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Diatom constraints on sea surface temperatures and sea ice distribution during the middle part of the Pliocene

By

John A. Barron [1]

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[1] MS 910, Menlo Park, CA 94025

ABSTRACT

Diatom data are presented for the middle part of the Pliocene (3.2-2.8 Ma) of 11 deep-sea cores from the Southern Ocean. The relative percentages of the subantarctic species *Fragilariopsis weaveri* (subantarctic) are compared with the Antarctic species *F. barronii* and *Rouxia* spp. to estimate the position of the Antarctic Polar Front during the middle part of the Pliocene as no more than 6° of latitude further south than its present position. When compared with modern oceanographic conditions, these data suggest that summer (December-March) [average] sea surface temperatures in the Southern Ocean during the middle part of the Pliocene were typically about 2°C warmer than present at latitudes between 55-65°S. Diatom assemblages and preservation suggest that, although sea ice was geographically less extensive during the middle part of the Pliocene Antarctic summer than it is at present, it was prominent in parts of the western Weddell Sea region near ODP Site 695. Together, these results concur more closely with the "stableist" theory of limited Pliocene Antarctic deglaciation than with the "dynamicist" theory of a major deglaciation at this time.

INTRODUCTION

A climatically warm interval in the middle part of the Pliocene, 3.2-2.8 Ma, is the focus of the PRISM Project of the U.S. Geological Survey (Dowsett and others, 1994) as well as a report by Barron (1996) on the relative percentages of diatom taxa in 5 deep-sea cores (DSDP 266, ODP 699A, ODP 747A, ODP 751A, and Eltanin core 50-28) from the Southern Ocean. According to Webb and Harwood (1991), this interval coincides with an episode of major deglaciation of East Antarctica. Diatom analyses suggest that assemblages containing greater numbers of *Nitzschia weaveri* over assemblages composed of *N. barronii* and *Rouxia* spp. are indicative of deposition beneath subantarctic waters lying to the north of the Antarctic Polar Front (APF) (Abelmann and others, 1990; Fenner , 1991; and Barron, 1996). (Note that *Nitzschia barronii*, N *weaveri*, and many other *Nitzschia* taxa have recently been transferred to the genus *Fragilariopsis* -see Appendix.) In addition to diatom data, Barron (1996) also used supporting evidence from calcareous nannofossils and benthic foraminifers and concluded that the APF may have migrated by as much as 6° of latitude further to the south in the southeastern Atlantic and Indian Oceans during the middle part of the Pliocene (hereafter referred to as the middle Pliocene for the sake of brevity). By using analogies with modern sea surface temperatures at the APF, Barron (1996) reasoned that summer sea-surface temperatures were no more than 3-4°C warmer than present at latitudes between 55° and 60°S.

The purpose of this paper is to report on diatom relative abundances in the middle Pliocene of 11 additional Southern Ocean deep-sea cores. The methods of Barron (1996) are similarly applied to infer the position of the APF and to provide constraints on estimates of summer sea surface temperatures and the extent of sea ice during the middle Pliocene.

MATERIALS AND METHODS

Samples were selected for diatom analysis from DSDP 274, DSDP 323, ODP 690B, ODP 693A, ODP 695A and Eltanin Cores 13-3, 13-17, 14-8, 16-4, 36-33, 50-33 (Table 1, Fig. 1). These cores were chosen because they lie relatively near (within about 10° of latitude) the present day APF, and because they contain a good middle Pliocene record. Available magnetostratigraphy and biostratigraphy - (DSDP 274 - McCollum, 1975), (DSDP 323 -Schrader, 1976), (Eltanin 36-33 - Keany, 1978), (Eltanin 13-3, 14-8, 13-17, 16-4, and 50-33 - Burckle and Abrams, 1987), (ODP 695A - Shipboard Scientific Party, 1988), (ODP 690B, 693A and ODP 695A - Gersonde and Burckle, 1990), and (ODP 690B - Speiss, 1990) were used to constrain the interval of study to approximately 3.2-2.8 Ma. Diatom biostratigraphy was further refined by the author, and ages for diatom datum levels after Harwood and others (1992) and Barron (1996) were used in developing age models for each core (Table 2).

Samples were disaggregated in a beaker by covering them with distilled water (5 times the volume of the sample) and stirring them with a disposable wooden stick. To prepare slides, the beaker was shaken and a drop of the suspension was taken after 5-10 s from near the top of the suspension, transferred to a 22 X 30 mm cover slip and allowed to dry overnight. Residue was then mounted in Hyrax (index of diffraction = 1.71). Whenever possible, at least 300 individual diatoms were counted using the counting techniques of Schrader and Gersonde (1978). Random traverses of the microscope slides were made under the light microscope at 1250X and diatoms were tabulated according to counting categories explained in the Appendix. Ages in this paper are after the Berggren and others (1985) geomagnetic polarity time scale, which are about 0.12 to 0.14 m.y. younger than ages referred to in the Cande and Kent (1995) geomagnetic polarity time scale.

RESULTS

Table 3 shows the relative percentages of various diatom taxa in the 11 deep-sea cores that were studied. Ages for each sample are derived from the age models (Table 2) and construction of age vs. depth plots.

Biostratigraphy

Diatom datum levels that are particularly useful in and around the middle Pliocene interval of study include the first occurrences (FO) of *Thalassiosira insigna* and *Fragilariopsis weaveri* at 3.2 Ma, the FO of *T. vulnifica* at 3.1 Ma, and the last occurrence (LO) of *T. complicata* at 3.06 Ma (Table 2)(Barron, 1996). Of these, the FO of *T. vulnifica* and the LO of *T. complicata* are particularly critical, because they are close to each other and the ranges of the two taxa overlap in time.

The LO of *T. complicata* was identified in all of the 11 deep-sea cores studied (Table 2). This datum level is well constrained by magnetostratigraphy in Eltanin cores 14-8, 13-3, and 50-33, whereas magnetostratigraphic control is less certain in Eltanin core 13-17 and ODP Hole 695A. The LO of *T. complicata* consistently falls within the middle normal event of the Gauss Normal Polarity Chron (C2An.2n) in the Southern Ocean cores investigated, which concur with the results of Barron (1996).

The FO of *T. vulnifica* was identified in all cores except DSDP 323 and Eltanin 50-33 at a stratigraphic level just below the LO of *T. complicata* (Table 2). However, occurrences of *T. vulnifica* have proven to be inconsistent in some south Pacific cores (Eltanin 13-17, 14-8, 16-4, and 50-33 and DSDP 323) where the taxon displays a reduced relative abundance (Table 3), presumably reflecting its ecological preferences. Gersonde and Bárcena (in press) suggested that *T. vulnifica* had its main occurrence in the northern belt of the Southern Ocean, away from the Antarctic continent, but Table 2 shows consistent and relatively common occurrences of this taxon near the Antarctic continent at DSDP Site 274 and ODP Site 693. These results support Fenner (1991), who noted that this endemic Antarctic species "shows no obvious preference for either Antarctic or subantarctic surface waters". Where *T. vulnifica* is consistently present and constrained by magnetostratigraphy (Eltanin 14-8 and 36-33, DSDP 695A), the FO of *T. vulnifica* lies stratigraphically just below the termination of the Mammoth Reversed Polarity Subchron of the Gauss (C2A.2r) at a level that approximates 3.1 Ma in the Berggren and others (1985) time scale.

Harwood and Maruyma (1992) reported a maximum age of 3.1 Ma for the FO of *Fragilariopsis kerguelensis*, whereas this taxon has been typically assigned an age of 2.7 Ma in the Southern Ocean (Baldauf and Barron, 1991). The results of this report show that *F. kerguelensis* was quite variable in its distribution in the Southern Ocean during the middle Pliocene (Table 3). It is virtually absent in higher latitude cores closer to Antarctica (i.e.., DSDP 274, ODP 693A, and ODP 690B), and overall, its occurrences in most cores is quite sporadic, as also reported by Barron (1996). The FO of F. *kerguelensis* does appear to occur between 3.1-3.0 Ma in Pacific Ocean Eltanin cores 13-17, 14-8 and 13-3 (Table 2), supporting the observation by Burckle (pers. comm.) that this taxon has an earlier FO in the Pacific Ocean sector than elsewhere in the Southern Ocean.

The diatom data from part of core 13-17 (13.84 to 16.86 meters below sea floor) are inconsistent with the results from the other cores and suggest that the stratigraphy may be reversed (Table 2). The Antarctic Marine Geology Research Facility at Florida State University, confirms (pers. comm., 1996) that it is possible that this section may have been mistakenly labeled upside down sometime during the past 25 years (Tom Janecek, pers. comm., 1996). When the depths of the magnetostratigraphic reversals published in Burckle and Abrams (1987) are recalculated to account for the section being upside down (values in parentheses in Table 2), the diatom biostratigraphic data for this core are in good agreement with that from the other cores.

Comments on Diatom Preservation

The results of diatom studies for the 11 deep-sea cores studied (Table 3) may be compiled to generate a biogeography for certain diatom taxa. It is apparent, however, that the diatom assemblages in the various samples investigated are influenced by varying degrees of preservation. For example, the ratio of robust taxa that are relatively resistant to dissolution (e.g., *Thalassiosira insigna* and *T. oliverana*) to more finely-silicified taxa (e.g., *Fragilariopsis* spp. and *Rouxia* spp.) may be more a factor of preservation than of environment. Similarly, robust taxa such as *Eucampia antarctica* and *Stephanopyxis* spp. are more likely to survive reworking and transport by bottom currents, so that their presence in a sample may not reflect contemporaneous conditions in the surface waters above a core site.

Scarcity of diatoms caused by poor preservation in a given sample is also indicated by total counts of diatoms that are below 200, namely, in most of Eltanin cores 13-17 and 13-3, the lower part of Eltanin core 50-33, and the upper part of ODP 693A.

Similarly, the relative percentage of reworked diatoms is a measure of the amount of redeposition that affected the sediment. Reworked diatoms are consistently numerous (>10%) in Eltanin core 14-8 and fairly common (typically >5%) in the upper parts of Eltanin core 13-17.

The quantitative data from Eltanin cores 13-17, 13-3, and 14-8 are considered to be of lesser quality than that from cores with better preserved and less altered diatom assemblages.

DISCUSSION

Tracking the Antarctic Polar Front

Of the cores studied, only Eltanin cores 13-3 and 16-4 lie north of the present day Antarctic Polar Front (APF) (Fig. 1). The remaining 9 cores, as well as the 5 cores previously studied by Barron (1996), lie at varying distances to the south. If it is possible to use diatoms to recognize the position of the APF during the middle Pliocene as suggested by Fenner (1991) and Barron (1996), the widespread geographic distribution of these cores should provide a means to constrain southward displacement of the APF.

Because Barron (1996) recognized major differences in preservation of diatom assemblages from the middle Pliocene from the Southern Ocean, he proposed comparing only the total *Fragilariopsis (Nitzschia*) spp. and *Rouxia* in a given assemblage. These small, relatively delicate taxa are of similar size and similar resistance to dissolution, and modern environmental studies (Fenner and others, 1976; Pichon and others, 1987) as well as studies of the Pliocene (Abelmann and others, 1990; Fenner, 1991) suggest that they should be sensitive indicators of oceanographic conditions in the Southern Ocean. Barron (1996) noted that although *Thalassionema nitzschioides* possesses valves of similar size, they are more resistant to dissolution and may be reworked from Miocene sediments. In addition, *T. nitzschioides* appears to be a less sensitive indicator of environment, as various forms of this taxa are found both north and south of the Antarctic Polar Front (Zielinski and Gersonde, in press).

The total contribution of *Fragilariopsis* spp., *Rouxia* sp., and *Nitzschia reinholdii* is tabulated in the rightmost column of Table 3. These finely-silicified, pennate taxa vary greatly in the middle Pliocene, ranging from 7.8% of the 2.96 Ma-assemblage in Eltanin core 14-8 to 80% of the 3.11 Ma-assemblage in ODP 690B. Percentages are lowest in Eltanin core 14-8 (average 25.8%) and highest at ODP 690A (average 69.8%), presumably reflecting differing preservation of the diatom assemblages.

In the manner of Barron (1996), the individual contributions of *Fragilariopsis weaveri*, *F. barronii*, and *Rouxia* spp. to the total *Fragilariopsis* + *Rouxia* spp. are plotted vs. age on Figure 2. Based on the findings of Abelmann and others (1990) and Fenner (1991), Barron (1996) argued that *F. weaveri* was more common in waters north of the APF during the middle Pliocene, whereas *F. barronii* and *Rouxia* spp. preferred the colder waters lying to the south.

Fragilariopsis weaveri dominates over *F. barronii* and *Rouxia* spp. throughout most of the intervals studied in Eltanin cores 36-33 and 50-33, suggesting that these cores lay north of the APF (Fig. 2). Comparative values of the two groups are more equitable throughout Eltanin core 16-4 and DSDP 323, suggesting that these sites lay near the APF during the middle Pliocene. Eltanin core 16-4, however, lies north of both Eltanin cores 36-33 and 50-33 and well north of the modern-day APF (Fig. 1), and one would expect a greater dominance of *F. weaveri* over the antarctic taxa. Perhaps, the scarcity of samples (2) studied from Eltanin 16-4 that correspond with the main interval of warmth (3.1-2.9 Ma) at Eltanin 14-8, 36-33 and 50-33 (Fig. 2) may be responsible for this anomaly. On the other hand, the extreme scarcity of *Thalassiosira vulnifica* in Eltanin core 16-4 (Table 2) suggests that the age model for that core may be incorrect, so that the wrong interval may have been sampled.

Eltanin core 14-8 displays a dominance revesal at about 3.0 Ma, with *F. weaveri* increasing in abundance at the expense of *F. barronii* and *Rouxia* spp. in younger samples (Fig. 2). All other cores show greater numbers *F. barronii* + *Rouxia* spp. compared to *F. weaveri* throughout the interval studied, implying that they lay beneath Antarctic waters south of the APF during the middle Pliocene.

The relative abundance of subantarctic and subtropical taxa can also be used to suggest whether a site lie north of the APF. *Nitzschia reinholdii* and *Thalassiosira convexa* var. *aspinosa* are subtropical Pliocene diatoms that are present in a number of the samples studied (Table 3). *Azpeitia tabularis*, which prefers warmer water temperatures between 10° and 20°C in the modern Southern Ocean according to Zielinski and Gersonde (in press), is also present in many of the Pliocene samples studied. Similarly, *Hemidiscus karstenii*, a species which Fenner (1991) showed to prefer subantarctic waters north of the APF, was also tabulated in a number of the samples investigated (Table 3).

The relative abundance of these four subantarctic to subtropical diatoms in each of the 11 deep-sea cores studied is shown on Figure 3. Eltanin cores 14-8 and 50-33 both display abundance peaks (ca. 10% of the total assemblage) of these "warmer" species between about 3.10 and 3.04 Ma, implying that these were periods of warmer surface water temperatures at these sites that may have been due to the APF migrating southward across the site. At both of these sites, *H. karstenii* constitutes the greater part of these acmes. Eltanin core 36-33 and DSDP 323 also display an abundance peaks dominated by *H. karstenii* during the same 3.10-3.04 Ma interval of time, but the amplitude of these peaks (ca. 5% of the assemblage) is only half of what it is at the other two sites.

Considering both paleoclimate indices (Figs. 2 and 3), Eltanin cores 14-8, 50-33, and 36-33 are the only cores that appear to have located south of the APF between 3.1 and 3.0 Ma. These three cores all lie just to the south of the present day APF (Fig. 1), so some southward displacement of the APF is implied during the middle Pliocene. Relatively common subantarctic diatoms in DSDP 323 (Figs. 2 and 3) suggest that the APF may have lain near (or slightly south of) that site. Clearly, analysis of additional samples from DSDP 323 would be helpful in clarifying that site's paleoclimatology.

Surprisingly, Eltanin cores 13-3 and 16-4, which lie north of the present day APF, do not contain especially warm middle Pliocene diatom assemblages (Figs. 2 and 3). Core 16-4 does possess relatively equitable numbers of the subantarctic *Fragilariopsis weaveri* and the antarctic *F. barronii* + *Rouxia* spp. groups, which suggest proximity to the APF (Fig. 2), but the numbers of other subantarctic and subtropical diatoms (Fig. 3) remain consistently low (<2%) throughout the interval studied. As stated earlier, the data from Eltanin core 13-3 are highly suspect because of the scarcity of diatoms - fewer than 150 diatoms were counted per microscope slide throughout the interval studied.

Keany (1978) studied the middle Pliocene radiolarian assemblages of Eltanin cores 16-4 and 36-33. Although he reported generalized cooling trend during the Gilbert Reversed-Polarity Chron and made no inferences about the position of the APF, his climate index did show a slight reversal, or warming trend during the middle Gauss Normal-Polarity Chron. Within this same Pliocene interval, Keany (1978) recorded relative abundance values of the radiolarian *Sponotrochus glacialis* to be >15%. Such abundances of *S. glacilalis* in excess of 10% of the assemblage are indicative of deposition north of the APF (Joseph Morley. written comm., 1994). Morley (written comm., 1994) based his conclusions on study of over 50 core tops in the Southern Ocean for CLIMAP (1981).

In conclusion, based of diatom as well as (in part) on radiolarian studies, Eltanin cores 14-8, 50-33, 16-4, and 36-33 are considered to have lain north of the APF during the 3.1 to 3.0 Ma interval of the middle Pliocene. DSDP 323 contains diatom assemblages that suggest the proximity of the APF during the middle Pliocene, while the other cores studied, with the exception of the suspect core Eltanin 13-3, most likely lie to the south of the APF.

The modern APF is compared with its suggested maximum southward position between 3.1 and 3.0 Ma on Figure 1. The 3 Ma APF is mainly drawn from Table 8 and Barron (1996), with areas of stability (little southward displacement) inferred for the Drake Passage and the Falkland Plateau region of the southwest Atlantic as well as for the southern end of Macquarie Ridge, southwest of New Zealand. Barron (1996) cited Lazarus and Caulet (1993) in arguing that the Drake Passage and southern end of Macquarie Ridge acted as stable pinning points for any southward migration of the APF during the middle Pliocene.

Constraints on SST Estimates

Table 4 shows the inferred location (north or south) of the APF relative to the deep-sea core sites studied in this report and those in Barron (1996) during the climatically warm interval between 3.1 and 3.0 Ma. Cores that are located well south of the modern APF (DSDP 274, ODP 690B, ODP 693A) that show no indications of having lain near the APF during the middle Pliocene (Figs. 3 and 4), have not been included. Neither has Eltanin core 13-3, because of the poor quality of its data.

Assuming that the APF during the middle Pliocene had a similar thermal structure as the modern APF, the data of Table 4 might be used along with modern sea surface temperature (SST) data to provide constraints on SST's during the middle Pliocene. Whereas Barron (1996) used an average of January-March sea surface temperatures (SST) as a summer average, Zielinski and Gersonde (in press) argue that it is more appropriate to use an average of December to March, because the diatom growth season in the Southern Ocean actually begins in December. Consequently, the summer average (Dec.-Mar.) for each of the deep-sea core sites has been included on Table 4 with data from Schweitzer (1993). Citing the data of Olbers and others (1992), Zielinski and Gersonde (in press) argue that the APF lies at a summer average SST value of 4°C.

Table 4 suggests that average summer SST's at about 55-65°S were about 2°C warmer than present between 3.1 and 3.0 Ma.

However, based on the monthly averaged SST data of Schweitzer (1993), it is reasonable to assume that February (peak summer) SST's were undoubtedly slightly higher (perhaps 3°C above modern values). These estimates are more conservative that the 3-4°C warming suggested earlier by Barron (1996), but they are in good agreement with SST estimates of Kennett and Hodell (1993) who argue that average SST's in the Southern Ocean were no more than about 3°C warmer than present during the warmest interval of the Pliocene (4.8 to 3.2 Ma).

Sea Ice Distribution

Fragilariopsis curta and *F. cylindra* are widely recognized sea-ice associated diatoms (Burckle and others, 1987; Leventer, 1992; Zielinski and Gersonde, in press). They are restricted to areas south of the Polar Front with summer sea surface temperatures below ca. 2°C, and relatively common (3-15%) occurrences of these taxa coincide with the location of the winter sea ice edge (Zielinski and Gersonde, in press).

Fragilariopsis curta and *F. cylindra* are most common in ODP 695A (Fig. 4), where they typically account for 3 to >10% of the diatom assemblage. Because Site 695 lies within a modern-day abundance zone (3-15%) of *F. curta* and *F. cylindra* as mapped by Zielinski and Gersonde (in press), similar abundances of these sea-ice-related taxa in the studied interval possibly imply that sea ice conditions near Site 695 during the middle Pliocene were similar to those of today. The assemblages of ODP 695A are further distinguished from the other middle Pliocene diatom assemblages studied by the common occurrence of *Chaetoceros* spores and *Thalassiosira antarctica* and persistent presence of *Actinocyclus actinochilus*, *Odontella weisfloggii*, and *Synedra* sp. The modern distributional data of Zielinski and Gersonde (in press) suggest that these diatoms may have been advected westward from sea-ice-influenced neritic environments along the Antarctic Peninsula, typical of the margin of the northern Weddell Sea today.

While modern-day sediments at Site 693 are also rich in *F. curta* and *F. cyclindrus* (15-30%)(Zielinski and Gersonde, in press), middle Pliocene values of this group never exceed 2% of the assemblage, implying either reduced sea ice during the middle Pliocene or dissolution of the middle Pliocene assemblages. Relatively high numbers of delicate *Fragilariopsis* species in the upper part of the section studied at ODP 693A would seem to imply that dissolution was not responsible for relatively low values of *F. curta* and *F. cylindra*.

Relative abundances of *F. curta* and *F. cylindra* in all other cores are typically less than 2%, implying that these cores lay north of the winter sea ice edge. These taxa are absent or very rare in Eltanin cores 14-8, 13-3, 36-33, and 16-4, all of which lie north of latitude 60°S.

Eucampia antarctica is not considered to be a sea-ice indicator, because its distribution in surface sediments has been shown to be discontinuous due in part to the robust nature of its valves and concentration by reworking and winnowing of bottom sediment (Zielinski and Gersonde, in press).

Modern diatomaceous oozes do not occur in the Southern Ocean south of the northernmost limit of December sea ice (Burckle and Cirilli, 1987). Consequently, the presence of the diatom-rich middle Pliocene sediments in high-latitude regions that are covered today by sea ice in December might be taken as evidence of a reduced distribution of sea ice during the middle Pliocene. Figure 5 compares the modern northern limit of December sea ice with the distribution of middle Pliocene deep-sea cores containing well-preserved diatoms. Within the Weddell Sea region ODP Sites 695 and 693, which lie south of the December sea ice limit, both contain well-preserved diatom assemblages in sediments dated between 3.1 and 3.0 Ma (Table 3). Similarly, DSDP 274, which lies beneath waters covered by modern day December sea ice, contains very well-preserved diatom assemblages in sediments dated at 3.1 to 3.0 Ma (Table 3), suggesting that December sea ice in the area was more restricted during the middle Pliocene than it is today (Fleming and Barron, 1996).

Further evidence for reduced sea ice near the coast of Antarctica during the middle Pliocene comes from Harwood's (1986) study of the diatoms of the Dry Valley Drilling Project (DVDP) 10 core. Harwood (1986) reports common and diverse diatom assemblages in samples taken from 152.10 and 150.18 meters below the sea floor, an interval that Ishman and Rieck (1992) correlate with the Kaena Reversed-Polarity Subchron of the Gauss-Normal Polarity Chron (2.92-2.99 Ma). Harwood (1986) also notes that the sea ice diatom *Fragilariopsis curta* is either absent or rare in these samples, additional support for limited sea ice during the diatom growing season (December-March).

The southerly spread of diatom-rich sediments in the high-latitude Southern Ocean during the middle Pliocene and the relatively low numbers of the sea-ice related diatoms *Fragilariopsis curta* and *F. cylindra* in Southern Ocean sediments both suggest that the sea ice edge in December (at the start of the diatom growth season) lay closer to Antarctica during the middle Pliocene and possibly did not much exceed the modern-day February sea ice limit (Fig. 5). Well-preserved middle Pliocene diatomaceous sediments in ODP 693, ODP 695, and DSDP 274 all lie north of this modern February sea ice limit. The DVDP 10 site is located beneath waters covered by modern day February sea ice, but it lies close to open waters to the east in the Ross Sea (Fig. 5).

CONCLUSIONS

Middle Pliocene (ca. 3.2 to 2.8 Ma) diatoms were examined in 11 Southern Ocean deep-sea cores: DSDP 274, DSDP 323, ODP 690B, ODP 693A, ODP 695A and Eltanin cores 13-3, 13-17, 14-8, 16-4, 36-33, 50-33. Age models for these cores are based on existing magnetostratigraphy and both published and refined diatom biostratigraphy. The following diatom datum levels proved to be useful within the middle Pliocene interval of study: the FO of *Fragilariopsis weaveri* at 3.2 Ma, the FO of *Thalassiosira vulnifica* at 3.1 Ma, and the LO of *T. complicata* at 3.06 Ma. *Fragilariopsis kerguelensis* was quite variable in its distribution in the Southern

Ocean during the middle Pliocene. Its occurrence in most cores is sporadic, and it is rarely observed in higher latitude cores closer to Antarctica (i.e.., DSDP 274, ODP 693A, and ODP 690B). In Pacific Eltanin cores 13-17, 14-8 and 13-3 the FO of F. *kerguelensis* approximates 3.1-3.0 Ma.

Preservation is variable in the diatom assemblages investigated. Most cores contain abundant diatoms with relatively high numbers of relatively delicate taxa (*Fragilariopsis* and *Rouxia*), indicating good to excellent preservation. Scarce diatoms and generally poorer preservation characterize most of Eltanin cores 13-17 and 13-3, the lower part of Eltanin core 50-33, and the upper part of ODP 693A. Reworked diatoms are consistently numerous (>10%) in Eltanin core 14-8 and fairly common (>5%) in the upper parts of Eltanin core 13-17.

In order to reduce preservational bias, finely silicified, pennate taxa (*Fragilariopsis* and *Rouxia* spp.) were considered separately in paleoclimatic studies. Domination of *F. weaveri* over the combined group of *F. barronii* and *Rouxia* spp. throughout most of the intervals studied in Eltanin cores 36-33 and 50-33 suggests that these cores lay north of the Antarctic Polar Front during the middle Pliocene. More equitable numbers of these two groups throughout Eltanin core 16-4 , suggesting that Eltanin 16-4 lay near the Antarctic Polar Front (APF). A dominance reversal in Eltanin core 14-8 at about 3.0 Ma, with *F. weaveri* increasing in abundance at the expense of *F. barronii* and *Rouxia* spp. in younger samples, implies that the APF moved northward across the site at about 3.0 Ma.

Comparison of the relative abundance of subtropical taxa (*Thalassiosira convexa* var. *aspinosa* and *Nitzschia reinholdii*) and additional subantarctic taxa (*Azpeitia tabularis* and *Hemidiscus karstenii*) in the 11 cores offers another means to detect the presence of warm subantarctic waters. Eltanin cores 14-8 and 50-33 display abundance peaks (ca. 10% of the total assemblage) of these "warmer" species between about 3.10 and 3.04 Ma, implying periods of warmer surface water temperatures at these sites, possibly as a result of a southward migration of the APF. DSDP 323 and Eltanin core 36-33 also show a minor abundance peak (ca. 5% of the assemblage) of these taxa during the same 3.10 to 3.05 Ma interval. Together, the two diatom paleoclimatic indices suggest that Eltanin cores 14-8, 50-33, and 36-33 probably lay north of the APF during most of the 3.1 to 3.0 Ma interval of the middle Pliocene. Based on the 3 samples studied from DSDP 323, that site probably lay near or slightly south of the APF. While diatom data for Eltanin core 16-4 is not conclusive, Keany's (1978) abundance values of the radiolarian *Sponotrochus glacialis* in excess of 15% of the assemblage are indicative of deposition north of the APF (Joseph Morley, written comm., 1994). The other deep-sea cores studied, with the exception of Eltanin 13-3, which contains poorly preserved diatom assemblages, most likely lie to the south of the APF.

Assuming that the APF during the middle Pliocene APF had a similar thermal structure as the modern APF, these diatom data suggest that average summer (December-March) SST's in the Southern Ocean between 55° and 65°S were about 2°C warmer than they are at present. When Barron's (1996) SST's estimates are recalibrated to include December, the beginning of the diatom growth season (Zielinski and Gersonde, in press), comparable values (ca. +2°C above modern averages for December through March) are obtained (Table 4).

The presence of diatomaceous sediments in the middle Pliocene of Weddell Sea ODP Sites 693 and 695 and Ross Sea DSDP Site 274 is taken as evidence that sea ice was absent at these locations in December at the beginning of the diatom growth season. Harwood's (1986) record of common and diverse diatoms, but low number of sea ice taxa, in sediment paleomagnetically dated as 2.99-2.92 Ma from DVDP core 10 in the Ross Sea is further evidence of reduced sea ice distribution during the middle Pliocene. The sea ice diatoms, *Fragilariopsis curta* and *F. cylindra* , make up less than 2% of the middle Pliocene diatom assemblages, in all of the deep-sea cores studied with the exception of ODP 695A, where they typically account for 3 to >10% of the diatom assemblage. The relative high numbers of *Chaetoceros* spores and *Thalassiosira antarctica* and the consistent presence of *Actinocyclus actinochilus*, *Odontella weisfloggii*, and *Synedra* sp. at ODP 695A are assumed to have been advected westward from sea-ice-dominated neritic environments along the Antarctic Peninsula. Consequently, summer sea ice was most likely present in the western Weddell Sea during the middle Pliocene.

The predicted +2°C warming summer SST's above modern values in the Southern Ocean between 65° and 55°S and the evidence for reduced, but not absent, summer sea ice suggest that any deglaciation of Antarctica during the middle Pliocene was limited in its extent.

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APPENDIX: TAXONOMY

The formal citation of diatom taxa mentioned in this paper is given below along with a reference to representative illustrations (separated from the taxon's name by a semicolon) and some appropriate remarks. The reader is referred to these references for a more thorough taxonomic treatment.

Actinocyclus actinochilus (Ehrenberg) Simonsen; as *Charcotia actinochilus* (Ehrenberg) Hustedt, 1958, pl. 7, figs. 57-80.

A. dimorphus (Castracane) Harwood et Maruyama, 1992, p. 700. pl. 13, figs. 3-5; pl. 17, figs. 19-20.

A. ingens Rattray s. ampl. Remarks: The various forms of *A. ingens* other than *A. ingens* var. *ovalis* are not separated here.

A. ingens var. *ovalis* Gersonde, 1990: Gersonde and Burckle, 1990, pl. 5, figs. 4-5. Remarks: Harwood and Maruyama's (1992) proposed transfer name *Hemidiscus ovalis* is rejected because that name is preoccupied (*H. ovalis* Lohman). If this taxon is truly a *Hemidiscus*, a new name should be proposed.

A. karstenii Van Huerck; Harwood and Maruyama, 1992, pl. 13, figs. 1, 2, 6-8, 10, 11, and 13.

Azpeitia tabularis (Grunow) Fryxell *et* Sims; Harwood and Maruyama, 1992, pl. 11, fig. 5.

Eucampia antarctica(Castracane) Mangin; as *E. balaustium* Castracane; Fenner, and others, 1976, pl. 5, figs. 7-9.

Fragilariopsis barronii (Gersonde) Gersonde et Bárcena, in press; as *Nitzschia barronii* Gersonde, 1991, p. 146, pl. 3, fig. 6; pl. 4, figs. 1-3; pl. 5, figs. 7-17.

F. curta-F. cylindra. Remarks: Sea ice-related forms, *F. curta* and *F. cylindra* were tabulated together. *F. curta* (Van Heurck) Hustedt; as *Nitzschia curta*(Van Heurck) Hasle, Fenner and others, 1976, pl. 4, figs. 5-9. *F. cylindra* (Grunow) Hustedt; as *N. cylindrus* (Grunow)Hasle, Fenner and others, 1976, pl. 4, figs. 10-15.

F. interfrigidaria (McCollum) Gersonde et Bárcena, in press; as *N. interfrigidaria* McCollum, 1975, pl. 9, figs. 7-9. Remarks: Included here are assymetric forms normally referred to *N. praeinterfrigidiaria* McCollum, 1975, pl. 10, fig. 1. These were found to range consistently above the reported 3.6 Ma extinction of *N. praeinterfrigidaria*.

F. kerguelenis (O'Meara) Hustedt, Hasle, 1965, p. 14, pl. 3, figs. 4 and 5; pl. 4, figs. 11-18; pl. 5, figs. 1-11; pl. 6, figs. 2-4; pl. 7, fig. 9; pl. 8, fig. 10; pl. 16, figs. 3-5. Also as *N. kerguelensis* (O'Meara) Hasle, Fenner and others, 1976, pl. 2, figs. 19-30.

F. ritscheri Hustedt; Hasle, 1965, p. 20, pl. 1, fig. 20; pl. 3, fig. 3; pl. 4, figs. 1-10; pl. 5, figs. 12, 13; pl. 6, fig. 1; pl. 7, fig. 8. Also as *N. ritscheri* (Hustedt) Hasle; Fenner and others, 1976, pl. 3, figs. 1-12.

F. weaveri (Ciesielski) Gersonde et Bárcena, in press; as *N. weaveri* Ciesielski, 1983, p. 655, pl. 1, figs. 1-10.

F. sp. cf. *F. arcula* (Gersonde) Gersonde et Bárcena, in press; as *N. arcula* Gersonde, 1991, p. 134. pl. 2, fig. 4; pl. 4, fig. 4; pl. 5, figs. 1-6.

F. spp. Remarks: Other taxa of *Fragilariopsis* were not separated.

Hemidiscus karstenii Jousé; Fenner, 1991, pl. 1. fig. 2. Remarks: No attempt was made to separate the various forms of this taxon.

N. reinholdii Kanaya ex Barron et Baldauf; Gersonde and Burckle, 1990, pl. 2, fig. 1.

Odontella weisflogii (Grunow in Van Heurck); as *Biddulphia weisflogii* Grunow in Van Heurck, 1881, pl. 100, figs. 1, 2.

Rhizosolenia spp. Remarks: The taxa of this genus are tabulated together.

Rouxia spp. Remarks: The various taxa of *Rouxia* (see Harwood and Maruyma, 1992, pl. 17) have not been separated.

Stellarima spp. Remarks: These are probably *S. microtrias* (Ehrenberg) Hasle et Sims; Hasle and Sims, 1986, p. 11, figs. 18-27.

Stephanopyxis spp. Remarks: The taxa of this genus are tabulated together.

Synedra sp. 1 &2 of Brady, 1979, pl. 6, fig. 6; Harwood and Maruyama, 1992, pl. 17, figs. 5-8. Remarks: Harwood and Maruyama (1992) note that "it is unclear whether this diatom belongs in *Synedra*.". This taxon bears a lot of resemblance to the sea ice genus *Thalassioneis* Round in Round and others, 1990 (p. 386).

Thalassionema nitzschioides Grunow; Fenner and others, 1976, pl. 14, fig. 11. Remarks: *T. nitzschioides* var. *parva* Heiden was not tabulated separately, because it was always very rare (<5% of total *T. nitzschioides*).

Thalassiosira antarctica Hustedt, 1958, pl. 3, figs. 1-3.

Thalassiosira complicata Gersonde, 1991, p. 150, pl. 3, figs. 1, 2; pl. 5, figs. 18-20; pl. 6, figs. 1-6; pl. 7, figs. 1-5.

T. convexa var. *aspinosa* Schrader; Gersonde and Burckle, 1990, pl. 3, figs. 2-3.

T. insigna (Jousé) Harwood et Maruyama; Harwood and Maruyama, 1992, pl. 14, figs. 3-5. Remarks: Only forms with clear hyaline center are tabulated here. Closely related forms are tabulated as *T. oliverana* including those forms referred to *T. insigna*/*T. inura* transitional forms by Harwood and Maruyama, 1992, pl. 14, figs. 8-10, 16.

T. inura Gersonde, 1991, p. 151, pl. 6, figs. 7-14; pl. 8, figs. 1-6.

T. kolbei (Jousé) Gersonde; Fenner, 1991, pl. 1, figs. 1, 4; pl. 2, figs. 3, 4.

T. lentiginosa (Janisch) Fryxell; Harwood and Maruyama, 1992, pl. 19, fig. 15. Remarks: *T. lentiginosa* var. *ovalis* (Castracane) Fryxell is included here.

T. oestrupii (Ostenfeld) Proschkina-Lavrenko; Harwood and Maruyama, 1992, pl. 16, figs. 5-7. Remarks: *T. tetraoestrupii* Bodén is also included here.

T. oliverana (O'Meara) Sournia; Harwood and Maruyama, 1992, pl. 14, figs. 1, 2, 6, 11, and 17. Remarsk: Includes *T. oliverana* var. *sparsa* Harwood et Maruyama, 1992, pl. 16, fig. 3 and forms referred to as *T. insigna*/*T. inura* transitional forms by Harwood and Maruyama, 1992, pl. 14, figs. 7-10, 16.

T. torokina Brady; Cieisielski, 1983, pl. 7, figs. 3-6.

T. vulnifica (Gombos) Fenner, 1991, p. 108, pl. 2, fig. 2; Mahood and Barron, in press, figs. 1-14, 25-26.

T. sp. aff *T. antarctica* Comber; Johansen and Fryxell, 1985, p. 158, figs. 15-17, 37-39. Remarks: Specimens observed appear to be resting spores.

T. spp. Remarks: Included here are various forms of Pliocene *Thalassiosira* figured by Harwood and Maruyama, 1992. They were not tabulated separately, because they are always sparse.

Thalassiothrix spp. Remarks: Mostly *T. longissima* Cleve et Grunow; Harwood et Maruyama, 1992, pl. 11, fig. 12. Fenner and others (1976) observed a continuous transition between *T. longissima* and *T. antarctica* Schimper.

Chaeotoceros spores. Remarks: These are undifferentiated.

Reworked diatoms. Remarks: Mostly included here are Miocene *Denticulopsis* spp.

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Table Captions

Table 1. Location and water depth of the deep-sea cores studied and interval containingmiddle Pliocene sediments.

Table 2. Age models for cores studied. LO = termination or last occurrence; FO = base or first occurrence; mbsf = meters below sea floor.

Table 3. Percentage abundance of selected diatom taxa in the middle Pliocene of DSDP 274, DSDP 323, ODP 690B, ODP 693A, ODP 695A and Eltanin Cores 13-3, 13-17, 14-8, 16-4, 36-33, 50-33. Ages from Table 2.

Table 4. Maximum position of the Antarctic Polar Front between 3.1 and 3.0 Ma based on diatom assemblages and estimated differences in summer sea surface temperatures between the middle Pliocene and the present. * = alternative APF position and SST estimate based on radiolarian data (J. Morley, written comm., 1994).

TABLE 1. Location and water depth of cores studied

Core/ Site	Latitude	Longitude	Water Depth (m)	Interval (mbsf)
Eltanin14-08	59°40' S	160° 17.4' W	3877	12.1-13.6
Eltanin13-17	65° 41' S	124° 6.8' W	4724	14.3-16.0
DSDP 323	63° 40.84' S	97° 59.69' W	5004	81-82.5
Eltanin 13-3	57° 0.3' S	89° 29' W	5094	9.9-10.5
ODP 695A	62° 23.5' S	43° 27.1' W	1300	14-32
ODP 693A	70° 49.9' S	14° 34.4' W	2359	35-46
ODP 690B	65° 9.63' S	01°12.3' E	2914	2.5-4.5
Eltanin 36-33	57°45' S	150° 53' E	3952	0.8-1.5
Eltanin 16-04	55° 36' S	160° 12' E	4151	0.6-1.0
Eltanin 50-33	61°05.1' S	170° 03.8' E	4550	7.5-9.0
DSDP 274	68° 59.81' S	173° 25.64' E	3300	76-84

TABLE 2. Age models of cores.

Event/Interval	Age (Ma)	Eltanin 14-8 (mbsf)	Eltanin 13-17 (mbsf)	DSDP 323 (mbsf)	Eltanin 13-3 (mbsf)	ODP 695A (mbsf)	ODP 693A (mbsf)	ODP 690B (mbsf)	Eltanin 36-33 (mbsf)	Eltanin 16-4 (mbsf)	Eltanin 50-33 (mbsf)	DSDP 274 (mbsf)
LO C2An.1n	2.47	11.0	12.2	no data	8.7	9.0		hiatus	0	not seen	5.6	no data
LO *Thalassiosira insigna*	2.5	10.8	12.1	77.6-78.1	8.6	6.4-11.2	21.9-31.4	hiatus	no data	0	5.8	<51.9
LO *Fragiolariopsis weaveri*	2.64					no data		hiatus	no data		6.05	not seen
FO *Cycladophora d. davisianna*	2.75	13.4?	13.8	no data	8.7	11.34-13.25	21.9-31.4	hiatus	no data		no data	no data
FO C2An.1n	2.92	12.0	14.2 (16.5*)	no data	10.0	14.0		hiatus	0.8	0.72	7.55	no data
LO C2An.2n	2.99	12.3	14.7 (16.0*)	no data	10.3	17.0		hiatus	0.95		7.95	no data
LO *Thalassiosira complicata*	3.06	12.46-12.61	15.4-15.6	81.99-82.51	10.30-10.38	22.83-23.30	39.76-41.5	2.38-2.57	1.30-1.39	.86-.95	8.05-8.24	78.51-81.34
FO *Fragilariopsis kerguelensis*		12.46-12.61	14.2-14.4?		10.39-10.48			not seen	0.80-0.89	.46-.55	not seen	not seen
FO C2An.2n	3.08'	13.15	15.4 (15.3*)	no data		24.5?		1.7-2.4	1.4	no data	8.4	no data
FO *Thalassiosira vulnifica*	3.1	13.22-13.36	15.0-15.2		10.39-10.48	26.30-27.84	41.50-42.96?	2.76-2.95	1.40-1.49	.86-.95	7.25-7.44	81.34-84.18
LO C2An.3n	3.18	no data		no data		26.0-27.5?		4.7-5.05	1.7	1.0	9	no data
FO *Fragilariopsis weaveri*	3.2	>13.37	14.2-14.4	>82.51	10.49-10.58	no data		2.57-2.76?	>1.50	>1.06	>9.05	not seen
FO *Thalassiosira insigna*	3.2		14.2-14.4	161.5-162.4			42.96-43.05	4.74-5.38	>1.50	>1.06	>8.85	84.18-85.82
FO C2An.3n	3.40	no data		no data		48.0	?	7.1-7.35	2.6	2.0	10.30	no data

TABLE 3. Relative abundances (%) of selected diatom taxa.

Interval (mbsf)	Ma	*Actinocyclus actinochilus*	*Actinocyclus dimorphus*	*A. ingens*	*A. ingens var. ovalis*	*A. karstenii*	*Azpeitia tabularis*	*Eucampia antarctica*	*Fragilariopsis barronii*	*F. curta-cylindra*	*F. interfrigidaria*	*F. kerguelensis*	*F. ritscheri*	*F. weaveri*	*F. spp*	*F. sp. cf. aurcula*	*Hemidsicus karstenii*	*Nitzschia reinholdii*	*Odontella weissflogii*	*Rhizsolenia spp.*	*Rouxia spp.*	*Stellarima spp.*	*Stephanopyxis spp.*	*Synedra*	*Thalassionema nitzschioides*	*Thalassiosira complicata*	*T. convexa var. aspinosa*	*T. insigna*	*T. inura*	*T. kolbei*	*T. lentiginosa*	*T. oestrupii*	*T. oliverana*	*T. torokina*	*T. vulnifica*	*T. cf. antarctica*	*T. spp.*	*Thx. longissima*	*Chaetoceros spores*	other diatoms	benthic diatoms	reworked diatoms	total counted	*Frag. + Roux. + N. reinholdii*
E13-17																																												
1602-1603	3.00					1.5		2.3	11.5	2.3	5.4	5.4	5.4	1.5	1.5	3.8				3.1	0.8	1.5	3.1		3.1			7.7					9.2	1.5			1.5	2.3	16.9			7.7	64.5	37.7
1580-1581	3.03		1.5	3.1		0.8			8.4	1.1	0.4	32.4	2.3	0.4	0.8	2.7				1.5	0.8	1.5	0.8		2.3			3.8			4.6	1.5	10.7	2.3		0.8	1.5	1.5	7.6		0.8	3.8	131	49.2
1561-1562	3.05							0.9	9.3	1.9	0.9	0.5	1.9		3.3	0.9				2.8	2.8	2.8	3.7		4.7			4.7		0.9	2.8		21.5			3.7	1.9	3.3	17.8		0.9	5.6	107	21.5
1540-1541	3.07			0.9			0.9	1.7	13.4	1.3	1.7	0.9	4.3		0.9	5.6				1.7	4.7	1.7	1.7		5.6	+					2.6	6.9	6.0		0.9	0.9	3.4	2.2	22.4	0.9	0.9	6.0	116	32.8
1519-1520	3.09						1.1	1.6	5.3	1.1	3.7		3.2	1.1		0.5				8.5	4.3	6.4	1.1		10.6	+					2.1	5.3	9.6		+	1.1	2.1	6.4	17.0	1.1		6.4	93.5	19.1
1499-1500	3.11			4.5					13.6		2.3		2.3	4.5		2.3				9.1	9.1	4.5			9.1	+						4.5	4.5	4.5				4.5	9.1			9.1	21.5	34.1
1480-1481	3.14		0.6	0.6			5.5	1.2	15.8	0.3	7.0		0.3	5.2	0.3	1.5	0.6			5.5	6.1	1.2	2.4		3.0	3.0					4.8	1.2	7.3	1.2		0.6	6.0	3.9	4.2	2.4	1.2	6.7	165	36.4
1459-1460	3.17		0.8					2.4	13.5		6.0	2.4	1.2	2.8		3.6				3.2	9.1	4.0	0.8		4.8	2.4						4.0	10.3	0.8		0.8	4.0	2.4	5.6	0.8	1.6	12.7	126	38.5
1439-1440	3.19						4.9		29.4		24.3	0.3		2.3		1.3	3.2	0.6		0.3	9.7				1.0	1.0		0.3			0.6	0.3	10.0				3.9	4.5	1.0		0.3	0.6	309	68.0
1420-1421	3.21		1.0				4.9		37.0		25.0					0.5		1.0			8.8				0.3	1.0						0.3	9.1				5.2	2.9	1.3			1.6	308	72.2
1401-1402	3.23		1.3				5.0	0.2	36.2		11.6			0.5		1.7	0.7	1.8		0.7	6.0				2.0	0.3						0.3	6.3				16.0	3.3	1.7	2.7	0.7	1.3	301	57.8
E14-8																																												
12.00-12.01	2.92			3.6			1.0	0.3	2.9		0.6	22.4								2.3					0.6			23.7			9.1		14.3		0.3		1.0	1.9		1.0		14.9	308	26.0
12.15-12.16	2.96			3.3			0.3		1.0		1.3	1.3		3.6	0.3					0.3	0.3		0.7		0.7			28.1			5.6	0.3	23.5					2.3	0.3	0.3		26.5	306	7.8
12.30-12.31	3.01		0.3	2.6		0.6	1.9		5.4		6.1	1.9		3.5			0.6			1.0	1.0		3.8					5.4		0.3	7.7		22.8					5.1	0.3	1.0		28.5	312	17.9
12.45-12.46	3.02		1.0	0.7		0.7	2.3		4.3		5.3	3.3		4.3			0.7			0.7	2.0		2.7		0.7			15.9			7.0	1.0	19.9		0.7		0.3	4.0		0.3		22.3	301	19.3
12.61-12.62	3.03		0.3	2.3			0.3	0.3	5.6		3.6			3.0			2.6			2.3	1.3		2.3			0.7		18.7	0.3		6.9		22.3		0.3			6.9				20.0	305	13.4
12.75-12.76	3.04		0.7	2.6	1.3		2.0	0.3	7.8		18.3			3.9	0.3	0.3	1.6	0.3		1.3	1.3		4.2		0.3	0.3		0.7	1.6	0.3	9.5	1.0	13.7					7.5	0.3			16.0	306	32.4
12.89-12.90	3.05		0.3	3.2		0.6	1.3	0.3	5.8		9.7			1.9			7.8	0.3		2.3	1.6		5.5		0.3	0.3		13.0			12.0		12.7		0.3		0.3	5.8	0.3			15.3	308	19.5
13.05-13.06	3.07		0.3	4.8		0.3	3.2		6.5		11.3			1.6	0.6	0.3	6.8			2.3	1.6		3.9		0.3	0.6		2.9			8.7		15.8					13.5		1.0		13.6	310	21.9
13.21-13.22	3.09			4.1			2.2		17.6		12.3			1.6	0.3		3.8			1.6	1.3		0.9		0.3	0.6		9.4	0.3	1.6	7.9		13.8		0.3			6.3	0.3			13.5	318	33.0
13.36-13.37	3.10		0.3	2.9			6.8		17.4		13.2			0.3	0.6	0.3	4.2	0.6		1.9	3.9		1.3		0.6	1.6		1.0			7.4		10.9					6.4	0.6			17.7	311	36.3
13.52-13.53	3.12		0.7	1.7		0.7	1.0		26.8		4.6					1.3	1.3			3.6	22.8		2.0		3.6	1.0		0.7	1.3		5.3	0.3	5.0					4.3	1.0			11.0	302	55.6
DSDP 323																																												
80.99	3.0*							36.1	36.1		3.3			21.3			0.7				4.9				1.3			1.0	0.3		6.6	2.9	1.4				0.7	2.3	1.3			1.0	305	65.6
81.99	3.04*		1.1				0.6	33.1	33.1		5.1			17.1		0.6	0.6				6.9	1.7			1.1			0.6	0.6								1.1	1.7	2.3			1.1	175	62.9
82.51	3.06*		1.4				1.4	19.4	19.4		2.8			19.4		1.4	2.8			1.4	6.9	1.4			2.8	1.4											2.8	4.2	4.2				72	50.0
E13-3																																												
9.97-9.98	2.90			15.0			2.0	1.0	22.0		4.0	19.0				1.0				3.0	2.0	2.0	7.0		7.0			1.0	2.0	1.0	7.0	5.0	11.0	1.0			5.0	13.0	1.0	3.0	1.0	2.0	132	48.0
10.10-10.11	2.93								19.6		4.3		2.2			2.2					10.9		8.7		8.7			4.3			4.3		17.4					13.0	4.3			8.7	23	39.1
10.19-10.20	2.96		0.7	6.4				0.7	13.5	0.7	5.7	2.8	0.7	0.7		0.7				5.0	3.5	2.8	12.1		12.1			0.7	1.4	1.4	7.1	2.1	5.0	1.4	1.4		4.3	8.5	3.5	0.7		2.1	141	28.4
10.29-10.30	2.99			1.9				1.9	17.1		6.7		1.9	1.9		1.9				4.8	6.7	5.7	3.8		3.8			1.0	1.9		6.7	3.8	9.5		1.0		1.0	5.7	2.9	1.9		1.9	105	36.2
10.38-10.39	3.07		1.1	9.1				3.4	17.0		11.4	1.1	1.1	2.3		0.6				2.3	5.7	1.1	6.8		6.8					2.3	4.5	1.1	13.6		1.1		2.3	5.7	1.1			1.1	87.5	39.2
10.48-10.49	3.15			2.5				2.5	25.0		12.5			2.5							10.0	5.0	5.0		5.0				2.5		2.5	2.5	5.0	2.5				2.5	5.0			2.5	40	50.0
10.58-10.59	3.23								8.3				4.2							8.3	16.7	4.2	4.2		4.2						4.2		16.7	4.2				8.3	12.5				24	29.2
ODP 695A																																												
11.34	2.67		2.7					1.0	7.6	4.3	1.0		3.3		2.0	3.0			1.0		14.3	2.3						0.7		0.7	4.7	22.3	5.0	1.0	2.3	11.6	3.6	0.7	7.6		0.7		301	35.5
13.25	2.85	0.7	0.7				0.7	2.0	8.0	7.0	0.7		3.0		0.7	5.3			3.3	2.0	10.3	2.0	1.7		0.3					0.7	2.3	2.0	10.0	2.0	2.3	4.0	3.3	1.7	25.2	1.0	0.3		301	34.9
14.75	2.94	0.3	0.6				0.6	0.3	5.9	10.3	1.3		2.8		1.3	6.9			1.3	0.9	14.7		0.9		0.6						0.9	1.9	0.6		0.6	5.0	1.9	1.3	40.9	0.6	0.3		320	43.1
16.25	2.96	1.0	1.0				2.6	3.5	5.4	1.3	2.9		0.3		1.3	3.5			2.2	1.9	9.0	3.2	16.0			0.3					3.5	3.2	11.5	2.6	2.2	1.9	0.3	2.6	15.1	0.6	0.3	1.0	312	23.7
17.75	2.98		0.7				0.7	0.3	2.6	5.9	2.3		4.3	0.3	1.3	6.9			1.3	1.3	15.5	0.7		2.0		0.7				0.3	2.3	1.3	7.2	0.7	0.3	18.4	1.3	1.3	24.3				304	39.1
19.33	3.00	0.3					0.3	0.3	1.0	4.9	1.0			0.7	0.3	5.2		0.3	1.3	2.6	14.1	2.6			0.3						2.0	2.3	5.9	0.3		22.3	3.6	0.7	26.2		0.3	0.3	305	27.5
21.25	3.03							0.9	4.0	6.8	0.3					14.3			0.6	0.9	25.0	0.6			0.3						1.2	2.5	1.9		0.9	16.7	1.2	1.2	19.6	0.3	0.3		322	50.5
22.83	3.04	0.7	0.7					1.7	4.3	2.3	0.7		2.3		1.0	7.9			0.3	2.3	14.6	2.0	0.3		0.7						0.3	1.3	1.3	0.7		29.8	1.4	1.3	22.8	0.7	0.7	0.3	302	33.1
23.30	3.05	1.0	0.7				0.7	7.2	2.9	1.3	0.7		0.3		0.7	7.5			0.3	2.6	11.4	3.3	4.9	0.7	0.3	1.6		0.3			1.6	5.6	2.0	3.3		20.9	3.9	2.0	11.8	0.3	0.7		306	24.8
24.68	3.07	1.3	0.3					4.0	0.7	7.6					0.7	8.0		0.3		1.3	15.0	1.3	4.0	0.3	0.3	2.7				0.7	2.3	4.7	6.0	0.3		16.9	2.7	1.7	15.9	0.3	0.3	0.3	301	32.2
26.30	3.09	0.7						2.9	1.0	7.2	0.7				0.7	7.8			0.7	0.3	16.0	1.6	12.4		0.3	1.0					0.3	4.2	4.6	0.3		22.5	3.0	0.7	11.4				307	33.2
27.84	3.12	0.3	0.3					6.5	0.6	6.2					1.2	10.2			0.3	0.6	9.6	0.6	13.0		0.3	1.6				0.3	1.9	7.5	3.7	0.3		16.8	3.7	0.3	13.4		0.6		322	28.0
29.15	3.13	0.7					0.7	3.0	2.0	6.0	1.0		0.3		1.0	6.6			0.3	2.6	14.6	1.0	2.3	16.6	0.3	4.3					2.3	6.0	4.6			5.6	3.7	1.3	11.9		0.7	1.0	302	31.5
32.37	3.17	0.6						4.2	2.2	3.2	0.3				0.6	7.7			1.0	0.3	13.7		1.3	1.3	0.3	2.2					2.2	3.5	5.1			24.9	2.5	0.3	22.0		0.3		313	27.8

TABLE 3 (cont'd)

Interval (mbsf)	Ma	*Actinocyclus actinochilus*	*Actinocyclus dimorphus*	*A. ingens*	*A. ingens var. ovalis*	*A. karstenii*	*Azpeitia tabularis*	*Eucampia antarctica*	*Fragilariopsis barronii*	*F. curta-cylindra*	*F. interfrigidaria*	*F. kerguelensis*	*F. ritscheri*	*F. weaveri*	*F. spp*	*F. sp. cf. aurcula*	*Hemidsicus karstenii*	*Nitzschia reinholdii*	*Odontella weissflogii*	*Rhizsolenia spp.*	*Rouxia spp.*	*Stellarima spp.*	*Stephanopyxis spp.*	*Synedra*	*Thalassionema nitzschioides*	*Thalassiosira complicata*	*T. convexa var. aspinosa*	*T. insigna*	*T. inura*	*T. kolbei*	*T. lentiginosa*	*T. oestrupii*	*T. oliverana*	*T. torokina*	*T. vulnifica*	*T. cf. antarctica*	*T. spp.*	*Thx. longissima*	*Chaetoceros spores*	other diatoms	benthic diatoms	reworked diatoms	total counted	*Frag. + Roux. + N. reinholdii*
ODP 693A																																												
31.93	2.82		3.2	3.2		3.2	3.2		3.2					3.2		1.6					4.8							3.2	3.2		6.5		35.5	6.5	3.2		3.2		6.5			6.5	31.0	12.9
33.43	2.86		4.8					3.6	10.8	0.6	1.2		1.8	0.6		3.0					3.6	1.2		1.2	1.2						4.8	2.4	22.8	8.4	13.2	1.2	3.6	0.6	1.2	3.6		4.8	83.5	21.6
34.93	2.90		5.1				1.7	1.7	6.8	1.7	0.8		3.4			2.5					6.8				0.8			8.5			6.8	1.7	18.6	5.1	6.8		1.7	0.8	15.3			3.4	59.0	22.0
36.43	2.93		3.4					1.1	7.3		1.7		5.0	1.7		1.1			1.1	2.2	7.3	1.1			1.1			24.6	1.1	1.1	4.5		20.1	4.5	5.6		1.1		1.1	2.2			89.5	24.0
37.93	2.98		4.7						20.9		7.0										2.3				2.3			4.7					46.5		4.7		4.7	2.3					21.5	30.2
39.76	3.03		1.4						15.2	0.7	3.4			2.1		3.4					10.3		1.4	1.4	1.4				1.4		15.2	2.8	19.3	1.4	2.8	1.4	2.8	2.8	8.3			1.4	72.5	35.2
41.50	3.08		1.3	0.3		0.6		0.9	22.9	0.9	10.3			0.9		4.1				2.8	14.7	0.6	0.6	0.6	0.3	0.9		0.9			3.4	1.3	13.8	0.6	0.6		5.6	3.8	5.3			1.6	319	53.9
42.96	3.11		1.0			0.3		0.6	20.8	1.0	13.1		0.3	1.9		1.9				1.0	19.2	0.6	0.3		0.6	0.6					1.0	1.3	15.1			1.6	4.2	2.2	10.3	0.3		0.6	312	58.3
43.95	3.14		2.3	0.3		0.6		0.6	26.6	1.3	11.4			1.0		2.3				1.3	21.8	0.3	0.6	0.6		1.0					1.3	1.3	11.0	0.3		0.3	2.9	1.6	9.1				308	64.3
44.25	3.15		0.7						26.9		15.3		0.7	0.7		2.3				2.3	20.6	0.3	1.0	1.0	0.3	0.3					2.0	1.3	11.0	0.3			2.0	2.0	8.0			1.0	301	66.4
45.27	3.17			1.3		0.9		0.3	23.0	0.6	10.1			1.9		3.5				2.5	16.4	0.3	2.2	0.6	0.9	0.6			0.3		2.8	0.6	16.1	0.6		0.6	3.2	2.2	6.3	0.3		1.6	317	55.5
45.74	3.18		1.8	0.3		1.2		0.6	23.4	0.3	8.4		3.0	0.3		3.9				1.5	14.4	2.1	3.3	0.9	0.6	0.3			0.3		3.3	1.2	12.3	2.1			4.8	2.7	6.3	0.6		0.3	334	53.6
46.64	3.20		0.6	1.3		1.3		1.9	21.0	1.6	7.8		1.6	1.3		2.9				1.0	23.6	1.3	1.0	0.3	1.0	1.3			1.3	0.3	2.3	0.6	5.5	0.3			3.9	4.5	9.7	0.3		0.3	309	59.9
ODP 690B																																												
2.57	3.09	1.9	0.3						48.8	0.6	7.8			0.6		4.0	0.9				10.6							1.2			3.7	0.6	9.9				1.9	6.2	0.6				322	72.4
2.76	3.10	0.3						0.3	42.5		3.3					5.6	1.0			0.3	19.6	0.3						0.3			3.0	1.0	12.0		0.3		0.7	5.3	1.3	0.7			301	71.1
2.95	3.11		0.3	1.3					34.9	0.6	5.1					5.4	1.0			0.6	34.0					0.3		1.6			1.6	1.0	5.7				1.0	3.8	1.0	0.3			312	80.0
3.16	3.12		2.3	1.0					20.3		4.7					3.7	5.7			0.7	33.7							3.0	0.7		1.0	1.0	7.3				0.7	8.0	2.3	1.7			300	62.4
3.33	3.13	1.3	0.3						13.0	0.7	0.7					5.5	2.0				59.6	0.3						0.7				0.7	1.6				1.3	1.6	10.1				307	79.5
3.55	3.14	0.9	0.6						12.5	1.3	0.3					4.4	7.5			0.3	48.9	0.3						0.3			0.9	1.9	1.3	2.2			1.9	2.2	11.9	0.3			319	67.4
3.76	3.15	1.7						0.7	31.8	0.3	4.3	1.3				3.3	1.0			0.3	18.9					1.7		1.7	0.7		0.3	0.7	16.9				2.3	7.6	4.0	0.7			302	59.9
4.19	3.17	1.3						0.3	11.6	0.6	5.1					4.8	0.3			0.6	41.2	0.3				2.9		0.3	3.2		0.3	2.3	19.0				0.3	1.6	3.5				311	63.3
4.57	3.19	1.0						1.3	22.6	1.0	4.7					2.3					41.2	1.0				2.0			1.0			2.0	13.3				1.4	0.3	5.0			0.3	301	71.8
E36-33																																												
0.79-0.80	2.95			17.9		0.6	0.9		4.5		1.8	0.3		11.3	0.9	0.3	1.2	0.3			1.5		0.9					1.2			6.8	0.3	44.3		0.3		0.6	3.0	0.3	0.3		0.6	336	20.8
0.89-0.90	2.97			11.8		0.7	0.3	0.7	2.3	0.3	1.3			8.9	0.3		0.3	0.7			1.3				1.0			1.0			9.5		53.3		1.0		0.3	3.0	1.0			1.0	304	15.1
0.99-1.00	2.99		0.7	5.9		0.3	2.6		14.1		2.0			15.7		0.3				0.3	4.9							0.7			5.6	1.0	42.0		0.3			2.6	0.7	0.3			305	37.0
1.09-1.10	3.01		0.3	5.7	2.3		3.0	1.0	11.3	0.3	5.0			5.3		0.3				0.3	3.0		0.3		0.7				1.3	0.7	16.3	0.3	32.0		0.3		1.0	6.7	0.7			1.7	300	25.3
1.19-1.20	3.035		1.3	13.1	1.3		1.3	0.7	7.5		0.7			29.4		0.3					1.6		0.7					1.0	1.0	0.7	9.2	2.0	25.5		0.3		0.3	2.0	0.3	0.3		2.0	306	39.5
1.29-1.30	3.06		0.3	15.3	8.7	0.3	2.3		9.7	0.3	3.0			23.3		0.3	1.3	0.3		1.0	1.7	0.3	1.0				0.3		3.0	1.3	10.7	0.7	19.7					2.7		1.7	0.3	2.0	300	38.7
1.39-1.40	3.09		2.3	2.0	8.3		0.7		13.6	0.3	3.0			18.5		0.3	2.6	0.3		1.0	3.6		1.7					0.3	1.0	0.3	13.9	0.3	29.1		0.7		0.3	2.3	0.3	0.3		2.0	302	39.7
1.49-1.50	3.12		2.3	2.3	0.7		0.3	2.0	25.3		5.6			9.9	0.3	0.7				0.3	10.2		1.6		0.3			1.6	0.3	1.0	11.2	0.7	17.1					3.6	1.3	1.0		1.3	304	52.0
E16-4																																												
0.45-0.46	2.70		1.0	3.5			1.3	0.3	6.5		1.3	0.6		14.8	0.3	0.3	0.6			0.3	1.3		0.3		0.3			17.4			4.5	0.3	37.4				0.3	2.6	0.6	1.0	0.3	2.6	310	25.2
0.55-0.56	2.78		0.6	0.6			0.6		11.6		2.6			16.1		0.3	0.3				5.5		1.3		1.0			13.2			4.5		29.6				1.6	2.9	2.6	0.3		4.8	311	36.0
0.65-0.66	2.87		0.7	0.3			0.7		21.6	0.3	2.0			16.3		0.7	0.7			0.7	9.6		0.3		1.0			5.0			8.0		21.6				0.7	2.0	2.0	1.0	0.3	4.7	301	50.5
0.75-0.76	2.95		1.0	1.3			1.6		15.4		2.9			15.1	0.3	0.3		0.3			7.1		1.0		1.3			7.4		0.6	7.4	1.0	30.5					2.3	0.3		0.3	2.6	311	41.5
0.85-0.86	3.04		0.3	0.3					15.8		2.3			19.0	0.3	0.6					10.3				0.6		0.3	13.2			3.2		27.3		0.3		0.3	1.0	0.3	1.0	0.3	3.2	311	48.2
0.95-0.96	3.12			1.0					14.4	0.3	3.9			18.3	0.3	0.3	0.3	0.7		0.7	4.9		0.7		1.0	0.3	0.3	2.9			8.5		34.3				1.3	1.3		0.3		3.9	306	43.1
1.05-1.06	3.20		0.7	2.0			0.7		13.5		2.6			17.4	0.7		0.3	0.3		0.7	5.6		2.0		0.7	0.7		11.2			8.2		25.0				1.0	2.0	0.7	0.3	0.7	3.3	304	40.1
E50-33																																												
7.04-7.05	2.83		1.4	2.3			0.5		1.4	0.5	0.9		0.5	6.3	0.5		2.7				3.6				0.5			9.0			1.4	0.5	63.3					1.4	0.9	0.5	1.4	0.9	221	13.7
7.24-7.25	2.87			3.4			0.3		5.0	0.3	1.2			3.1	0.3	0.3	0.3			0.3	2.2	0.3			1.6			4.3			3.4	0.3	66.5		0.3			0.9	1.6	0.3	0.6	3.1	322	12.4
7.44-7.45	2.91		1.3	1.6		0.7			2.3		0.7		0.7	6.6	0.7	1.0					2.3				0.3			4.9			5.2		66.2	0.3				0.7	1.6	0.3	0.3	2.3	305	14.1
7.64-7.65	2.94		0.7	3.0			0.3		2.0	0.3	0.3			13.0	0.3	0.3	0.3				1.7	0.3			1.0			1.3			7.0	0.3	64.5					0.7	0.3	0.3		2.0	301	17.9
7.84-7.85	2.98			16.3					0.7	0.3	2.0			17.6		0.3	1.3			0.3	1.0				0.3			1.3			4.9		49.5				0.3	1.0	0.7	0.3		2.0	307	21.8
8.04-8.05	3.02			28.0					3.9	0.7	2.0		0.3	8.1	0.3		1.0	0.3			3.9				0.7			1.3			11.1		31.3				0.3	1.0	2.0			3.9	307	19.5
8.24-8.25	3.05		1.3	19.3			0.7		5.2	0.3	2.0		0.3	8.5	0.3	0.7	7.9	1.0		1.0	2.6		0.7		1.0						9.5		28.9				0.3	1.3	3.0	1.0	0.3	3.0	305	21.0
8.44-8.45	3.09		4.8	6.0			3.6	1.2	11.9		4.8			8.3	2.4	2.4	3.6				3.6	1.2	1.2		3.6						11.9	1.2	17.9						2.4	1.2	1.2	6.0	84	33.3
8.64-8.65	3.12								17.2	3.4	3.4			6.9	6.9	3.4					13.8										10.3	6.9	17.2						6.9	3.4			29	55.2
8.84-8.85	3.15		1.2	1.2			3.7		8.6	1.2	6.2			14.8	2.5	1.2					8.6				1.2			1.2			6.2		24.7	1.2				4.9	4.9			6.2	81	43.2
9.04-9.05	3.19		2.6	0.5					12.2	0.5	7.1			11.2	1.0	0.5					5.1		3.6		1.0						15.8	0.5	23.5				1.0	3.1	5.1	0.5	2.0	3.1	196	37.8

TABLE 3 (cont'd)

Interval (mbsf)	Ma	*Actinocyclus actinochilus*	*Actinocyclus dimorphus*	*A. ingens*	*A. ingens var. ovalis*	*A. karstenii*	*Azpeitia tabularis*	*Eucampia antarctica*	*Fragilariopsis barronii*	*F. curta-cylindra*	*F. interfrigidaria*	*F. kerguelensis*	*F. ritscheri*	*F. weaveri*	*F. spp*	*F. sp. cf. aurcula*	*Hemidsicus karstenii*	*Nitzschia reinholdii*	*Odontella weissflogii*	*Rhizsolenia spp.*	*Rouxia spp.*	*Stellarima spp.*	*Stephanopyxis spp.*	*Synedra*	*Thalassionema nitzschioides*	*Thalassiosira complicata*	*T. convexa var. aspinosa*	*T. insigna*	*T. inura*	*T. kolbei*	*T. lentiginosa*	*T. oestrupii*	*T. oliverana*	*T. torokina*	*T. vulnifica*	*T. cf. antarctica*	*T. spp.*	*Thx. longissima*	*Chaetoceros spores*	other diatoms	benthic diatoms	reworked diatoms	total counted	*Frag. + Roux. + N. reinnoldii*
DSDP 274																																												
76.34	2.96	0.5	3.9	0.5				1.5	1.0		0.5		4.4			4.4				1.5	4.4	0.5	6.9		5.9			0.5	6.4			7.4	12.3	1.0	1.5	0.5	3.0	1.0	23.2	0.5	2.5	4.4	203	14.8
76.62	2.97	1.0	2.6	1.0				1.7	0.3	1.3	0.7		21.8		0.7	9.2				3.0	18.5		0.7		2.0			1.0				2.6	3.3		4.3	1.3	1.6	1.0	16.5		1.3	2.6	303	52.5
76.85	2.98		2.9	1.0				0.3		0.6	0.6		28.1			11.9				2.9	15.2		0.3		1.3				0.3			2.9	2.9	0.6	1.6	1.9	2.1	0.6	18.7		0.6	2.3	310	56.5
77.10	2.99	1.6	7.7	1.3				1.9		0.3	1.0		14.1		0.3	8.7				1.9	13.5	0.3	1.9		1.3			0.6	0.6	0.3	1.9	1.6	2.3	0.3	9.6	7.7	1.3	1.3	14.1	0.3	0.6	1.3	311	37.9
77.35	2.99	1.0	8.7	2.6				5.1		1.9	0.6		18.6		0.6	6.8				3.5	8.7		2.6		2.3			0.3	1.0	0.6	1.0	2.6	7.4	1.0	7.7	2.3	0.6	1.6	8.0	0.3	1.3	1.3	311	37.3
77.65	3.00	3.9	8.1	0.3				3.9	0.3		0.3		26.1			5.2				2.3	16.1	0.6	0.3		0.3			0.6	0.6	0.3		1.6	1.9	0.3	7.1	1.6	2.9	0.6	11.9		0.6	1.9	310	48.1
77.98	3.01	1.0	3.8	1.3				5.4		2.2			30.1			4.2					18.6	1.3	1.0					1.0		0.6		0.3	2.6	1.0	6.4	1.0	2.6	0.3	15.1				312	55.1
78.15	3.01	1.0	4.0	0.7				2.3	0.3	1.0			33.0		0.7	6.0				0.3	19.0	0.3	1.0		0.3			1.0		0.3	0.7	1.7	3.3		6.0	2.7	1.0	0.7	12.3	0.3		0.3	300	60.0
78.51	3.02	2.9	2.9	0.3				1.6		1.3	0.6		14.2		0.3	6.8				1.3	22.7	0.3	0.3		2.9			1.0	2.6			6.8	1.9	0.3	4.5	1.6	1.6	0.3	17.8		1.0	1.9	309	46.0
81.34	3.10		0.9	0.9					1.9	0.9	0.9		3.8			3.8				4.7	4.7	0.9	8.5		13.2			0.9	2.8			6.6	4.7	0.9	0.9		0.9	1.9	20.8	0.9	2.8	10.4	106	16.0
84.18	3.17		1.0					1.9	5.8		1.9		1.9			1.9				5.8	7.8		6.8		7.8	2.9			9.7	1.9		2.9	1.9	1.9		1.0	2.0	4.9	19.4	1.0		7.8	103	19.4

TABLE 4. Maximum southern postion of Antarctic Polar Front at 3.1-3.0 Ma and estimated change of sea surface temperatures vs. modern values.

Maximum southern position of APF at 3.1 to 3.0 Ma	Ave. modern summer SST at site	Difference between modern average summer SST at APF (4°C) and summer SST at 3.1-3.0 Ma
S of Eltanin 14-8	2.65°C	>+1.35°C
S of Eltanin 36-33	3.55°C	>+0.45°C
S of Eltanin 16-4	5.5°C	no change
S of Eltanin 50-33	3.75°C	>+0.25°C
N of Eltanin 13-17	0.25°C	<+3.75°C
Near or S of DSDP 323	2.35°C	>+1.5°C
N of ODP 695A	-0.4°C	<+4.6°C
Barron (1996) data:		
S of ODP 747	1.95°C	>+2.05°C
S of DSDP 266	2.55°C	>+1.5°C
N of ODP 699	4.0 °C	no change
S of ODP 699 at 53°S*	2.0°C	+2.0°C
N of ODP 751	0.75°C	<+3.25°C
N of Eltanin 50-28	0.85°C	<+3.15°
N of PS1448	0.4°C	<+3.5°C

Figure Captions

Figure 1. Location of the deep-sea cores studied and comparison of the modern position of the Antarctic Polar Front (APF, solid line)(from Gordon and Molinelli, 1982) and its suggested position (dashed line) between 3.1 and 3.0 Ma. Solid circles, cores studied for the present paper; empty squares, cores studied or discussed by Barron (1996).

Figure 2. Relative percentage of the subantarctic diatom, *Fragilariopsis weaveri*, and the antarctic taxa, *F. barronii* and *Rouxia* spp., plotted against age for the middle Pliocene in the 11 Southern Ocean deep-sea sites studied. Data from Table 3.

Figure 3. Relative percentage of the subtropical diatoms *Thalassiosira convexa* var. *aspinosa* and *Nitzschia reinholdii* and the subantarctic diatoms *Hemidiscus karstenii* and *Azpeitia tabularis* plotted against age for the middle Pliocene in the 11 Southern Ocean deep-sea sites studied. Data from Table 3.

Figure 4. Relative percentage of the sea-ice related diatoms *Fragilariopsis curta* and *F. cylindra* plotted against age for the middle Pliocene in 5 of the 11 Southern Ocean deep-sea sites studied. (The other sites contain extremely low or no *F. curta* & *F. cylindra.*) Data from Table 3.

Figure 5. Comparison of the distribution of deep-sea sites containing well-preserved diatoms of the middle Pliocene (age 3.1-3.0 Ma) with the modern-day limits for sea ice in December (dashed line) and February (gray line). Stippled areas - RIS, Ross Ice Shelf; ERIS, Edith Ronne Ice Shelf. Sea ice limits from Schweitzer (1995).

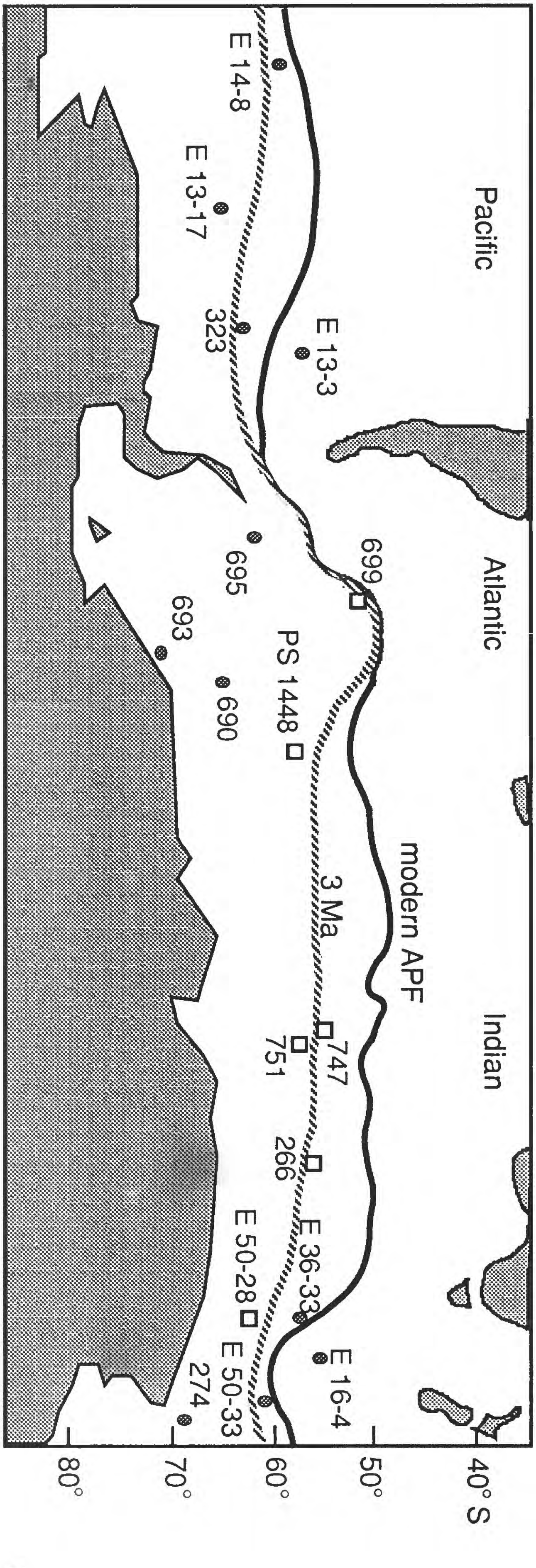
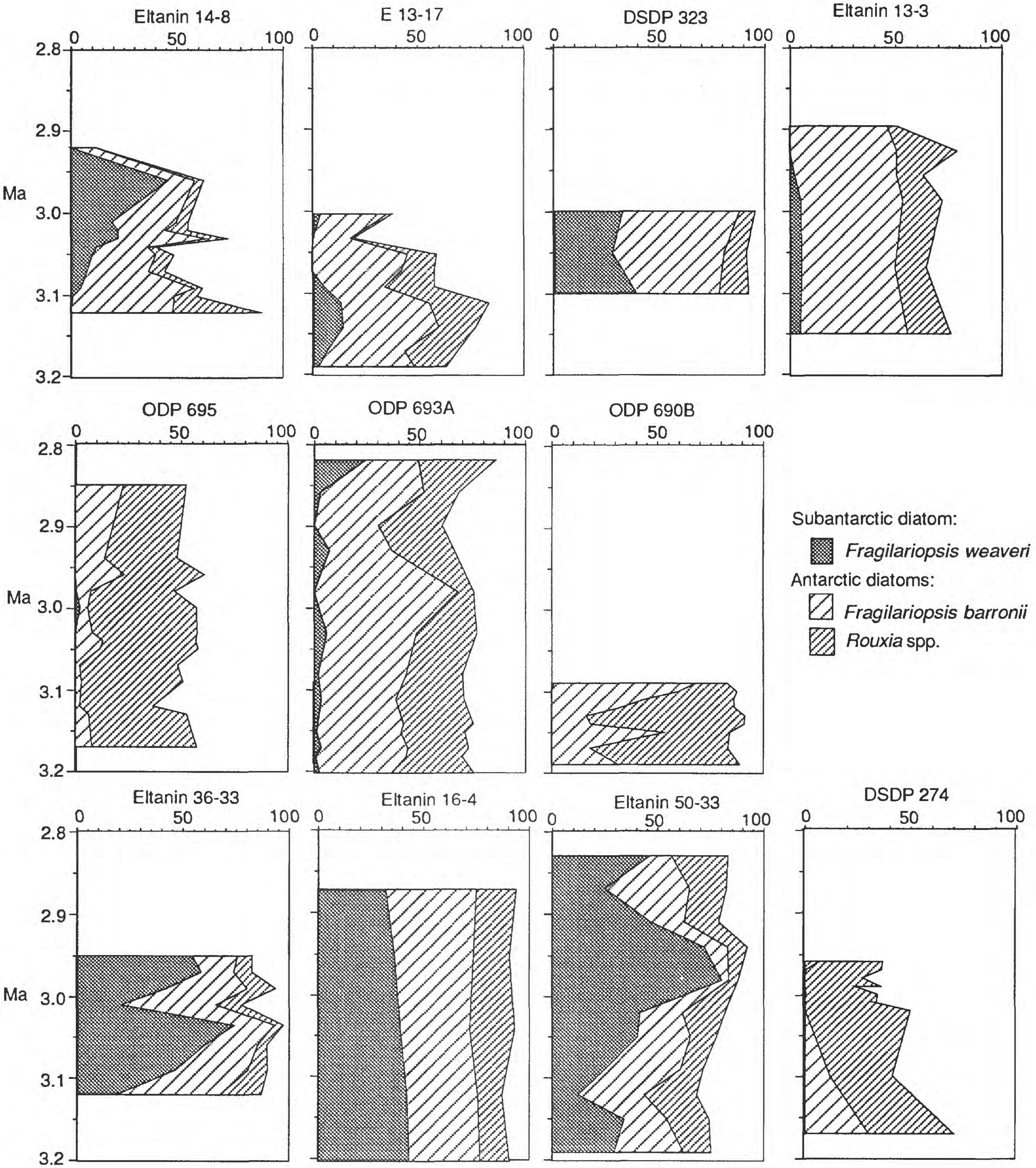

Pacific
Atlantic
Indian
modern APF
3 Ma
E 14-8
E 13-17
323
E 13-3
699
695
693
PS 1448
690
747
751
266
E 36-33
E 50-28
E 16-4
E 50-33
274
40° S
50°
60°
70°
80°

Figure 1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E 13-17
DSDP 323
Eltanin 13-3
ODP 695
ODP 693A
ODP 690B
Eltanin 36-33
Eltanin 16-4
Eltanin 50-33
DSDP 274
0
50
100
2.8
2.9
3.0
3.1
3.2
Ma
Subantarctic diatom:
Fragilariopsis weaveri
Antarctic diatoms:
Fragilariopsis barronii
Rouxia spp.

Figure 2

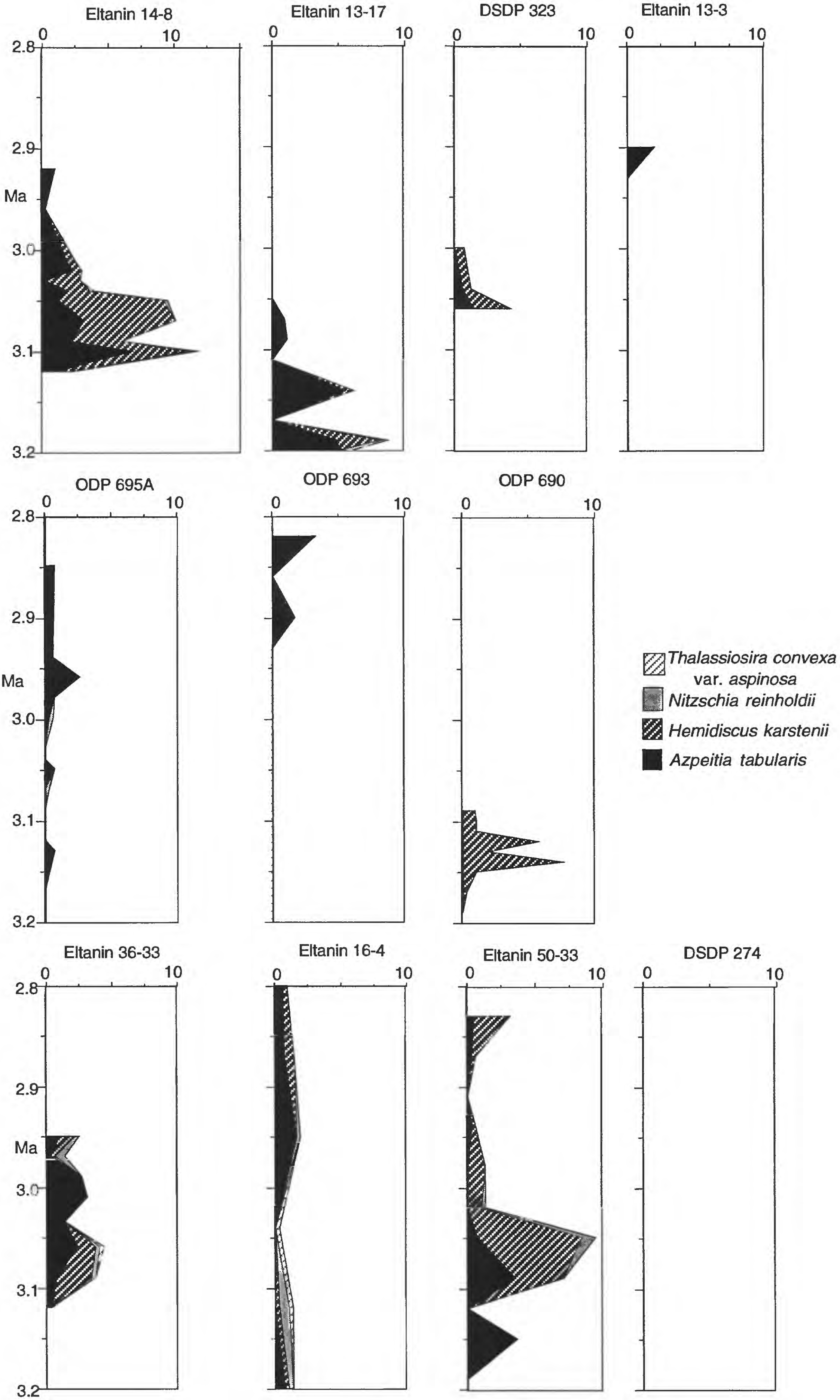
Eltanin 14-8
Eltanin 13-17
DSDP 323
Eltanin 13-3
ODP 695A
ODP 693
ODP 690
Eltanin 36-33
Eltanin 16-4
Eltanin 50-33
DSDP 274
0
10
2.8
2.9
3.0
3.1
3.2
Ma
▨ Thalassiosira convexa var. aspinosa
▒ Nitzschia reinholdii
▨ Hemidiscus karstenii
■ Azpeitia tabularis

Figure 3

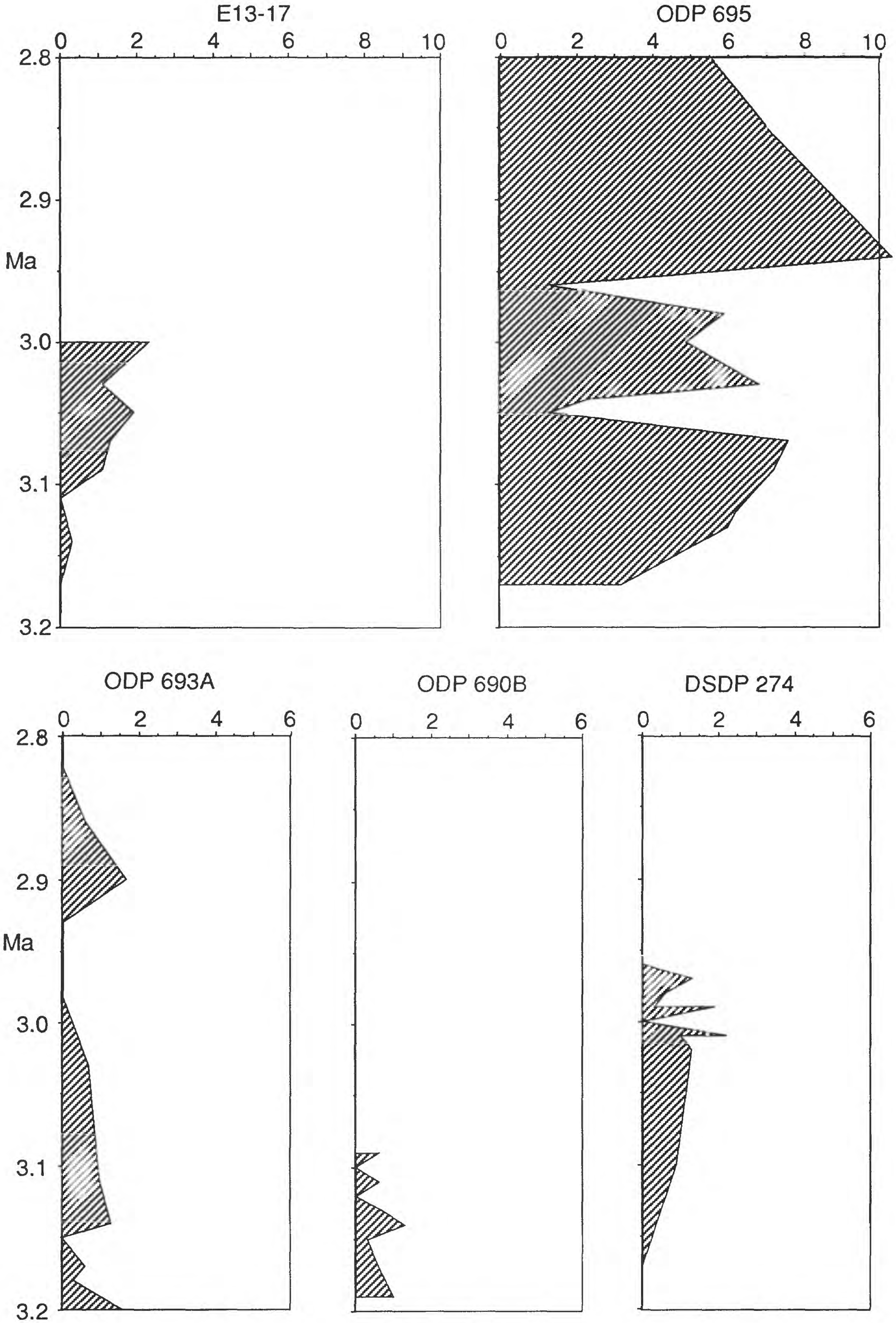
E13-17
0
2
4
6
8
10
ODP 695
0
2
4
6
8
10
2.8
2.9
Ma
3.0
3.1
3.2
ODP 693A
0
2
4
6
ODP 690B
0
2
4
6
DSDP 274
0
2
4
6
2.8
2.9
Ma
3.0
3.1
3.2

Figure 4

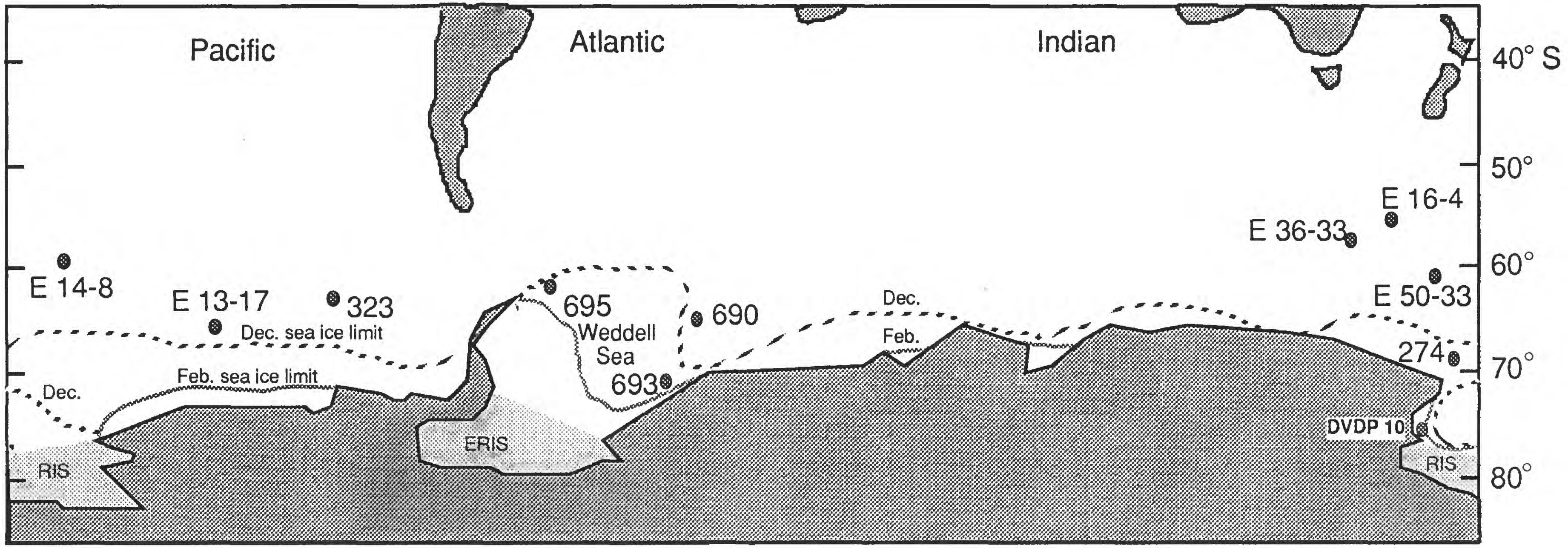
Pacific
Atlantic
Indian
40° S
50°
60°
70°
80°
E 14-8
E 13-17
323
Dec. sea ice limit
Feb. sea ice limit
Dec.
RIS
ERIS
695
Weddell
Sea
693
690
Dec.
Feb.
E 16-4
E 36-33
E 50-33
274
DVDP 10
RIS

Figure 5