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Joe C. Jennings, Jr. for the degree of Master of Science

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Title: Meridional Fluxes of Dissolved Silicon in the Southern Ocean

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Meridional fluxes of silica across the Southern Ocean polar front are attributed to two different processes which generally act in opposite directions. Equatorward low frequency fluxes of silica inferred from ISOS current meter data in the Drake Passage are approximately balanced by poleward meridional diffusion of silica along surfaces of constant potential density. Considering only these two processes, a balance of the silicon budget in the Circumpolar Current can be achieved. The poleward diffusive flux along shoaling density surfaces may maintain the high silicon concentrations characteristic of Antarctic surface waters south of the frontal zone.

Meridional Fluxes of Dissolved Silicon in the Southern Ocean

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Typed by Regina A. Tison for Joe C. Jennings, Jr.

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"I get by with a little help from my friends."

Lennon-McCartney

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ABSTRACT

Meridional fluxes of silica across the Southern Ocean polar front are attributed to two different processes which generally act in opposite directions. Equatorward low frequency fluxes of silica inferred from ISOS current meter data in the Drake Passage are approximately balanced by poleward meridional diffusion of silica along surfaces of constant potential density. Considering only these two processes, a balance of the silicon budget in the Circumpolar Current can be achieved. The poleward diffusive flux along shoaling density surfaces may maintain the high silicon concentrations characteristic of Antarctic surface waters south of the frontal zone.

MERIDIONAL FLUXES OF DISSOLVED SILICON IN THE SOUTHERN OCEAN

INTRODUCTION

Most previous studies of the marine cycle of silicon have been either concerned with the global balance between river input and oceanic sedimentation (Berger, 1970; Heath, 1974; Wollast, 1974) or have treated local vertical cycling (Grill, 1970; Kido and Nishimura, 1975). To increase the utility of dissolved silicon as a tracer of water movements, a more quantitative study of the advective and diffusive fluxes within and between the major ocean basins is required. We are studying the oceanographic processes in the Southern Ocean to assess their role in maintaining the observed distributions of dissolved and particulate silicon in this region. Because it connects the other ocean basins zonally, the Southern Ocean must necessarily play a key role in the transport of properties between them. Additionally, the Southern Ocean phytoplankton community is dominated by diatoms (El-Sayed and Turner, 1974) and its underlying basins receive a substantial sedimentary input of biogenic particulate silicon (Lisitzin, 1967).

Other studies which have treated various aspects of the Southern Ocean silicon cycle include Burton and Liss (1973), Schutz and Turekian (1965), Edmond (1973), and Hurd (1977). Schutz and Turekian (1965) and Burton and Liss (1973) proposed that glacial weathering of the Antarctic continent could be a major source of dissolved silicon in the Southern Ocean, but Hurd showed that the low dissolution rate of terrigenous particulate silicon in glacial flours precluded their being a significant source. Edmond (1973) constructed a dissolved silicon budget for the

Southern Ocean in an attempt to indirectly assess the role of glacial flours and concluded that the large internal fluxes of dissolved silicon made his mass balance approach insensitive to such relatively small net fluxes into and out of the oceanic reservoir.

In this paper, we present estimates of the meridional fluxes of dissolved silicon across the Polar Frontal Zone accomplished by different physical processes and their significance to the phytoplankton community. Only in the last 15 years have reliable data on dissolved silicon distributions in this region been collected, and there remain large gaps in the seasonal and spatial coverage. Our knowledge of the distribution of primary productivity, production of biogenic particulate silicon, and the nature and magnitude of Southern Ocean dynamics is similarly incomplete. Thus, there is large uncertainty in our attempts to quantify these processes.

We here propose a meridional balance of the Southern Ocean silicon cycle which is consistent with the conceptual scheme of cross-frontal meridional circulation suggested by Bryden (1980). Bryden (1980) proposed that eddies could accomplish the meridional flux of heat necessary to balance the heat budget with no net mass transport, and that the meridional distribution of properties in the Southern Ocean could be maintained by eddies rather than by large scale meridional advection.

BACKGROUND

In Figure 1, typical meridional sections of property distributions in the Drake Passage are illustrated. Except for the larger meridional scale, meridional sections from the other Southern Ocean regions discussed are very similar (cf. Reid et al., 1977; Jacobs and Georgi, 1977; Horibe, 1970, 1971). The isopleths of dissolved silicon slope upward from north to south, approximately paralleling the sloping isopycnals. The Polar Frontal Zone is the region of steepest isopycnal slope and separates the main volume of the Antarctic Circumpolar Current from the Subantarctic waters to the north. The dramatic increase in surface dissolved silicon concentrations illustrated in Figure 2 has been used to delineate the frontal zone (Bogdanov et al., 1969; Gordon et al., 1977). Detailed descriptions of the Southern Ocean water masses have been presented by Nowlin et al. (1977), Reid et al. (1977), Callahan (1972), and Jacobs and Georgi (1977).

Estimates of the zonal transport of dissolved silicon within the Antarctic Circumpolar Current (ACC) have been treated in a preliminary form elsewhere (Jennings and Gordon, 1978). The zonal transport of dissolved silicon south of the Polar Front was found to be essentially constant ($\sim 1 \times 10^8$ g Si s^{-1}) across transects of the ACC south of Australia, South America, and Africa. Thus, there was no suggestion of significant net transport of dissolved silicon between the ocean basins. The zonal transport estimates are subject to the accuracy and appropriateness of the geostrophic approximation, and all transport calculations were based on Austral summer data. In a separate work (Nelson and Gordon, 1980), estimates of the rates of biological cycling of dissolved and particulate silicon have been presented. The significance of the meridional fluxes of dissolved silicon presented here to the biological cycling of silicon is discussed in a later section.

Two different approaches have been used to calculate the meridional fluxes presented here: the low frequency eddy transport based on current meter heat flux calculations, and the diffusive flux based upon gradients along isopycnal surfaces.

Bryden (1979, 1980) and Sciremammano (1980) have discussed the nature of the low frequency heat fluxes estimated from the current meter records in the Drake Passage, and Bryden (1979) has shown that these fluctuations are compatible with baroclinic instability theory. The conversion of potential to kinetic energy via the mechanism of baroclinic instability leads to the formation of eddies with horizontal scales of 30-120 km (Bryden, 1980) which result in a cross-isopycnal transfer of properties in the frontal zone. Sciremammano (1980) notes that these events have time scales of 5-60 days and longer and that only 3-10 of these events occur per year. Cold core eddies have been observed in the Southern Ocean (cf. Legeckis, 1977; Joyce and Patterson, 1977). That these eddies are non-isopycnal processes is both inherent in baroclinic instability theory and qualitatively observable in the temperature records of the moored current meters. Figure 3 reproduces a temperature record from one of the frontal zone moorings in the Drake Passage and a plot of temperature on an isopycnal surface in the same region. The potential temperature on $\sigma_2 = 37.09$ from 28 stations comprising four transects across the Drake Passage varies from 1.28-1.36°C, a range of only 0.08°C. In the current meter record from 1519 m (Figure 3), oscillations of 0.4-0.8°C are observable which cannot be explained by isopycnal processes.

DATA AND METHODS

The data used in constructing these estimates of meridional silicon fluxes come from a number of recent cruises in the Southern Ocean. Table I lists the data sets used. Because the data came from many different ships and years, variable systematic discrepancies between the data sets are present. No attempt has been made to intercompare dissolved silicon concentrations except internally within a given data set. Only the relative changes in concentration across the front and the slopes of Si/θ plots are compared between data sets.

Silicon is present in seawater primarily as dissolved orthosilicic acid and as suspended particles of both terrigenous and biogenic origin. In this paper "dissolved silicon" is used to describe all forms of aqueous silicon which respond to the colorimetric determination in common use. "Particulate silicon" includes all forms of silicon present in the solid phase. Concentrations are usually reported as μM or μ moles kg^{-1}; in this work the dissolved silicon concentration units are μM, these are converted to g Si m^{-3} in the flux computations. (Note: 1 μM ≅ 1 μg - at l^{-1}.)

Si Flux Estimated from Heat Fluxes

Bryden (1979) has used long-term current meter records of temperature and velocity in the Drake Passage to construct estimates of low frequency cross-frontal heat fluxes for the Southern Ocean. Sciremammano (1980) has presented similar calculations for different years and discussed their significance.

In estimating these heat fluxes, the record length means are subtracted from the temperature and velocity data and the residual perturbations about these means are multiplied to give an estimate of the eddy or low frequency heat flux. For periods of roughly 3-100 days, Bryden (1979) found statistically significant poleward heat fluxes at all depths in the Drake Passage. There were no current meters in the upper 500 m of the water column and topography restricts the circulation of Antarctic Bottom Water (ABW) through the passage, so these estimates are strictly applicable only to the Circumpolar Deep Water (CDW) which comprises most of the Southern Ocean water column.

We estimate the flux of dissolved silica from the low frequency heat flux by noting that from the depth of the subsurface temperature maximum to that of the deep silicon maximum a linear relationship exists between the steadily increasing concentration of dissolved silicon (Si) and the decreasing potential temperature (θ). Figures 4 and 5 show illustrative Si/θ relationships for stations from the different data sets used. For 2.0°C > θ > 0.2°C, the approximate temperature range of CDW (Carmack's [1977] Warm Deep Water), dissolved silicon concentrations increase from ~80 μM to ~135 μM. The linearity of the θ/Si relationship at individual stations is evident in Figure 5. Considering the different sources of the data, the slopes of the Si/θ regressions agree very well. For the purposes of these calculations a representative value of $-30\ \mu M\ °C^{-1}$ (-8.4×10^{-1} g Si $m^{-3}\ °C^{-1}$) was assigned to $\Delta Si/\Delta\theta$. From Bryden's (1979) work we have $\overline{\Delta T \Delta V}$ (Bryden's $\overline{T'V'}$), the mean value of the low frequency heat flux; which when multiplied by our $\Delta Si/\Delta\theta$ gives an estimate of the flux of dissolved silicon due to these low frequency motions: $\overline{\Delta Si \Delta V}$. In Bryden's coordinate system, a positive $\overline{\Delta T \Delta V}$ results in a southward heat flux and since $\Delta Si/\Delta\theta$ is negative in the CDW, the inferred flux of dissolved silicon is northward.

Meridional Flux of Si Along Isopycnals

A second estimate of meridional silicon flux is possible using the technique of isopycnal analysis. The concept of maximal mixing along constant potential density surfaces is well established. Lynn and Reid (1968), Pingree (1972), and others have extended the utility of this approach to abyssal waters by computing potential density with respect to a constant depth near the depth of the features of interest; typically, the potential density is computed at reference levels of 0, 1000, 2000, 3000, and 4000 m, and the anomaly of potential density at these levels referred to as σ_0, σ_1, σ_2, etc. Because the frontal zone is characterized by steeply sloping isopycnals throughout the water column, the density surfaces on which our calculations are based were chosen to coincide with nutrient and/or salinity extrema. The gradients of dissolved silicon across the Polar Frontal Zone along these selected isopycnal surfaces were used to estimate a diffusive flux.

In the Upper Circumpolar Deep Water (UCDW), $\sigma_1 = 32.20$ was chosen to represent the density of the nutrient maximum layer. This corresponds to a σ_0 of 27.54. At the depth of the deep nutrient minimum/salinity maximum in the Lower Circumpolar Deep Water (LCDW), $\sigma_2 = 37.09$ ($\sigma_0 = 27.82$) was the characteristic density surface used. These density surfaces are approximately the same as the 50 cl ton^{-1} and 30 cl ton^{-1} specific volume anomaly surfaces used in Callahan's (1972) analysis of the zonal flow in the Pacific sector of the Southern Ocean. For each of the data sets used, three or more stations were chosen which comprised a transect of the Polar Frontal Zone. A variety of features have been used to define the location of the Polar Front; in keeping with the spirit of this paper, the front is defined in terms of a sharp increase in surface dissolved silicon from <10 μM to >20 μM. Figure 2 illustrates this feature in several transects of the Drake Passage. For each station selected, dissolved silicon concentrations were interpolated to the depth of the selected density surfaces and the meridional gradient along these surfaces determined. Figure 6 illustrates these gradients in the Drake Passage.

Because of the vertical and horizontal separation between data points, not all of the data available proved amenable to this treatment. Some data sets had poor vertical resolution of the nutrient extreme and the otherwise excellent GEOSECS data set has inadequate horizontal resolution for our purposes near the frontal zone. Closely spaced stations in Drake Passage were judged to give the best estimate of the horizontal scale of the cross-frontal gradients. Table II summarizes the cross-frontal gradients of dissolved silicon found in different regions of the Southern Ocean on the $\sigma_1 = 32.20$ and $\sigma_2 = 37.09$ isopycnals.

To estimate the diffusive flux of silicon, it was assumed that the sign and strength of the gradients on the selected density surfaces was maintained over a vertical extent of the water column comparable to the observable extent of the water masses whose cores are represented by the density surfaces. Qualitative support for this assumption can be derived by overlaying contoured sections of dissolved silicon and cruises of the Hakuho Maru and the FDRAKE 75 cruise of R/V Melville (Horibe, 1970, 1971; Nowlin *et al.*, 1977). A vertical extent of 1 km was assumed for the nutrient maximum layer and of 1.5 km for the nutrient minimum/S maximum layer in the results presented here.

To calculate the diffusive flux of silicon along isopycnal surfaces, it was necessary to obtain a value for the horizontal eddy diffusion coefficient (K_h). Garrett (1979) and Armi (1979) have discussed the problems implicit in using eddy diffusion coefficients, and Garrett (1979) has stressed the importance of distinguishing between mixing along isopycnal surfaces and truly horizontal mixing. This distinction becomes particularly important in frontal regions where the isopycnal surfaces slope steeply.

Horizontal eddy diffusion coefficients in the oceans are in the range of 10^2 to 10^5 m^2 s^{-1} (cf. Garrett, 1979; Pond and Pickard, 1978; Fiadeiro and Craig, 1978; Needler and Heath, 1975; Veronis, 1975). Gill and Bryan (1971) used a horizontal eddy diffusion coefficient of $\sim 10^4$ m^2 s^{-1} in a model of Antarctic circulation. The larger values of K_h are appropriate for ocean scale mixing and include the effects of mesoscale eddies. On smaller scales, Joyce (1977) and Georgi (1980) have discussed fine structure along the Polar Front with a vertical scale of 50-100 m and a horizontal scale of a few km and have noted that horizontal diffusivities of $\sim 10^2$ m^2 s^{-1} are implied by the fine structures of the T and S distributions. We must assume that similar variability exists in the nutrient distributions, as the standard hydrographic casts used to sample nutrient distributions rarely resolve these vertical or horizontal scales. Our selection of an eddy diffusion coefficient to parameterize cross-frontal isopycnal mixing is complicated by the fact that the mesoscale eddies which accomplish poleward heat transport and equatorward silicon transport act in the opposite direction to diffusion along isopycnals. A representative range of $K_h = 10^2$ to 10^3 m^2 s^{-1} is used in these calculations.

RESULTS

Low Frequency Flux

By assuming that the low frequency heat fluxes computed for the Drake Passage are typical of the Polar Frontal Zone as a whole it is possible to estimate the meridional flux of silicon due to these motions. Based on a statistical analysis of hydrographic data, Lutjeharms and Baker (1980) conclude that eddy-generation is likely along the entire Antarctic Polar Front, which tends to support such an extrapolation. Sciremammano (1980) has summarized the mean poleward heat fluxes from three years of current meter records in or near the Frontal Zone in the Drake Passage. The three year mean heat flux was $\sim 4 \times 10^{-1}$ Cal cm^{-2} s^{-1}, which includes the 1975 current meter records from which Bryden (1979) computed a one year mean of $\sim 3 \times 10^{-1}$ Cal cm^{-2} s^{-1}. There was no obvious depth dependence to the flux (Sciremammano, 1980). Taking the circumpolar radius to be 2×10^{4} km at 60°S and 2.0 km as the average vertical extent of the consistent $\Delta Si/\Delta\theta$ relationship in the Frontal Zone yields an estimated equatorward flux of $\sim 8 \times 10^{7}$ g sec^{-1} of dissolved silicon.

The relative infrequency and small horizontal scales of these eddies (compared to typical hydrographic station spacing) explains how a significant meridional flux of dissolved silicon can be accomplished without being resolved in hydrographic surveys. Decay of such eddies north of the Frontal Zone would accomplish a lateral and vertical enrichment of the Subantarctic waters without recourse to the classical meridional circulation scheme in the Southern Oceans involving the equatorward flow of Antarctic Intermediate Waters formed by mixing across the Frontal Zone.

Flux Along Isopycnal Surfaces

The calculated cross-frontal diffusive flux of silicon along isopycnal surfaces is summarized in Table III. These calculations were broken down regionally because the gradient of dissolved silicon on density surfaces in the Southeast Atlantic and Southeast Indian Oceans was very weak or absent, and the gradient on the $\sigma_2 = 37.09$ surface changed sign in the Western Indian Ocean (see Table II). Across the entire Pacific sector of the Southern Ocean, dissolved silicon concentrations decrease from north to south through the Frontal Zone on the isopycnal surfaces studied. The density surfaces shoal more rapidly across the front than do the isopleths of dissolved silicon allowing a poleward diffusive flux of silicon. In the Southwestern Indian Ocean, the upward slope of the $\sigma_0 = 27.54/\sigma_1 = 32.20$ isopycnal is greater than that of the local isopleths of dissolved silicon again implying a poleward diffusive flux of silicon along isopycnals across the front. On the deeper $\sigma_2 = 37.09$ surface, however, dissolved silicon concentrations increase toward the south, indicating an equatorward diffusive flux in this part of the water column. This gradient is apparently maintained over a larger zonal extent than that on the $\sigma_0 = 27.54/\sigma_1 = 32.20$ surface; the poleward gradient found in Conrad 17 sections at 40°E and 60°E on $\sigma_2 = 37.09$ is still present at GEOSECS stations at 105°E. There is no apparent gradient on the $\sigma_0 = 27.54/\sigma_1 = 32.20$ surface at the GEOSECS stations. In the Southeastern Indian Ocean the gradients are ~ 0 on both of the density surfaces used in this analysis.

The poleward diffusion of dissolved silicon along density surfaces is in the same sense as the transfer suggested in the classical scheme of meridional circulation (presumably advective) presented by Sverdrup et al. (1942). The tongue-like dissolved silicon maxima evident in the published sections from the Scorpio, Phoenix, and Southern Cross expeditions (Horibe, 1970, 1971; Stommel et al., 1973) is the source of this isopycnal flux in the South Pacific and possibly in the Southwestern Indian Ocean as well although it could not be traced across the Southeastern Atlantic with the data sets used. Edmond et al. (1979) present a section of silicon vs. σ_4 for GEOSECS stations in the Western Indian Ocean which shows a southward diffusing tongue of high dissolved silicon, but the section does not extend sufficiently far south to be traced into the Antarctic region nor is this tongue evident in the Southwestern Indian Ocean sections presented by Jacobs and Georgi (1977). In the Southeastern Atlantic, mixing with high salinity, low dissolved silicon NADW reverses the direction of the dissolved gradient on the σ_2 = 37.09 surface, leading to the equatorward diffusive flux calculated for the Southwestern Indian Ocean.

DISCUSSION

When the equatorward low frequency flux and the poleward diffusive flux estimates are compared, they are seen to be of approximately the same magnitude. The low frequency flux is probably overestimated as it was assumed that the eddies which contribute to the flux cross the frontal zone only once and are not reincorporated into their waters of origin. There is also large uncertainty in the selection of an appropriate eddy diffusion coefficient, and gaps in the available data have forced us to omit the Southeast Atlantic and Southeast Indian Oceans from explicit consideration. While inclusion of these areas would certainly alter the quantitative estimates, the qualitative conclusions should remain the same. Keeping in mind the many sources of error in this analysis, it is suggested that the two mechanisms discussed (mesoscale eddies and smaller scale isopycnal mixing), result in an approximate meridional balance of the silicon budget of the Antarctic Circumpolar Current.

One implication of the meridional dissolved silicon balance suggested is that the diffusive flux along isopycnals results in a vertical enrichment of waters south of the frontal zone as the isopycnal surfaces are ~ 1000 m shallower in the Antarctic zone than in the Subantarctic. The poleward diffusion along isopycnals contributes to maintaining the high dissolved silicon concentrations characteristic of Antarctic Surface Water.

To determine the significance of the vertical transport accomplished by the poleward diffusive flux to the phytoplankton community, an estimate of the biological uptake and removal of dissolved silicon within the euphotic zone is required. Direct measurements of the uptake of dissolved silicon in the Antarctic zone south of New Zealand suggest that an average of ~ 1×10^{-1} g Si m^{-2} day^{-1} of biogenic particulate silicon are produced within the euphotic zone (Nelson and Gordon, 1980). A second, indirect estimate using the average ^{14}C uptake in the euphotic zone of 1.34×10^{-1} g C m^{-2} day^{-1} reported by El-Sayed and Turner (1974) and an average Si:C ratio (wt:wt) in diatoms of ~ 1:1 (Lisitzin, 1967) yields an assimilation rate of dissolved silicon of ~ 1.3×10^{-1} g Si m^{-2} day^{-1}. Assuming that light limitation restricts the season of active growth to 120 days yr^{-1} south of the frontal zone, the annual production of biogenic particulate silicon calculated from these assimilation rates is (1.2 to 1.7) $\times 10^{1}$ g Si m^{-2} yr^{-1}. Much of this particulate silicon redissolves within the euphotic zone (Wollast, 1974; Nelson and Gordon, 1980). Probably no more than 50% of the dissolved silicon assimilated is actually removed from the euphotic zone as sinking particulate silicon, making the effective annual depletion of the surface waters (0.6 to 0.8) $\times 10^{1}$ g Si m^{-2} yr^{-1}. Over an areal extent south of the frontal zone of 20×10^{6} km^{2} (Gordon and Taylor, 1975) this removal is ~ 1.4×10^{14} g Si yr^{-1}.

The fraction of the poleward diffusive flux of dissolved silicon which can be mixed into the euphotic zone occurs between the $\sigma_0 = 27.3$ and $\sigma_0 = 27.6$ density surfaces as these isopycnals shoal from depths > 1000 m in the Subantarctic to ~ 100 m south of the frontal zone (see Figure 1). At lower densities the isopycnal flux is equatorward, and isopycnals deeper than $\sigma_0 = 27.6$ do not shoal sufficiently to accomplish transport into the mixed layer. If these two isopycnals are taken to be 500 m apart at the frontal zone, using the average isopycnal gradient of 1.4×10^{-6} g Si m^{-4}, $K_y = 10^{2} - 10^{3}$ m^{2} s^{-1}, and a linear extent along a convoluted front of 3×10^7 m in the Pacific and Indian Oceans gives a poleward flux of 2×10^6 to 2×10^7 g Si s^{-1} or ~ 6×10^{13} to 6×10^{14} g Si yr^{-1}. This annual flux is 40% to 400% of the estimate of annual removal. Thus, poleward diffusion within the nutrient maximum core layer alone may be sufficient to balance the biological removal of dissolved silicon and maintain the characteristically high concentrations found in Antarctic surface waters. This vertical enrichment also acts to replace dissolved silicon removed from the surface waters by the formation of Antarctic Bottom Water.

The possible role of meridional advection has been ignored in this treatment, under the assumption that it was not a significant factor in maintaining the observed property distributions. The model studies of Gill and Bryan (1971) tend to support this assumption. Recent discussions of intermediate water formation (McCartney, 1977; Gordon et al., 1977) do not invoke large-scale equatorward advection of Antarctic Surface Water. Calculations by de Szoeke and Levine (1980) indicate that the mean geostrophic meridional salt flux across the frontal zone is negligible.

To illustrate the relative effect of meridional advection, water with 100 μM of dissolved silicon can transport ~ 3×10^6 g Si s^{-1} Sv^{-1}, so meridional volume transports of 10 Sv could result in advective fluxes of the same order as the lower frequency and diffusive fluxes calculated here. Assuming that meridional advection would be mass-balanced by a return flow, the net effect of any meridional circulation depends on the concentration differences of properties north and south of the frontal zone rather than on the total concentrations. The wind-driven Ekman transport of the Southern Ocean is the most likely source of significant meridional advection of dissolved silicon. The predominantly westerly winds over the Southern Ocean should drive a northward flow in the surface Ekman layer which is balanced by a return flow at depth. de Szoeke and Levine (1980) estimate the Ekman transport to be 24 Sv. They are not able to identify the exact nature or location of the return flow but suggest that it may occur in narrow, intense bottom currents. Such currents are not resolved in the hydrographic data available. If the surface Ekman transport is balanced by a deeper return flow, then a net poleward advection of dissolved silicon should occur because of the increase in concentration with depth. The difference in dissolved silicon concentrations between surface and bottom waters near the Polar Front is ~ 100 μM (see Figure 1). Thus an equatorward meridional volume transport of 30 Sv in the surface Ekman layer balanced by a deep return flow could result in a net poleward advective flux of ~ 9×10^7 g Si s^{-1}, as large as the low frequency equatorward flux. Because the equatorward Ekman transport is distributed over the entire Southern Ocean and the nature and location(s) of any return flow are unresolved, it is not possible to assess the importance of this transport to the Southern Ocean budget of dissolved silicon.

The bottom water dissolved silicon budget may also be examined in terms of the meridional mechanisms suggested. Recent estimates of the production of Antarctic Bottom Water (AABW) suggest that from 5 to 10 Sv are produced (Carmack, 1977). This bottom water has a dissolved silicon concentration of ~ 120 μM south of the frontal zone and thus could represent an equatorward transport of as much as 3.6×10^7 g Si s^{-1} if this bottom water is actually transported northward across the Polar Frontal Zone. Estimates of the northward transport of AABW (cf. Gordon and

Taylor, 1975) tend to be based on the requirements of a balanced heat budget. As Bryden (1979) has shown, the poleward eddy heat flux in the Southern Ocean is large enough to satisfy the heat budget without requiring the net advection of AABW across the front. If the requirement for northward flow of bottom waters to balance the heat budget is relaxed, meridional advection of AABW need not represent a sink for dissolved silicon in the Southern Ocean.

Edmond et al. (1979) and Schlemmer (1978) have documented the bottom water Si/θ relationships in the basins marginal to the Antarctic continent. Except for the eastern region of the Southeast Pacific and the northern Weddell-Enderby basins, a bottom water $\Delta Si/\Delta\theta$ with an average value of ~ +25 $\mu M \cdot {}^{\circ}C^{-1}$ is observed below the deep dissolved silicon maximum. If the poleward heat fluxes computed for the deepest moorings in the Drake Passage are representative (1.6×10^{-1} °C cm s^{-1}; Bryden, 1979), a poleward low frequency flux of roughly 1 to 2×10^7 g Si s^{-1} is implied. There must also be poleward diffusion of dissolved silicon into the relatively low silicon AABW found south of the frontal zone (cf. Edmond et al., 1979; Schlemmer, 1978; Jacobs and Georgi, 1977). These calculations are only approximate at best, but suggest that equatorward transport of dissolved silicon in AABW may represent a source of dissolved silicon to the Southern Ocean.

SUMMARY

The conceptual scheme of the circumpolar dissolved silicon balance proposed here is that low frequency mesoscale processes, such as cold-core eddies, transport dissolved silicon northward leading to vertical and lateral enrichment of the Subantarctic waters. Diffusion along isopycnals transports dissolved silicon southward (and upward) to close the cycle. The poleward diffusive flux along steeply sloping isopycnals can balance the biological removal of silicon from the euphotic zone. In the Antarctic Bottom Water, below the deep dissolved silicon maximum, both the low frequency and diffusive fluxes are poleward. This scheme assumes that meridional advection is of negligible importance in transporting properties across the frontal zone.

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Table I

Region	Data Sources
S.W. Atlantic	GEOSECS Atlantic Final Hydrographic Data Report, July 21, 1972 to May 31, 1973, R/V KNORR
S.W. Pacific	Physical and Chemical Data from the Southern Ocean between Australia and Antarctica, USNS ELTANIN Cruise 41, December 20, 1969 to February 16, 1970, S.I.O. Ref. 72-19, 1972.
S.W. Indian	CONRAD 17, unpublished hydrographic data
S.W. Atlantic	CONRAD 18-01, February 2 to March 12, 1975, FDRAKE, a component of ISOS, Data Report, LDGO, July, 1976
S.W. Pacific	ELTANIN Reports, Cruises 47-50, 1971 and 52-55, 1972, S. S. Jacobs *et al.*, LDGO Technical Report CU-2-74, 1974
S. Indian	Unpublished hydrographic data from GEOSECS Indian Ocean Expedition
S.W. Pacific	Unpublished hydrographic data from R/V KNORR Cruise 73, September 1978
S.W. Pacific	Unpublished hydrographic data from R/V ZUBOV, collected January 24 to March 1, 1977
Drake Passage	Oceanographic Data collected aboard R/V T. G. THOMPSON during FDRAKE 76, Legs I and II. Data report by T. Whitworth, W. D. Nowlin, Jr., L. I. Gordon, and G. C. Anderson, Ref. 78-1-D, Texas A&M Research Foundation, 1978
Drake Passage	Oceanographic Station data collected aboard R/V Melville during FDRAKE 75. Data report by W. D. Nowlin, Jr., T. Whitworth, III, L. I. Gordon, and G. C. Anderson, Ref. 77-2-D, Texas A&M Research Foundation, 1978
S.W. Pacific	Oceanographic data of KH-68-4 (Southern Cross Cruise) of the Hakuho Maru, Ocean Research Institute, Tokyo, Japan, 1970
S.E. Pacific	Oceanographic data of KH-71-5 (Phoenix Expedition) of the Hakuho Maru, Ocean Research Institute, Tokyo, Japan, 1973

Table II

Density Surface	Meridional Gradient of Dissolved Silicon, $\Delta Si/\Delta y$ ($\mu M\ km^{-1}$)				
	S.W. Pacific	S.E. Pacific	Drake Passage	S.W. Indian	S.E. Indian
$\sigma_0 = 27.54/\sigma_1 = 32.20$	-5.4×10^{-2}	-4.2×10^{-2}	$-(2\ \text{to}\ 6) \times 10^{-2}$	-2.2×10^{-2}	~ 0
$\sigma_2 = 37.09$	-3.6×10^{-2}	-3.3×10^{-2}	$-(2\ \text{to}\ 6) \times 10^{-2}$	$+3.6 \times 10^{-2}$	~ 0

Table III

Poleward Diffusive Flux (g Si s^{-1})

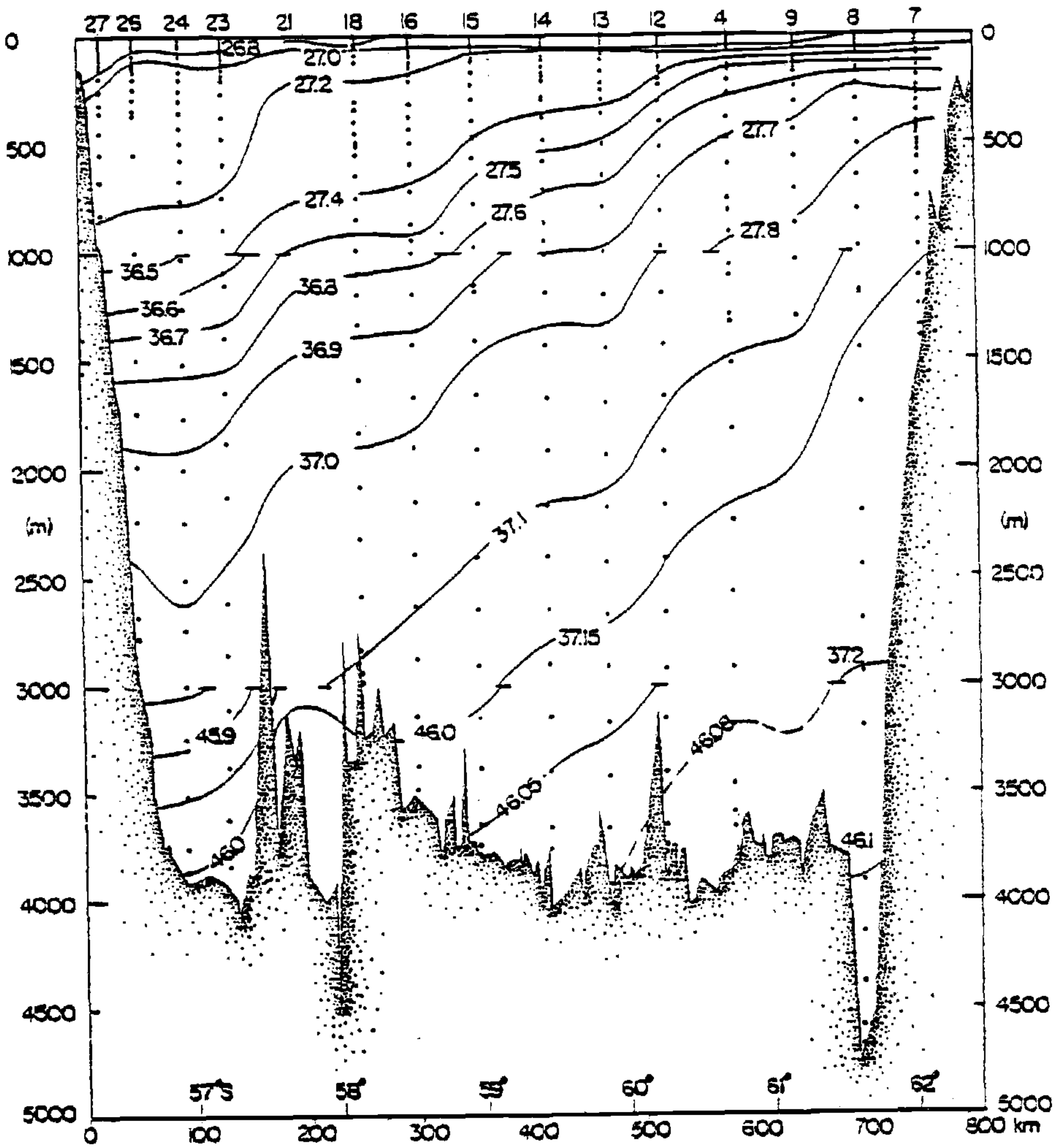
Core Layer (Representative Density Surface)	Pacific and Drake Passage (150°E 30°W)	Indian Ocean (30°E 80°E)	Total
Nutrient Maximum (σ_0 = 27.54/σ_1 = 32.20)	+2.8 x 10^6 to 2.8 x 10^7	+8.4 x 10^5 to 8.4 x 10^6	+3.6 x 10^6 to 3.6 x 10^7
Nutrient Minimum (σ_2 = 37.09)	+3.0 x 10^6 to 3.0 x 10^7	-9.0 x 10^5 to-9.0 x 10^6	+2.1 x 10^6 to 2.1 x 10^7
Net Flux	+5.8 x 10^6 to 5.8 x 10^7	-6.0 x 10^4 to 6.0 x 10^5	+5.7 x 10^6 to 5.7 x 10^7

Equatorward Eddy Flux (g Si s^{-1})

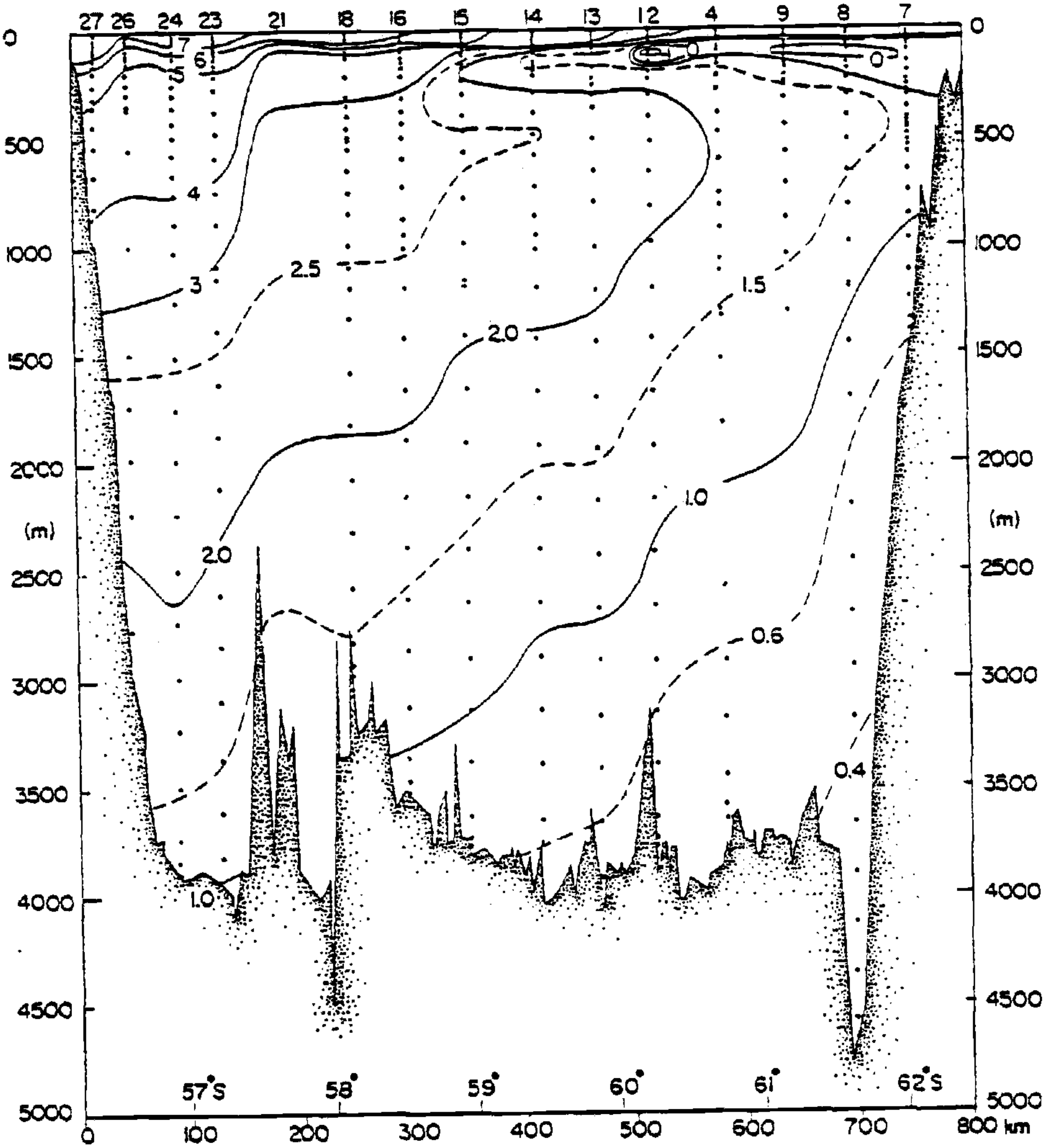
Water Mass	$\overline{\Delta Si/\Delta\theta}$ (μM $°C^{-1}$)	$\overline{V'T'}$ (°C m s^{-1})	Flux of Silicon (g Si s^{-1})
Circumpolar Deep Water	-30	3.0 x 10^{-3}	-1.0 x 10^8
Antarctic Bottom Water	+25	1.6 x 10^{-3}	+1.2 x 10^7
			-8.8 x 10^7

Summary of Flux Calculations. Diffusive fluxes were calculated using an average $\Delta Si/\Delta y$ of 5 x 10^{-2} μM km^{-1} in the nutrient maximum layer and 3.5 x 10^{-2} μM km^{-1} in the nutrient minimum/salinity maximum layer. These layers were taken to be 1 x 10^3 m and 1.5 x 10^3 m thick respectively over a frontal extent twice the linear distance along the front to account for the convoluted nature of the frontal zone. The range of values results from the use of 10^2 m^2 s^{-1} to 10^3 m^2 s^{-1} for K_h. Low frequency eddy fluxes were computed assuming a vertical extent of 2 x 10^3 m and 5 x 10^2 m of the $\Delta Si/\Delta\theta$ relationship in cow and AABW respectively.

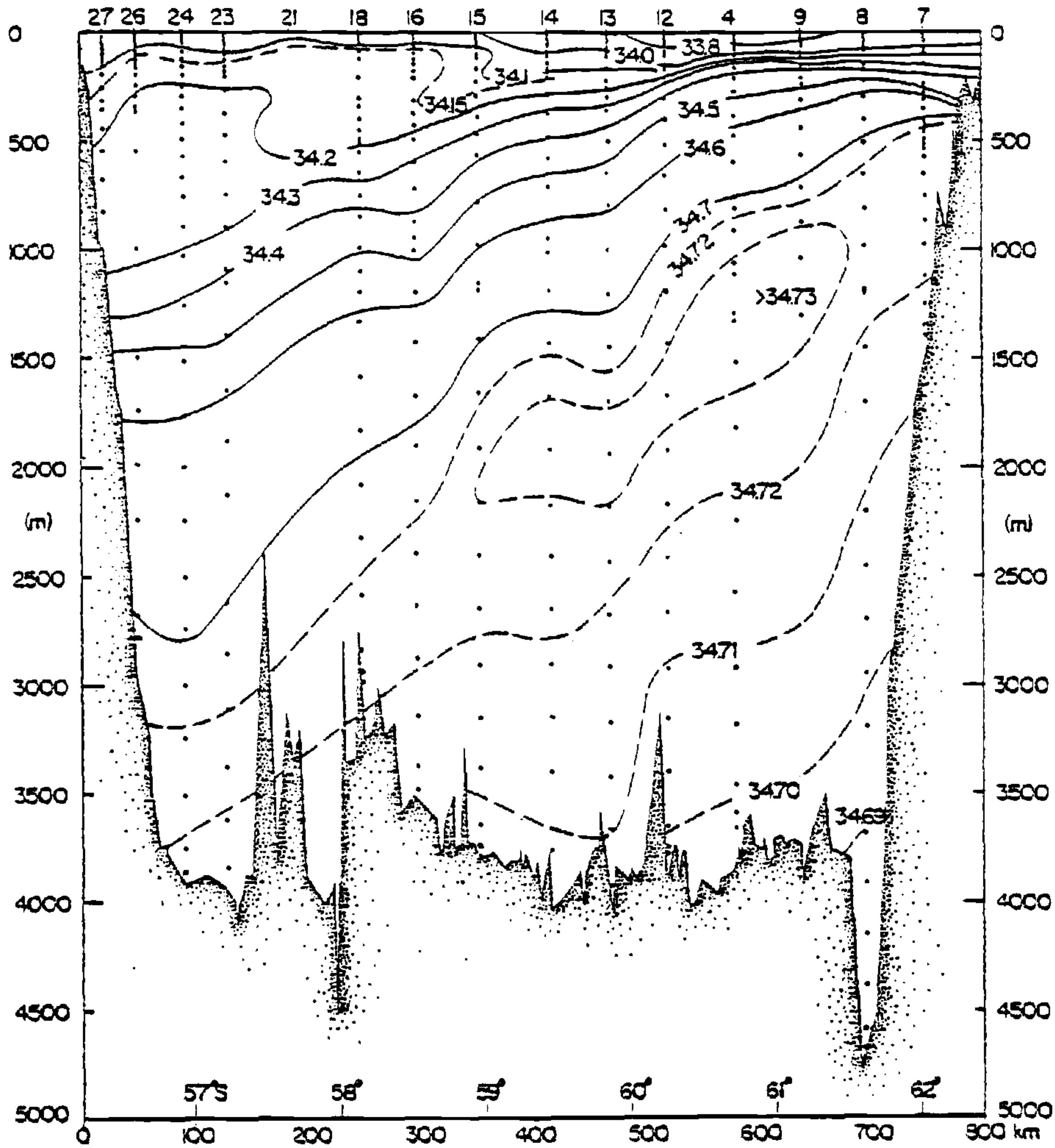
Figure 1. Meridional property distributions in the Drake Passage; contoured data from FDRAKE 75, section II. (a) Potential density relative to 0, 2000, and 4000 dbar, (b) Temperature (°C), (c) Salinity (°/$_{oo}$), (d) Dissolved silicon (μM), (e) Nitrate (μM), and (f) Phosphate (μM). (Sections prepared by W. D. Nowlin, Jr. and T. Whitworth, III.)


27 26 24 23 21 18 16 15 14 13 12 4 9 8 7
26.8
27.0
27.2
27.4
27.5
27.6
27.7
27.8
36.5
36.6
36.7
36.8
36.9
37.0
37.1
37.15
37.2
45.9
46.0
46.05
46.08
46.1
(m)
57°S 58° 59° 60° 61° 62°
0 100 200 300 400 500 600 700 800 km

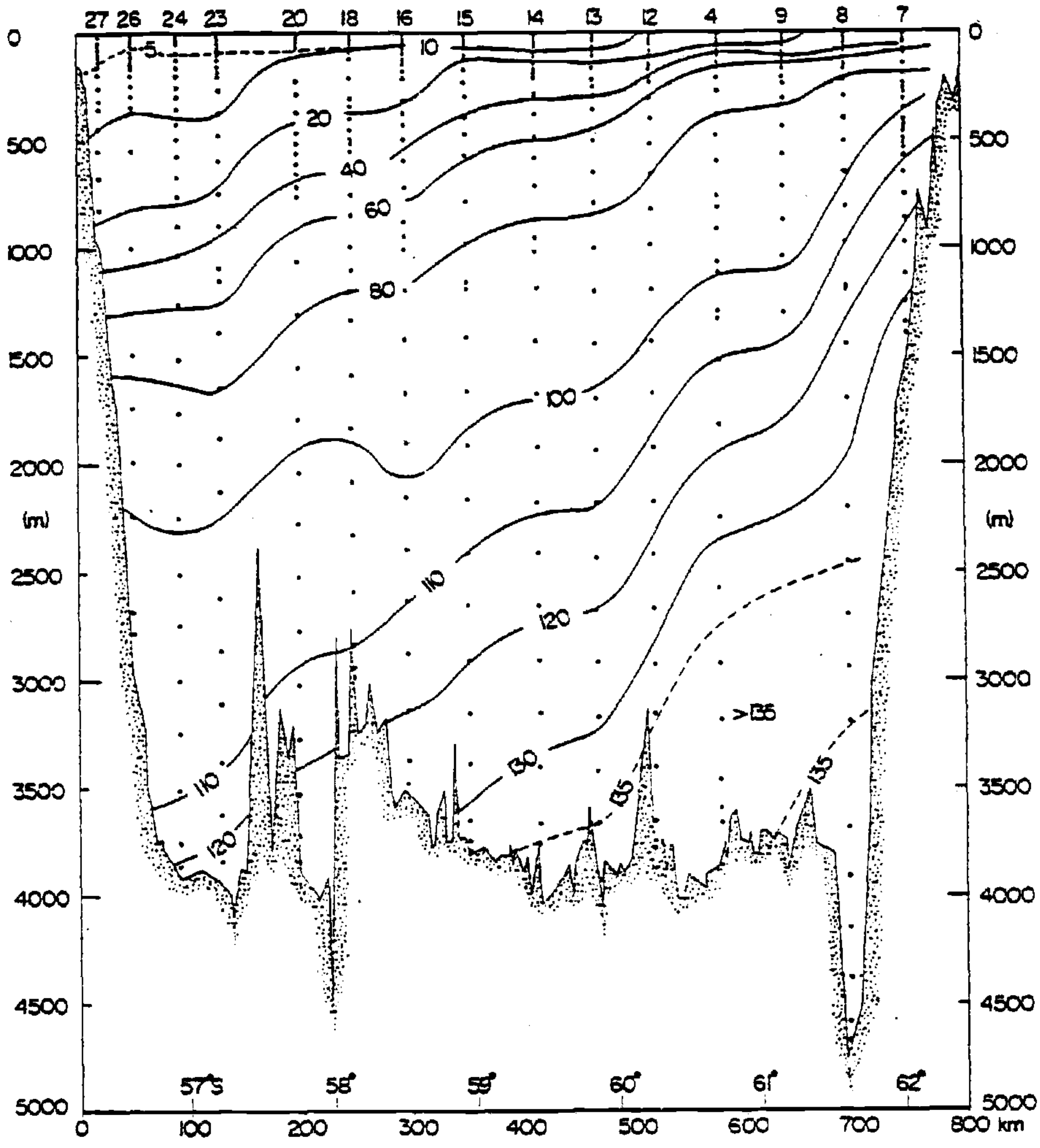
(a)


27 26 24 23 21 18 16 15 14 13 12 4 9 8 7
0
500
1000
1500
2000
(m)
2500
3000
3500
4000
4500
5000
7
6
5
4
3
2.5
2.0
2.0
1.5
1.0
0.6
0.4
1.0
0
57°S
58°
59°
60°
61°
62°S
0
100
200
300
400
500
600
700
800 km

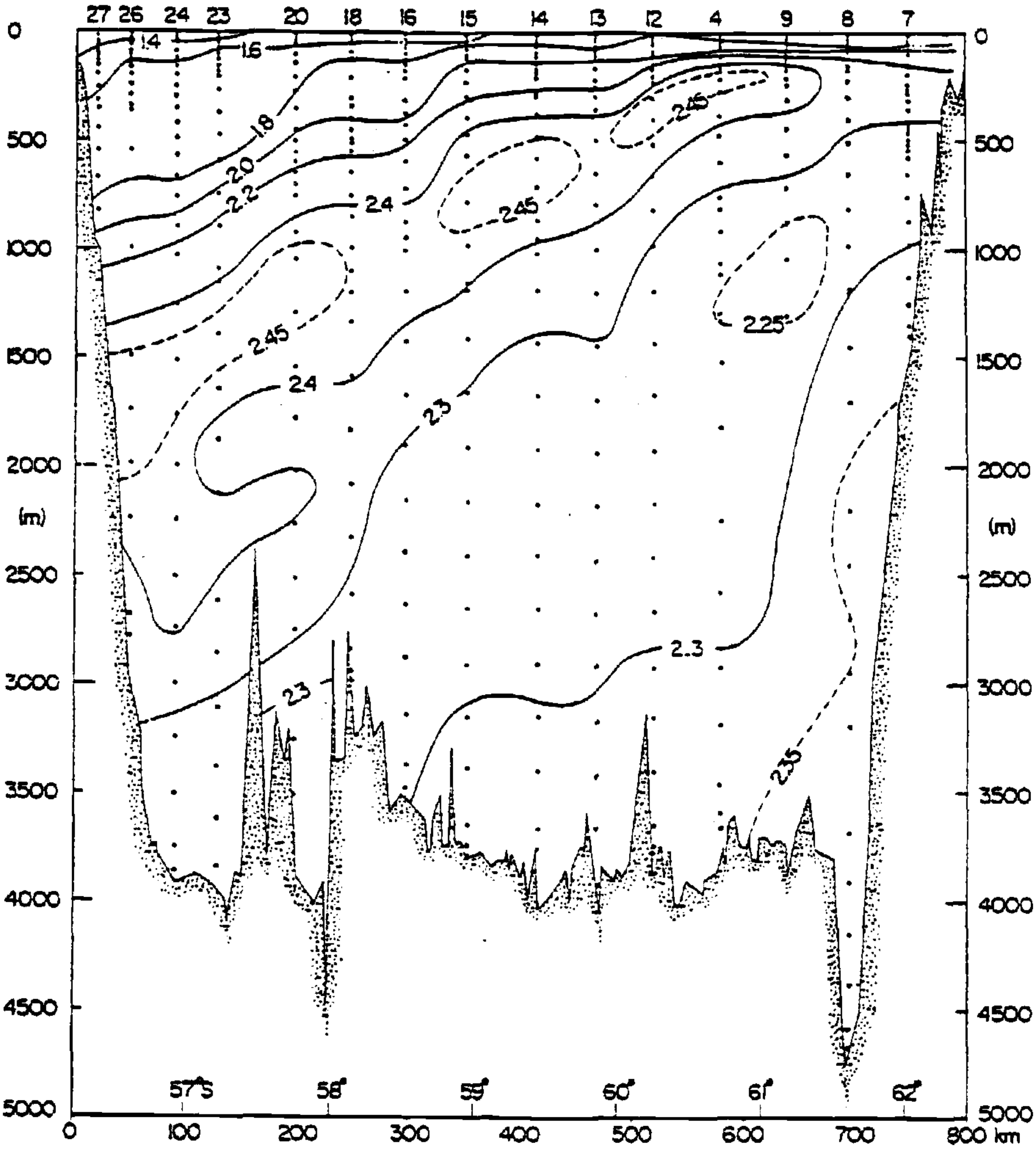
(b)


27 26 24 23 21 18 16 15 14 13 12 4 9 8 7
33.8
34.0
34.1
34.15
34.2
34.3
34.4
34.5
34.6
34.7
34.72
>34.73
34.72
34.71
34.70
34.69
(m)
57°S 58° 59° 60° 61° 62°
0 100 200 300 400 500 600 700 800 km
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000

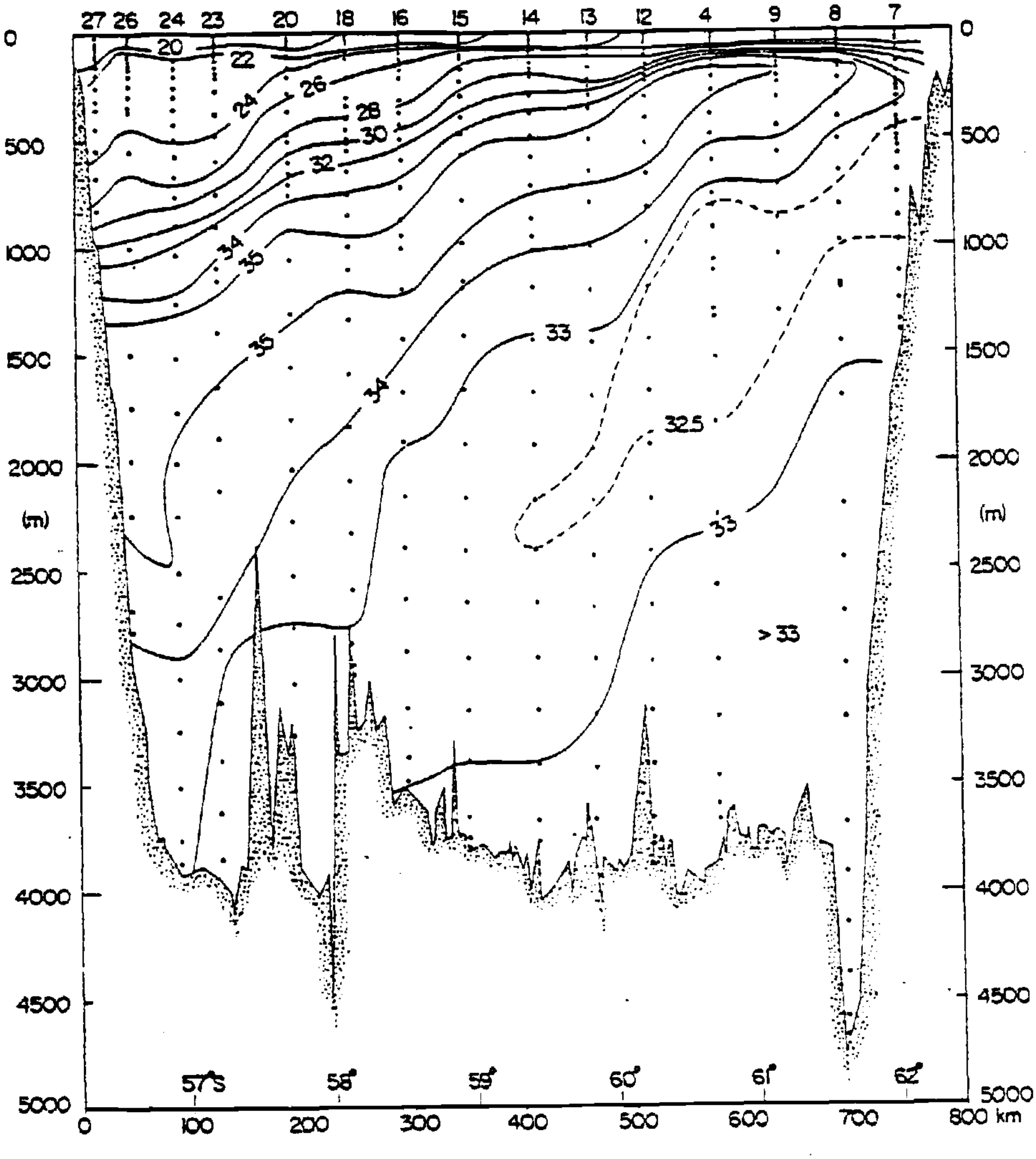
(c)


27 26 24 23 20 18 16 15 14 13 12 4 9 8 7
5
10
20
40
60
80
100
110
120
130
135
>135
(m)
57°S 58° 59° 60° 61° 62°
0 100 200 300 400 500 600 700 800 km
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000

(d)


27 26 24 23 20 18 16 15 14 13 12 4 9 8 7
1.4
1.6
1.8
2.0
2.2
2.4
2.45
2.3
2.25
2.35
0
500
1000
1500
2000
(m)
2500
3000
3500
4000
4500
5000
57°S
58°
59°
60°
61°
62°
0
100
200
300
400
500
600
700
800 km

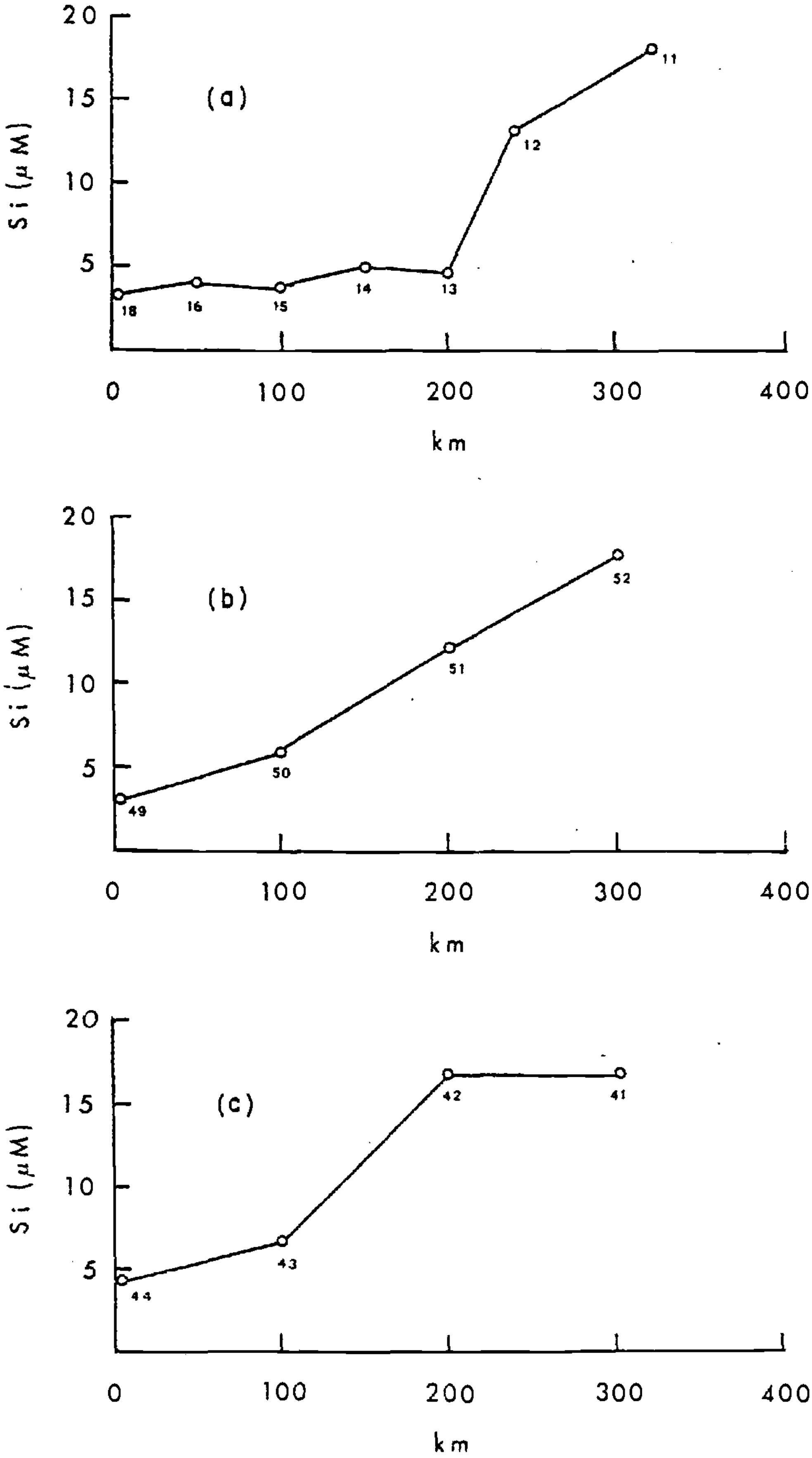
(e)



27 26 24 23 20 18 16 15 14 13 12 4 9 8 7
20
22
24
26
28
30
32
34
36
35
34
33
32.5
33
>33
0
500
1000
1500
2000
(m)
2500
3000
3500
4000
4500
5000
57°S
58°
59°
60°
61°
62°
0
100
200
300
400
500
600
700
800 km

(f)

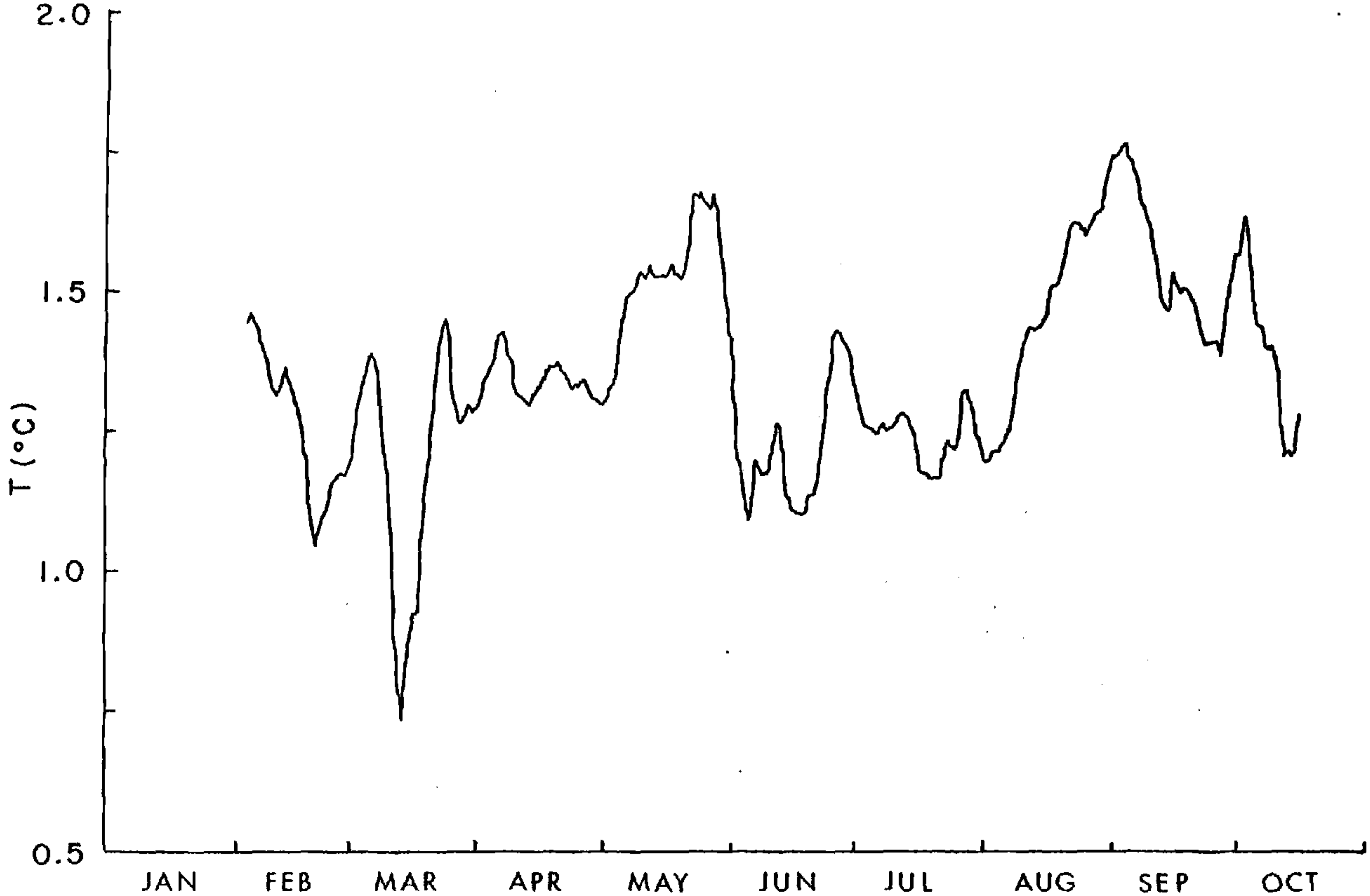
Figure 2. Meridional gradients of dissolved silicon in Drake Passage surface waters. FDRAKE 75 station numbers indicated by small numerals. Distance is southward from the northernmost station. (a) Section II, (b) Section V, (c) Section IV.



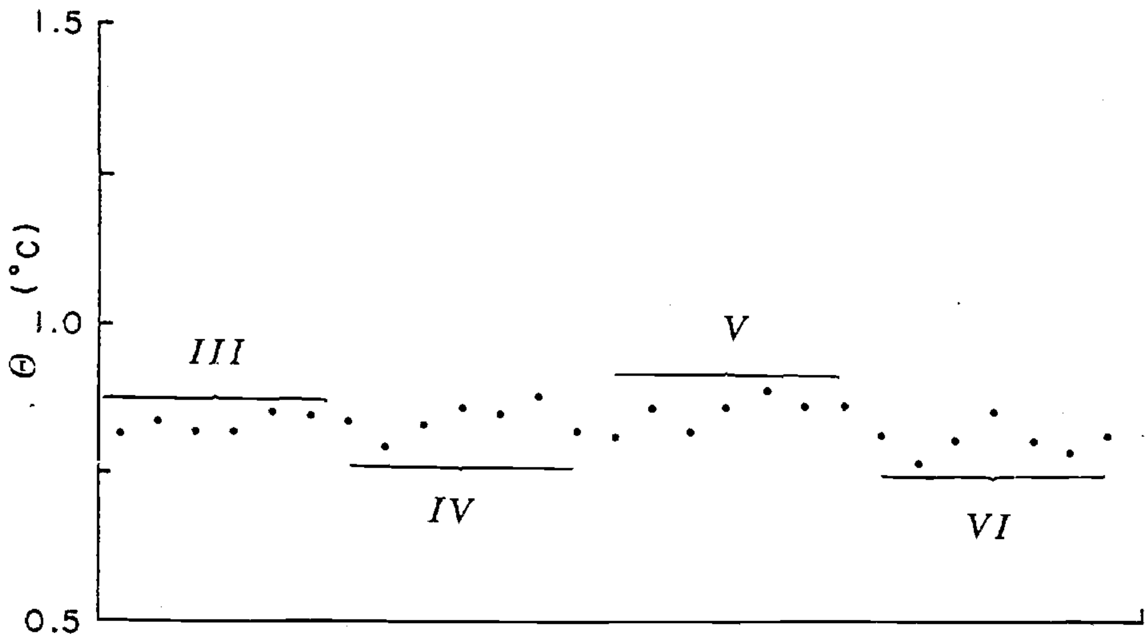
20
15
10
5
(a)
Si (μM)
18
16
15
14
13
12
11
0
100
200
300
400
km
20
15
10
5
(b)
Si (μM)
49
50
51
52
0
100
200
300
400
km
20
15
10
5
(c)
Si (μM)
44
43
42
41
0
100
200
300
400
km

Figure 3. (a) Temperature record from 2000 m at 1977 ISOS mooring central. (Supplied by R. D. Pillsbury.)

(b) Potential temperature on the $\sigma_2 = 37.09$ isopycnal for four transects of the Drake Passage. FDRAKE 75 hydrographic section numbers are indicated by Roman numerals.



(a)



(b) STATION SEPARATION ≐ 100 km

Figure 4. Composite θ/Si diagram for stations south of the Polar Front Zone. Stations are from Drake Passage, Scotia Sea, and S. Atlantic.

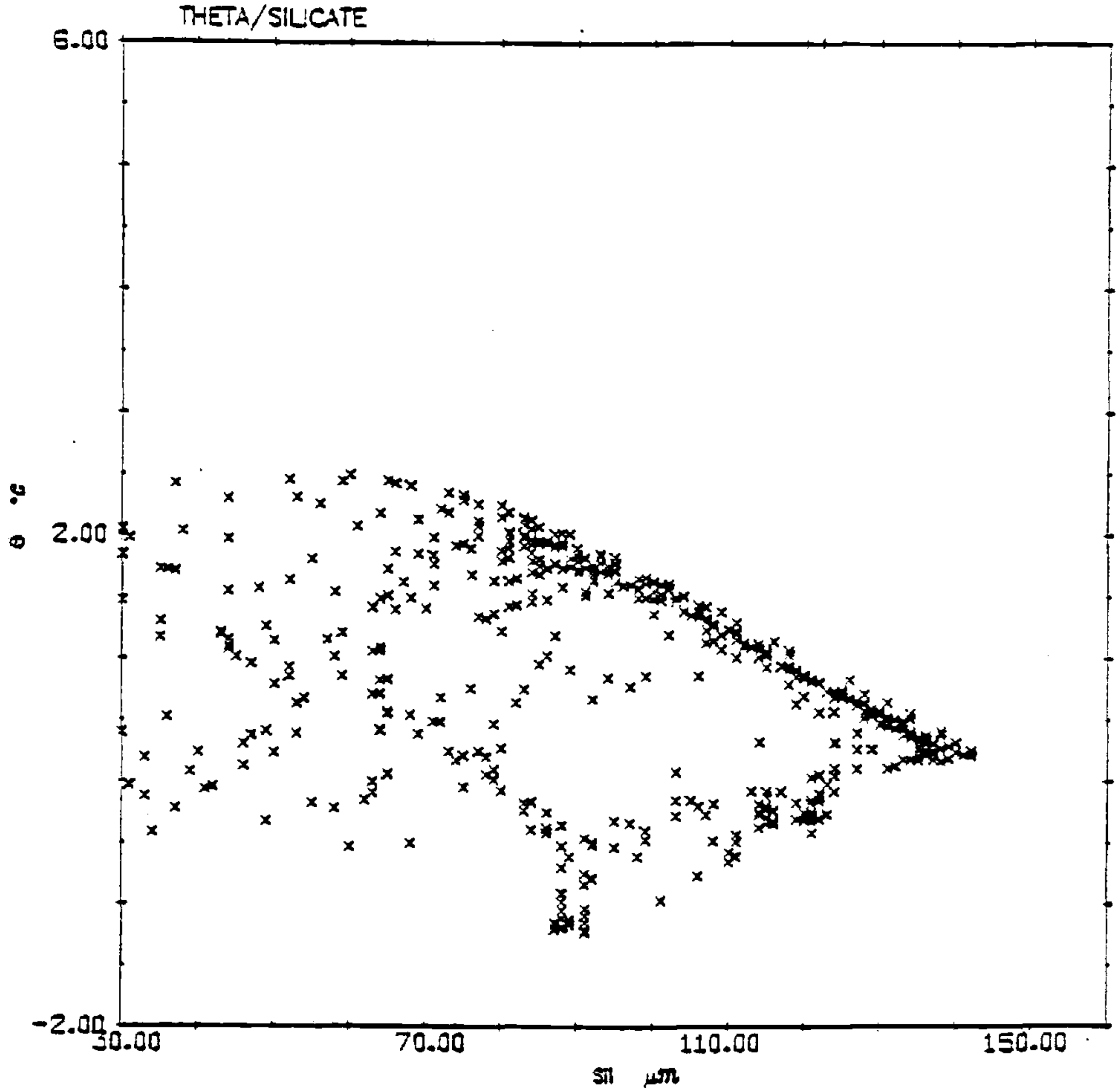
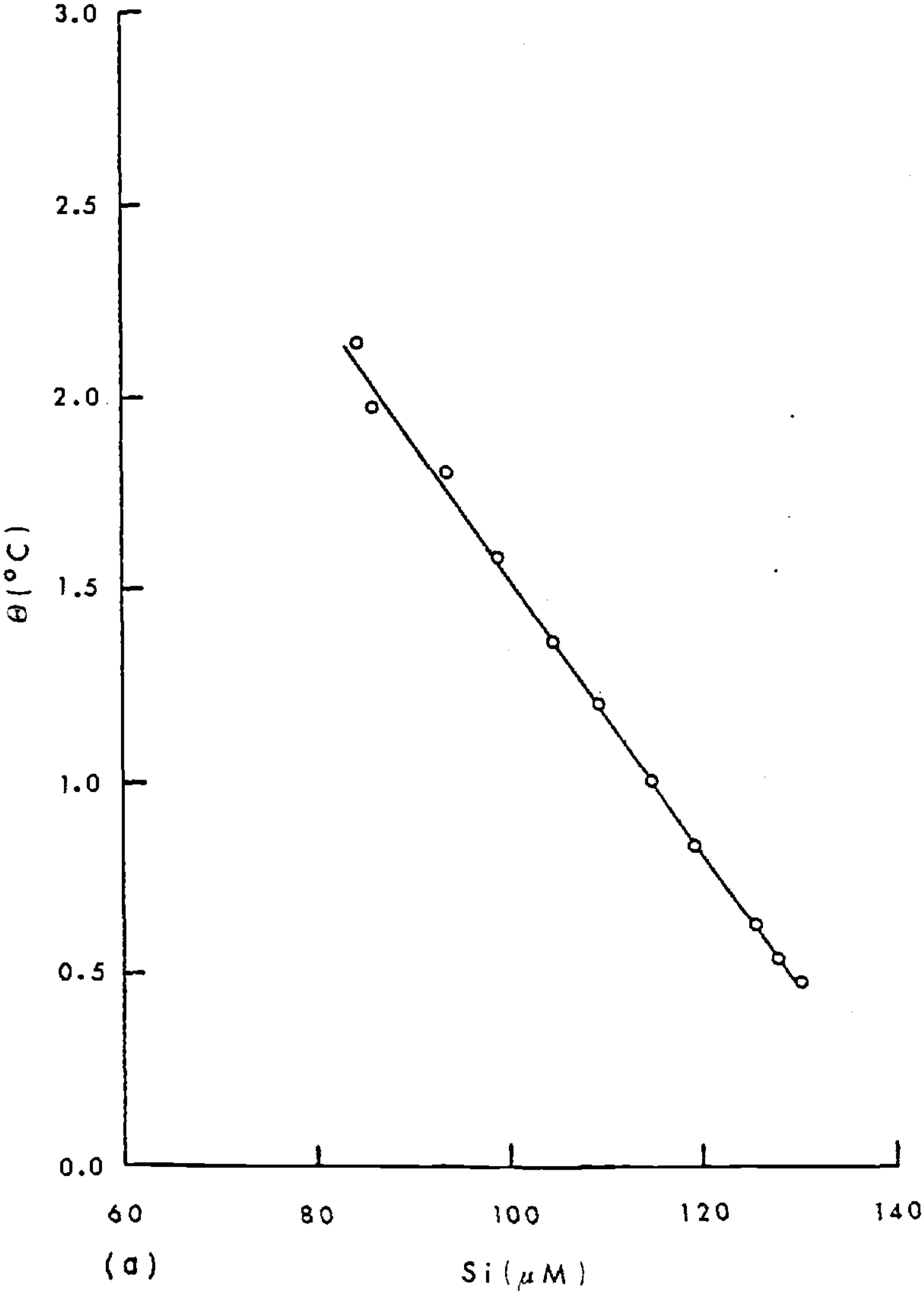
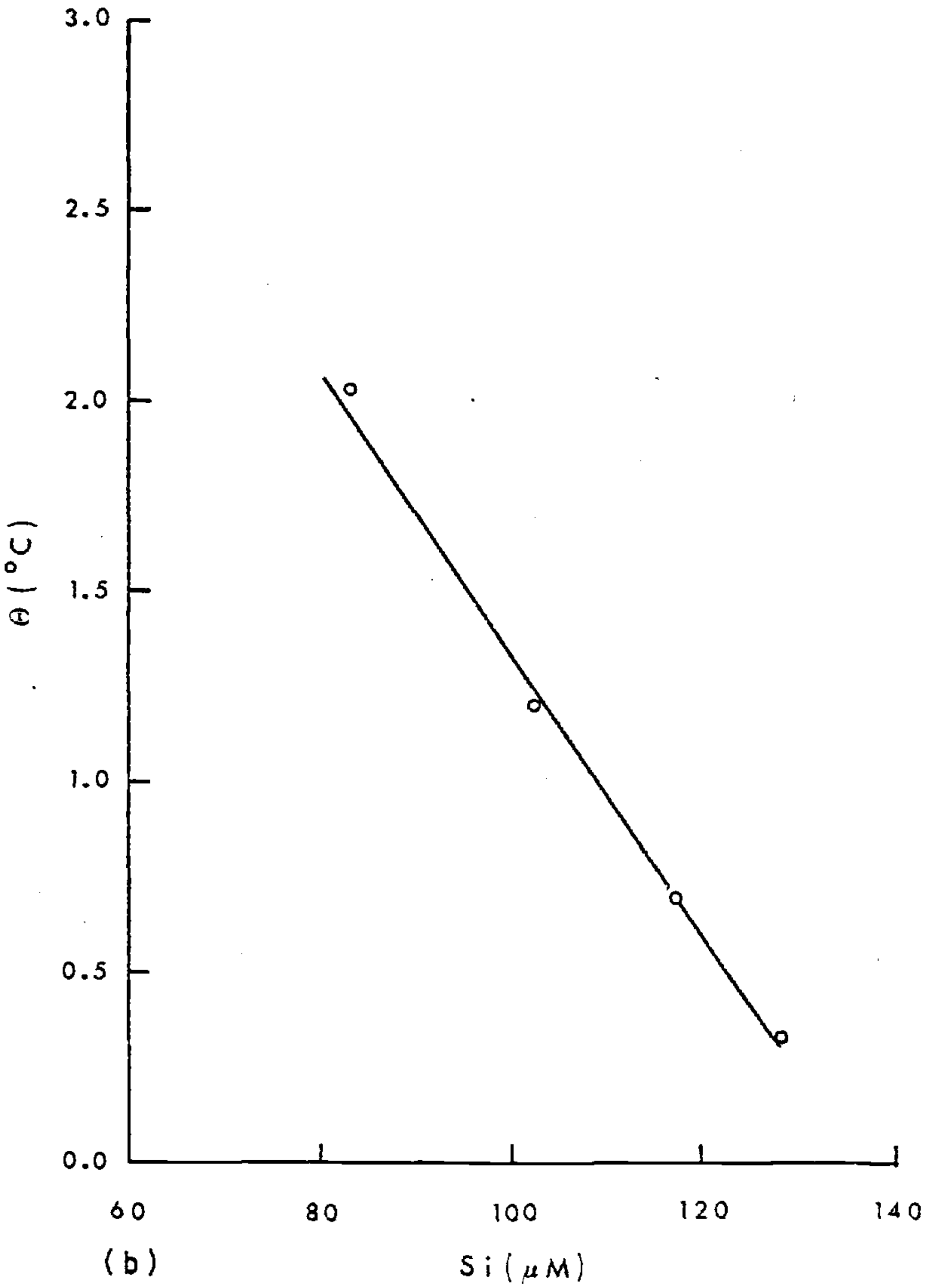
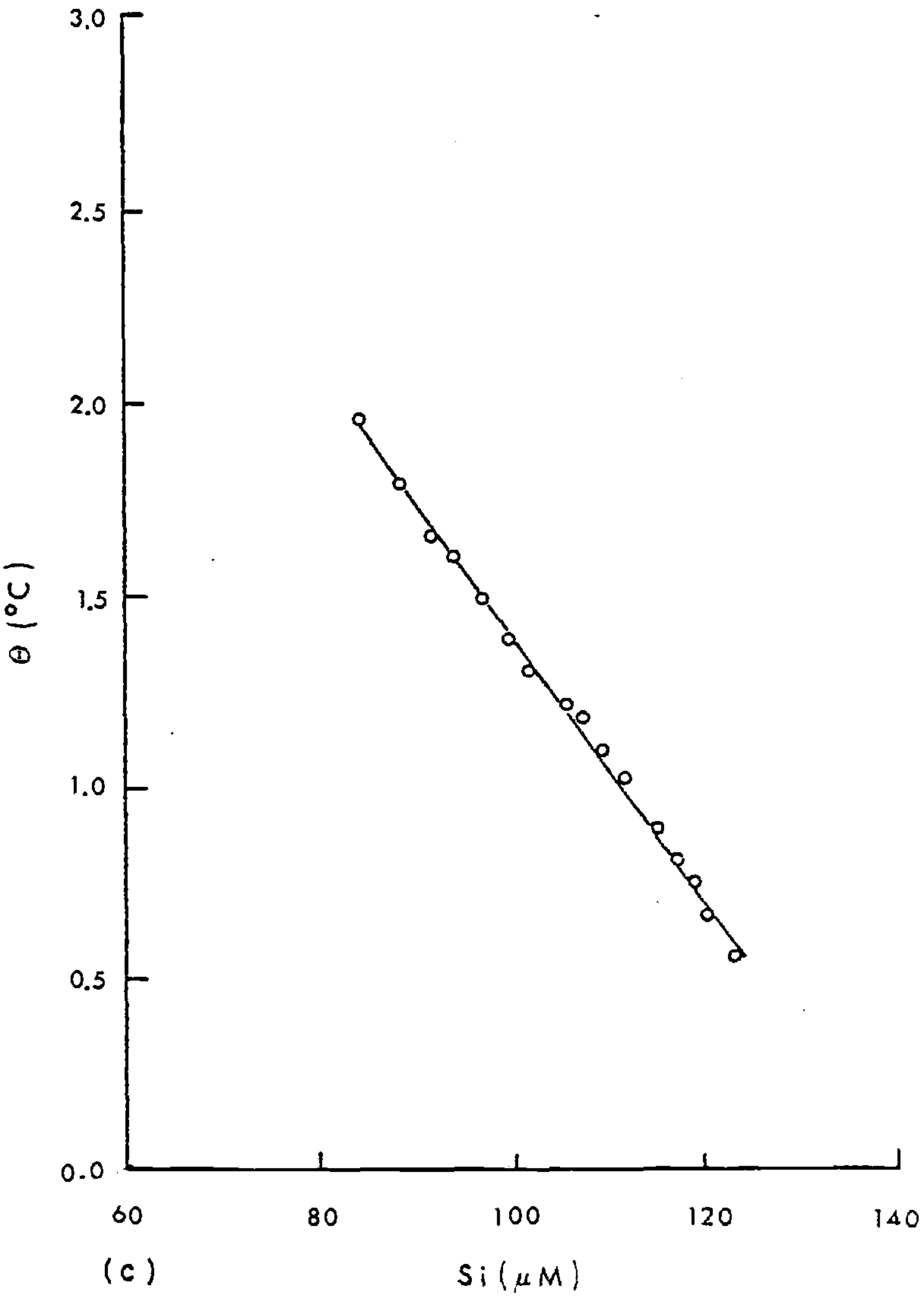

THETA/SILICATE
6.00
2.00
-2.00
θ °C
30.00
70.00
110.00
150.00
Si µm

Figure 5. θ/Si relationship in the Circumpolar Deep Water. (a) Drake Passage, FDRAKE 76 Stn 11, (b) S.W. Indian Ocean, CONRAD-17 Stn 280, (c) S.E. Indian Ocean, GEOSECS Stn 433, (d) S.W. Pacific, KNORR-73 Stn 40.

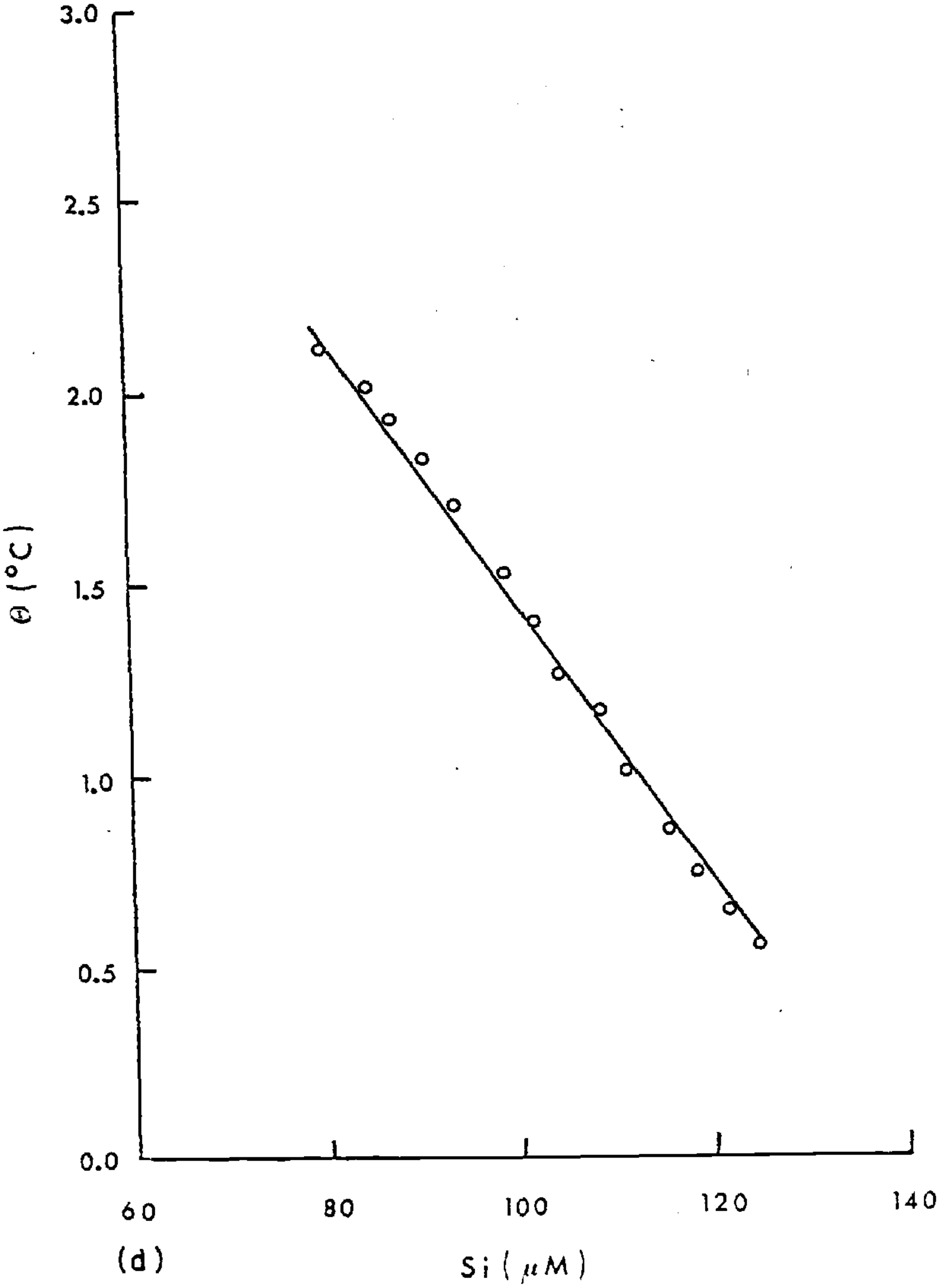

3.0
2.5
2.0
1.5
1.0
0.5
0.0
θ (°C)
60
80
100
120
140
(a)
Si (μM)



(b)

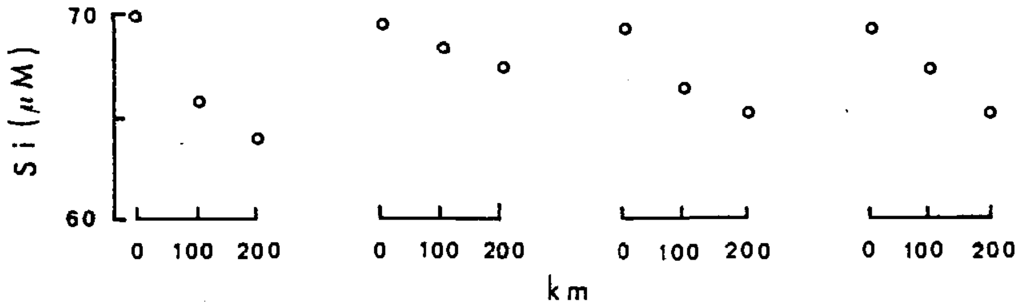


(c)

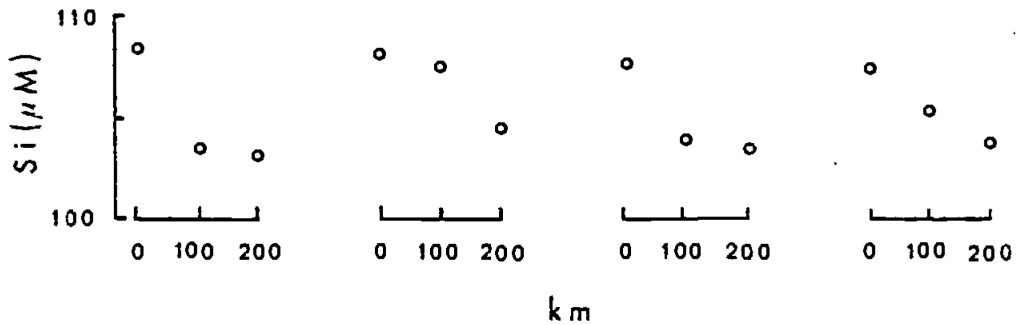


(d)

Figure 6. Meridional gradients of dissolved silicon on isopycnal surfaces from four transects of the Drake Passage. Each set of three stations represents a transect of the frontal zone, distance is southward from the northernmost station.



$\sigma_1 = 32.20$



$\sigma_2 = 37.09$