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NOAA Technical Report NMFS 32

Nutrient Distributions for Georges Bank and Adjacent Waters in 1979

A. F. J. Draxler, A. Matte,
R. Waldhauer, and J. E. O'Reilly

July 1985

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

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Malcolm Baldrige, Secretary
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John V. Byrne, Administrator
National Marine Fisheries Service
William G. Gordon, Assistant Administrator for Fisheries

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Nutrient Distributions for Georges Bank and Adjacent Waters in 1979

A. F. J. DRAXLER, A. MATTE, R. WALDHAUER, and
J. E. O'REILLY[1]

ABSTRACT

In this report we describe the temporal and spatial distributions of inorganic nutrients over Georges Bank and in adjacent waters and discuss major features with respect to the nutrient environments of phytoplankton. Nitrate and orthophosphorus were rapidly depleted from the surface layer of much of the study area in spring, but major differences were found between the shallow areas on Georges Bank and the surrounding stratified waters. In the "well-mixed" area of Georges Bank, the depletion encompassed the entire water column and ammonium became the dominant form of inorganic nitrogen throughout. Dissolved silicon was depleted slowly over central Georges Bank, reaching a minimum concentration in September while orthophosphorus gradually increased during the summer. The nutrient environment of phytoplankton over central Georges Bank may be described as vertically uniform but temporally changing in the relative availability of the various nutrients. In areas that undergo stratification (e.g., the central Gulf of Maine), a quasi-steady state was established as the surface water layer formed, consisting of declining nutrient gradients from below the euphotic layer to the top of the water column. These intergrading nutrient environments are relatively stable through time. Destratification reintroduced nutrients to depleted areas beginning in October; however, dissolved silicon was again depleted over shallow Georges Bank in late autumn though nitrate remained abundant. Slope water has been found to enter the bottom layer of the Gulf of Maine via the Northeast Channel. High nutrient concentrations observed in the bottom water of the Northeast Channel are consistent with this mechanism being the nutrient source for the Gulf of Maine.

INTRODUCTION

The study area includes the Gulf of Maine which is bounded by the coasts of the United States from Cape Cod through Maine, New Brunswick and southwestern Nova Scotia, Canada, from Long Island to Cape Sable, with the mouth of the Bay of Fundy between (Fig. 1). The water perimeter southwest from Nova Scotia consists of a series of banks and channels. Clockwise from Cape Sable to Cape Cod they are: the channel south of Cape Sable, Browns Bank, Northeast Channel, Georges Bank, Great South Channel, and Nantucket Shoals. Minimum depths over the banks and maximum sill depths in the channels are given in Table 1. There are three major basins in the Gulf (Georges, Wilkinson, and Jordan) which are separated by a system of swells which rise, in the shallowest case (Cashes Ledge at lat. 42°53′N, long. 68°57′W), to within 8 m of the surface.

Circulation within the Gulf of Maine has been described as a large counterclockwise gyre (Bumpus 1976) divided vertically into three layers (Hopkins and Garfield 1979). A surface layer about 50 m deep, known as the Gulf of Maine surface water (MSW), is formed in spring from the winter mixed layer (<120 m deep) due to a buoyancy increase resulting from freshwater runoff and increasing temperatures. This leaves Maine Intermediate Water (MIW) between 50 and 120 m. The amount of Scotian shelf water entering the Gulf of Maine to become a progenitor of these layers is unclear and a matter of some controversy (see Hopkins and Garfield 1979, for discussion). Maine Bottom Water (MBW) is by definition "unaffected directly by air-sea interactions" and exchange of MBW water with other systems is limited to inflow of slope water over the sill of the Northeast Channel and vertical exchange with MIW which is driven by the dissipation of tidal energy.

On Georges Bank, a clockwise gyre is established in spring and persists through autumn when the entire bank may be swept by MSW (Bumpus 1976). Within the 60 m isobath, the water column is vertically well-mixed at all times (Colton et al. 1968) and sufficiently well-isolated that the surface temperature may be several degrees warmer in spring or colder in summer and autumn than surrounding waters (Loder et al. 1982). There is a net southwestward movement of water from the Great South Channel and the south side of Georges Bank toward the New York Bight (Bumpus 1976). Slope water south of Georges Bank and southern New England is subject to periodic perturbations by passing Gulf Stream eddies (Christ and Chamberlin 1980).

Table 1.—Extremes of topography in the study area (Uchupi 1965).

Minimum depths over banks	
Browns Bank	29 m
Georges Bank	3 m
Nantucket Shoals	about 6 m
Maximum depths of channels	
Channel south of Cape Sable	about 130 m
Northeast Channel	234 m
Great South Channel	71 m
Maximum depths of basins	
Georges Basin	377 m
Wilkinson Basin	295 m
Jordan Basin	311 m

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[1] Northeast Fisheries Center, Sandy Hook Laboratory, National Marine Fisheries Service, NOAA, Highlands, NJ 07732.

Upwelling has been reported in two areas. One is immediately north of the Great South Channel and involves MIW (Magnel et al. 1981); the other is an area of centrifugal upwelling south of Cape Sable that presumably brings up slope water (Garrett and Loucks 1976). Onwelling has been observed at several points along the shelf-slope interface (Metcalf 1958; Worthington 1958; Wright 1976; Christ and Chamberlin 1979, 1980) and is probably a frequent, episodic event.

The importance of the area to fisheries may be appreciated from the value attached to commercial landings (Table 2). At a lower level of the food chain, phytoplankton primary productivity in the central region of Georges Bank is greater than in any region on the continental shelf between Cape Hatteras and Nova Scotia (O'Reilly and Busch 1984), except for the sewage-enriched New York Bight apex. As we have indicated above, the hydrography is related closely to the bathymetry as are phytoplankton biomass distributions (O'Reilly and Evans-Zetlin 1982). These are, in turn, interrelated with the availability of inorganic nutrients, both through supply and removal. This paper describes the coarse-scale distribution of nutrients and patterns of change in these distributions in Georges Bank and adjacent waters in 1979, and how these affect the nutrient environments of the phytoplankton.

Table 2.—New England fish landings and value (from U.S. Department of Commerce 1982).

	Landings	
	Million kg	Million dollars
Commercial (1981)	317	356
Recreational (1979)	8	—
Foreign in FCZ (1981)	[1]58	—
Value added to GNP		[2]1,125

[1]Estimate based on New England landings being about 75% of total North Atlantic commercial landings and foreign landings of 77×10^6 kg for the North Atlantic Fishery Conservation Zone (FCZ).

[2]Estimate based on the ratio of New England wholesale to U.S. wholesale value for fish landed.

METHODS

Seawater samples were collected using 5 L Niskin bottles on 11 National Marine Fisheries Service cruises, as part of the MARMAP and Ocean Pulse programs, between May 1979 and March 1980. In water depths <100 m, we use a Niskin bottle rigged to close upon contacting the seabed. This bottle was "equilibrated" at up to 10 m from the bottom for 5 min along with the other bottles on the cast. After the upper bottles were tripped by messenger, the entire string was slowly lowered until the depressor touched, closing the bottom bottle. Subsamples of 30 ml each were pressure filtered (<0.07 atm) through Whatman GF/F glass fiber filters (nominal pore size 0.7 μm) into acid-cleaned glass tubes for ammonium determinations and polyethylene tubes for nitrite, nitrate, reactive phosphorus, and dissolved silicon determinations. We found that 10 ml of sample was sufficient to remove silicon contamination from the glass fiber filter and therefore we allowed approximately 30 ml to pass. Sample containers were then rinsed twice with sample water before a 30 ml subsample was collected. Ammonium samples were immediately treated with phenol solution, which is the first reagent of the colorometric analysis (Liddicoat et al. 1975), and then frozen (Degobbis 1973). After filtering, the samples to be used for analysis of the other nutrients were frozen at −20°C within approximately 0.5 h of Niskin bottle closure, depending on station depth. Parallel measurements made from the same bottle cast included temperature, salinity, chlorophyll *a* and phaeopigments, dissolved oxygen, and, at two stations per day, ^{14}C primary production. Pigment estimates were made to a depth of 75 m and productivity to the depth of 1% light level as determined using a submersible quantum sensor (400-700 nm).

Nutrient analyses were performed at the shore laboratory. Ammonium analyses were completed manually (Liddicoat et al. 1975); other nutrient concentrations were estimated on a Technicon Autoanalyzer. Nitrite and nitrate were determined with the naphthylethylenediamine-sulfanilamide system using copper amalgamated cadmium reduction of nitrate (Wood et al. 1967). To measure reactive phosphorus the molybdate-ascorbic acid method was used (Murphy and Riley 1962). The reactive silicon measurement was similar with appropriate addition of oxalic acid (Brewer and Riley 1966). On two intercalibration exercises with Brookhaven National Laboratory (BNL), we compared concentration estimates for the five nutrient species on unfiltered, fresh (BNL) and filtered, frozen (SHL) paired samples ($n \cong 150$). Coefficients of correlation (*r*) were 0.95, 0.99, 0.95, 0.83, and 0.91 for nitrate, nitrite, ammonium, phosphorus, and silicon, respectively, indicating that methods in this study are comparable with others currently in use (Walsh et al. in press).

Isopleths of nutrient concentration at stations along the four transects shown in Figure 1 were generated by a computer program — SYMAP (Harvard University 1971). Bottom profiles were taken from Uchupi (1965) with additional points on the shallow areas of Georges Bank from recent navigation charts. In the rendering of the concentration contours (Figs. 2-30) from the computer printouts, care was taken to include each value (represented by a dot) in the appropriate concentration interval, and emphasis was given to horizontal homogeneity where the computer program tended to obscure these features because of the greater distance (in mapping units) between stations than between depths at a station.

In some analyses, data from the stratified season were combined by analyzing the July to October data together, we do not mean to imply that the concentrations of nutrients in such areas are independent of time; however, the variation with time at a given depth (relative to the 1% light level depth) from July to early October was small compared with gradients in the vertical direction.

RESULTS

Spring Depletion of Nutrients From Surface Waters

Nitrate nitrogen, orthophosphorus, and dissolved silicon are depleted seasonally from the upper water column of the Gulf of Maine and the waters south and west of Georges Bank. By our May (1979) sampling, depletion was well established, to a depth of 20 m or more at some stations, but was not discernible in waters deeper than about 60 m in March (1980). The distribution of depleted water in the Gulf of Maine during May was not uniform. Intense (NO_3 concentrations <0.2 μM) and deep depletions were found on transects 5 and 7 in the southern Gulf of Maine (Figs. 11, 28) while along transect 6, the only low nutrient content was in the surface (1 m) samples at the northern stations (Fig. 20).

Of particular interest is the nitrate minimum on transect 7 which appears to have been subsurface. Its origin may have been hydrological, as well as biological; i.e., it may have resulted from water, depleted of nitrate further west, having been transported eastward by the surface currents in the Northeast Channel reported by Ramp et al.[2]

On the south side of Georges Bank in May, depletion in the upper water column was more uniform and generally shallower (10 m or less) than in the Gulf of Maine. Along transect 8, in May (Fig. 3), the depleted layer was present at all stations and extended to between 10 and 20 m.

By July the depleted layer had deepened to > 20 m over most of transect 8 (Fig. 4) and was more than 50 m deep over the continental slope. In the Gulf of Maine, in August (there were no samples taken in July), the layer was deeper than 20 m everywhere except at the very northernmost stations where, for example, on transect 6 (Fig. 23) nitrate stratification was completely absent.

Bottom-Layer Gulf of Maine Nutrient Reservoir

High concentrations of nutrients were present in the deep waters of the Gulf of Maine throughout the year. Nitrate concentrations in excess of 15 μM (and once on transect 6 in September, >25 μM) were found in the deep water (>100 m) of the central and western Gulf of Maine at all times except March 1980. The same was true for dissolved silicon at a concentration of at least 10 μM and frequently >15 μM and for orthophosphorus at 0.6 and 1.0 μM.

The movement of the nutrient contour lines follows seasonal patterns. Along transects 5 and 6, the 15 μM nitrate isopleth progressed southward and upward from May through August to its maximum southward position in September. It then retreated northward from October through December. Along transect 5, orthophosphorus increased from >0.6 μM in May through August to >1.0 μM from September through November. If only the southern part of the Gulf of Maine on this transect is considered, the migration of the phosphorus isopleths follows the same pattern as those of nitrate.

The variations in dissolved silicon in this water mass are not as readily amenable to general description. While the temporal changes in the positions of the silicon isopleths have some characteristics in common with nitrate and phosphorus, apparently moving northward and southward, no simple progression is evident in these data for this species. For example, the largest volume of water containing more than 15 μM silicon was observed on transects 5 and 6 in May in the northern half of the Gulf (Figs. 11, 20). Nitrate and phosphorus distributions were similar to silicon on transect 6 but not on transect 5.

Depletion Over Georges Bank

The beginning of the depletion of (presumably) uniform winter concentrations of nitrate throughout the water column over Georges Bank was evident in March (Figs. 10, 19). Orthophosphorus and dissolved silicon concentrations were also lower over the Bank (transects 5 and 6) in March than in the waters to the north and south. A similar condition was present at the inshore end of transect 8, at this time, where nitrate and silicon were depleted. Along this transect, the shallow water (<60 m) appeared like central Georges Bank in May, the 60 to 80 m area like Great South Channel (transect 5), and the deeper than 80 m area like the eastern end of Georges Bank (transect 7). Phosphorus distributions, however, were uniform except for two samples at the shelf break (200 m).

By May, the patterns in the various areas of the Bank had started to diverge. Over central Georges Bank (<60 m) nitrate and phosphorus were reduced to <0.2 and 0.1 μM, respectively (Fig. 20). Nitrite was present at <0.05 μM throughout the water column while silicon concentrations were higher (except at 1 m) than at adjacent stations on the transect. Over the deeper areas of the Bank (transects 5 and 7; Great South Channel and the eastern end) nitrate and, to a lesser extent, phosphorus concentrations in the bottom waters were low, relative to adjacent stations; in the surface layer (to ∿30 m) they were higher than at adjacent stations (Figs. 11, 28). From the data available, silicon concentrations in Great South Channel appear not to be substantially different than in March; however, on transect 7 the entire water column over the Bank was lower in silicon concentration (<5 μM) than at adjacent stations.

Similar conditions existed through the summer except that silicon concentrations on transect 6 declined to <0.5 μM in the shallowest area by mid-September (Fig. 24) and phosphorus on transect 6 and phosphorus, silicon, and nitrate on transect 5 stratified by September (Fig. 15). The vertical homogeneity of nitrate over the shallow area of central Georges Bank persisted into late October (Fig. 25).

Regenerated Nitrogen-Ammonium

Ammonium concentrations were almost always higher in portions of the study area with a depth between approximately 40 and 60 m than at deeper or shallower stations. These waters with higher ammonium concentration were usually in the lower half of the water column, frequently most concentrated at depths above the bottom sample and present from March through November. Because this ammonium is isolated from any advective source, it is likely part of the recycled nitrogen as defined by Dugdale and Goering (1967).

In the upper water column, high ammonium concentrations (2-10 μM) were found in five samples. Three were from the upper 10 m near the shelf break and of these, two were found in December on transects 6 and 7 (Figs. 26, 30). On transect 6 the high ammonium was associated with a relatively high phosphorus concentration. There appears to have been a 10-fold increase in ammonium between 10 and 19 December on transect 8 (Figs. 8, 9) at the most northern stations sampled on 10 December. However, the >2 μM concentration found on 19 December occurred in only one sample (20 m) and the station on the former date was located 6 km further south, so it might have been missed on 10 December. Further seaward, however, the 0.2 μM isopleth was clearly displaced by the 0.5 μM isopleth between the two samplings. The time period for the activity was therefore about 9 d. The last of the five upper water column observations was found at a depth of 1 m in August on transect 5 (Fig. 14) and was the highest of the study (>10 μM). It was found in an area characterized by intense hydrographic and, therefore, chemical activity (the upwelling along the north edge of Great South Channel). The 20 m sample contained nearly 2 μM ammonium and the upper 30 m of water column was also rich in nitrate, phosphorus, and silicon

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[2] Ramp, S., R. Schlitz, and W. R. Wright. 1985. The deep flow through the Northeast Channel of the Gulf of Maine. Unpubl. manuscr., 54 p. Northeast Fisheries Center Woods Hole Laboratory, National Marine Fisheries Service, NOAA, Woods Hole, MA 02543.

Regeneration of inorganic nitrogen in deeper waters of the Gulf of Maine is suggested by elevated ammonium concentrations in two samples, one >1.5 μM and one between 0.2 and 0.5 μM (Fig. 24) found on transect 6 in September. The vertical gradient may indicate transport upward or restriction of ammonification to near-bottom waters.

Movement of Nutrients Onto the Shelf

The presence of slope water nutrients on the continental shelf is most clearly seen along transect 8 (Figs. 2-9). The 0.5, 1, 2, and 5 μM nitrate isopleths successively occupied the bottom of the inshore station between March (when the concentration there was 0.2 μM) and mid-September. A sample with a nitrate concentration of >10 μM was found in October but the isopleth was no longer continuous with the offshore water. Also in September, the highest concentration of nitrate (>25 μM) on this transect was observed in the bottom sample near the shelf break. Nitrate concentrations were in the range of 15 μM before and after this maximum. Further east, on transects 5 and 6, a similar, though less distinct, pattern was found. The maximum northward excursion of the 10 μM nitrate isopleth appears to have occurred in September and a concentration in excess of 25 μM was also found at the bottom of the deepest station on transect 5 at this time (Fig. 15). These movements coincide with those in the MBW discussed above.

In bottom waters of the Northeast Channel (the presumed source for MBW), high nitrate (>15 μM), phosphorus (>1 μM), and silicon (>15 μM) concentrations were present during March and May. These had decreased to >10, 0.2-0.6, and 5-10 μM, respectively, by autumn.

Resupply of Surface Layer From Below

Destratification in autumn, beginning in shallower areas and progressing to deeper areas, introduced large quantities of nitrate into the previously depleted surface layer. At the inshore stations on transect 8 between mid-September and mid-October (Figs. 6, 7), surface nitrate concentration increased from 0.2 to 2-5 and 1-2 μM, respectively. The process continued through both samplings in December when most of the upper water column nitrate values were between 2 and 5 μM on this transect. Chlorophyll *a* concentrations (O'Reilly and Evans-Zetlin 1982) suggested that phytoplankton activity continues throughout the winter so that vertical nutrient uniformity may never have been attained in some areas. It is clear, however, from the positions of the 5 and 10 μM isopleths in March 1980 that the offshore end of the transect was essentially destratified with respect to nutrients.

On the north side of Georges Bank, early indications of resupply of nitrate to the upper water column are evident along transect 5 in late October (Fig. 17). There was a slight increase in nitrate on the south flank of the Bank along transect 6 at that time while large amounts of dissolved silicon had been introduced (Fig. 25). By December (Fig. 26) considerable nitrate was present over central Georges Bank (2-5 μM) with higher values to the north. In the Gulf of Maine, based on the incomplete sampling along transect 6 and nitrate concentrations on transect 5 in March 1980, nearly uniform distributions are probably achieved at some time during the winter.

With no summer data for transect 7, we cannot determine whether resupply in autumn is a factor over the eastern end of Georges Bank; however, values in December were higher than in October and higher over the Bank than in water to the north and south.

Upwelling of bottom water to the depleted surface layer was observed in May and August on transect 5 (Figs. 11, 14). At one station (~90 m deep), just north of Great South Channel, the nitrate isopleths curve upward so that the 5 and 1 μM isopleths reach the sea surface. Similar patterns of distribution were observed for phosphorus and silicon in August and for phosphorus in May. The phenomenon was not observed at stations south of lat. 41°N nor north of lat. 41°30'N. It was not observed in March and the area was not sampled in June, July, or September. There was, however, some upward bending of isopleths in October and November, particularly for phosphorus, but increased vertical mixing in the surface layer associated with destratification at this time may have diluted concentrated nutrients near the surface even if upwelling had continued.

Subsurface Nitrite Maximum

A subsurface maximum nitrite concentration was found on all transects in the Gulf of Maine. It was most frequently noted in the 30 m sample but was deeper in May on transect 6 (to 75 m). It was also observed on transect 5 in October (Figs. 16, 17) but not in March, May, August, September, or November. On transect 6 it was observed in May, August, and October, but not in December.

DISCUSSION

Of the nutrient distributional characteristics observed, the nearly complete removal of nitrate nitrogen from the surface layer in spring is the most important in defining the nutrient environment of phytoplankton. In some areas the decrease in concentration is nearly 100-fold between March and May. Since the waters over central Georges Bank do not stratify, depletion in the "well-mixed" area takes place throughout the water column and therefore has an even greater effect on the nutrient environment of phytoplankton there. If one assumes a primary production rate of 1 g carbon/m^2 per d (O'Reilly and Busch 1984), a carbon to nitrogen uptake ratio of 106:16 (Redfield et al. 1963), and a semi-enclosed circulation in the well-mixed area over Georges Bank, the March nitrate stock will supply the phytoplankton nutrient demand for only 1 to 3 mo. Since primary production is sustained at high levels through the summer over central Georges Bank, inorganic nitrogen must be supplied from: 1) recycled nitrogen released from the seabed as settled organic matter is mineralized; 2) ammonium nitrogen recycled in situ from earlier planktonic production; 3) nitrate-rich slope water crossing the shelf from the south along the bottom followed by vertical mixing; or 4) nitrate advected from MIW and vertically mixed by the dissipation of tidal energy. (It is unlikely that horizontal transport of surface waters onto Georges Bank contributes significantly since surface waters of surrounding stratified areas are also depleted.) In the case of areas that do stratify (e.g., central Gulf of Maine), the resupply of nitrogen is limited to transport through the pycnocline and remineralization that takes place before dead cells, detritus, and zooplankton pellets settle out of the euphotic zone.

Aerobic mineralization of organic matter by the seabed constitutes < 10% of the total mineralization on an areal basis (Thomas et al. 1978) and observed rates of ammonium flux from the seabed are low (Draxler and Phoel 1980); i.e., most of the mineralization occurs in the water column. This is also suggested by the fact that the majority of our ammonium maxima for central Georges Bank were found off the bottom. However, unlike phytoplankton in the deeper, vertically stratified areas surrounding Georges Bank which benefit from nutrients released by the seabed only upon turnover, phytoplankton in the well-mixed area over Georges Bank may benefit immediately from these nutrients because of continuous vertical mixing.

Ammonium concentrations for MBW indicate that while regeneration of inorganic nitrogen does take place (Fig. 24), this is an insignificant source for primary production because it is eclipsed by the amount of nitrate available in the overlying MIW. This is not the case in the "well-mixed" area over Georges Bank. Ammonium concentrations generally increased in the bottom water at stations 40 to 60 m deep between spring and late summer (Figs. 19-23). Ammonium nitrogen was the dominant form of inorganic nitrogen in the well-mixed area between July and September (Draxler and Waldhauer 1982), at times constituting more than 90% of the inorganic nitrogen pool throughout the water column, both because its concentration increased and because the concentration of nitrate decreased. If the rate of ammonium formation is relatively uniform in the waters of central Georges Bank, its abundance in the lower water column of certain areas implies that this nitrogen is less rapidly reused by the system there than it is in shallower areas. We infer from the low levels of all forms of inorganic nitrogen at shallow central Georges Bank stations (e.g., lat. 41°30′N, Fig. 23) that nitrogen from any of the possible sources is rapidly assimilated due to continuous vertical mixing and high rates of primary production. The paucity of inorganic nitrogen in this area may be compared with transect 8 where cross-shelf movement introduced more than 10 μmole/L of nitrate to the 50 m level in July (Fig. 4) and where in excess of 2 μM ammonium was observed to a depth of 30 m in May (Fig. 3). Nitrogen in the bottom waters of transect 8 is of limited availability to phytoplankton due to stratification as Ketchum et al. (1958) showed in an area to the west, off Block Island. In contrast, the movements of nutrient isopleths on the southern flank of Georges Bank and in the MBW provide evidence for nutrient transport from deep reservoirs to the central Bank where it can be introduced into the euphotic zones by vertical mixing.

Whereas nitrate nitrogen was depleted from the well-mixed area of Georges Bank during a short period in spring, the dissolved silicon concentration was highest in spring and declined gradually through the summer. Silicon concentrations recovered rapidly as nitrate replenishment began in October, but were again depleted by December though nitrate was by then abundant. Phosphorus generally increased from late spring through summer in the area. The competing and complementing processes of removal and resupply (plankton assimilation, remineralization, advective and diffusive transport) affect the concentration of each of the nutrients at different rates with the result that phytoplankton in the well-mixed area are presented with a nutrient environment that is continually changing in the relative availability of nitrogen, phosphorus, and silicon. This, in turn, implies that at any one place there will be continually changing, "best competitor," phytoplankton assemblage through time.

In stratified areas, nutrient depletion was persistent, as seen in the nutrient profiles, but was not uniform nor exhaustive throughout the euphotic zone and identifiable nutrient gradients developed. Using Figure 31, we can examine the conditions more closely. In Figure 31A we have arbitrarily divided the data from shelf and Gulf of Maine deep stations (>120 m), sampled during the highly stratified season (July-early October), into three depth intervals: 1) from 10 m above the 1% light level to the surface; 2) the 1% light depth ± 5 m; and 3) from 10 m to 45 m below the 1% light level. Not only was there a relationship between nutrient concentrations and depth, but the relationship between nutrients within depth strata changed with depth; i.e., the slope of the nitrate:phosphorus lines at the 1% light level and in the water below were both about 16:1 but the 1% light depth region was depleted by about 4.0 μmole of nitrate per liter and/or 0.2 μmole of phosphorus per liter when compared with the deeper water. In the top layer, the nitrate concentration was independent of phosphorus suggesting that they are related to the 1% light level data but collapsed along the functional regression line.

The depiction in Figure 31A of discrete strata was actually a continuum of intergrading layers. As may be seen in Figure 31B, while phosphorus changed continually with depth, nitrate was essentially exhausted at about 13 m above the 1% light depth. Also shown in the figure are the average upper and lower limits of the thermocline (with 95% confidence intervals) and the 95% confidence interval about the 1% light depth from the 10 stations for which hydrographic data are available. The confidence intervals of the upper and lower thermocline limits decrease from ±9.1 and ±17.0 m, respectively, when calculated on the basis of depth from the sea surface, to ±6.9 and ±15.0 m when calculated relative to the 1% light level depth. The position of the average 1% light level depth and the average center of the thermocline at these 10 stations differed by only 2.5 m.

These relationships serve to illustrate in a qualitative way the thermocline-nutrient-phytoplankton-light interactions operating in this area that determine the nutrient environment of the phytoplankton. These include: 1) the pycnocline acting as an impediment to the vertical movement of nutrients, the unavailability of which limits phytoplankton densities; 2) the extent of light penetration being partially dependent on phytoplankton densities and vice versa, while nutrient concentrations (in the euphotic zone) are partially determined by rates of phytoplankton uptake as well as rates of remineralization of organic material; and 3) the density gradient in the pycnocline providing a means for some phytoplankters to control their vertical position in order to make optimal use of light and nutrients. The cohesiveness of the July through early October data, as seen in Figure 31, implies a temporal stability through the period. We can view the nutrient environment of deeper parts of the study area as relatively constant through time (when located relative to the 1% light level) but vertically graduated through the water column.

While nitrate, phosphorus, and silicon existed in monotonic vertical gradients, nitrite was found as a subsurface maximum layer on some transects in the Gulf of Maine. Figure 32 shows the frequency with which the maximum nitrite concentration in the upper 120 m (MSW and MIW) occurred in depth intervals defined on the basis of our normal sampling depths (1, 10, 20, 30, 50, 75, and 100 m) during July through September in the deep, stratified portion of the Gulf of Maine (bottom depths > 120 m). The average number of observations in each depth interval is 30 (ranging from 37 in 0-5 m to 26 in the 62.5-87.5 m interval). The average depth of the 1% light level at these stations was 28.8 m. It may be seen that most of the nitrite maxima are at the limit of or below the euphotic zone and that the maxima in the second most frequent interval (40-62.5 m) are in waters with higher nitrite concentrations than other intervals. The nitrite layer may have developed by microbial oxidation of ammonium as described in Pacific coastal areas (Ward et al. 1982) or by phytoplankton reduction of the abundant nitrate nitrogen being transported upward (Olson 1981), or by both. Of the two transects on which we observed a midwater nitrite maximum, and had ammonium measurements (Figs. 18, 25), one (transect 5) had an ammonium maximum and the other did not. Data collected in 1980 and 1981 include more measurements of ammonium which may be useful in addressing this question further.

In general then, while the well-mixed area of Georges Bank has a temporally changing nutrient environment, areas that stratify seasonally (e.g., the central Gulf of Maine) reach a quasi-steady state that persists for several months, in which nutrient environments are vertically arrayed in parallel with light, temperature, and salinity layering. Areas that are homogeneous with respect to phytoplankton biomass segregate along similar lines. The well-mixed area of Georges Bank has the highest annual average chlorophyll concentration of 20 subareas examined in our study area, while stratified subareas generally have low standing stocks of phytoplankton (O'Reilly and Evans-Zetlin 1982). The subareas along the north side of Georges Bank also have high chlorophyll concentrations (second only to the central, well-mixed area). Phytoplankton in these transitional subareas may benefit from the nutrient reserves below the euphotic zone because of vertical mixing associated with the dissipation of tidal energy in stratified water masses that impinge on the northern flank of Georges Bank again indicating the close association of bathymetry, nutrients, and phytoplankton. This may be important in determining the standing stocks of phytoplankton biomass and rates of primary production.

Finally, with respect to the flow of nutrients into and out of the study area, Hopkins and Garfield (1979) calculated that the influx of water to the Gulf of Maine across the Scotian Shelf is episodic and of low magnitude. Our 1979 nutrient data support this view in that we observed no highly concentrated nutrient inputs to the MIW which might be attributable to this source. Our data for the Northeast Channel are consistent with both Hopkins and Garfield's (1979) analysis that slope water, of high nutrient content, enters the Gulf of Maine through the channel and is the source for MBW and with Ramp et al.'s (footnote 2) report of outflow from the Gulf of Maine in the surface layer of the Northeast Channel.

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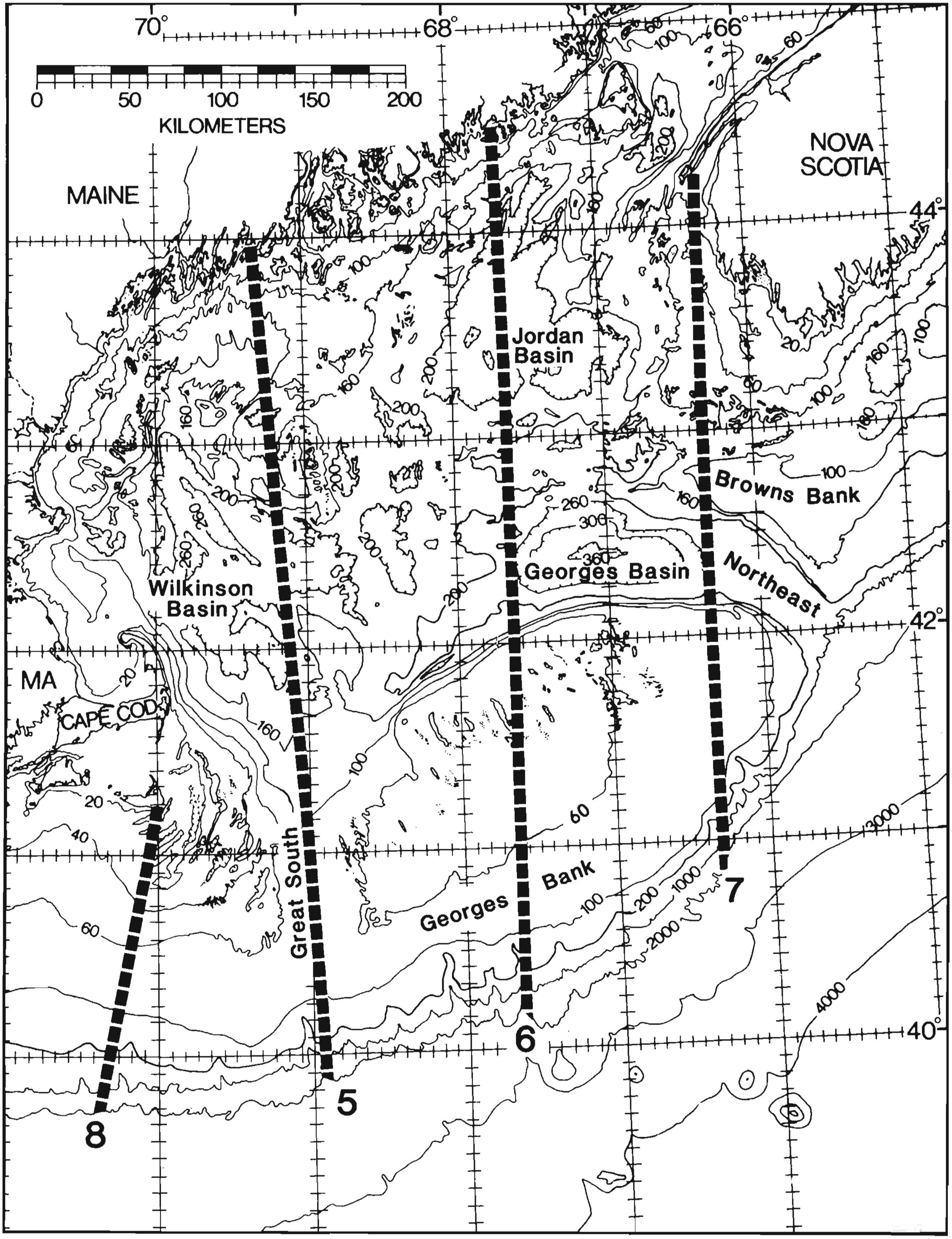

Figure 1.—Bathymetry (from Uchupi 1965) of the study area and location of transects.

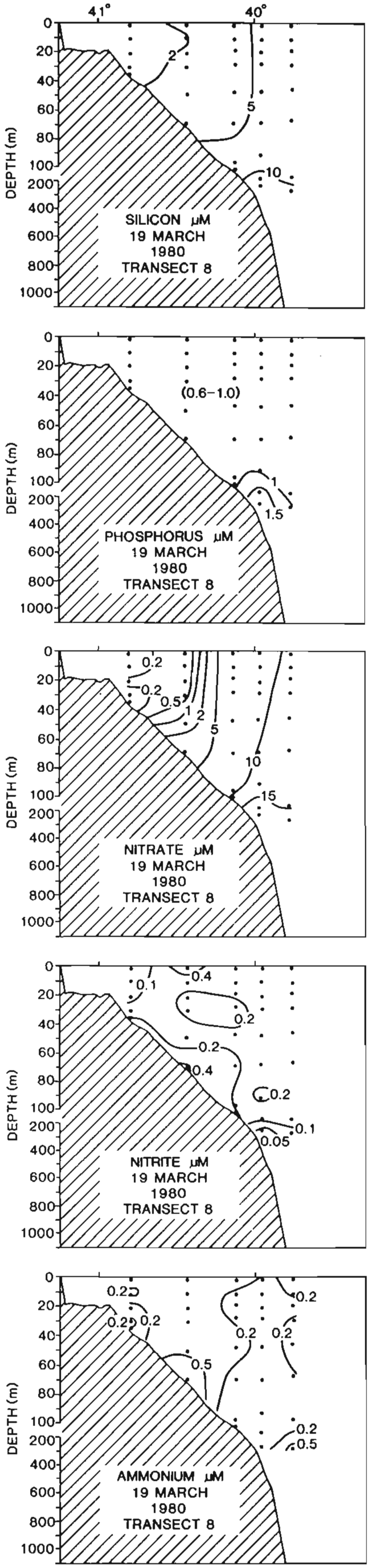

Figure 2.—Distribution of inorganic nutrients on Transect 8, 19 March 1980.

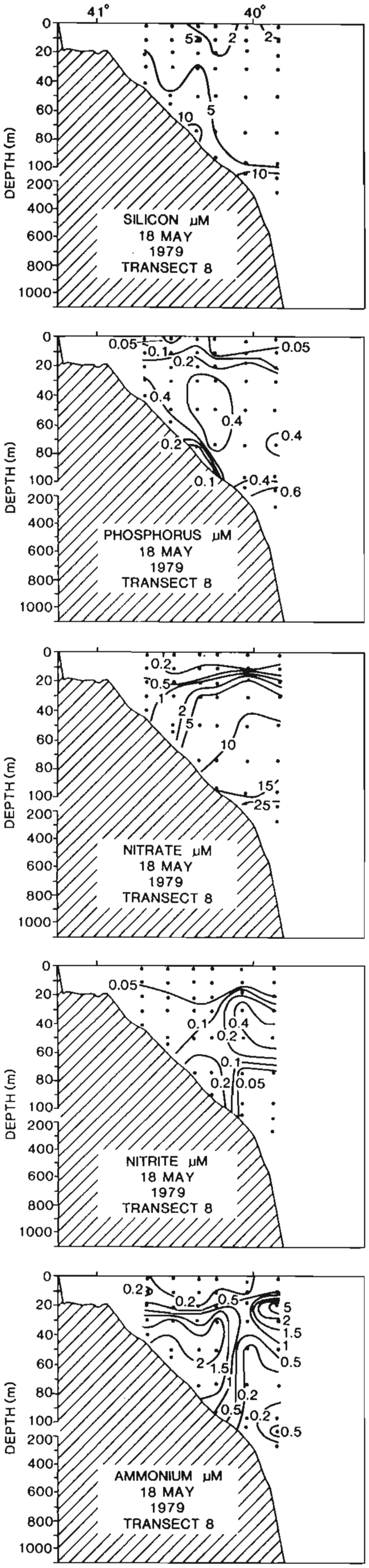

Figure 3.—Distribution of inorganic nutrients on Transect 8, 18 May 1979.

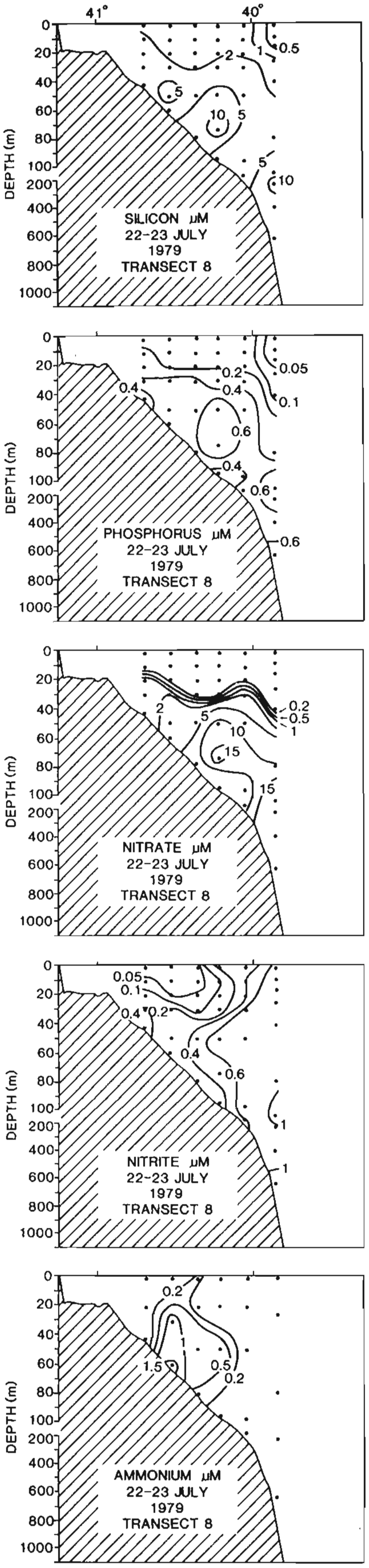

Figure 4.—Distribution of inorganic nutrients on Transect 8, 22-23 July 1979.

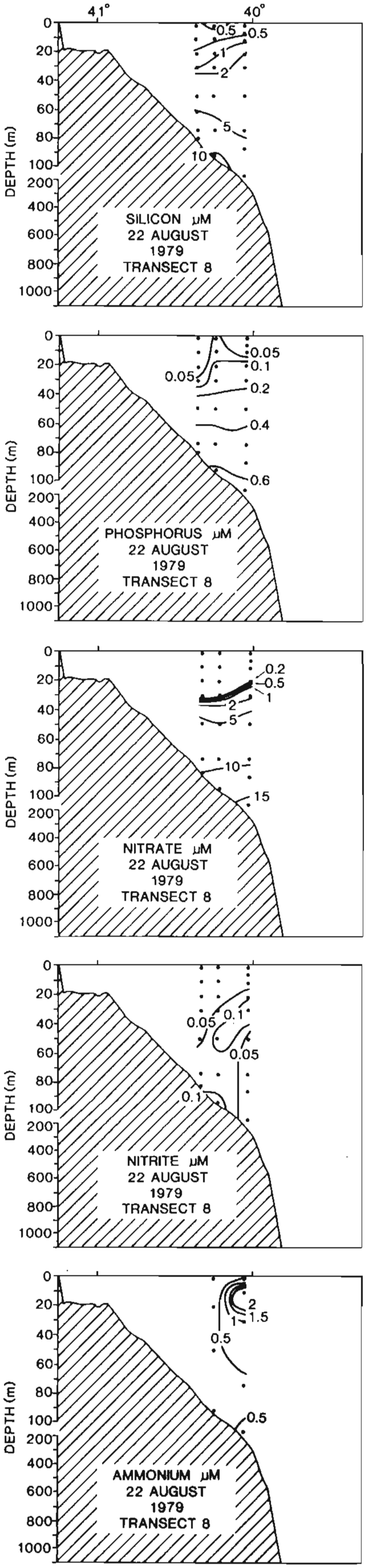

Figure 5.—Distribution of inorganic nutrients on Transect 8, 22 August 1979.

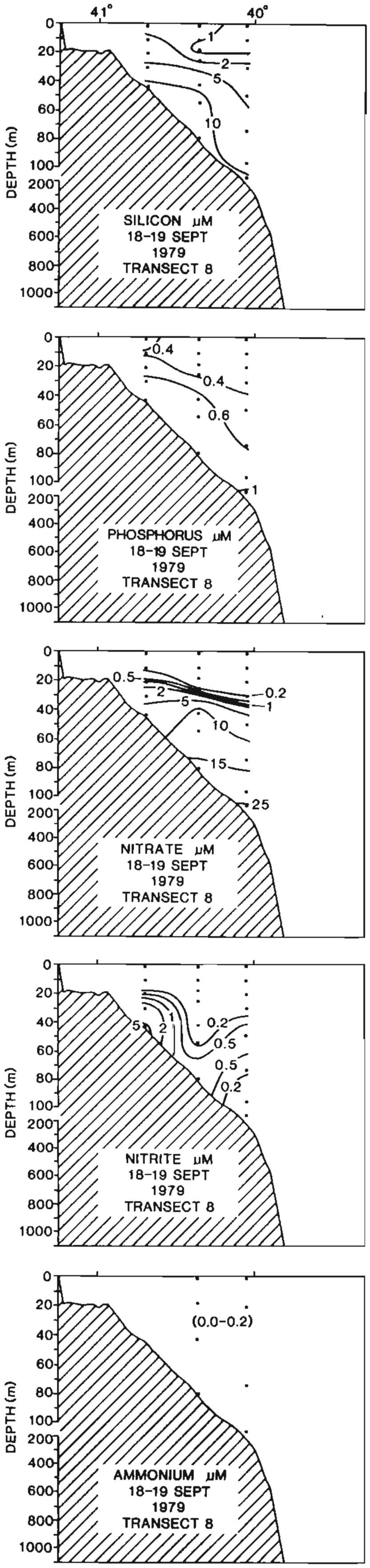

Figure 6.—Distribution of inorganic nutrients on Transect 8, 18-19 September 1979.

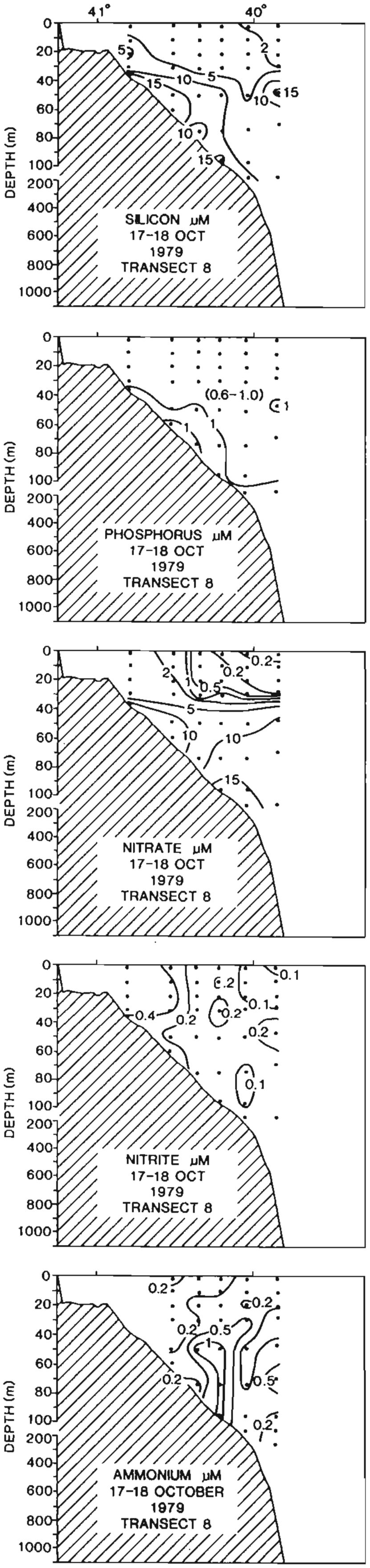

Figure 7.—Distribution of inorganic nutrients on Transect 8, 17-18 October 1979.

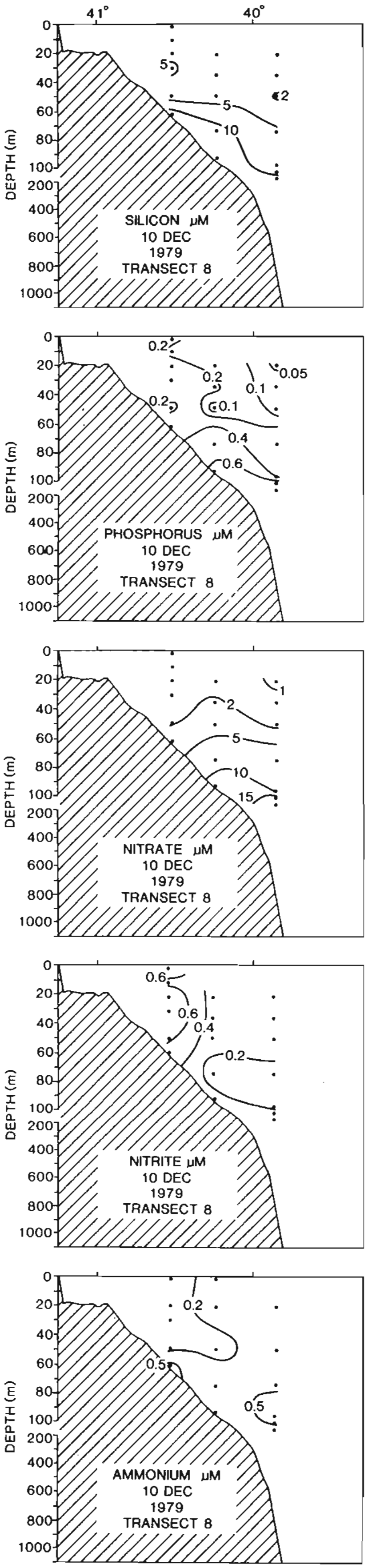

Figure 8.—Distribution of inorganic nutrients on Transect 8, 10 December 1979.

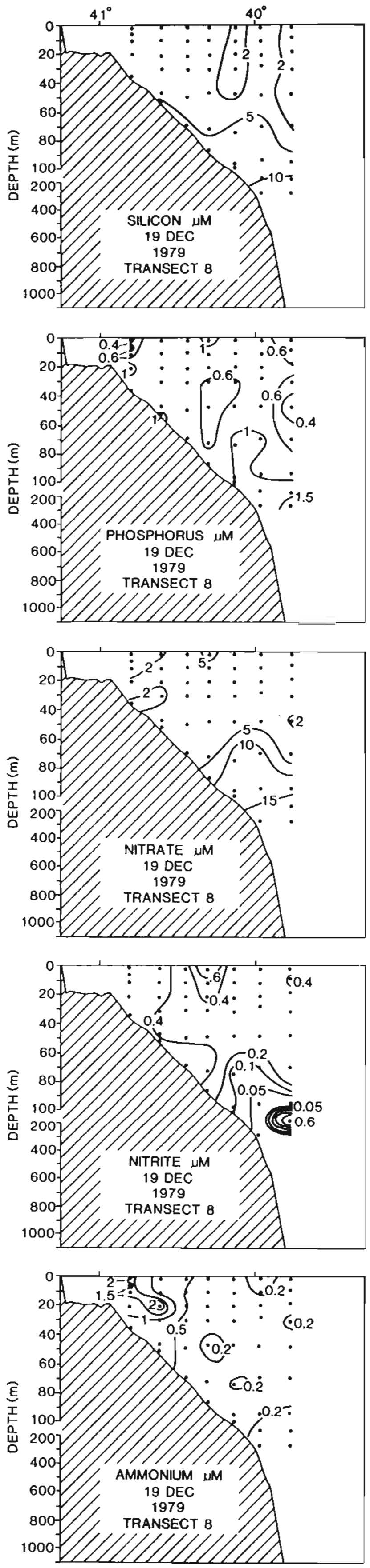

Figure 9.—Distribution of inorganic nutrients on Transect 8, 19 December 1979.

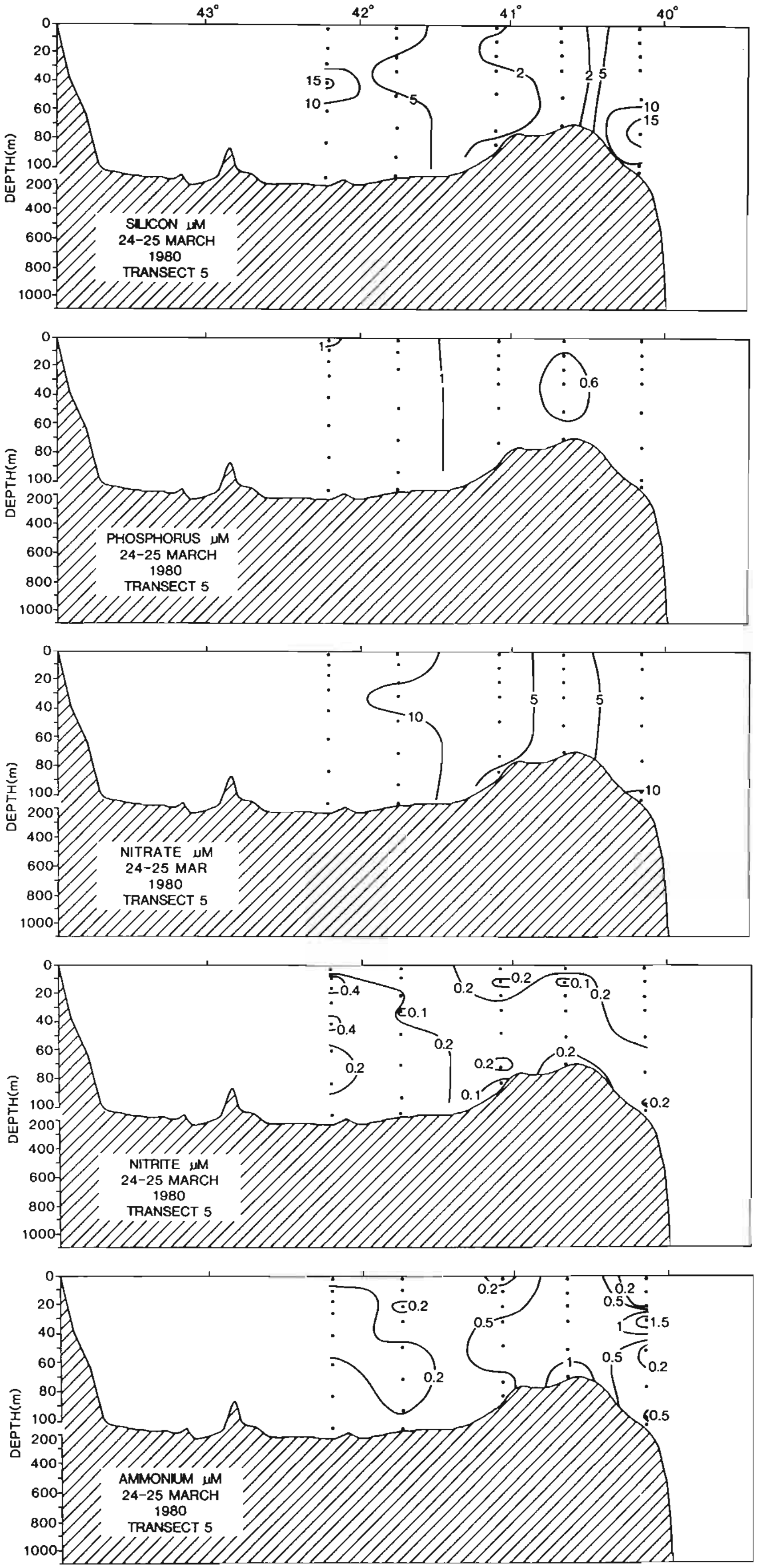

Figure 10.—Distribution of inorganic nutrients on Transect 5, 24-25 March 1980.

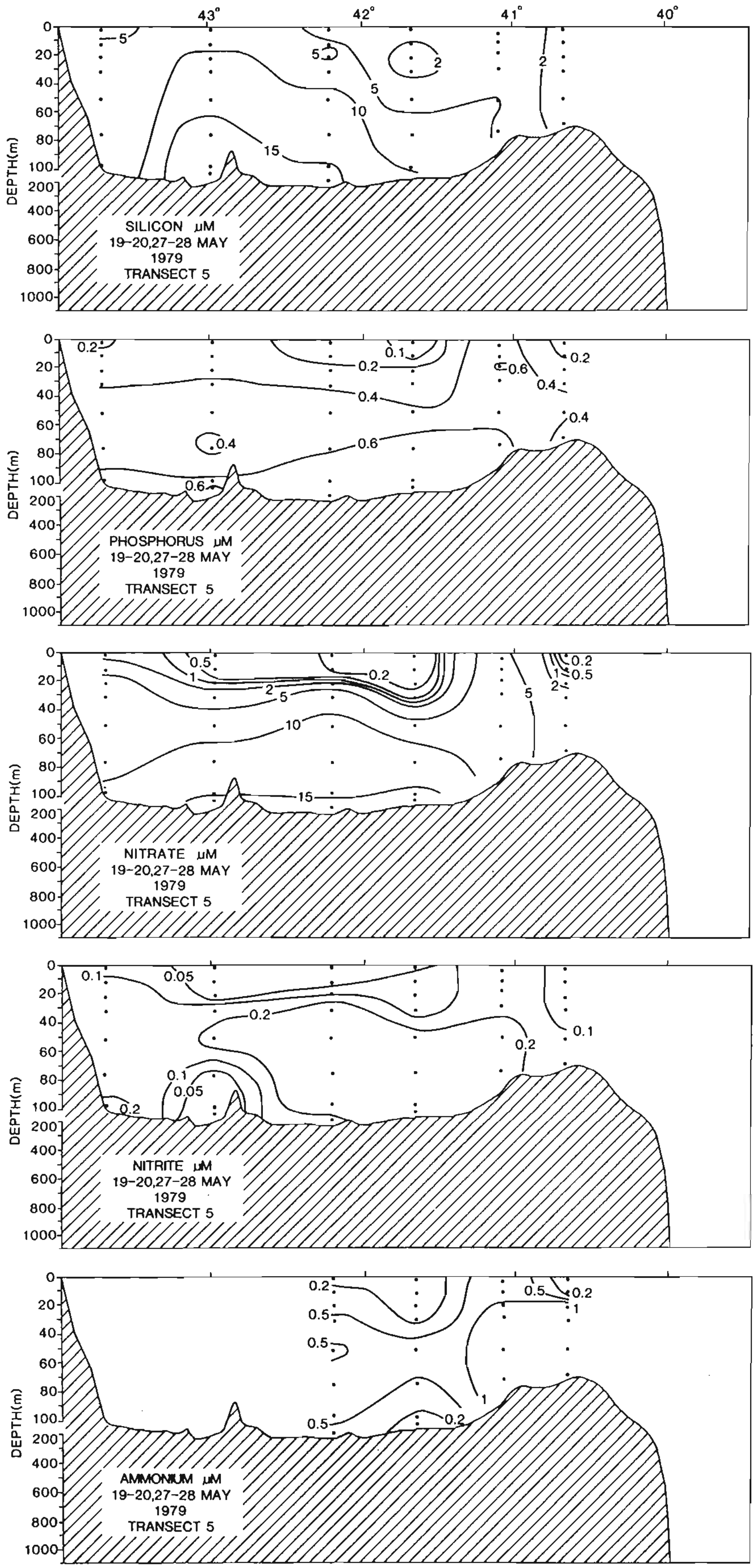

Figure 11.—Distribution of inorganic nutrients on Transect 5, 19-20, 27-28 May 1979.

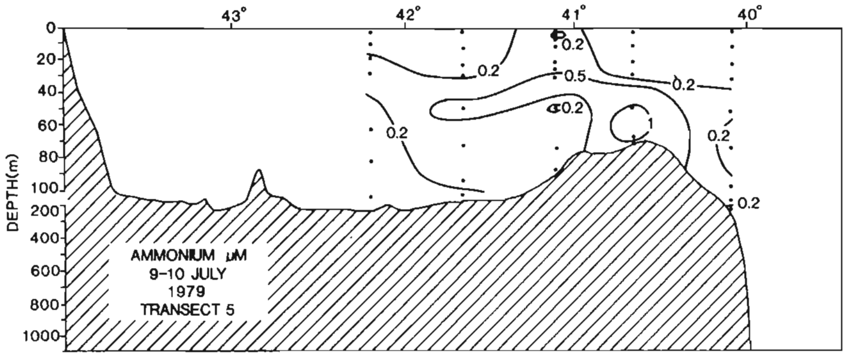

Figure 12.—Distribution of inorganic nutrients on Transect 5, 9-10 July 1979.

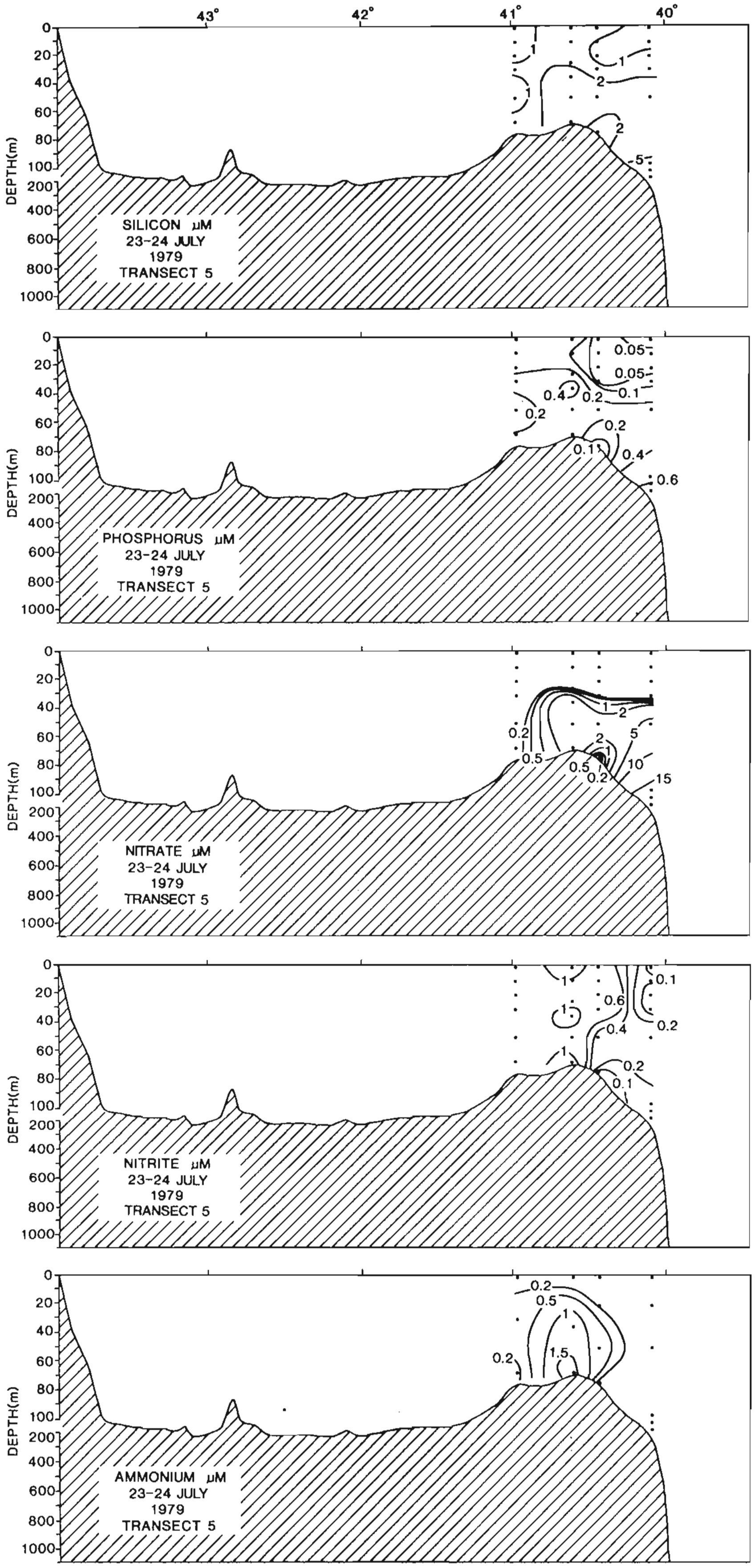

Figure 13.—Distribution of inorganic nutrients on Transect 5, 23-24 July 1979.

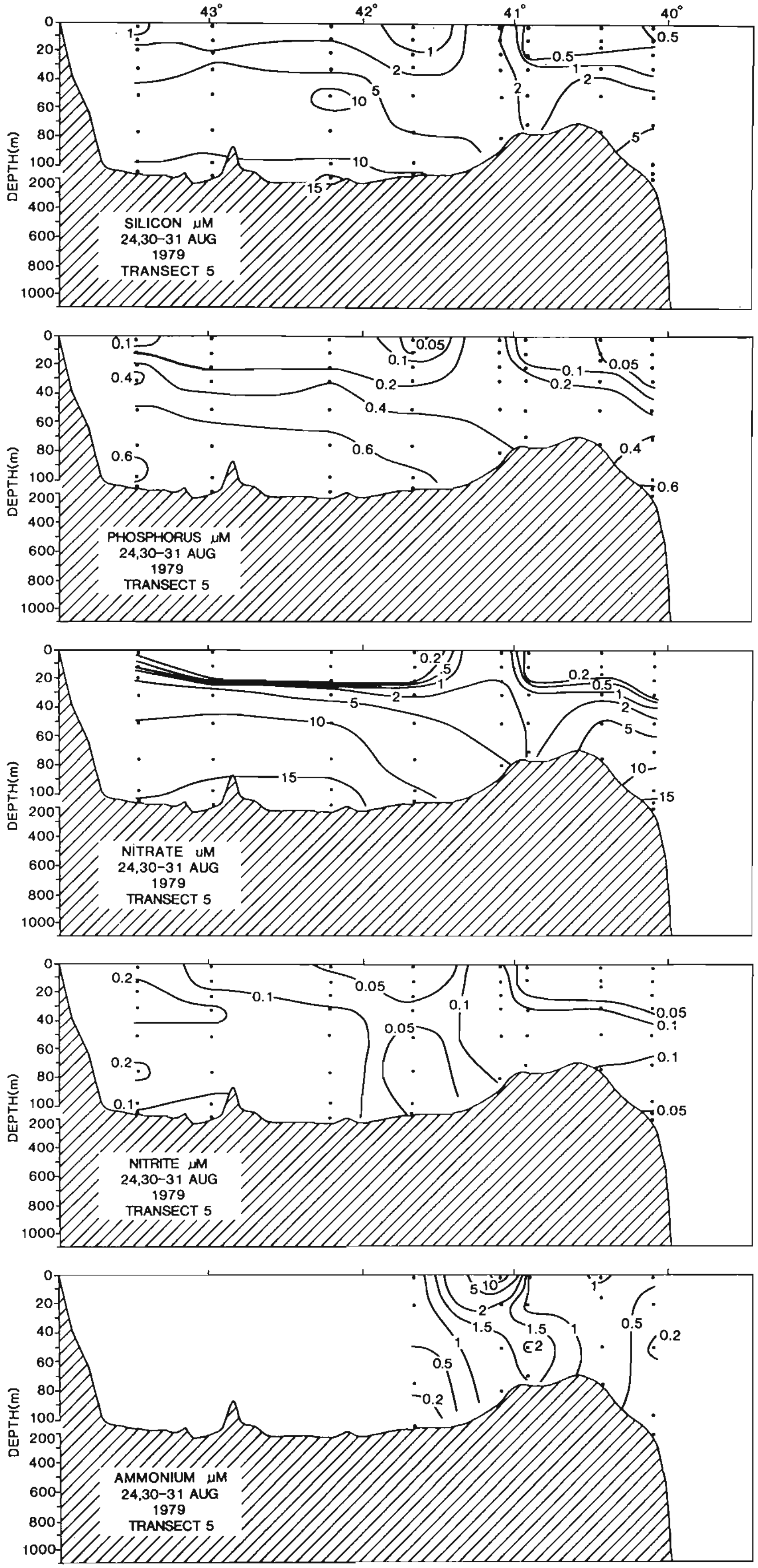

Figure 14.—Distribution of inorganic nutrients on Transect 5, 24, 30-31 August 1979.

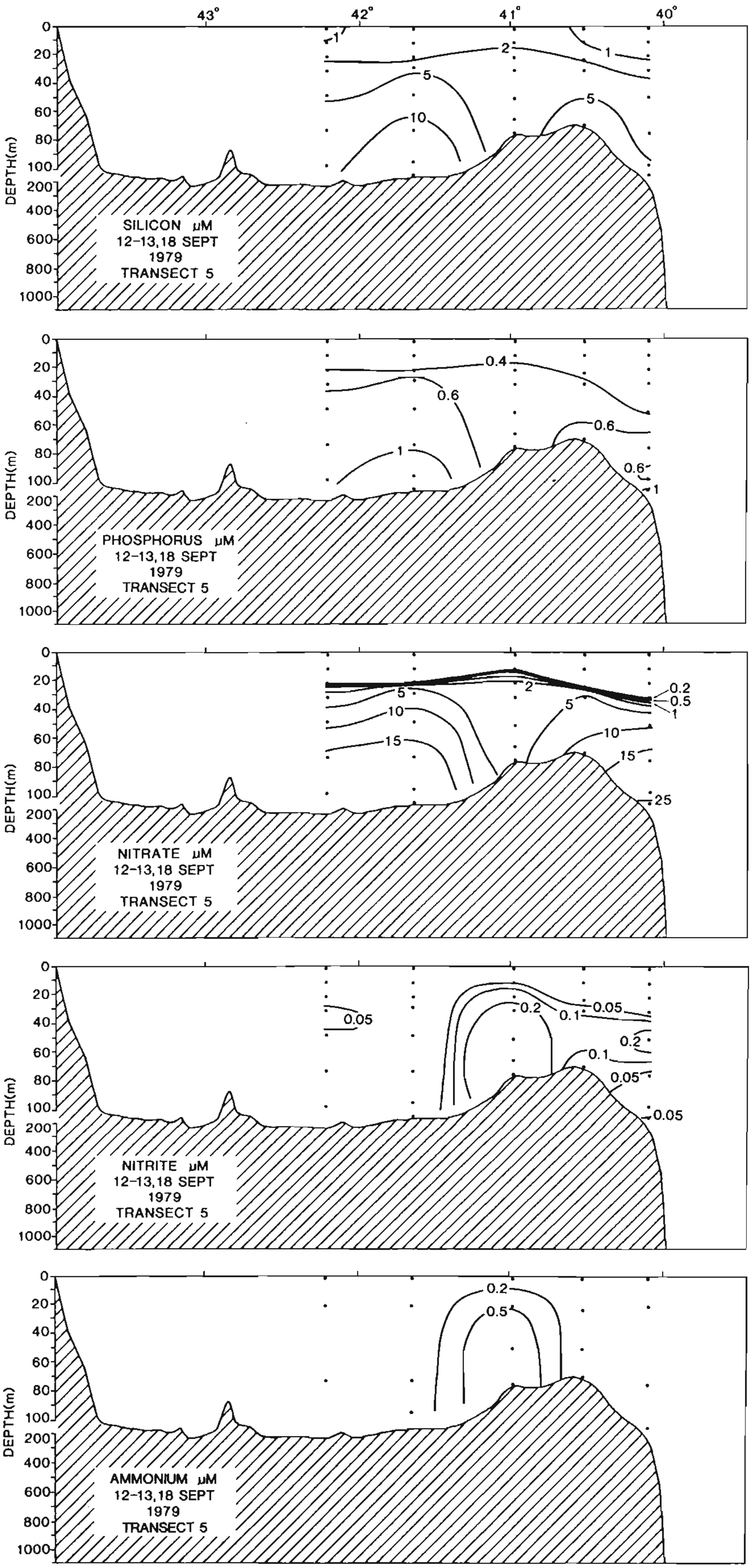

Figure 15.—Distribution of inorganic nutrients on Transect 5, 12-13, 18 September 1979.

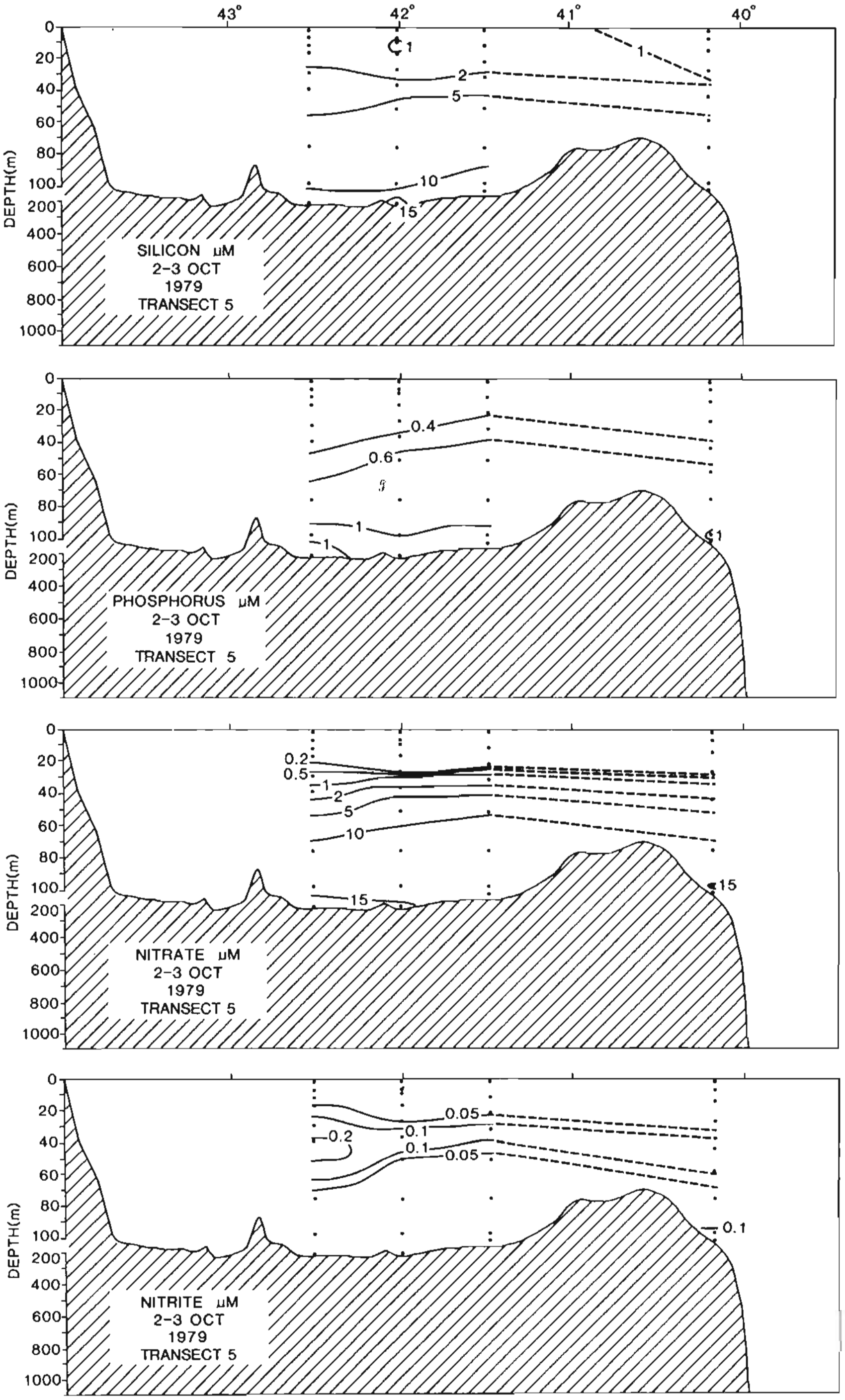

Figure 16.—Distribution of inorganic nutrients on Transect 5, 2-3 October 1979.

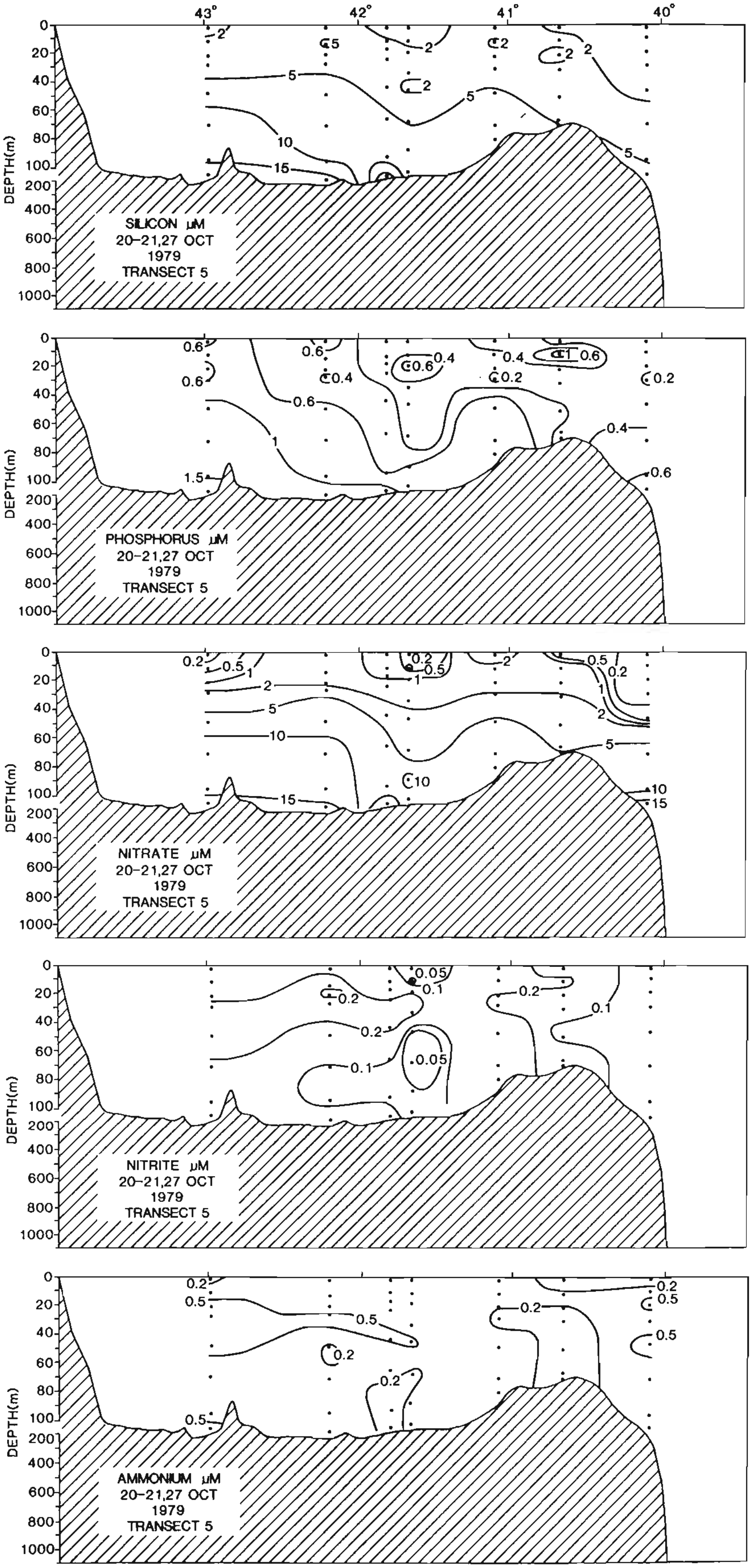

Figure 17.—Distribution of inorganic nutrients on Transect 5, 20-21, 27 October 1979.

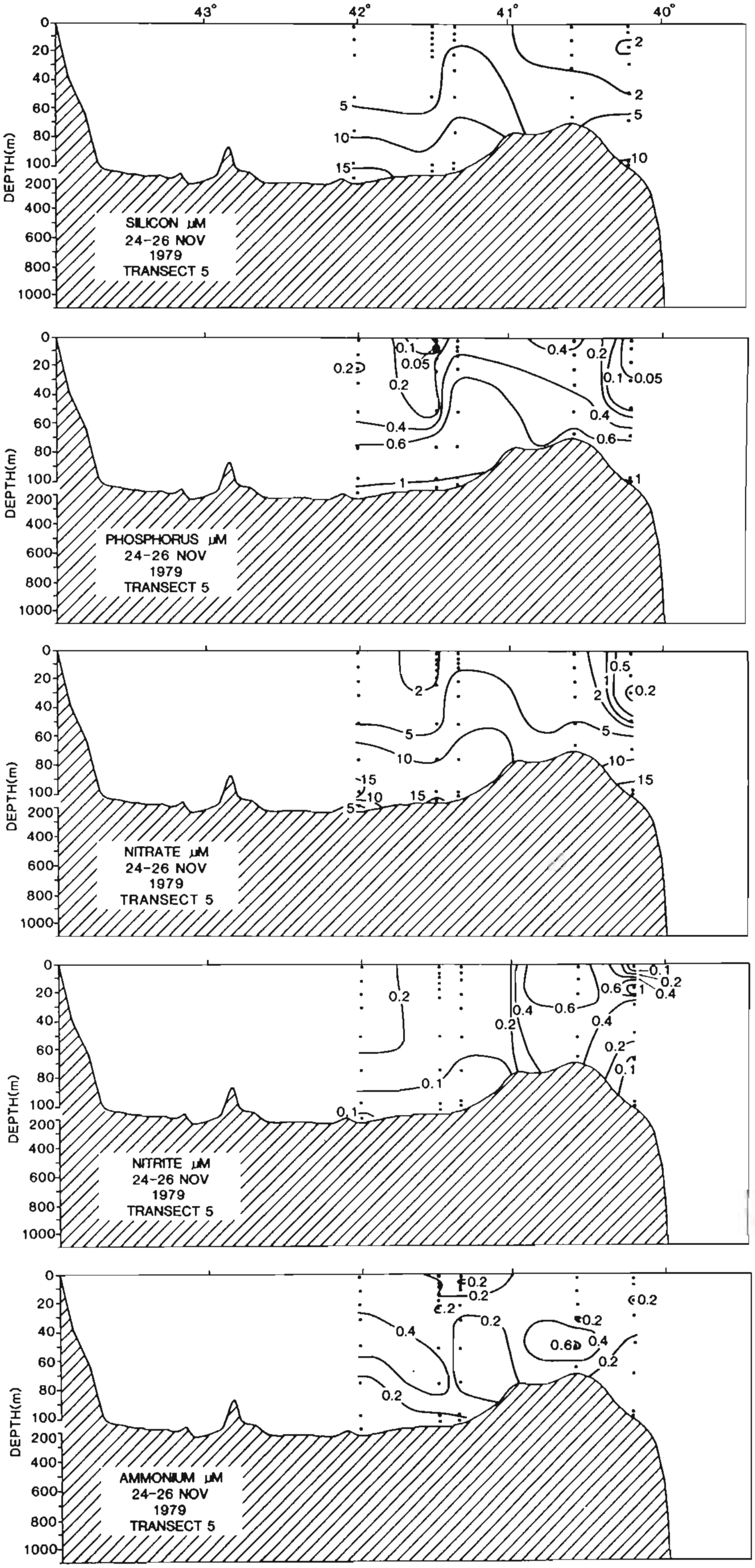

Figure 18.—Distribution of inorganic nutrients on Transect 5, 24-26 November 1979.

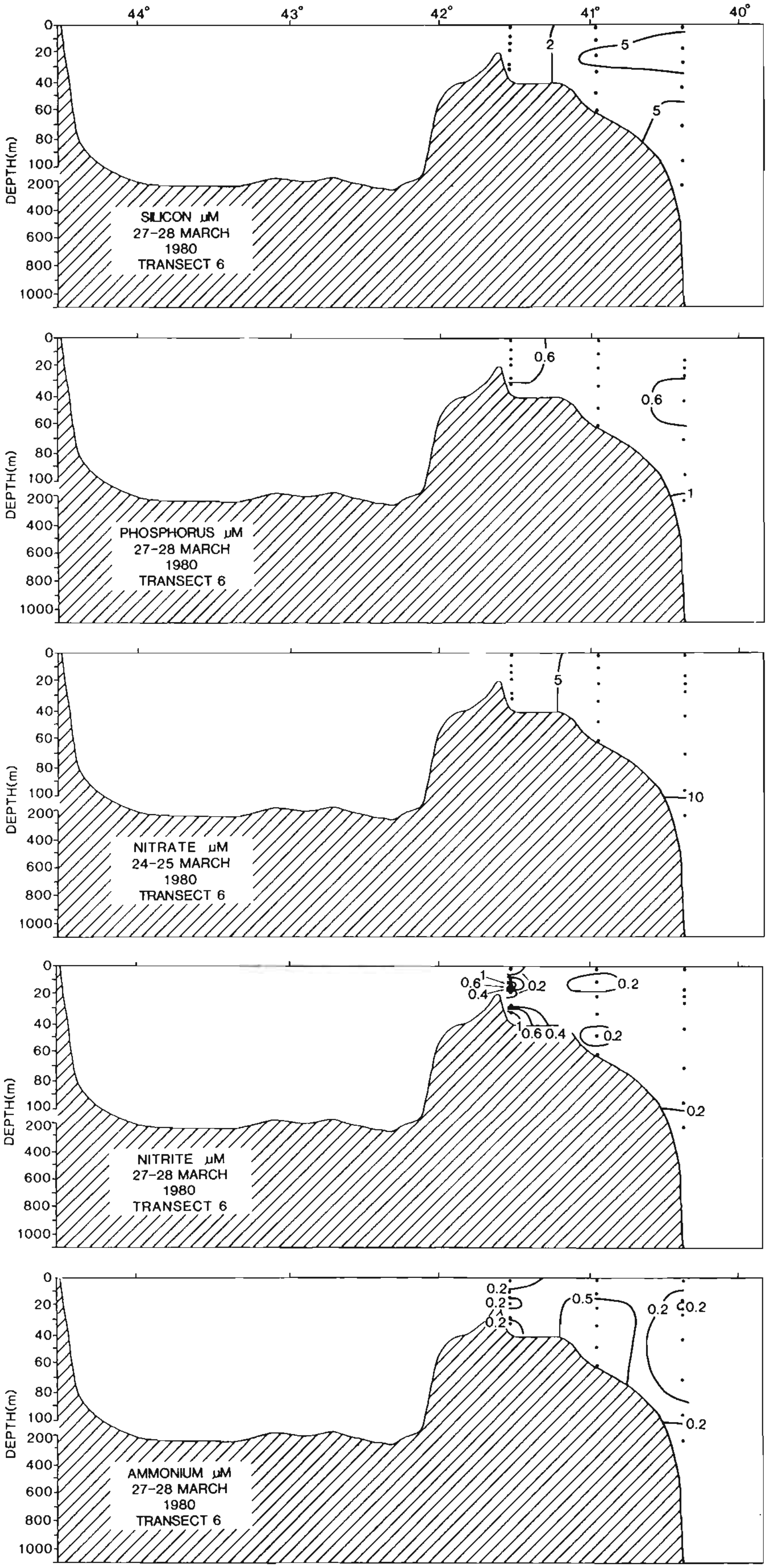

Figure 19.—Distribution of inorganic nutrients on Transect 6, 27-28 March 1980.

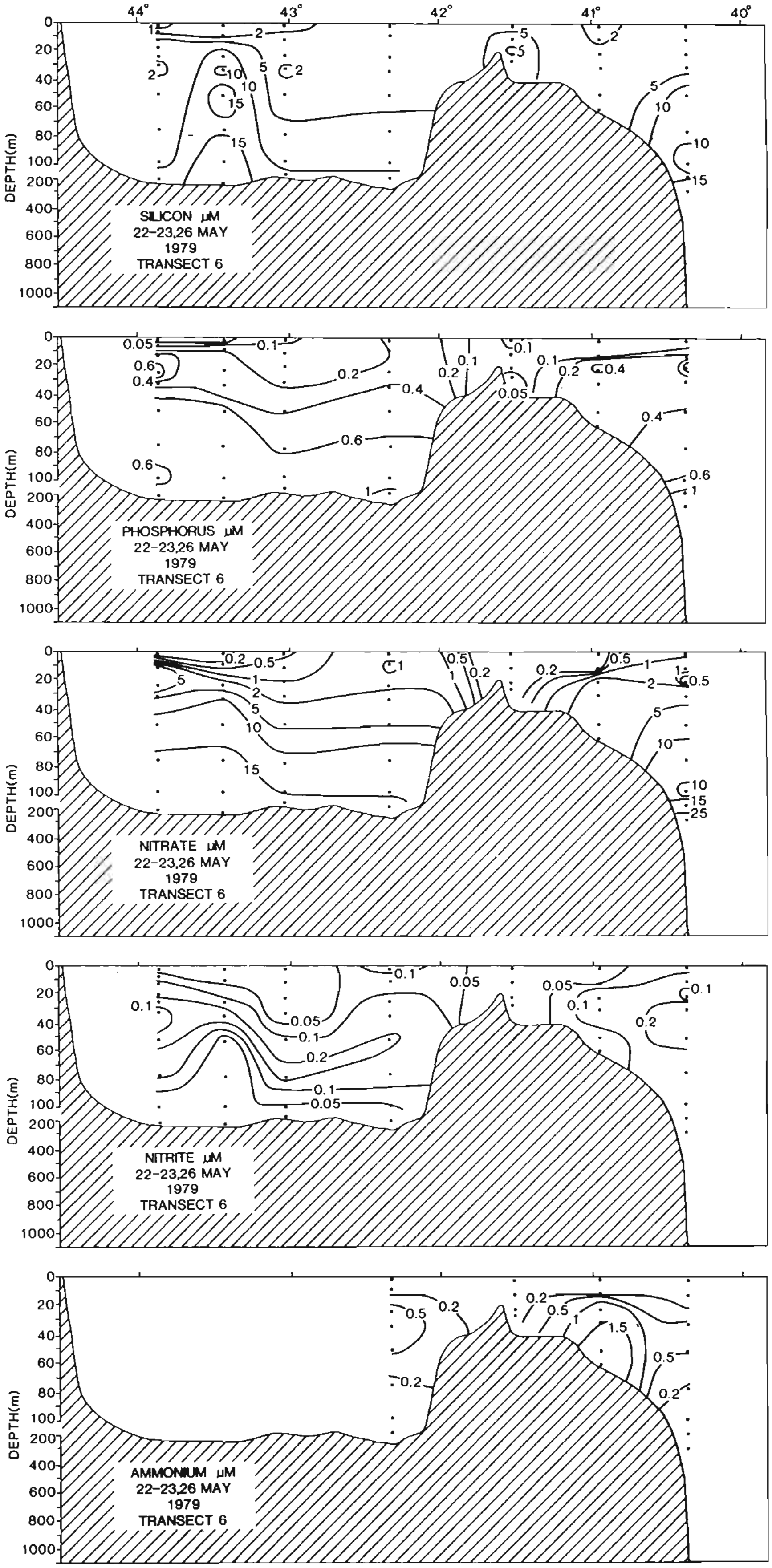

Figure 20.—Distribution of inorganic nutrients on Transect 6, 22-23, 26 May 1979.

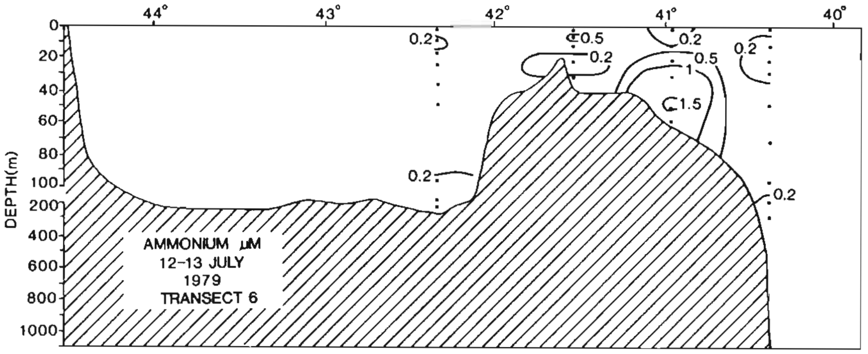

Figure 21.—Distribution of inorganic nutrients on Transect 6, 12-13 July 1979.

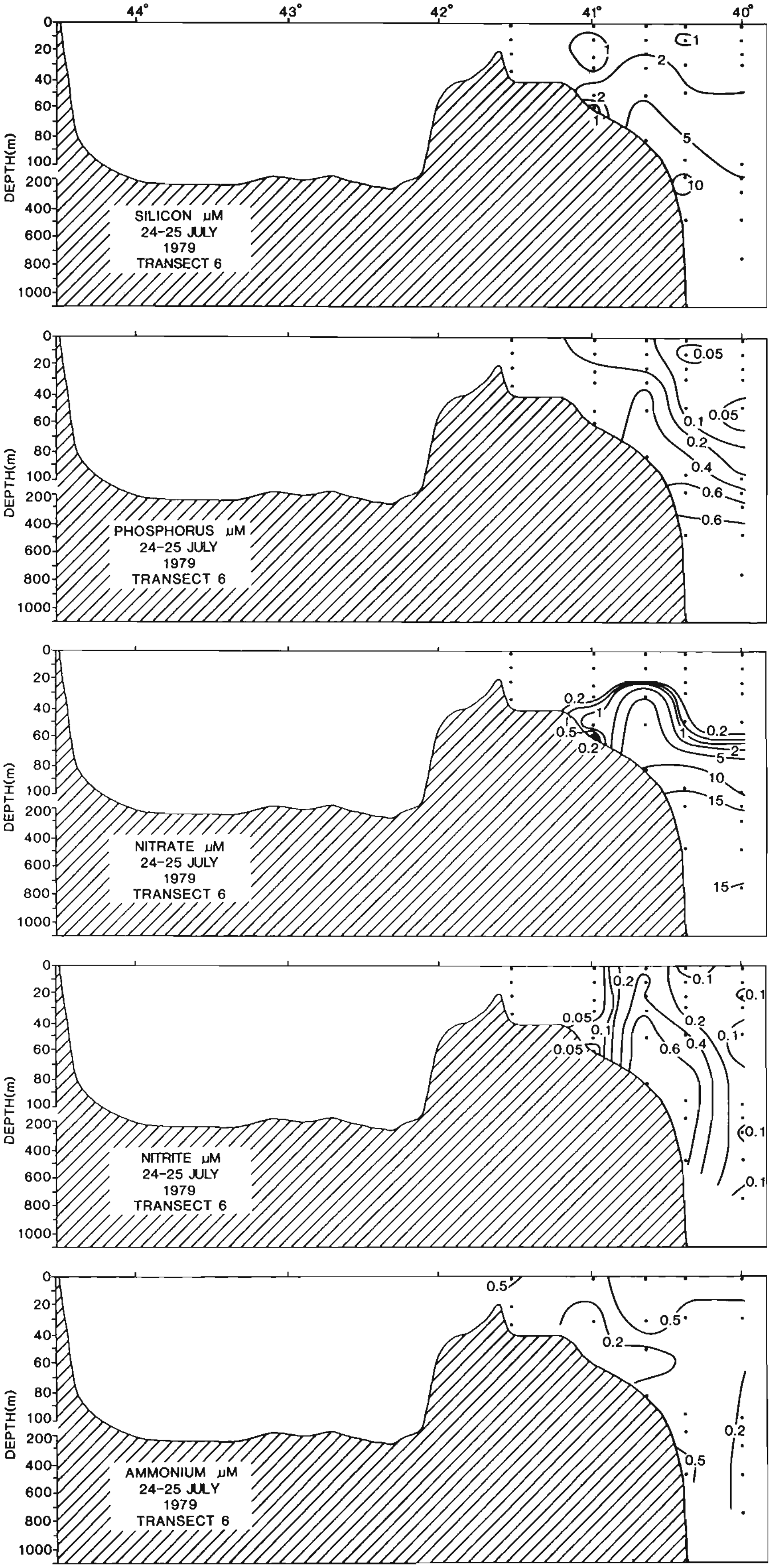

Figure 22.—Distribution of inorganic nutrients on Transect 6, 24-25 July 1979.

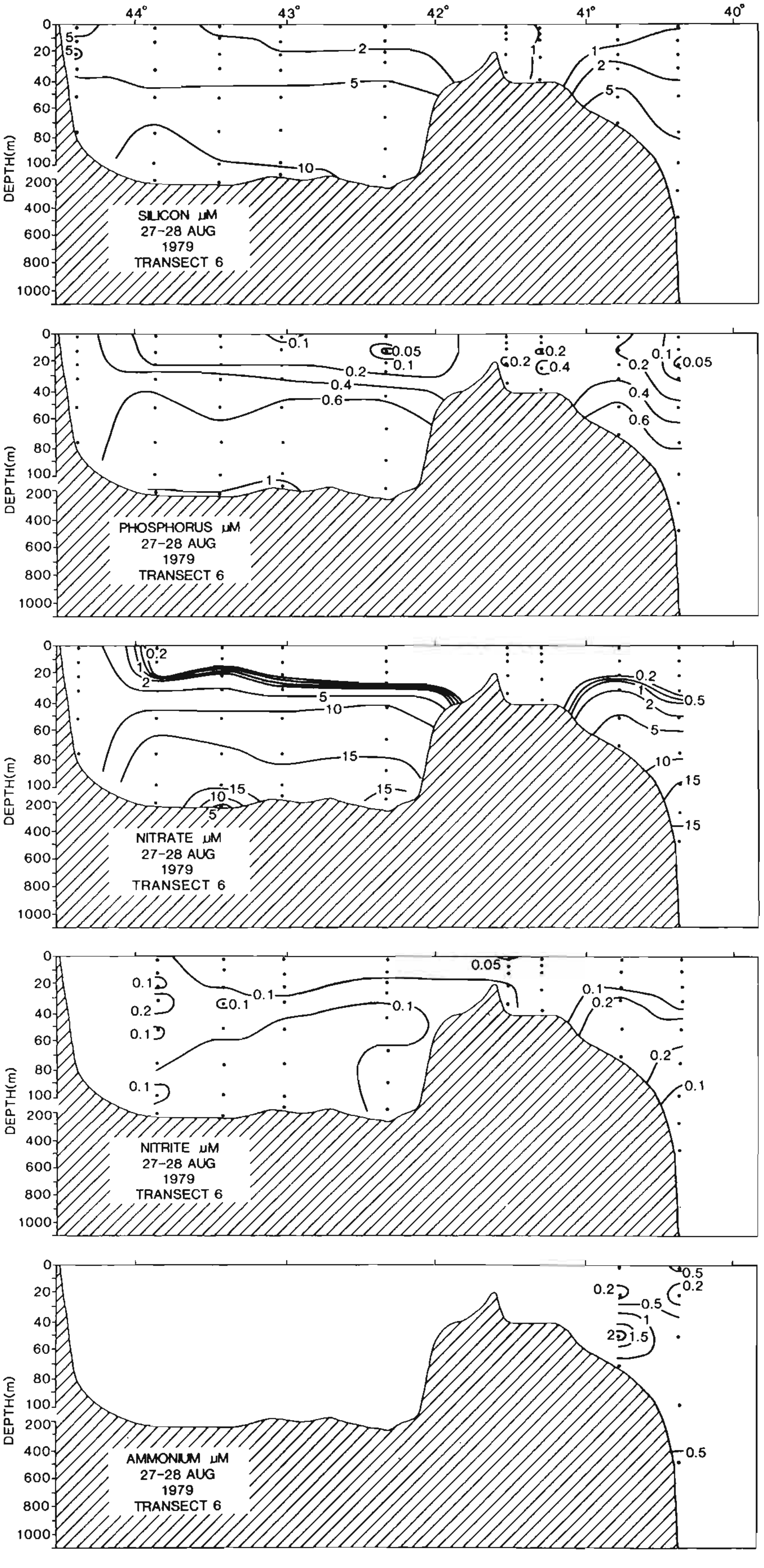

Figure 23.—Distribution of inorganic nutrients on Transect 6, 27-28 August 1979.

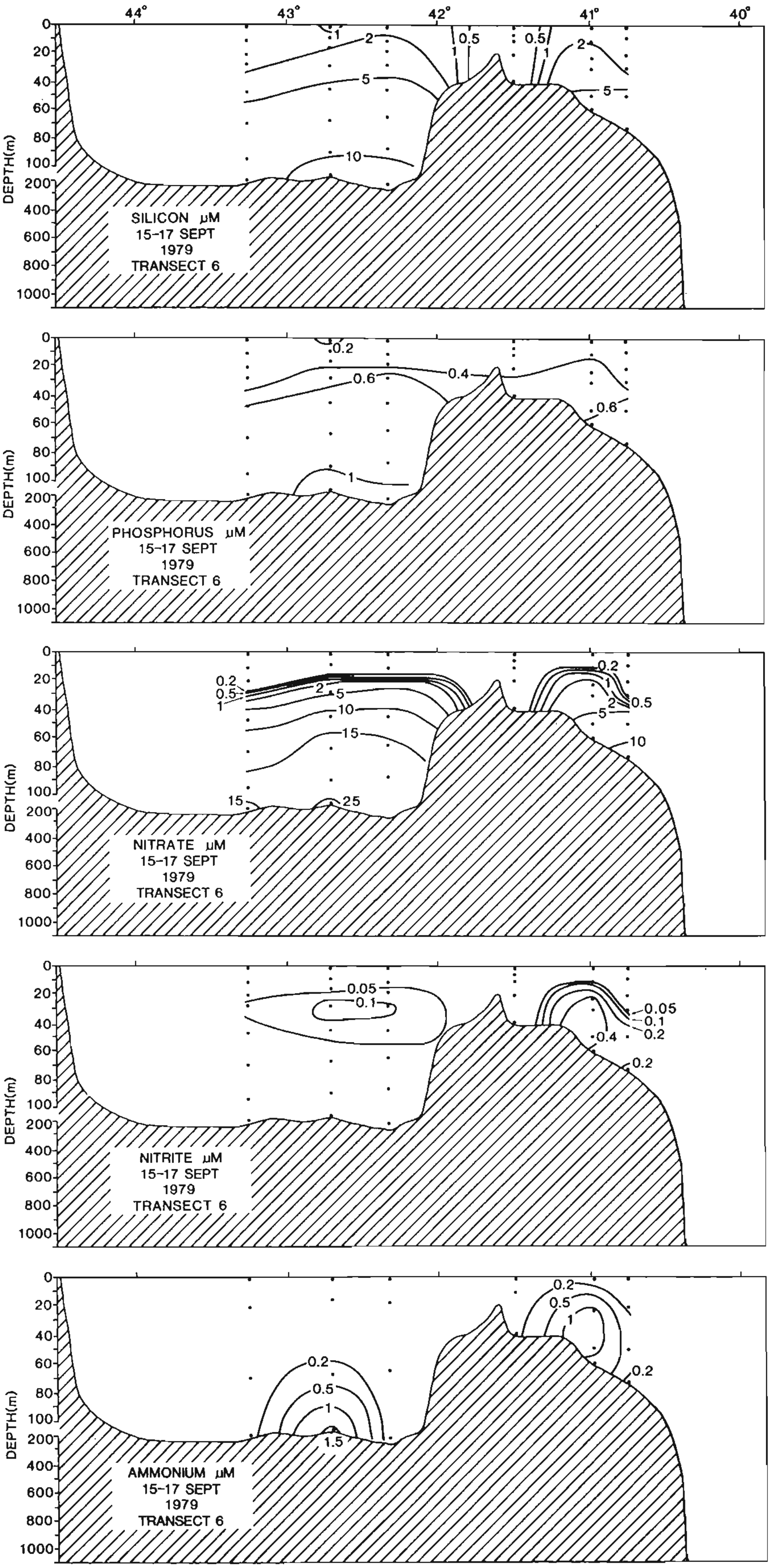

Figure 24.—Distribution of inorganic nutrients on Transect 6, 15-17 September 1979.

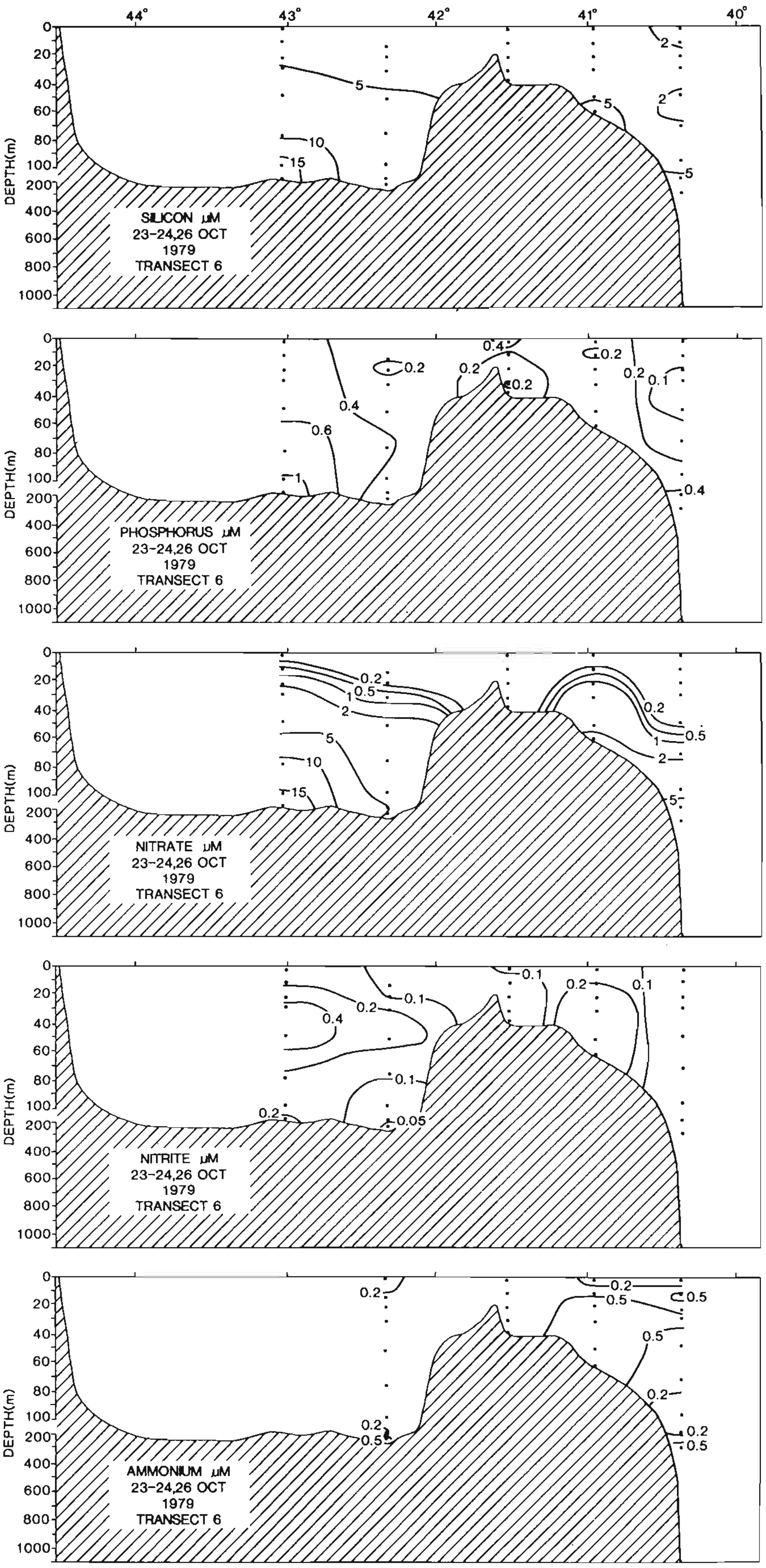

Figure 25.—Distribution of inorganic nutrients on Transect 6, 23-24, 26 October 1979.

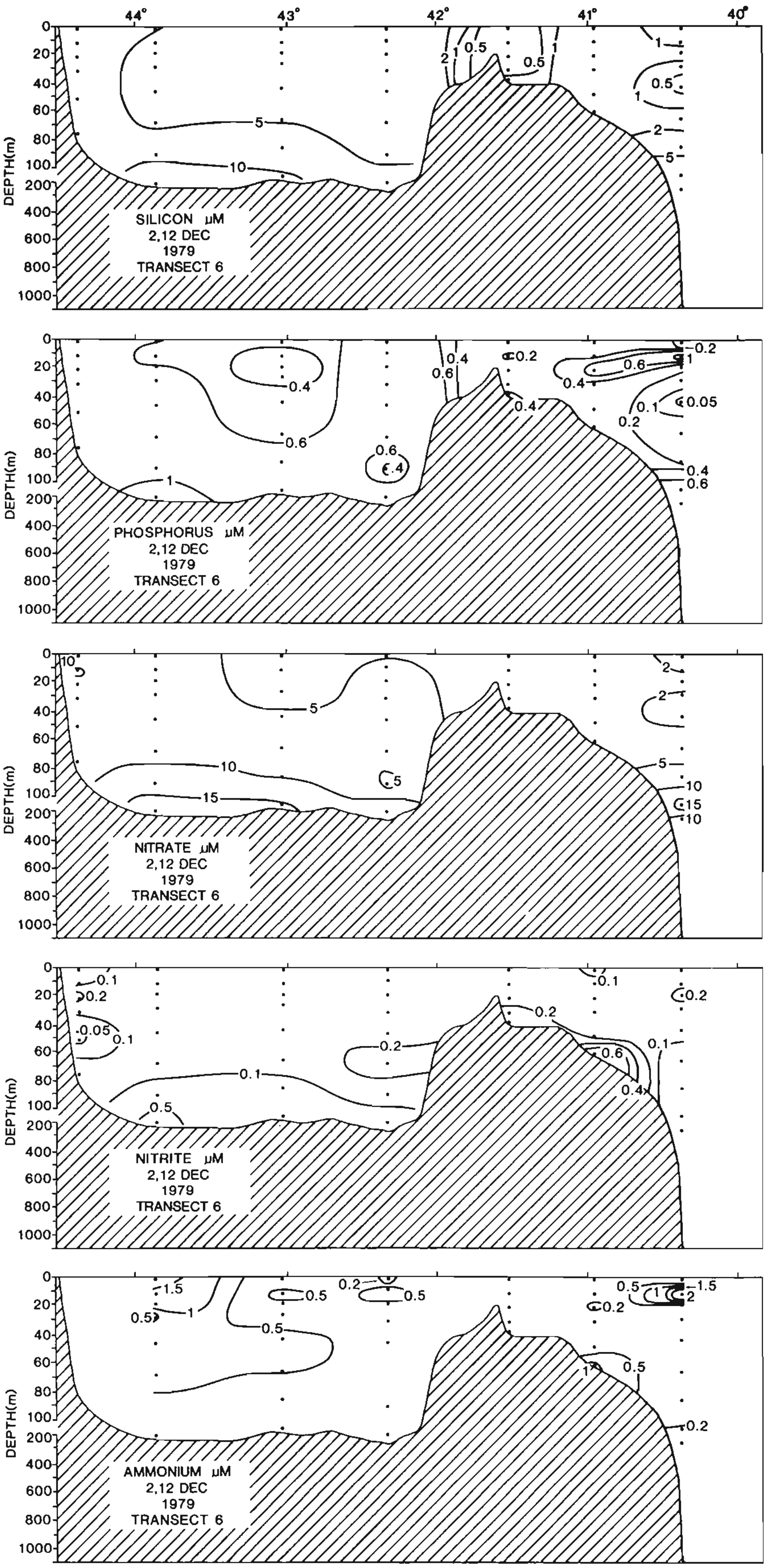

Figure 26.—Distribution of inorganic nutrients on Transect 6, 2, 12 December 1979.

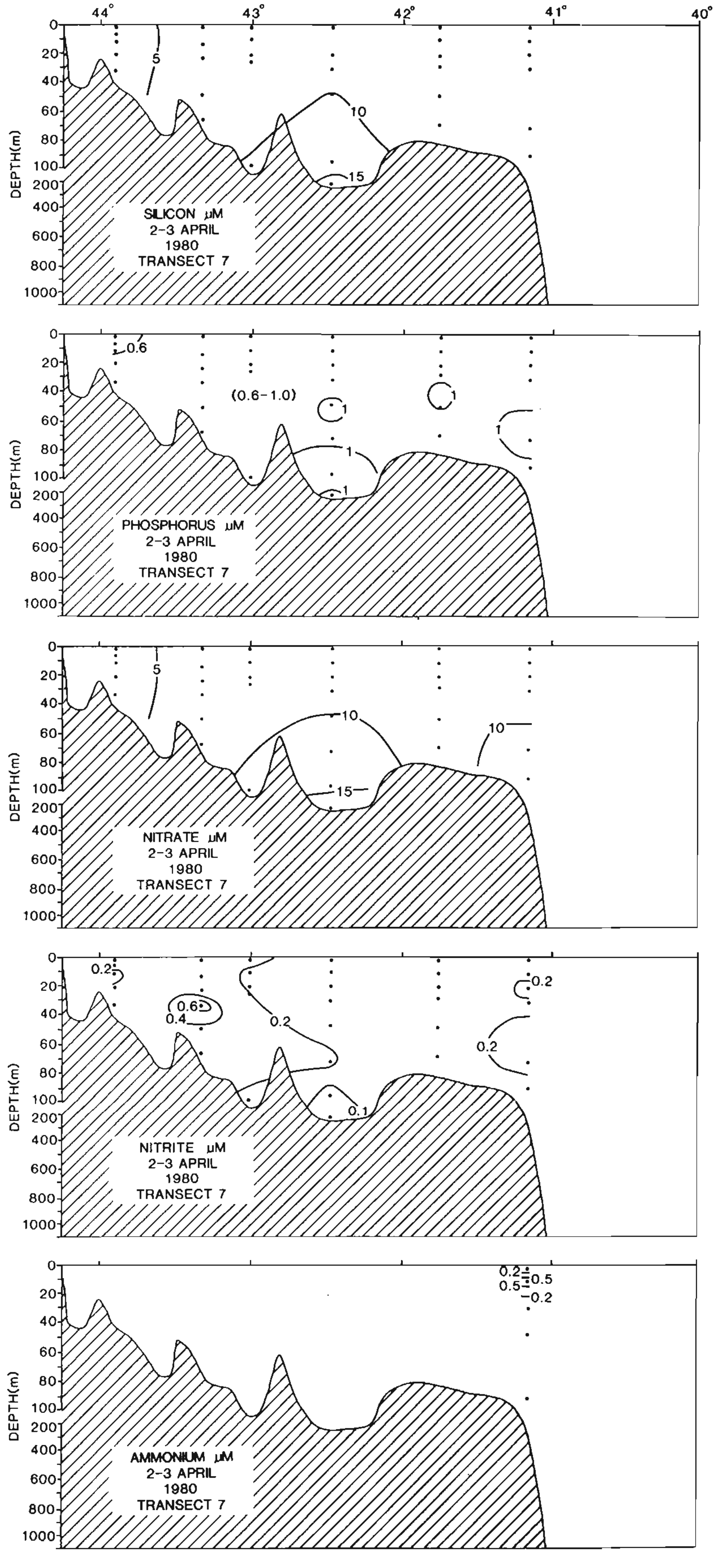

Figure 27.—Distribution of inorganic nutrients on Transect 7, 2-3 April 1980.

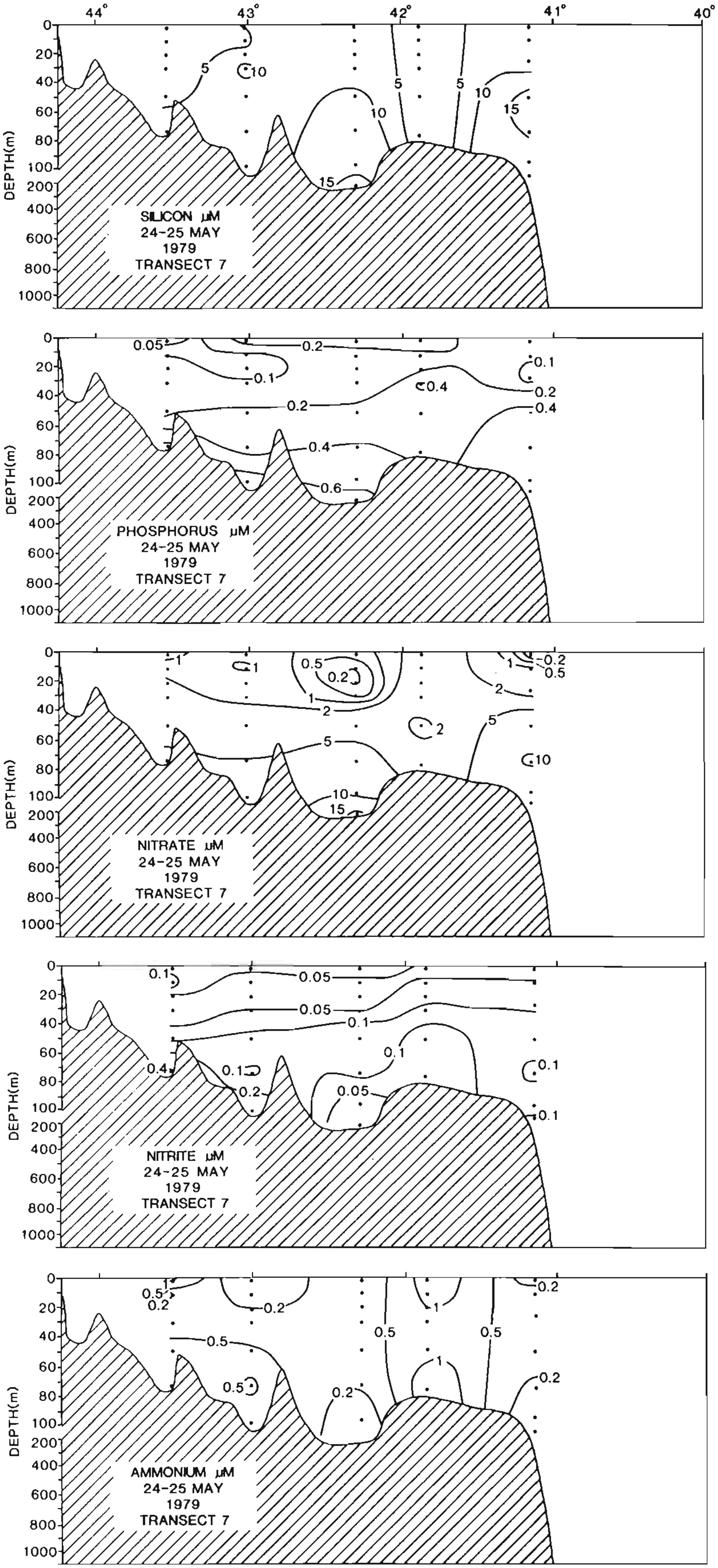

Figure 28.—Distribution of inorganic nutrients on Transect 7, 24-25 May 1979.

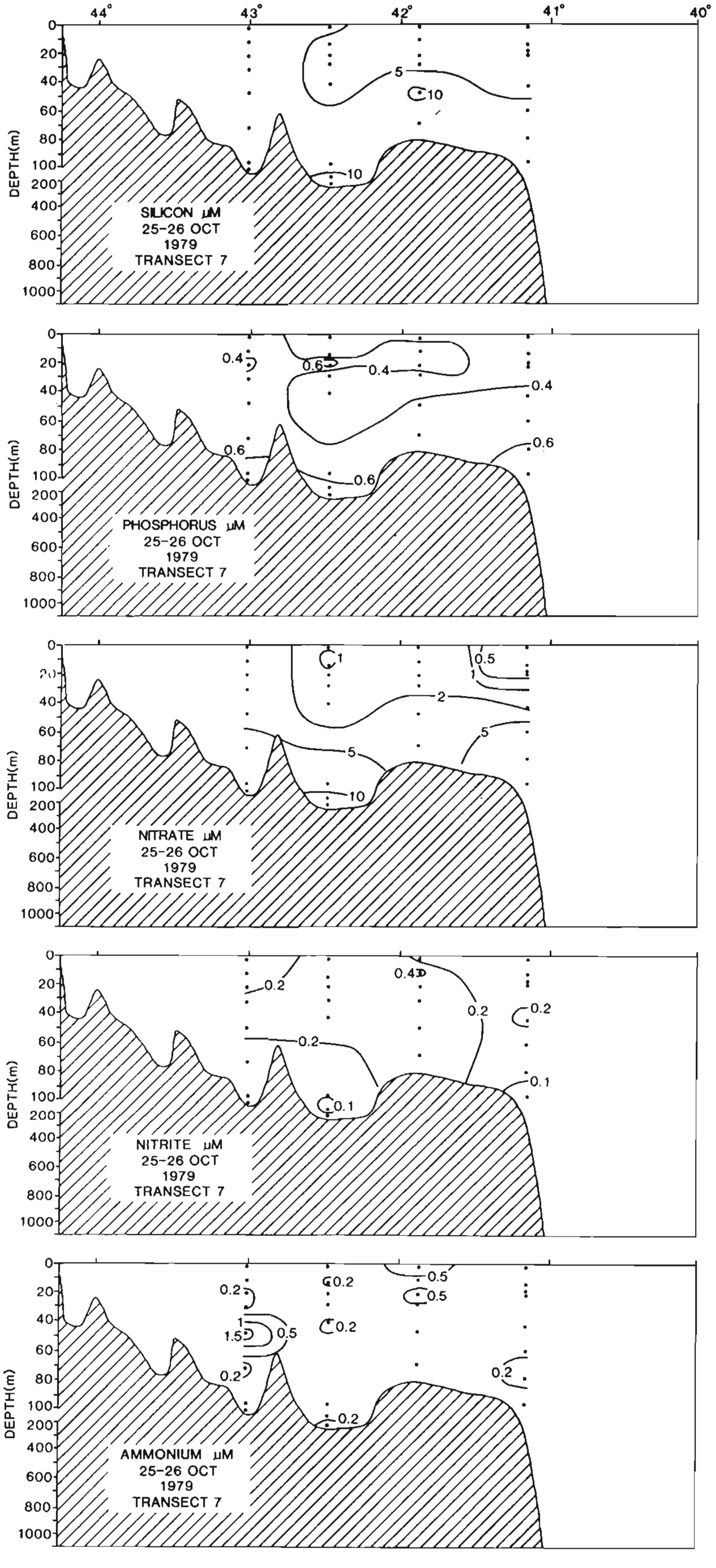

Figure 29.—Distribution of inorganic nutrients on Transect 7, 25-26 October 1979.

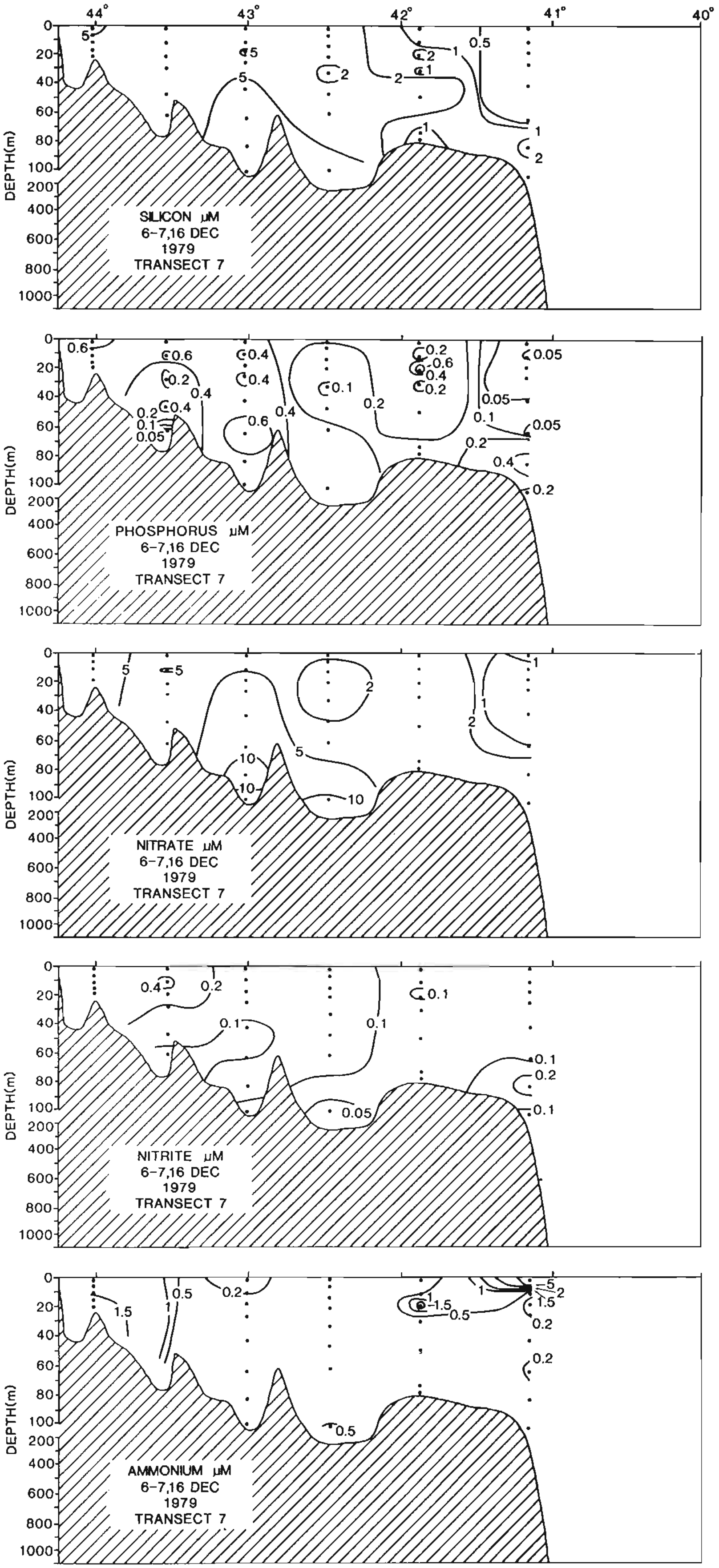

Figure 30.—Distribution of inorganic nutrients on Transect 7, 6-7, 16 December 1979.

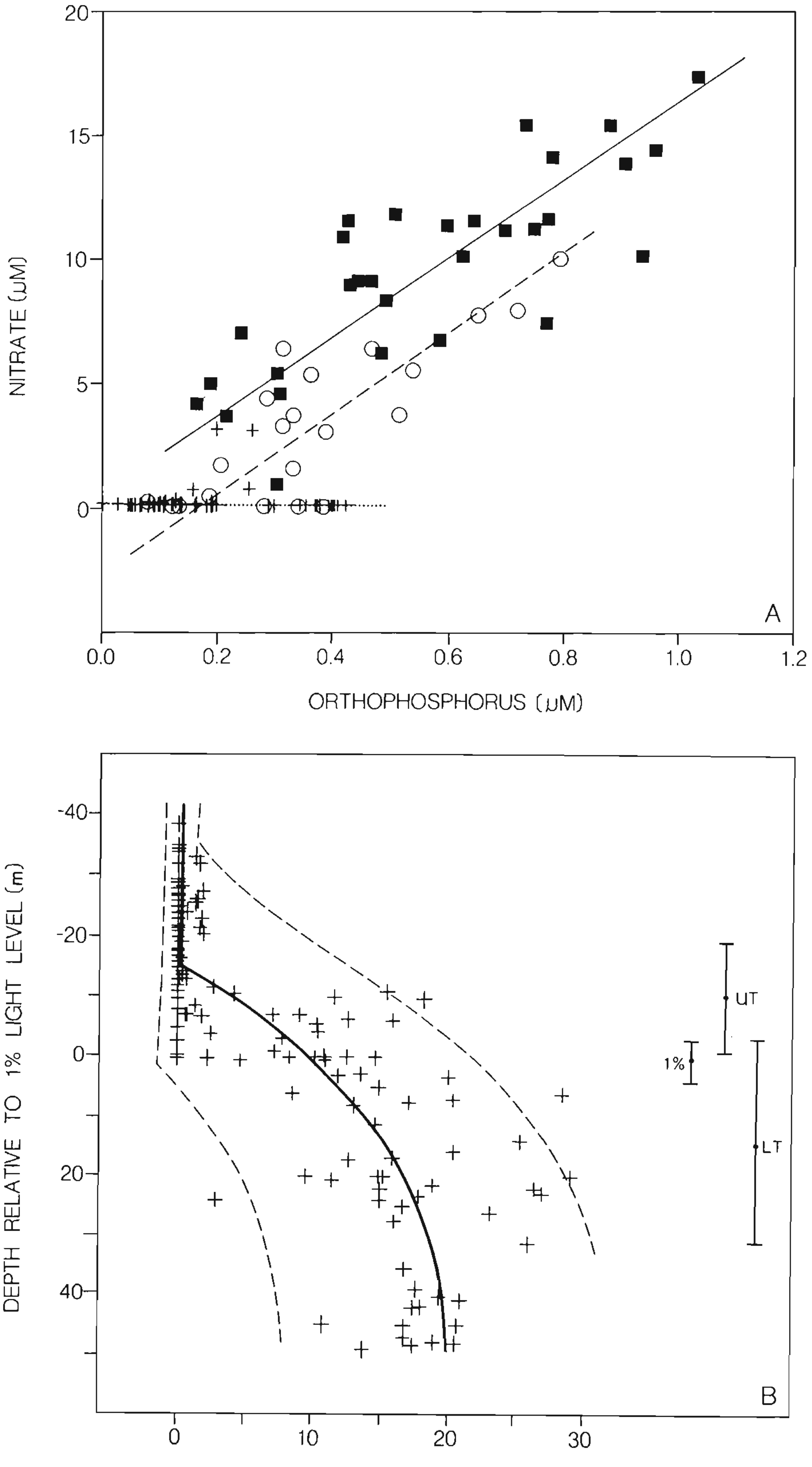

Figure 31.—Nitrate-orthophosphorus relationships in stratified areas, July to October 1979. A) Samples from 10 m above the 1% light level depth to the surface (+); the 1% light depth ± 5 m (circles); and from 10 to 45 m below the 1% light level depth (squares); lines fitted by functional regression (Ricker 1973; least $\Sigma\Delta X \cdot \Delta Y$). B) Two line segment third order polynomial regression fit of N/P versus depth relative to 1% light level depth (positive downward) with 95% confidence bands; means and 95% confidence intervals for 1% light level depth (1%) and upper (UT) and lower (LT) limits of the thermocline (n = 10 stations).

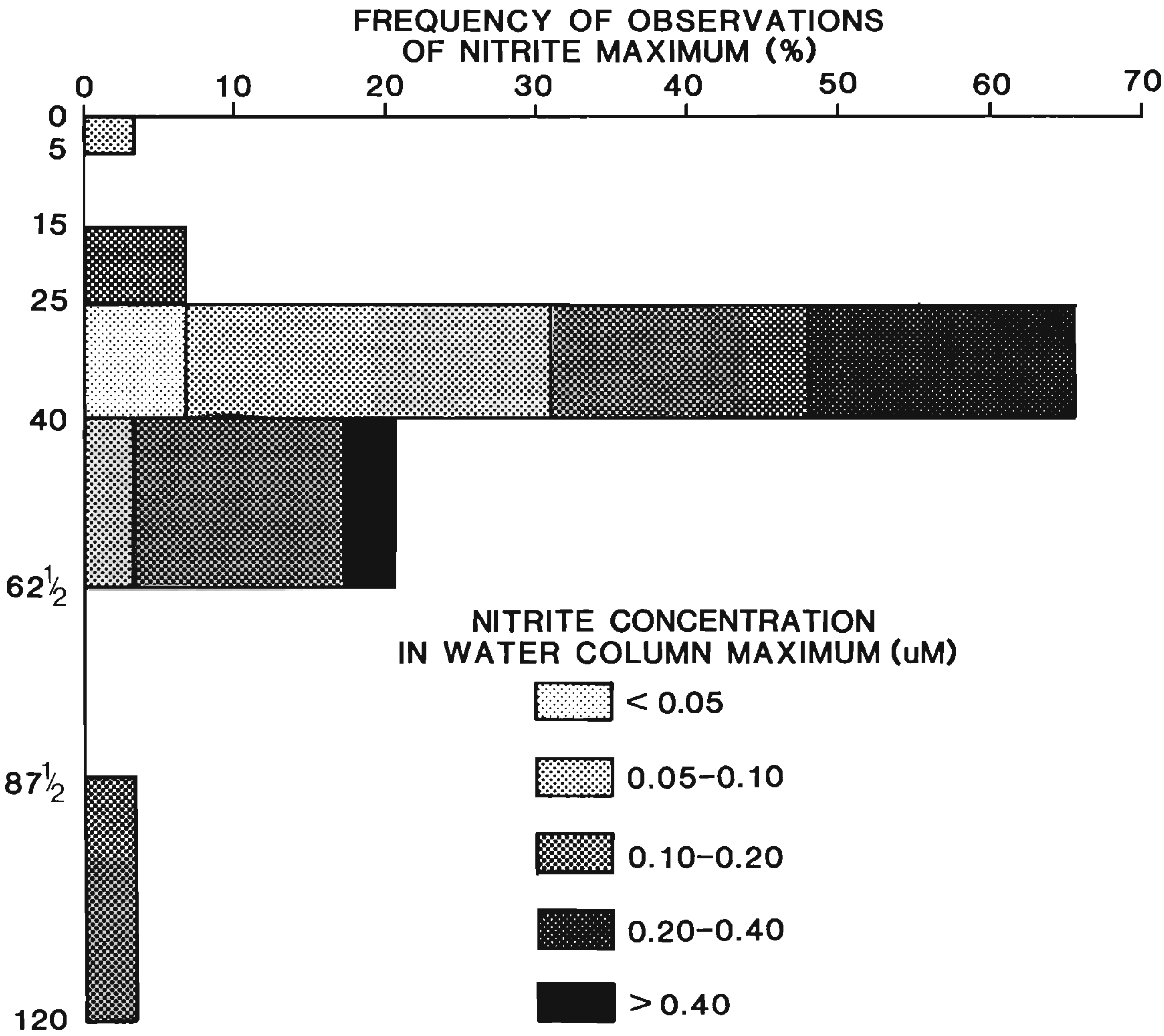

Figure 32.—Frequency with which the nitrite maximum at a station was found in a given depth interval and the concentration of that maximum for the Gulf of Maine, July-October 1979 at stations deeper than 120 m.