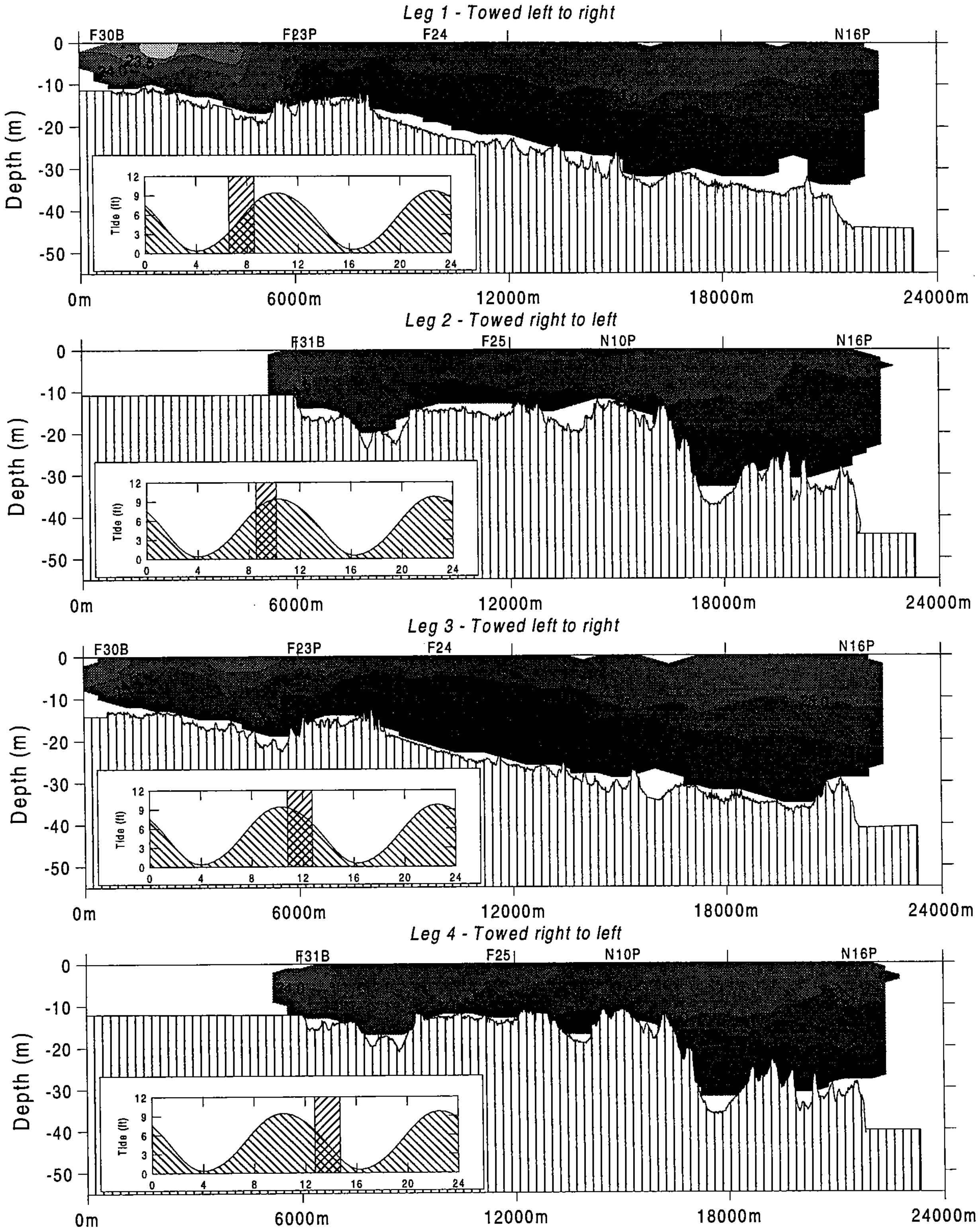
Temperature (°C) during Survey W9403 (22-Mar-94)



Sigma-T during Survey W9404 (09-Apr-94)

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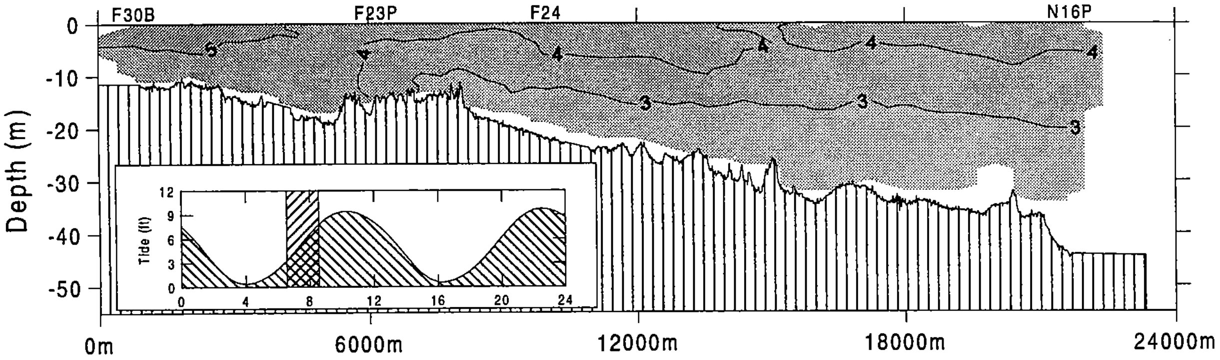

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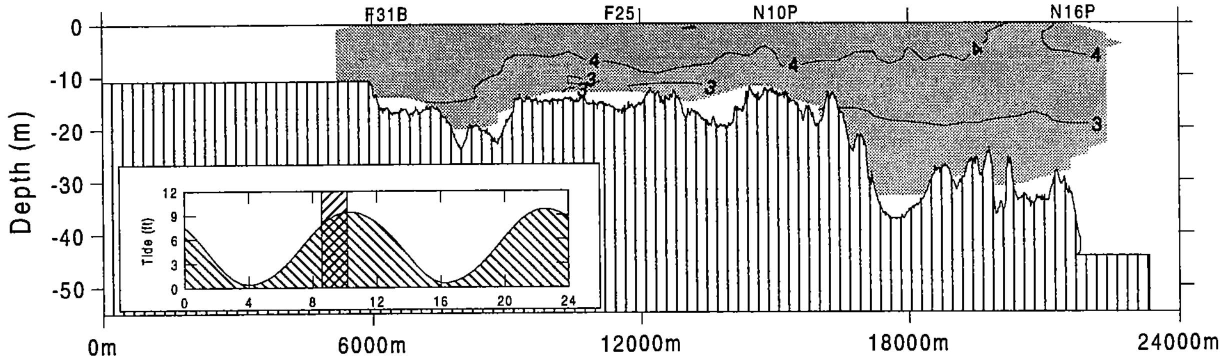

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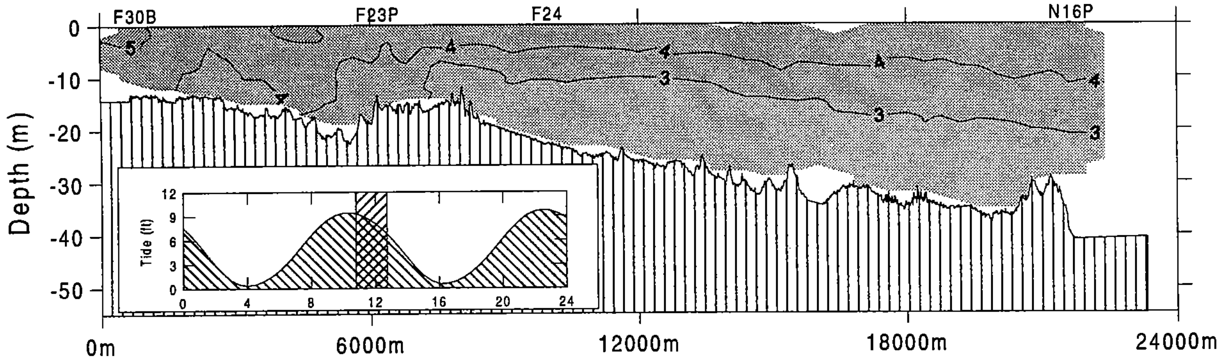

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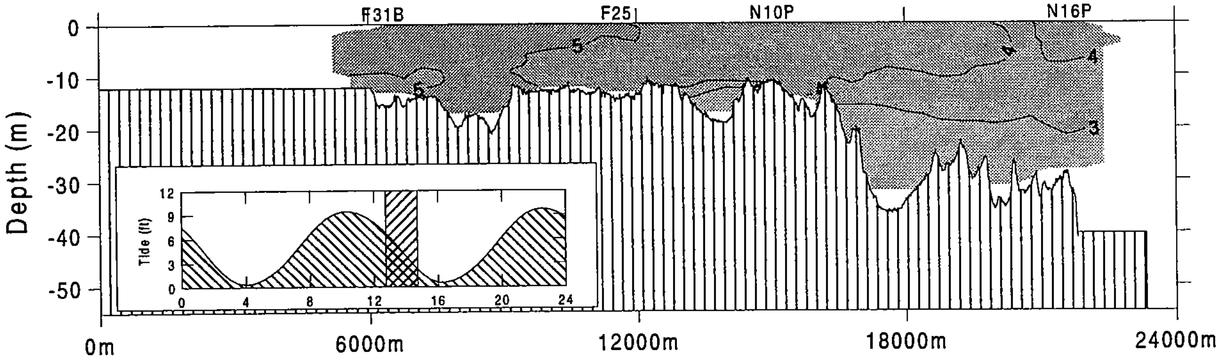
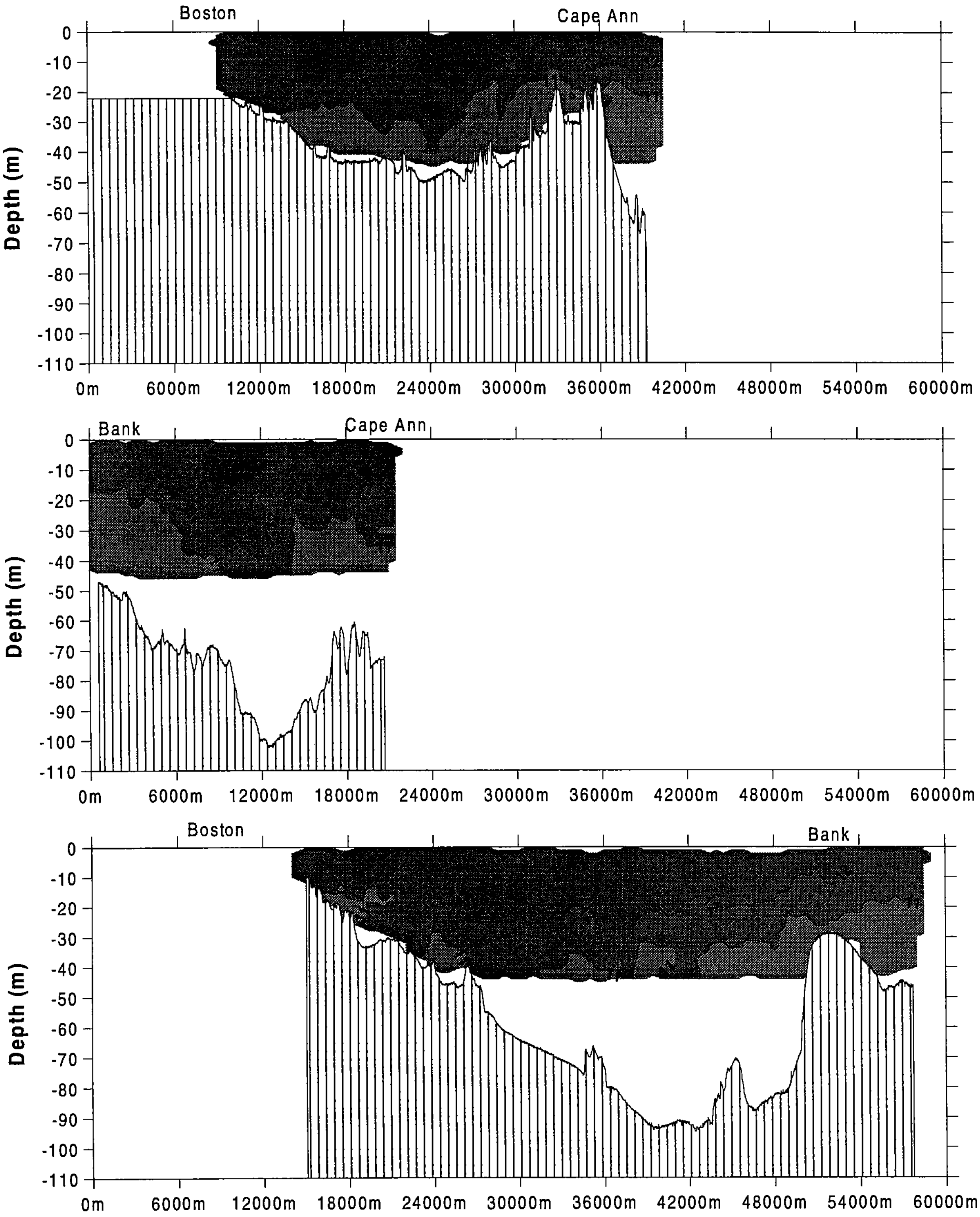


Temperature (°C) during Survey W9404 (09-Apr-94)



Dissolved Oxygen (mg/L) during Survey W9404 (10-Apr-94)

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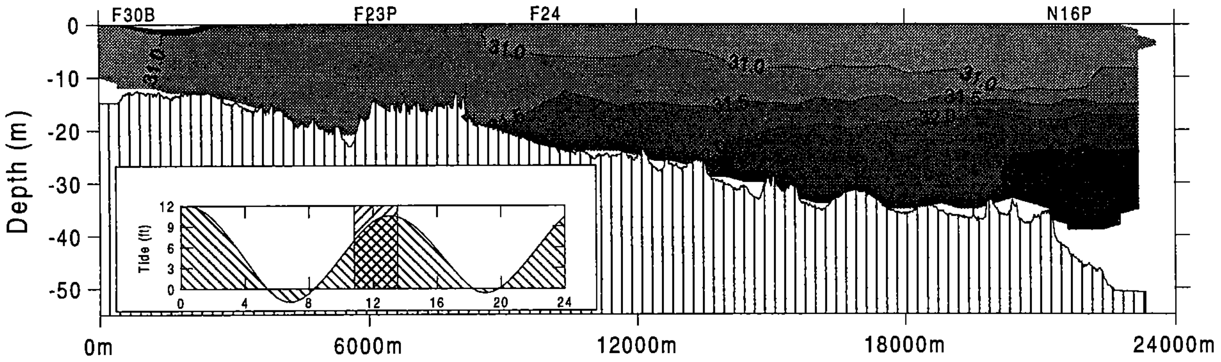

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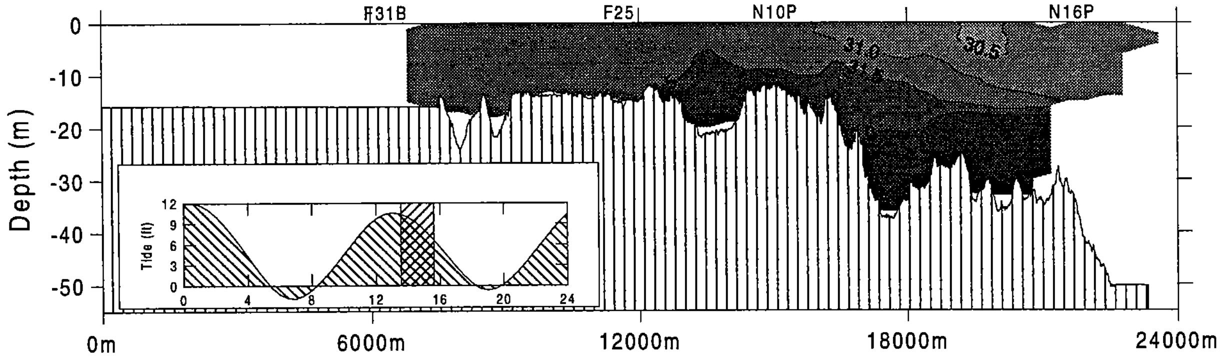

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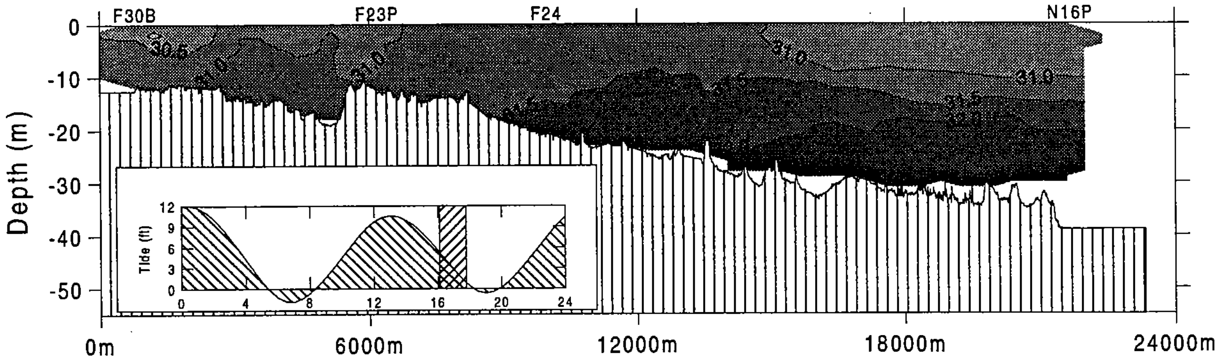

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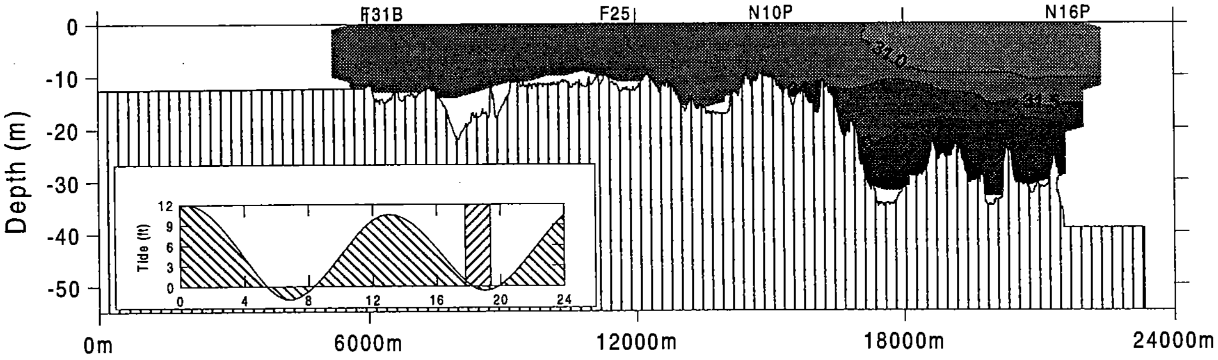
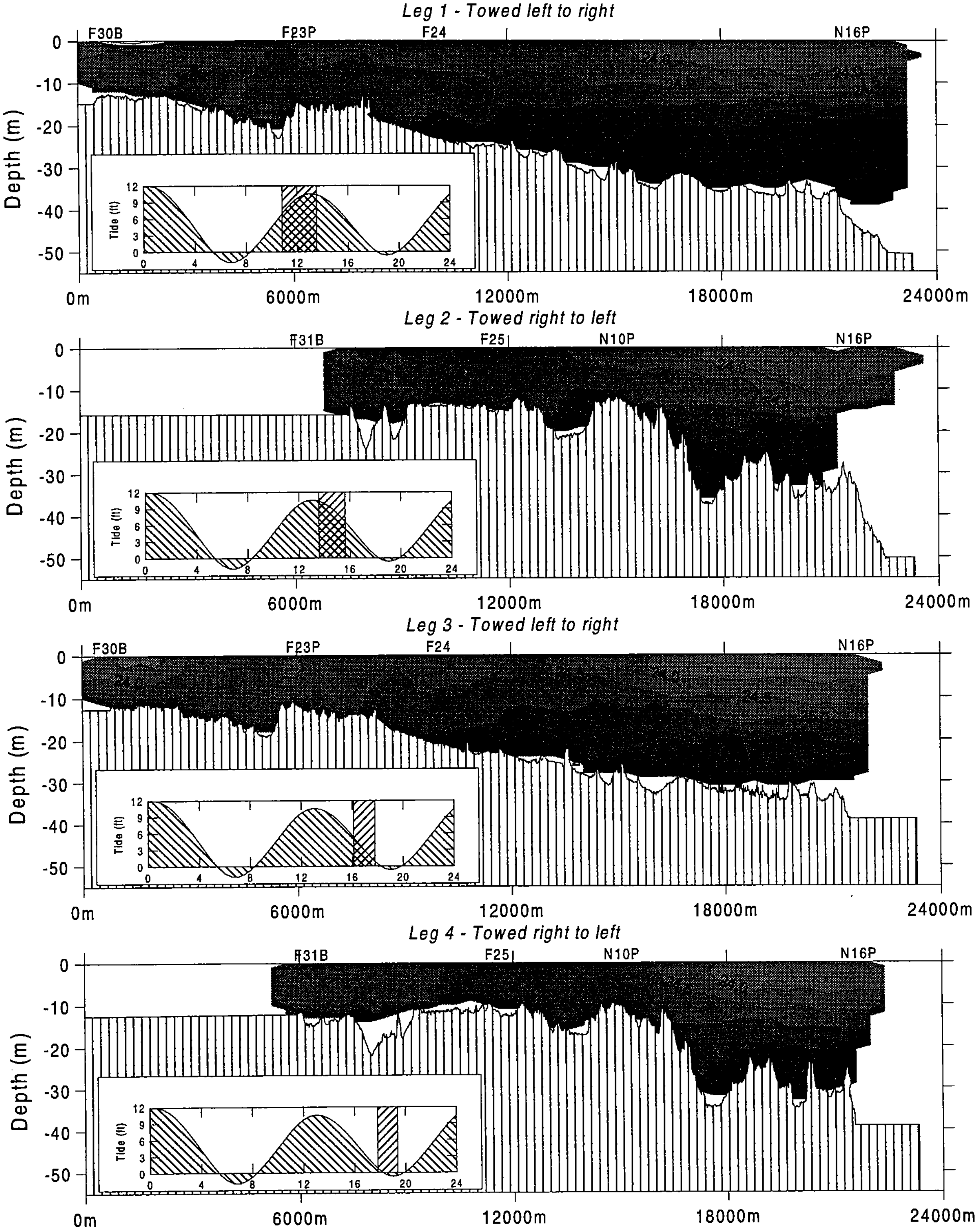
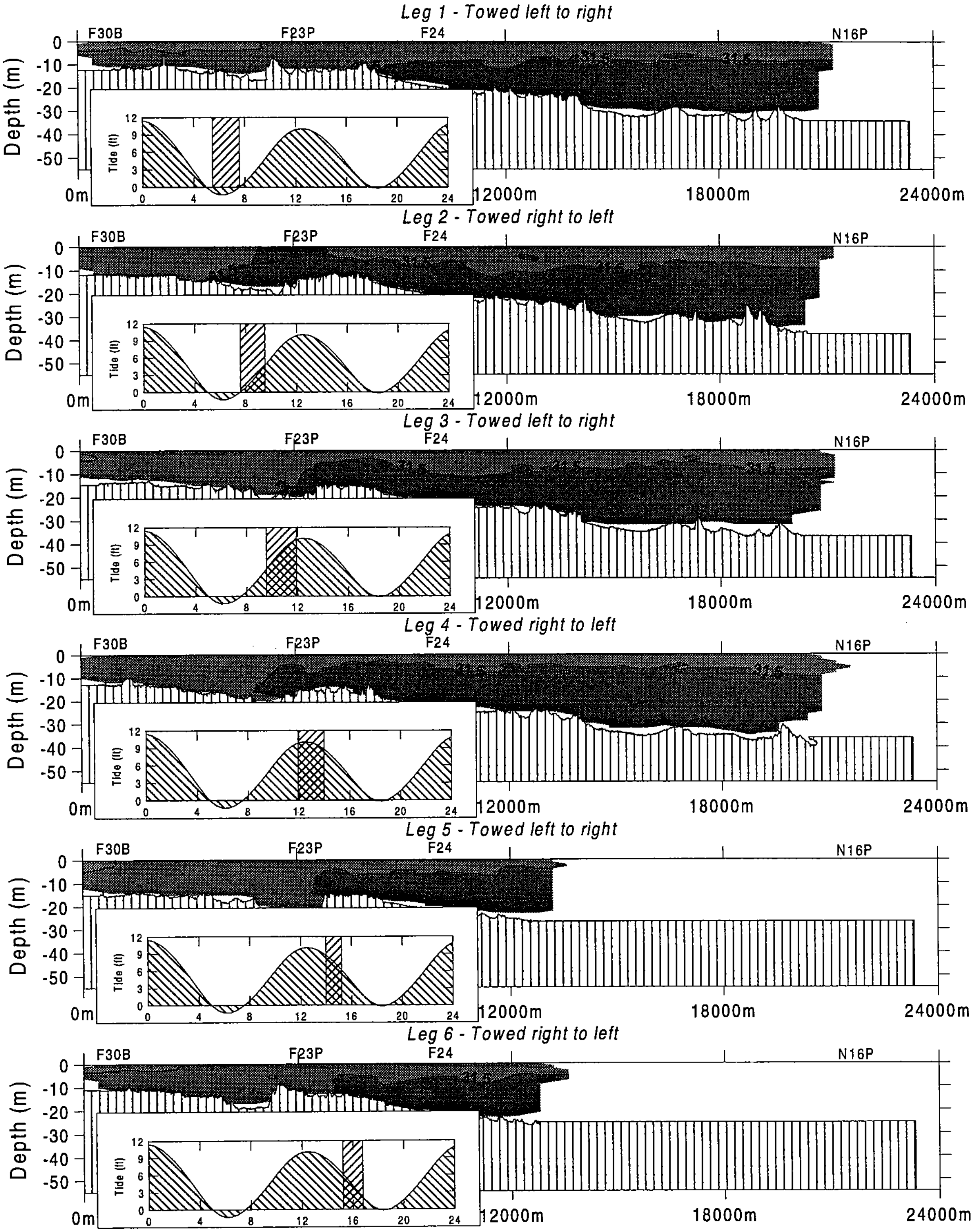


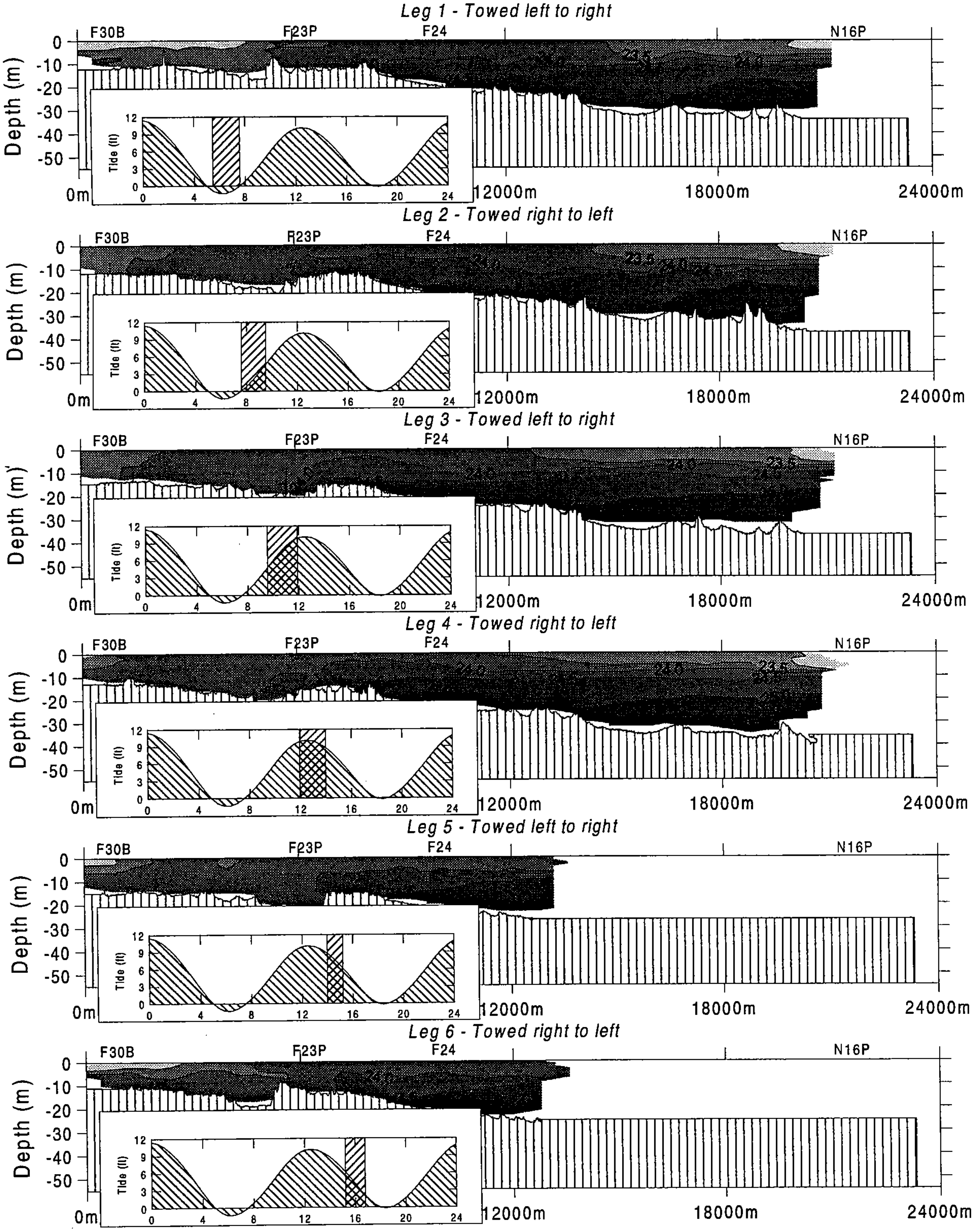
Salinity (PSU) during Survey W9405 (28-Apr-94)



Sigma-T during Survey W9405 (28-Apr-94)



Salinity (PSU) during Survey W9407 (25-Jun-94)



Sigma-T during Survey W9407 (25-Jun-94)

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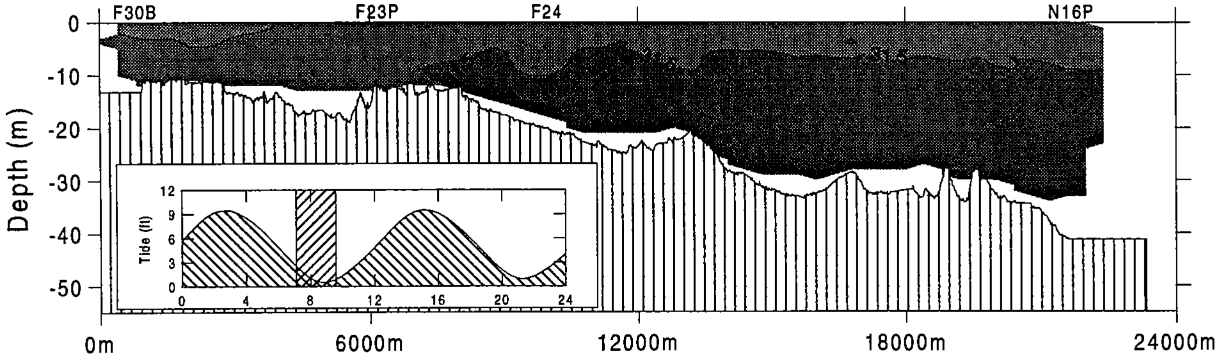

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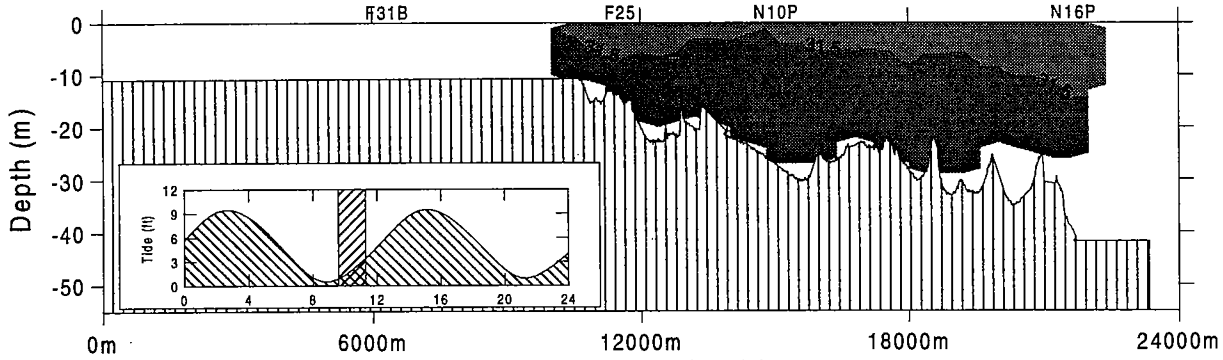

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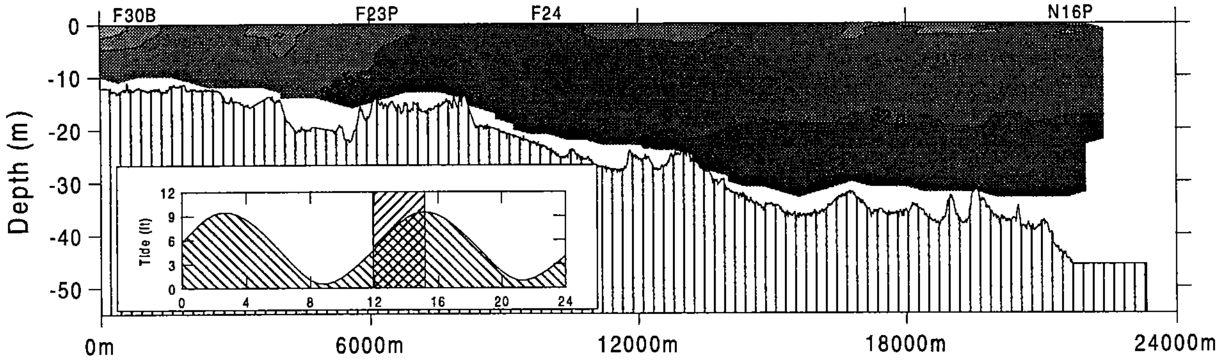

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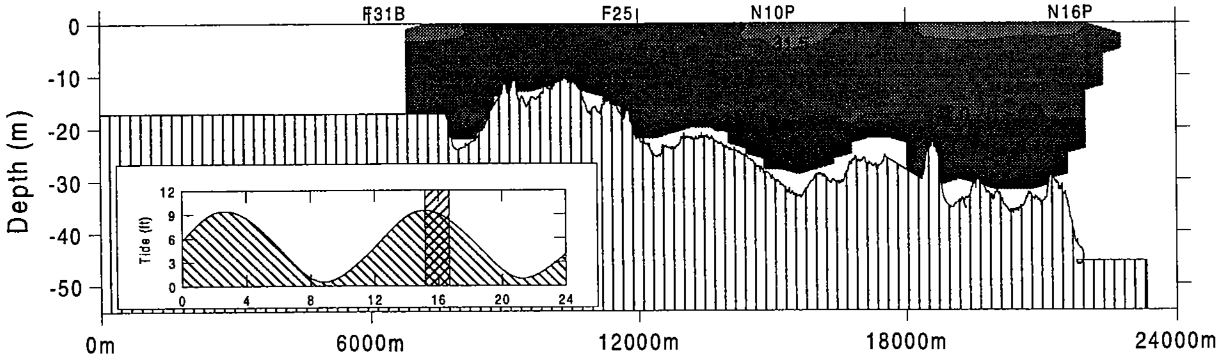

Salinity (PSU) during Survey W9409 (28-Jul-94)

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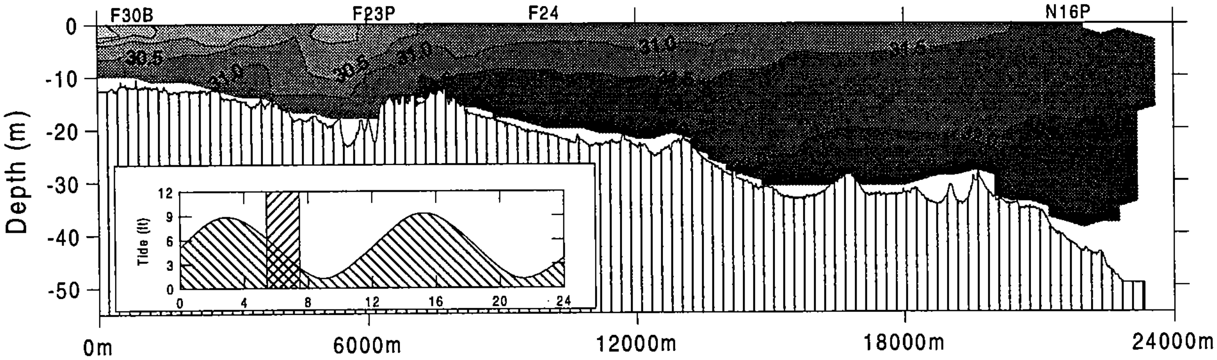

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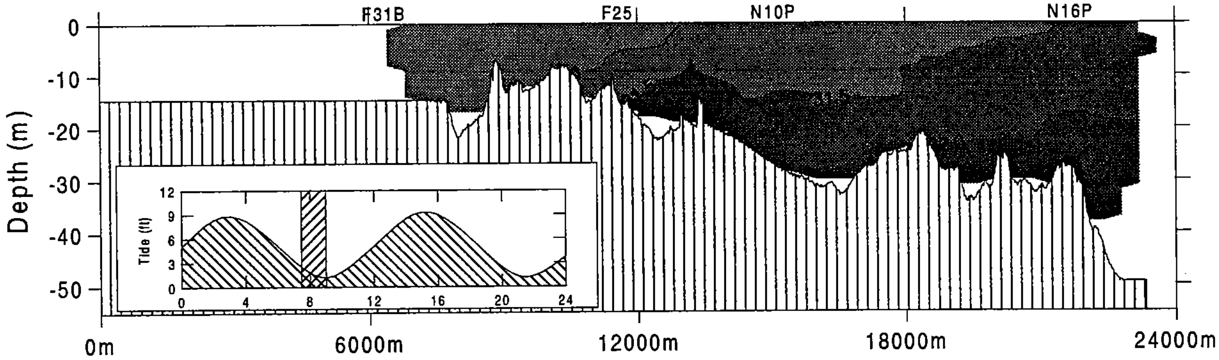

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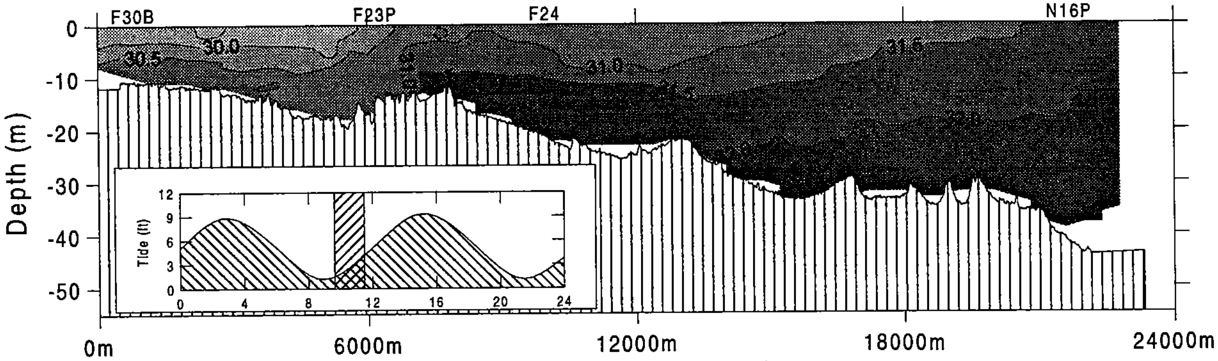

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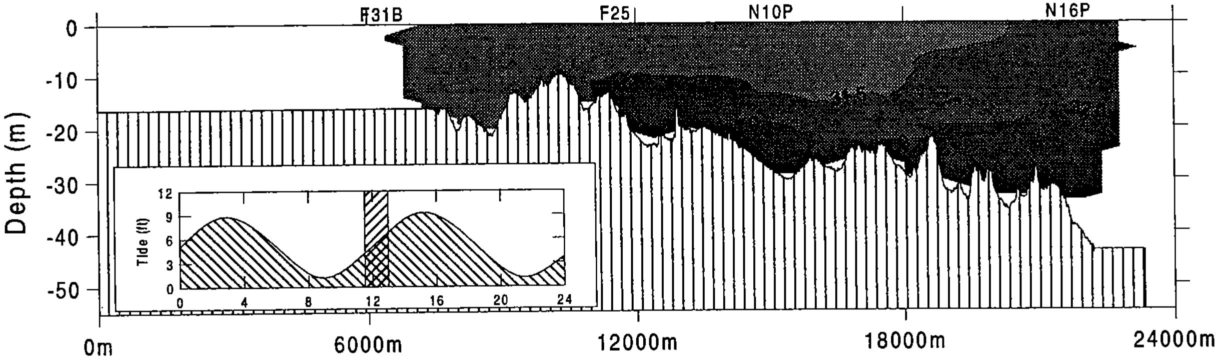
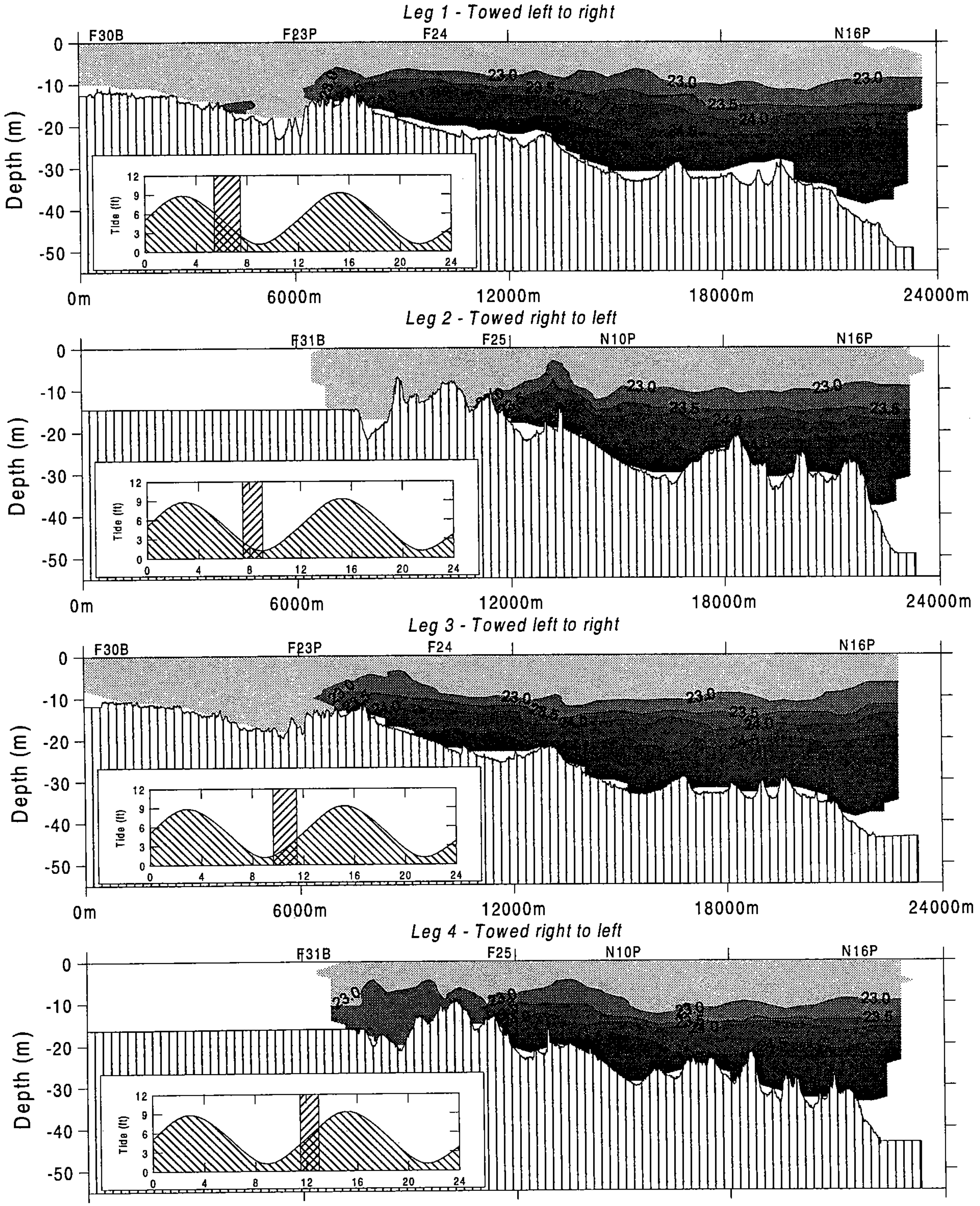


Salinity (PSU) during Survey W9411 (27-Aug-94)



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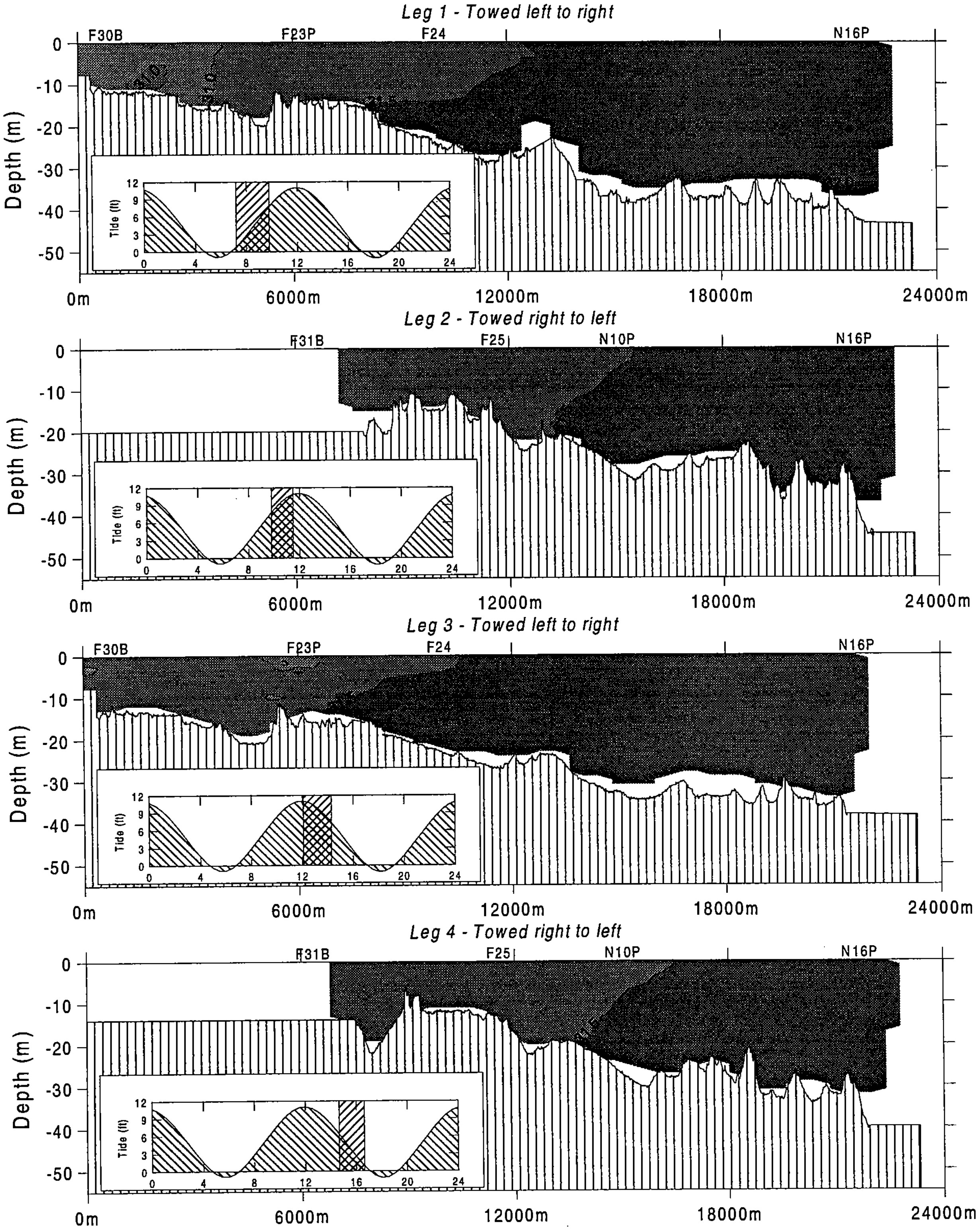
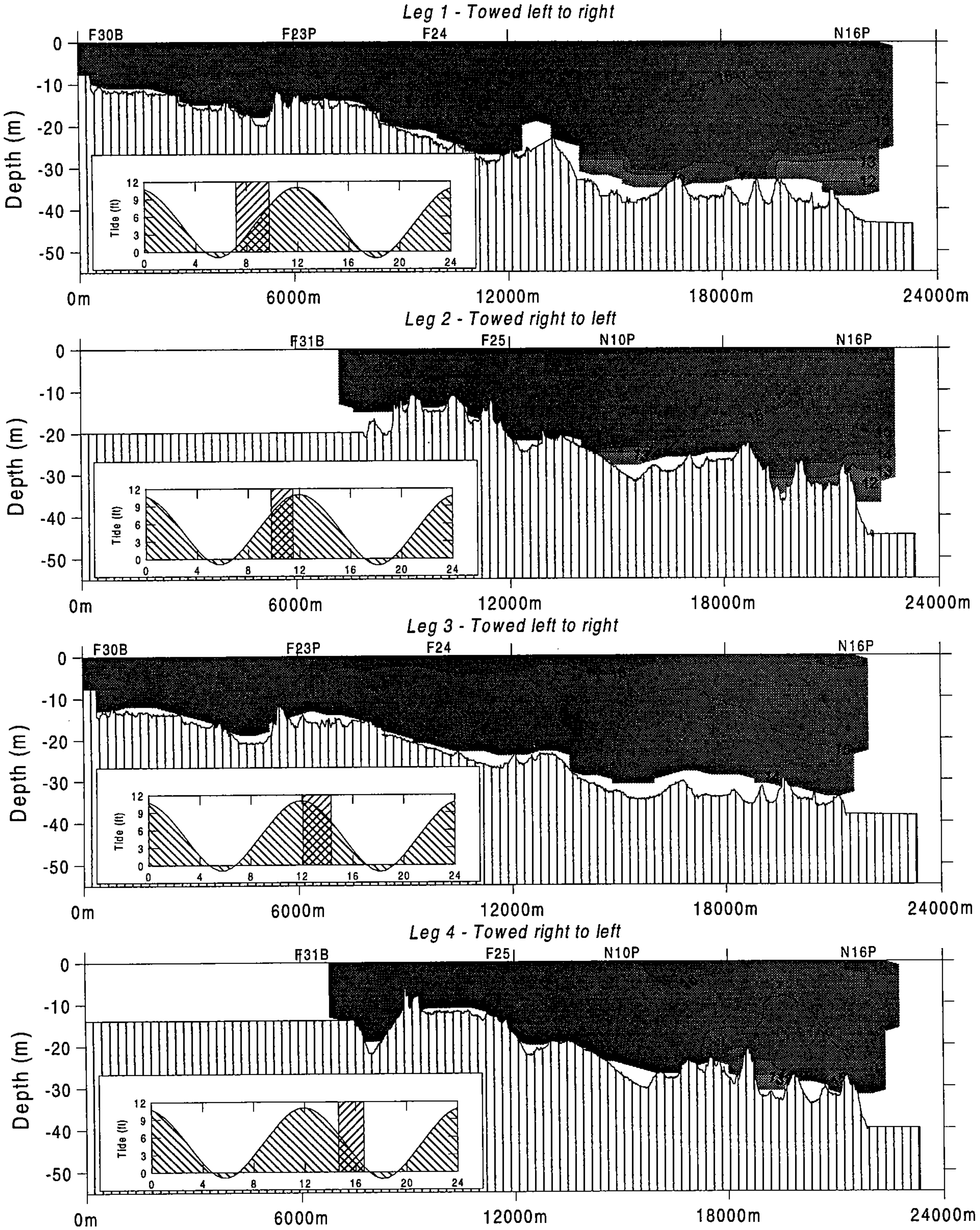
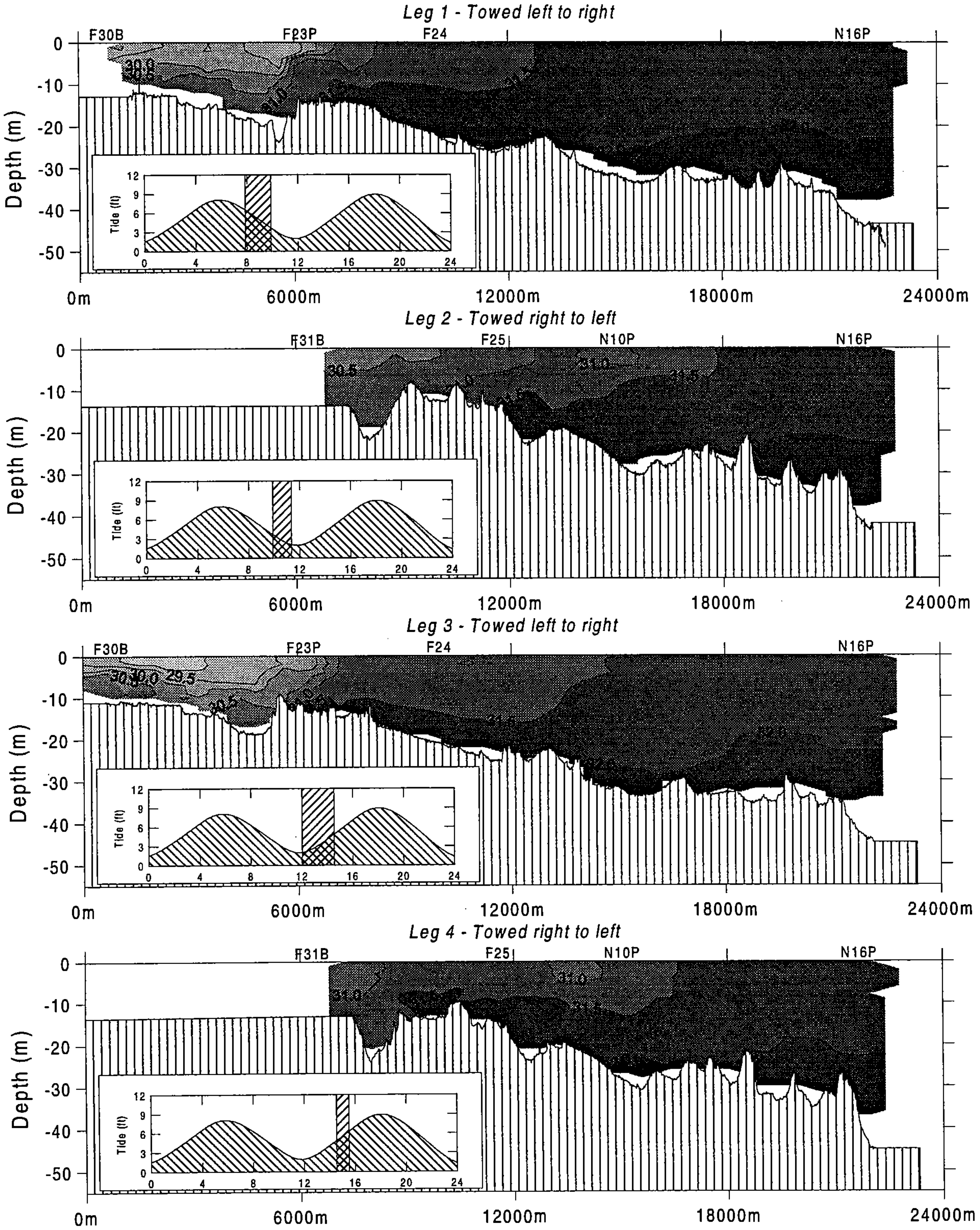
Sigma-T during Survey W9411 (27-Aug-94)



Salinity (PSU) during Survey W9412 (07-Sep-94)

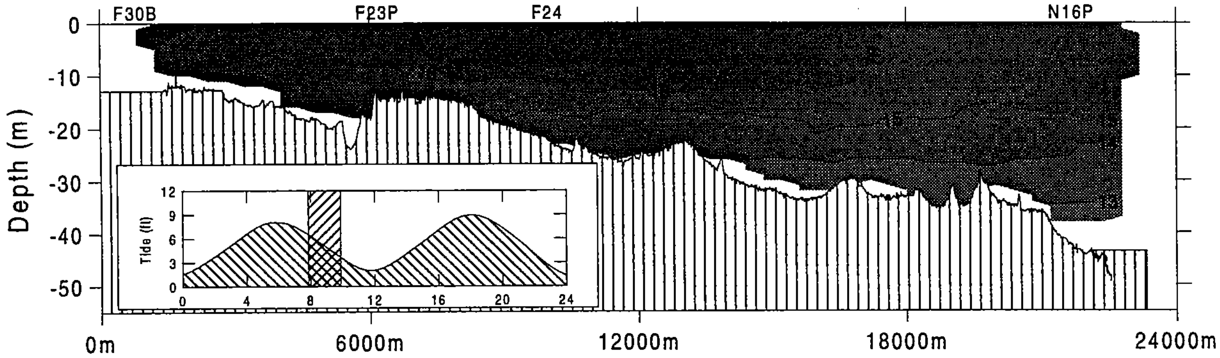


Temperature (°C) during Survey W9412 (07-Sep-94)



Salinity (PSU) during Survey W9413 (29-Sep-94)

Leg 1 - Towed left to right



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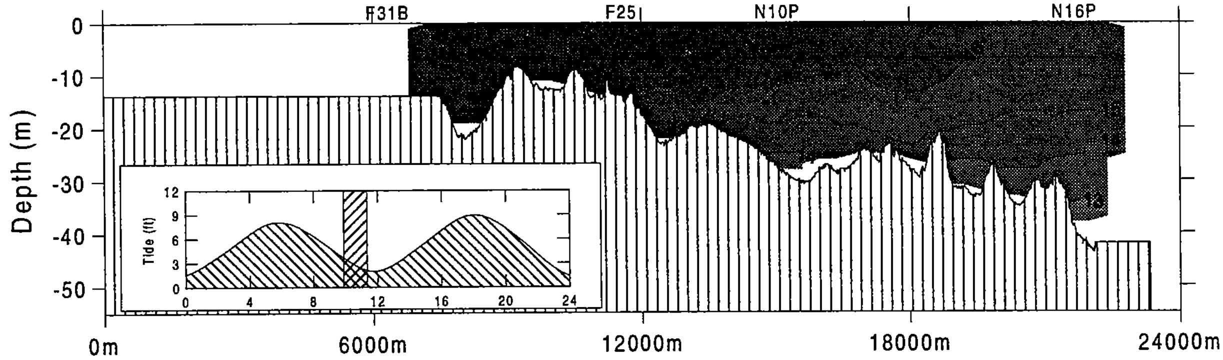

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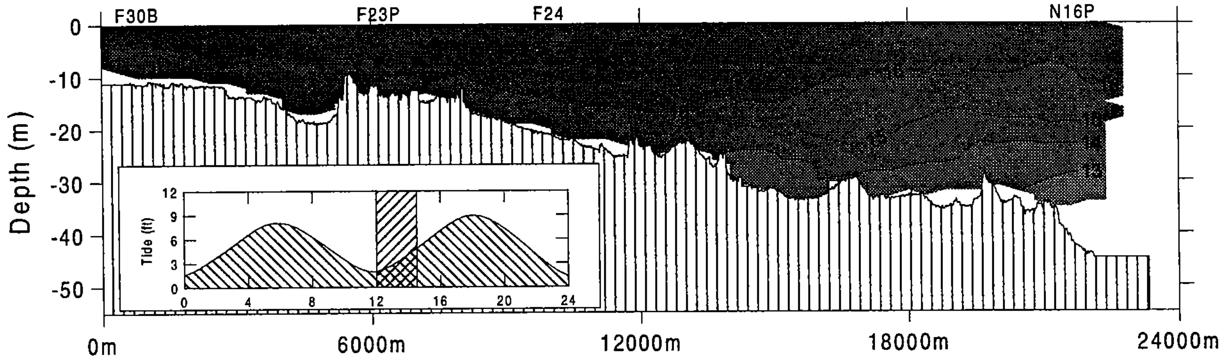

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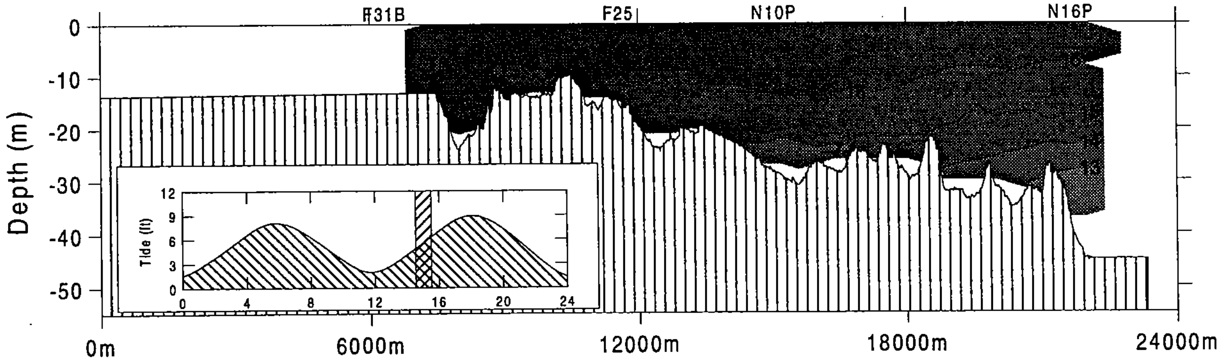
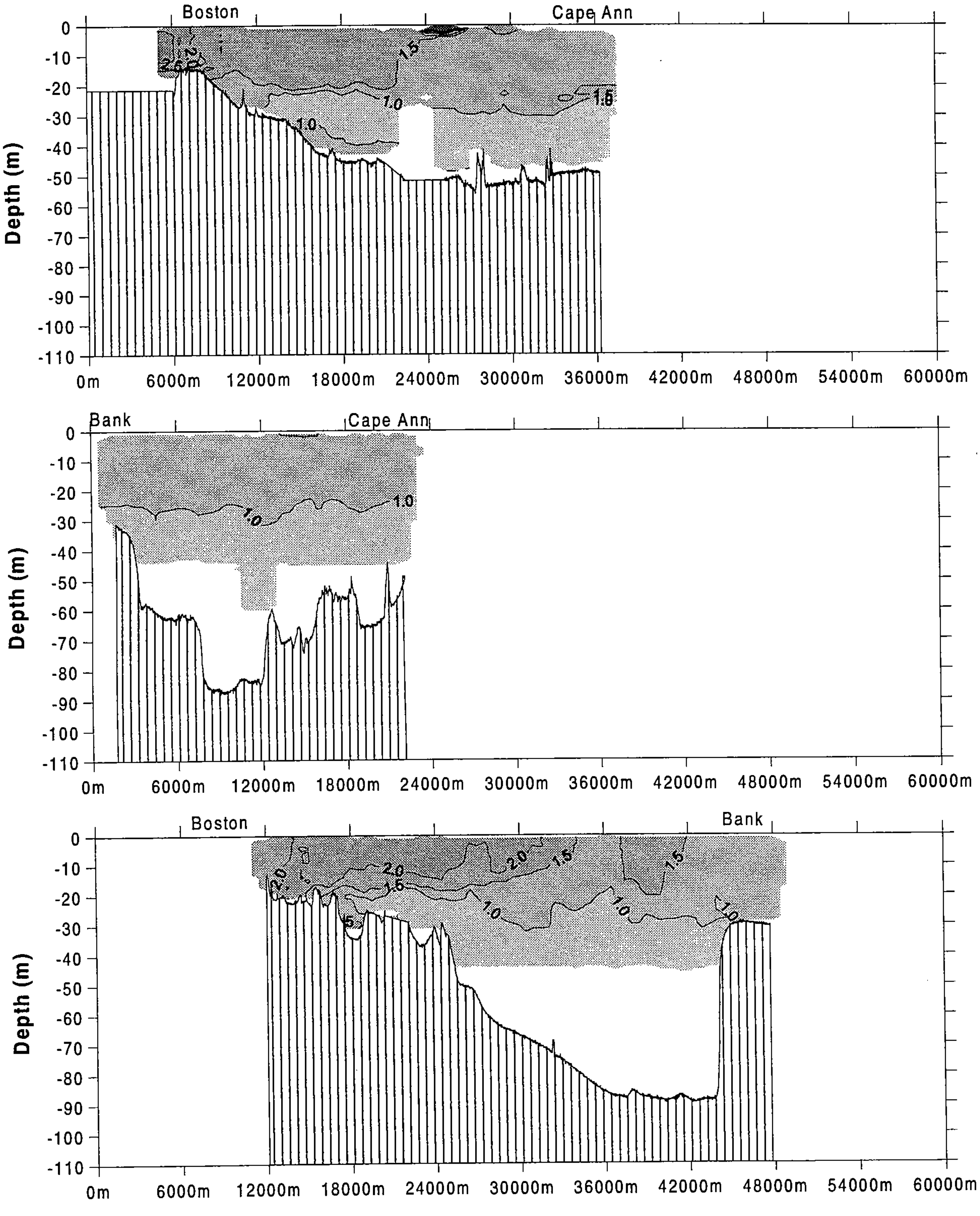
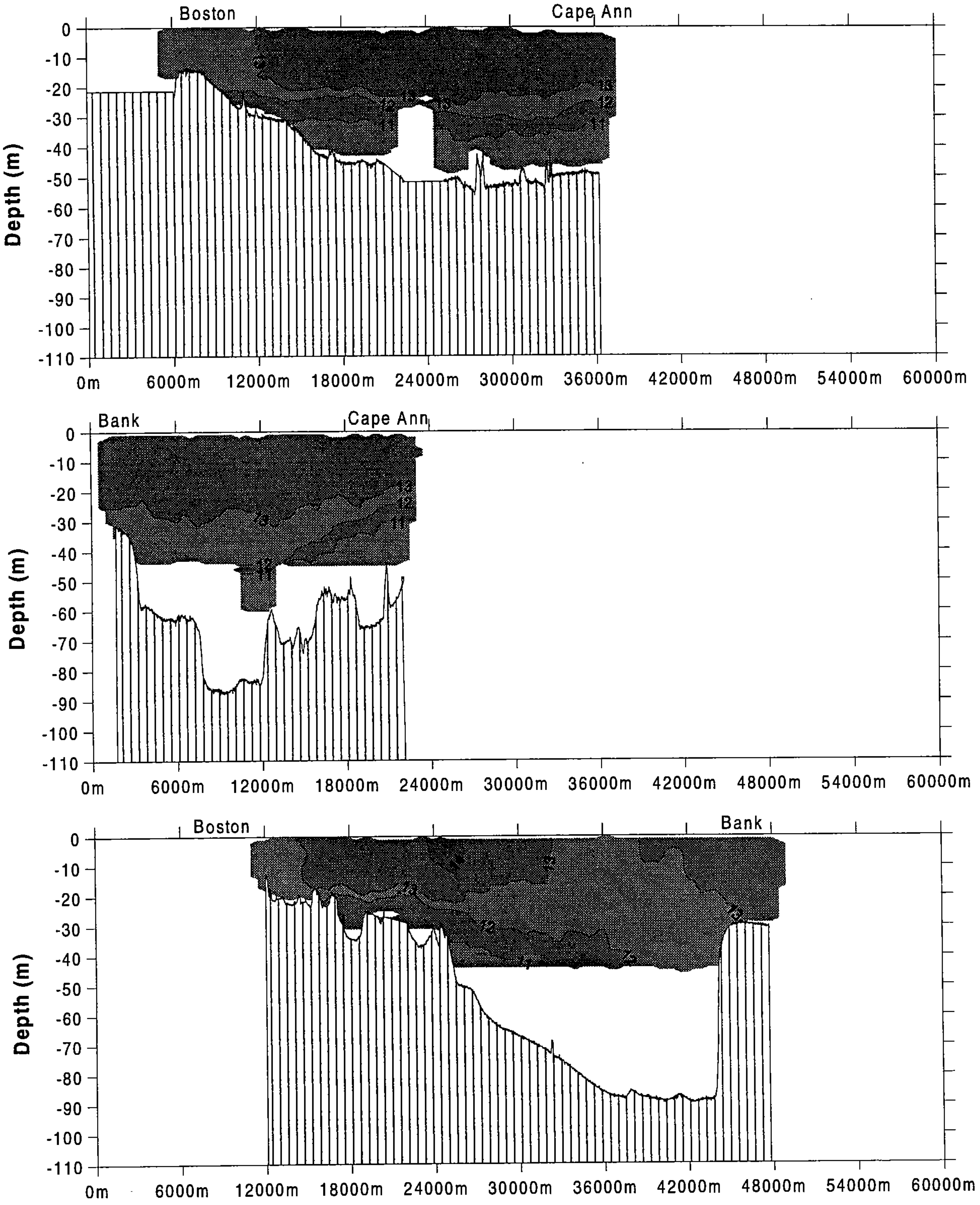


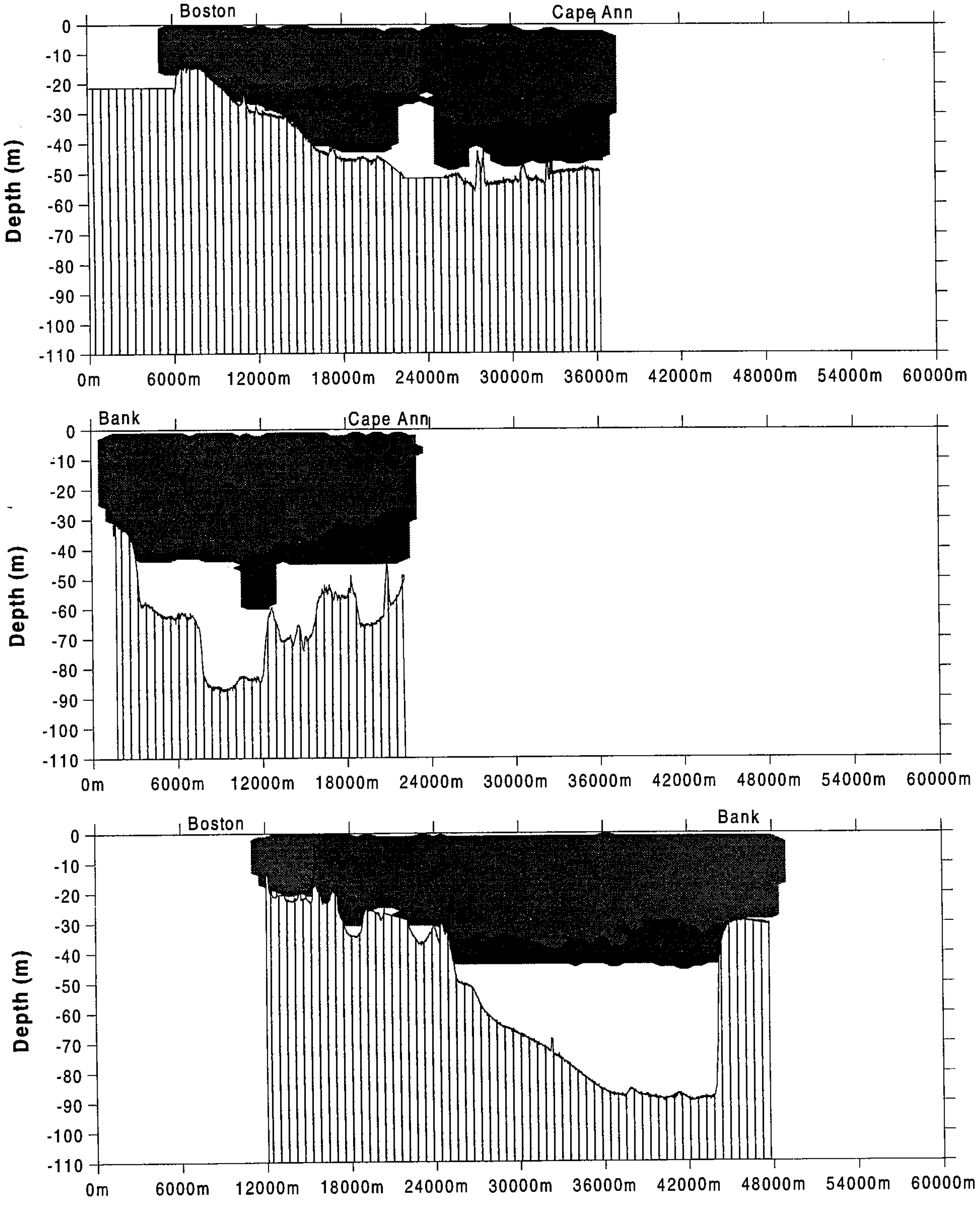
Temperature (°C) during Survey W9413 (29-Sep-94)



Beam Attenuation (1/m) during Survey W9414 (15-Oct-94)



Temperature (°C) during Survey W9414 (15-Oct-94)



Salinity (PSU) during Survey W9414 (15-Oct-94)

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