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**(subpolar) oceanic frontal systems have varied in concordance with Oligocene-Miocene glacial-interglacial climate variability.**

## 1. Introduction

The proportion of the East Antarctic ice sheet that is presently grounded below sea level is much larger than originally assumed (Fretwell et al., 2013). This implies that much more ice is sensitive to basal melting by warm waters than previously thought (Shepherd et al., 2012; Rignot et al., 2013; Wouters et al., 2015), and that a much higher amplitude and faster rate of sea-level rise under future climate scenarios than previously thought (IPCC, 2013). Studying the state and variability of Antarctic ice volume during past episodes with high atmospheric $CO_2$ concentrations ($pCO_2$) might provide additional understanding into ice/ocean feedback processes. Foster and Rohling (2013) compared sea-level and atmospheric $pCO_2$ concentrations on geological timescales and highlighted that global ice sheets were fairly insensitive to climate change under atmospheric $pCO_2$ between 400 and 650 parts per million in volume (ppmv). During the Oligocene and Miocene atmospheric $pCO_2$ ranged between 400 and 650 ppmv (Foster et al., 2012; Badger et al., 2013; Greenop et al., 2014). Crucially, similar $pCO_2$ levels are expected for the near future given unabated carbon emissions (IPCC, 2013), implying that global ice volume may not change much under these $pCO_2$ scenarios.

In contrast to the invariant global ice volume inferred by Foster and Rohling (2013), a strong (up to 1 per mille; ‰) variability is observed in deep-sea benthic foraminiferal oxygen isotope (hereafter benthic $\delta^{18}O$) data (Pälike et al., 2006; Beddow et al., 2016; Holbourn et al., 2007; Liebrand et al., 2011; 2017). These

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benthic $\delta^{18}O$ data reflect changes in continental ice volume (notably on Antarctica), in combination with deep-sea temperature, with the latter strongly coupled to polar surface-water temperature, as deep-water formation was predominantly located at high latitudes (Herold et al., 2011). High-amplitude variations in benthic $\delta^{18}O$ thus suggest either (I) strong climate dynamics in the high latitudes with relatively minor ice-volume change (which is in accordance with numerical modelling experiments (Barker et al., 1999) and the inferences of Foster and Rohling (2013)), or (II) strong fluctuations of the Antarctic ice-volume, with relatively subdued temperature variability (which is in accordance with indications for an unstable Antarctic ice sheets under warmer-than-present climates (Cook et al., 2013; Greenop et al., 2014; Rovere et al., 2014). Indeed, if one assumes present-day δ-composition (-42‰ versus standard mean ocean water (SMOW)) for the Oligocene–Miocene Antarctic ice-sheets and modern deep water temperature (2.5°C), then the Oligocene–Miocene benthic $\delta^{18}O$ fluctuations suggest long-term ice-sheet variability ranging between a present-day size for 27–23 Ma and absence during numerous other time intervals (Liebrand et al., 2017). Meanwhile, deep-sea temperatures have fluctuated considerably on geologic time scales (as is evident from ice-free geologic episodes –e.g., Zachos et al., 2008), suggesting there is no reason to assume that it did not fluctuate during the Oligocene or Miocene as well. Therefore, likely a combination of deep-sea temperature and ice-volume changes is represented in these records, but it is intrinsically impossible to determine the relative contribution of both factors from benthic $\delta^{18}O$ data alone. Clearly, ice-proximal reconstructions of climate, ice sheet and oceanographic conditions are required to provide an independent assessment of the stability of ice sheets under these $pCO_2$ conditions.

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While the Oligocene–Miocene may, in terms of $pCO_2$ conditions, bear analogy to our future, any such investigation must take into account the uncertainties involved in Antarctic paleotopography, which determines the proportion of marine-based versus land-based ice during the Oligocene. A lower Antarctic continent would result in more ice sheets being potentially sensitive to basal melt, and as such a higher sensitivity of the ice sheet to climate change. On top of this, one should take note of the fundamentally different paleogeographic configuration of the Southern Ocean during that time as compared to today (Figure 1). The development and strength of the Antarctic Circumpolar Current (ACC) connecting the Atlantic, Indian and Pacific Ocean basins (Barker and Thomas, 2004; Olbers et al., 2004) depend on the basin configuration (width and depth of the gateways and position of continental landmasses). The exact timing when the ACC reached its modern-day strength is still uncertain, ranging from the Middle Eocene (41 Ma) to as young as Miocene (23 Ma, Scher and Martin, 2004; Hill et al., 2013; Scher et al., 2015). Whether, and if so, how the development of the ACC has influenced latitudinal heat transport, ice-ocean interactions and the stability of Antarctic continental ice remains even more elusive.

To directly assess the role of ice-proximal oceanography on ice-sheet stability during the Oligocene–Miocene, ice-proximal proxy-records are required. Several ocean drilling efforts in the past have been undertaken to provide insight in the history of the Antarctic ice sheets (Cooper and O'Brien, 2004; Barker et al., 1998; Wise and Schlich, 1992; Barrett, 1989; Robert et al., 1998; Wilson et al., 2000; Harwood et al., 2006; Exon et al., 2004; Escutia et al., 2011a). For some of these sedimentary archives, establishment of age control was particularly challenging due to the paucity of useful and proper means to calibrate the record to the international

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time scale. As a consequence, their full use for the generation of paleoceanographic proxy records and ice sheet reconstructions has remained limited.

In 2010, Integrated Ocean Drilling Program (IODP) Expedition 318 drilled an inshore-to-offshore transect off Wilkes Land (Fig. 1a), a sector of East Antarctica that is assumed to be highly sensitive to continental ice-sheet melt (Escutia et al., 2011b). The sediments recovered from IODP Hole U1356A are from the continental rise of this margin (Escutia et al., 2011b) and hence contain a mixture of shelf-derived material and pelagic sedimentation. Dinoflagellate cyst events in this record have been accurately tied to the international time scale through integration with calcareous nannofossil, diatom and magnetostratigraphic data (Bijl et al., in press). The result is a – for Southern Ocean standards – solid stratigraphic age frame for the Oligocene–Miocene part of the record of Hole U1356 (Fig. 2; Table 1). In this paper, we investigate the dinocyst assemblages from this succession by utilizing the strong relationships between dinocyst assemblage composition and surface-water features of today's Southern Ocean (Prebble et al., 2013). We reconstruct the oceanographic regimes during the Oligocene and mid-Miocene, and speculate on their implications for oceanographic settings. We further compare the palynological data with detailed sedimentological descriptions from Salabarnada et al. (submitted this volume). Pairing the sedimentological interpretation and biomarker-derived absolute sea surface temperature (SST) reconstructions from the same core (Hartman et al., submitted this volume) with our dinocyst assemblage data, we assess the oceanographic variability off Wilkes Land from the dinocyst assemblages both at glacial-interglacial and long-term times scales.

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## 2. Material

### 2.1 Site description for IODP Hole U1356A

Samples were taken from IODP Hole U1356A, drilled on the continental rise of the Wilkes Land Margin, East Antarctica (Figure 1a; present coordinates 63°18.6' S, 135°59.9' E; Escutia et al., 2011b). We use the paleolatitude calculator www.paleolatitude.org of van Hinsbergen et al. (2015) to reconstruct the paleolatitudinal history of the site (Figure 1, between -59.8±4.8°S and -61.5±3.3° S between 34 Ma and 13 Ma, respectively). The single hole at Site U1356 reaches a depth of 1006.4 m into the seabed (Escutia et al., 2011b). Oligocene to late Miocene sediments were recovered between 890 and 3 mbsf (Figure 2; Tauxe et al., 2012; revised according to Bijl et al., in press). The uppermost 95 meters of the hole were poorly recovered; sediments consisted of unconsolidated mud strongly disturbed by rotary drilling (Escutia et al., 2011b). Hence, we focused our investigation on the interval between Cores 11R to 95R Section 3 (95.4 to 894 mbsf; 10.8-33.6 Ma; Figure 2).

### 2.2 Lithology in IODP Hole U1356A

In the ~~studied~~ interval between 95.4 and 894 mbsf, nine lithologic units have been recognized during shipboard analysis (Figure 2; et al., 2011b). Salabarnada et al. (submitted this volume) presents a detailed lithologic study of the Oligocene sediments. ~~For the~~ grouping of our results, we use the ~~lithologic~~ facies from Salabarnada et al. (submitted this volume), as outlined in Table 2. For the Miocene interval of Site U1356, such a detailed lithologic description is not yet available; therefore we treat the Miocene sediments as one ~~separate~~ lithologic unit in this

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paper. For the Miocene, we here give a brief summary of the observations published in the IODP Expedition 318 post-cruise report (Escutia et al., 2011b). Miocene sediments between 95 and 400 mbsf reflect increasing consolidation down-core, and comprise diatom ooze and diatom-rich silty clays. The more consolidated bedding has caused better preservation of original bedding structures. From 278.4 to 459.4 mbsf, the lithology lacks gravel-sized clasts, but is otherwise similar to up-core.

### 2.3 Bio-magnetostratigraphic age model for IODP Hole U1356A

Stratigraphic constraints for the Oligocene–Miocene succession from IODP Hole U1356A are provided through calcareous nannoplankton, radiolarian, diatom and sparse palynological biostratigraphy, complemented with magnetostratigraphy (Tauxe et al., 2012). Bijl et al. (in press) and Crampton et al. (2016) have updated the existing age model for Site U1356 for the Oligocene and Miocene part of the succession, respectively. Thereby, they recalibrated to the international time scale of Gradstein et al., 2012. We here follow these new insights of the age model (Table 1). We infer ages by linear interpolation between tie points (Figure 2; Table 1).

### 2.4 Depositional setting IODP Site U1356

The depositional setting of Site U1356 changed from a shallow mid-continental shelf in the early Eocene (Bijl et al., 2013a) to a deep continental rise setting in the Oligocene (Houben et al., 2013) due to subsidence of the Wilkes Land Margin (e.g., Close et al., 2009). Regional extrapolation of the lithology at U1356A via seismic profiles suggests a mix of distal-fan and hemipelagic sedimentation during the early Oligocene, grading into channel-levee deposits towards the later Oligocene

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(Escutia et al., 2011b). The boundary between these two different depositional settings occurs at ~650 mbsf; there, sedimentation rates increase, and the documentation of mass-transport deposits from this depth upwards suggest shelf-derived erosion events on the Wilkes Land continental slope (Escutia et al., 2011b).

## 3. Methods

### 3.1 Palynological sample processing

We refer to Bijl et al. (in press) for sample processing and analytical procedures used. Both were according to standard procedures (e.g., Bijl et al., 2013b). The 25 species of dinocysts new to science, which are formally (2 species) and informally (23 species) described in Bijl et al. (in press) fit into known and extant genera and therefore could be confidently included in the ecological groups as described below.

### 3.2 Ecological grouping of dinocyst taxa

Bijl et al. (in press) provided additional statistical evidence to distinguish *in situ* dinocysts from those that are reworked from older strata. In this paper, we follow the interpretations of Bijl et al. (in press) and divide the dinocyst species into a reworked and an *in situ* part (Table 3). To use the *in situ* dinocyst assemblages for oceanographic reconstructions, we rely on the observation that many taxa in the fossil assemblages have morphologically closely related modern counterparts. This approach takes advantage of studies on present-day relationships between Southern Ocean microplankton in general and dinoflagellates in particular and their surface-water characteristics (e.g., Eynaud et al., 1999; Esper and Zonneveld, 2002, 2007;

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Prebble et al., 2013). We assign Oligocene–Miocene dinocyst taxa to present-day eco-groups interpreted from the clusters identified by Prebble et al. (2013), which seem to be closely related to the oceanic frontal systems in the Southern Ocean (Figure 3). Supporting evidence for the ecologic affinities for the dinocyst groups comes from empirical data (Sluijs et al., 2005), for instance when it comes to the oceanic affinities of *Nematosphaeropsis labyrinthus*, *Operculodinium* spp., *Pyxidinopsis* spp., and *Impagidinium* spp. There is further abundant evidence, both empirically (e.g., Sluijs et al., 2003; Houben et al., 2013) and from modern observations (Zonneveld et al., 2013; Prebble et al., 2013; Eynaud et al., 1999), which link the abundance of protoperidinioid dinocysts to high surface-water primary productivity. The arguably most important inference from the surface-sample study of Prebble et al. (2013) is that *Selenopemphix antarctica* is common to dominant (10-90%) in proximal sea-ice settings south of the Antarctic polar front (AAPF). Notably, none of the surface samples outside of the AAPF have dominant *Selenopemphix antarctica* (Prebble et al., 2013). Another important observation is that the surface samples south of the AAPF are devoid of gonyaulacean dinocysts, with the exception of two species of *Impagidinium* (i.e., *I. pallidum* and *I. sphaericum*) which can occur, although neither abundantly (Prebble et al., 2013) nor exclusively (e.g., Zevenboom, 1995; Zonneveld et al., 2013), in ice-proximal locations. Another important observation is the occurrence of abundant *Nematosphaeropsis labyrinthus* exclusively in regions outside of the Subantarctic Front, and particularly close to the Subtropical Front. In summary, from proximal Antarctic to outside the frontal systems, Prebble et al. (2013) documents dominance of *S. antarctica* south of the AAPF, dominance of other protoperidinioid dinocysts at and N of the AAPF, mixed protoperidinioid and

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gonyaulacoid dinocysts (with a notable common occurrence of *Nematosphaeropsis labyrinthus* at the SAF and mixed gonyaulacoid dinocysts at and outside of the STF. These trends represents the transition from sea-ice influenced to cold upwelling/high nutrient to warm-temperate/lower nutrient conditions, respectively. We use the affinities obtained by Prebble et al. (2013) to reconstruct past oceanographic conditions at the Wilkes Land continental margin.

## 4. Results

### 4.1 Palynological groups

In our palynological analysis we separated palynomorph groups into four categories: *In situ* dinocysts, reworked dinocysts (following Bijl et al. (in press), Table 3), acritarchs and terrestrial palynomorphs. Our palynological slides further contain a varying amount of pyritized diatoms and a minor component of amorphous palynofacies, which is not further considered in this study. The relative abundance of the four palynomorph groups varies considerably throughout the record, as do their absolute abundances (Figure 4). Reworked dinocysts are present to common throughout the record, but are particularly abundant in the lowermost 40 meters of the Oligocene and in the Upper Oligocene. *In situ* dinocysts dominate the palynomorph assemblage during the mid-Oligocene and mid-Miocene. Chorate, spheromorph and *Cymatiosphaera*-type acritarchs (which are not further taxonomically subdivided in this study) dominate the assemblage during the late Oligocene and into the mid-Miocene, while terrestrial palynomorphs (which are considered *in situ* and not reworked from older strata (Strother et al., 2017)) are a constant minor component of the total palynomorph assemblage (Fig. 4).

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### 4.2 *In situ* dinocyst assemblages

Throughout the Oligocene, *in situ* dinocyst assemblages are dominated by protoperidinioid dinocysts, notably *Brigantedinium* spp., *Lejeunecysta* spp., *Malvinia escutiana,* and *Selenopemphix* spp. (Figure 4), all of which are considered associated with heterotrophic dinoflagellates. Among these protoperidinioid cysts, *S. antarctica* is common to abundant only in the first 1.5 million years of the Oligocene represented in the core material (33.6–32.1 Ma), and during and after the mid-Miocene climatic transition (<14.2 Ma; Fig. 5). The remainder of the record is generally devoid of *S. antarctica*. This is much in contrast to the dinocyst assemblages at Site U1356 today, which are dominated by this taxon (Prebble et al., 2013). Instead, other protoperidinioid dinocysts dominate, such as *Brigantedinium* spp., several *Lejeunecysta* species and *Selenopemphix nephroides*, which have close affinities to high-nutrient conditions in general (e.g., Harland et al., 1999; Zonneveld et al., 2013) but are not specifically restricted to sea-ice-proximity or the Southern Ocean. Today, these three genera dominate dinocyst assemblages in high-nutrient regions at or outside of the AAPF (Prebble et al., 2013). We also encountered a varying abundance of protoperidinioid dinocysts, which could not be placed with confidence into established protoperidinioid dinocyst genera. These are grouped under protoperidinioid spp. pars (Figure 4), and are here assumed to exhibit the same heterotrophic life-style as the other protoperidinioid dinocyst genera.

Next to peridinioid dinocysts, also gonyaulacoid dinocysts occur commonly to abundantly throughout the record from Site U1356. They comprise both known and previously unknown (Bijl et al., in press) species of *Batiacashaera, Pyxidinopsis,*

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*Nematosphaeropsis, Impagidinium,* and *Operculodinium* (Fig. 4; 5). Except for the extinct genus *Batiacasphaera,* all the other genera are still extant and are formed by phototrophic dinoflagellates. The abundance of these presumably mostly autotrophic taxa (Zonneveld et al., 2013) goes at the expense of the assumed heterotrophic protoperidinioid dinocysts. A remarkable increase is noted associated with the mid-Miocene Climate Optimum (between ~17 and 15 Ma; Fig. 4, 5; Sangiorgi et al., in review). Of these taxa, *Nematosphaeropsis* is thought to be associated with frontal systems of the present-day Southern Ocean (Prebble et al., 2013) and also in the North Atlantic Ocean (Boessenkool et al., 2001; Zonneveld et al., 2013).

### 4.5 Comparison between palynological data and lithological interpretations

The Oligocene sediments from Site U1356 comprise distinctive alternations of lithologic facies throughout the section (Salabarnada et al., submitted this volume; Figure 2). They are interpreted to reflect changes in the oceanographic regime, with relations to glacial-interglacial changes (Salabarnada et al., submitted this volume). Carbonate deposits, pelagic claystones and bioturbated, carbonate-bearing silty claystones were interpreted as interglacial deposits, while the laminated lithologies reflect glacial deposits (Salabarnada et al., submitted this volume). Mass-transport deposits reflect times of major sediment transport from the continental shelf. The lower Oligocene glauconitic sandstones were interpreted to reflect episodes of redeposition of winnowed upper Eocene shelf sediments (Sluijs et al., 2003; Houben, 2012). We here evaluate and compare the palynological content of each of these lithologies, both in terms of absolute and relative abundance of the main

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palynomorph groups: reworked dinocysts, *in situ* dinocysts, acritarchs and terrestrial palynomorphs and relative abundance of *in situ* dinocyst eco-groups.

### 4.5.1 Palynomorph groups and lithology

There are distinct differences in the relative and absolute abundances of palynomorph groups between the different lithologies (Figure 6). The highest relative and absolute abundances of reworked dinocysts occur in the lower Oligocene reworked glauconitic sandstones, which is in line with previous inferences of Houben et al. (2013). The mass-transport deposits contain abundant reworked dinocysts. The relative and absolute abundance of *in-situ* dinocysts does not vary much between the different lithologies, with the exception of the pelagic clays, in which *in situ* dinocysts are much lower in relative and absolute abundance (Figure 6). The opposite pattern emerges for acritarchs, which reach highest relative and absolute abundances in the pelagic clays (Figure 6). Terrestrial palynomorphs are most abundant in the glauconitic contorted sandstones (Figure 6).

### 4.5.2 *In situ* dinocyst eco-groups and lithology

We also compared the *in situ* dinocyst eco-groups with predominant lithological facies (Figure 7). The abundance of *Selenopemphix antarctica* is low throughout the record (0-5%), with the exception of the interval post-dating the Miocene Climatic Optimum (MCO) interval and the lowermost Oligocene. We note that in the lower Oligocene, high abundances of *S. antarctica* and *Malvinia escutiana* are mostly connected to glauconitic sandstones and the mass-transport deposits, and rarely occur in the other lithologies (Figure 7). We however think that these species

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represent part of the *in situ* assemblage in an otherwise dominantly reworked dinocyst assemblage, because these were never found in Eocene sediment in the region before. *Lejeunecysta* spp. shows significantly higher relative abundances in the mass-transport and glacial deposits, and substantially lower abundance in the pelagic clays, interglacial deposits and in the Miocene. *Brigantedinium* spp. shows invariable relative abundances in the different lithologies, and the *Protoperidinium* spp. pars group shows highest abundance in the pelagic clays (Figure 7). Overall, the relative abundances of all (proto)peridinioid dinocysts in the *in situ* assemblage is highest in the glacial deposits and pelagic clays, and substantially lower in interglacial deposits and in the Miocene. Indeed, several gonyaulacoid dinocyst taxa (such as *Nematosphaeropsis* spp., *Pyxidinopsis* cpx, *Operculodinium* spp., and *Impagidinium* spp.) show higher relative abundances in interglacial than in glacial deposits. We thus observe a marked difference in the relative abundances of gonyaulacoid dinocysts over peridinioid dinocysts between glacial and interglacial deposits.

## 5. Discussion

### 5.1 Paleoceanographic interpretation of the dinocyst assemblages

#### 5.1.1 Surface-ocean nutrient conditions

The dominance of heterotrophic dinoflagellate cysts in the Oligocene-Miocene dinocyst assemblages indicate overall high nutrient levels in the surface waters. We infer therefore that in general, surface-waters overlying Site U1356 experienced upwelling associated to the AAPF during most of the Oligocene and Miocene. However, and surprisingly, the occasionally abundant oligotrophic cyst taxa encountered in our record suggest that at times, surface waters were much less

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nutrient-rich, supporting an oligotrophic dinoflagellate assemblage. These dinocysts are outer shelf to oceanic or outer neritic taxa (e.g., Sluijs et al., 2005; Zonneveld et al., 2013; Prebble et al., 2013), which makes it unlikely they were reworked from the continental shelf. Indeed, these taxa show low relative abundances in the mass-transport deposits (Figure 6); hence, we interpret that these taxa are part of the *in situ* pelagic assemblage and reflect warming of surface waters rather than them being reworked. Although species within these genera have relatively long stratigraphic ranges extending back into the Eocene, most of the species encountered at U1356 have never been found in Eocene continental shelf sediments in the region (e.g., Bijl et al., 2011; 2013a, b; Brinkhuis et al., 2003a, b; Levy and Harwood, 2000; Wrenn and Hart, 1988). This lends further support against them being reworked from Eocene shelf material, in addition, the statistical approach also interprets these species to be part of the *in situ* assemblage (Bijl et al., in press). Now that we have abundant evidence that these autotrophic taxa are part of the *in situ* pelagic assemblage, we can interpret these assemblages in terms of their paleoceanographic affinities. The occasional abundance of oligotrophic taxa suggests nutrient levels must have been low compared to the same region today. The absence of these taxa in modern surface waters south of the AAPF is probably caused by a combination of factors: low sea surface temperatures, isolation by strong eastward currents, but also the abundance and seasonal concentration of nutrients, which make the Antarctic proximal surface waters a very specialistic niche. Apparently, surface water conditions during the Oligocene and Miocene were such that these oligotrophic species could at times proliferate so close to the Antarctic margin.

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### 5.1.2 sea-surface temperature

The average dinocyst assemblages in our record point to the Southern margin of New Zealand and Tasmania as the best modern analogue (inferred from Prebble et al., 2013; Figure 2). Those regions today feature a mix between protoperidinioid dinocysts and gonyaulacoid dinocyst genera such as *Nematosphaeropsis*, *Operculodinium* and *Impagidinium*. These assemblages occur at present in surface-waters with mean annual temperatures of 8-17°C (Prebble et al., 2013). A bayesian approach on the $TEX_{86}$ index values at U1356 (presented in Sangiorgi et al., submitted; Hartman et al., submitted this volume) indicates exactly the same region as modern analogues for the $TEX_{86}$ index values found (Hartman et al., submitted this volume) as for the dinocysts (Prebble et al., 2013); both approaches indicate the same paleotemperature range for the Oligocene-Miocene at U1356. These two proxies thus independently point to a temperate, much warmer paleoceanographic regime close to Antarctica during the Oligocene and Miocene with the nearest modern analogue being offshore Southern New Zealand and Tasmania. Supporting evidence for temperate Oligocene-Miocene surface waters comes from the abundance of nannofossils encountered in the same Oligocene-Miocene sediments (Escutia et al., 2011b). Today, carbonate-producing plankton is not abundant in high-latitude surface waters south of the AAPF (Eynaud et al., 1999). Moreover, the remains of the few carbonate-producing organisms living at high latitudes rarely reach the ocean floor because strong upwelling of relatively $CO_2$-rich, corrosive waters (e.g., Olbers et al., 2004). Hence, the presence of carbonate-rich intervals during the Oligocene-Miocene at Site U1356, along with the encountered oligotrophic, temperate dinocysts, suggests fundamentally warmer surface-water conditions than at present.

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5.1.3 Paleoceanography

The strong similarity of Oligocene–Miocene dinocyst assemblages at Site U1356 to those today occurring much further north (e.g., around Tasmania and Southern New Zealand (Prebble et al., 2013) suggests a fundamentally different *modus operandi* of Southern Ocean oceanography. The strict latitudinal separation of dinocyst assemblages throughout the Southern Ocean today (Prebble et al., 2013) is likely due to the different water masses present across the oceanic fronts where strong wind-driven divergence around 60° S (known as the Antarctic Divergence; e.g., Olbers et al., 2004), strong sea-ice season and/or the vigorous Antarctic Circumpolar Current are in place. The strength and position of the AAPF during the Oligocene–Miocene is not well understood. GCM experiments under Miocene boundary conditions suggest that west and east wind drifts prevailed south and north of 60°S, respectively (Herold et al., 2011). This position of the winds determines the average position of the Antarctic Divergence at 60°S during the Oligocene and Miocene, like today. This would mean that Site U1356 likely was directly overlain by the AAPF. However, the significantly warmer, more oligotrophic character of the dinocyst assemblages offshore Wilkes Land throughout the Oligocene–Miocene argues against a close position to the AAPF. The position of the AAPF relative to the position of Site U1356 strongly determines the likelihood of southward transport of low-latitude waters towards the site. A southward position of the AAPF relative to Site U1356 would greatly enhance the possibility for southward migration of temperate water masses towards the site. A northward position of the AAPF relative to the site, would make such much more difficult. The presence of carbonate in these deep marine

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sediments also suggests that upwelling of corrosive waters through the (proto-) Antarctic Divergence was either much reduced or located elsewhere. Therefore, we deduce that the occurrence of the oligotrophic, temperate dinocysts is evidence for a southward position of the AAPF relative to the position of Site U1356.

The separate averaging of dinocyst assemblages for glacial and interglacial deposits (Figure 7) allows us to reconstruct the glacial-interglacial surface oceanographic changes throughout the Oligocene. This approach suggests that substantial paleoceanographic dynamics were associated with Oligocene glacial-interglacial cycles. Alongside the 2–3 °C SST variability during glacial-interglacial cycles at this same site (Hartman et al., submitted this volume), dinocyst assemblages contain more oligotrophic, temperate dinocysts during interglacial time intervals compared to glacial intervals when more eutrophic, colder dinocysts proliferated. This could be the result of a slight latitudinal movement of oceanic frontal systems (notably the AAPF), as has been reconstructed for the Southern Ocean fronts during the most recent glacial to interglacial transition (e.g., Kohfeld, et al. 2013). The difference in dinocyst assemblages between glacial and interglacial deposits might be explained by a south position of the AAPF during interglacials, allowing for temperate oligotrophic surface waters to reach the Site, while during glacials the AAPF migrated northward over Site U1356, causing cold, high-nutrient conditions.

### 5.2 Implications for Oligocene-Miocene ocean circulation

Only in the lowermost Oligocene and in strata representing the mid-Miocene climatic transition and later (14.4 Ma and younger) the dinocyst assemblages bear similarities to modern proximal-Antarctic assemblages (Prebble et al., 2013), with

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high abundances of *Selenopemphix antarctica*. Even in those intervals, however, the relative abundances of *S. antarctica* does not reach present-day values at the same site. The absence of a strong shift towards modern-day-like assemblages in our record can be interpreted to reflect a weaker-than-present ACC, in line with numerical models (Herold et al., 2012; Hill et al., 2013). The ACC itself represents an important barrier for latitudinal surface-water transport towards the Antarctic margin, in addition to the Antarctic Divergence (Olbers et al., 2004). Our data suggest an increase in the influence of oligotrophic dinocysts at the Antarctic margin during the late Oligocene and during the MMCO, which argues against the installation of a vigorous ACC at 30 Ma (Scher et al., 2015): No profound changes in surface paleoceanography emerge from our dinoflagellate cyst data around 30 Ma, and there is no major change in the benthic $\delta^{18}O$ (Figure 5). Instead, if the Tasmanian Gateway had opened to an extent that allowed ACC development (Scher et al., 2015), the ACC must have been much weaker than at present throughout the Oligocene and Miocene. The strongly different dinocyst assemblages compared to present-day at Site U1356 throughout our record implies to us that a strong coherent ACC was not installed until after the MMCT (11 Ma). This is consistent with inferences from the lithology at the same site (Salabarnada et al., submitted this volume), suggesting a proto-ACC much weaker than at present and, likewise, weaker Southern Ocean frontal systems. An alternative explanation is, that the ACC increased in strength during the Oligocene–Miocene, but that this strengthening had no influence on the dinocyst assemblages at Site U1356. However, the vigorous nature of the ACC influencing surface as well as bottom waters and governing eddy water circulation in the Southern Ocean (Olbers et al., 2004) makes such a scenario very unlikely. Nevertheless, to firmly clarify whether

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the strength of the ACC changed to its present-day force only after the MMCT (as suggested by our data), ocean-circulation modelling of time slices younger than the Oligocene will be required.

### 5.3 Implications for ice sheet and sea-ice variability

The abundance of our sea-ice indicator *Selenopemphix antarctica* throughout the record is consistently lower than that in present-day dinocyst assemblages at Site U1356 (Prebble et al., 2013; Figure 3). This suggests that sea-ice conditions were never as severe as today throughout the studied time interval. Only during two time intervals sea-ice indicators suggest some sea ice near the Site: the first 1.5 million years following the Oi-1 glaciation (33.6–32.1 Ma; Figure 5), and during and after the mid-Miocene climatic Transition (14–11 Ma; Figure 5). Numerical ice-sheet/sea-ice modelling (DeConto et al., 2007) suggests sea-ice to develop only if the continental ice sheets reach the coastline. Our lack of sea-ice indicators during most of the Oligocene and Miocene could thus suggest that the Antarctic continental ice sheet was much reduced during this time. The finding of a weaker sea-ice season throughout most of the Oligocene–Miocene at Site U1356 has major implications for regional paleoceanography because it suggests a decrease in the potential formation of Antarctic bottom waters at this site.

The abundance of our oligotrophic taxa broadly co-varied with long-term Oligocene-Miocene benthic $\delta^{18}O$: During times of low $\delta^{18}O$ values in deep-sea benthic foraminifera (and thus high deep-sea temperatures and less ice volume; e.g., at 32 Ma, 24 Ma and 15 Ma; Figure 5), the abundance of oligotrophic temperate dinocysts was large (Figure 5). At times of higher $\delta^{18}O$ values, lower deep-sea temperatures and

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higher ice volume (e.g. at 33.5 Ma, 27 Ma, 23 Ma and 13 Ma; Figure 5) temperate dinocysts were reduced in abundance and high-nutrient, sea-ice indicators (re)appeared. Altogether, this suggests on long time scales, that there was stronger influence of warm surface waters at the Wilkes Land Margin at times when ice sheets were smaller and climate was warmer, and less influence of warm surface waters during times of larger ice sheets, hence a connection between ice sheet and oceanographic variability.

Oxygen-isotope mass-balance calculations suggest that a modern-day-sized Antarctic ice sheet appeared at the Eocene/Oligocene boundary (DeConto et al., 2008). Benthic $\delta^{18}O$ records suggest that ice sheets fluctuated considerably in size during the subsequent Oligocene and Miocene (Liebrand et al., 2017). Based on the heavy $\delta^{18}O$ values for Oligocene benthic foraminifera from Maud Rise, it was inferred that Antarctic ice sheets were near-present-day size throughout the Oligocene (Hauptvogel et al., 2017). Both isotope studies of Liebrand et al (2017) and Hauptvogel et al. (2017) assume constant temperatures of the deep sea and similar-to-present-day $\delta^{18}O$ of the continental ice. Our data instead show that the regional paleoceanography, together with surface-ocean temperature (Hartman et al., submitted this volume), can vary considerably both on the long term as on orbital time scales. It remains to be seen whether the variability in paleoceanography found here can be extrapolated to larger parts of the Antarctic margin, including to those regions of deep-water formation. Given the high temperatures and absence of strong sea ice influence, the Wilkes Land margin was likely not the primary sector of deep-water formation, although there is ample evidence for bottom-current activity at the site (Salabarnada et al., submitted this volume). However, if the oceanographic and

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climate variability we reconstruct offshore Wilkes Land characterises also regions of deep-water formation, some (if not much) of the variability both on long and off orbital time scales in benthic $\delta^{18}O$ records is related to deep-sea temperature rather than Antarctic ice volume (see also Hartman et al., submitted this volume). Meanwhile, we find little support in our study for the large continental ice sheets during the Oligocene as concluded by Hauptvogel et al. (2017), given the absence of dominance of sea-ice dinoflagellate cysts and *in situ* terrestrial palynomorphs (Strother et al., 2017). As an alternative explanation to the difference in $\delta^{18}O$ values between Maud Rise and Equatorial Pacific during the Oligocene (Hauptvogel et al., 2017), we suggest that these two records have recorded the characteristics of two fundamentally different deep water masses, with those at Maud Rise being much colder and saltier than those at Shatsky Rise.

## 6. Conclusions

The dinocyst assemblage changes in the Oligocene–Miocene (33.6–10 Ma) of Site U1356 were interpreted in terms of surface paleoceanography based on a comparison of these assemblages to present-day dinocyst assemblages. This approach allows us to hypothesize that the Southern Ocean paleoceanography during the Oligocene–Miocene was fundamentally different from that of today. A strong sea-ice signal (yet still weaker than that of today) emerges for the Wilkes Land Margin only for the first 1.5 million years of the Oligocene (33.6–32.1 Ma) and the mid-Miocene climatic transition (14-10 Ma). The remainder of the Oligocene–Miocene record of surface waters off Wilkes Land were warm, relatively oligotrophic and lack indications of a prominent sea-ice season. Upwelling at the Antarctic Divergence must have been profoundly weaker during Oligocene and Miocene times, compared to today. Furthermore, the continental ice sheet must have been much reduced at the Wilkes Land sub-glacial basin for most of the Oligocene-Miocene compared to today, and continental ice sheets were retreated inland. The strength of the influence of warm oligotrophic surface water was strongly coupled to deep-sea $\delta^{18}O$ values: With enhanced low-latitude influence of surface water during times of light $\delta^{18}O$ in the deep sea and *vice versa*. The absence of (a trend towards more) oceanographic isolation of the Wilkes Land margin throughout the Oligocene to mid-Miocene suggests that the ACC did not obtain its full, present-day strength until at least the mid-Miocene Climatic transition. Moreover, we note considerable glacial-interglacial variability in this oceanographic setting, with stronger influence of oligotrophic, low-latitude surface waters over Site U1356 during interglacial times and more eutrophic, colder influence during glacial times. This may suggest considerable latitudinal migration of the AAPF over Oligocene and Miocene glacial-interglacial cycles.

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