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Distribution of Particulate Organic Matter in the Southern East China Sea: Implications in Production and Transport

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ABSTRACT

Repeated surveys in October, 1992 and May, 1993 in the southern East China Sea showed a high abundance of particulate organic carbon in the upwelling area around the shelf break northeast of Taiwan. Particulate nitrogen was well correlated with particulate organic carbon with a $\Delta C/\Delta N$ atomic ratio of 6.3-6.7. The vertical distribution of the particulate organic carbon had a surface maximum at many stations. Such distribution was not directly related to phytoplankton biomass but controlled by the primary production rate which also showed an eminent maximum close to the surface. The POC residence time in the upper water column varied from 2 to19 days for different water types. For the coastal water and upwelling center, the residence time was calculated to be 3-8 days; for the nutrient-poor shelf and Kuroshio waters, 7-19 days. The sinking flux of particulate organic carbon at the bottom of the euphotic zone in the Kuroshio water was calculated from the standing stock and the particle residence time to be 3.3 mmol $C/m^2/d$, which represents 18% of the potential primary productivity; the sinking flux of particulate nitrogen 0.29 $mmol/m^2/d$. Beneath the Kuroshio current in the Okinawa Trough, we found patches of relatively high particulate organic carbon concentration at depths between 500 and 750 m on both cruises. This was the first evidence of the lateral transport of particulate organic carbon across the shelf break to the deep sea off northeastern Taiwan. Such a process may have been responsible for the enrichment of organic carbon in the sediments on the slope.

(Key words: Particulate organic carbon, Particulate nitrogen, East China Sea, Kuroshio, Primary productivity, Chlorophyll, Nutrients, Cross shelf transport)

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I. INTRODUCTION

The southern East China Sea which witnesses the interplay between the strong western boundary current, namely, the Kuroshio, and the wide continental shelf, is one of the most active regions in the oceans in terms of biogeochemical fluxes. A permanent upwelling area was found at the shelf break north of Taiwan (Fan, 1980; Liu, *et al.*, 1992a, b), but the nutrient-rich upwelling water was underlain with organic poor sediments (Lin *et al.*, 1992). On the other hand, a zone of high organic carbon content was discovered on the continental slope to the northeast of Taiwan (Lin *et al.*, 1992). This phenomenon suggests the production of particulate organic matter (POM) in the nutrient-rich shelf water followed by a loss of POM to the deep sea through lateral transport. However, no real direct observation has been reported for the POM distribution in this region to support such a conjecture.

This study presents observations of high particulate organic carbon (POC) and particulate nitrogen (PN) concentrations surrounding the upwelling center, which suggests an intense production of POM. The potential primary productivity which was calculated from the Chl. *a* distribution gives insight into the biogenic particle dynamics in the euphotic zone. It also shows a patchy distribution of high POC in the intermediate water above the continental slope, which suggests an active transport of organic matter to the deep sea.

Although the continental shelves represent less than 20% of the area of world oceans, the total primary productivity could be as important as the ocean interior (Walsh, 1991). The production of POM in the marginal seas is important not only for the assessment of marine resources but also for the understanding of the marine carbon cycle. The preferential deposition of organic carbon on the continental slope appears to be a widespread phenomenon. In the continental margin off the coast of southeast China in the northern South China Sea, a relatively high organic carbon content has also been observed in the sediments on the lower slope (Lai and Liu, 1994). A similar distribution was observed on the continental slope off the eastern coast of the U.S.A. (Walsh *et al.*, 1985). Therefore, the burial of organic carbon on the continental slope represents an important sink of carbon in the ocean. The processes related to this carbon sink warrant a careful investigation as recommended by the Joint Global Ocean Flux Study (JGOFS) and Land-Ocean Interaction in the Coastal Zone (LOICZ), two core projects of the International Geosphere-Biosphere Program (IGBP) (Chen *et al.*, 1992; IGBP, 1992; JGOFS, 1994).

2. MATERIALS AND METHODS

The study area was in the southern East China Sea north of Taiwan (Figure 1). Sampling was carried out on two cruises on the research vessel *Ocean Researcher I*: Cruise 331B during October 4-9, 1992, and Cruise 352D during May 5-9, 1993. The two of these were the respective last cruises of the two intensive observation periods (IOPs) of the KEEP program.

A CTD-Rosette assembly with Niskin or Go-flo bottles was used to obtain temperature and salinity profiles and seawater samples. The CTD unit was a SeaBird SBE9/11 model with a Sea-Tech fluorometer. Samples for dissolved oxygen, salinity and nutrient analyses were collected from hydrocasts. The oxygen samples were pickled immediately after collection following Carpenter's (1965) recommendation. The salinity samples were stored in 100 ml glass bottles with Poly-seal caps.

Particulate matter was collected from two liters of sea water samples which were obtained with Niskin or Go-flo bottles and stored in calibrated opaque PVC bottles. The volume

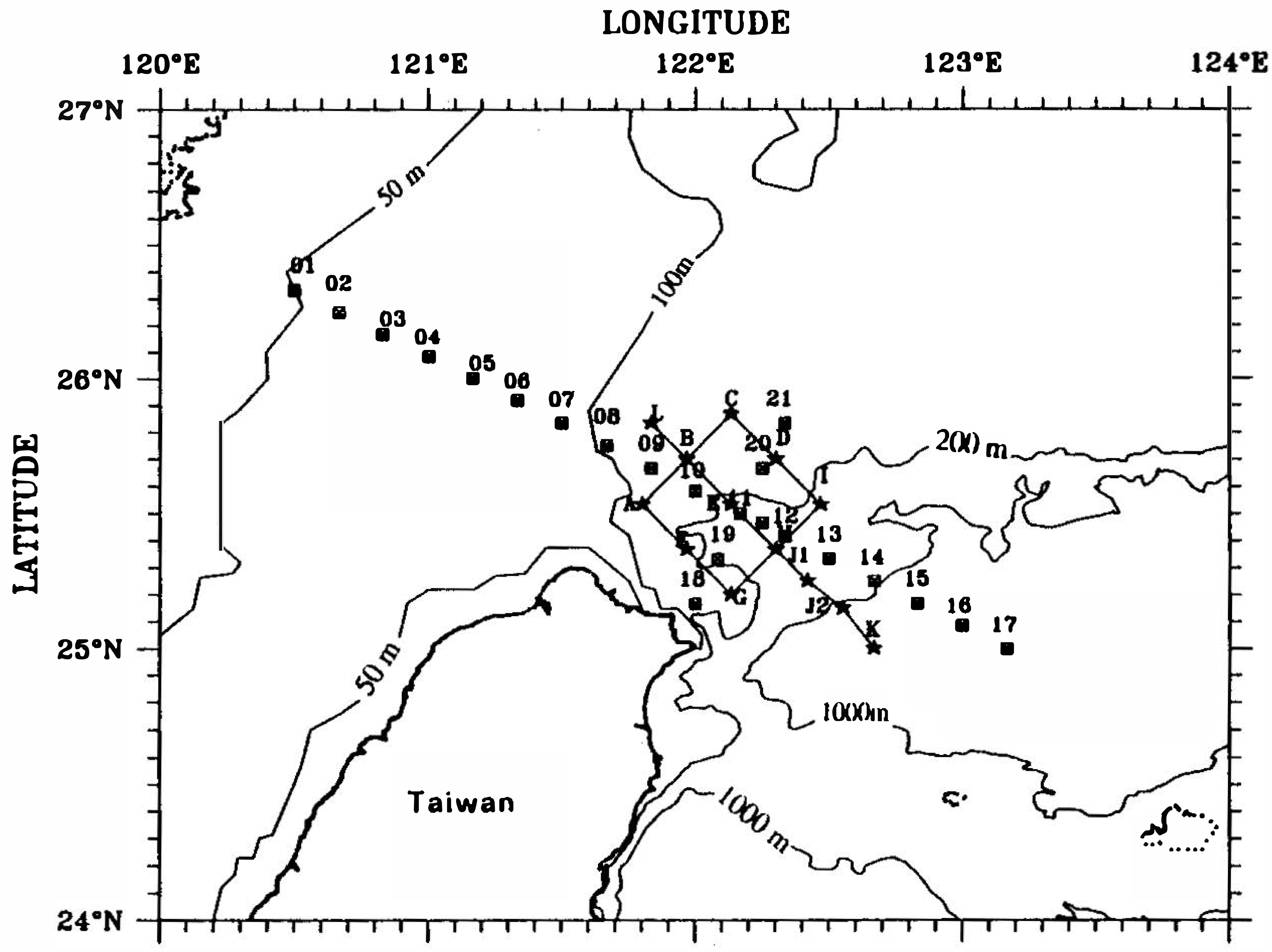


Fig. 1. The sampling stations in this study. Stations from Cruise 331B on Ocean Researcher I during October 4-9, 1992 are indicated by stars, and those from Cruise 352D during May 5-9, 1993 are indicated by squares. Station 11A, which is located midway between Stations 11 and 12, is not labeled to avoid an overlapping of labels.

of each water sample was measured before filtration with the water depth in the bottle measured with a dipping stick. The precision was better than $\pm 2\%$. The seawater was filtered through a Whatman 25 mm GF/F glass fiber filter, which was pre-heated at 450°C to reduce background carbon. The filters were frozen immediately and stored in a freezer. Returned to the laboratory, the samples were dried in a freeze-dryer.

A Heraeus CHN Rapid Elemental Analyzer was used to analyze the total organic carbon (TOC) content and total nitrogen content in the filtered particulate matter. Carbonate carbon was removed by adding a few drops of 1N HCl solution to the particulate matter on the filter and drying it at 50°C in an oven. The blank values, which were determined for each batch of samples and deducted from the raw data, were measured by analyzing GF/F filters wetted with seawater. The blank values were 1.2-1.4 μmole for carbon and 0.8-1.0 μmole for nitrogen. The precision of the measurements was determined by analyzing five replica samples obtained at the same depth. The standard deviations of the replica samples were ± 0.2 μM for the POC analysis and ± 0.13 μM for the PN analysis.

The dissolved oxygen concentration was determined by measuring the absorbance of the total iodine in the pickled samples after acidification (Pai *et al.*, 1993). The CTD data were checked against the manually determined salinity. When returned to the home laboratory, the frozen samples for the nutrient analyses were defrosted under running water, and the nitrate was analyzed with a flow injection analyzer (Liu *et al.*, 1992b; Gong, 1992).

The chlorophyll *a* concentration was calculated from the readings of the fluorometer which was attached to the CTD. The conversion was based upon the empirical relationship (Gong *et al.*, 1993; Gong, personal communication):

$$[\text{Chl } a](\mu g/\text{L}) = 0.527 * F - 0.051 \quad (1)$$

where F is the fluorometer reading with the scaling factor set to 5.0. The error is within ± 0.1 μg/L.

3. RESULTS

The sampling stations on Cruise 352D encompassed the inner shelf, the outer shelf and the Okinawa Trough, whereas those on Cruise 331B covered only the region around the shelf break and slope. The results of Cruise 352D are presented in greater detail because the wider sampling area provided samples of various types of waters at different trophic conditions. The results from Cruise 331B are shown as additional evidence. The hydrographic conditions are described and, then, the distribution of POC are presented with reference to the hydrographic backdrop.

The hydrography observed on Cruise 352D represented a typical condition frequently observed throughout the year (Liu *et al.*, 1992b). Current meter observation indicates that the Kuroshio intruded onto the continental shelf north of Taiwan before mid-April and the intrusion ceased at the time of the cruise (Chuang and Liang, 1994). The temperature section (Figure 2A) showed a well developed upwelling dome at the shelf break. A sea surface temperature minimum occurred in the vicinity around Stations 9 and 10, which signaled the upwelling center. The upwelled water had a rather uniform salinity between 34.6 and 34.7 psu at the shelf break (Figure 2B).

On the seaward side of the upwelled water, the subsurface isotherms shoaled shoreward at Stations 13 and 14 (Figure 2A). The horizontal temperature gradient reflects the geostrophic balance across the strong flow of the Kuroshio. A subsurface saline tongue of 34.8 psu, which characterized the salinity maximum of the Subtropical Water (Nitani, 1972), coincided with the shoaling isotherms. On the landward side, a pool of warm saline water alternately existed with a fresher cooler water near the coast.

The T-S diagram (Figure 3) showed that the water at Station 17 was the typical Kuroshio water originating from the West Philippine Sea (Nitani, 1972), whereas the shelf waters were much more variable. They represented mixtures of three major water types, namely, the Kuroshio surface water, the upwelled Kuroshio subsurface water and the coastal water. The water at Station 2 with a uniform temperature but a wide salinity range was designated the Northern Taiwan Strait (NTS) water by Chern and Wang (1989) representing a mixture between the China Coastal water and the outer shelf water (Liu *et al.*, 1992a). Station 4 represented a transitional water. The water at Stations 8 to 12 represented the upwelled Kuroshio subsurface water which had a uniform salinity but a wide temperature range. The water at Station 6 had a rather uniform temperature and salinity, which were similar to the characteristics of the Kuroshio surface water. This water which was well mixed may have been left over from the previous episode of Kuroshio intrusion in April 1993 (Chuang and Liang, 1994) or transported northward from the Taiwan Strait during the relaxation of the northeast monsoon (Wang and Chern, 1989). The waters at Stations 13 and 14 were the slope water which was characterized by isopycnal mixing between the Kuroshio water and the shelf water (Wong *et al.*, 1991).

Within the upwelling dome, oxygen had a low degree of saturation (Figure 4A). The surface water at Station 10 was undersaturated with oxygen, which must have resulted from the rapid replacement of surface water with the upwelled subsurface water. The nitrate distribution (Figure 4B) resembled the degree of oxygen saturation. The 100% oxygen saturation isopleth coincided with the 0.5 μM nitrate isopleth, which is not shown. These findings were consistent with previous observations (Liu *et al.*, 1992 a, b). The well-mixed water in the mid-shelf at Station 6 was almost devoid of any nitrate. The coastal water in the inner shelf had low but significant concentration of nitrate, which may have originated from riverine sources.

The chlorophyll *a* distribution derived from fluorometry (Figure 4C) showed that phytoplankton clustered on both sides of the upwelling center, while the upwelling center was less abundant in chlorophyll *a* than the water around it. The highest concentration of chlorophyll *a* (0.8 μg/L) was found at Station 9. The vertical chlorophyll *a* maximum occurred at

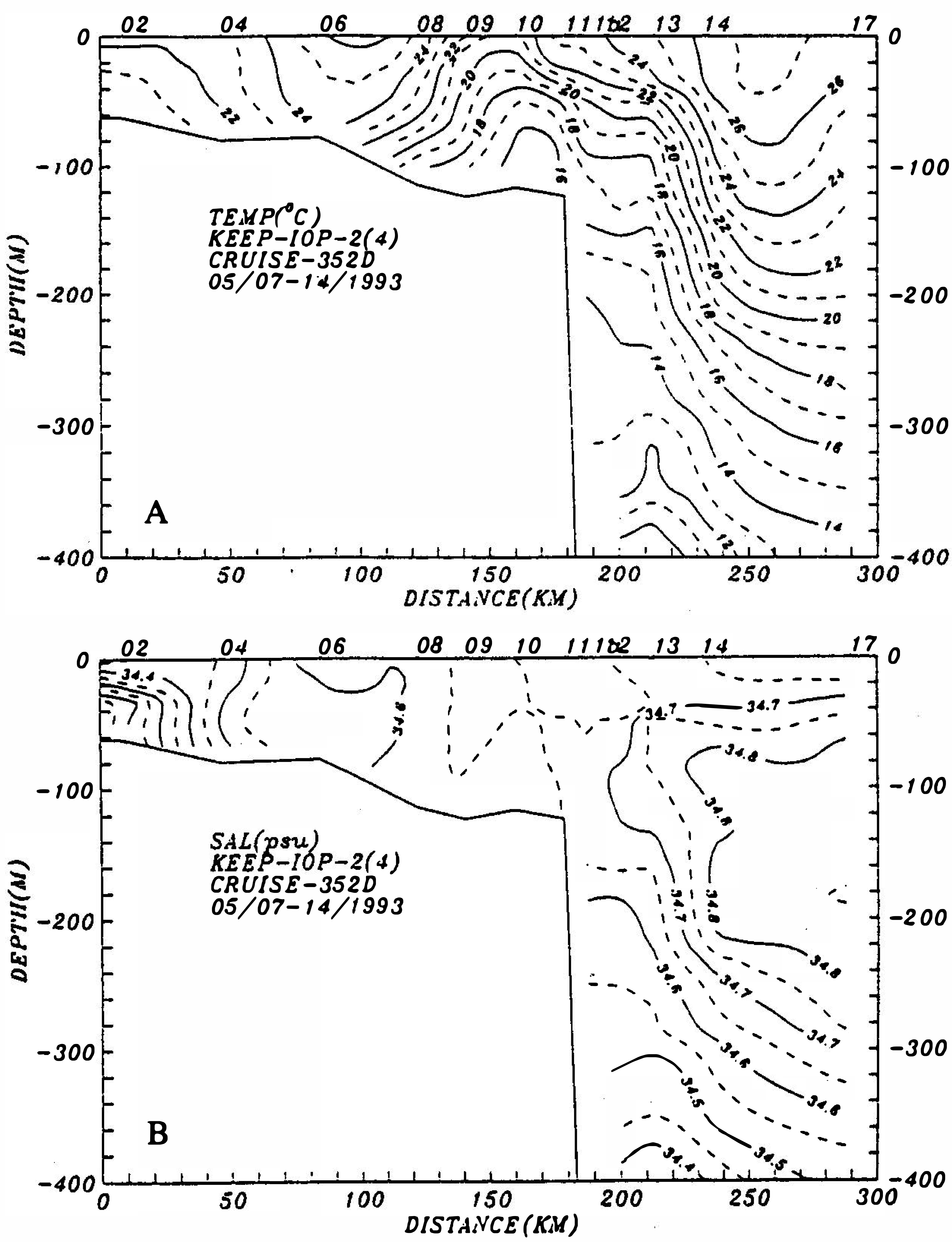


Fig. 2. The hydrographic sections for the upper 400 m obtained with CTD along the long transect on Cruise 352D. The localities of the stations are shown on top of the plots. (A) Temperature (°C), (B) Salinity (psu).

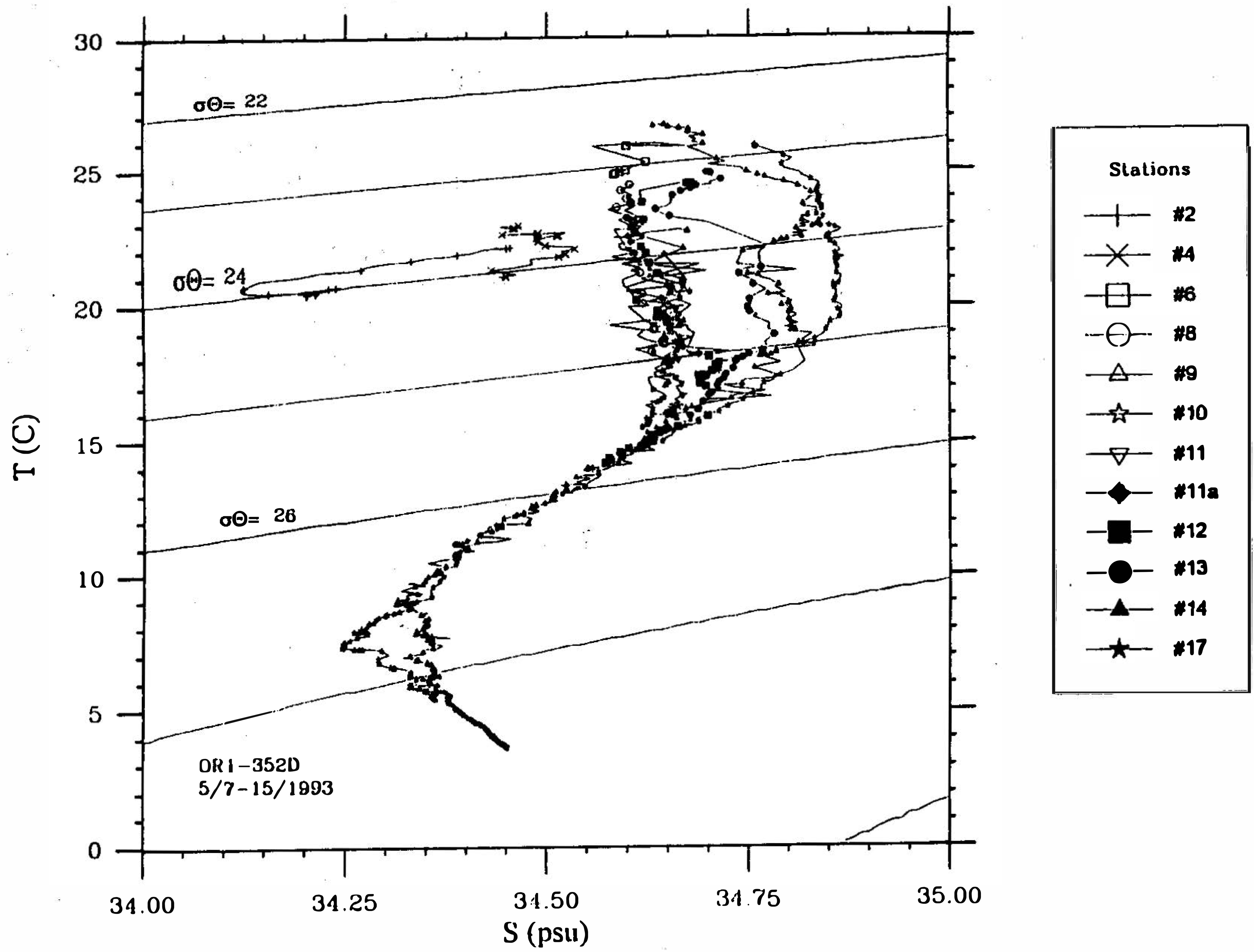
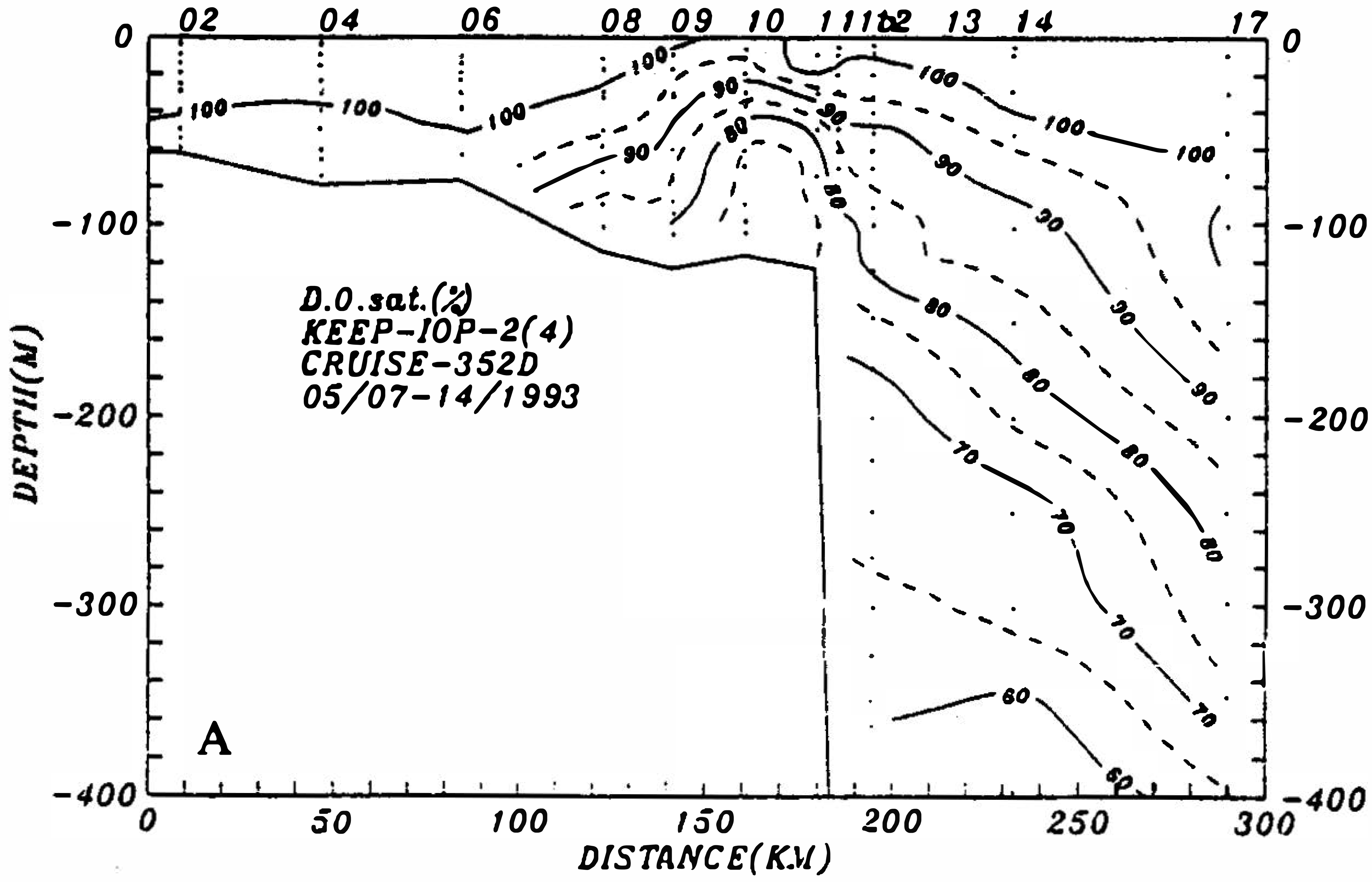


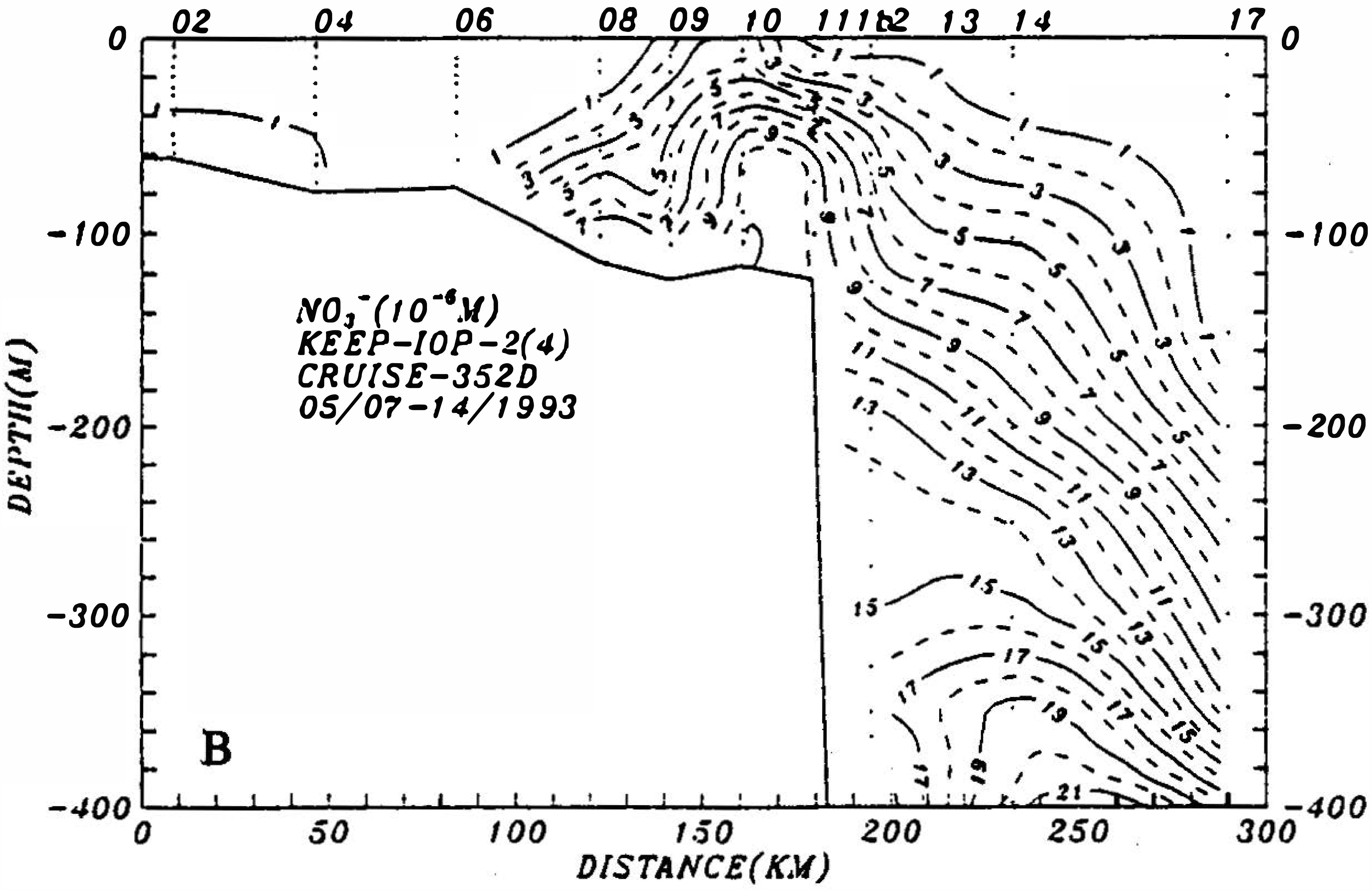
Fig. 3. The T-S diagram for Stations 2-17 on Cruise 352D.

about 40 m in the middle and outer shelf and extended seaward with gradual deepening. At Station 17, the chlorophyll *a* maximum (0.35 $\mu g/L$) was at 80 m, just above the nitracline. In contrast to other stations, the most landward station showed a chlorophyll *a* maximum (0.65 $\mu g/L$) very close to the surface. Shoaling of the chlorophyll *a* maximum in the coastal water reflected the shallowness (20 m) of the euphotic zone (Shiah *et al.*, 1995), which was probably caused by the turbidity of the water that limited the penetration of light.

The distribution of POC is shown in two sections of different depth ranges (Figure 5). The shallow section (Figure 5A) shows the POC variation in the upper layer from 0 to 200 m with a contour interval of 1 μM. The deep section shows the POC distribution in the depth range of 100-1000 m with a contour interval of 0.5 μM.

The distribution of POC in the upper 200 m showed both similarities to and differences from the chlorophyll *a* distribution. The major difference lied in the vertical distribution. Instead of a subsurface maximum shown by most chlorophyll *a* profiles, the POC maximum always occurred in the surface layer. Besides, a bottom maximum (5 μM) was observed in the coastal waters attributable to sediment resuspension. However, the lateral regimes of POC distribution were quite similar to those of chlorophyll *a*. A high abundance of POC (up to 20 μM) occurred in the upwelled water where a high primary production was expected (Shiah *et al.*, 1995). The coastal water also had a rich abundance of POC (up to 14 μM). Between the two waters, a POC-poor water corresponded to the nutrient-devoid low-chlorophyll *a*





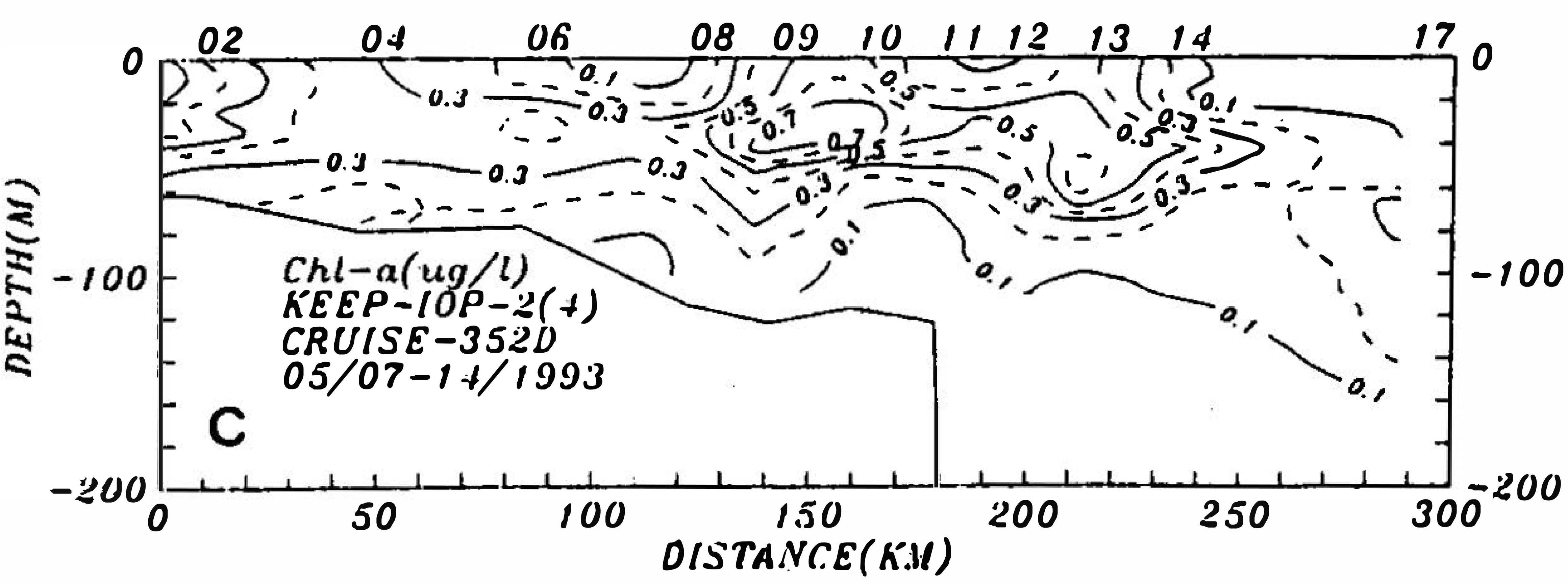


Fig. 4. Vertical distribution of some chemical parameters along the long transect observed on Cruise 352D. (A) Degree of oxygen saturation (%), (B) Nitrate (μM), and (C) Chlorophyll *a* (μg/L).

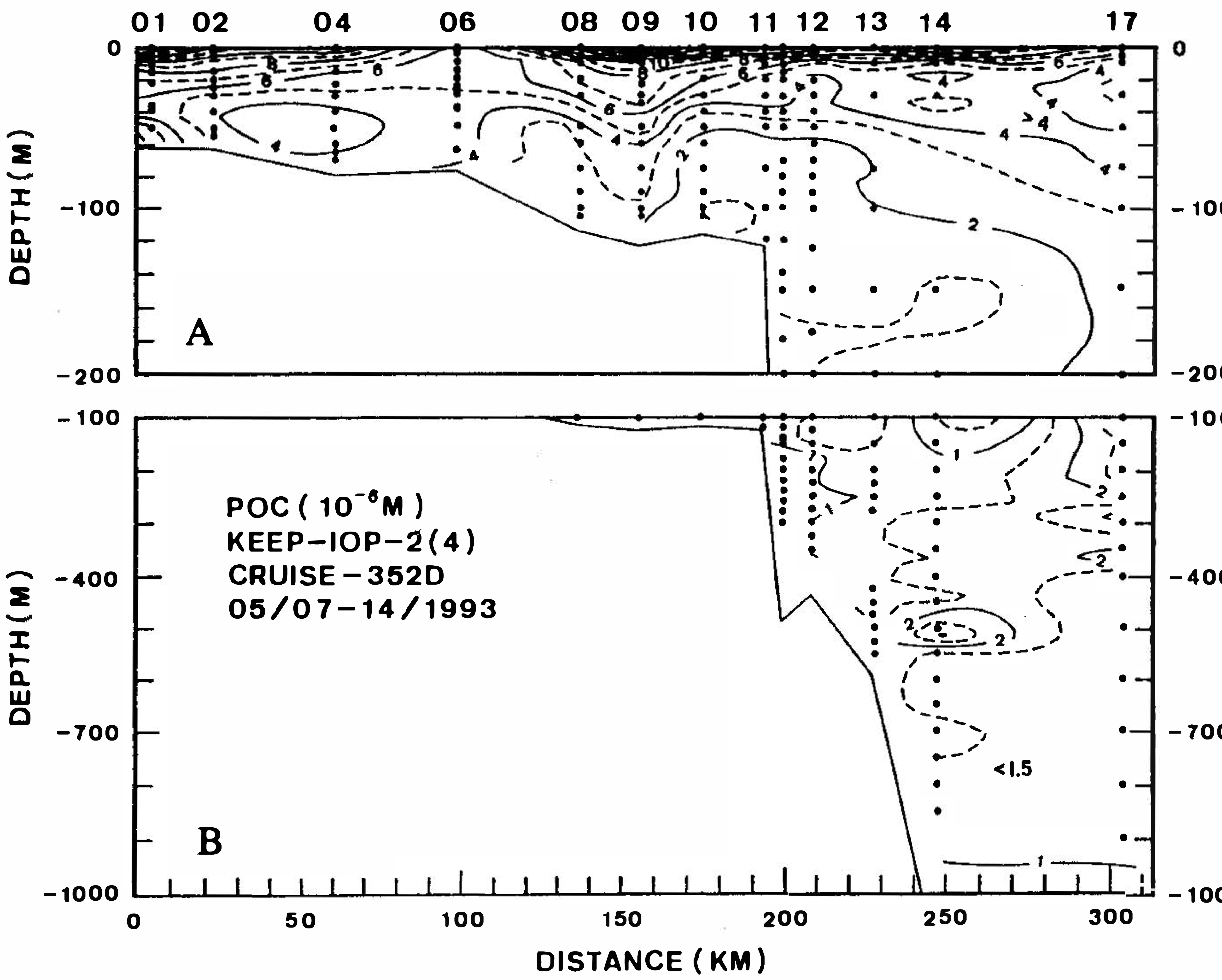


Fig. 5. The vertical distribution of POC along the long transect of Cruise 352D. (A) Section for the upper 200 m. The contour interval is 1 μM. (B) Section for depths from 100 to 1000 m. The contour interval is 0.5 μM.

water. In the Okinawa Trough, the surface POC maximum existed as an extension from the shelf, but a subsurface POC maximum occurred at the depth of 80 m corresponding to the subsurface chlorophyll *a* maximum.

Below 100 m, the POC concentration dropped to below 2 μM at most stations. The lowest POC concentration (<1 μM) in the intermediate water between depths of 200 and 500 m was found near the continental slope where the Kuroshio upwelling took place as indicated by the doming isotherms (Figure 2A). This is consistent with the notion that the upwelling water comes from the Kuroshio intermediate water (Liu *et al.*, 1992a) which is expected to be POC poor due to the oligotrophic condition in the overlying water. Surprisingly, a mid-depth POC maximum (3.2- 3.7μM) was observed at 500-525 m at both Stations 13 and 14. A lesser but detectable POC peak (1.3-1.7 μM) was observed between 650 and 750 m at Station 14. At Station 17 the POC concentrations in the same depth range (500-800 m) were all less than 1.2 μM.

On Cruise 352D, a short transect (Stations 18~21) normal to the long transect near the shelf break was also surveyed. As expected, the temperature contour section (Figure 6A) showed a doming structure in the along-shelf direction completing the three-dimensional structure of the upwelling dome. The upwelling water was low in POC (Figure 6B). The strongest outcropping of subsurface water was at Station 20 on this transect as indicated by the lowest sea surface temperature. The highest POC concentration (14 μM) was found at Station 11 on the flank of the strongest upwelling. The strong horizontal thermal gradient

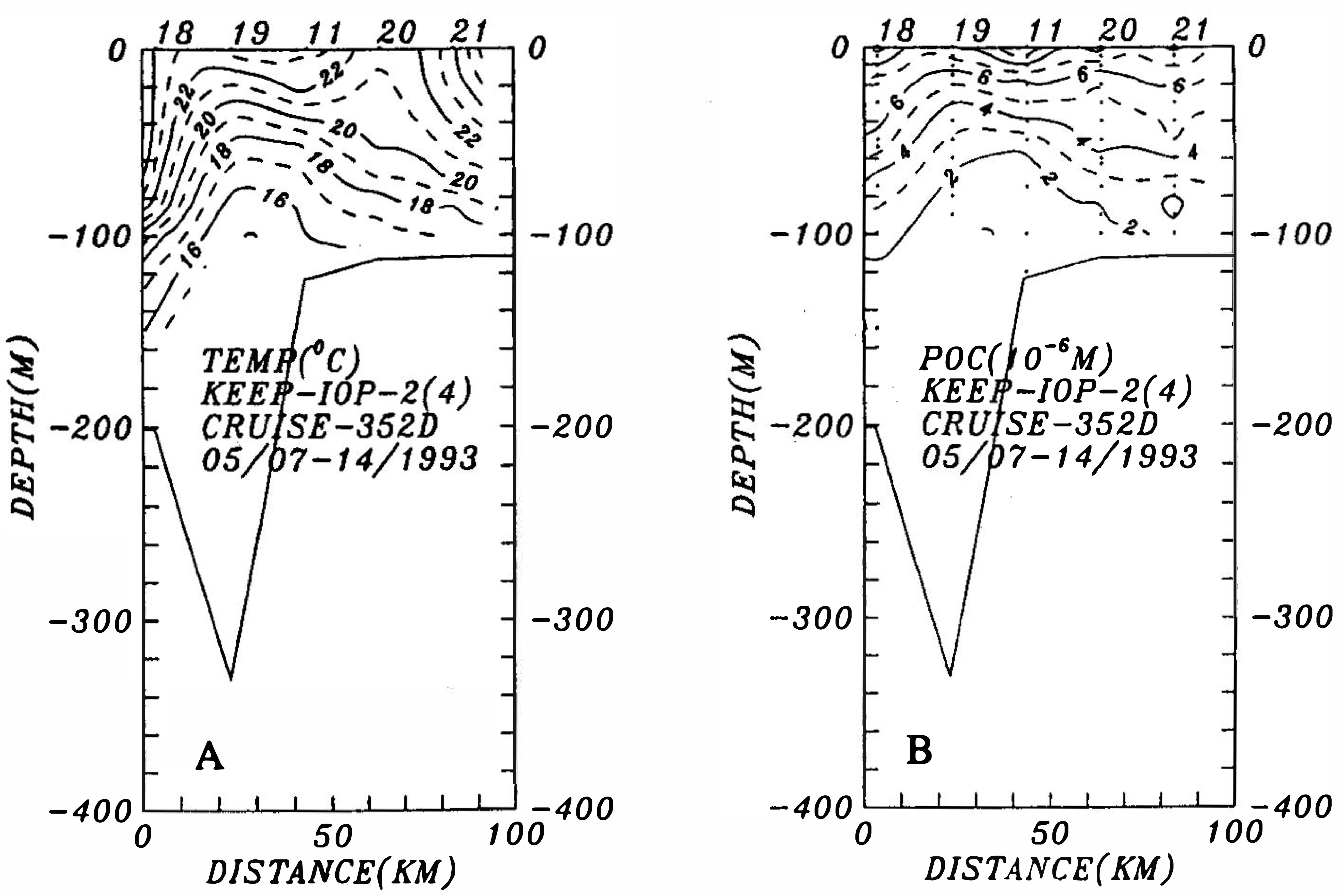


Fig. 6. Section contours for temperature (A) and POC (B) along the short transect of Cruise 352D.

on the left (southwest) side of the section suggested a current flowing against the upwelling water similar to that observed by Wang and Chern (1990). This current may be an important outflow of the shelf water. The surface water at Station 18 had quite a high concentration of POC (11 μM), which may represent an important POC transport from the shelf to the Kuroshio.

On Cruise 331B, the temperature section along the long transect (Figure 7) showed a surface temperature minimum at the shelf break, characterizing the upwelling center. However, the isotherms below 50 m were rather flat in the vicinity of the shelf break. There was no such doming of the isotherms in the subsurface water as that observed on Cruise 352D, suggesting weak upwelling. The strong flow of the Kuroshio was indicated by the tilting of the isotherms at Stations J2 and K.

The distribution of POC in the upper 200 m (Figure 8A) showed high abundance of POC at the shelf break. Unlike that observed on Cruise 352D, the maximum POC concentration (13 μM) along the long transect was found at the upwelling center, Station E, rather than on the flank of the upwelling center. In the Kuroshio, the POC distribution showed a surface maximum and dropped quickly to less than 5 μM below 10 m. The 5 μM isopleth drew a distinctive boundary between the upwelled water and the Kuroshio water in the upper 100 m beneath the surface layer.

The distribution of POC in the intermediate water between depths of 200 and 500 m (Figure 8B) observed on Cruise 331B was quite different from that observed on Cruise 352D. The POC concentration in the water adjacent to the continental slope was the highest rather than the lowest and decreased with distance from the slope. The isopleth of 1.5 μM separated the POC rich water hugging to the slope from the POC poor water beneath the Kuroshio current. On the other hand, a mid-depth maximum of POC in the deep water was also observed on Cruise 331B. The POC concentration reached 1.5-2.0 μM at depths of

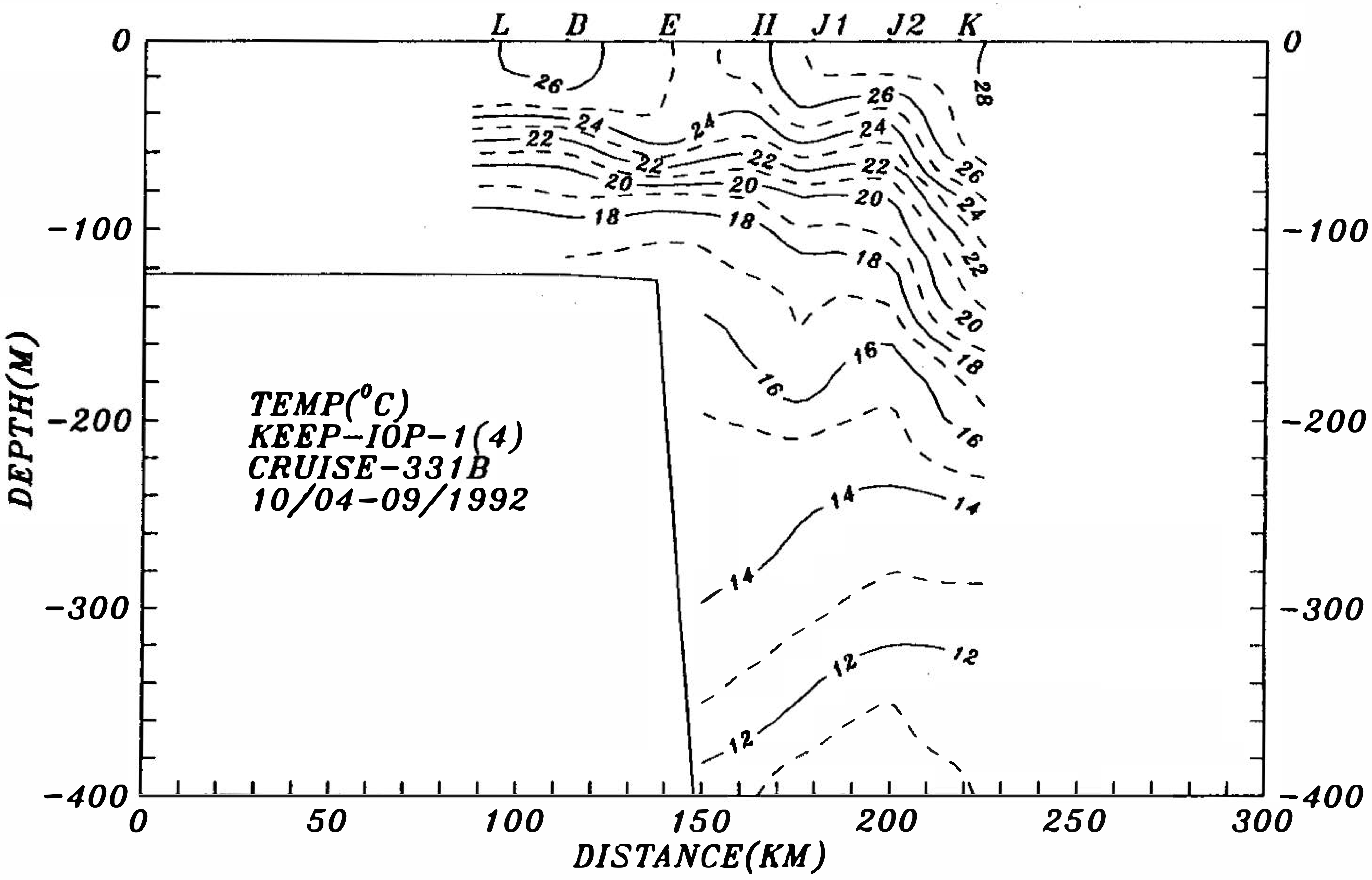


Fig. 7. The temperature section for the upper 400 m along the long transect of Cruise 331B.

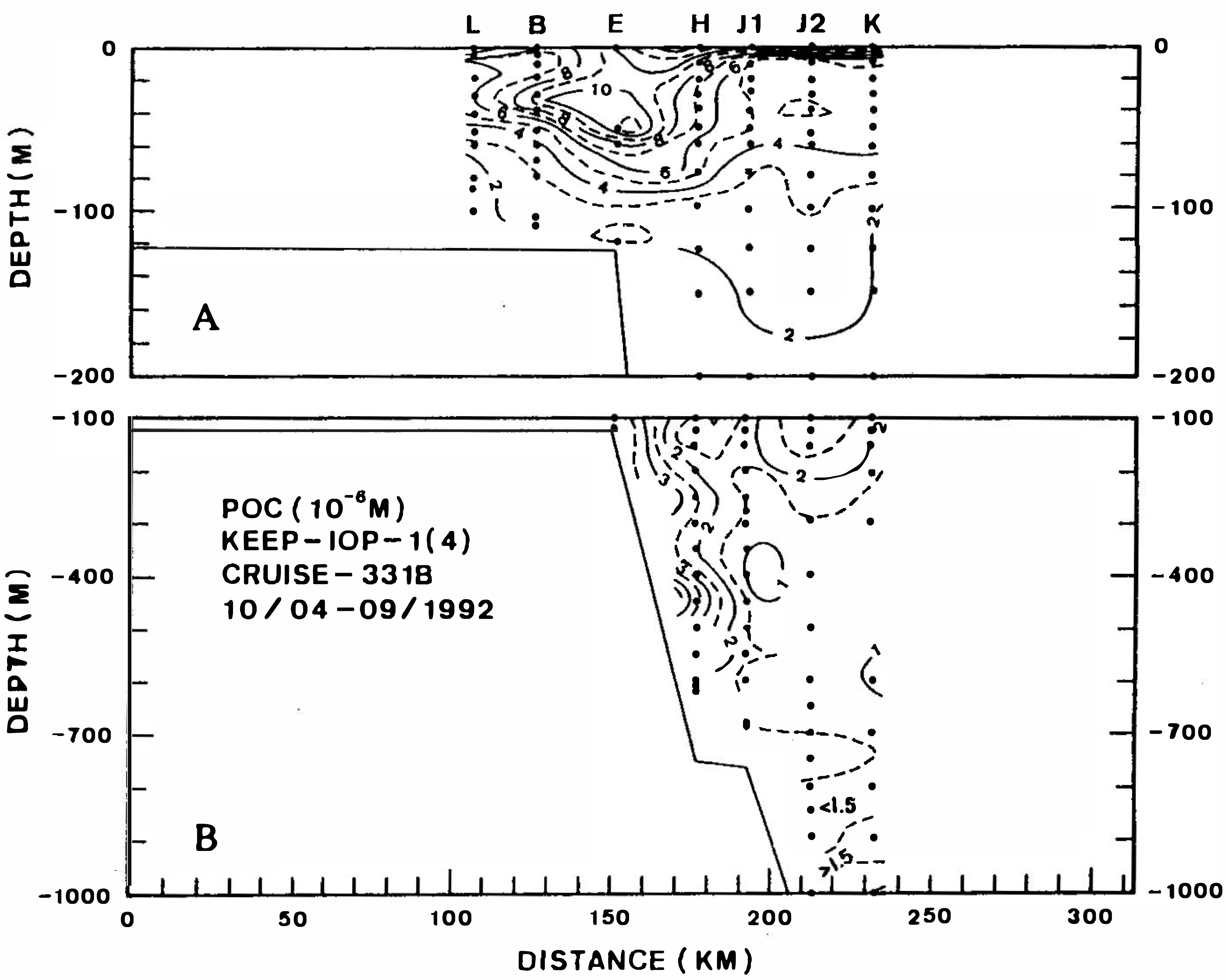


Fig. 8. The same as Fig. 5 except for Cruise 331B.

700-750 m at Station J2. This POC peak was at almost the same depth as and in a similar location to that observed on Cruise 352D. This coincidence strongly points to the fact that this phenomenon was not an artifact.

The distribution of particulate nitrogen (PN) resembled that of POC as expected. The correlation between POC and PN was very good (Figure 9). The correlation coefficients (R^2) were better than 0.89. The slopes of the linear regression of PN against POC were 0.157 and 0.150 for the two cruises, corresponding to $\Delta C/\Delta N$ atomic ratios of 6.37 and 6.67. These ratios were very close to the Redfield ratio of 6.63 (Redfield *et al.*, 1963). This agreement lends reliability to the analysis in this study. The relationship between POC and PN also provided a means to detect carbon contamination in the samples which may have resulted from the oil released by the ship. The contaminant was usually high in carbon but low in nitrogen.

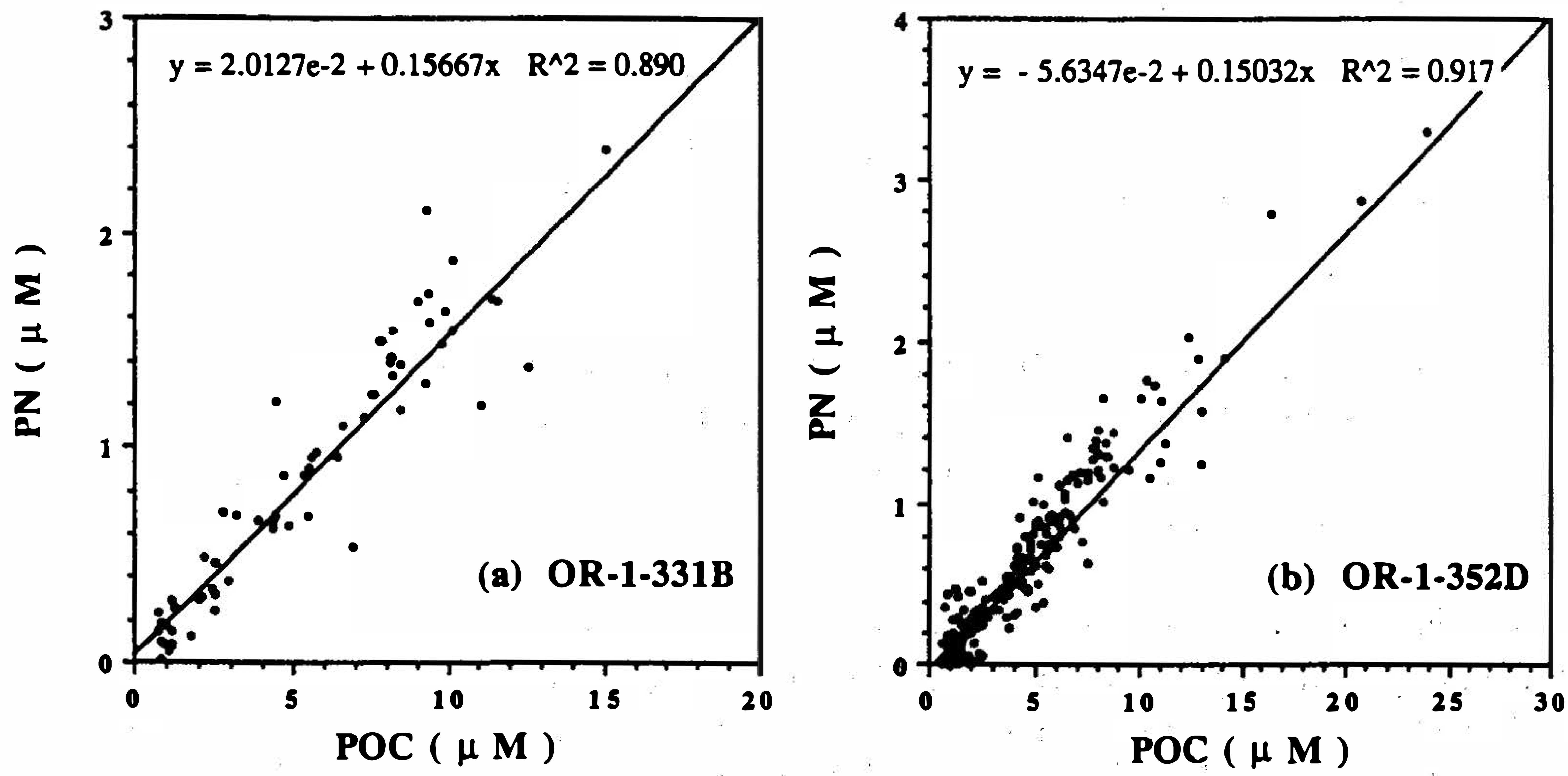


Fig. 9. The relationship between POC and PN. (a) Cruise 331B, (b) Cruise 352D.

4. DISCUSSION

4.1 Particulate Organic Matter in the Upper Water Column

Particulate organic matter was highly enriched in the upper water column, but it diminished rapidly with depth. Within the top 100 m, the POC concentration varied by a factor of 3 to 5, while the lateral variation over 300 km was only within a factor of 2 to 3. The upwelling region at Stations 8-14 is used here as an example to find out the controlling factors for the vertical variation of POC.

The POC concentrations observed in the upper 100 m at all stations in the upwelling region on Cruise 352D followed a decreasing trend with depth (Figure 10a). The distribution was well fitted (Figure 10) with an expression as follows:

$$\text{POC}(\mu\text{M}) = 12.7 - 5.6 * log(Z) \quad (2)$$

where Z is the depth (m) which must be greater than or equal to 1. The correlation coefficient (R^2) is 0.77. However, the mean vertical distribution of chlorophyll *a* was quite different (Figure 10b). Obviously, the concentration of POC was not directly related to the standing stock of phytoplankton.

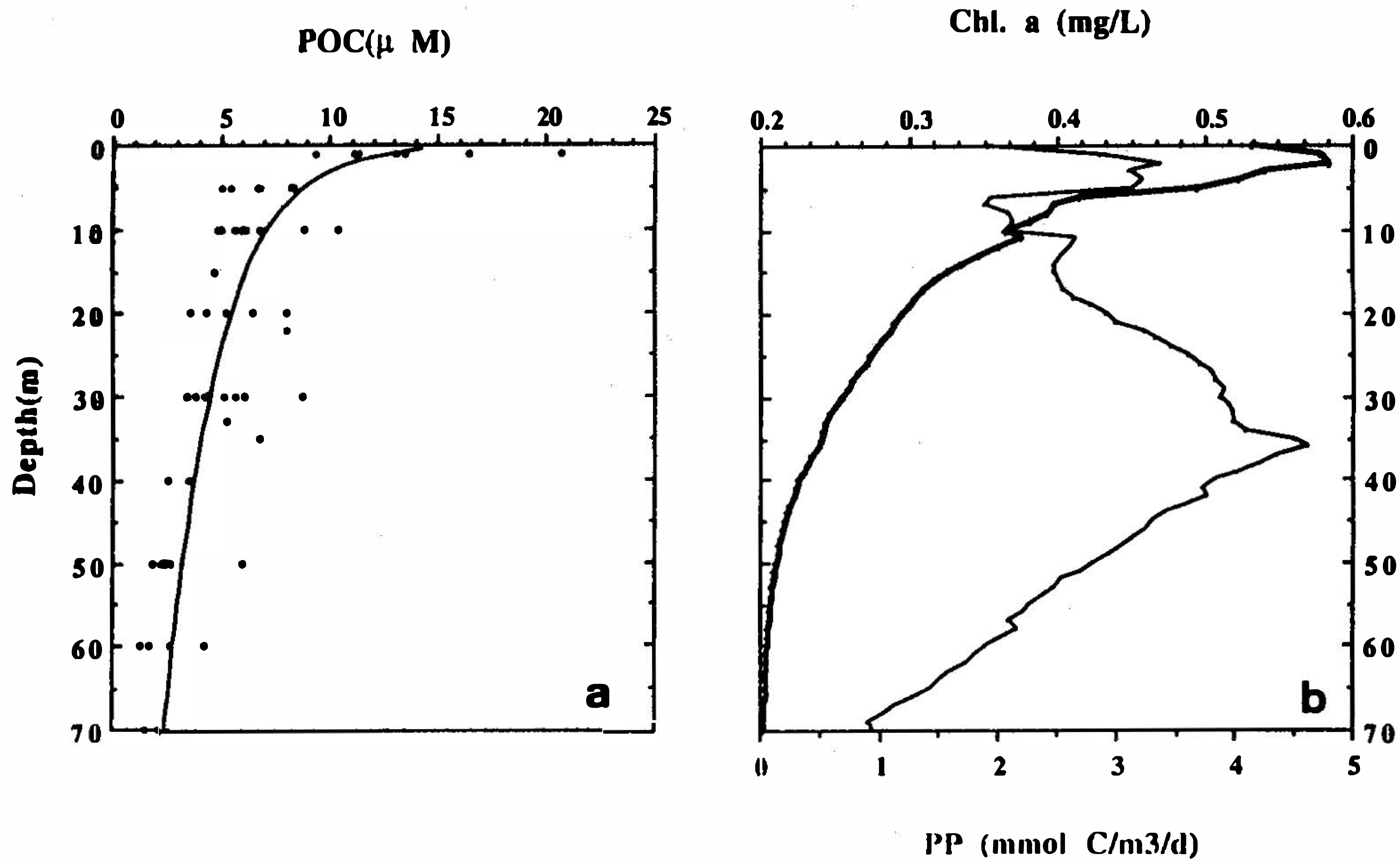


Fig. 10. (a) Left panel: The vertical distribution of POC in the upwelling area during Cruise 352D. (b) Right panel: The mean vertical distribution of chlorophyll *a* and primary production in the upwelling area during the same cruise.

On the other hand, the primary production in the upwelling region was found to decrease exponentially with depth (Shiah *et al.*, 1995). The primary production at each depth can be estimated from the chlorophyll *a* specific production rate (P^B) and the chlorophyll *a* concentration. The P^B at Stations 8 and 11 in May, 1994 was determined (Shiah *et al.*, 1995) to be as follows:

$$P^B = P^B max^* \exp(-0.0734 * z), \qquad (3)$$

where P^Bmax was 142 mgC/mg chlorophyll *a*/d. Thus, the primary production rate was calculated for the upwelling region from the mean chlorophyll *a* concentration at each depth. The calculated primary production shows a maximum very close to the surface. In the subsurface layer, it decreases rapidly with depth, resembling the POC profile, and continues to diminish to less than 5% of the maximum value at the depth of 35 m which is about the euphotic zone depth in the shelf water (Shiah *et al.*, 1995).

Evidently, primary production is the dominant process that controlled the vertical POC distribution. When the calculated primary production rate was plotted against the POC concentration, it showed a reasonably good positive correlation (Figure 11). The linear trend suggests a close match between the production rate and removal rate which should be proportional to the POC abundance. The removal was probably accomplished both by the divergence of water at the upwelling center and also by biological consumption. The coupling between the phytoplankton growth and consumption by grazing and microbial decomposition often exists in the euphotic zone (Banse, 1992). However, unlike primary production, POC concentration did not approach zero below the euphotic zone. The intercept on the abscissa, 1.5 μM, probably represents a background concentration of detrital POC. The slope of the linear regression line (0.3/d) may be considered a removal rate constant for the freshly produced POC. This gives a mean turnover time of 3.3 days for the fresh phytodetritus. In contrast, the background POC which probably consists of resuspended particulates or refractory detritus should have a longer turnover time.

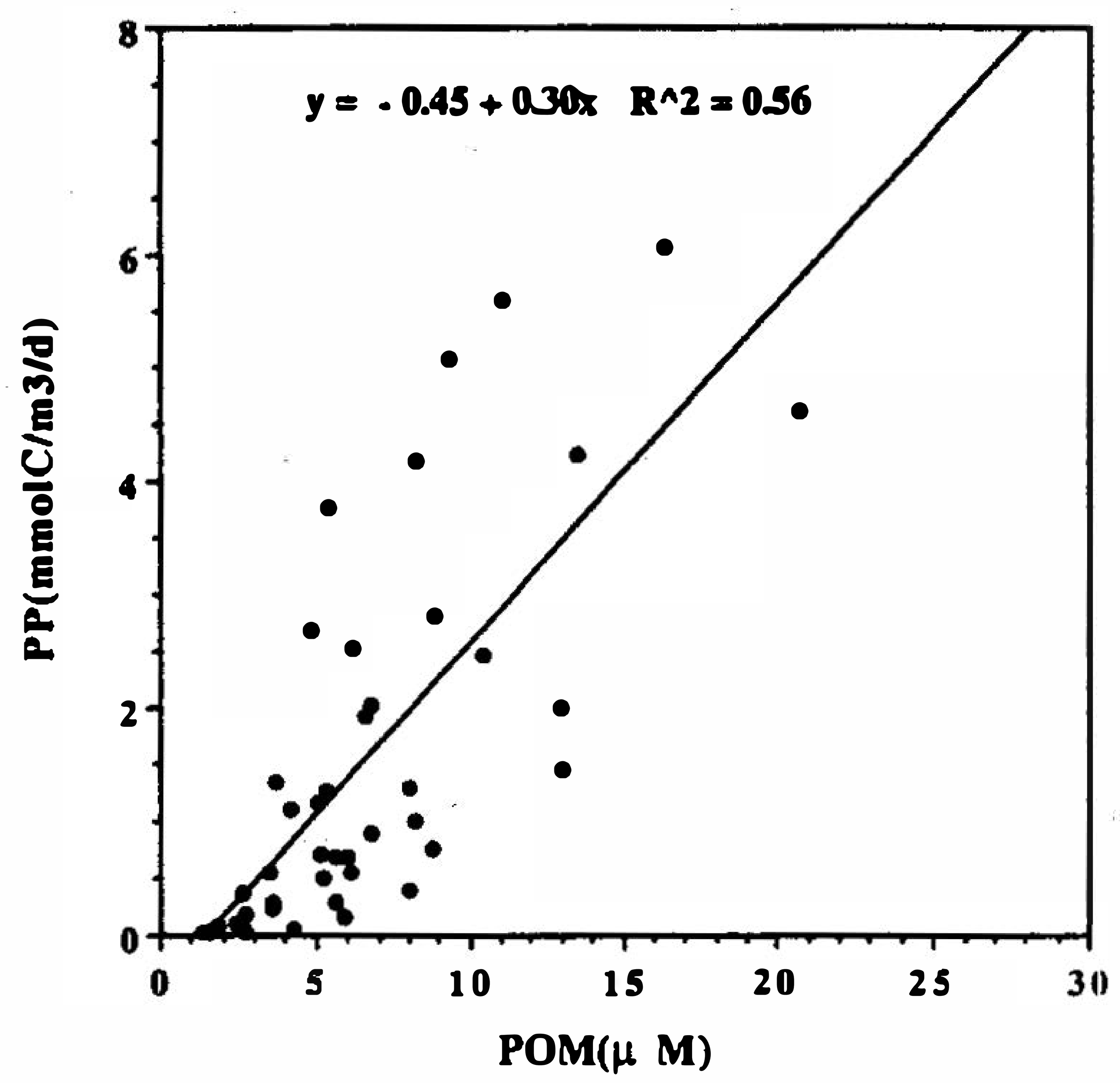


Fig. 11. The primary production versus POC concentration in the upwelling region.

The lateral variation of the integrated quantities or inventories of various bio-elements reflected different biogeochemical conditions in different water types across the shelf and slope (Figure 12). The integration was perfonned for the shelf and slope waters over the depth range from 0 to 70 m which was about the maximum depth with significant concentrations of chlorophyll *a*. For stations with water depths of less than 70 m, the integration was calculated to the bottom depth. For Station 17, the integration was performed over the range of 0 to 90 m which is the depth just below the subsurface chlorophyll *a* maximum at 80 m.

The inventory of nitrate (mole/m^2) in the top 70 m clearly defined the upwelling area to be within 40 km on both sides of the shelf break. The upwelling center was marked by the nitrate maximum slightly landward from the shelf break. The variation of the nitrate inventory was almost symmetric with respect to the center. The integrated values of chlorophyll *a* showed two local maxima at Stations 9 and 13, one on each side of the upwelling center. The newly upwelled water usually contains little phytoplankton (Yoder *et al.*, 1981; Chen, 1992). There is a time lag (the aging time) between the nutrient supply and phytoplankton growth. While the upwelled water drifted away from the divergent center, the chlorophyll *a* maximum representing a sizable standing stock of phytoplankton was developed. The peaks were of about equal intensity, but their distances from the center were not equal. If the development of the two chlorophyll *a* maxima took the same length of time, the greater distance of the chlorophyll *a* maximum from the center might have resulted from a higher drifting velocity. Hence, the cross-shelf drifting velocity of the surface layer in the upwelling region may be higher on the seaward side. This may imply that a greater fraction of the upwelled water was lost to the Kuroshio probably by entrainment.

The POC and PN inventories followed the trend of chlorophyll *a*, which is expected because POM is controlled by primary production which is in turn controlled by the standing stock of phytoplankton. However, the maximum values of POC and PN on the seaward side were less pronounced than the peaks on the other side, unlike those of chlorophyll *a* (Table 1). The peak heights on the seaward side were about 2/3 of the others.

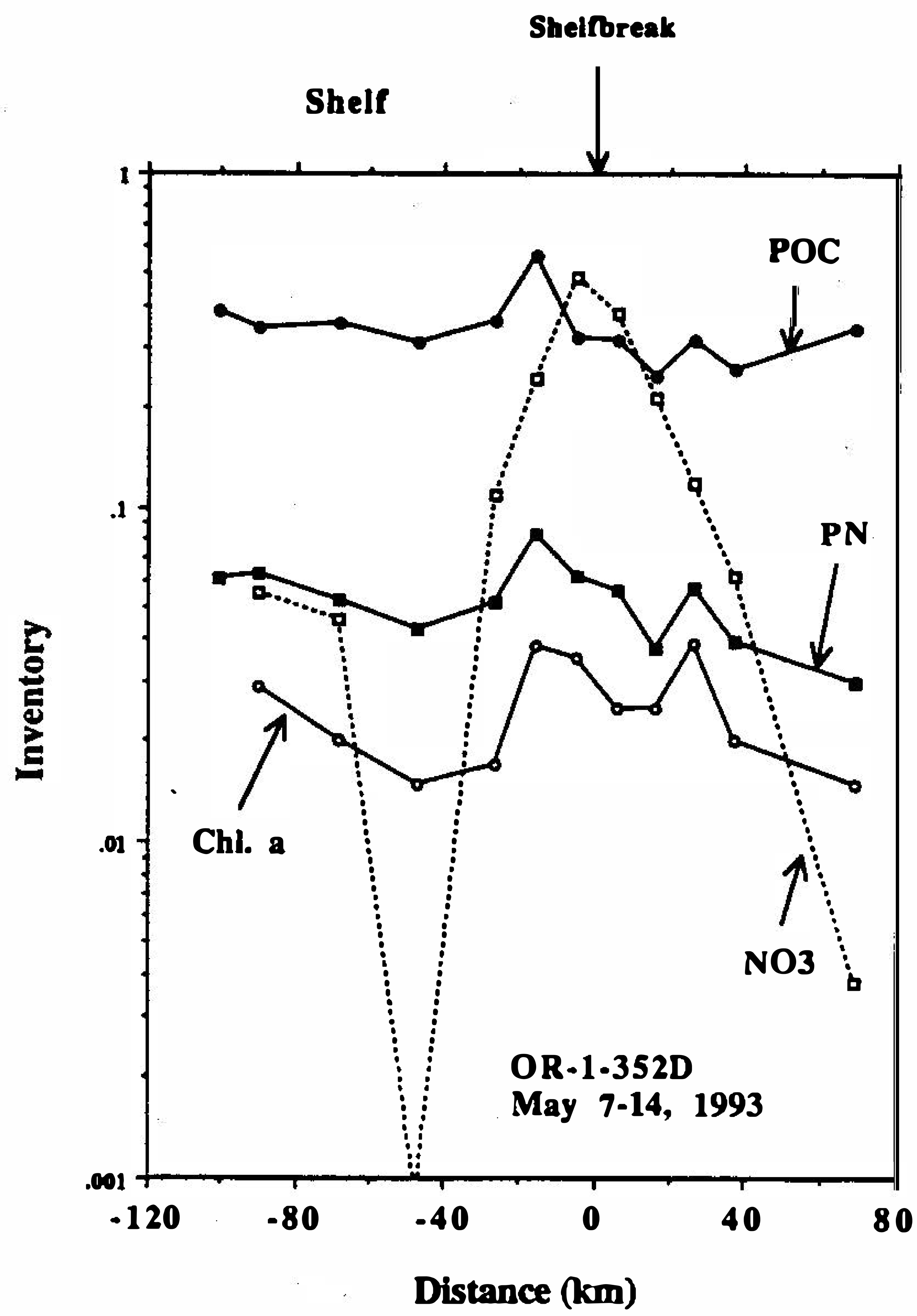


Fig. 12. The variation of chemical inventories, i.e., integrated quantities in the upper 70 m, along the long transect of Cruise 352D. The distance was measured with the shelf break set to zero. Dots and solid squares represent POC and PN, respectively. Open squares and circles represent nitrate and chlorophyll *a*, respectively. The units are in mole/m^2 except for chlorophyll *a* which is in g/m^2.

Under a steady state condition, the residence time can be calculated from the standing stock of POC and the production or removal rates. The potential primary production rate can be estimated from the chlorophyll *a* profile at each station, using the P^B measured in May, 1994 (Shiah *et al.*, 1995). For shelf waters, the P^B shown in Equation (3) was used. For station 17, the following relationship determined at the same station in May, 1994 was used:

$$P^B = P^B\text{max}^*\exp(-0.03096 * z), \tag{4}$$

where P^Bmax was 73 mgC/mg Chl. *a*/d. For Station 1 where the chlorophyll *a* data were not available, the primary production rates measured at the same station and same month in 1994 was adopted. The potential primary productivity (PPP) was calculated by integrating the estimated production rate in the euphotic zone (Table 1).

Table 1. Inventories of bio-elements and chlorophyll *a* in the top 70-90 m along the long transect of sampling stations on Cruise 352D. The potential primary productivity (PPP) and residence time (T) of POC are also listed.

Sta	NO_3^- (mol/m^2)	Chl *a* (g/m^2)	POC (mol/m^2)	PN (mol/m^2)	PPP (mol/m^2/d)	T (d)
1			0.385	0.0609	0.158*	2.4
2	0.055	0.029	0.342	0.0626	0.094	3.6
4	0.046	0.020	0.352	0.0521	0.052	6.7
6	0.001	0.015	0.312	0.0426	0.036	8.6
8	0.110	0.017	0.363	0.0514	0.027	13.6
9	0.241	0.038	0.559	0.0824	0.077	7.2
10	0.486	0.035	0.319	0.0616	0.098	3.3
11	0.380	0.025	0.316	0.0561	0.065	4.9
12	0.212	0.025	0.248	0.0374	0.077	3.2
13	0.120	0.039	0.316	0.0572	0.080	4.0
14	0.062	0.020	0.258	0.0397	0.034	7.6
17	0.004	0.015	0.344	0.0300	0.018	19.1

*Value adopted from Shiah *et al.*, (1995)

The calculated residence time for POC ranged from 2 days to 19 days (Table 1). The residence time (2-4 days) was the shortest in the coastal waters (Stations 1 and 2). The residence time for the nutrient-poor shelf waters at Stations 4 and 6 was 7-9 days. Most stations in the upwelling area (Stations 9-14) had a POC residence time within 3-8 days but Station 8 appeared to be an anomaly. The calculated residence time was 14 days which was caused by high POC and low chlorophyll *a* inventory. The calculated values of the POC residence time for the upwelling area were mostly higher than the previous estimate of the turnover time of 3.3 days for the fresh phytodetritus. This indicates that the residence time of POC is a composite of two types of materials, the labile fresh material with a shorter turnover time and the refractory material with a longer turnover time. The residence time, 19 days, calculated for the Kuroshio water was the longest. The relatively short residence time in the coastal and upwelling areas indicates more efficient removal. The coastal water has abundant copepods and high zooplankton biomass in the southern East China Sea in spring (He *et al.*, 1990). Therefore, the shorter residence time of POC in the coastal water may have been caused by stronger grazing pressure. In contrast, the long residence time in the Kuroshio water could have been caused by a low gazing pressure.

The particle residence time in the Kuroshio water can be estimated by ^{234}Th scavenging rate (Wei, 1991). From the deficiency of ^{234}Th in the upper 90 m observed in April, 1991 (Wei, 1991), a mean residence time was calculated to be 103 days, which is considerably longer than the POC residence time. From the standing stocks and the particle residence time, the sinking fluxes of POC and PN from the top 90 m were calculated to be 3.3 and 0.29 mmol/m^2/d, respectively. The POC flux from the euphotic zone may be considered the new production (Eppley, 1989). Compared to the integrated potential primary productivity (0.018 mol C/m^2/d), the new production represented about 18% of the primary production. The fluxes of POC and PN at 90 m can also be estimated from primary productivity using the relationships reported for the eastern North Pacific (Pace *et al.*, 1987) to be 2.3 mmol

C/m^2/d and 0.29 mmol N/m^2/d, respectively. The POC fluxes estimated from two entirely different methods are in reasonable agreement, while those for PN are identical, suggesting that the assumptions made in the foregoing discussions are acceptable.

4.2 Cross-shelf Transport of POC

Based upon measurements of total extractable manganese, Wei *et al.* (1990) suggested the existence of a mid-depth particle maximum in the Okinawa Trough. In this study, evidence of relatively high organic particle concentration between 500 and 750 m in the intermediate water beneath the Kuroshio is shown. This depth range was slightly shallower than that (800-1000 m) observed for the manganese plume (Wei *et al.*, 1990) but both were within the depth range (500-1400 m) for organic carbon rich sediments on the slope off northeastern Taiwan (Lin *et al.*, 1992).

The oligotrophic water of the Kuroshio was not likely an important source of the patches of POC observed in the underlain water. The most probable source of the POC was in the shelf water where high primary productivity was elevated. The lateral transport of POM from the shelf to the deep water may be related to several physical processes, including tidal motion, internal motion, the Kuroshio, and its counter current at the shelf break. Recently, Chung (1993) reported the fluctuation of particle fluxes at the continental slope in phase with the cross-shelf current velocity. Tsai (1993) also reported a high particle concentration coupled with the offshore movement of water at the shelf break. These observations suggest a lateral transport of the particulate matter associated with the oscillatory water movement of the strong tidal and internal motion in the cross shelf direction (Lee, 1992). The POC distribution observed on Cruise 331B suggests cascading of particulate matter down the slope. This could have been caused by the sweeping motion of the tides. Such a scenario existed only when the upwelling was weak., The up-slope motion could have reduced the down slope transport of the particles. In fact, Chung (1993) also reported that particle fluxes did not always covary with the cross-shelf tidal current.

An alternative mechanism may have also been responsible for the down slope transport of particles. The upwelling process is suggested to be related to the Kuroshio counter current along the upper shelf (Chuang *et al.*, 1993; Tang and Tang, 1994). The offshore tongue of the particulate matter may have been activated by the Ekman transport at the bottom of the counter current (Y. Hsueh, personal communication). If this is the case, then the particle-rich layer must be very close to the bottom and may evade detection. The scenario observed on Cruise 352D may be such a case.

The existence of particle maximum in the intermediate water above the slope may have been caused by the "insulating effect" suggested by Csanady and Shaw (1983). They reported that the bottom current fluctuation reached a minimum at the middle of a steep continental slope where the water column became very quiescent. The quiescence may have insulated the fine particles from disturbance and preserved the patchiness of the particle distribution. Otherwise, the clouds of particulate matter would be homogenized throughout the water column. The settling of organic carbon rich fine particles in this quiescent zone is also responsible for the preferential deposition of organic carbon on the continental slope (Walsh *et al.*, 1988).

5. SUMMARY AND CONCLUSIONS

A survey along the long transect across the continental shelf in the southern East China Sea on Cruise 352D in May 1993 showed that a large standing stock of POC (up to 0.56

mole C/m^2) existed in the upwelling area around the shelf break. There were two maxima of POC standing stock, one on each side of the upwelling center, which corresponded to the maxima of chlorophyll *a*. A similar enrichment of POC in the upwelled water was observed on Cruise 331B in October, 1992. The POC and PN concentrations were well correlated with a $\Delta C/\Delta N$ ratio (6.3-6.7) in good agreement with the Redfield ratio. The vertical POC distribution in the shelf water showed a conspicuous surface maximum, which was evidently controlled by the primary production rate. Additionally, the potential primary production rate calculated from the chlorophyll *a* profiles showed an eminent maximum near the surface.

The residence time of POC in the upper water column was calculated from the standing stock of POC and the integrated potential primary productivity. Probably due to the high grazing pressure, the shortest residence time was 2-4 days for the coastal waters. The upwelling area also showed a short residence time of 3-8 days. The longest residence time of 19 days was found for the oligotrophic waters in the Kuroshio. The POC flux beneath the euphotic zone in the Kuroshio was calculated from the ^{234}Th deficit to be 3.3 mmol $C/m^2/d$, which is about 18% of the potential primary productivity. This percentage may be considered a new production f ratio. The PN flux was calculated to be 0.29 $mmol/m^2/d$.

Beneath the Kuroshio, the POC concentration was usually less than 1.2 μM, but the mid-depth maxima of 1.5-3.5 μM POC were observed in the intermediate water between 500 and 750 m on both cruises. These patches of organic carbon rich particles were a direct evidence of the lateral transport of POC across the shelf break to the deep sea.

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REFERENCES

Banse, K., 1992: Grazing, temporal changes of phytoplankton concentrations, and the microbial loop in the open ocean, In: P. Falkowski *et al.* (Eds.), Primary productivity and Biogeochemical Cycles in the Sea, 409-440.

Carpenter, J., 1965: The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. *Limnol. Oceanogr.*, **10**, 141-143.

Chen, C. T. A., Y. C. Chung, V. Damiani, S. Krishnaswami, K. K. Liu, E. Okemwa, and G. Quraishee, 1992: Report to JGOFS, The Continental Margin Studies Group, JGOFS-6, Bermuda, Oct. 2, 1991. *Bull. Marine Sci. Technol.*, **10**, 1-5.

Chern, C., and J. Wang, 1989: On the water masses at northern offshore area of Taiwan. *Acta Oceanogr. Taiwanica*, **22**, 14-32.

Chuang W. S., and W. D. Liang, 1994: Seasonal variability of the Kuroshio water across the continental shelf northeast of Taiwan. *J. Oceanogr.*, **50**, 531-542.

Chuang, W.-S., H. W. Li, T. Y. Tang, and C. K. Wu, 1993: Observations of the countercurrent on the inshore side of the Kuroshio northeast of Taiwan. *J. Oceanogr.*, **49**, 581-592.

Chung, Y. C, 1993: Chemical and geochemical studies of suspended particles in the sea northeast of Taiwan and development of sediment trap technique. The 4th KEEP and WOCE Conference, Feb. 1993.

Csanady, G. T., and P.-T. Shaw, 1983: The "insulating' effect of a steep continental slope. *J. Geophys. Res.*, **88**, 7519-7524.

Eppley, R. W., 1989: New production: history, methods and problems. In: W. H. Berger, V. Smetacek, and O. Weffer (Eds.), Dahlem Workshops in "Productivity of the Ocean: Present and Past", 85-97, Wiley, N.Y.

Fan, K.-L., 1980: On upwelling off northeastern shore of Taiwan. *Acta Oceanogr. Taiwanica*, **11**, 105-117.

Field, J., 1992: JGOFS and LOICZ proposed joint continental margins program. U.S. JGOFS Newsletter-June 1992, 11-12.

Gong, G. C., 1992: Chemical hydrography of the Kuroshio front in the sea northeast of Taiwan. Ph. D. Dissertation, Inst. of Oceanogr., National Taiwan Univ., 204pp.

Gong, G. C., W. R. Yang, and Y. H. Wen, 1993: Correlation of chlorophyll *a* concentration and Sea Tech fluorometer fluorescence in seawater. *Acta Oceanogr. Taiwanica*, **31**, 117-126.

He, D., C. Wang, and H. Liu, 1990: A study of zooplankton distribution patterns and indicator species in Kuroshio upsteam area and adjacent East China Sea, Proc. Japan-China Joint Symposium of the Cooperative Study on the Kuroshio, Nov. 1989, Tokyo Sci. Technol. Agency, Japan, 302-316.

IGBP, 1992: Joint Global Ocean Flux Study-Implementation Plan. JGOFS Rep. #9, IGBP, Stockholm.

JGOFS, 1994: Report of the JGOFS/LOICZ Task Team on Continental Margin Studies. JGOFS Rep. #15, SCOR, ICSU.

Lai, Z.-L., and K.-K. Liu, 1994: The distribution of carbon, nitrogen and sulfur in surficial sediments on the continental shelf and slope in the northern South China Sea. *Acta Oceanogr. Taiwanica*, **32**, 30-44.

Chen, Y. l. l., 1992: Summer phytoplankton community structure in the Kuroshio Current-related upwelling northeast of Taiwan. *TAO*, **3**, 305-320.

Lee, D., 1992: A study on the vertical structure of the semi-diurnal tide at the shelf break off northeastern Taiwan. M.S. Thesis, Inst. Oceanogr., National Taiwan Univ., 108pp.

Lin, S., K.-K., Liu, P., Chen, and F.-Y., Chang, 1992: Distribution of organic carbon in the KEEP area continental margin sediments. *TAO*, **3**, 365-377.

Liu, K.-K., G.-C., Gong, C.-Z., Shyu, S.-C., Pai, C.-L., Wei, and S.-Y., Chao 1992a: Response of Kuroshio upwelling to the onset of northeast monsoon in the sea north of Taiwan: observations and a numerical simulation. *J. Geophys. Res.*, **97**, 12511-12526.

Liu, K.-K., G.-C., Gong, S., Lin, C.-Y., Yang, C.-L., Wei, S.-C., Pai, and C.-K., Wu, 1992b: The year-round upwelling at the shelf break near the northern tip of Taiwan as evidenced by chemical hydrography. *TAO*, **3**, 243-275.

Nitani, H., 1972: The Beginning of the Kuroshio, In: H. Stommel and K. Yoshida (Eds.), Kuroshio, Univ. of Tokyo Press, Japan, 129-156.

Pace, M. L., G. A. Knauer, D. M. Karl, and J. H. Martin,1987: Primary production, new production and vertical flux in the eastern Pacific Ocean. *Nature*, **325**, 803-804.

Pai S.-C., G.-C., Gong, and K.-K., Liu, 1993: Determination of dissolved oxygen in seawater by direct spectrophotometry of total iodine. *Mar. Chem.*, **41**, 343-351.

Redfield, A. C., B. H. Ketchum, and F. A. Richards, 1963: The influence of organisms in the composition of seawater. In: M. N. Hill (Ed.), The Sea, Interscience, N.Y. Vol. 2, 26-77.

Shiah, F. K., G. C. Gong, and K. K. Liu, 1995: A preliminary survey on primary productivity measured by the 14C assimilation method in the KEEP area. *Acta Oceanogr. Taiwaninca*, **34**, 1-16.

Tang, T. Y., and W. T. Tang, 1993: Current on the edge of continental shelf northeast of Taiwan. *TAO*, **5**, 335-348.

Tsai, T. H., 1993: Influence of tidal current on the suspended particles in the shelf water north of Taiwan. The 4th KEEP and WOCE Conference, Feb. 1993.

Walsh, J. J., 1991: Importance of continental margins in the marine biogeochemical cycling of carbon and nitrogen. *Nature*, **350**, 53-55.

Walsh, J. J., P. E. Biscaye, and G. T. Csanady, 1988: The 1983-1984 Shelf Edge Exchange Processes (SEEP)-I experiment: hypotheses and highlights. *Cont. Shelf Res.*, **8**, 435-456.

Walsh, J. J., E. T. Premuzic, J. S. Gaffney, G. T. Rowe, G. Harbottle, R. W. Stoenner, W. L. Balsam, P. R. Betzer, and S. A. Macko , 1985: Organic storage of CO2 on the continental slope off the mid-Atlantic bight, the southeastern Bering Sea and the Peru coast. *Deep Sea Res.*, **32**, 853-883.

Wang, J., and C.-S. Chern, 1989: On the Kuroshio branch in the Taiwan Strait during wintertime. *Prog. Oceanogr.*, **21**, 469-491.

Wang, J., and C.-S. Chern, 1990: A transect across the thermohaline front north of Taiwan in winter time. *Acta Oceanogr. Taiwanica*, **25**, 31-54.

Wei, C.-L., S.-J. Sun, and C.-S. Huang, 1990: Manganese distribution in the water column off northeastern Taiwan-a preliminary investigation. *Acta Oceanogr. Taiwanica*, **26**, 85-93.

Wei, C. L., 1991: Studies of scavenging phenomenon in the upper water column off northeast Taiwan – Application of ^{234}Th/238U disequilibrium. *Acta Oceanogr. Taiwanica*, **26**, 13-19.

Wong, G. T.-F., Pai, S.-C. Pai, K.-K. Liu, C.-T. Liu, and C.-T. A. Chen, Variability of the chemical hydrography at the frontal region between the East China Sea and the Kuroshio north-east of Taiwan. *Estuar. Coast. Shelf Sci.*, **33**, 105-120.

Yorder, J. A., L. P. Atkinson, T. N. Lee, H. H. Kim, and C. R. McClain, 1981: Role of Gulf Stream frontal eddies in forming phytoplankton patches on the outer southern shelf. *Limnol. Oceanogr.*, **26**, 1103-1110.