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Sea ice and productivity changes over the last glacial cycle in the Adélie Land region, East Antarctica, based on diatom assemblage variability

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Abstract

Diatoms can provide important paleoenvironmental information about seasonal sea ice extent, productivity, sea surface temperature and ocean circulation variability, yet there are relatively few studies analysing the last glacial cycle near the Antarctic continent. This study examines diatom assemblages over the last glacial cycle from core TAN1302-44, from off Adélie Land, East Antarctica. Four distinct diatom assemblages were identified using principal components analyses. The PC 1 assemblage is associated with the interglacial, sedimentary facies, Facies 1, and comprises *Thalassiosira lentiginosa, Actinocyclus actinochilus, Eucampia antarctica*, *Azpeitia tabularis* and *Asteromphalus hyalinus*, suggesting that MIS 5e and Holocene interglacial time periods were characterised by seasonal sea ice environments with similar ocean temperature and circulation. The PC 2 assemblage is associated with the glacial, Facies 2, and comprises *Fragilariopsis obliquecostata, Asteromphalus parvulus, Rhizosolenia styliformis, Thalassiosira tumida, Chaetoceros dichaeta*, and a *Eucampia antarctica* terminal/intercalary ratio. This indicates that, during the MIS 4-2 glacial there was an increase in the length of the sea ice season compared with the interglacial period, yet still no permanent sea ice cover. The PC 2 assemblage is also associated with the glaciation and deglacial facies. There is an initial increase of PC 2 at the start of MIS 5d-a glaciation stage and then a gradual increase throughout late MIS 4-2, suggests that sea ice cover steadily increased reaching a maximum at the end of MIS 2. The PC 3 assemblage is associated with all four facies and comprises *Actinocyclus ingens*, *Actinocyclus actinochilus*, *Thalassiosira oliverana* and *Fragilariopsis kerguelensis*, suggesting that reworking of sediments and an influx of older sediments occurred throughout the last glacial cycle. Finally, the PC 4 assemblage is associated with the deglacial, glaciation, and glacial facies and comprises *Fragilariopsis kerguelensis*, *Thalassiothrix antarctica, Chaetoceros bulbosum* and *Eucampia antarctica,* suggesting that during the last glaciation, the last two deglacials, and the early glacial, there was a period of enhanced upwelling of nutrient-rich, warmer water, which is inferred to reflect an increase in Circumpolar Deep Water. Interestingly, the diatom data suggest the onset of increased Circumpolar Deep Water during the last deglacial occurred after the rapid loss of a prolonged sea ice season at the end of last glacial. Together, these results suggest changes in ocean circulation and sea ice season

https://doi.org/10.5194/egusphere-2022-1009
Preprint. Discussion started: 4 October 2022

were important factors during climate transitions. The results fill a gap in our understanding of the sea ice extent and ocean circulation changes proximal to East Antarctica over the last glacial cycle.

1 Introduction

Ocean circulation near Antarctica's ice sheets is changing under the influence of climate change (Prichard et al. 2009; Depoorter et al. 2013; Alley et al. 2015; Silvano et al. 2018; Rignot et al. 2019; Minowa et al. 2021). Two significant parameters in the atmosphere-ocean-ice sheet interaction system are duration and extent of seasonal sea ice and the ocean's thermohaline circulation. Antarctic sea ice is recognised as an important driver of climate as it affects the CO_2 exchange between the Southern Ocean and the atmosphere (Crosta et al. 2004; Kohfeld & Chase 2017), planetary albedo and the ocean's thermal gradients (Gersonde & Zielinski 2000). Locally its seasonal variation can affect ice shelves, increasing melting at the marine edge (Massom et al. 2018), ultimately destabilising the ice sheet (Prichard et al. 2012). Furthermore, its seasonal expansion and retreat influences primary productivity; by limiting light and lowering temperatures, thus decreasing productivity, although meltwater can also stimulate phytoplankton blooms (Knox 2006). The second significant parameter affecting climate is the ocean's thermohaline circulation. On the Antarctic margin this is driven by the formation of Antarctic Bottom Water (AABW), and the upwelling of Circumpolar Deep Water (CDW). Modern observations suggest that Antarctic ice sheet melt rates increase with enhanced upwelling of CDW (Prichard et al. 2012; Rignot et al. 2019; Minowa et al. 2021) and with a decrease in the production of AABW (Williams et al. 2016; Silvano et al. 2018). Understanding the past changes in sea ice and oceanography, especially during past climate transitions and warmer than present interglacials, may provide further insight into the mechanisms of atmosphere-ocean-ice sheet interaction, to predict future changes and provide analogues for future outcomes under a warming climate (Masson-Delmotte et al. 2013).

Studies of diatom assemblages from deep ocean sediments can be used to reconstruct past ocean environments, including the extent and duration of seasonal sea ice, surface ocean circulation, and productivity (Cooke & Hays 1982; Pichon et al. 1992; Taylor & McMinn 2001; Crosta et al. 2004; Gersonde et al. 2005; Armand et al. 2005). Diatom studies are based on the identification and quantification of individual species and groups of species, which are used to reconstruct paleoenvironments based on an understanding of the species' modern habitat (Table S1) from both water column (Medlin and Priddle 1990; Ligowski 1992; Moisan and Fryxell 1993) and from surface sediment studies (Zielinski and Gersonde 1997; Armand et al. 2005; Crosta et al. 2005). However, the interpretation can be influenced by processes such as selective dissolution within the water column and/ or sediment (Shemesh, Burckle & Froelich 1989; Zielinski & Gersonde 1997), winnowing of lighter species' valves by bottom currents (Taylor, McMinn & Franklin 1997; Post et al. 2014), or variable influx of terrigenous matter (Kellogg & Truesdale 1979; Schrader et al. 1993). Therefore, when reconstructing the past environment, it is important to consider all these processes.

https://doi.org/10.5194/egusphere-2022-1009
Preprint. Discussion started: 4 October 2022

There are many diatom-based studies of the interglacials, especially from the Holocene period (McMinn 2000; Taylor and McMinn 2001; Leventer et al. 2006; Crosta et al. 2007; Maddison, Pike & Dunbar 2012). However, advanced ice sheets or permanent sea ice in past glacials led to reduced, or no diatom productivity on the Antarctic margin (Pudsey 1992; Lucchi 2002; Hartman et al. 2021). Additionally advancing ice sheets would have removed most of the sediment record from the continental shelves (Domack 1982; Escutia et al. 2003). This may be one of the reasons why there are so few studies from proximal Antarctica detailing the composition of diatom communities during glacial periods and the last glacial to interglacial cycle (Caburlotto et al. 2010; Holder et al. 2020; Hartman et al. 2021; Li et al. 2021; Chadwick et al. 2022).

Overall, limited previous paleoenvironmental studies based on diatoms from the Antarctic continental slope suggest that, during the last glacial cycle, there was seasonal sea ice cover over the Adélie region (Caburlotto et al. 2010), permanent sea ice cover in the Western Ross Sea (Tolotti et al. 2013), and a prolonged sea ice season in several regions including off Cape Adare, the Ross Sea (Hartman et al. 2021), off Enderby Land (Li et al. 2021) and off the Sabrina Coast (Holder et al. 2021). However, occasional glacial diatom blooms have been recorded from near Cape Adare (Hartman et al. 2021), and the Weddell Sea (based on studies of foraminifera; Smith et al. 2010). These blooms have been suggested to represent localised polynyas (Arrigo & Van Dijken 2003) during the glacials. Only a couple of studies have looked into climate transitions during the last glacial cycle on the Antarctic margin. They show that during the last deglacial there was a decrease of the sea ice season and an increase in upwelling of CDW over the Enderby Land and Ross Sea continental margin (Li et al. 2021; Tolotti et al. 2013), while the last glaciation stage is reported to comprise oscillations in the sea ice season (Hartman et al. 2021). Here we use diatom assemblages to understand the changes in the duration of the sea ice season and in CDW upwelling in the Adélie region over the last glacial cycle, ~140 ka, including the deglacial and glaciation transitions.

2 Materials and Methods

2.1 Site description

Core TAN1302-44 (Tan_44) was recovered from the WEGA channel, on the continental slope north of Adélie Land and the George Vth Land coastline (Adélie region), at 64°54.75 S, 144°32.66 E, from 3,095 m depth (Fig. 1) by R/V Tangaroa in February 2013 during voyage TAN1302 (Williams 2013). The location is ~100 km north of the continental shelf break. The core site is located within the modern seasonal sea ice zone, covered by sea ice from April to November each year (Fig. 1, Spreen, Kaleschke & Heygster 2008; Fetterer et al. 2017). The major oceanographic features of this region, which directly influence the site (Caburlotto et al. 2006; Williams et al. 2008), include Adélie Bottom Water (Adélie AABW), which forms below ~2,000 m from mixing of cooler Dense Shelf Water (DSW) formed on the shelf with warmer and nutrient rich CDW, and the wind-driven, westward flowing Antarctic Slope Front (ASF; Jacobs 1991; Williams et al. 2008; Fig. 1). The Antarctic Circumpolar Current (ACC), depicted in Fig 1. (Southern Boundary of the Antarctic Circumpolar Current front),

https://doi.org/10.5194/egusphere-2022-1009
Preprint. Discussion started: 4 October 2022

does not influence the core site but the ACC has a significant influence over Southern Ocean productivity and diatom species distribution (Supplement, Table S1).

2.2 Biogenic silica

Analyses of biogenic silica were undertaken at 20 cm intervals down Tan_44. This study uses a modified wet-leaching technique (Mortlock and Froelich 1989; and DeMaster 1981), based on the premise that dissolution of fragile diatom tests is more rapid than the dissolution of silica from non-biogenic sources e.g. quartz grains. The time-series approach introduced by DeMaster (1981) was used. For quality control, two in-house standards were used from the Chilean and the Antarctic margin (Tooze et al. 2020). If the silica concentrations of the standards or the samples decreased with time during the hourly measurements, the whole experiment was repeated. The overall reproducibility of the method, assessed as the relative standard deviation of the standards, was +/-7%.

2.3 Si/Al

X-ray fluorescence scanning (XRF) was completed at 2 mm resolution using an ITRAX scanner (Gadd and Heijnis 2014) at the Australian Nuclear Science and Technology Organisation (ANSTO). The scanning was performed on u-channel sub-samples of the cores (of dimensions 2x2 cm, 1 m-long sections), which were stored in plastic containers and covered by thin plastic film. Anomalous spikes in data, identified as significant increases or decreases occurring on mm-scale, were removed. The data was then smoothed using a 3-point average.

2.4 Radiocarbon dating

Radiocarbon dating was undertaken to support age model development, using the Acid Insoluble Organic Matter (AIOM) method, conducted at ANSTO, Sydney in April 2017 according to Hua et al. (2001); Fink et al. (2004); and Stuvier and Polach (1997). The raw radiocarbon ages were calibrated using CALIB, version 7.1, using the regional variation to the global marine reservoir correction, ΔR, of 830 yrs ±200 yrs, following previous work done in this region by Domack et al. (1989).

2.5 Facies model

A facies model was developed using the lithological characteristics and the combination of other data, primarily biogenic silica, Si/Al, and ice rafted debris (IRD). These data are described in the supplement (Fig. S1; Fig. S2). The facies model comprises four facies which alternate down core and their characteristics are summarised in Table 1.

https://doi.org/10.5194/egusphere-2022-1009
Preprint. Discussion started: 4 October 2022

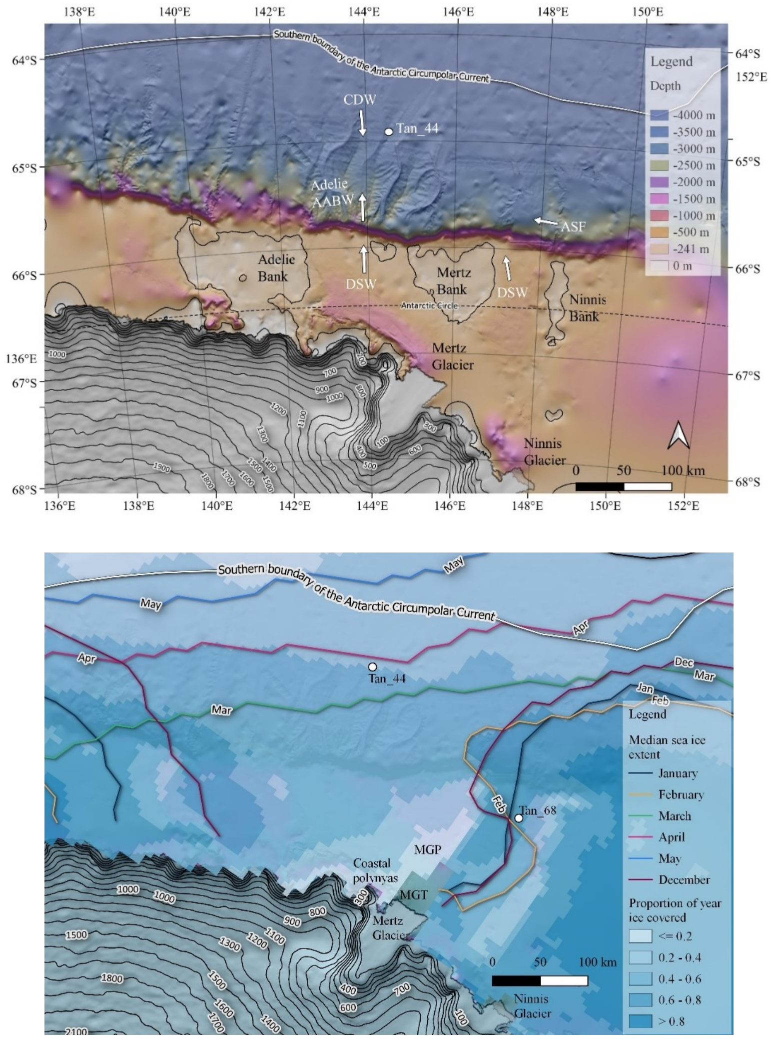

Figure 1 *Top*: location of core Tan_44 with respect to the regional bathymetry (Arndt et al. 2013); oceanography (Orsi et al. 1995; Williams et al. 2010) and cryosphere (Helm et al. 2014). The Mertz and Ninnis glaciers (Helm et al. 2014) are dominant glacial features in the region. Adélie and Mertz banks are prominent geomorphological features on the continental shelf, while deep channels are prominent on the continental slope. Tan_44 is located within the WEGA channel, on the continental slope. The site is influenced at present by Adélie sourced Antarctic Bottom Water (Adelie AABW), circumpolar deep water (CDW), and along slope flow of Antarctic Slope Front (ASF; Williams et al. 2010). *Bottom*: modern seasonal sea ice cover (Fetterer et al. 2017; Spreen, Kaleschke & Heygster 2008), darkest blue showing regions covered by ice for more than 80% of the year. The lightest blues indicates areas covered by ice less than 20% of the year, indicating the Mertz Glacier Polynya (MGP) and the coastal polynyas, where the main proportion of Adélie DSW forms, west of the Mertz Glacier Tongue (MGT; Williams et al. 2010). The figure shows the core site is covered by sea ice from April to November each year

https://doi.org/10.5194/egusphere-2022-1009
Preprint. Discussion started: 4 October 2022

Table 1 Summary of the characteristics of the four facies present in core Tan_44.

CHARACTERISTICS:	FACIES:			
	1) OLIVE SANDY MUD	2A) OLIVE MUD	2) GREY MUD	1A) OLIVE GREY MUD
Colour	Olive; grey (base layer)	Olive	Grey	Olive grey
Structure	Massive; bioturbation; rare laminae	Massive; bioturbation;	Massive; bioturbation; laminae; traction structures	Massive; bioturbation;
IRD (grains/5 cm)	0-36	0-10	0-14	1-15
% Vf-f sand	1-19	1-7	0-5	0-6
% Vc silt	8-27	3-18	4-13	7-17
Zr/Rb	0.6-2.3	0.5-1.9	0.4-1.4	0.7-1.4
% Biogenic silica	3-22	4-10	3-18	10-11
% Microfossil estimates	trace-10%D; 10-80%R	0-5%; 50-80% R	0-5% D; 0-90% R	5%D; 50-97% R
Si/Al	15-28	14-23	12-20	16-21
Ba/Ti	0.01-0.06	0-0.06	0-0.04	0.03-0.05
INTERPRETATION:	Interglacial	Deglacial	Glacial	Glaciation

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2.6 Tan_44 Age Model

The age model of Tan_44 is based on the facies model and two radiocarbon dates from the top 25 cm of the core (Fig. 2; Table S2). The main characteristics of the facies suggest glacial to interglacial variability influenced the productivity proxies (biogenic silica, Si/Al and Ba/Ti; Wilson et al. 2018; Salabarnada et al. 2018; Wu et al. 2017; Bonn et al. 1998; Grobe & Mackensen 1992) and IRD (Patterson et al. 2014; Fig. S1), which show a strong coincidence with the global benthic $\delta^{18}O$ stack (Fig. 2; Lisiecki & Raymo 2005). The radiocarbon dates (Fig. 2) indicate the top of the core was deposited between 16.2- 5.2 ka, suggesting Facies 1 is of Holocene and Facies 2A of Late Pleistocene age.

2.7 Diatom counts and Shannon Wiener biodiversity index

Diatoms assemblages were counted for samples taken every 10 cm down core Tan_44. The samples were processed following the methods outlined in Taylor & McMinn (2001). A small section of the sediment core (<0.5 cm thick) was soaked in 15% hydrogen peroxide overnight, to remove organic matter and to disaggregate any clay. The samples were rinsed with deionised water through a 100 µm and a 10 µm sieve, in order to obtain a >10 µm, <100 µm grain fraction. This fraction was left overnight to settle. Excess water above the sample was pipetted out, and the remaining sample was stored in a 100 ml tube. A drop from each shaken tube was pipetted onto a glass cover slip over a hotplate at 50°C, to evaporate excess water. The samples were then mounted with Norland Optical Adhesive 61 and cured in sunlight. Diatom identification and counts were undertaken using a Nikon light microscope (Eclipse Ci, DS-Ri2) at 1000 X magnification. Each sample was traversed until >400 valves were counted. Broken valves that were >50% complete were included in the count and in the case of elongated species, such as *Thalassiothrix* and *Trichotoxon* that are subject to fragmentation, only the ends were counted. Low valve numbers, of less than 400 valves per slide, were encountered in samples at 80 cm, and from 350-300 cm. The numbers of valves within the 350-320 cm samples were extremely low (7-16 valves per slide).

https://doi.org/10.5194/egusphere-2022-1009
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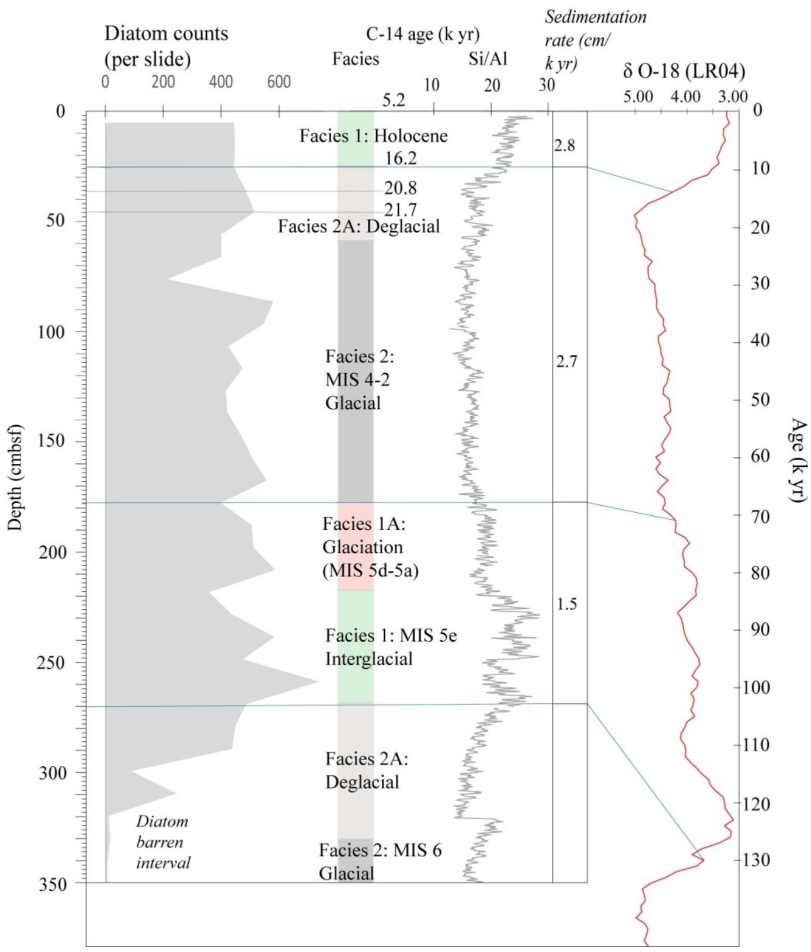

Figure 2 Diatom counts, facies model and Si/Al for core Tan_44. The age model is based the facies model and supported by radiocarbon dating and comparison of Si/Al to the global benthic stable isotopes stack LR04 (Lisiecki and Raymo, 2004). The age of facies contacts are derived from the marine isotope stage boundaries (Lisiecki and Raymo 2004).

Due to the scarcity of valves in these samples, only samples from 290-5 cm are included in statistical analysis. The number of diatom valves on a whole slide is considered a qualitative measure of diatom abundance.

The relative abundance of each species was expressed as the number of valves of that species divided by the total valve count (expressed as %). Species with <2% in at least one sample were excluded from the distribution and statistical analysis, except in cases where species were grouped together, due to similarity in habitat indicators (i.e., *Fragilariopsis* sea ice species) or morphology (i.e., *Thalassiothrix* and *Trichotoxon*), in which case the representative species of a group needed to be >2% in at least one sample, but members of the group

https://doi.org/10.5194/egusphere-2022-1009
Preprint. Discussion started: 4 October 2022

only required >1 valve per sample to be included in a group. An assessment of the diversity of diatoms in each sample was determined using the Shannon-Wiener diversity index. The Shannon-Wiener diversity index (Spellerberg et al. 2003) was calculated according to the formula:

$$H = -\sum_{i=1}^{n}[p_i \, x \ln p_i]$$

2.8 Statistical analyses

The diatom data set was analysed using a hierarchical cluster analysis and principal component analysis (PCA), in Statistical Package for Social Sciences (SPSS) software package. Cluster analysis (Burckle 1984; Truesdale & Kellogg 1979) involved calculating the average distance between groups. The PCA (Taylor, McMinn & Franklin 1997; Zielinski & Gersonde 1997) was undertaken in two stages. In Q-mode, investigating relationships between variables (species), and in R-mode, analysing relationships between samples (Shi 1993). The factor variance used to extract the number of components for Q-mode analysis was established at >10 % variance. The factor variance used to extract the number of components for R-mode analysis was established at >0.4 %. Factor variance is the amount of the total variance of all of the variables accounted for by each component (factor) (https://www.ibm.com/docs/en/spss-statistics). Outputs from both Q and R analyses underwent a Varimax rotation. Rotation maintains the cumulative percentage of variation explained by the chosen components (in this case >8% and >1.4%), but the variation is spread more evenly over the components (https://www.ibm.com/docs/en/spss-statistics). Finally, to demonstrate the strength of the correlation between the components and productivity proxies (Si/Al and biogenic silica), regression analyses were undertaken using SPSS.

3 Results

3.1 Biogenic silica and Si/Al

Biogenic silica varied from 0-22% (Fig. 3). Higher Si/Al values occurred within interglacial facies and lower values occurred within the glacial facies. The highest values found in the top 40 cm (10-22%), at 260-140 cm (12-16%), and at the base of the core at 540-520 cm (3-11%), coinciding with olive/grey sandy mud (Facies 1/ interglacial) and olive grey mud (Facies 1A/ glaciation). Moderate to low values (3-10%) occurred in olive mud (Facies 2A/ deglacial) and grey mud (Facies 2/ glacial), with the exception of 18% at 140 cm within Facies 2 (Fig. 3).

3.2 Species distribution, biodiversity, and abundance

All samples contained well-preserved diatom assemblages with little evidence of dissolution, such as frustule thinning. Of the 53 species identified in 34 samples (Table S5), 24 species were included in the species

https://doi.org/10.5194/egusphere-2022-1009
Preprint. Discussion started: 4 October 2022

distribution and statistical analysis (Fig. 3). Relatively high Shannon Wiener index values of 1.6 -2 were found at 40 cm and at 220-130 cm, within the glaciation and glacial (MIS 4-2) facies (Fig. 3). The most abundant species was *Thalassiosira lentiginosa* (Fig. 3), which comprised >20% of the total throughout the core and >55% of the total from 50-5 cm and 270-230 cm, coinciding with the interglacial and deglacial facies, respectively. The minimum abundances for this species were between 170-60 cm, coinciding with the glacial facies (Fig. 3). The second most abundant species was *Eucampia antarctica* (Fig. 3). It had maximum abundances of 18-62%, occurring in the 210-60 cm interval (glacial and glaciation facies) and within the 290-280 cm sample (glacial and deglacial facies). Relatively high *Eucampia* abundances, >30%, were found at 140-110 cm, at 210 cm, and 290-280 cm, while exceptionally high values (59-62%) occurred within 100-70 cm. The lowest abundances of *Eucampia antarctica* were found in the 50-5 cm interval (2-8%), and 270-220 cm (2.7-18%), both within interglacial and deglacial facies.

The following section describes species that comprised 25% or less relative abundance (Fig. 3). *Fragilariopsis kerguelensis* was the third most abundant species, with maximum values (17-25%) found at 220-210 cm and 50-40 cm, within the glaciation/interglacial and deglacial facies, respectively. These are also the intervals where both the *Thalassiosira lentiginosa* and *Eucampia antarctica* numbers decreased. High abundances of *Actinocyclus actinochilus* (7-13%) occurred at 140-50 cm and 290-280 cm (glacial and deglacial facies), while lower values (4-7%) were found at 240-150 cm (glacial, interglacial and glaciation facies) and low values (1.6-4%) at 40-5 cm (interglacial, deglacial). *Actinocyclus ingens* was found at 60 cm (at 11% abundance) and at 280 cm (at 3% abundance), within two different glacial to deglacial facies boundaries. The *Fragilariopsis* group, which was mostly comprised of *F. obliquecostata* with lower abundances of *F. sublinearis, F. linearis, F. cylindrus* and *F. angulata,* attained maximum abundances of 8% at 160-200 cm, within the glacial facies. *Thalassiosira oliverana* and *Thalassiosira tumida* ranged in abundance between 0- 8% and 0- 4%, respectively. Maximum *T. oliverana* abundances were at 20-5 cm, 50 cm, 210-190 cm, 240-230 cm, and at 280 cm within the interglacial, deglacial and glacial facies. Maximum *T. tumida* abundances were at 240-220 cm and 190-160 cm, within interglacial and glacial facies.

The following species occurred at a maximum abundance of 4% in at least one sample. *Chaetoceros dichaeta,* was found at 200 cm within the glaciation facies; *Chaetoceros bulbosum*, found at 40 cm within the deglacial facies; *Rhizosolenia* group, which is dominated by *Rhizosolenia styliformis,* and contains lower abundances of *Rhizosolenia antennata* (twin process), is found at 80 cm, 140 cm, and 200-160 cm, all within the glacial facies; the *Thalassiothrix group*, dominated by *Thalassiothrix antarctica* (while, *Thalassiothrix longisima* and *Trichotoxon reinboldii* are sparce) was found at 40 cm and 260 cm, within the deglacial and interglacial facies, but as mentioned above, the abundance may be underestimated as samples at 40 cm and 270 cm (deglacial intervals) had high visual abundances of broken *Thalassiothrix* valves (deglacial facies). *Thalassiosira oestrupii* had higher abundances at 50-30 cm, 140-130 cm and at 240 cm, within the deglacial, glacial and interglacial facies, respectively; *Asteromphalus parvulus* was found at 180-160 cm, 200 cm and at 240-230 cm, within the glacial and interglacial facies, respectively; and *Asteromphalus hyalinus* was found at 170-150 cm, at 240 cm and at 270 cm, within the glacial, interglacial and deglacial facies.

https://doi.org/10.5194/egusphere-2022-1009
Preprint. Discussion started: 4 October 2022

Eucampia antarctica terminal/ intercalary ratios were highest (0.4-0.8) at 140-20 cm, in the glacial, deglacial and interglacial facies; an unusually high ratio of 1.4 occurred at 50 cm in the deglacial facies (Fig. 3). However, this high value is coincident with sea ice species indicators, such as *Fragilariopsis* species. This value may be unreliable due to the very low abundance of *Eucampia antarctica* (2%). Consistently high values of the ratio (0.4-0.8) together with high counts of *Eucampia antarctica* valves in general, were found within 140-60 cm, coincident with upper MIS 4-2 glacial (Fig. 3). Relatively high values (0.4) of the ratio were also found in the glaciation facies. Relatively low values (0-0.3) of the ratio were found in the lower glacial (MIS 4-2) interval.

The interval from 350-320 cm is considered barren (Fig. 3), that is, it contains only a few specimens of robust valve forms such as *Thalassiosira lentiginosa*, *Eucampia antarctica* and *Actinocyclus actinochilus* (Table S5), which could have been reworked. This interval also contains pyritised shells, which are also found at 80-60 and at 320-300 cm (Fig. S1).

https://doi.org/10.5194/egusphere-2022-1009
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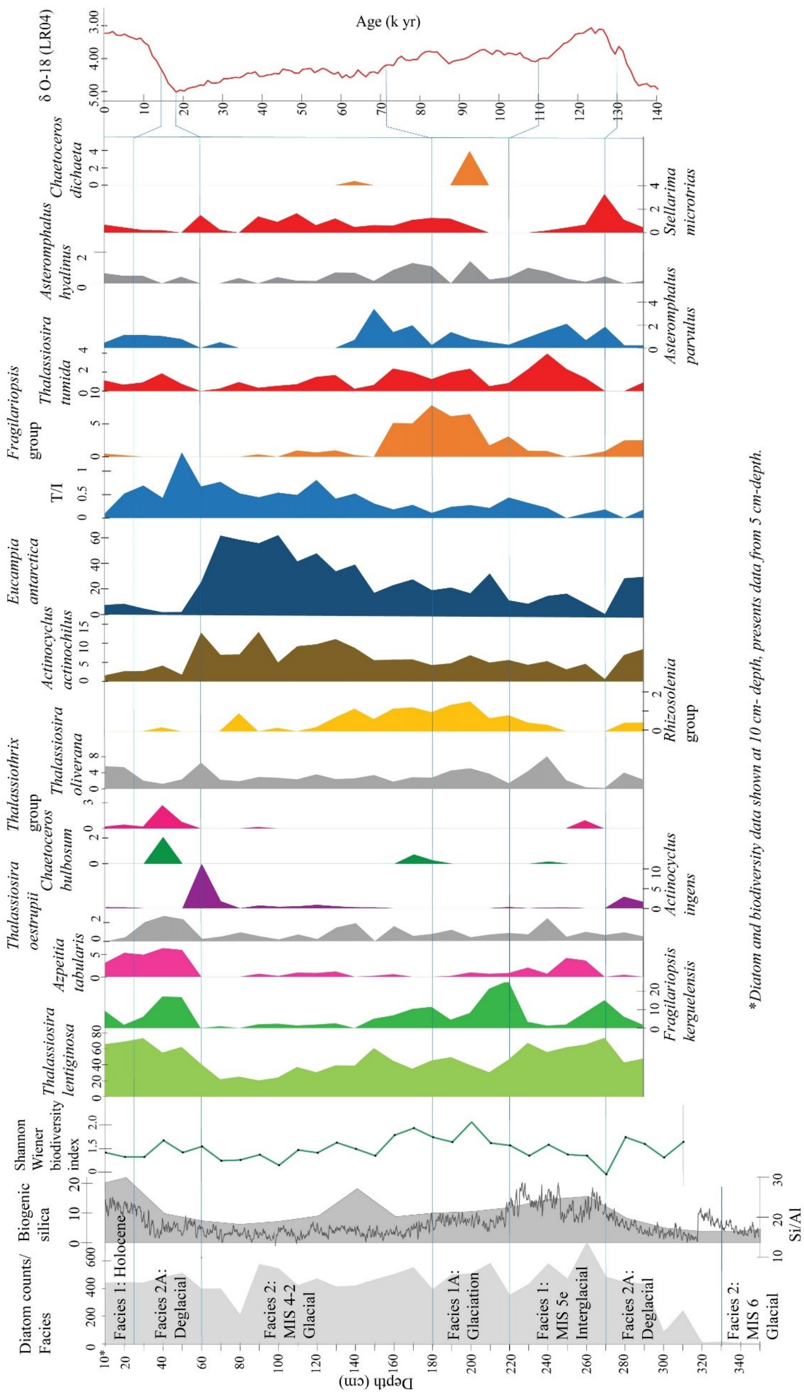

Figure 3 Tan_44 distribution of main species, species groups and *Eucampia Antarctica* terminal/ intercalary (T/I) ratio. Results include valve counts (per slide), facies interpretation (vertical lines), biogenic silica (%), Si/Al (XRF) and the Shannon-Wiener biodiversity index. The facies model is shown, in comparison to LR04 (Lisiecki & Raymo 2005).

https://doi.org/10.5194/egusphere-2022-1009
Preprint. Discussion started: 4 October 2022

3.3 Cluster and principal component analyses

Cluster analysis groups samples according to the similarity of the sample assemblages (Shi 1993). The groupings, illustrated by a dendrogram, can represent similar environments, and therefore aid in the reconstructions of paleoenvironments. Based on the relative abundance of diatom species and species groups, three clusters were identified (Fig. 4), with a dissimilarity index of 4%. The two largest groups, Cluster 1 and Cluster 2, correlate well with interglacial and glacial facies, respectively (Fig. 4).

Cluster 1 includes samples from 5 cm, 210-110 cm and 290-230 cm. This cluster, which contains open ocean species (Fig. 3), is associated with the interglacial, deglacial and glacial facies. Cluster 2 includes samples from140-60 cm. This cluster is associated with the glacial facies, represented by sea ice and ice edge species (Fig. 3). Cluster 3, which includes samples from 50-20 cm and 220 cm, is associated with the deglacial interval and is represented by *Thalassiosira lentiginosa* and *Fragilariopsis kerguelensis*.

The Q-mode PCA analysis identified four components that together explained 52% of sample variance (Table S3; Table 2). Component 1 (PC 1) explains 18% of the variance and contains contributor species associated with open ocean and sea ice edge environments. Species determining this component are *Thalassiosira lentiginosa*, *Actinocyclus actinochilus*, *Eucampia antarctica*, *Azpeitia tabularis*, and *Asteromphalus hyalinus.* Component 2 (PC 2) explains 16% of the variance and is associated with sea ice or the coastal Antarctic environment. These are the *Fragilariopsis* group (dominated by *Fragilariopsis obliquecostata*), *Asteromphalus parvulus*, the *Rhizosolenia* group (dominated by *Rhizosolenia styliformis*), *Thalassiosira tumida,* and *Chaetoceros dichaeta*. Component 3 (PC 3) explains 8.6% of the variance and its contributor species are associated with open ocean environment. These are *Actinocyclus ingens*, *Actinocyclus actinochilus*, *Thalassiosira oliverana*, and *Fragilariopsis kerguelensis.* Component 4 (PC 4) explains 8.6% of the variance and its contributor species are associated with the open ocean, high nutrient, and warmer ocean environments. These are the *Fragilariopsis kerguelensis*, *Thalassiothrix* group, *Chaetoceros bulbosum*, and *Eucampia antarctica*.

R-mode PCA analysis identified four main components, explaining 99% of the down core variance (Table S4; Fig. 5). The variance is mostly explained by PC 1 and PC 2, with PC 3 explaining <20% and PC 4 <2% of the variance. PC 1, the open ocean assemblage, explains 43% of the variance and shows high factor loadings at 40-5 cm and 270-150 cm. Both of these intervals coincide with Cluster 1 and 3, in the interglacial, deglacial, glaciation and early MIS 4-2 facies. PC 2, the sea ice, and ice-edge species assemblage (Table 2), explains 36% of the variance and shows high factor loadings at 140-60 cm, 170 cm, 210 cm, and 290cm. These intervals coincide with Cluster 2, in the glacial facies and Cluster 1 in the early MIS 4-2 glacial, glaciation and deglacial facies (Fig. 5). PC 3, the reworked assemblage explains 19% of the variance and shows high factor loadings at 60-20 cm, 230-220 cm, and 270 cm intervals. These intervals coincide with Cluster 3, and Cluster 1 (sample 270 cm), in the deglacial, interglacial, and glaciation facies. PC 4, the high nutrient, warmer, open ocean assemblage, explains 1.4% of the variance, and has elevated factor loading at 40 cm, 180-160 cm, 220-210 cm, and 280-270 cm, in the deglacial, early glacial, and glaciation facies.

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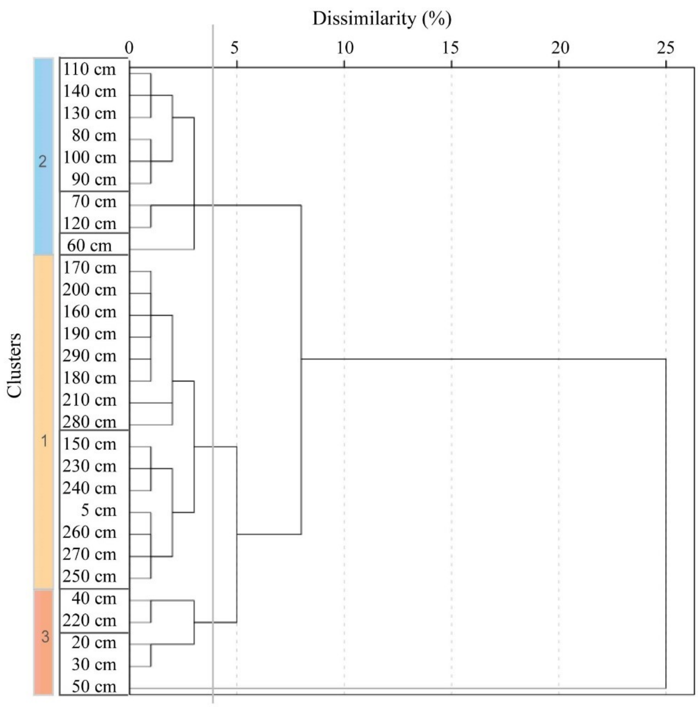

360 **Figure 4** Hierarchical cluster analysis dendrogram illustrating agglomeration of four clusters at dissimilarity of 8%.

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Preprint. Discussion started: 4 October 2022

Table 2 Species assemblages (PC 1-PC 4) according to Q-mode principal component analysis (further information can be found in Table S2).

Factor loadings	Principal components	Environment
	P1	
> +/-0.5	*Thalassiosira lentiginosa*	Open ocean
	Actinocyclus actinochilus	Sea ice edge
	Eucampia antarctica	
	Azpeitia tabularis	
	Asteromphalus hyalinus	
	P2	
>+/-0.5	*Fragilariopsis* group*	Sea ice
	Astermomphalus parvulus	Coastal
	Rhizosolenia group**	Ice edge
	Thalassiosira tumida	Coastal
	Chaetoceros dichatea	
> -0.4	*Terminal/intercalary ratio*	
	P3	
> +/-0.4	*Actinocyclus ingens*	Reworking
	Actinocyclus actinochilus	by bottom
	Thalassiosira oliverana	currents
	Frailariopsis kergulensis	
	P4	
> +/-0.4	*Fragilariopsis kerguelensis*	High nutrient
	*Thalassiothrix group****	Warmer water
	Chaetoceros bulbosum	
	Eucampia antarctica	

* mainly *F obliquecostata*
** mainly *R styliformis,* less *R antennata f antennata*
*** *Thalassiothrix longissima; Thalassiothrix antarctica, Trichotoxon reinboldii.*

3.4 Correlation between diatom assemblages and productivity

Regression analysis shows a statistical relationship between PC 1 and PC 2 assemblages, and Si/Al and biogenic silica (BSi), with r^2 values ranging from 0.2-0.5 (Table 3). PC 1 assemblage shows a positive correlation to Si/Al (PC 1=-0.32+(0.49 x Si/Al)), and to biogenic silica (PC 1=0.33+(0.23 x BSi)). PC 2 shows a negative correlation to Si/Al (PC 2=1.66+(-0.06 x Si/Al)) and to biogenic silica (PC 2=0.87+(-0.03 x BSi)). In contrast, PC 3 and PC 4 assemblages have no correlation with either Si/Al or biogenic silica, showing r^2 values <0.1.

Table 3 Correlation (r^2) between each PC components and Si/Al and biogenic silica.

Assemblage	Si/Al	Biogenic silca
PC 1 open ocean	**0.34**	**0.16**
PC 2 sea ice	**0.5**	**0.27**
PC 3 reworked	0.06	0.12
PC 4 high productivity	0.01	0.08

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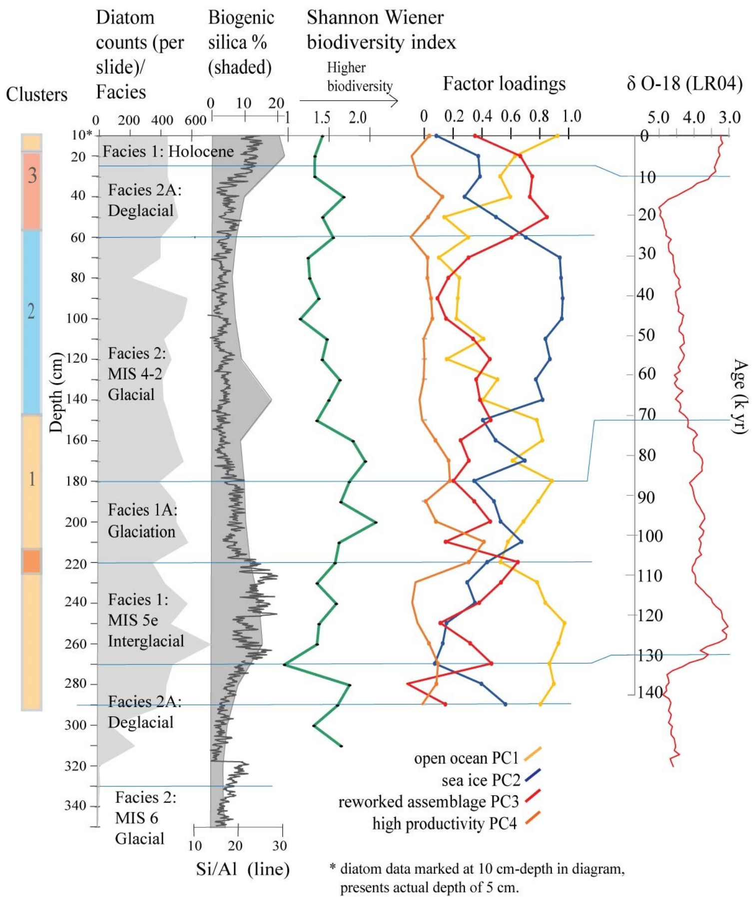

Figure 5 Principal Component (PC 1-PC 4) factor loadings down core Tan_44 and Shannon-Wiener biodiversity index (green). Shaded areas show intervals of high factor loadings (dominance) of the assemblages and, of higher biodiversity. Also included are cluster results, relative diatom counts, sediment facies (horizontal lines), biogenic silica, Si/Al and LR04 curve (Lisiecki & Raymo 2005).

4 Discussion

4.1 Diatom assemblages, clusters, and sedimentary facies

Principal component analysis distinguished four diatom assemblages. PC 1 and PC 2 incorporated most of the variance, while PC 3 and PC 4 were less influential (Fig. 5). The assemblages and their environmental interpretation are described below.

4.1.1 The open ocean assemblage (PC 1)

The PC 1 assemblage comprises open ocean species, *Thalassiosira lentiginosa*, *Eucampia antarctica*, and *Fragilariopsis kerguelensis* (Johansen and Fryxell 1985; Garrison and Buck 1989; Medlin and Priddle 1990; Zielinski and Gersonde 1997); ice edge species, *Actinocyclus actinochilus* (Medlin and Priddle 1990; Ligowski, Godlewski and Lukowski 1992; Garrison and Buck 1989; Armand et al. 2005), and warmer water species, *Azpeitia tabularis* (Zielinski and Gersonde 1997; Romero et al. 2005). Therefore, the PC 1 assemblage is interpreted to present an open ocean environment, relatively warmer ocean, with a seasonal sea ice cover (Table 2) similar to the modern-day environment over the core site.

The composition of the PC 1 assemblage further suggests that selective species preservation, due to reworking by bottom currents and/or dissolution processes, had been active. The presence of a combination of robust species, e.g., *Eucampia antarctica*, *Fragilariopsis kerguelensis*, and *Actinocyclus actinochilus,* suggests that some level of reworking of sediments influenced the assemblage composition (Shemesh, Burckle, and Froelich, 1989; Taylor and McMinn 1997). These species have been found within assemblages considered to have been influenced by reworking off Cape Darnley in Prydz Bay (Taylor and McMinn 1997) and the continental slope of the Ross Sea (Truesdale and Kellogg 1979). Reworking is corroborated by the knowledge that the site is currently influenced by the down slope flow of Adélie AABW and along slope currents, including the ASF (Fig. 1; Williams et al. 2008). Furthermore, the presence of unusual abundances of *Thalassiosira lentiginosa* (Fig. 3), a species usually associated with open ocean assemblages (Taylor and McMinn 1997; Truesdale and Kellogg 1979; Crosta et al. 2005) suggests that there is some level of dissolution affecting the PC 1 assemblage composition (Shemesh, Burckle, and Froelich, 1989). Such high abundances of *T. lentiginosa* are not observed in modern sediments in the Adélie region (Leventer 1992), or elsewhere within the sea ice zone on the Antarctic margin (Zielinski and Gersonde 1997; Armand et al. 2005; Crosta et al. 2005). Despite the influence of reworking and dissolution, the PC 1 assemblage is still considered to be autochthonous and dominated by *in-situ* deposition associated with open ocean, warmer water, and sea ice edge species. The presence of *Azpeitia tabularis,* a species not commonly associated with reworking or dissolution, further confirms this position.

4.1.2 The sea ice assemblage (PC 2)

The largest contributions to the PC 2 assemblage (Table 2) are from the *Fragilariopsis* group, comprising mainly *Fragilariopsis obliquecostata*, a species which currently lives in sea ice and at the sea ice edge (Ligowski, Godlewski & Lukowski 1992; Medlin & Priddle 1990; Moisan & Fryxell 1993). In Antarctic continental margin surface sediments from the Ross Sea, Weddell Sea and Prydz Bay, *Fragilariopsis obliquecostata* appears where sea ice cover is present >7 months per year (Armand et al. 2005). Other species in PC 2 include the coastal species, *Asteromphalus parvulus* (Kopczynska et al. 1986; Scott and Thomas 2005), cool open ocean species, the *Rhizosolenia* group, comprising mainly *Rhizosolenia styliformis*, the open water/ sea ice edge species *Thalassiosira tumida* (Garrison & Buck 1989) and the coastal and sea ice edge species *Chaetoceros dichaeta* (Beans et al. 2008; Kopczynska, Weber & El-Sayed 1986; Ligowski 1983). This

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Preprint. Discussion started: 4 October 2022

interpretation is further supported by the *Eucampia antarctica* terminal/ intercalary ratio, a sea ice and sea ice edge proxy (Fryxell 1991), with values generally ranging from 0.0-0.8 (Fig. 3). Based on a combination of sea ice and sea ice edge/ coastal species, the PC 2 assemblage is interpreted as resulting from an environment proximal to the permanent sea ice edge with a long sea ice duration, as currently observed in the Ross and Weddell Seas (Fetterer et al. 2017).

4.1.3 The reworked assemblage (PC 3)

The PC 3 assemblage comprises *Actinocyclus ingens*, *Actinocyclus actinochilus*, *Thalassiosira oliverana*, and *Fragilariopsis kerguelensis*. *Actinocyclus ingens* is an extinct species, associated with 0.65-1.25 M old sediments (Harwood et al. 1992). *Thalassiosira oliverana* and *Fragilariopsis kerguelensis* are species associated with open ocean environments (Medlin and Priddle 1990; Kopczynska 1986; Garrison and Buck 1989), while *Actinocyclus actinochilus* is associated with sea ice edge environments (Medlin and Priddle 1990; Garrison and Buck 1989). However, these species (except *A. ingens*) have robust valves that can survive transport by bottom currents (Shemesh, Burckle & Froelich 1989; Taylor and McMinn 1997; Truesdale and Kellogg 1977). PC 3 is therefore interpreted as a reworked assemblage (allochthonous), transported from elsewhere by bottom water transport, with no *in situ* deposition, and hence no environmental signal. The reworking is supported by the presence of *Actinocyclus ingens*, which is an extinct species and was probably transported to Tan_44 from older sediments on the margin. *Actinocyclus ingens* is only found at 60 cm and 290-280 cm depth (Fig. 3). The 60 cm interval also contains pyritised shells (Fig. S1).

4.1.4 The high productivity assemblage (PC 4)

This assemblage includes *Fragilariopsis kerguelensis,* the *Thalassiothrix* group, of which *Thalassiothrix antarctica* is the most common, *Chaetoceros bulbosum* and *Eucampia antarctica* (Table 2). *Fragilariopsis kerguelensis* and *Eucampia antarctica* are open ocean species (Kopczynska 1998; Garrison and Buck 1989; Beans et al. 2009) found in abundance in surface sediments, between coastal Antarctica and the subtropical front (Zielinski and Gersonde 1997; Crosta et al. 2005). *Thalassiothrix antarctica* is associated with diatom blooms that occur in modern coastal and shelf waters, such as in Prydz Bay (Ligowski 1983) or in naturally fertilised areas, such as the Kerguelen Plateau (Rembauville et al. 2015). *Chaetoceros bulbosum* is found in the open ocean, generally south of the Polar Front (Kopczynska 1998). Zielinski and Gersonde (1997) consider *Thalassiothrix antarctica* and *Chaetoceros* species from the Weddell Sea sediments to be indicators of high productivity. *Thalassiothrix antarctica* is not found in modern sediments off Adélie region, where only *Chaetoceros* blooms are evident (Leventer 1992). However, Beans et al. (2009) found that this species can sometimes be abundant in waters off Adélie Land. Based on the conclusions of Zielinski and Gersonde (1997) and Rembauville et al. (2015), the PC 4 assemblage is suggested to be indicative of a higher nutrient environment and higher productivity than in the present Adélie region. Thus, the PC 4 assemblage is considered indicative of high nutrient input and upwelling of warm water.

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Preprint. Discussion started: 4 October 2022

4.2 Palaeoecological interpretation

4.2.1 Interglacial (MIS 5e and Holocene)

The interglacial facies is associated with PC 1 (open ocean assemblage; Fig. 5; Table 2), and to a lesser extent with PC 2 (sea ice assemblage). The dominance of the PC 1 assemblage suggests that the Holocene and MIS 5e environments had seasonal sea ice, with open ocean (during the summer) and sea ice cover (during winter, spring, and autumn), similar to the modern situation (Fig. 1). The inference of the seasonal presence of sea ice is strengthened with the moderate presence of PC 2 assemblage, which represents increased sea ice duration. PC 1 also provides evidence of reworked and a dissolution-affected assemblage. Indeed, strong bottom currents, such as AABW, and ASF, which sweep the continental slope off Adélie Land, at present (Fig. 1; Williams et al. 2010), may have been active throughout the Holocene and MIS 5e. Furthermore, the reworking by bottom currents may have been stronger at times. This is further suggested by the slight presence of PC 3, which represents reworked assemblages. Lastly, the PC 1 assemblage is associated with elevated productivity, which is supported by high Si/Al and biogenic silica, but lower biodiversity (Fig. 5). Low biodiversity is likely affected by poor preservation (dissolution and reworking), but potentially also reflects modern diatom blooms, which are typically of lower biodiversity (Beans et al. 2008). The close similarity of diatom assemblages between the two interglacial facies, MIS 5e and Holocene, suggests that ocean temperature, circulation, and seasonal sea ice duration in the Adélie region were similar during these two interglacial periods (Fig. 5).

4.2.2 Glaciation MIS 5d-5a (interglacial to glacial transition)

The early glaciation facies is associated with an increased PC 2 (sea ice assemblage) and a minor increase in PC 4 (high productivity assemblage), while the late glaciation is associated with increasing PC 1 (open ocean assemblage), a gradually decreasing PC 2 and a minor increase in PC 4 (Fig. 5). The increase in PC 2 in the early glaciation, relative to the MIS 5e interglacial, therefore suggests that the sea ice season initially increased in duration, in response to cooling. This is coupled with periods of slightly elevated PC 4 suggesting intervals of elevated nutrient input and warmer water influx, potentially reflecting periods of increased rates of CDW upwelling, relative to the present-day. Although PC4 is a minor component of the diatom assemblage, the presence of both elevated PC 4 and PC 2 (Fig. 5), suggests both an increase of sea ice (and thus cooling) and a warm water influx, occurred over the Adélie region during the early glaciation stage. This may have occurred during different seasons, i.e., the sea ice season may have increased over autumn, winter, and spring, while CDW influx may have increased during summer.

The productivity proxies, Si/Al, and biogenic silica are low, indicating a decrease in productivity throughout the glaciation (Fig. 5). However, the opposite is indicated by the continued presence of PC 1, which suggests high productivity.

The Shannon Wiener index suggests that the late glaciation (like the early glacial, MIS 4-2) was a time of relatively high biodiversity (Fig. 5) relative to the MIS 5e and Holocene interglacials. This may be due to a more diversified environment, that is, the increased sea ice season, and times of increased CDW influx may have produced a more diversified community. Interestingly, the early glaciation, also characterised by elevated PC 2 and PC 4, is associated with lower biodiversity. In the modern shelf environment, a greater diatom biodiversity is found near the Astrolabe Glacier, rather than near the Mertz Glacier, where productivity is higher, yet dominated by fewer species (Beans et al. 2008). Thus, the biodiversity in the samples may reflect this natural variability seen in the diatom assemblages in the Adélie region today.

4.2.3 Glacial (MIS 4-2)

Diatom assemblages can be used to subdivide the MIS 4-2 glacial interval into early and late glacial stages (Fig. 5). The early glacial stage, comprising increased loadings of PC 1 (open ocean assemblage) and increased loadings of PC 2 (sea ice assemblage), is similar to the glaciation, suggesting an initially prolonged sea ice season relative to the interglacial periods. The early glacial stage also contains assemblages aligned with PC 4, suggesting an increased rate of CDW influx, and periods of increased seasonal blooms. The diatom assemblages at the start of the glacial have a higher biodiversity, similar to the glaciation stage. This likely reflects the diversity of assemblages including sea ice (PC 2) and high productivity (PC 4). After this initial increase in PC 2 and PC 4, the assemblages align with PC 1, suggesting temporary reversal of cooling, and an increase in productivity. Although the PC 1 shows evidence of increased/ high productivity, the other productivity proxies, Si/Al, and biogenic silica show the opposite, that the overall glacial productivity in this region was low. This is consistent with data from the broader Antarctic margin data (Bonn et al. 1998) and from the glaciation and deglacial facies. The reason for these opposing productivity signals is not clear, however, Hartman et al. (2021) also found similar results, with a low biogenic silica and Ba signal, yet an increase in *Chaetoceros* resting spores and *Eucampia antarctica* valves within the glacial record off Cape Adare (Ross Sea). In the late glacial, from 150-100 cm, the assemblage aligns with a gradual increase in PC 2 and a decrease in PC 1, suggesting a gradual increase in the duration of the sea ice season (Fig. 5). In the late glacial stage, from 100-70 cm, the assemblages align with PC 2, the sea ice assemblage, suggesting maximum duration of the sea ice season occurred during the late glacial stage (MIS 2).

The similarities in diatom assemblages between glaciation and early glacial stage suggests cooling of the ocean started long before the onset of the glacial and then continued slowly (with the exception of a period of warming during the late glaciation stage) until the maximum cooling was reached, at the end of the last glacial (Fig. 5). This is consistent with gradual cooling reaching a maximum at the end of MIS 2, as seen in Antarctic ice cores (Jouzel et al. 1993) and Sea Surface Temperatures (SST) from global sediment cores (Kohfeld & Chase 2017), including records based on diatom assemblages from the Southern Ocean north at 56 °S (Crosta et al. 2004; Chadwick et al. 2022). The assemblage composition of the late glacial stage is suggestive of a long sea ice season duration, an environment which at present occurs in the Ross and Weddell Seas (Truesdale & Kellogg 1979; Zielinski & Gersonde 1997). This suggests that the permanent/ summer sea ice edge, during the late

https://doi.org/10.5194/egusphere-2022-1009
Preprint. Discussion started: 4 October 2022

glacial stage, was closer to the core site than it is today, indicating that the core site was covered by near permanent sea ice during the peak glacial. However, the persistent presence of the *Thalassiosira lentiginosa* provides evidence that open ocean conditions existed over the Tan_44 site, during part of the year.

4.2.4 Deglacials (glacial to interglacial transitions): MIS 2 to Holocene and MIS 6 to MIS 5e

The deglacial facies (between MIS 6 to MIS 5e and MIS 2 to Holocene), is generally associated with an increase in PC 1 (open ocean assemblage), and a decrease in PC 2 (sea ice assemblage), relative to the glacial (Fig. 5). PC 3 (reworked assemblage) is increased throughout the entire MIS 2 to the Holocene deglacial, and at the beginning and the end of the MIS 6 to MIS 5e deglacial, while PC 4 (high productivity assemblage) is slightly increased during both deglacials. The dominance of PC 1 suggests that there was an increase in productivity throughout the deglacial, although the productivity proxies, biogenic silica, and Si/Al, are low. The minor influence of PC 4 suggests an increase in CDW, relative to the glacial period. Tolotti et al. (2013), and Li et al. (2021), also suggest, based on the presence of diatom species, that increased CDW influx occurred during the last deglacial in the Ross Sea and off Enderby Land, respectively. Lastly, the start of the MIS 2/1 deglacial (and end of MIS 6/5 deglacial) is marked by the rapid decrease in the PC 2 assemblage (Fig. 5), which suggests that the sea ice season duration rapidly declined. This is consistent with the rapid sea ice retreat for the last two deglacial transitions from distal Southern Ocean (at 56°S) by Crosta et al. (2004) and Chadwick et al. (2022).

In conclusion, the sea ice season duration decrease occurred relatively rapidly, and prior to CDW increase as evidenced by the increase in PC 4 between 50-40 cm depth (Fig. 5). Therefore, something other than increase in CDW influx influenced sea ice retreat. However, a more detailed study of diatom assemblages is needed in order to determine the relative timing and a more detailed chronology of these deglacial changes.

4.2.5 Diatom barren MIS 6 glacial and relatively low diatom MIS 6 to MIS 5e deglacial

The 350-320 cm interval is considered diatom barren, having 7-22 valves per slide, while the 310-300 cm interval has a low relative diatom count of 88-245 valves per slide (Fig. 3; Table S5). Both of these intervals suggest a different environment in the late MIS 6 glacial and early MIS 6/5e deglacial compared to the 290-0 cm interval described and statistically analysed above. The diatom barren interval at 350-320 cm, and relatively low diatom interval at 310-300 cm, may be due to the original assemblage having been affected by dilution at the sea floor by turbidity currents (Kellogg & Truesdale 1979; Schrader et al. 1993; Escutia et al. 2003), or by a permanent sea ice cover which reduced productivity allowing only reworked diatoms to be transported to the site by bottom currents (Table S5). The presence of micropyrite within the 320-300 cm section suggests low oxygen levels could have prevailed during the time, brought on by either fast sedimentation, such as turbidity currents (Presti et al. 2011), or by an extensive sea ice cover (Lucchi et al. 2007). Interestingly, pyrites are found also within the 80-60 cm section, which comprises an increase of the reworked assemblage (PC 3; Fig. 5) at the end of the MIS 4-2 glacial facies.

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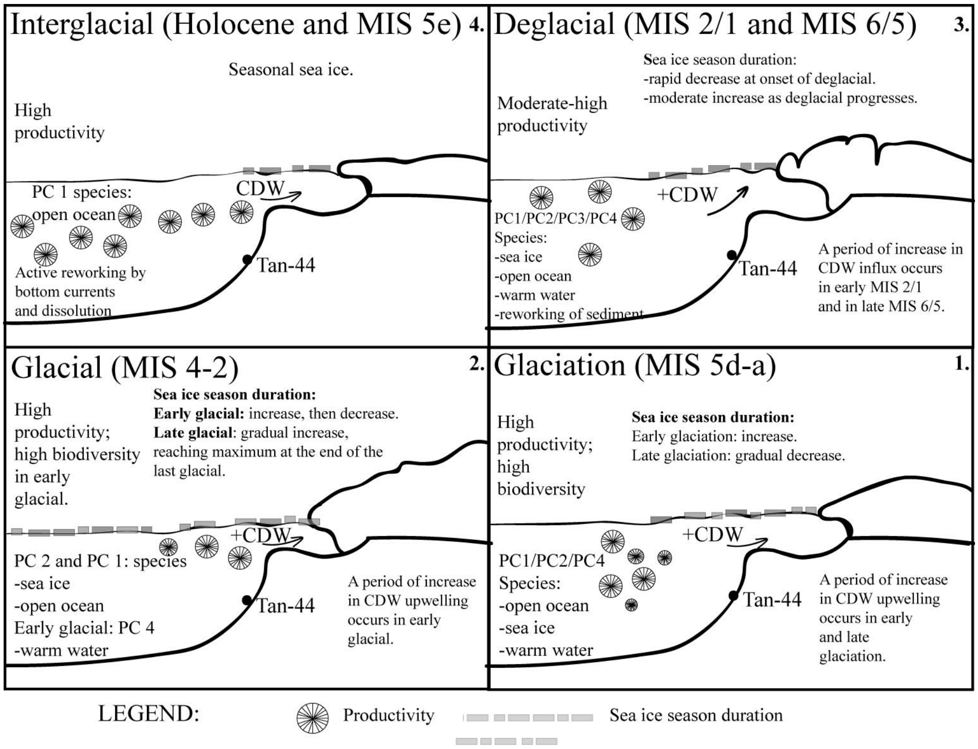

Figure 6 Sea ice and productivity interpretation across the last glacial cycle (~140- ~5ka) based on diatom assemblage variability. During Holocene and MIS 5e interglacial periods, the seasonal sea ice cover at the site is similar to present-day. Sea ice cover initially increases then decreases in glaciation (MIS 5d-a); and early MIS 4-2 glacial. The sea ice then, gradually increases during late MIS 4-2 glacial, reaching a maximum seasonal duration at the end of the last glacial. During the early glacial, early glaciation and the end of glaciation (MIS 5d-a; i.e., last interglacial to glacial transition) and during the deglacials (i.e., last two glacial to interglacial transitions) the influx rate of CDW increased for a period of time, relative to modern influx rates, as suggested by the presence of the high nutrient/ warmer PC 4 assemblage. This study suggests the sea ice decreased rapidly at the end of the last glacial, and that the increase in CDW influx occurred after the retreat of sea ice during the last deglacial.

5 Conclusion

Diatom assemblages in Tan_44 (64.5°S) varied on a glacial to interglacial timescale over the last 140 k yrs, and their composition was influenced by both *in situ* productivity and bottom current reworking processes. However, the assemblages were mainly influenced by environmental changes connected to sea ice duration and changing ocean circulation over the core site. The following is a summary of conclusions reached in this study (Fig. 6):

- The PC 1 assemblage dominance in the interglacial facies suggests open ocean and seasonal sea ice environments during MIS 5e and Holocene which are similar to today. The close correspondence of assemblages between the two interglacials suggests that both surface water conditions, related to sea surface temperature and sea ice duration were similar between the two interglacials.

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Preprint. Discussion started: 4 October 2022

- The unusually high dominance of *Thalassiosira lentiginosa* in the PC 1 assemblage in the interglacial facies suggests the assemblage was affected by dissolution and also by reworking by bottom currents.
- The presence of the PC 2 assemblage in the MIS 4-2 glacial facies suggests an environment with a long sea ice season. However, the presence of both PC 2 and PC 1 assemblages provides evidence that the summer sea ice edge was located further south than the core site, at 64.5°S, in the Adélie region.
- The duration of the sea ice season, as indicated by the presence of PC 2, started to increase during the early glaciation stage (MIS 5d-5a), and in the early MIS 4-2 glacial, and continued to increase throughout the late MIS 4-2 glacial, reaching a maximum extent towards the end of the glacial (MIS 2).
- The abrupt decrease of the PC 2 assemblage at the end of the last glacial suggests a relatively rapid decline in the sea ice season.
- The glaciation stage and the early glacial are similar: they contain an initial increase in sea ice duration (PC 2). Furthermore, both glaciation and early glacial periods contain a slight influence of PC 4, suggesting an increased CDW influx occurred synchronously with the increase in sea ice duration. This may have occurred during different times of the year.
- PC 1, PC 2, and PC 4 were expressed during climate transitions, that is, during the deglacial and glaciation. This suggests the presence of open water and increased seasonal sea ice environments but also periodic increases of nutrients and warmer water, interpreted as upwelling of CDW in the Adélie region, during these times.
- Biodiversity was highest during the glaciation stage and the start of the last glacial, and lowest during the late glacial and the interglacial periods. The higher biodiversity during glaciation and the start of the glacial could be the result of a more diversified environment relative to other periods. This may have been due to increased CDW influx during the spring and summer, and an extended sea ice season during winter spring or autumn. The lower biodiversity during the glacial is likely due to the overall increased sea ice season.

This new diatom data set provides an understanding of the changes in sea ice proximal to East Antarctica over the last glacial cycle. It provides new insight into the extent of the summer sea ice in the last glacial, the winter sea ice extent during the last interglacial, and also suggests changes within seasonal sea ice with respect to CDW, during climate (glacial to interglacial) transitions. These are important parameters to constrain climate models to understand the importance of the influence of Antarctic Sea ice on global climate over the last 140 ka. Further marine sediment core and sea ice data is required to improve the spatial and temporal changes in sea ice.

Data availability

The data is available at PANGEA.

Competing interest

The authors declare there is no conflict of interest in relation to work presented in this study and in the Supplement.

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