

3. Miocene Climate Evolution of the Southern Ocean – Sea Surface Development as Derived from the Diatom Record (ODP Sites 689, 690, 1088 and 1092)

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3.1 Abstract

Four ODP Sites (689, 690, 1088, 1092) located on a meridional transect across the Atlantic Sector of the Southern Ocean were studied to reveal the thermal development of the Middle and Late Miocene and the coupled variability of the Antarctic ice volume. Occurrences and abundance fluctuations of selected diatom species are used to derive evidences of thermal differences in surface water masses. Diatom classification into a warm- and a cold-water related group was used to calculate relative paleotemperatures (RPT) and estimate the development of the latitudinal thermal gradient (LTG).

Results coincide with climate evidences provided by the eustatic sea level curve. Discrepancies to the global oxygen isotope curve are ascribed to temperature-, salinity-, and vital effects blurring the signal. Relative warm- water masses and low latitudinal thermal differentiation occurred between 14.8 to ca. 13 Ma. This is followed by the stepwise establishment of a cold surface water ocean culminating with the development of cold-water assemblages in the present Subantarctic area around 10.8 Ma, a period of lowest sea level in the Miocene. A first short period of increased thermal decoupling of the Southern Ocean occurred between 10.8 to 10.4 Ma. A rapid warming in the Antarctic Circumpolar Current (ACC) caused this latitudinal differentiation. This is followed by a period of lowered thermal differences and relative warmth between 10.3 and 9.6 Ma. Starting at 9.6 Ma increasing thermal isolation of the Southern Ocean water masses might be related to the onset of major West Antarctic ice sheet (WAIS) build up. The establishment of diatom assemblages consisting of species having close affinities to modern sea-ice related taxa around 9-8.5 Ma supports the idea of a distinct cooling of Weddell Sea surface waters related to a major expansion of the Antarctic ice sheet surface.

3.2 Introduction

The Miocene is known as a period of progressive cooling and growth of the Antarctic ice sheets combined with a relative warming in the low latitudes which results in increasing latitudinal gradients (Shackleton and Kennett, 1975; Miller et al. 1991; Flower and Kennett, 1994). The growth of the Antarctic cryosphere is closely related to the opening of tectonic gateways, such as the Tasmanian Gateway and the Drake Passage, that present the main prerequisites of the development of an unrestricted ACC system, which isolated Antarctica thermally. The timing of these tectonic events however, is yet not well constrained because of the complexity of tectonic movements in both areas (Lawver et al., 1992, Cande et al., 2000). Recent drilling during ODP Leg 189 points to an opening of the Tasman Seaway close to the Eocene/Oligocene boundary (Shipboard Scientific Party, 2001) and geochemical proxies obtained from ODP Leg 177 Site 1090 in the Atlantic sector of the Southern Ocean have been interpreted to record an establishment of a deep water Drake Passage in the earliest Oligocene, around 32.8 Ma (Latimer and Fillipelli, 2002). This is in contrast to earlier estimates indicating an opening in the late Oligocene or earliest Miocene (Barker and Burrell, 1977). Despite the existence of a deep water ACC allowing thermal isolation of Antarctica, the Early and Middle Miocene represents a period of relative warmth, with an East Antarctic ice sheet that was distinctly smaller than during the colder Oligocene, as indicated by the deep-sea stable isotope record (Zachos et al., 2001) and relatively high sea level stands (Haq et al., 1987, Abreu and Anderson, 1998). Only after the Mid-Miocene climatic optimum, centered around 17-15 Ma, the isotope and sea level data point to gradual cooling and reestablishment of a major ice sheet on the Antarctic continent. The most important development in the Late Miocene was the build-up of the West-Antarctic Ice Sheet (WAIS), which started to take place in the early Late Miocene according to sedimentological and clay mineralogical data obtained from ODP Leg 113 (Kennett and Barker, 1990).

On a long-term scale both, the benthic isotope record and the eustatic sea level curve, indicate similar trends (Barrett, 1999). However, a more detailed view of both climate records reveals distinct differences that are yet not explained. In the Middle and Late Miocene distinct mismatches occur e.g. around 16, 15 and 11 Ma, when the sea level curve indicates substantial sea level lowering, while the isotope record provides no support for such instability of the Antarctic ice sheet. Wise et al. (1992) outlined that oxygen isotope data may be controversially interpreted, as a result of inaccurate estimation of components, such as tem-

perature, salinity effects but also “vital effects” of the measured foraminifer taxa, influencing the oxygen isotope values and their significance as a tracer for ice volume changes. Using the magnesium/calcium ratio in benthic foraminifers as an independent record of deep-sea temperature, Lear et al. (2000) concluded that in average 85% of the isotope signal can be attributed during the Middle and Late Miocene to ice-volume build up.

To augment our understanding of the middle and upper Miocene Southern Ocean climate and related ice volume variability, we use the diatom record obtained from a latitudinal transect across the Atlantic sector of the Southern Ocean. Diatoms are useful proxies for the reconstruction of surface water parameters, as shown by transfer-function-based reconstructions of middle and upper Pleistocene Southern Ocean surface water temperatures (e.g. Pichon et al., 1987; Zielinski et al., 1998; Kunz-Pirrung et al., 2002; Bianchi and Gersonde, *subm.*) and sea-ice distribution (e.g. Crosta et al., 1998; Gersonde and Zielinski, 2000). While such studies based on modern analogs provide quantitative values of surface water parameters, paleotemperature reconstructions of pre-Pleistocene sequences must mainly rely on the distribution of extinct taxa and thus only allow the estimation of relative temperature changes. However, studies based on the abundance fluctuations and distribution of extinct diatoms have been completed successfully for the delineation of climate variability in Middle Miocene sections from the Northern and Equatorial Pacific (Koizumi, 1990; Barron, 1992b) as well as in the Pliocene of the Pacific and Southern Ocean (Barron, 1992b and 1996). The latter studies were focused to decipher the magnitude and extend of the mid-Pliocene warming event. Barron (1992b) used a modification of a diatom temperature equation originally proposed by Kanaya and Koizumi (1966), based on the simple ratio of the abundance of diatom species designated to represent warm and cold-water indicators. In our study we use the simple equation proposed by Barron (1992b) to learn more on the thermal evolution of the Southern Ocean during the middle and late Miocene and link these data with the global isotope and sea level records. The comparison of the thermal development at the different sites located on a latitudinal transect also allows the estimation of changes in latitudinal thermal gradients that provide further insights into the Miocene Southern Ocean energy balance.

3.3 Material and methods

3.3.1 Location of sites

We investigated Miocene diatom assemblages recovered at four ODP sites located on a latitudinal transect across the Atlantic Southern Ocean sector. The transect extends from Maud Rise (ca. 65°S) ODP Leg 113 Sites 689 and 690 (Shipboard Scientific Party, 1988a, b), across the northern Meteor Rise (46°S) to the Agulhas Ridge (41°S), ODP Leg 177 Sites 1092 and 1088 (Shipboard Scientific Party, 1999a, b), respectively (Fig. 3.1).

The Maud Rise Sites 690 and 689 are located nearby to each other (distance 116 km) at water depths of 2914 m and 2080 m, respectively. These sites are located close to the East Antarctic continent in the south-eastern realm of the Weddell Gyre, approx. 1000 km south of the Polar Front.

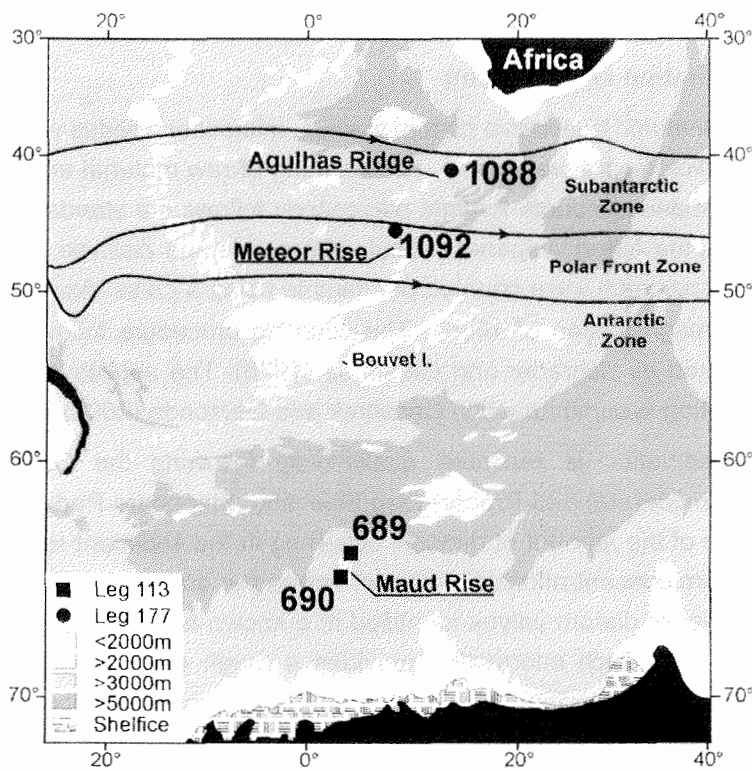


Figure 3.1: Site locations along a latitudinal transect across the Atlantic sector of the Southern Ocean are shown. Frontal zones according to Peterson and Stramma (1991).

Both sites can be spliced to form a continuous composite recording a period between 14.5 Ma and 6.5 Ma. The sediments from this composite (Site 689: 10-63 meters below sea floor (mbsf) and Site 690: 14-50 mbsf) are of pelagic origin and consist mostly of biogenic siliceous ooze (Shipboard Scientific Party, 1988 a, b). Site 1092 is located close to the Subantarctic Front (SAF). The studied section is between 60 and 209 meters composite depth (mcd) and includes a continuous composite sequence obtained from a splice of four holes to 188 mcd. The sediments consist of nannofossil ooze with variable amounts of foraminifers, diatoms and radiolarians (Shipboard Scientific Party, 1999a). The northernmost Site 1088, drilled in 2082 m water depth, is located in the northern portion of the Subantarctic Zone (SAZ) and consists in the studied section (30-220 mcd) predominantly of carbonate (mostly nannofossil) oozes (Shipboard Scientific Party, 1999b). Diatoms are a subordinate component and occur in a reliable preservation only in a few intervals.

3.3.2 Preparation and counting

For quantitative and qualitative diatom studies, microscope slides with randomly distributed microfossils were used. The cleaning of raw material and the preparation of permanent mounts for light microscopy follows the standard technique developed at the Alfred Wegener Institute (Gersonde and Zielinski, 2000). Up to 400 diatom specimen were counted per sample using a Zeiss "Axioskop" microscope at a magnification of 1000 \times . The counting procedure followed the concepts proposed by Schrader and Gersonde (1978). The applied diatom taxonomy information is summarised in Censarek and Gersonde (2002).

Diatom preservation is recorded qualitatively following the OPD scheme: G(good), M(moderate) and P(poor) (see Scientific Shipboard Party, 1999c). As an indication of the amount of diatoms occurring in the sediment record we calculated diatom concentrations (number of valves per gram dry sediment) based on the number of diatom valves identified in a known area of the individual microscopic slides. Such information provides a rough estimate on changes in preservation and deposition of biogenic opal and allows deciphering specific productivity regimes.

The counting results are archived in the PANGAEA information system at the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven (AWI) (<http://www.pangaea.de>).

3.3.3 Chronology

Age models combining geomagnetic and diatom biostratigraphic record for the studied Miocene sections of Sites 689, 690, 1088 and 1092 are taken from Censarek and Gersonde (2002). Range charts showing the site-by-site stratigraphic occurrences of selected diatom species are available from a data report (Censarek and Gersonde, subm. a). The geomagnetic data obtained at Site 1088 are not interpretable (Shipboard Scientific Party, 1999b). As a consequence, the stratigraphy used at Site 1088 only relies on a combination of diatom and calcareous nannofossil biostratigraphic data (Censarek and Gersonde, 2002; Marino and Flores, 2002) limiting the accuracy of the stratigraphic correlation of Site 1088 with the three other studied sites.

Ages are tied to Geomagnetic Polarity Time Scale (GPTS) presented by Berggren et al. (1995). For direct comparison of this time scale with the previously used GPTS of Berggren et al. (1985) both time scales including their deviation are shown in Figure 3.2. A detailed description of the nomenclature of geomagnetic events is available from Cande and Kent (1992).

3.3.4 Paleotemperature estimates and diatom classification

For estimation of changes in paleotemperatures at the individual sites we apply the simple ratio established by Barron (1992b):

$$\text{RPT} = dw / (dw + dc),$$

where "dw" and "dc" are the total number of diatoms indicating warm-water and cold-water conditions, respectively. The resulting value represents a relative paleotemperature ("RPT") estimate between the value 0 (100 % cold-water dwellers) and 1 (100% warm-water dwellers). We choose to name this value "RPT" instead of Barron's paleoclimate ratio "Tw" (Temperature warm-water) to point out the relativity of this term. The comparison of relative paleotemperatures obtained from Sites 689/690 (southern Southern Ocean) and Site 1092 (northern Southern Ocean) are used to estimate the latitudinal thermal gradient (LTG) across the Southern Ocean.

Out of the 72 diatom taxa and taxa-groups counted for this study only five are extant, which allows a delineation of the autecological demands of the taxa based on first-order observations. Of those taxa, we placed *Azpeitia tabularis*, *Hemidiscus cuneiformis*, *Thalassiosira oestrupii* and the *Thalassionema nitzschioides*-group within the group of warm-water indicators (Tab. 3.1). *H. cu-*

neiformis represents a true warm-water taxon (Fryxell et al., 1986), which at present is excluded from Southern Ocean waters as revealed from surface sediment studies (Zielinski and Gersonde, 1997). *Azpeitia tabularis* belongs to a genus that generally shows a warm-water distribution (Fryxell et al., 1986). However, it represents the only exception within the genus *Azpeitia* occurring preferentially in the colder environments of the Southern Ocean. It has been reported from Southern Ocean surface sediments below surface waters, that range in temperature between 0-20°C displaying maximum abundances at temperatures above 10°C, characteristic of the Subantarctic Zone (Zielinski and Gersonde, 1997). Although, *T. oestrupii* has a cosmopolitan distribution (Fryxell and Hasle, 1980) we placed it in the warm-water group because its maximum occurrences in Southern Ocean surface sediments were recorded from the Subantarctic Zone with surface water temperatures above 12°C. The taxa combined within the *Thalassionema*-group consist of *T. nitzschioides* and the varieties *T. nitzschioides* var. *inflatum*, *T. nitzschioides* var. *lanceolatum* and *T. nitzschioides* var. *parvum*. Of those, the varieties *inflatum* and *parvum* have strong affinities to subtropical and tropical regions (Moreno-Ruiz and Licea, 1995; Hasle, 2001). *T. nitzschioides* and the *T. nitzschioides* var. *lanceolatum* are claimed to show a cosmopolitan distribution (Hasle, 2001) also being present in Southern Ocean waters. Nevertheless we also place *T. nitzschioides* and its variety *lanceolatum* within the warm-water group because their southernmost occurrence is in Subantarctic waters (Zielinski and Gersonde, 1997). Morphotypes such as the cold-water related *T. nitzschioides* fo. 1, which preferentially dwells in waters of the Polar Front and Antarctic Zone (Zielinski and Gersonde, 1997), have not been encountered in the studied sections. Another extant taxon, belonging to the genus *Thalassiothrix* has not been considered because the valves of this taxon were mostly preserved as fragments that make a light-microscopic differentiation between *T. antarctica*, a cold-water dweller and *T. longissima*, a temperate species (Hasle, 2001), impossible. However, both species are indicators for high primary productivity and upwelling conditions at frontal systems (Kemp and Baldauf, 1993; Kemp et al., 1995).

The classification of the extinct taxa, making up the majority of the middle and upper Miocene assemblages, into warm- and cold-water related species must rely upon an interpretation of their autecological demands. This interpretation is based on (1) the relationship of the occurrence pattern of taxa with well defined autecological demands (e.g. extant taxa) and extinct taxa, (2) the geographical and stratigraphical distribution, on a Southern Ocean and global scale, and (3)

the generic affiliation, in case the genus can be linked to a specific thermal environment.

Classification of extinct taxa

Warm-water-indicating group (Tab. 3.1):

Although both, *Hemidiscus karstenii* and *Hemidiscus triangularis*, are species that are most probably endemic to the southern high latitudes we placed them into the warm-water group. This interpretation considers, that in general taxa belonging to the genus *Hemidiscus* are related to warmer water conditions (Hasle et al., 1995). Further evidence comes from the Pleistocene record of *H. karstenii*, where the taxon displays prominent occurrences restricted to the climatic optima of interglacials in the Subantarctic realm (Burckle, 1982) making this taxon a stratigraphic tool in the Pleistocene of the northern belt of the Southern Ocean (Gersonde and Bárcena, 1998). Little is known about the distribution of *H. triangularis*. Ciesielski (1983) reported rare to few abundances of *Cosmoidiscus insignis* var. *triangula*, the Basionym for *H. triangularis* (Harwood and Maruyama, 1992), from the Southwest Pacific. This species is found with few abundances in subantarctic sediments of the Southwest Atlantic (Ciesielski, 1986). Considering that *H. triangularis* is not yet documented at sites south of the Polar Front we classified this taxa into the warm-water indicating group. Co-occurrences of *H. triangularis* and *A. tabularis* support this classification.

Fragilariopsis reinholdii occurred from high to low latitudes, but reach highest abundances in relative warm subtropical water masses (Sancetta and Silvestri, 1986; Barron, 1992b). In our study *F. reinholdii* was only found at sites in the northern area of the Southern Ocean referring to the relative warm-water affinity of this species.

Crucidentricula nicobarica is included into the warm diatom group, because of their dominant occurrence beside some few recently occurring warm-water species (e.g. *Thalassionema nitzschioides*, *Thalassiothrix longissima*) in Miocene sediments of the Guadalquivir Basin (Spain) (Bustillo and Lopez-Garcia, 1997). *Crucidentricula nicobarica* was most dominant in Equatorial Pacific sediments, where it occupies more than a half of the diatom assemblage, which documented also the warm-water affinity of this taxa (Barron, 1985a).

A. ingens has a longer stratigraphic range in high latitudes compared to low latitudes (Barron, 1985b), which refers to a generally cold-water affinity. Barron

and Keller (1983) did not include this species in the cold diatom group in the study of Northeast Pacific sediments, because of their common abundances in equatorial sites. However, we considered *A. ingens* as warm-water taxa, because of the dominant co-occurrence in the Southern Ocean with the warm-water indicator *Azpeitia tabularis* (Censarek and Gersonde, subm. a).

A.ingens var. *nodus* is documented beside from Southern Ocean sediments from high- and mid-latitudes of the North Pacific (Gersonde, 1990; Barron, 1985b). Also the co-occurrence with *A. tabularis* points to a relative warm-water affinity *A.i.* var. *nodus*.

A.ingens var. *ovalis* is only found at southern high latitudes. Gersonde (1990), who described this variety, mentioned that *Hemidiscus karstenii* fo.1 (Ciesielski, 1983), which is documented with common abundances from Subantarctic deposits is possibly *A.ingens* var. *ovalis*. *Hemidiscus karstenii* fo.1 occurred at a period where the assemblage is dominated by the undoubtedly warm-water species *F. reinholdii* and *H. karstenii*. We include this variety of *A. ingens* in the warm-water group also due to her higher abundances at the region of circumpolar current as at the southern Southern Ocean area (Gersonde and Burckle, 1990; Censarek and Gersonde, subm. a). This classification is provided by the co-occurrence of *A. ingens* var. *ovails* with higher abundances of warm-water taxa *A. tabularis*.

Table 3.1: Thermal classification of the selected diatom species, which are considered for relative paleo-temperature estimation.

Selected diatom species	
Warm-water species	Cold-water species
<i>Actinocyclus ingens</i>	<i>Denticulopsis praedimorpha</i>
<i>A. ingens</i> var. <i>nodus</i>	<i>Denticulopsis dimorpha</i>
<i>A. ingens</i> var. <i>ovalis</i>	<i>Denticulopsis ovata</i>
<i>Azpeitia tabularis</i>	<i>Nitzschia denticuloides</i>
<i>Crucidentacula nicobarica</i>	<i>Fragilariopsis aurica</i>
<i>Fragilariopsis reinholdii</i>	<i>Fragilariopsis arcua</i>
<i>Hemidiscus cuneiformis</i>	<i>Fragilariopsis praecurta</i>
<i>Hemidiscus karstenii</i>	<i>Fragilariopsis donahuensis</i>
<i>Hemidiscus triangularis</i>	
<i>Thalassionema</i> spp.	
<i>Thalassiosira oestrupii</i>	

Derivation of the cold-water indicating group (Tab. 3.1):

Denticulopsis ovata and *Nitzschia denticuloides* are endemic species in the Southern Ocean (Yanagisawa and Akiba, 1990; Barron and Baldauf, 1995), which indicates the cold-water affinities of the species and causes the grouping as cold-taxa. Possible precursors of *D. ovata* are *D. dimorpha* and *D. praedimorpha* (Yanagisawa and Akiba, 1990). *D. dimorpha* is established in the Southern Ocean and later migrated in the northern mid- and high latitudes. There are not found in equatorial deposits (Yanagisawa and Akiba, 1990).

Highest abundances of *D. dimorpha* are found in the northern Southern Ocean area, which can be attributed to less dominance of *D. ovata* compared to the northern Southern Ocean. *D. praedimorpha* is only documented from the southern high latitudes (Yanagisawa and Akiba, 1990) and from a single North Pacific site (Barron, 1980). Highest abundances of *D. praedimorpha* are documented for the southern Southern Ocean (Censarek and Gersonde, subm. a) causing the classification as relative cold-water species.

All reported occurrences of *D. ovata*, *D. dimorpha* or *D. praedimorpha* are out of phase to abundance occurrences of distinct warm-water taxa as e.g. *A. tabularis* indicating the general cold-water affinity of this group causing also the classification as cold taxa.

Fragilariopsis aurica, *F. arcuata*, *F. praecurta* and *F. donahuensis* are included as cold-water related, caused by their endemic occurrence and higher abundance in southern regions of the Southern Ocean. All species has an earlier first occurrence datum (FOD) in the southern Southern Ocean compared to the northern Southern Ocean indicating also their cold-water affinities (Censarek and Gersonde, 2002; Fig. 3.2). Gersonde (1991) described *F. praecurta* as possible precursor of the recent occurring *F. curta*, which is used to reconstruct the sea-ice boundary (Gersonde and Zielinski, 2000).

Excluded taxa:

Yanagisawa and Akiba (1990) remark that *D. simonsenii* is a cosmopolitan diatom documented with higher abundances and longer stratigraphical range at high, especially northern high latitudes. This species was excluded from the calculation, because of its occurrence with similar abundances in the southern and the northern area of the Southern Ocean synchronous with definite warm

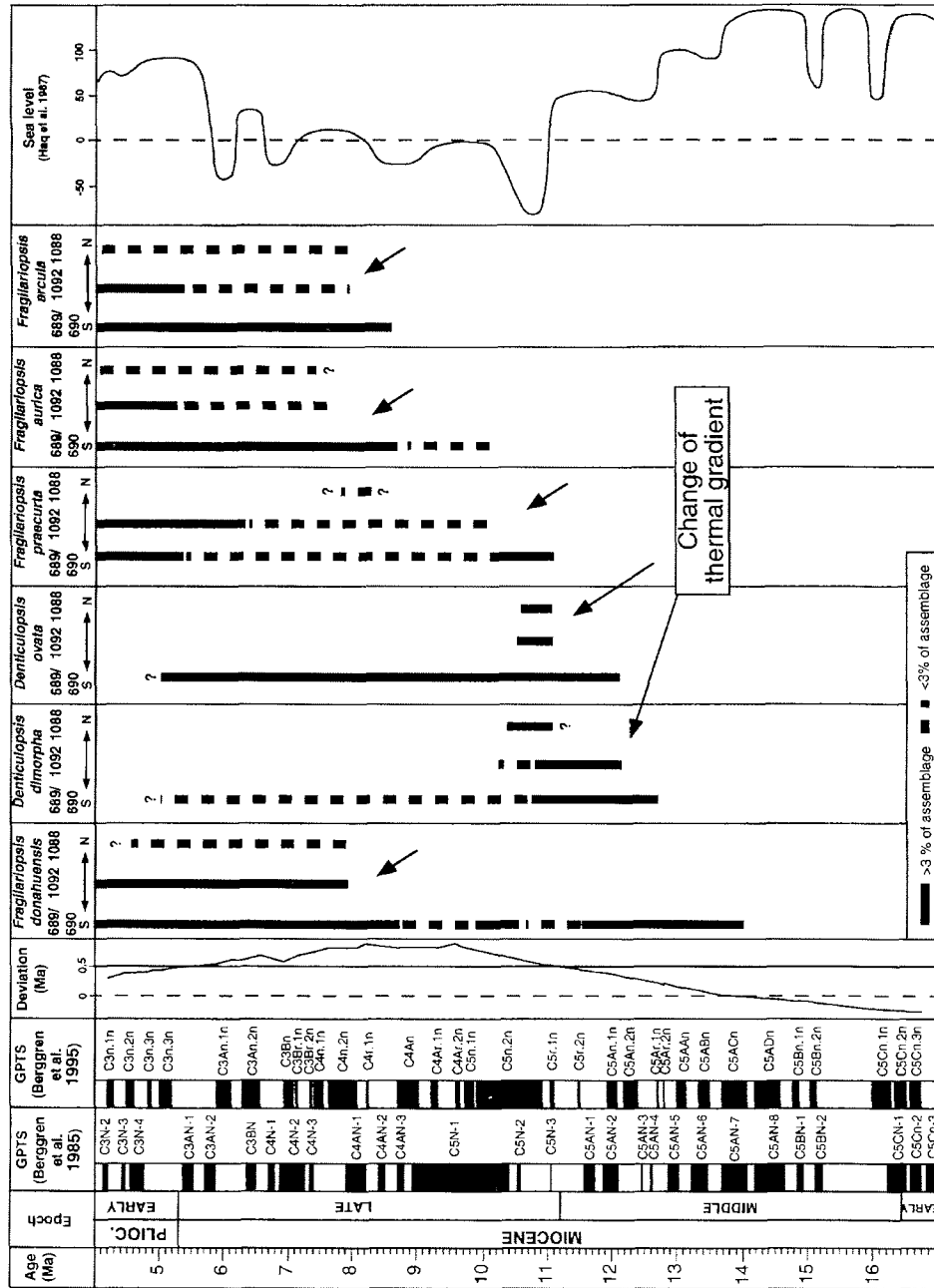


Figure 3.2: Comparisons of stratigraphic ranges of selected cold-water diatoms indicate times of a changing thermal gradient. Similar occurrence datums at Site 1092 and 1088 indicate a similar surface water mass. For reasons of comparison geomagnetic polarity time scales (GPTS) of Berggren et al. (1985, 1995) including their deviation are shown. The sea level curve of Haq et al. (1987) indicating the general climate history is also presented.

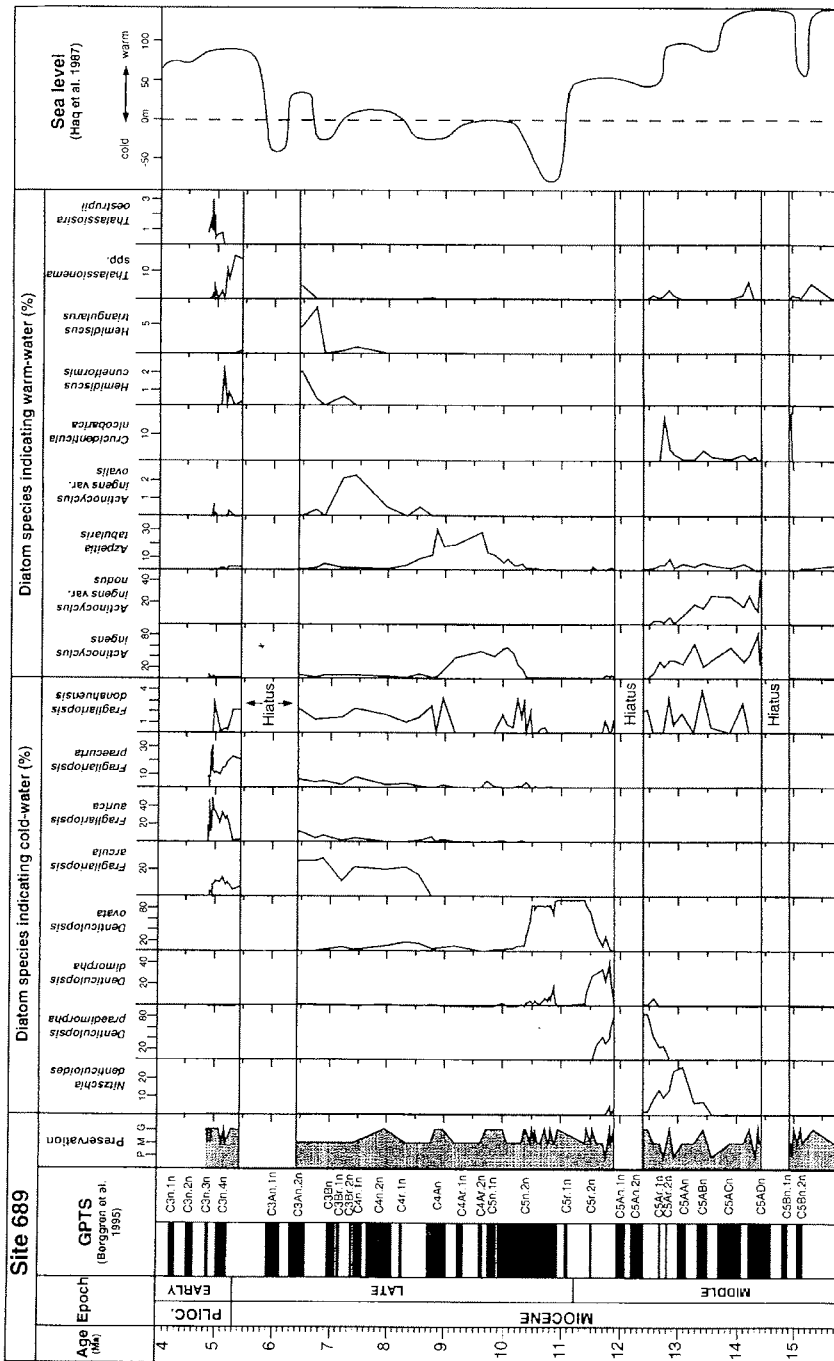


Figure 3.4: Relative abundances of warm- and cold-water indicating diatom taxa and diatom preservation at Site 689 are shown. Further, the GPTS of Berggren et al. (1995) and the sea level curve (Haq et al., 1987) are presented.

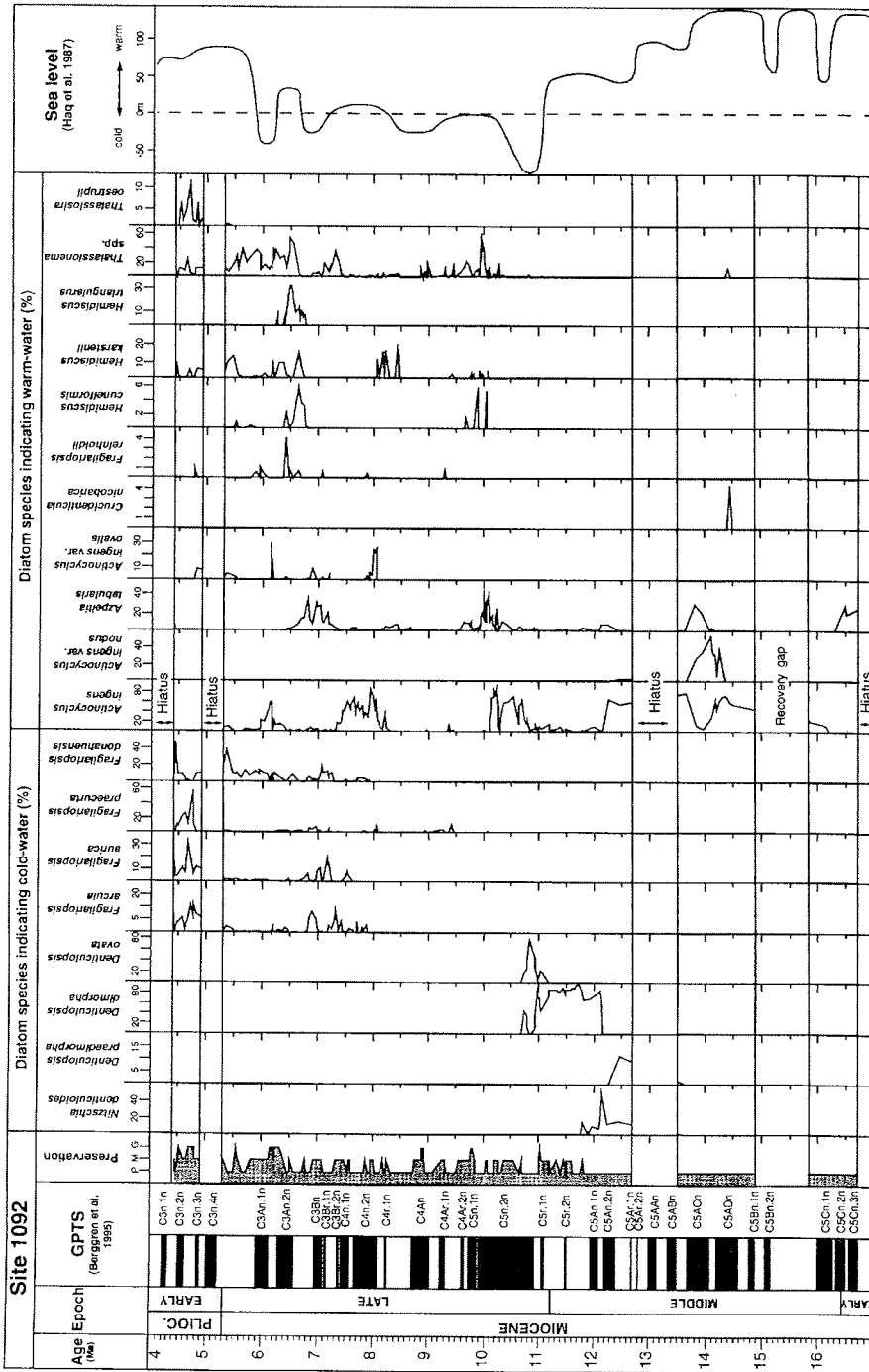


Figure 3.5: Relative abundances of warm- and cold-water indicating diatom species at Site 1092 and diatom preservation are presented. Further, the GPTS of Berggren et al. (1995) and the sea level curve (Haq et al., 1987) are shown.

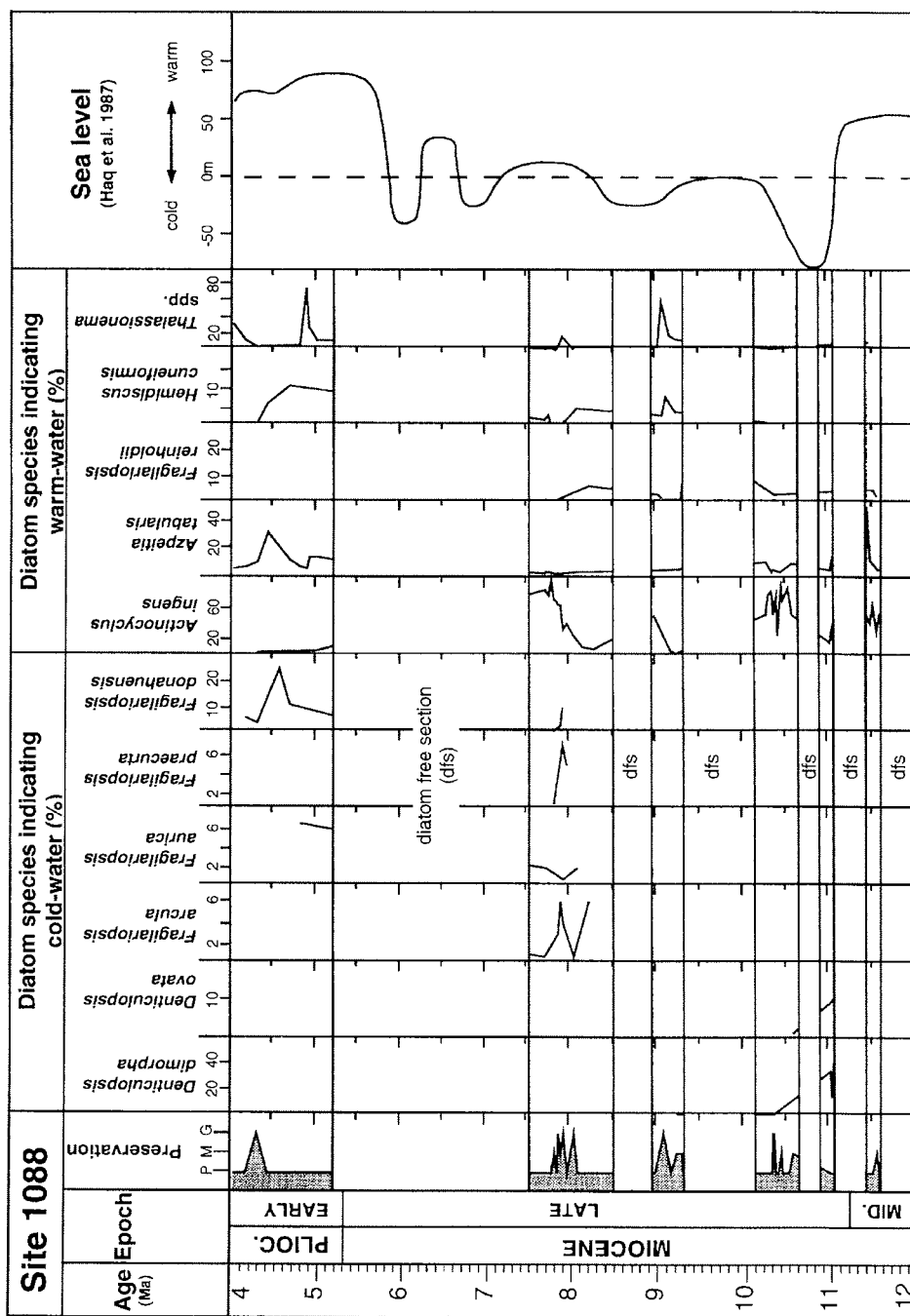


Figure 3.6: Relative abundances of warm- and cold-water indicating diatoms of Site 1088 and diatom preservation are presented. Further the eustatic sea level curve (Haq et al., 1987) is presented.

and cold species indicating the adaptation on a wide temperature range (Censarek and Gersonde, 2002). *D. crassa* and *D. hustedtii* are documented from the middle to high-latitudes, with higher abundances in the northern hemisphere. We exclude these species because of rare abundances and partly sporadically occurrences in the high southern latitudes (Yanagisawa and Akiba, 1990; Censarek and Gersonde, subm. a).

Other species from data set are excluded due to rare or trace occurrence or unidentifiable thermal demands.

3.4 Results

3.4.1 Relative paleotemperatures and the latitudinal thermal gradient

The Maud Rise Sites 690 and 689 show, as expected, similar RPT values, indicating the same thermal conditions in an more or less uniform surface water mass (Fig. 3.7). Slight differences around 10 Ma and between 9 and 8 Ma can be attributed to lower sample resolution at Site 690. Between 17 and ca. 13.5 Ma relative warm surface waters occurred throughout the Southern Ocean. Warm-water indicating *A. ingens*, *A. ingens* var. *nodus*, *C. nicobarica* and *A. tabularis* represent the dominating assemblage in this period. A cold time spread followed reaching up to ca 10.5 Ma. In this period the successively replacing cold-water species *N. denticuloides*, *D. praedimorpha*, *D. dimorpha*, *D. ovata* dominated. Site 1092 shows a comparable thermal development, whereby the cold time spread at the Middle to Late Miocene ends earlier (ca. 10.8 Ma) than at Sites 689/690 (Fig. 3.7). This is primarily indicated by an earlier dominant occurrence of warm-water species *A. ingens* at the northern Southern Ocean (Site 1092). RPTs document warm conditions at the early Late Miocene throughout the Southern Ocean (Fig. 3.7). They are turning back to cooler conditions at the southern sites between 9 and 8.5 Ma, whereas at Site 1092 warm conditions prevailed up to the Early Pliocene. This southern Southern Ocean cooling is documented by higher abundances of cold-water indicating group *F. aurica*, *F. arcula*, *F. praecurta* and *F. donahuensis* at Sites 689/690 in combination with lower abundances of the warm-water taxa *A. ingens* and the *Thalassionema*-group.

Occurrences of *Hemidiscus cuneiformis*, a recently in the southern high latitudes extinct warm-water taxon, point at 9.9 Ma in the northern Southern Ocean and around 6.6 Ma even in the southern studied area to probably warmer than present-day temperatures.

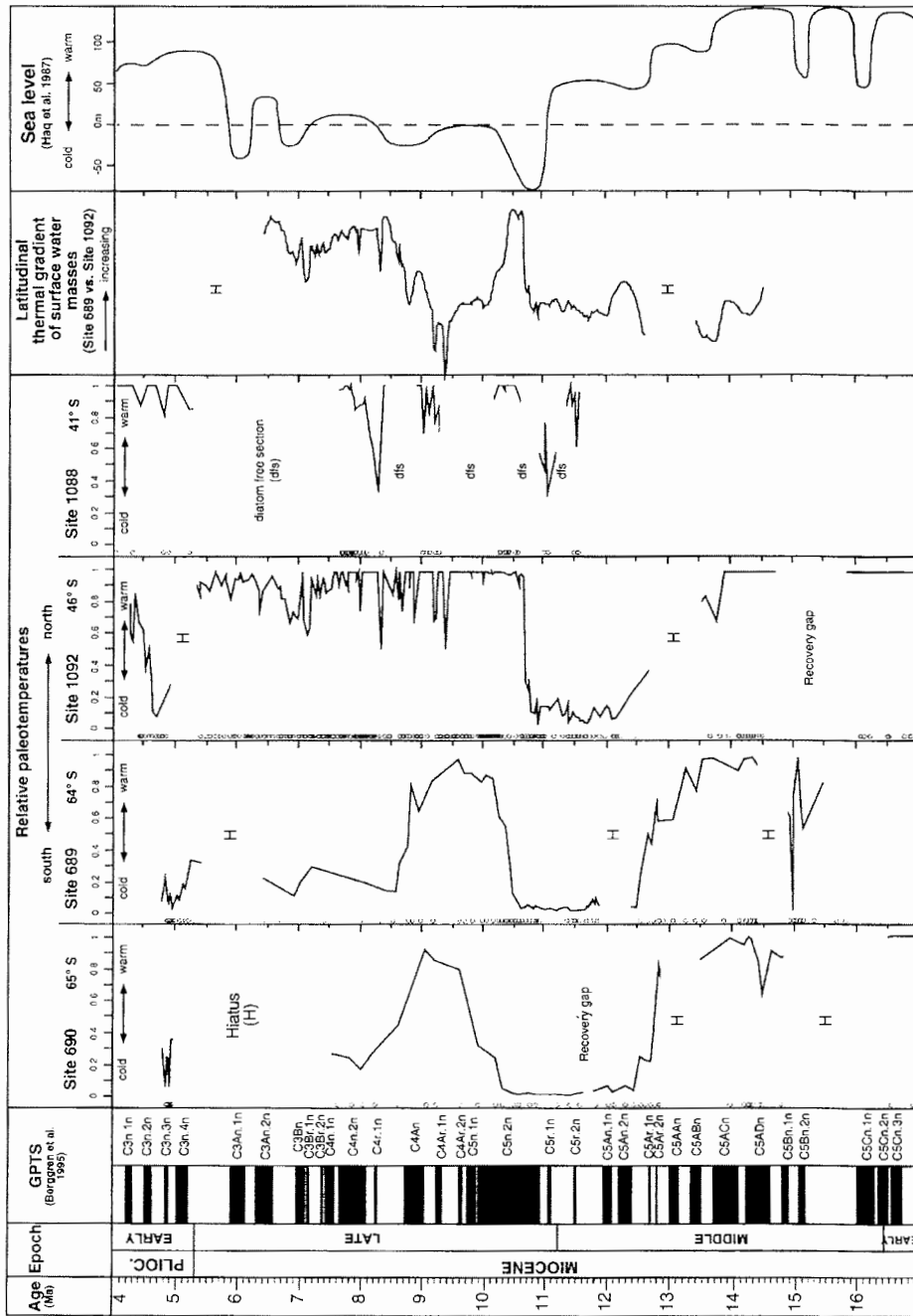


Figure 3.7: Relative paleotemperatures for Sites 689, 690, 1088 and 1092 reflect the thermal demand of diatom assemblages. The thermal gradient between northern (Site 1092) and southern (Site 689) area of the Southern Ocean are presented. Higher values indicate higher thermal differences between surface water masses. Further, the GPTS of Berggren et al. (1995) and the sea level curve (Haq et al., 1987) are shown. Small circles - sample positions. H - hiatus.

This stands in contrast to the RPTs, which refer in general to cold surface water conditions at these times. The carbonate-dominated Site 1088 shows mostly poor diatom preservation and low abundances resulting in sections without significant amounts of siliceous microfossils. At ca. 11.1 Ma and ca. 8.3 Ma colder surface water occurred indicated by *D. dimorpha*, *D. ovata*, *F. arcula* and *F. praecurta* in absence of a higher amount of warm-water indicating species, respectively.

All other assemblages recorded at Site 1088 refer to more or less warm conditions. Characteristic for the northern Southern Ocean area is the dominant occurrence of *A. ingens* between ca. 8 and 7 Ma (Figs. 3.5, 3.6). At the Maud Rise sites this species is an inferior component of the diatom assemblage (Figs. 3.3, 3.4). The Late Miocene thermal development of Site 1088 is as far as delineated similar to Site 1092. This can also be derived from the first occurrences (FOs) of cold-water related diatoms (Fig. 3.2).

A high latitudinal thermal gradient (LTG) between Sites 689/690 and 1092, representing the southern and the northern part of the Southern Ocean, appears around 10.5 Ma and between 8.6 to 6.4 Ma. The following younger portion around the Miocene/Pliocene boundary is cut by hiatuses. The high gradient at around 10.5 Ma is caused by a faster warming and earlier onset of warming in the northern Southern Ocean. Only one interval of long time increase in LTG occurs from 9.3 and 8.6 Ma, all other changes happened faster. The lowermost gradient (around 9.5 Ma) results from the unusual constellation of high abundances of the warm diatoms *A. ingens* and *A. tabularis* in the south (Figs. 3.3, 3.4) in combination with a poor preservation and a generally low amount of species in the north (Figs. 3.5, 3.6).

3.4.2 Diatom concentrations

At Sites 690 and 689 diatom concentration maxima occurred between 11.7 and 11 Ma in a calcareous nannofossil dominated sediment section, which is monospecifically build up by a cold-water tolerant coccolithophoridae (Wei and Wise, 1990). Furthermore, high diatom concentrations are documented at Site 689 for the period between ca. 16 and 15 Ma (Fig. 3.8). At Site 1092 low diatom concentration occurred during the middle and the lower portion of the upper Miocene up to ca. 7 Ma where values increased. Highest concentrations are reached at 6.1 and 4.8 Ma (Fig. 3.8). The carbonate dominated sediments at Site 1088 consist of portions containing only low amounts of diatom valves

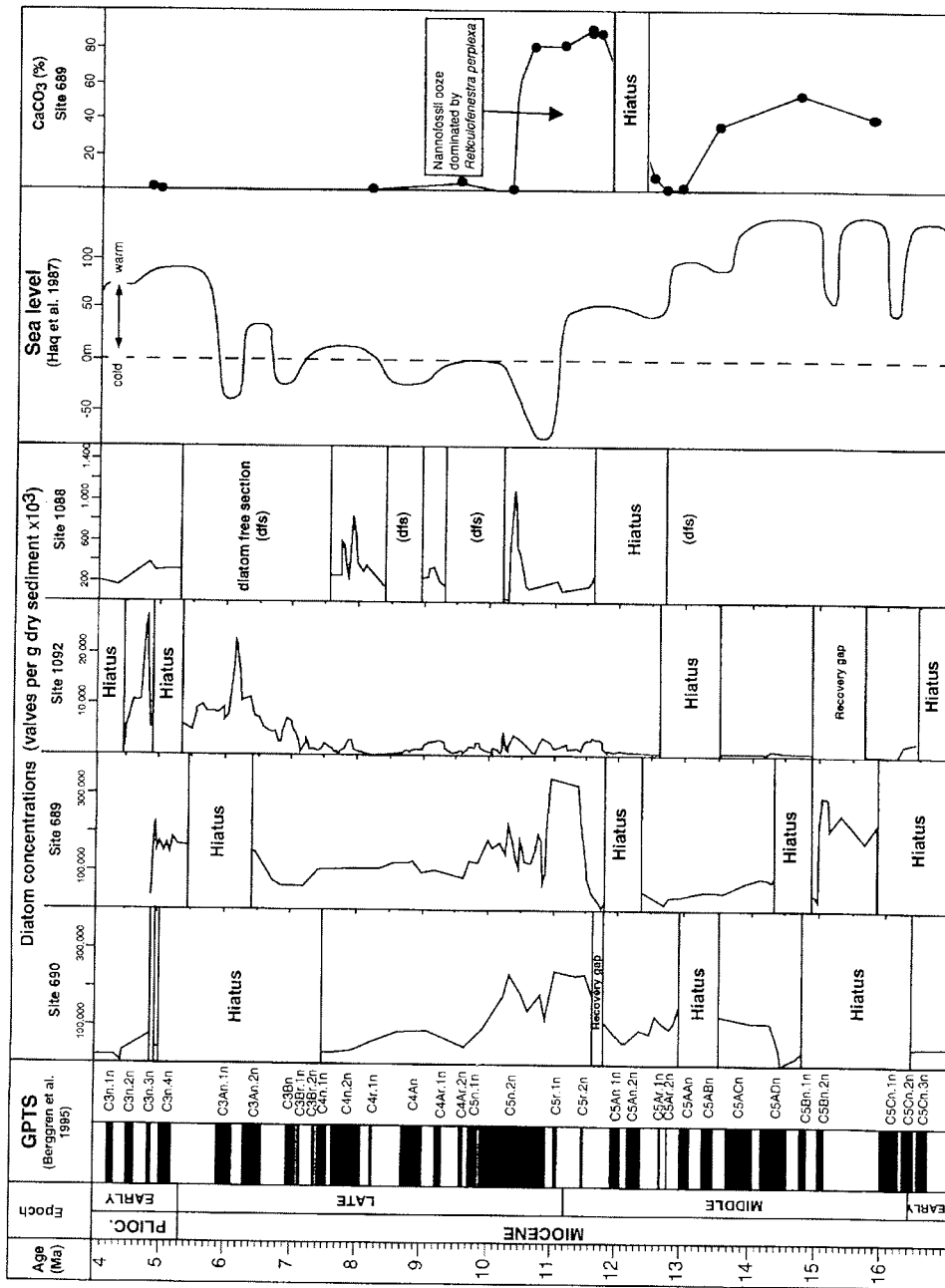


Figure 3.8: Diatom concentrations at Sites 690, 689, 1092 and 1088 are shown beside the sea level curve (Haq et al., 1987) and the CaCO₃ curve (Shipboard Scientific Party, 1988a).

alternating with huge diatom free sections. Increased diatom concentrations are found at 10.3 and around 8 Ma. A strong northward decrease of diatom concentrations is shown (Fig. 3.8). Detailed opal measurements for Sites 1092 and 1088 will be presented by Diekmann et al. (subm.).

3.5 Discussion and conclusions

3.5.1 Middle Miocene cooling

From the RPTs and the LTG a more detailed insight in thermal evolution can be derived considering coupled processes. We assume that the best conditions for ice volume accumulation in Antarctica are a warm northern Southern Ocean coupled with a cold southern Southern Ocean climate, which provides a high evaporation moistening the atmosphere and a cooling of the atmosphere increasing precipitation, respectively. Therefore, a high LTG refers to increased ice accumulation. These processes are comparable to the so-called "Panama paradox", which describes the heat transport to the north linked to increased evaporation and precipitation inducing the northern hemisphere glaciation (Berger and Wefer, 1996).

The major build up of the East Antarctic Ice Sheet (EAIS) started after the Middle Miocene climate optimum (Kennett, 1977; Flower and Kennett, 1995). The onset of cooling is documented by the isotope curve at ca. 14.5 Ma and at the sea level curve at around 13.5 Ma (Fig. 3.9). The RPT values refer to a slightly faster cooling starting between 13.5 and 13 Ma. This cooling might have been linked to the closure of the seaway between the Tethys and the Indian Ocean at 14.5 Ma, which led to the replacement of Tethian- and the Mediterranean Outflow Water by North Atlantic Deep Water (NADW). The termination of the Tethian Outflow Water, which was a major factor of meridional heat transport to the southern high latitudes, is proposed to cause the major growth of the EAIS (Ramsey et al., 1998). Between 13 and 12 Ma investigated sediments are characterised by hiatuses in all four cores (Fig. 3.9), which coincide with the global hiatus event NH3 by Keller and Barron (1987). The hiatus occurrences refer to increased deep-water flux, which might be attributed to the onset of southward flowing NADW at ca. 13 Ma (Ramsay et al., 1998).

The RPTs document cool surface waters up to 10.8 Ma within the Southern Ocean at times of a low LTG, which implies a lower ice volume accumulation. This interpretation coincides with the sea level curve (Haq et al., 1987), which

documents a level of 50 m above recent values between 12.8 and 11.2 Ma referring to warmer global climates. This stands in contrast to the oxygen isotopes indicating a general uniform cooling between ca. 13.5 and 8 Ma (Fig. 3.9). Slight age discrepancies between the sea level data and the results from the diatom record can be ascribed to the lower resolution of the sea level curve and interpolation inaccuracies occurred at the transfer to the GPTS of Berggren et al. (1995).

3.5.2 Late Miocene thermal decoupling of the Southern Ocean from the adjacent oceans

At the Maud Rise high carbonate contents are documented between ca. 11.8 and ca. 10.6 Ma (Shipboard Scientific Party, 1988a, b). These sediments are mostly build up by the cold-water tolerant Coccolithophoridae *Reticulofenestra perplexa* (Fig. 3.8) (Wei and Wise, 1990). Subsidence of the carbonate compensation depth (CCD) supported by sea level lowering can be assumed as prerequisite for this extraordinarily carbonate preservation in this high latitudes. The high diatom concentrations in combination with increased sedimentation rates (Censarek and Gersonde, 2002) indicate high productivity at this period.

Barron and Baldauf (1995) proposed a diatom assemblage turnover event in the early Late Miocene, indicating climate changes. This coincides with a period of strong global sea level decrease pointing to an increasing ice volume in Antarctica. At this period diatoms document the establishment of a high LTG between 10.8 and 10.4 Ma (Fig. 3.9). However, no evidences on climate changes can be derived from the global oxygen isotope curve (Fig. 3.9). The high LTG is mainly deduced by an earlier dominant occurrence of the warm-water indicating *A. ingens* at Site 1092 as at Sites 689/690. Constituted by the abundant occurrence of *A. tabularis* around 10 Ma and its relation to the *A. ingens* occurrences at the different sites, this gradient can not be an artefact of inaccuracy in the age models. Furthermore, age models feature a magnetostratigraphical age point at 10.949 Ma (Base of Chron C5n.2n) and the reliable FODs of *A. kennettii*, which present at the southern Sites an age of 10.15 Ma and at the northern Southern Ocean an age of 10.3 Ma (Censarek and Gersonde, 2002). There are no evidences for a hiatus around 10.6 Ma at Site 1092 that would account for a fast change from a cold to a warm diatom assemblage.

The global sea level curve points between ca. 10.3 and 9.3 Ma to a warmer period reaching more or less recent conditions (Fig. 3.9). This coincides with RPTs

documenting a warm time period throughout the Southern Ocean resulting in a decreasing LTG. Both, the sea level curve and the diatom records imply decreasing ice volume in Antarctica.

Evidences from the ice-rafted debris record and glacially triggered turbidites refer to the incipient of the WAIS build up between 10 and 8 Ma (Kennett and Barker, 1990; Hillenbrand and Ehrmann, 2001). The LTG increased strongly between 9.5 and 8.6 Ma and documented possibly the onset of the major WAIS build up in detail (Fig. 3.9). In contrast the oxygen isotope curve did not refer to any larger thermal or ice volume changes.

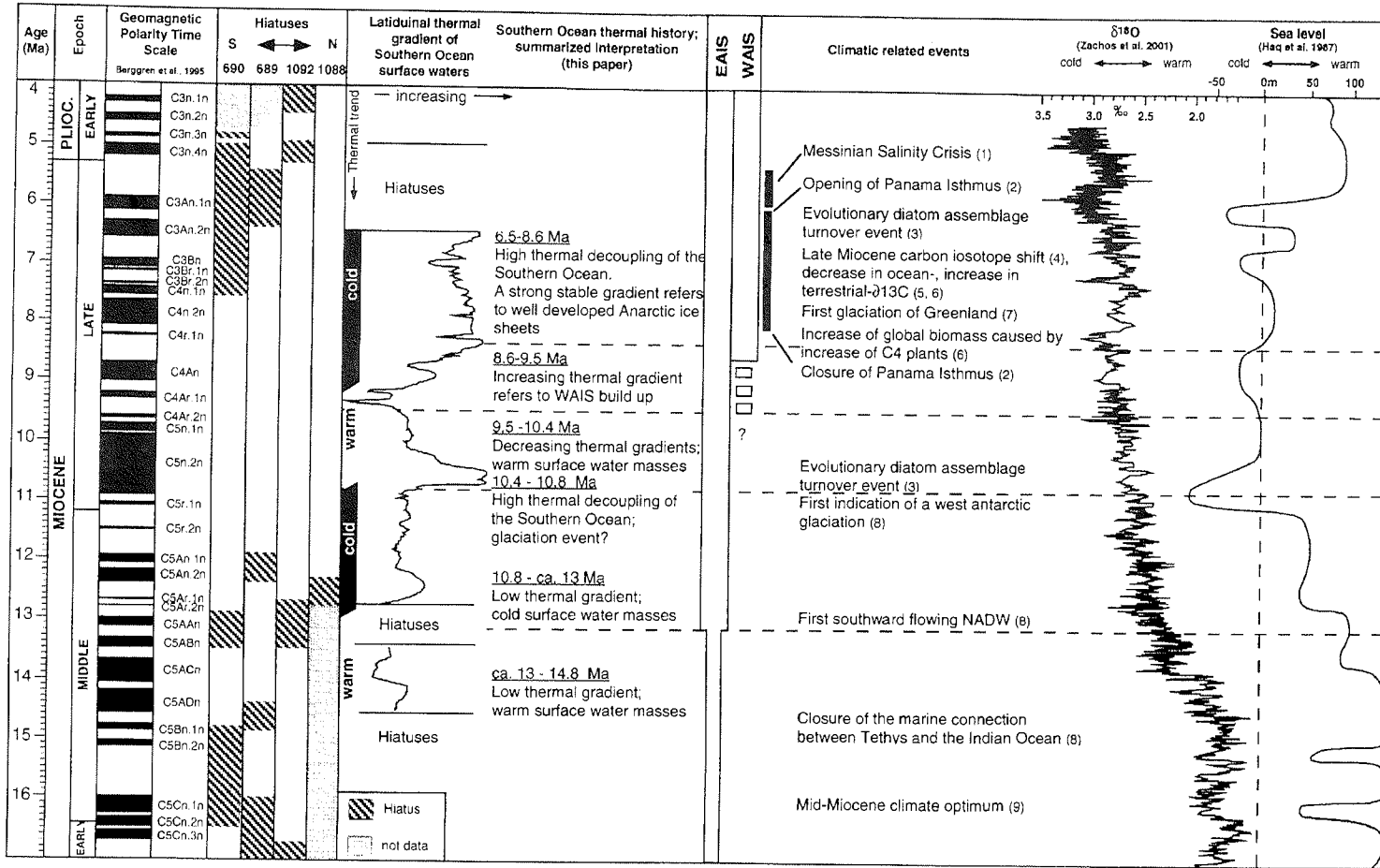
A long time spread characterised by a stable high LTG occurred between 8.6-6.5 Ma documenting the strong thermal decoupling of the Southern Ocean and imply the continuous existence of Antarctic cryospheric environment.

The low RPTs at this time period in the southern area of the Southern Ocean (Sites 689/690) is deduced mainly by higher abundances of cold-water indicating diatoms *F. aurica*, *F. arcula*, *F. praecurta*, *F. donahuensis*. If we assume that *F. praecurta* is the phylogenetic precursor of the recent sea-ice indicating taxa *F. curta* as speculated by Gersonde (1991), which might also concern the morphologic similar species *F. aurica*, Late Miocene sea-ice development might be documented in their abundance pattern. However, more detailed studies on higher resolution sediment sequences and the coupling to an independent sea-ice indicating parameter are required to interpret the abundance peaks of *F. praecurta* and *F. aurica* e.g. at the northern Polar Front Zone (Site 1092).

The occurrence of *H. cuneiformis* in the Southern Ocean at 9.9 and at 6.6 Ma (Sites 689, 1092), indicating warmer than present-day temperatures, must be ascribed to distinct short ranging warming events. Such a warm period occurring around 6.6 Ma, which is just before the Mediterranean isolation started (Krijgsman et al., 1999), is documented in detail by diatom abundances at ODP Site 704 (Censarek and Gersonde, *subm. c*).

However, all four studied sites are characterised by the lack of sediment sections in the latest Miocene preventing the continuous estimation of thermal development. Accomplishing the reconstruction of the Southern Ocean surface water evolution and Antarctic cryospheric variability Late Miocene sections of ODP Leg 114 Sites 701 and 704 representing two of the few cores containing a complete Messinian section are studied (Censarek and Gersonde, *subm. c*).

The main climate-changing events in the Late Miocene might be the temporary closure of the Panama Isthmus between 8-6 Ma (Collins et al., 1996a, b)



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in combination with the depressions of the North Atlantic deep-water gateways (Lavver et al., 1990; Myhre and Thiede, 1995; Wright and Miller, 1996). This constellation might enable an Atlantic Ocean circulation pattern similar to the recent, which would result in generally increased latitudinal climate gradients and furthermore in high latitudes cryospheric build up. Larsen et al. (1994) reported the first glaciations in Greenland at around 7.3 Ma according to the GPTS of Berggren et al. (1995). Glacial till, diamictites and ice-rafted debris were found at ODP Leg 151 Sites 914-917 of southeast Greenland supporting the assumption of this early glacier occurrence.

The establishment of an Atlantic Ocean circulation system similar to present-day would occur synchronously with global biomass growth and the increase of C4 plants starting at 8 Ma (Cerling et al., 1997; Pagani et al., 1999). The possible connection between a changed ocean circulation and the global carbon flux is a topic for further studies.

This postulated strong change in ocean circulation might be documented in the diatom record by the stable high LTG.

The global climate evolution documented in the sea level curve coincides in huge portions with the thermal development of the Southern Ocean derived from the diatom record. This good agreement corroborates the assumption that a high LTG indicates ice accumulation in Antarctica. However, climate development as documented by the sea level curve or the diatom record stand in contrast to the temperature and ice volume information carried by the global oxygen isotope signal. This discrepancy must be ascribed to the different effects influencing isotopes.

Figure 3.9 (left): Different paleoclimatic indicators delineate Middle and Late Miocene climate history: The latitudinal thermal gradient curve and an overview of hiatus occurrences of the investigated sites (689, 690, 1088 and 1092) are presented. Further, the GPTS of Berggren et al. (1995) and the sea level curve (Haq et al., 1987) are included. Generally acknowledged climate related events are listed. References: (1) Krijgsman et al. 1999, (2) Collins et al., 1996a and 1996b, (3) Barron and Baldauf, 1995, (4) Hodell et al., 1994, (5) Pagani et al., 1999, (6) Cerling et al. 1997, (7) Larsen et al., 1994, (8) Ramsay et al., 1998, (9) Kennett et al., 1977. Increasing $\delta^{18}\text{O}$ -values of the compiled global isotope curve of Zachos et al. (2001) reflect the overall increased cooling since the Middle Miocene optimum (ca. 15-17 Ma).