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[1] In the modern marine environment the silicoflagellate genus *Dictyocha* is rare, or absent, south of the Antarctic polar front (APF); the genus *Distephanus*, in contrast, is dominant. In sediments recovered from ODP Site 1165, 1600 km south of the front, however, three intervals where *Dictyocha* is abundant are interpreted to represent Pliocene warm events. Comparison of our data with *Ciesielski and Weaver*'s [1974] modern core top silicoflagellate relationship with sea surface temperature (SST) indicates that at Site 1165 mean annual SST was approximately 5°C at 3.7 Ma (event I), and approximately 4°C at 4.3–4.4 Ma (event II) and 4.55–4.8 Ma (event III). Event I represents a 5.5°C warming, and events II and III represents a 4.5°C warming relative to modern mean annual SST. *Dictyocha* is absent from other Site 1165 Pliocene intervals, which suggests that cooler SST (<2°C) prevailed. The warm events detected at Site 1165 may represent times when North Atlantic Deep Water production and ocean heat transport into the Southern Ocean exerted maximum influence. *INDEX TERMS:* 1635 Global Change: Oceans (4203); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3030 Marine Geology and Geophysics: Micropaleontology; *KEYWORDS:* Pliocene, silicoflagellate, temperature, NADW

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1. Introduction

[2] This study uses silicoflagellates (unicellular marine phytoplankton) to reconstruct early to middle Pliocene sea surface temperature (SST) from the Southern Ocean's Ocean Drilling Program (ODP) Leg 188 Site 1165. The manuscript reviews Southern Ocean SST reconstruction from paleontological, sedimentological, and isotope proxies and seeks to explain the different SST estimated. Our study discusses how Southern Ocean SST may have interacted with increased thermohaline circulation (THC) during the Pliocene, most notably when North Atlantic Deep Water (NADW) circulation and atmospheric CO_2 levels increased.

1.1. Study Area

[3] ODP Leg 188 Site 1165 (64.380°S, 67.219°E) is located in the Southern Ocean on the east Antarctic continental rise in a water depth of 3537 m offshore from Prydz Bay and centered over the Wild Drift (Figure 1). The drift is an elongate sediment body formed by the interaction of sediment, from the continental shelf, and westward flowing ocean currents, on the continental rise [*Shipboard Scientific Party*, 2001], and mixed with pelagic siliceous ooze (primarily diatoms and silicoflagellates) "raining out" from the overlying water column.

[4] The upper ~50 m below seafloor (mbsf) of sediment from Hole 1165B consists of brown, diatom-bearing, silty clay spanning the upper Pleistocene to lower Pliocene. The Southern Ocean diatom zonal scheme of *Harwood and Maruyama* [1992] applies directly to these strata. The diatom stratigraphy suggests that there is a disconformity at ~17.1 mbsf of 0.5–0.6 myr duration. Integrated biostatigraphic and magnetostratigraphic data also indicate disconformities at ~6.0, 14.4, 15.6, and ~16.0 mbsf [*Florindo et al.*, 2003; *Whitehead and Bohaty*, 2003], but their duration cannot be resolved through diatom biostratigraphy. Silicoflagellate data were not collected between ~17.1 mbsf and 24.47 mbsf due to low fossil abundance. Silicoflagellate data were collected between 24.47 mbsf and 49.97 mbsf, which spans the time interval ~3.2–~5.0 Ma.

[5] Site 1165 occurs within Antarctic waters. It is ~1600 km south of the Antarctic polar frontal zone (APFZ), which spans that area between the Subantarctic front (SAF) and Antarctic polar front (APF). Across both fronts major transitions in surface water temperature and salinity occur. The APF separates Subantarctic and Antarctic surface waters, where there is a change of approximately 3°C in surface water temperature (from 2°C to 5°C) and ~0.2‰ in salinity [*Gordon*, 1971; *Gordon and Molinelli*, 1982]. The climate conditions at Site 1156 differs greatly from that north of the APF, average summer (January–March) SST is 0.5°C, average winter (July–September) SST is −1.8°C, and annual mean SST is approximately −0.5°C [*Gordon and Molinelli*, 1982]. The steep latitudinal changes in temperature and salinity across the APF cause considerable differences in phytoplankton biogeography between Ant-

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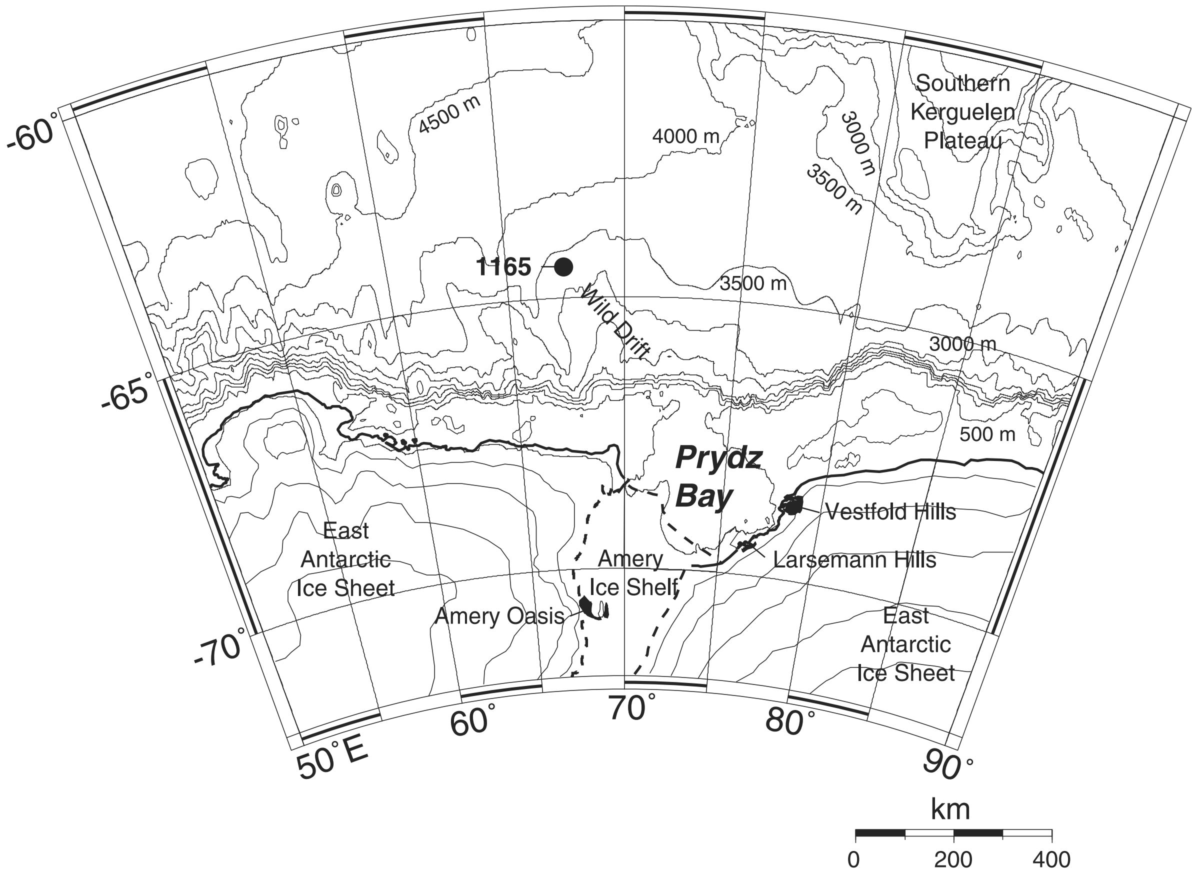

Figure 1. Location ODP Site 1165 on the Wild Drift, Southern Ocean.

arctic surface waters, at Site 1165, and Subantarctic surface waters north of the APF [*Bohaty and Harwood*, 1998].

1.2. North Atlantic Deep Water and Thermohaline Circulation

[6] The strength of THC and the amount of NADW influx into the Southern Ocean during the Pliocene may have influenced SST at Site 1165, the physical structure of the APFZ, and temperature gradients across the APF and SAF. Our study compares SST at Site 1165 to other studies, which show that that NADW influx increased during the Pliocene.

[7] The influx of NADW to the Southern Ocean via THC has a major impact on modern global heat distribution. Modern THC operates in a conveyor belt-like transport system (reviewed in detail by *Broecker* [1997]), which transports warm, salty, surface water from the tropics to the North Atlantic. From the North Atlantic, the surface water cools and sinks to form NADW, and then flows south. The majority of NADW then forms Circumpolar Deep Water (CDW) [*Wong et al.*, 1998], the largest volume of water in the Southern Ocean. Vertically mixed CDW penetrates onto the Antarctic continental shelf [*Middleton and Humphries*, 1989; *Wong et al.*, 1998] and relatively warm CDW upwelling around Antarctica [*Gordon*, 1981] promotes sea-ice melt [*Crowley*, 1992].

[8] In the Southern Ocean, CDW also combines with dense (cold and saline) Antarctic Bottom Water (AABW) formed by brine exclusion during sea-ice formation. The newly formed bottom water flows at depth away from south polar latitudes into the Pacific and Indian Oceans. Here the ocean is strongly stratified, but sufficient mixing between warmer, less-dense surface waters decreases the density of the deep water. The density deficit that is established at lower latitudes drives deep-water renewal and the transport of surface water to the North Atlantic, thus sustaining the THC conveyor belt.

1.3. Pliocene Ocean Circulation and Global Warming

[9] The Pliocene may have been the most recent time when global temperatures were significantly warmer than today [*Crowley*, 1996]. Warm intervals during the Pliocene are largely explained by two factors: enhanced THC and increased atmospheric CO_2 levels. The average Pliocene CO_2 level was 380 ppm (peaking at 425 ppm), based on interpretations from the carbon isotopic composition of marine organic matter [*Raymo et al.*, 1996]. This average is 35% higher than the preindustrial level and is 3–14% higher than that recorded in 1999 [*Raymo et al.*, 1996; *Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Increased ocean heat transport due to enhanced THC may also explain Pliocene warming [*Crowley*, 1996]. Each of these two factors is not necessarily exclusive, as CO_2 increases may partially drive THC [*Crowley*, 1996; *Kim and Crowley*, 2000].

[10] Isotope studies suggest that both THC and NADW influx to the Southern Ocean increased during the early Pliocene [*Billups et al.*, 1998; *Ravelo and Andreasen*, 2000]. A simultaneous increase in equatorial surface water transport to the North Atlantic may explain Pliocene warming in the Northern Hemisphere. The effect of increased NADW influx to the Southern Ocean is unclear, but two hypotheses have been proposed:

[11] 1. Increased NADW production resulted in a gradual warming of the Southern Ocean [*Billups et al.*, 1998] via enhanced THC. Increased NADW formation would have helped to dissipate heat globally, but may have also enhanced global warming through sea-ice reduction and the resulting decrease in global albedo [*Raymo et al.*, 1996].

[12] 2. Enhanced NADW formation may have caused a net heat loss from the Southern Hemisphere, as warmer surface waters (from the tropics, south of the equator) are drawn into the North Atlantic Basin. Enhanced NADW formation during the Pliocene would have caused Southern Hemisphere cooling. In contrast, if THC were to slow or cease, warm surface water would not be exported from the Southern Hemisphere and the region would warm [*Crowley*, 1992].

[13] A decrease in latitudinal temperature gradients, relative to today, is evidence to support increased THC during the Pliocene [*Dowsett et al.*, 1996]. If global temperatures increased solely due to increased atmospheric CO_2, warming would have occurred evenly at all latitudes [*Dowsett et al.*, 1996]; but during the Pliocene, equatorial temperatures remained similar to today, or may have even cooled slightly [*Billups et al.*, 1998], while preferential heating occurred at high latitudes [*Rind*, 1998]. This provides evidence for increased THC in the Pliocene that redistributed more heat to higher latitudes.

[14] Two forcing mechanisms capable of increasing global THC in the Pliocene are thought to have been possible. Either seawater density gradients were altered (after the Central American seaway closed 4.7–4.2 Ma [*Haug et al.*, 2001]), or sea-ice formation in the Southern Ocean was reduced during a slight atmospheric CO_2 increase that caused global warming [*Kim and Crowley*, 2000]. However, global climate models suggest that greatly elevated CO_2 levels (four times the preindustrial level) will weaken or potentially stop THC [*IPCC*, 2001], but when the climate models are run for longer time periods THC is re-established [*IPCC*, 2001]. Extended warming, as may have occurred in the Pliocene [*PRISM Project Members*, 1995], is thought to be required for THC to become re-established [*Raymo et al.*, 1996]. Research is required, therefore, to document the magnitude and duration of the warm climatic intervals in the Pliocene Southern Ocean in a step toward addressing the mechanism for past changes in ocean circulation.

[15] For warming to be detected adjacent to East Antarctica, major warming within the Antarctic region would be required. Site 1165 is an ideal location to study Pliocene SST in the Southern Ocean due to its southern location and the completeness of the Hole 1165B sediment sequence [*Shipboard Scientific Party*, 2001].

1.4. Silicoflagellate SST Reconstruction

[16] Silicoflagellates are assigned to the kingdom Eukaryota, algal division Heterokontophyta, and the class Dictyochophyceae [*Van den Hoek et al.*, 1995]. The relative abundance of the silicoflagellate genera *Dictyocha* and Distephanus in seafloor surface sediments changes abruptly at the APF [*Ciesielski*, 1974; *DeFelice and Wise*, 1981; *Pichon et al.*, 1987]. In the Southern Ocean between Antarctica and Australia, *Dictyocha* is common north of the APF, where summer (January–March) SST is > 5°C; *Distephanus* is abundant south of the APF [*Ciesielski and Weaver*, 1974]. *Dictyocha* in surface sediments is also limited to sites north of the APF [*DeFelice and Wise*, 1981] from the Atlantic and western Indian Oceans sectors of the Southern Ocean [*Pichon et al.*, 1987]. The ratio of *Dictyocha* to *Distephanus* was determined from 48 phleger and trigger-core surface sediment samples collected between Australia and Wilkes Land, Antarctica [*Ciesielski*, 1974]. The ratio of *Dictyocha* to *Distephanus* has proved to co-vary with mean annual SST [*Gordon*, 1971] and this measurement is a useful tool to reconstruct past SST [*Mandra*, 1969; *Mandra and Mandra*, 1970; *Jendrzejewski and Zarillo*, 1971; *Ciesielski*, 1974; *Ciesielski and Weaver*, 1973, 1974; *Bohaty and Harwood*, 1998].

[17] From the ratio of *Dictyocha* to *Distephanus* warmer surface waters in the Southern Ocean during the Pliocene have been inferred. *Dictyocha* is abundant in four Pliocene intervals at four sites between 56°S and 69°S, which are between 300 km and 550 km south of the present APF [*Ciesielski and Weaver*, 1974]. Three intervals of abundant *Dictyocha* (~3.7, ~4.4 and ~4.7 Ma) have also been identified from the Kerguelen Plateau, ODP Sites 748 and 751 (~58°S) and are interpreted to represent either a 900 km southern migration of the APF from its present location or a decrease in the temperature gradient across the APFZ [*Bohaty and Harwood*, 1998]. The latitudinal variation in the modern APF position is partially controlled by seafloor topography [*Lazarus and Caulet*, 1993]. The Elan Bank at ~57°S, which rises over 2000 m in depth and extends 500 km west from the Kerguelen Plateau, may have stabilized the southern position of the APF during the middle Pliocene [*Barron*, 1996].

2. Methods

[18] The relationship between modern mean annual SST and the ratio of *Dictyocha* to *Distephanus* in core top samples was identified by *Ciesielski and Weaver* [1974]. In the current study we use this relationship, but apply a "silicoflagellate index," defined here as the percentage of *Dictyocha* within the silicoflagellate assemblage to the Pliocene strata from Site 1165.

[19] Silicoflagellate data were collected from ~10 cm sample increments throughout the Pliocene interval of Hole 1165B (24.47–49.97 mbsf). Smear slides were prepared from the samples and mounted with Norland Optical Adhesive 61 (refractive index = 1.56). Silicoflagellate identification was carried out using an Olympus BH-2 light microscope at 1000x magnification (oil immersion objective) (Appendix A). The smear slides were scanned for silicoflagellates, and ~100 specimens from the genera *Dictyocha* and *Distephanus* counted per sample (Appendix 2[1]). Those

[1] Supporting appendices are available at ftp://ftp.agu.org/apend/pa/2002PA000829.

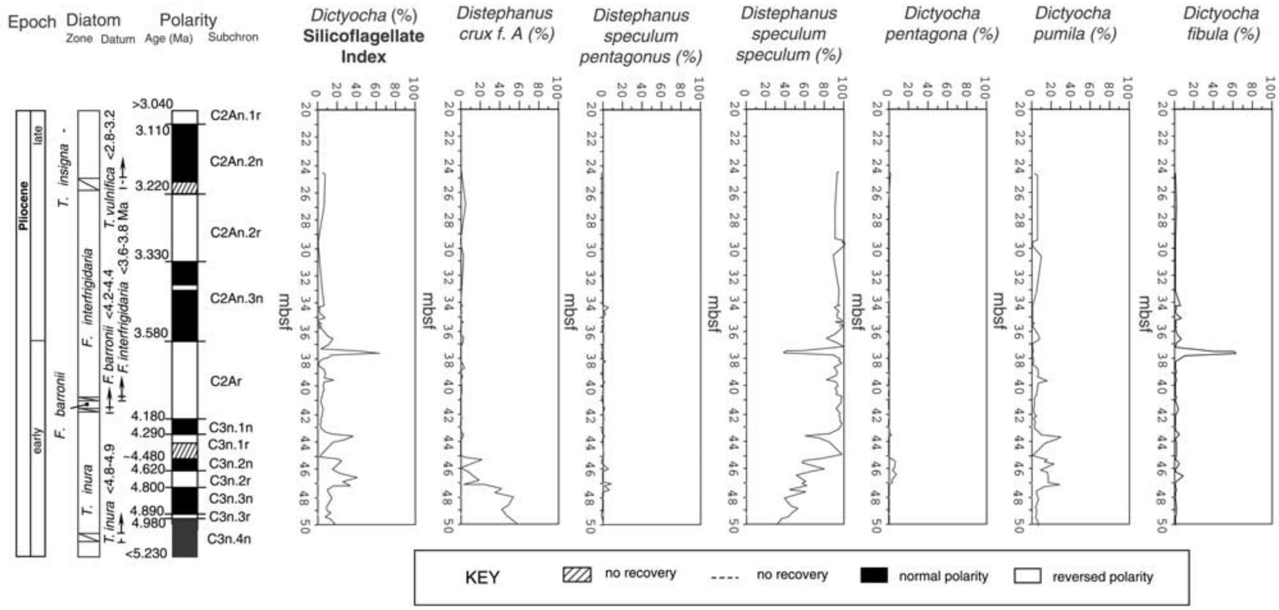

Figure 2. Relative abundance (percent) of the most abundant silicoflagellates and silicoflagellate index from the Pliocene interval from Hole 1165. Corresponding diatom and magnetostratigraphic ages are from *Florindo et al.* [2003], and *Whitehead and Bohaty* [2003].

samples with <80 silicoflagellate specimens were removed from further data analysis. The extinct species *Distephanus crux* (Ehrenberg) Haeckel, *Bachmannocena* spp., and aberrant forms of *Distephanus* and *Dictyocha* were also excluded from the ratio, because their paleoecology is unknown (as in the work of *Bohaty and Harwood* [1998]).

3. Results

[20] Three events where *Dictyocha* abundance increases (up to ~36% and 62%) are recorded from Site 1165 (Figure 2). The first event, dominated by *Dictyocha fibula* Ehrenberg, saw abundance increase to 62% between 37.37 mbsf and 37.57 mbsf. Two more events occur between 43.57 mbsf and 43.77 mbsf, and 46.17 mbsf and 47.07 mbsf. Both are dominated by *Dictyocha pumila* (Ciesielski) Bukry, which increased to 36% and 40%, respectively.

[21] *Distephanus speculum speculum* (Ehrenberg) Haeckel is the most abundant species from this genus in the Pliocene section of Hole 1165B. *Distephanus crux* is rare, but a marked increase in abundance was observed below 45.37 mbsf. Similarly, *Bachmannocena* spp. was present only in trace abundance, but a minor increase was observed below 49.36 mbsf.

4. Discussion

4.1. Interpreting the Silicoflagellate Index

[22] The three episodes of increased *Dictyocha* abundance in Hole 1165B are dated through diatom biostratigraphy and magnetostratigraphy as being at ~3.7 Ma, 4.3–4.4 Ma, and ~4.55–4.8 Ma; they are named here as events I, II and III, respectively (Figure 3). Site 1165 is 1600 km south of the modern APF and the presence of the *Dictyocha* events represents an extreme southern occurrence for this genus. We consider the events to reflect higher SST in the Pliocene relative to today (Figure 3). Although conditions similar to those north of the APF now occurred at Site 1165 (64°S) during the Pliocene, it is possible that the position and structure of the oceanographic fronts were very different from today.

[23] The distribution and abundance of silicoflagellates in the water column are influenced by a variety of factors (such as water temperature, salinity, nutrient availability, and grazing), but the relationship is neither simple nor consistent [*Sancetta*, 1990]. The habitat preference of *Dictyocha,* from studies in the Northern Hemisphere, is ambiguous. *Dictyocha* is reported to prefer warm surface waters [*Ciesielski and Weaver*, 1974], yet *Takahashi* [1987] finds it common in the northern Pacific Ocean regardless of surface water temperature. The occurrence of *Dictyocha* in the relatively cold waters of the northern Pacific may be explained by transportation within warmer surface water eddies. *Sancetta* [1990], for example, finds *Dictyocha* common in warm water rings in the northeastern Pacific. Similar observations have been reported in warm water rings from the Gulf Stream in the North Atlantic [*Takahashi and Blackwelder*, 1992].

[24] In the Southern Ocean, *Dictyocha* is limited in surface sediments to sites north of the APF [*DeFelice and Wise*, 1981; *Pichon et al.*, 1987], which suggests that their biocoenoses is restricted to surface waters north of the front. Modern plankton data from a South Atlantic transect show that the major change in distribution is further north at the Subantarctic front (SAF); *Dictyocha fibula* reaches maxi-

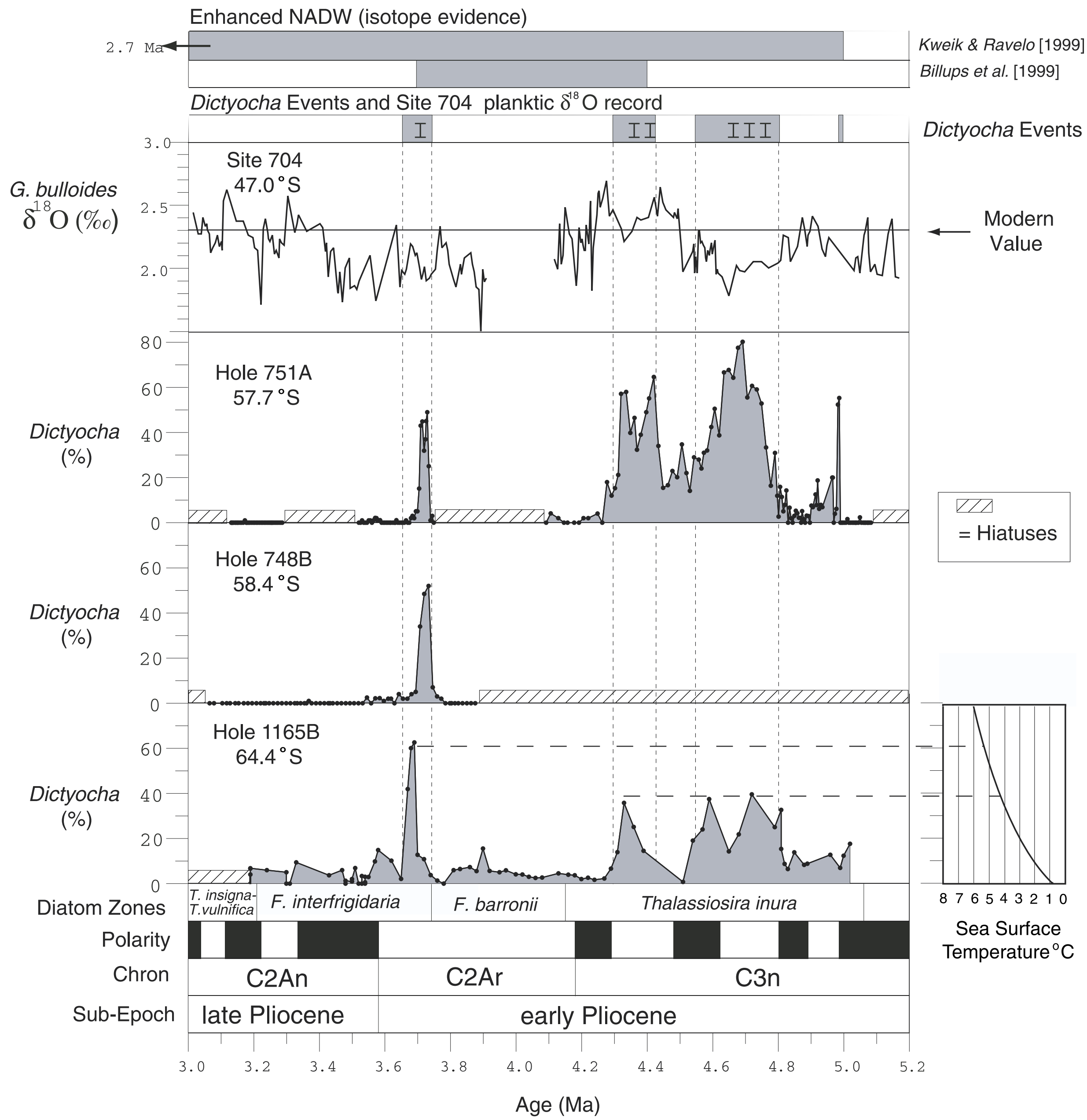

Figure 3. Site 1165 *Dictyocha* percent (this study) and age control [*Florindo et al.*, 2003]. Three *Dictyocha* events (I, II, and III) were identified at Site 1165 and correlate to *Dictyocha* events identified at ODP Sites 748 and 751 [*Bohaty and Harwood*, 1998]. *Dictyocha* planktic formaminfera $\delta^{18}O$ values from ODP Site 704 [*Hodell and Venz*, 1992]. The *Dictyocha* percent relationship to summer sea surface temperature is from *Ciesielski and Weaver* [1974].

mum abundance between here and the Agulthas front (Figure 4) [*Eynaud et al.*, 1999]. Features of the modern Southern Ocean's circum-Antarctic surface water and atmospheric systems may inhibit *Dictyocha* incursions south of the APF. Today, cold water-bodies in the Southern Ocean occasionally become trapped in eddies that spiral northward off the APF jet stream [*Pickard and Emery*, 1990], causing diatoms from Antarctic waters to appear sporadically at low latitudes [*Crawford et al.*, 1997]. Relatively warm water rings also occasionally spiral southward from the APF jet stream into Antarctic waters [*Gouretski and Danilov*, 1994]; however, this would cause negligible *Dictyocha* transport southward because their abundance is originally low near the APF [*Eynaud et al.*, 1999]. Cyclonic, circum-Antarctic, low-pressure systems over the APFZ form effective cloud and precipitation barriers that extend for several kilometers above the ocean surface [*Shaw*, 1979]. Precipitation removes airborne particles from below the troposphere [*Delmas and Legrand*, 1989] and prevents aerial transport of *Dictyocha* into the Southern Ocean. For *Dictyocha* to be

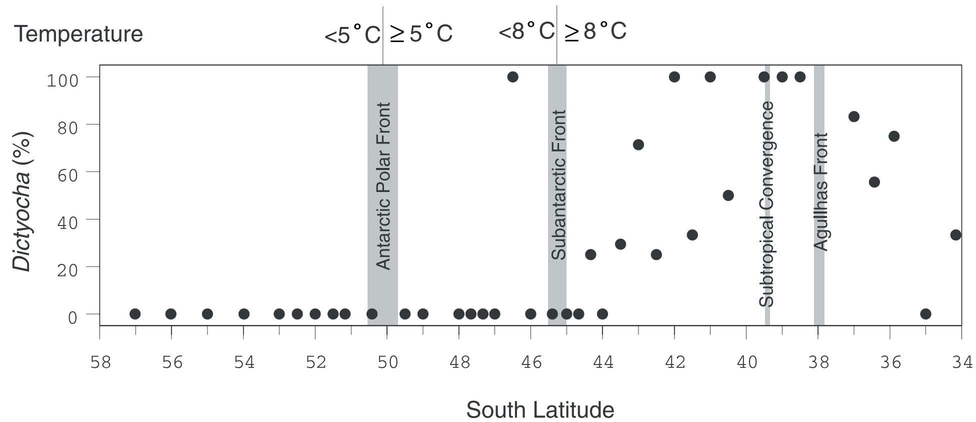

Figure 4. Latitudinal abundance of *Dictyocha* in surface water samples from a transect across the South Atlantic (data from *Eynaud et al.* [1999]).

deposited at Site 1165; therefore a change in atmospheric, and more likely, a change in oceanic conditions is required.

[25] We consider low SST to be the major factor preventing the incursion of *Dictyocha* south of the modern APF. Comparison between Pliocene and modern silicoflagellate data [*Ciesielski and Weaver*, 1974] suggests that a mean annual SST increase up to 5.5°C occurred during event I at Site 1165, resulting in a summer maximum SST of approximately 5°C. During events II and III, warming by approximately 4.5°C occurred, producing summer maximum SST at Site 1165 of 4°C. The lack of *Dictyocha* in other Pliocene intervals at the site suggests cooler SST of <2°C prevailed throughout much of this period.

4.2. Correlation to Other Pliocene SST Records

[26] The early to middle Pliocene is generally recognized as an interval of elevated global temperature [*Crowley*, 1996; *Dowsett et al.*, 1996]. Early to middle Pliocene Southern Ocean SST has been previously reconstructed using paleontological evidence, as well as sedimentological and isotope proxies. This evidence and its SST interpretation at Site 1165 are discussed below.

4.2.1. Paleontology

[27] Events with high *Dictyocha* abundance have been identified north of Site 1165 on the Kerguelen Plateau at ODP Sites 748 and 751 [*Bohaty and Harwood*, 1998] (Figure 3; Appendices 3 and 4). Event I correlates to an event at the base of the *Fragilariopsis interfrigidaria* zone at Sites 748 and 751; events II and III may correlate with two unnamed events on the Kerguelen Plateau, within the *Thalassioisira inura* zone at Site 751 (Figure 3). The *Dictyocha* events also appear to be useful biostratigraphic markers in the Indian sector of the Southern Ocean. For instance, event I is an easily identifiable event, nearly coincident with the first occurrence (FO) of *F. interfrigidaria* (McCollum) Gersonde and Bárcena at ~3.7 Ma.

[28] Southern Ocean silicoflagellate paleotemperatures have been interpreted from Eltanin and Deep Sea Drilling Project (DSDP) cores [*Ciesielski and Weaver*, 1974]. On the basis of the diatom stratigraphy, the *Dictyocha* events at Site 1165 can be correlated to events at DSDP Site 266 referred to as G-II, G-IV, and G-V [*Ciesielski and Weaver*, 1974]. The G-II event at Site 266 was identified in Sample 266 - 7-4, 45 (124.95 mbsf), which contains 11% *D. fibula* (originally identified as *Dictyocha aspera* (Lemmermann) Burky and Foster) [*Ciesielski and Weaver*, 1974]. This *Dictyocha* event is coincident with the FO of *F. interfrigidaria* between Samples 266-7-2, 45–47 (121.96 mbsf) and 266-7-4, 120–122 (125.71 mbsf) at Site 266 [*McCollum*, 1975] and therefore correlative to event I at Site 1165. Events G-IV and G-V fall between ~130 mbsf and 140 mbsf at Site 266 [*Ciesielski and Weaver*, 1974]. These events can be correlated to Site 1165 based on the FO of *Fragilariopsis barronii* (Gersonde) Gersonde *and* Bárcena (4.2–4.3 Ma) (identified as *Nitzschia angulata* Hasle), which occurs between Samples 266-7-CC (129.50 mbsf) and 266-8-1, 55–57 (130.06 mbsf), and the FO of *Fragilariopsis praeinterfrigidaria* (McCollum) Gersonde and Bárcena (4.9–5.8 Ma), between Samples 266-9-4, 99–101 (145.50 mbsf) and 266-9-CC (148.50 mbsf). Therefore events G-IV and G-V at Site 266 fall within the *T. inura* zone and are most likely correlative to events II and III at Site 1165. Another important stratigraphic feature of these two events is the dominance of *D. pumila*.

[29] Southern Ocean SSTs were warmer than present during the middle and early Pliocene, as interpreted from diatom, coccolithophorid, foraminiferal, and radiolarian distribution in the Southern Ocean [*Ciesielski and Weaver*, 1974; *Keany*, 1978; *Abelmann et al.*, 1990; *Bohaty and Harwood*, 1998; *Whitehead et al.*, 2001]. In the Southern Ocean sector from ~76°E to 150°E during the early Pliocene (Chrons C2Ar and C3n), Antarctic radiolarians from the APFZ dominated assemblages deposited up to ~350 km south of the current APF (e.g., Eltanin core Site E50-28) [*Keany*, 1978]. The southern incursion of radiolarians may correlate to *Dictyocha* events II and III at Site 1165. Subantarctic planktic foraminifera also penetrated ~900 km south of the current APF during the Pliocene, at ODP Sites 747, 748, 751 and DSDP Site 265 [*Berggren*, 1992; *Jenkins*, 1993; *Ivanova and Ivanova*, 1996a, 1996b]. On the Kerguelen Plateau, abundant coccolithophorids were deposited south of the modern APF, in association with

Dictyocha events in the *T. inura* and *F. interfrigidaria* zones at Sites 748 and 751 [*Bohaty and Harwood*, 1998]. Coccolithophorids on the Kerguelen Plateau suggest that the summer SST exceeded 5°C, which is consistent with a 4°C warming interpreted by *Bohaty and Harwood* [1998]. From the coast at Prydz Bay (~68°S), extant diatoms were deposited within the early Pliocene Sørsdal Formation [*Harwood et al.*, 2000], during a brief interval between 4.2 Ma and 4.1 Ma. We have revised the biostratigraphic age of the Sørsdal Formation to the *Berggren et al.* [1995] timescale from the presence of *Fragilariopsis praecurta* (last occurrence 4.1 Ma [*Gersonde and Burckle*, 1990]) and *Fragilariopsis barronii* (first occurrence 4.2 Ma [*Winter and Iwai*, 2002]), which indicates that the deposit falls between events I and II at Site 1165. Microfossil data from the Sørsdal Formation suggests that summer SST was 1.6°C to 3°C warmer than today [*Whitehead et al.*, 2001]. It is likely that the Sørsdal Formation was not deposited during maximum warming, which may explain why the relative SST increase at this high latitude location was less than that detected to the north at Site 1165. This is consistent with the oxygen isotope record from ODP Site 846, which illustrates that climatic conditions were highly variable between 4.5 Ma and 4.1 Ma [*Shackleton et al.*, 1995].

[30] From Maud Rise in the Weddell Sea (~64° S), ~1500 km south of the modern APF, there is evidence for an early Pliocene climatic optimum (within Subchron C3n.4n) when SST was 10°C to 5°C warmer than today [*Abelmann et al.*, 1990]. Although the optimum predates the Site 1165 silicoflagellate record, warm conditions were recognized at Maud Rise throughout the Subchron C3n followed by cooling in the Subchron C2Ar [*Abelmann et al.*, 1990]. This trend is similar to that interpreted from Site 1165 (Figure 3). Cool water radiolarians and diatoms endemic to Antarctica first appear on the Maud Rise within Subchron C3n.2n [*Abelmann et al.*, 1990], which coincides with the cooler interval that separates the Site 1165 *Dictyocha* events II and III.

4.2.2. Sedimentology

[31] Variation in biogenic carbonate and silica deposition has been used to indicate movement of the APF [e.g., *Froelich et al.*, 1991; *Burckle et al.*, 1996]. Today, calcareous sediments are dominant north of the SAF and siliceous sediments are dominant south of the APF; a mixture of both sediments occurs within the intermediate APFZ [*Hodell and Warnke*, 1991; *Burckle et al.*, 1996]. High carbonate intervals at ODP Site 737, deposited when the APF moved south from today's location, suggest that Southern Ocean warming was only short-lived in the early Pliocene [*Burckle et al.*, 1996].

[32] The lack of appreciable carbonate from other Southern Ocean sediment records has been used to infer negligible warming in the early Pliocene [*Burckle et al.*, 1996]. However, many of these records were deposited near or below the carbonate compensation depth (CCD), which lies below water depths of 2000 m on the Kerguelen Plateau [*Goodell*, 1973] and 1500 m on the Antarctic continental shelf [*Quilty*, 1985] (e.g., ODP Sites 693, 697, 744, and 745). Additionally, many records are in close proximity to Antarctica where they received significant terrigenous input (e.g., CIROS 2, DVDP 10, 11 [*Winter and Harwood*, 1997]). Deposition below the CCD or high terrigenous input prevents simple interpretation of SSTs from bulk carbonate content. This pertains to Site 1165, at 3537 m water depth, which was most likely well below the CCD during the Pliocene [*Shipboard Scientific Party*, 2001].

[33] At high latitudes in the Southern Ocean, increased biogenic deposition (notably silica) has been linked to sea-ice reduction and increased SST [*Burckle*, 1984]. This is evident in early Pliocene sediments from the Bellingshausen Sea (ODP Sites 1095 and 1096) near the Antarctic Peninsula [*Hillenbrand and Fütterer*, 2001].

[34] There is no consistent relationship between ice rafted debris (IRD) deposition and SST in early Pliocene strata from the Southern Ocean [*Bohaty and Harwood*, 1998; *Anderson*, 1999]. IRD deposition was consistently high throughout the Southern Ocean ~4.5 Ma to 4.2 Ma [*Hodell and Warnke*, 1991; *Breza*, 1992]; a period that spans both warm and cool silicoflagellate events identified at Kerguelen Plateau Site 751 [*Bohaty and Harwood*, 1998]. A warm event at Site 751, ~3.7 Ma, is also associated with high IRD [*Bohaty and Harwood*, 1998].

[35] IRD data must be interpreted with caution, however, as numerous factors affect iceberg calving rates, and hence IRD deposition. Iceberg calving can increase during both ice sheet growth and retreat. Calving, dispersal, and drift trajectory are also dependent on sea-ice condition, ocean currents, and wind [*Anderson*, 1986; *Breza*, 1992; *Anderson*, 1999]. Altered sediment deposition rates and erosion (i.e., winnowing) can also concentrate IRD [*Whitehead and McMinn*, 2002], which may be misinterpreted as increased iceberg calving. We cannot use IRD data alone to interpret SST in the Southern Ocean. Rather, IRD data must be combined with paleotemperature data, as done to interpret Heinrich events in the Northern Hemisphere [*Oerlemans*, 1993; *Verbitsky and Saltzman*, 1994], to understand the climatic significance of the Southern Ocean's Pliocene IRD record.

4.2.3. Isotopes

[36] Isotopes have been used to reconstruct Southern Ocean SST, notably from ODP Site 704 just north of the Southern Ocean (~47°S) [*Hodell and Venz*, 1992; *Kennett and Hodell*, 1993]. Variations in $\delta^{18}O$ are a result of changing ice sheet volumes and must be considered in conjunction with SST estimates. Planktic $\delta^{18}O$ values from the early to middle Pliocene are ~0.5–0.6‰ less (minima 0.75‰ less) than Holocene values [*Kennett and Hodell*, 1993]. A reduction of this amount can accommodate either a 2.5°C SST warming at Site 704 or a 60% East Antarctic Ice Sheet (EAIS) reduction, but not both [*Hodell and Venz*, 1992]. A partial EAIS deglaciation equivalent to a 20 m sea level rise (equivalent to a 0.2‰ $\delta^{18}O$ decrease) would accommodate a 1°C to 2°C SST warming at Site 704 and is consistent with the oxygen isotope record (up to 0.4‰ $\delta^{18}O$ decrease) [*Kennett and Hodell*, 1993]. A similar trend has been observed from the Tasman Sea, where a 1.5°C warming is interpreted from the planktic $\delta^{18}O$ isotope record at DSDP Site 593 (~41°S) [*Head and Nelson*, 1994].

[37] An alternative hypothesis for the Site 704 isotope record explains ice sheet expansion associated with higher SST (i.e., *Prentice and Matthews'* [1991] "snow gun hypothesis"). The hypothesis enables elevated SST to explain the reduced early Pliocene $\delta^{18}O$ values at Site 704 without the need to account for EAIS reduction [*Warnke et al.*, 1996]. This is consistent with the proportionally higher Southern Ocean SST estimates from microfossils (i.e., 4.5° to 5.5°C warming at Site 1165), when current or increased ice sheet volume is factored into the "low" early Pliocene $\delta^{18}O$ values from Site 704 [*Warnke et al.*, 1996]. Seismic data from the Antarctic continental shelf supports evidence for two or three episodes of early Pliocene ice sheet expansion [*Bart*, 2001]. Early Pliocene eustatic sea levels lower than today are evident from the northeast Gulf of Mexico [*Greenlee and Moore*, 1988], and loosely correlate to decreased planktic $\delta^{18}O$ at 3.6 Ma and 4.7–4.8 Ma at Site 704 [*Bart*, 2001]. Lower sea levels than today occurred on the Pacific Ocean Enewetak Atoll 3.7–3.8 Ma and 5.0 Ma (dates revised to the *Berggren et al.* [1995] timescale); however, eustatic sea levels 30–35 m higher than today also occurred during these times [*Wardlaw and Quinn*, 1991], which indicates that a large Antarctic ice sheet was not sustained throughout the early Pliocene.

[38] A new approach to interpret ice volumes integrates benthic foraminiferal $\delta^{18}O$ values with Mg/Ca ratios that reflect water temperature near the seafloor [*Lear et al.*, 2000; *Billups and Schrag*, 2002]. The highest resolution Pliocene study of this kind has been undertaken on Kerguelen Plateau ODP Site 747 (~54°S, at 1695 m water depth) [*Billups and Schrag*, 2002]; however, the resolution is still relatively low (thirteen samples spanning ~3.5 myr of strata). The findings suggest early Pliocene temperatures were comparable, or only slightly cooler, than temperatures throughout much of the Miocene, but specific warming or cooling events may have been missed by the low sampling resolution. A cooling of approximately 4°C occurred in the late Pliocene [*Billups and Schrag*, 2002], but a critical interval between 3.1 Ma and 2.5 Ma, of interpreted warming [*Moriwaki et al.*, 1992; *Wilson et al.*, 1998], is disconformably absent from Site 747 [*Harwood et al.*, 1992].

[39] The planktic isotope record from Site 704 shows little correlation with *Dictyocha* events I and II at Site 1165 (Figure 3). There are numerous explanations for this lack of correlation, which includes differences in the age models or different temperature histories at the two sites. Ice volume and temperature affect $\delta^{18}O$ values, as do changes in surface water salinity and pH, which complicate the isotope interpretation [*Spero et al.*, 1997] and may explain the discrepancy between these proxies. There is some similarity, however, between a decrease in $\delta^{18}O$ at Site 704 and *Dictyocha* event III at Site 1165, which points toward some consistency between parts of these records.

[40] The $\delta^{18}O$ isotope record suggests that in the Pliocene, Southern Ocean SST were lower than values obtained from paleontological reconstructions [*Kennett and Hodell*, 1993; *Warnke et al.*, 1996; *Bohaty and Harwood*, 1998]. These differences may be geographical, as at low latitudes small temperature increases of 1.5°C (~41°S, DSDP Site 593) and 1°C to 2°C (~47°S, Site 704) were interpreted from planktic $\delta^{18}O$ isotopes [*Kennett and Hodell*, 1993; *Head and Nelson*, 1994]. At higher latitudes, SST increased 4°C (~58°S at Sites 748 and 751) and 4.5°C to 5.5°C (~64°S, Site 1165), as interpreted from silicoflagellate data [*Bohaty and Harwood*, 1998; this study]. A declining latitudinal temperature gradient in the Pliocene may only be associated with a minor temperature increase at Site 704, due to the southern movement or change in the latitudinal temperature gradient across Subantarctic surface water. The larger temperature transitions across the SAF and APF, currently south of Site 704, could have become less steep and/or moved southward [*Bohaty and Harwood*, 1998], leading to relatively greater warming of Antarctic surface waters at Sites 748, 751 and, notably, Site 1165.

4.3. Mechanisms for Southern Ocean Warming

[41] Distinct warm intervals in the early Pliocene at Site 1165 contribute toward our understanding of THC. The Pliocene is recognized as an interval of strengthened THC, between 5.0 Ma and 2.7 Ma [*Kwiek and Ravelo*, 1999] and in particular between 4.4 Ma and ~3.7 Ma [*Billups et al.*, 1998]. The *Dictyocha* events at Site 1165 represent distinct pulses of warming in the Southern Ocean that do not span the entire duration of enhanced NADW influx that occurred throughout much of this period. It is possible that the *Dictyocha* events at Site 1165 represent intervals of maximum NADW influx into the Southern Ocean ~3.7 Ma, 4.3–4.4 Ma, and ~4.55–4.8 Ma.

[42] Recent climate models indicate that enhanced THC (notably increased NADW influx) was a consequence of Pliocene warming, not the cause [*Kim and Crowley*, 2000]. *Kim and Crowley* [2000] proposed that a reduction in sea-ice formation in the Southern Ocean would have created a meridional deep-water gradient that promoted thermohaline overturning in the North Atlantic and increased NADW production. The cause for sea-ice loss in the Pliocene is thought to have been a slight atmospheric CO_2 increase [*Kim and Crowley*, 2000]. Reduced sea-ice concentration throughout the early Pliocene was documented from the Bellingshausen Sea ODP Sites 1095 and 1096 [*Hillenbrand and Fütterer*, 2001]. It is possible that the distinct warming intervals, represented by increased *Dictyocha* abundance at Site 1165, occurred during intervals of higher atmospheric CO_2 than occurred in the middle to late Pliocene (reconstructed by *Raymo et al.* [1996]). Detailed early Pliocene atmospheric CO_2 records are required to test this. Alternatively, the warming interpreted from *Dictyocha* abundance at Site 1165 could have been the result of complicated feedback processes that resulted in warming of Southern Ocean surface waters.

5. Conclusion

[43] A middle to early Pliocene SST reconstruction is derived from silicoflagellate data collected from ODP Hole 1165B. Three events with high *Dictyocha* abundance, between ~36% to 62%, were identified. These events occurred ~3.7 Ma, 4.3–4.4 Ma, and ~4.55–4.8 Ma, as interpreted from diatom and magnetostratigraphic data [*Florindo et al.*, 2003; *Whitehead and Bohaty*, 2003].

Comparison of these data with *Ciesielski and Weaver*'s [1974] modern core top silicoflagellate relationship with SST indicates that at Site 1165 SSTs were 5.5°C and 4.5°C warmer than modern mean annual SST values.

[44] A review of previous studies identified that discrepancies occur between SST estimates from isotope, sedimentological and paleontological proxies. There appear to be problems interpreting SST from sedimentological proxies, where carbonate analyses have been made on cores deposited below the CCD, and from IRD data that has not been interpreted in conjunction with other paleoenvironmental data. More reliable SST estimates may arise from isotope and paleontological techniques, but some differences in these proxies may be geographical, due to differential warming at different latitudes in the Southern Ocean. It is believed that the latitudinal temperature gradient declined globally during the Pliocene warming [*Dowsett et al.*, 1996; *Rind*, 1998] and this appears consistent with early Pliocene Southern Ocean SST reconstructions.

[45] *Dictyocha* could only have been deposited at Site 1165 if the APF was ~1600 km south of its current position, or more likely the temperature gradient of this front was less steep across the Southern Ocean. The mechanism for warmer Southern Ocean SST during much of the Pliocene may have been strengthened THC, between 5.0 Ma and 2.7 Ma [*Kwiek and Ravelo*, 1999], which decreased the temperature gradient across the APF. Strengthened THC is associated with enhanced NADW influx into the Southern Ocean, which may have peaked at ~3.7 Ma, 4.3–4.4 Ma, and ~4.55–4.8 Ma, creating the higher SSTs at Site 165 that supported *Dictyocha*. Alternately, other studies suggest that enhanced NADW influx may have resulted from Pliocene warming (due to elevated atmospheric CO_2), which may have caused a reduction in sea-ice formation in the Southern Ocean that created a meridional deep water gradient that promoted THC and increased NADW production [*Kim and Crowley*, 2000]. Further research on the link between Pliocene atmospheric CO_2 levels, sea-ice conditions, and the SST record from Site 1165, and other sites, may help resolve this.

Appendix A: Taxonomy

[46] Silicoflagellate taxonomy from Site 1165 are as follows: (1) kingdom PROTISTA; (2) subkingdom PROTOPHYTA; (3) class CHRYSOPHYCEAE; (4) order SILICOFLAGELLATA Borgert, 1891.

A1. Genus *BACHMANNOCENA* (Locker, 1974) Bukry, 1987

[47] All silicoflagellates consisting solely of a basal ring are grouped into the genus *Bachmannocena* (Locker). We do not follow the taxonomy established by *Locker and Martini* [1986], who separate such morphotypes into the genera *Septamesocena, Mesocena*, and *Paramesocena* (as in the work of *Amigo* [1999]).

[48] 1. *Bachmannocena* sp. A: multiple sides to the basal ring with multiple spines.

[49] 2. *Bachmannocena* sp. B: 6 sides to the basal ring and 6 spines at the joins of these sides.

[50] 3. *Bachmannocena* sp. C: 4 sides to the basal ring and 4 spines at the joins of these sides.

[51] 4. *Bachmannocena sp. D*: 3 sides to the basal ring and 3 spines at the joins of these sides.

[52] 5. *Bachmannocena* sp. E: 2 sides to the basal ring and 2 spines at the joins of these sides.

A2. Genus *DICTYOCHA* Ehrenberg, 1837

[53] The genus *Dictyocha* lacks an apical ring, and instead possess a bar that joins the struts that extend in from the basal ring [*Perch-Nielsen*, 1985]: (1) *Dictyocha fibula* Ehrenberg 1840; (2) *Dictyocha pumila* (Ciesielski) Bukry; (3) *Dictyocha pentagona* (Schulz) Bukry and Foster 1973.

[54] 1. *Dictyocha* sp. A: 6 sides to the basal ring and 3 apical-ring portals.

[55] 2. *Dictyocha* sp. B: 6 sides to the basal ring and 2 apical-ring portals.

[56] 3. *Dictyocha* sp. C: 3 sides to the basal ring and 2 apical-ring portals.

A3. Genus *DISTEPHANUS* Stöhr, 1880

[57] The genus *Distephanus* is characterized by a basal and apical ring [*Perch-Nielsen*, 1985]: (1) *Distephanus speculum speculum* (Ehrenberg) Haeckel 1887; (2) *Distephanus speculum* var. *pentagonus* Lemmermann 1901.

[58] 1. *Distephanus speculum* f. A: the apical ring is close to the circumference of the basal ring.

[59] 2. *Distephanus crux* f. A (Ehrenberg) Haeckel 1887: 4 sides to the basal ring.

[60] 3. Distephanus crux f. B (Ehrenberg) Haeckel 1887: 3 sides to the basal ring.

[61] 4. *Distephanus xenus* Bukry, 1985.

[62] 5. *Distephanus* sp. A: aberrant forms with multiple apical rings.

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