Response to Reviewer 1, Kasia Śliwinska, by Bijl et al.

GENERAL COMMENTS At the beginning, I would like to apologize for the delay in delivering my review. It was great to get an opportunity to comment on this paper. For some time now, I have been working on the Oligocene from the North Atlantic region. Even though our study areas are so far from each other, one cannot fully understand the paleoclimatic changes in the high northern latitudes and the global ocean circulation under the early icehouse world, without an insight into the oceanic regime in the southern high latitudes. This paper provides an important and unique record of the paleogeographical reconstruction of the Oligocene to middle Miocene of the East Antarctica based on dinoflagellate cysts. Authors apply selected dinocysts genera and taxons as proxies for sea-ice reconstruction, nutrients, and temperature. The changes in the composition of dinocysts assemblages is additionally correlated with the sedimentology and organic biomarker data. I find this manuscript interesting and very needed piece of work for our understanding of the oceanic circulation under the early icehouse world conditions. A concern however, is the way the sedimentological data are incorporated into the text. The results of the present study (i.e. changes in the dinocysts assemblages) need to be clearly presented, and other data (sedimentology, biomarkers) should be carefully included but only as a data supporting the results based on dinocysts. The part about the lithology should not be included in the section with the results but as e.g. the background information. Also, a term “Miocene deposits” (Table 2) doesn’t not carry any sedimentological information. Why do the authors not keep the terminology by Salabarnada et al. (submitted this volume) in this case? This expression is not used in the main text, but “Miocene sediments”. The manuscript is well written, however, there is still room for improvement (see my suggestions below). Overall, the manuscript represents a substantial contribution to the scientific progress within the scope of Climate of the Past. I am certain that it will be of great interest for readers of the journal.

We appreciate the positive assessments by Śliwińska regarding our manuscript, and her indications as to how to improve our manuscript even further. Śliwińska posed several concerns and suggestions, which we can definitely use to improve our manuscript. We herein respond to these concerns and suggestions in detail.

SPECIFIC COMMENTS In the Supplementary material, in the sheet with the dinocysts counts I see only Selenopemphix cf. antarctica. Is that a typo or the specimen observed in the present study only partially resemble the holotype? If it different, then I think that this needs a bit of attention in the text.
This is indeed a typo, it does fall within the species definition of the holotype. We will amend this in our next version of the paper.

Bijl et al. (in press) have already discussed which dinocysts are in situ and which not, so I think that the first section of the discussion can be tightened up a bit.
The first section of our discussion aims at providing the necessary details to put forward new arguments than those proposed in Bijl et al., in press (now Bijl et al., 2018) to strengthen and support the reason why we believe that the gonyaulacoid dinocysts are *in situ*. Therefore we do not find this redundant but rather complimentary to the results of Bijl et al., 2018, as indicated in lines 366-368. This paper targets a different audience than that of Journal of Micropaleontology, an audience that does not necessarily want to read detailed micropaleontological contemplations, but is merely interested in the paleoceanographic reconstructions. Such reconstructions are based on detailed micropaleontological information that is now published in Bijl et al., 2018, should the reader be interested. Journal of Micropalaeontology is an open access journal, hence available to everyone. Because of the above, we opt for maintaining the first section of the manuscript as

is.

Also, since dinocysts play a key role in this study, I would consider to include a plate with photos of the most important taxa.
Bijl et al. (2018, Journal of Micropalaeontology) also features a large number of dinocyst plates, and the publication is open access. This paper however is targeted to present the paleoceanographic reconstructions, using the dinocysts as a tool rather than the purpose of the study. With that aim in mind, and anticipating on the audience expected, we decided that plates are irrelevant in this paper. However, we added reference to the plates as published in Bijl et al. 2018 in the methods section (3.1)

Terrestrial palynomorphs can include everything from saccate-pollen to spores or fungal hyphae, and thus suggests e.g. a different depositional setting for the site. Therefore, I think that it may be a bit risky to put them into one category without mentioning any details. One way to fix this is to give appropriate overheads in the "dinocysts counts" spreadsheet in the supplementary excel file (i.e. in situ dinocysts, reworked dinocysts, terrestrial palynomorphs, etc.) and refer to this file in the main text.
An extensive presentation of the terrestrial palynology and the vegetation and climate reconstructions derived from it, is out of the scope of this paper, and will be presented elsewhere at a later stage. For the purposes of our paper, we portray the total terrestrial organic component in our samples as a crude and qualitative proxy for terrestrial input. Since details of terrestrial palynomorphs are meant to be presented in another study, we only recorded broad categories of terrestrial palynomorphs in our counts, which we present in the figure and in the supplementary tables.

The strong upwelling occurring today around Antarctica is causing low abundances of carbonates at the sea-floor. How does the upwelling (suggested in line 363) support the presence of carbonate rich intervals during the Oligocene and Miocene (e.g. line 401)? I think that this needs to be explained a bit more clearly.
This is explained around lines 429-433, where the oceanographic reconstructions are discussed.

TECHNICAL CORRECTIONS Within the entire text "Margin" with a capital letter in "the Wilkes Land Margin". Please correct where needed.
We will change 'Margin' to lower case throughout

It needs to be clearly stated when the authors talk about "dinoflagellates" and when about "dinoflagellate cysts (dinocysts)". "sea-ice" or "sea ice", please choose only one version
We will check throughout for consistency

Please define: "common" or "abundant"
We will rephrase throughout and specify to avoid ambiguity.

Abstract: Please avoid repetitions: "time intervals" line 25,27,44 **Done** Lines 25-29: "may bear information to resolve"? **Rephrased** please rephrase the two sentences. Lines 37-38: Consider rephrasing to "Our record shows that a sea-ice indicator, Selenopemphix antarctica, occurs only in the earliest Oligocene, following the full Antarctic continental glaciation, and after the Middle Miocene Climatic Optimum". **Done** Line 39: "during the remainder of the : : :" – please rephrase Line 39: perhaps it is better to write: "the composition of the dinocyst assemblages imply" **Rephrased**

Section 1: Line 51: please rephrase: ": : :much more ice is: : :" **Rephrased** Lines 72-84:

perhaps these two very long sentences could be made into few shorter ones. **Sentences were shortened** Lines 95-96: marine-ice? I think that “sea-ice” sounds better **We talk about marine-based ice and not sea ice in those lines, which have a rather different meaning.** Line 96: does it mean “a continent with a low topography”? If yes, then please rephrase “a lower Antarctic” **Done** Line 115: please rephrase “: : :establishment of age control: : :” **Rephrased** Line 125: perhaps “recently” instead of “accurately” **Rephrased** Line 127-128: this sentence is poorly constructed **Rephrased** Line 133-134: it sounds a bit weird to compare with “detailed sedimentological descriptions”, I think that it should rather be written that the authors “correlate changes in the dinocyst as- semblages with the changes in the lithology” or something like that. **Rephrased** Line 135-139: this sentence is missing something. Please rephrase. **Rephrased**

Section 2: Keep this section in the passive voice. **We used passive voice more than in the previous manuscript, but not in every case to avoid a too passive tone, which to our opinion does not read well.** Line 149: “upper Miocene” not “late Miocene” **Rephrased** Line 165-170: this sentence is poorly constructed. It is not correct to write that “the lithology lacks” something **Rephrased** Line 166-170: diatom ooze and diatom-rich clay: which one is a turbidite and or hemipelagite (see Table 2)? **We agree that our initial analyses lacked a detailed description of the Miocene facies. In the new version of the manuscript we will add the detailed Miocene lithology to the Oligocene one. We have already made this amendment in anticipation of this rebubuttal and noticed, however, that this does not affect our conclusions and drawn earlier.** Line 178-179: this sentence is poorly constructed **Rephrased**

Section 3: Line 196-197. Avoid active voice. **Avoided in most cases.** Please rephrase both sentences. For me it sounds a bit weird to say “surface sample”. What about “a sample from the sea surface” instead? **We agree with the comment and will rephrase surface-samples to surface-sediment samples.** “Another important information” is used in line 227 and 231. Consider rephrasing to avoid repetition. **Rephrased** Line 235-236: What does “N” mean? I think it is better to write “north”. **Done** Please rephrase the sentence to make it more clear. Please explain all the abbreviations used in the text for the first time, e.g. GCM, STF and SAF. **Checked and done**

Section 4.1: Please describe the individual groups in the same order as they are mentioned at the beginning of the paragraph. **We will change the order.** Line 249-250: “amorphous organic matter (particles)” instead of “amorphous palynofacies”. **Done** Line 252: it should be “rare to common” not “present to common”. **Rephrased** In this section it should also be explain how authors define: “rare, “common” and “abundant”. **Rephased to avoid ambiguity** Line 257: one can not write “dominate the assemblage during the late Oligocene”. It should be either “are the dominating group in the assemblages from the upper Oligocene” or “were dominating/most abundant during the late Oligocene”. **Rephrased**

Section 4.2: Line 266: if it is not an observation made by the authors, I would suggest to add a reference here. **Done** Line 267-269: I suggest to rephrase the sentence: “is common to abundant between 33.6 to 32.1 Ma (earliest Oligocene) and after 14.2 Ma (i.e. during and after the mid-Miocene climatic transition)” **Done** Line 270: please remove “generally”. **Done** Line 270-281: please consider to rephrase this part, so it will be clear what was the assemblage composition in the Oligocene-Miocene and what is today. **Rephrased** Line 289: please remove “noted” **Done** Line 291: Instead of “Of these taxa” it should be “ Of the gonyaulacoid taxa” and add “spp.” after Nematosphaeropsis. **Changed to *N. labyrinthus*.** Line 294: it should be Section 4.3 not 4.5. Please correct in the following headings accordingly, i.e. 4.3.1 and 4.3.2. **Done** Lines 296-306: I am not certain if the part describing the lithology fits in the result section. This is not a result of the current study, but rather a summary of the (already interpreted) lithological observations by

Salabarnada et al. However, I see that this is an important part for the manuscript, I suggest to keep it, but incorporate it into the earlier part of the manuscript. **Indeed, lithological details can be avoided and we now refer to Salabarnada et al., for details.** Section 4.5.1: Line 314: perhaps it should be: ": : :occur in the reworked glauconitic sandstones of the lower Oligocene age."? **Done** Line 315: Keep sentences short: ": : :sandstones. This is in line: : :" **Done** Line 316: Great, that what one can expect! Section 4.5.2 Please, avoid expressions as "we compare", "we note", etc. Please change it into the passive voice. **Done** Lines 327-328: repetition of "interval" **Rephrased** Line 330: "restricted to" or "limited to" instead of "connected to" **Rephrased** Line 333: "in the Eocene sediments" **done**
Line 334-336: I suggest to rewrite like this: "Within the Oligocene strata Lejeunecysta spp. (: : :) lower abundance in the interglacial deposits and pelagic clays. The taxon is also less abundant in the Miocene." **Rephrased**

Section 5. Discussion Line 353: why upwelling? Is that the only possibility? **We believe that, given the geographic setting, upwelling is the only possibility. We now indicate that more clearly in the text** Lines 354- 356: circular argumentation, that abundant oligotrophic cyst taxa support oligotrophic dinoflagellate assemblage **Rephrased to avoid circular argumentation** Line 357: which taxa? It may be a good idea to list them here as a reminder for readers **We really want the reader to focus on the paleoceanographic inferences. As we have elaborately described the species in the results section, we do not repeat the species names here.** Line 359-362: "we interpret that these taxa are part of the in situ pelagic assemblage and reflect warming of surface waters rather than them being reworked" – I think that this needs rephrasing. **Done** What is more, which taxa are considered as indicators of warming? Is this based on the present study or the literature? If on the literature, then please provide proper references here. **Done** Line 366-367: this sentence is poorly constructed **Rephrased** Lines 368-369: active voice should be avoided here **Avoided** Lines 370-372: grammatically something is missing in this sentence. **Rephrased** Line 381: what does "the average assemblage" means? **Rephrased** Lines 387, 391: add "Site" before U1356 **Done** Line 391: please add "succession at Site U1356". **Done** Lines 393-394: repetition of lines 381-382 **Repetition avoided** Line 365-396: it sounds weird to compare "Oligocene-Miocene surface waters" with "the same Oligocene-Miocene sediments". Please consider rewriting **Agreed. Rephrased** Line 407: "i.e." instead of "e.g." **Done** Line 420: "more oligotrophic character of the dinocyst assemblages" – please rephrase **Rephrased** Line 430: "an evidence" **Done** Lines 449-450: this sentence is poorly constructed **Rephrased** Line 451: modern dinocysts assemblages? **Rephrased** Line 455: ": : :ACC. This is in line with numerical: : :" **Done** Line 460: please explain what does abbreviation MMCO means, perhaps even earlier in the text **Spelled out** Line 465: consider different order, like: "weaker throughout the Oligocene and the Miocene, than at present" **Done** Line 467: please remove "to us" **Done** Line 476: please explain what does abbreviation MMCT means, perhaps earlier in the text **Done** Line 533: "records have recorded"- please rephrase **Done**

Section 6 Avoid repeating "fundamentally different" so close to each other (Lines 534 and 542), or "that of today" (line 542 and 543), "compared to today" (lines 548, 550) **Done** Lines 545-547: please consider rephrasing this sentence. **Done** Line 608: it should be "data compiled from Site" **Rephrased** Line 611: please use passive voice **Done** Line 613: perhaps it should be "or calibrating our data against age-scale" **Rephrased** Line 622: "sandstones" – please correct in the entire text **Done**

Figure captions and references:
"Bijl et al. in press" not in the reference list "Salabarnada et al. submitted this volume" not in the reference list. **We added these references**

Fig. 2 – Why does the colour lines reflecting various lithology have different length? **This was done to improve clarity** What does (o) and (y) mean? **Now explained in the caption** Please align overheads "Miocene" and "Oligocene". **Done** Please explain what the grey colour in the palmag column implies. **Now explained in the caption**"(from Tauxe et al.,2012, but recalibrated to GTS2012 of Gradstein et al., 2012; see Table 1 and modified based on Crampton et al., 2016)" - this sentence is poorly constructed **Rephrased**
Fig. 4 and 5 – what is determining the order of the dinocysts? Shouldn't Spiniferites cpx be moved to the right? **Agreed, done** And actually, is Spiniferites cpx needed on the figure if it is not even mentioned in the main text? **Yes it is, as it is one of the most common dinocyst genera in many places.** The same with Corrudinium, Cerebrocysta – these are not mentioned in the text. If they are merged in a complex with Pyxidinopsis spp. then please clearly state it in the text or supplementary. **Now mentioned in the text.**
Fig. 4 – I think that it is necessary to mark the position of unconformities in e.g. the column with "epoch and stage". Otherwise, Chattian followed immediately by Burdigalian looks a bit odd. **Done** The intervals which look like barren in the column with " Total palynomorphs/ dinocysts", are not marked as such in the following plots in the figure, therefore the figure looks a bit chaotic. **Many barren samples are positioned close to productive samples. The plot is meant to provide the reader with a comprehensive image of the palynological assemblages, similarly to the way they were presented and discussed in the text.** The overheads for "total palynomorphs/dinocysts" and "Palynomorph relative abundance" should be aligned with the overheads to the right (i.e. dinocysts taxa and genera). **Done** Also, I would suggest to add a column with sample position on this and the following figure. **The sample intervals are already plotted in Figure 2. We believe that this information is no longer needed when interpreting the data in figures 4 and 5.** Are all other dinocysts recorded in the assemblages "oligotrophic/outside oceanic fronts" as suggested by the color/filling in the plot? **We clarified this in the results section in the text.** It is not clear to me why "oligotrophic/outside oceanic fronts" has two colors (red and dotted orange). **We choose to give *Operculodinium* spp. another color because it is such a well-known and paleoceanographically significant genus both in this region and in the northern hemisphere.** Why are absolute abundances not shown in the same way as the relative abundances? **Absolute abundances of the different dinocyst groups are not mentioned or discussed in the text, nor they do have a readily interpretable paleoceanographic signal.**
Fig. 5 – While in Fig.2 Oligocene and Miocene are divided into "late", "middle" and "early" , on figs 4 and 5 they are divided into stages. Adding a subdivision of the Oligocene and Miocene into "late", "middle" and "early" on figures 4 and 5 will help readers to directly correlate it with figure 2. **Agreed. Done** This may be a good place to mark a position of the climatic events mentioned in the main text, such as the Oi-1 glaciation and MMCO. **Agreed. Done** Please add that the figure shows the distribution of the "in situ dinocyst", like in figure 4. **Done in the caption**
Fig. 6-7: According to table 2 "Miocene deposits" consist partially of turbidites. Isn't that a bit odd that turbidite deposits yield so many in situ dinocysts? **We agree and thought about this. Possibly, turbidites in the Miocene transport very young sediments from the shelf. This causes reworking in these turbidites to be overlooked as there is no age gap between the species encountered in the turbidites from those encountered in the pelagic sediments. We will add this to the main text of the paper, and in any case we now separate turbidite deposits from pelagic sediments.** However, Fig.7 – I would write something like that: "The distribution of eco-groups within various lithologies encountered in Site: : :" in the figure caption. **Done**

With my best regards

Kasia K. Sliwinska

Please also note the supplement to this comment:
https://www.clim-past-discuss.net/cp-2017-148/cp-2017-148-RC1-supplement.pdf

Rebuttal to Anonymous Referee #2 by Bijl et al.

This paper presents environmental interpretations of a new dinoflagellate cyst dataset from Oligocene and Miocene sediments from a drill core collected off the Wilkes Land coast. The environmental interpretations are partly underpinned by published studies on the distribution of dinoflagellate cysts in modern sea floor sediments. In particular, assemblages are identified that are interpreted to correlate with sea ice. The authors use these assemblages to conclude that sea ice was more prevelant during the earliest Miocene [**We assume R2 means Oligocene here**], and also following the Middle Miocene Climatic Optimum. They also observe that assemblages representative of interglacial conditions are similar to assemblages of modern temperate oligotrophic waters, and thus infer that this reflects a migration of the polar frontal system to the south of the drill site. This is an interesting paper, and the dataset is important. It will be of interest to the research community.
I have four main comments on the approach used and the conclusions drawn
(1) The authors note that in modern settings, Selenopemphix antarctica is dominant in 'proximal sea ice settings south of the Antarctic Polar Front' (but also that these modern samples from Antarctic waters have a range of 10-90% S. antarctica). The authors then infer that the intervals in the Wilkes Land core containing the highest relative abundance of S. antarctica represent depositional environments proximal to sea ice. However, S. antarctica is never above _15% in any of the samples reported in this study (Figure 7): this taxon is not dominant. **[Fig. 7 only reports the mean and 1sd of the data. The maximum abundance of *S. antarctica* is 39%. We will make the raw data available in a revised version]** For context, samples with concentrations of up to 20% S. antarctica occur in modern Southern Ocean samples as far north as the Subtropical Front (e.g. Zonneveld et al. 2013, doi.org/10.1016/j.revpalbo.2012.08.003). Even if high abundance (>80%) of S. antarctica were indicative of sea ice (which is itself not clearly demonstrated, partly given the poor modern correlation between the polar front and sea ice extent, and partly due to the very sparse coverage of modern samples south of the polar front), that high abundance is not the case in the samples reported in this paper. The modern analogue approach used by the authors to infer the presence of sea ice is inconclusive in this instance: the data presented could be just as easily used to infer a complete lack of sea ice for the duration of the record, as sea ice variability. **We agree with the reviewer that the complete compilation by Prebble et al. (2013) leaves ambiguity about the reliability of *S. antarctica* as sea ice indicator, and that the absence of this species should be taken as absence of sea. Sites south of the subtropical front with lower abundances of *S. antarctica* are all close to the polar front itself, and are in regions with lower palaeobathymetry (e.g., Kerguelen and in the South Atlantic). This causes highly variable distribution patterns around such bathymetric highs (see, e.g., Armand et al., 2008). Meanwhile, on the Antarctic continental shelf proper, where admittedly few published data is available in the Prebble et al. (2013) compilation, *Selenopemphix antarctica* does dominate the palynomorph assemblages in all sites available. The dominance of *S. antarctica* in assemblages can be found in the Wilkes Land margin itself (Site U1357; Hartman et al., in prep-a), in the Ross Sea (Hartman et al., in prep-b), Prydz Bay (Storkey, 2006), in the Indian Ocean (Marret and De Vernal, 1997) and in the Weddell Sea (Esper and Zonneveld, 2002; Harland and Pudsey, 1999). We echo the studies from Houben et al. (2013) and Sangiorgi et al. (2018), which elaborately discus the potential of *S. antarctica* as sea-ice indicator and its ecological meaning. We understand that the explanation in our manuscript falls short in providing the reader sufficient information on this matter. In a new version of the manuscript, we will support our inference of *S. antarctica* as sea ice indicator (and its absence as indicator of longer-than-today open water season) more elaborately than we did so far.**

(2) The authors conclude they demonstrate 'variability on glacial/interglacial timescales'. This is possibly true, but it has not been illustrated in a convincing way. The key to their interpretation, I think, is figures 6 and 7, where the relative abundance of different dinoflagellate cysts are illustrated for different lithologies. However, there is no evidence presented in this paper that these lithologies are deposited under different glacial conditions. They instead refer to Salabarnada et al.

(in review submitted to CPD). Salabarnada et al. describe a glacial 'Facies 1', and an interglacial 'Facies 2'. Although the present authors rely on the cyclo-stratigraphy of Salabarnada et al. for their glacial-interglacial interpretation, they choose (confusingly) to apply a different lithological scheme in the present paper. Thus, in Table 2, the authors assign 'Silty claystones and sandstones' to (glacial) Facies 1 of Salabarnada et al., and 'carbonated rich and pelagic clay lithologies to (interglacial) Facies 2. Notwithstanding this, the dinoflagellate cyst assemblages shown in Figures 6 and 7 do not vary in a consistent way between either the glacial and interglacial facies described by Salabarnada et al., or by the glacial and interglacial lithologies assigned by the authors (line 300-302). The different lithologies do contain different dinoflagellate cyst assemblages, but these differences do not appear to fall along the glacial/interglacial divisions proposed by either Salabarnada et al. or the authors.
We agree that the different presentation of the lithologic facies in our ms and that of Salabarnada et al may generate confusion. In a new version of the manuscript, we will make this consistent. In anticipation of this review, we have already revisited the Miocene lithology, made a detailed description and integrated the facies into the other lithologies described in Salabarnada et al. This did not lead to any different conclusions than those already made, namely a higher relative abundance of protoperidinioid dinocysts in glacial deposits, and more gonyaulacoid dinocysts in interglacial deposits, with the lithologic interpretations being made independent of the dinocyst results in Salabarnada et al, CP (https://doi.org/10.5194/cp-2017-152).

However [**if**] the authors choose to respond to this comment, at a minimum the abstract should be adjusted to removed the implication that glacial/interglacial has been investigated for the entire record (line 46), as only Oligocene samples have been explored for this variability, and I strongly suggest marking clearly on Figures 6 and 7 which lithologies represent glacial and which interglacial deposition, or perhaps grouping samples together - the seven columns/lithologies do not communicate clearly the variability the authors claim to have identified.
We agree with the reviewer, a new version of the manuscript will present the dinocyst data in fewer lithologic groups. Moreover, the detailed lithologic interpretations will be continued into the Miocene part of the sequence. This will only reinforce the interpretations of different dinocyst assemblages between glacial and interglacial deposits.

(3) The authors rely on unpublished (submitted, in review) work to justify their division of the dinoflagellate cyst assemblage into in situ and reworked components. This is an important step in their data processing, and important to completely assess this paper, but the information is not available to review at present.
The paper is now published and available open access in Journal of Micropalaeontology.

(4) The discussion is fairly speculative/not well supported by the data presented – but is thought provoking, and should be retained.
Because the reviewer does not substantiate which part he/she finds speculative, we cannot reply any further to this comment at this stage. We will thoroughly revisit the discussion and evaluate any speculative aspects.

Minor comments follow:
L299 relation not relations -**done**
L353 can the authors discount input of terrestrial nutrients instead of upwelling? **We can for most of the record, with reason and argument, not with unequivocal proof. Given the relatively small catchment area, and deteriorated climate, the low relative abundance of palynomorphs (those that are there are mostly wind-transported pollen) and absence of terrestrially-derived amorphous organic matter, and the average outer neritic/oceanic nature of the dinocyst assemblage, we argue for marine nutrients instead of terrestrially-derived. Although, the Miocene Climatic Optimum might have an additional terrestrially-derived nutrient source. We shall add this to the manuscript.**

L422 replace ‘a close position’ with ‘proximal’? **This was not found, possible lost in revision**

References:

Esper, O. and Zonneveld, K.A.F.: Distribution of organic-walled dinoflagellate cysts in surface sediments of the Southern Ocean (eastern Atlantic sector) between the Subtropical Front and the Weddell Gyre, Marine Micropaleotology, 46, 177-208, 2002.

Harland, R. and Pudsey, C. J., 1999. Dinoflagellate cysts from sediment traps deployed in the Bellingshausen, Weddell and Scotia seas, Antarctica. Marine Micropaleontology. 37, 77-99.

Hartman, J.D., Bijl, P.K., Sangiorgi, F., et al., in prep-a. Palynological assemblages from the Holocene of IODP Site U1357A, Wilkes Land margin, Antarctica. to be submitted to Journal of Micropaleontology

Hartman, J.D., Sangiorgi, F., Bijl et al., in prep-b. A multi-proxy reconstruction for MIS5 to MIS9 of the Antarctic marginal ice zone in the Ross Sea: sea-ice cover, productivity and temperature for Site AS05-10, Drygaski basin. to be submitted to Paleoceanography and Paleoclimatology.

Houben, A.J.P., Bijl, P.K., Pross, J., Bohaty, S.M., Passchier, S., Stickley, C.E., Röhl, U., Sugisaki, S., Tauxe, L., Van De Flierdt, T., Olney, M., Sangiorgi, F., Sluijs, A., Escutia, C., Brinkhuis, H.: Reorganization of Southern Ocean plankton ecosystem at the onset of Antarctic glaciation, Science, 340, 341-344, 2013.

Marret, F. and De Vernal, A., 1997. Dinoflagellate cyst distribution in surface sediments of the southern Indian Ocean. Marine Micropaleontology. 29, 367-392.

Prebble, J. G., Crouch, E. M., Carter, L., Cortese, G., Bostock, H., Neil, H., 2013. An expanded modern dinoflagellate cyst dataset for the Southwest Pacific and Southern Hemisphere with environmental associations. Marine Micropaleontology. 101, 33-48.

Sangiorgi, F., Bijl, P.K., Passchier, S., Salzmann, U., Schouten, S., McKay, R., Cody, R.D., Pross, J., Van De Flierdt, T., Bohaty, S.M., Levy, R., Williams, T., Escutia, C., Brinkhuis, H.: Southern Ocean warming and Wilkes Land ice sheet retreat during the mid-Miocene, Nature Communications, 9 (1), art. no. 317, 2018.

Storkey, C.A.: Distribution of marine palynomorphs in surface sediments, Prydz Bay, Antarctica. MSc thesis Victoria University of Wellington, New Zealand. http://hdl.handle.net/10063/21, 2006.

Reply to Reviewer 3 (S. Gallagher) by Bijl et al.

This is an excellent description and interpretation of organic microfossils from the Oligo-Miocene strata off Wilkes Land Margin and their palaeoceanographic significance. I have made extensive comments and suggestions in the attached annotated pdf tex to this paper.
I would like to add the following to the discussion:
I appreciate the utility of using isotopes to interpret Antarctic Ice Sheet variability as summarised by Liebrand et al 2017 (www.pnas.org/cgi/doi/10.1073/pnas.1615440114) and this approach is used extensively when discussing the Cenozoic greenhouse icehouse transition. However, there are other sections that have been interpreted using backstripping and stratigraphic data in the Gippsland (Oligocene) and New Jersey (Oligo-Miocene) margins that reflect glacio-eustasy in the Oligocene and relative ice volume (Gallagher et al., 2013), it would be useful to consider the significance of these near field and far field sections in any section reviewing ice volume variability. Gallagher, S. J., G. Villa, R. N. Drysdale, B. S. Wade, H. Scher, Q. Li, M. W. Wallace, and G. R. Holdgate (2013), A near-field sea level record of East Antarctic Ice Sheet instability from 32 to 27 Myr, Paleoceanography, 28, doi: 10.1029/2012PA002326.
This is a good suggestion, we will add this to the revised manuscript.

More specific comments are below:
Lines 116-117 please clarify these lines they are bit vague. **-done**
Line 132: I don't think the word is speculate here, perhaps hypothesize? **-done**
Section 3 Methods: Bijl et al in press, I presume this means the paper published in Jl Micropal so please correct as it is not even in the reference list. **indeed. Done**
Line 217: what does empirical data mean here? **Now better explained**
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Page 22 line 507 onward, as mentioned above there are other records that point to ice sheet instability in the time period being considered, please include in discourse.
Lines 518-527 are too speculative and should be left out or moderated.
In conclusion, once the text has been clarified and the suggestions considered this will be useful addition to the relatively sparsely documented Antarctic (palaeo)climate and oceanographic records.

Please also note the supplement to this comment:
https://www.clim-past-discuss.net/cp-2017-148/cp-2017-148-RC3-supplement.pdf **–We will carefully incorporate the comments that were annotated into a new version of the ms.**

Oligocene–Miocene paleoceanography off the Wilkes Land margin (East Antarctica) based on organic-walled dinoflagellate cysts

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Abstract

Next to atmospheric CO_2 concentrations, ice-proximal oceanographic conditions are a critical factor for the stability of Antarctic marine-terminating ice sheets. The Oligocene and Miocene epochs (~34–5 Ma ago) were time intervals with atmospheric CO_2 concentrations between those of present-day and those expected for the near future. As such, these past analogues may provide insights into ice-sheet volume stability under warmer-than-present-day climates. We present organic-walled dinoflagellate cyst (dinocyst) assemblages from chronostratigraphically well-constrained Oligocene to mid-Miocene sediments from Integrated Ocean Drilling Program Expedition (IODP) Site U1356. Situated offshore the Wilkes Land continental margin, East Antarctica, the sediments from Site U1356 have archived the dynamics of an ice sheet that is today mostly grounded below sea level. We interpret dinocyst assemblages in terms of paleoceanographic change on different time scales, i.e., with regard to both glacial-interglacial and long-term variability. Our record shows that a sea-ice related dinocyst species, *Selenopemphix antarctica*, occurs only for the first 1.5 Ma of the early Oligocene, following the onset of full continental glaciation on Antarctica, and after the mid-Miocene Climatic Optimum. Dinocysts suggest a weaker-than-modern sea-ice season for the remainder of the Oligocene and Miocene. The assemblages generally bear strong similarity to present-day open-ocean, high-nutrient settings north of the sea-ice edge, with episodic dominance of temperate species similar to those found in the present-day subtropical front. Oligotrophic and temperate surface waters prevailed over the site notably during interglacial times, suggesting that

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the positions of the (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 interpreted (Fretwell et al., 2013). This implies that a larger part of the continental ice sheet 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 higher amplitude and faster rate of sea-level rise is to be expected under future climate warming than previously acknowledged (IPCC, 2013). Studying the amount and variability of Antarctic ice volume in periods with high atmospheric CO_2 concentrations (pCO_2) provides additional insight into ice/ocean feedback processes. Foster and Rohling (2013) compared sea-level and atmospheric pCO_2 concentrations on geological timescales. Their study suggests that global ice sheets were rather insensitive to climate change when atmospheric pCO_2 ranged 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 preserved 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 (primarily on Antarctica) and deep-sea temperature. The latter is strongly coupled to polar surface-water temperature, as deep-water formation was predominantly at high latitudes at that time (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 would be in accordance with numerical modelling experiments (Barker et al., 1999) and the interpretation of Foster and Rohling (2013)), or (ii) strong fluctuations in Antarctic ice volume, with relatively subdued temperature variability (which would be in accordance with indications for unstable Antarctic ice sheets under warmer-than-present climates (Cook et al., 2013; Greenop et al., 2014; Rovere et al., 2014; Sangiorgi et al., 2018). If one assumes a present-day $\delta^{18}O$ composition (-42‰ *versus* standard mean ocean water (SMOW)) for Oligocene–Miocene Antarctic ice-sheets and modern deep-water temperature (2.5°C), the benthic $\delta^{18}O$ fluctuations during the Oligocene–Miocene suggest long-term ice-sheet variability to have fluctuated considerably (Liebrand et al., 2017). Similarly strong fluctuations were observed in sedimentary records from the Gippsland Basin, southeast Australia (Gallagher et al., 2013). Meanwhile, deep-sea temperatures have fluctuated considerably as well during the Oligocene and Miocene (Lear et al., 2004), which is further evident from ice-free geologic episodes (Zachos et al., 2008). Therefore, a combination of deep-sea temperature and ice-volume changes is likely represented in these records. Further 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 higher-than present-day pCO_2 concentrations.

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While Oligocene–Miocene climates may bear analogy to our future in terms of $p\text{CO}_2$ concentrations, the uncertainties and differences in Antarctic paleotopography must be considered in any such comparison, as this factor critically determines the proportion of marine-based *versus* land-based ice. An Antarctic continent with low topography would result in more ice sheets being potentially sensitive to basal melt and as such a higher sensitivity of these ice sheets to climate change. Moreover, the fundamentally different paleogeographic configuration of the Southern Ocean during that time as compared to today should also be considered (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 (i.e., the width and depth of the gateways as well as the position of the 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 has remained poorly understood.

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 expeditions have been undertaken in the past to provide insight in the history of the Antarctic ice sheets (Barrett, 1989; Wise and Schlich, 1992; Barker et al., 1998; Robert et al., 1998; Wilson et al., 2000; Cooper and O'Brien, 2004; Exon et al., 2004; Harwood et al., 2006; Escutia and Brinkhuis, 2014). For some of the retrieved sedimentary archives, age control was particularly challenging due to the

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paucity of useful means to calibrate them to the international time scale. As a consequence, the full use of these archives 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 interpreted to be highly sensitive to continental ice-sheet melt (Escutia et al., 2011). The sediments recovered from IODP Site U1356 are from the continental rise of this margin (Escutia et al., 2011) and hence contain a mixture of shelf-derived material and pelagic sedimentation. Dinocyst events in this record have been recently tied to the international time scale through integration with calcareous nannofossil, diatom and magnetostratigraphic data (Bijl et al., 2018). By Southern Ocean standards, the resulting stratigraphic age frame for the Oligocene–Miocene record of Site U1356 (Fig. 2; Table 1) is of high resolution. In this paper, we investigate the dinocyst assemblages from this succession by utilizing the strong relationships between dinocyst assemblage composition and surface-water conditions of today's Southern Ocean (Prebble et al., 2013). We reconstruct the oceanographic regimes during the Oligocene and mid-Miocene, and evaluate their implications. We further compare the palynological data with lithological observations and their interpretations from Salabarnada et al. (submitted, this volume). Pairing the sedimentological interpretations and biomarker-derived absolute sea-surface temperature (SST) reconstructions from Site U1356 (Hartman et al., submitted, this volume) with our dinocyst assemblage data, we reconstruct the paleooceanographic conditions off Wilkes Land and assess their variability both on glacial-interglacial and longer-term times scales.

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2. Material

2.1 Site description for IODP Hole U1356A

Samples were taken from IODP Hole U1356A, the only hole from Site U1356, cored 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., 2011). The paleolatitude calculator of van Hinsbergen et al. (2015) was used 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). Hole U1356A reaches a depth of 1006.4 m into the seabed (Escutia et al., 2011). Oligocene to upper Miocene sediments were recovered between 890 and 3 mbsf (meters below sea floor, Figure 2; Tauxe et al., 2012; revised according to Bijl et al., 2018). The uppermost 95 meters of the hole were poorly recovered; sediments consisted of unconsolidated mud strongly disturbed by rotary drilling (Escutia et al., 2011). Hence, we focused our investigation on the interval between Cores 11R to 95R Section 3 (95.4–894 mbsf; 10.8–33.6 Ma; Figure 2).

2.2 Lithology in IODP Hole U1356A

In the interval between 95.4 and 894 mbsf, nine lithologic units have been recognized during shipboard analysis (Figure 2; Escutia et al., 2011). Salabarnada et al. (submitted, this volume) present a detailed lithologic column of the Oligocene and Miocene sediments. The lithologic facies described in Salabarnada et al. (submitted, this volume) will help us compare paleoceanographic differences between climatic extremes. Salabarnada et al. (submitted this volume) distinguished various lithologies along with interpretations of their depositional settings which can be summarized as:

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1) laminated silty clay sediments (interpreted as glacial deposits; hereafter Fg), 2) bioturbated siltstones and claystones that in some intervals are carbonate-cemented (interpreted as interglacial deposits, hereafter Fi), and 3) perturbed mass transport deposits (MTDs): slumps and debris flows. We refer to Salabarnada et al. (submitted this volume; Fig S2) for a detailed description of these facies, and to the supplementary datasets on pangaea for more detailed separation of our palynological results per facies type.

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 by magnetostratigraphy (Tauxe et al., 2012). Bijl et al. (2018) and Crampton et al. (2016) have updated the existing age model for Site U1356 for the Oligocene and Miocene parts of the succession, respectively. In their efforts, they recalibrated the tie points to the international time scale of Gradstein et al. (2012). We here follow their revision of the age model (Table 1). We infer ages by linear interpolation between tie points (Figure 2; Table 1).

2.4 Depositional setting at IODP Site U1356

The depositional setting at Site U1356 changed from a shallow mid-continental shelf in the early Eocene (Bijl et al., 2013a) to a deep continental rise environment by the Oligocene (Houben et al., 2013) due to subsidence of the Wilkes Land margin (e.g., Close et al., 2009). Regional correlation of the facies at Hole U1356A via seismic profiles suggests a mix of distal-submarine fan and hemipelagic sedimentation during

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the early Oligocene, grading into channel-levee deposits in the later Oligocene (Escutia et al., 2011). The boundary between these two different depositional settings is at ~650 mbsf; there, sedimentation rates increase, and the documentation of mass-transport deposits from this depth upwards suggests shelf-derived erosion events on the Wilkes Land continental slope (Escutia et al., 2011).

3. Methods

3.1 Palynological sample processing

The sample processing and analytical protocols as followed in this study are in accordance with standard procedures and have been previously described by Bijl et al. (2013b; 2018). The 25 species of dinocysts new to science, which are formally (2 species) and informally (23 species) described in Bijl et al. (2018), fit into known and extant genera, and therefore could be confidently included in the ecological groups as described below. We refer to Bijl et al. (2018) for an extensive overview (including plates) of the dinocyst species encountered.

3.2 Ecological grouping of dinocyst taxa

Bijl et al. (2018) 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. (2018) and divide the dinocyst species into a reworked and an in situ group (Table 2). 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 the present-day relationship between

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Southern Ocean microplankton in general and dinoflagellate cysts in particular and their surface-water characteristics (e.g., Eynaud et al., 1999; Esper and Zonneveld, 2002, 2007; 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 appear to be closely related to the oceanic frontal systems in the Southern Ocean (Figure 3). Supporting evidence for the ecologic affinities of the dinocyst groups comes from empirical data, such as correlation of abundances with other sediment properties or proxies (Sluijs et al., 2005; Egger et al., 2018), for instance with regard to the affinities of *Nematosphaeropsis labyrinthus*, *Operculodinium* spp., *Pyxidinopsis* cpx. (this includes *Corrudinium* spp. and *Cerebrocysta* 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) that links the abundance of protoperidinioid dinocysts to high surface-water productivity. The arguably most important inference from the surface-sediment sample study of Prebble et al. (2013) is that *Selenopemphix antarctica* is common to dominant (10–90%) south of the Antarctic polar front (AAPF). In particular, the Antarctic continental shelf exhibits a consistently high relative abundance of *Selenopemphix antarctica*. In addition to the surface samples of Prebble et al. (2013), this is also evident at the Wilkes Land margin proper (IODP Site U1357; Hartman, Bijl and Sangiorgi, pers. obs.), at Prydz Bay (Storkey, 2006), in the Weddell (Harland and Pudsey, 1999) and Ross Seas (Hartman, Bijl and Sangiorgi, pers. obs), and in the southern Indian Ocean (Marret and de Vernal, 1997): samples all contain very abundant to dominant (>50 to 90%) *S. antarctica*. The dominance of this species

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becomes even stronger when considering that assemblages in these surface samples often include cysts that are not easily preserved in older sediments such as that of *Polarella glacialis.* Leaving these dinocyst out of the dinocyst sum increases the relative abundance of *Selenopemphix antarctica* in surface samples. Notably, surface-sediment samples outside of the AAPF never have dominant (~90%) *Selenopemphix antarctica* (Prebble et al., 2013). Another important observation is that the surface-sediment samples south of the AAPF are generally devoid of gonyaulacean dinocysts, with the exception of two species of *Impagidinium* (i.e., *I. pallidum* and *I. sphaericum*) that may occur, although neither abundantly (Prebble et al., 2013) nor exclusively (e.g., Zevenboom, 1995; Zonneveld et al., 2013), in ice-proximal locations. Abundant *Nematosphaeropsis labyrinthus* occurs exclusively in regions outside of the Subantarctic Front, and particularly near the Subtropical Front. Thus, we conclude from the available literature a dominance of *S. antarctica* south of the AAPF, a dominance of other protoperidinioid dinocysts at and north of the AAPF, mixed protoperidinioid and gonyaulacoid dinocysts (with a notable occurrence of *Nematosphaeropsis labyrinthus* at the sub-Antarctic front (SAF), and mixed gonyaulacoid dinocysts at and outside of the subtropical front (STF). These trends represent a north-south transition from sea-ice-influenced to cold upwelling/high nutrient to warm-temperate/lower nutrient conditions, respectively. We use these affinities to reconstruct past oceanographic conditions at the Wilkes Land continental margin.

4. Results

4.1 Palynological groups

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In our palynological analysis we separated palynomorph groups into four categories: reworked dinocysts (following Bijl et al. (2018); Table 2), in situ dinocysts, acritarchs, and terrestrial palynomorphs. Our palynological slides further contain a varying amount of pyritized diatoms and a minor component of amorphous organic matter, which is not further considered in this study. The relative and absolute abundances of the four palynomorph groups vary considerably throughout the studied interval (Figure 4). Reworked dinocysts are ubiquitous throughout the record, and are particularly abundant in the lowermost 40 meters of the Oligocene and in the Upper Oligocene. In situ dinocysts dominate mid-Oligocene and mid-Miocene palynomorph assemblages, Chorate, sphaeromorph and *Cymatiosphaera*-like acritarchs (which are not further taxonomically subdivided) dominate the assemblage in the Upper 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 (a few % of the total palynomorph assemblage) component of the total palynomorph assemblage (Fig. 4). The terrestrial palynomorphs and the paleoclimatic and paleoecological interpretations derived from them will be presented in another study.

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 cysts of heterotrophic dinoflagellates (e.g., Esper and Zonneveld, 2007). Among these protoperidinioid cysts, *S. antarctica* is frequently present (up to 39% of the in situ assemblage), but

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only between 33.6 and 32.1 Ma (earliest Oligocene) and after 14.2 Ma (i.e., during and after the mid-Miocene climatic transition; Fig. 5). The remainder of the record is almost entirely devoid of *S. antarctica*. This is much in contrast to the dinocyst assemblages nearby Site U1356 today, which are dominated by this taxon (Prebble et al., 2013). Instead of *S. antarctica*, other protoperidinioid dinocysts dominate during the Oligocene and Miocene, 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 settings at or outside of the AAPF (Prebble et al., 2013). A varying abundance of protoperidinioid dinocysts could not be placed with confidence into established protoperidinioid dinocyst genera. These are grouped under 'protoperidinioid spp. pars' (Figure 4; Bijl et al., 2018) and are here assumed to exhibit the same heterotrophic life-style as the other protoperidinioid dinocyst genera.

Next to protoperidinioid dinocysts, gonyaulacoid dinocysts also occur in relatively high abundances throughout the record from Site U1356. They comprise both known and previously unknown (Bijl et al., 2018) species of *Batiacashaera, Pyxidinopsis, Corrudinium, Cerebrocysta, Nematosphaeropsis, Impagidinium, Operculodinium*, and *Spiniferites* (Fig. 4; 5). The 'others' group represents exclusively gonyaulacoid species such as *Invertocysta tabulata* and *Gelatia inflata*. Except for the extinct genera *Batiacasphaera* and *Cerebrocysta* and some genera in the 'others' group, all the other genera are still extant and represent phototrophic dinoflagellates (Zonneveld et al., 2013). Their abundance is at the expense of the assumed heterotrophic

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protoperidinioid dinocysts. A marked increase in abundance of gonyaulacoid cysts is associated with the mid-Miocene Climate Optimum (MMCO between ~17 and 15 Ma; Fig. 4, 5; Sangiorgi et al., 2018). Of the gonyaulacoid taxa, *Nematosphaeropsis labyrinthus* is associated with frontal systems of the present-day Southern Ocean (Prebble et al., 2013) and of the North Atlantic Ocean (Boessenkool et al., 2001; Zonneveld et al., 2013).

4.3 Comparison between palynological data and lithological facies

The Oligocene-Miocene sediments from Site U1356 comprise distinctive alternations of lithologic facies throughout the section (Salabarnada et al., submitted, this volume; Figure S2). Laminated (Fg) and bioturbated sediments, that are in some intervals are carbonate-rich (Fi) alternate on orbital time scales and this pattern is in some intervals disrupted by slumps and/or debris flows. We here evaluate and compare the palynological content of each of these facies both in terms of absolute and relative abundance of the main palynomorph groups: reworked dinocysts, in situ dinocysts, acritarchs and terrestrial palynomorphs, and relative abundance of in situ dinocyst eco-groups.

4.3.1 Palynomorph groups and lithology

There are distinct differences in the relative and absolute abundances of the palynomorph groups between the different lithologies (Figure 6). The highest relative and absolute abundances of reworked dinocysts occur in the slump and Fi facies (Fig. 6), particularly those of early Oligocene age (EOT slumps and bioturbated siltstones in Supplementary datasets), in line with observations of Houben et al. (2013).

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Reworking is a minor component of the palynomorph assemblage in the other lithologies for most samples, with a higher absolute abundance in Fi deposits than in glacial deposits. This suggests that submarine erosion of Eocene continental shelf material was particularly prominent during interglacial times, when arguably sea level along the Wilkes Land margin was lower (Stocchi et al., 2013). The relative and absolute abundance of *in-situ* dinocysts is highest in the interglacial and glacial deposits and the slumps (Figure 6). Acritarchs reach highest relative and absolute abundances in Fi facies and in the debris flows (Figure 6). Terrestrial palynomorphs are most abundant in the lower Oligocene slumps and Fi sediments (Supplementary tables) but have low relative abundance in all lithologies (Figure 6).

4.3.2 In situ dinocyst eco-groups and their abundance per facies

The in situ dinocyst eco-groups are also compared with the lithological facies (Figure 7). The Fg glacial facies contains generally more peridinioid (heterotrophic) dinocysts, while the Fi interglacial facies contains more gonyaulacoid (oligotrophic) dinocysts, but more information is to be seen when focussing on the individual eco-groups. The abundance of *Selenopemphix antarctica* is low throughout the record (0–5%), with the exception of the interval post-dating the MMCO and the lowermost Oligocene, where the taxon reaches occasionally more than 20% (Figs. 4, 5). *S. antarctica* reaches highest abundances in the slump facies and Fg and is less abundant in the other lithologies (Figure 7). *Selenopemphix* spp. reaches highest relative abundances in the Fg facies. *Lejeunecysta* spp. and *Protoperidinium* spp. pars. show no noticeable variance in relative abundance in any of the lithologies. *Brigantedinium* spp. is clearly higher abundant in the Fg facies than in the Fi facies.

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Malvinia escutiana abundances seem to be higher in Fi than in Fg (Figure 7), although this species has a stratigraphic occurrence that is limited to the early Oligocene (Bijl et al., 2018). *Nematosphaeropsis labyrinthus*, *Pyxidinopsis* cpx, *Operculodinium* spp., and *Impagidinium* spp. reach higher relative abundances in Fi than in Fg facies, whereas the abundance of *Batiacasphaera* spp. seems invariant to facies.

5. Discussion

5.1 Paleoceanographic interpretation of the dinocyst assemblages

The composition of the dinoflagellate cyst assemblages in the Wilkes Land record reflect changes in surface-ocean nutrients, sea- surface temperature conditions and paleoceanographic features. We will discuss these implications in the following.

5.1.1 Surface-ocean nutrient conditions

The general dominance of heterotrophic dinocysts in the Oligocene–Miocene assemblages indicates overall high nutrient levels in the surface waters. Given the offshore geographic setting, we therefore infer that surface waters at Site U1356 experienced upwelling associated to the AAPF during most of the Oligocene and Miocene. We can exclude the possibility that nutrients were brought to the site via river runoff given the anticipated small catchment area that experienced liquid precipitation in the Wilkes Land hinterland, the low amounts of terrestrially-derived (amorphous) organic matter in the palynological residues and relatively low branched over isoprenoid tetraether (BIT) index values (Hartman et al., submitted this volume) that indicates predominantly marine organic matter. The exception may

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be the mid-Miocene climatic Optimum (Sangiorgi et al., 2018) when considerable soil-derived organic matter reached the site.

The occasionally abundant gonyaulacoid cyst taxa encountered in our record suggest that at times surface waters were much less nutrient-rich supported the growth of oligotrophic dinoflagellates. Notably, these taxa are typical for outer-shelf to oceanic or outer neritic settings (e.g., Sluijs et al., 2005; Zonneveld et al., 2013; Prebble et al., 2013), which makes it unlikely that they were reworked from the continental shelf. Indeed, they show low relative abundances in the perturbed deposits (Figure 7). Although the members of these genera have relatively long stratigraphic ranges extending back into the Eocene, most of the species encountered at Site U1356 are not present in Eocene continental shelf sediments in the region (e.g., Wrenn and Hart, 1988; Levy and Harwood, 2000; Brinkhuis et al., 2003a, b; Bijl et al., 2011; 2013a, b). This makes it unlikely that they are reworked from Eocene strata. In addition, statistical analysis also yields that these species are part of the in situ assemblage (Bijl et al., 2018). These different lines of evidence lead us to interpret them as part of the in situ pelagic assemblage in our study, which allows us to interpret their paleoceanographic implications based on their modern affinities. The absence of these taxa in modern surface waters south of the AAPF is probably caused by a combination of different factors: It can be connected to low sea-surface temperatures and an isolation by strong eastward currents, but also the abundance and seasonally concentrated availability of nutrients, all of which make the proximal surface waters off Antarctica a highly specialistic niche unfavourable for these species. Apparently, surface-water conditions during the Oligocene and Miocene were

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such that these oligotrophic species could at times proliferate so close to the Antarctic margin.

5.1.2 Sea-surface temperature

The best modern analogues for the dinocyst assemblages in our record are to be sought off the southern margins of New Zealand and Tasmania (as inferred from Prebble et al., 2013; Figure 2). Today, these regions feature a mix between protoperidinioid dinocysts along with gonyaulacoid dinocyst genera such as *Nematosphaeropsis*, *Operculodinium* and *Impagidinium*. These assemblages prevail in surface waters with mean annual temperatures of 8–17°C (Prebble et al., 2013) and therefore suggest relatively warm surface water temperatures close to the Wilkes Land margin. In support of this, a bayesian approach on the TEX$_{86}$ index values at Site U1356 (presented in Sangiorgi et al., 2018; Hartman et al., submitted, this volume) also suggests the Southern Ocean mid-latitudes as a modern-analogue region and reconstructs a paleotemperature range of 8–20°C for the Oligocene–Miocene at Site U1356, with values in excess of 24°C for the late Oligocene (Hartman et al., submitted, this volume). Futher, supporting evidence for temperate Oligocene–Miocene surface waters comes from the abundance of nannofossils encountered in the sediments (Escutia et al., 2011; Salabarnada et al., submitted this volume). Today, carbonate-producing plankton is rare in high-latitude surface waters south of the AAPF (Eynaud et al., 1999). Moreover, the remains of the few pelagic carbonate-producing organisms living at high latitudes rarely reach the ocean floor because of 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

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along with the encountered oligotrophic, temperate dinocysts suggests fundamentally warmer surface-water conditions than today.

5.1.3 Surface paleoceanography

The strong similarity of Oligocene–Miocene dinocyst assemblages at Site U1356 with those today occurring much further north (i.e., around Tasmania and Southern New Zealand (Prebble et al., 2013) suggests a fundamentally different *modus operandi* of Southern Ocean surface oceanography. The strict latitudinal separation of dinocyst assemblages in the Southern Ocean today (Prebble et al., 2013) is likely due to different surface 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. Climate model (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 wind orientation determined the average position of the Antarctic Divergence at 60°S during the Oligocene and Miocene, similar to today. This suggests that Site U1356 was likely directly overlain by the AAPF. However, the significantly warmer, more oligotrophic dinocyst assemblages off Wilkes Land throughout the Oligocene–Miocene argue against proximity to the AAPF. The position of the AAPF relative to that 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 a southward migration of temperate surface water masses towards the

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site. A northward position of the AAPF relative to the site would make such a latitudinal migration much more difficult. The presence of carbonate in these deep marine 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 an evidence for a southward position of the AAPF relative to the position of Site U1356. This would allow a higher connectivity between the site and the lower latitudes, and promote preservation of carbonate on the sea floor. Also, such an oceanographic setting would be in line with reduced sea ice along the Wilkes Land margin.

The separate averaging of dinocyst assemblages for glacial and interglacial facies from Site U1356 (Figure 7) allows us to reconstruct glacial-interglacial changes in surface-water conditions throughout the Oligocene. First of all, our observations suggest that Oligocene glacial-interglacial cycles were connected to substantial paleoceanographic dynamics off Wilkes Land. In agreement with the 2–3 °C SST variability as documented for this site during glacial-interglacial cycles (Hartman et al., submitted, this volume), dinocyst assemblages contain more oligotrophic, temperate dinocysts during interglacial times compared to glacial times when more eutrophic, colder dinocysts proliferated (Fig. 7). This could be the result of a slight latitudinal movement of oceanic frontal systems (notably the AAPF) as it has been reconstructed for the Southern Ocean fronts during the most recent glacial to interglacial transition (e.g., Bard and Rickaby, 2009; Kohfeld, et al., 2013; Xiao et al., 2016). In such a scenario, the AAPF would reach a southern position during interglacials, allowing for temperate oligotrophic surface waters to reach the site,

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while it would migrate northward over Site U1356 during glacials, thereby causing cold, high-nutrient surface-water conditions and obstructing low-latitude influence.

5.2 Implications for Oligocene–Miocene ocean circulation

At Site U1356, dinocyst assemblages bear similarities to present-day proximal-Antarctic assemblages (Prebble et al., 2013) only in the lowermost Oligocene and in strata deposited after the mid-Miocene Climate Optimum (after 14.2 Ma); in particular, they are characterized by high abundances (up to 39%) of *Selenopemphix antarctica*. Even in those intervals, however, the relative abundances of *S. antarctica* do not reach present-day values at the same site (Prebble et al., 2013). The absence of a strong shift towards modern-day-like assemblages in our record can be interpreted to reflect a weaker-than-present ACC. This interpretation is 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 as recently inferred by Scher et al. (2015): No particular change in sea-surface conditions emerges from our dinoflagellate cyst data around 30 Ma, and there is no major change in the benthic $\delta^{18}O$ data either (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 throughout the Oligocene and Miocene than at present, which has also emerged from modelling experiments (Hill et al., 2013). The strongly different dinocyst assemblages compared to present-

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day nearby Site U1356 throughout our record imply that a strong coherent ACC was not installed until after the mid-Miocene Climatic Transition (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) in combination with the high sensitivity of dinoflagellates to changes in surface-water conditions (e.g., Zonneveld et al., 2013; Prebble et al., 2013) makes such a scenario very unlikely. Nevertheless, to firmly clarify whether the ACC reached its present-day strength only after the MMCT (as suggested by our data), ocean-circulation modelling of time slices younger than the Oligocene (Hill et al., 2013) will be required.

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Our results also seem difficult to reconcile with indications of bottom-water formation at the Wilkes Land margin, as seen from neodymium isotope analyses on the same sediments (Huck et al., 2017). It could be that bottom water formation took place only when surface waters cooled down in wintertime, and the organic proxies are more representative of spring/summer conditions. Salabarnada et al. (this volume) interpret bottom-current activity in the Oligocene at Site U1356 and suggest it may be spilling over from the Ross Sea, like today. Our dinocyst results and the SST reconstructions by Hartman et al. (submitted this volume) suggest that surface waters at the Wilkes Land margin were too warm to allow local bottom-water

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formation, therefore our data also supports the suggestion that bottom water along the Wilkes Land margin was sourced from the Ross Sea.

5.3 Implications for ice-sheet and sea-ice variability

The relative abundances of the sea-ice-related *Selenopemphix antarctica* are consistently lower in our record than in present-day dinocyst assemblages nearby Site U1356 (Prebble et al., 2013; Figure 3). This suggests that sea-ice conditions were never similar to today during the studied time interval. More specifically, our dinocysts suggest the occurrence of sea ice near the site only during two time intervals: 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 (after 14.2 Ma; Figure 5). Numerical ice-sheet/sea-ice modelling (DeConto et al., 2007) has suggested 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 point towards a much-reduced Antarctic continental ice sheet during that time. The finding of a weaker sea-ice season throughout most of the Oligocene–Miocene at Site U1356 is important because it suggests a decrease in the potential formation of Antarctic bottom waters at this site.

The relative abundance of oligotrophic dinocyst taxa broadly follows long-term Oligocene-Miocene benthic δ^{18}O trends (see Fig. 5): During times of low δ^{18}O values in deep-sea benthic foraminifera (and thus high deep-sea temperatures and/or less ice volume; e.g., at 32 Ma, 24 Ma and 15 Ma; Figure 5), the abundance of oligotrophic temperate dinocysts was high (Figure 5). At times of higher δ^{18}O values, lower deep-sea temperatures and higher ice volume (e.g., at 33.5 Ma, 27 Ma, 23 Ma,

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and 13 Ma; Figure 5), temperate dinocysts were reduced in abundance and high-nutrient, sea-ice indicators (re)appeared. Altogether, on long time scales this pattern suggests that there was a 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 existed between ice- sheet expansion/retreat and paleoceanography.

Oxygen-isotope mass-balance calculations suggest that a modern-day-sized Antarctic ice sheet formed at the Eocene/Oligocene boundary (DeConto et al., 2008). Benthic δ^{18}O records suggest that ice sheets must have fluctuated considerably in size during the subsequent Oligocene and Miocene (Liebrand et al., 2017), although this inference lacks an independent assessment of the deep-sea temperature effect in these δ18O values. The same conclusion was reached based on detailed microfossil, geochemical and facies analyses on sediments from the Gippsland Basin, southeast Australia (Gallagher, et al. 2013). This study suggests that ice volume during the early Oligocene varied by as much as 140-–40% of its present-day size, of which the maximum ice volume estimates far exceed those implied by our data,. However, there is consistency in the observation of considerable glacial-interglacial and long-term dynamics in the ice-ocean system. This is in contrast to the heavy δ^{18}O values for Oligocene benthic foraminifera from Maud Rise (ODP Site 690), which lead to suggest Antarctic ice sheets were near-present-day size throughout the Oligocene (Hauptvogel et al., 2017). It remains to be seen whether the variability in paleoceanography as indicated by our data can be extrapolated to larger parts of the Antarctic margin, including regions of deep-water formation. Given the high temperatures and only weak sea-ice influence, the Wilkes Land margin was likely not

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the primary sector of deep-water formation (see, e.g., Herold et al., 2012), although there is ample evidence for bottom-current activity at the site (Salabarnada et al., submitted, this volume; Huck et al., 2017). Instead, it appears that bottom-water formation during the Oligocene was taking place along the Wilkes Land coast (Huck, et al. 2017). If the oceanographic and climate variability that we reconstruct offshore Wilkes Land also characterises regions of deep-water formation, some (if not all) of the variability both on long and on orbital time scales as documented in benthic δ^{18}O records would be due to changes in 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 (and, by implication, marine-terminating) continental ice sheets in this sector of East Antarctica during the Oligocene as implied by Hauptvogel et al. (2017) given the absence of dominance of sea-ice dinocysts and the presence of in situ terrestrial palynomorphs (Strother et al., 2017). As an alternative explanation for the difference in δ^{18}O values between Maud Rise (Site 690) and the equatorial Pacific (Site 1218) during the Oligocene (Hauptvogel et al., 2017), we suggest that these two sedimentary archives have recorded the characteristics of two different deep-water masses, with those at Maud Rise (Site 690) being much colder and more saline than those in the equatorial Pacific (Site 1218).

6. Conclusions

The dinocyst assemblages in the Oligocene–Miocene (33.6–11 Ma) of Site U1356 were interpreted in terms of surface-water paleoceanography via comparison with present-day dinocyst distribution patterns. Based on our results, we suggest that the

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Oligocene–Miocene surface paleoceanography of the Southern Ocean was fundamentally different from that of today. A sea-ice signal (yet still weaker than at present) emerges for the Wilkes Land margin only for the first 1.5 million years of the Oligocene (33.6–32.1 Ma) and during and after the mid-Miocene climatic transition (after 14.2 Ma). During the remainder of the Oligocene–Miocene, surface waters off Wilkes Land were warm and relatively oligotrophic; notably, they lack indications of a prominent sea-ice season. Upwelling at the Antarctic Divergence was profoundly weaker during Oligocene and Miocene times than at present, or significantly displaced southward from its present-day position. Furthermore, the continental ice sheets were much reduced at the Wilkes Land sub-glacial basin for most of the Oligocene–Miocene compared to today. The influence of warm oligotrophic surface waters appears strongly coupled to deep-sea δ^{18}O values, suggesting enhanced low-latitude influence of surface waters during times of light δ^{18}O in the deep sea and *vice versa*. The absence of (a trend towards a stronger) paleoceanographic isolation of the Wilkes Land margin throughout the Oligocene to mid-Miocene suggests that the ACC may not have attained its full, present-day strength until at least after the mid-Miocene Climatic transition. Moreover, we note considerable glacial-interglacial amplitude variability in this oceanographic setting. Stronger influence of oligotrophic, low-latitude-derived surface waters prevailed over Site U1356 during interglacial times and more eutrophic, colder waters during glacial times. This pattern may suggest considerable latitudinal migration of the AAPF over the course of Oligocene and Miocene glacial-interglacial cycles.

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Acknowledgements

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Author contributions

PKB, FS, CE, and JP designed the research. AJPH, FS and PKB carried out dinocyst analyses for the earliest Oligocene, Miocene, and Oligocene-Miocene boundary interval, respectively. AS and CE provided the lithological data. PKB integrated, cross-validated and compiled the data, and wrote the paper with input from all co-authors.

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Figure captions

Figure 1. Paleogeography of the Southwest Pacific Ocean and position of IODP Site U1356 (red star) at (a) 0 Ma, (b) 10 Ma, (c) 20 Ma, and (d) 30 Ma. Figures are modified after Bijl et al. (2018). Reconstructions were adapted from G-plates, with plate circuit from Seton et al. (2012) and absolute plate positions of Torsvik et al. (2012).

Figure 2. Age model for the Oligocene–Miocene interval of Hole U1356A. Core recovery, lithostratigraphic facies after Salabarnada et al. (this volume; see also Sangiorgi et al., 2018) and lithostratigraphic units (Escutia et al., 2011), Samples taken for palynology and age-depth plot (tie points were derived from Tauxe et al., 2012, which has been recalibrated to the GTS2012 time scale of Gradstein et al., 2012 and modified based on Crampton et al., 2016)). Grey intervals in paleomagnetic data reflect unknown paleomagnetic orientation, either due to absence of core recovery or poor signal. (o) = old end; (y) = young end. Figure modified from Bijl et al. (2018).

Figure 3. Generic representation of present-day distributions of dinocysts in surface sediments in the Southern Ocean. The dinocyst pie charts represent average dinocyst assemblage compositions for surface sediments underneath oceanic frontal zones in the Southern Ocean. Figure modified from Sangiorgi et al. (2018), data replotted from Prebble et al. (2013).

Figure 4. Core recovery and lithostratigraphic facies (after Salabarnada et al., this volume, and Sangiorgi et al., 2018) and lithologic units (Escutia et al., 2011),

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chronostratigraphic epochs (E = Eocene) and stages (L = Lutetian, Burd. = Burdigalian, Ser. = Serravallian, T. = Tortonian), absolute palynomorph (grey) and in situ dinocyst (black) concentrations (# per gram of dry sediment, presented on a logarithmic scale), palynomorph content (reworked dinocysts, in situ dinocysts, acritarchs, terrestrial palynomorphs (given in percentages of total palynomorphs), and relative abundance of in situ dinocyst eco-groups (in percentage of in situ dinocysts) for the Oligocene–Miocene of Hole U1356A.

Figure 5. Compilation of benthic foraminiferal oxygen isotope data from Site 588 (Zachos et al., 2008), Site 1090 (Zachos et al., 2008) Site 1218 (Pälike et al., 2006), , Sites 1264/1265 (Liebrand et al., 2017), Site U1334 (Holbourn et al., 2015), Site U1337 (Beddow et al., 2016), all calibrated to the GTS2012 time scale (Gradstein et al., 2012) with in situ dinocyst assemblage data from Site U1356 (see Fig. 4 for legend). For presentation of the dinocyst data (see Fig. 4 for legend), the age-depth model specified in Figure 2 and Table 1 was used.

Figure 6. Comparison of absolute (left bar, in # * gr $^{-1}$ dry weight) and relative (right bar; in % of total palynomorphs) abundances of palynomorph groups per lithology for Hole U1356A. Average (black lines) and 17–83% percentile (coloured bar) of absolute and relative abundances of total palynomorphs, reworked dinocysts, in situ dinocysts, acritarchs, and terrestrial palynomorphs grouped for the different facies (Salabarnada et al., submitted this volume).

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Figure 7. Abundance/concentration of in situ eco-groups within various lithologies at Hole U1356A. Average (black line) and 17–83% percentile (coloured bar) of relative abundances of grouped taxa from samples from the different facies (Salabarnada et al., submitted this volume).

Table captions

Table 1. Age constraints for the Oligocene–Miocene of Hole U1356A.

Table 2. List of assumed in situ and reworked dinoflagellate cyst taxa encountered in this study. See Bijl et al. (2018) for informal species descriptions and discussion about which species are considered reworked and in situ.

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We however think believe that these species to represent part of the in situ assemblage in an otherwise dominantly reworked dinocyst assemblage, because these they were have never been found in Eocene sediment in the region before.

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and reflect warming of surface waters rather than them being reworked. The occasional abundance of oligotrophic taxa suggests nutrient levels must have been low compared to the same region today.