

Response to referee David Lazarus and an anonymous referee on “Expansion and diversification of high-latitude radiolarian assemblages in the late Eocene linked to a cooling event in the Southwest Pacific” by K. M. Pascher et al.

K. M. Pascher et al.

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We acknowledge the thorough review by David Lazarus and an anonymous referee that provided helpful comments on improving our manuscript. We will respond to each comment below (referees' comments are shown in italics) and explain how we address each point.

Response to referee David Lazarus

Comment on prior studies: *My first substantial criticism is that too little of this prior work is made visible to the reader of the current ms. Although several of these prior studies are cited, they are cited without providing any real information as to their content. Indeed, one might get the false impression from the Pascher ms that rather little has been known until now of southwestern Pacific plankton biogeographic evolution, or that the timing of ocean water mass origins is a new discovery, or that the sections used in this study have not been extensively examined already for radiolarian faunal characteristics. A brief but proper review of prior studies and the significance of the new ms results in the context of this prior work needs to be added to the introduction section of the paper.*

Response: We agree with this comment and have revised the introduction chapter accordingly and included a review of previous work (in blue, see below). Other parts of the introduction have been modified slightly.

Although Lazarus, Hollis and Apel (2008) used the same set of cores from the Southwest Pacific, and Hollis et al. (1997) and Crouch and Hollis (1996) analysed the radiolarian fauna of parts of DSDP sites 277, 280 and 281, respectively, we re-investigated the radiolarian fauna for all DSDP sites in this study, including new quantitative data and analysis, study of infill samples and review and application of revised identifications in light of more recent work, notably the study of ODP Site 1172 (Suzuki et al., 2009).

Revised text in Introduction:

The climate history of the early Paleogene has been established by geochemical proxies for temperature, loosely linked to paleontological data. The primary proxy record, stable oxygen isotope ($\delta^{18}\text{O}$) values of benthic foraminifera, shows a trend from an early Cenozoic greenhouse climate to an icehouse climate with the major shift in benthic $\delta^{18}\text{O}$ values of $\sim +1.5\%$ in the earliest Oligocene (~ 34 Ma) (Shackleton and Kennett, 1975; Diester-Haass et al., 1996; Zachos et al., 2001). After a prolonged period of maximum warmth during the Early Eocene Climatic Optimum (EECO) centred around 53–51 Ma, long-term cooling was interrupted by the Middle Eocene Climatic Optimum (MECO), a ~ 500 kyr period of warmth peaking ~ 40 Ma that has been linked to an increase in atmospheric $p\text{CO}_2$ (Bohaty and Zachos, 2003; Bohaty et al., 2009; Bijl et al., 2010). Organic biomarker-based climate proxies (Liu et al., 2009; Bijl et al., 2010) suggest the Southwest Pacific sea

surface temperatures were tropical during the MECO (28°C) and continued to be warm throughout the late Eocene (24–26°C), cooling only slightly across the Eocene-Oligocene transition (EOT) (~22°C). The generally warm conditions of the Eocene are consistent with fossil-based reconstructions of Southern Ocean circulation developed from high-latitude drill cores (Kennett, 1977; Nelson and Cooke, 2001; Kennett and Exon, 2004), in which subtropical waters are interpreted to extend close to the Antarctic margin until the late Eocene. However, the latest generation of ocean circulation and climate modelling simulations fail to simulate high-latitude warmth in the Eocene (Hollis et al., 2012; Lunt et al., 2012). Even under hyper-greenhouse conditions, the models produce a cyclonic gyre that blocks subtropical waters from penetrating southward beyond 45°S (Huber and Sloan, 2001; Huber et al., 2004).

High-latitude warmth also conflicts with evidence for the initiation of Antarctic glaciation in the latest Eocene from both fossil and geochemical proxies (Lazarus and Caulet, 1993; Scher et al., 2014; Barron et al., 2015). Following the MECO event, benthic $\delta^{18}\text{O}$ values increased to their maximum Eocene values of ~2.3‰ at about 37.3 Ma during a short-lived cooling episode in the early late Eocene, designated as the Priabonian Oxygen Isotope Maximum (PrOM) event (Scher et al., 2014). Further climate oscillations are reported for the late Eocene (Vanhof et al., 2000; Pälike et al., 2001; Bohaty and Zachos, 2003; Villa et al., 2008; Westerhold et al., 2014) prior to the expansion of Antarctic ice that defines the EOT.

Identifying the initial timing and development of a high-latitude fauna in the Southern Ocean helps to constrain the development of the Southern Ocean frontal systems and, in turn, heat transfer between low and high latitudes. Kennett (1978) provided a first summary on the biogeographic development of planktic biota in the circum-polar Southern Ocean throughout the Cenozoic. He inferred that the development of distinct polar plankton assemblages was related to the evolution of the Antarctic-Circumpolar-Current (ACC) and the Antarctic Polar Front (AAPF). This change was associated with the breakup of southern continents at the EOT and implicated as the main causal mechanisms for Antarctic glaciation. Subsequent deep-sea drilling campaigns resulted in more detailed studies about regional change in plankton, that were synthesized by Lazarus and Caulet (1993) into a set of circum-polar maps across specific time intervals. Moreover, these authors also carried out the first synthesis of radiolarian paleobiogeography for the region and found a pattern of increasing endemism in the Southern Ocean across the EOT. Nelson and Cooke (2001) undertook a comprehensive review of previous work and presented a synthesis on the oceanic front development in the Southwest Pacific during the Cenozoic. According to these authors, a proto-Subtropical Front was established in the late Eocene (ca. 35 Ma) and an Antarctic Polar Front (AAPF) in the early Oligocene. A more detailed study of radiolarian paleobiogeographic patterns and trends in the Southwest Pacific was done by Lazarus et al. (2008), who found increased endemism in the radiolarian fauna in the late Eocene (ca. 35 Ma). Further radiolarian studies from the Atlantic sector of the Southern Ocean were performed by Funakawa and Nishi (2008), who recorded the first expansion of an Antarctic assemblage significantly earlier (38.5 Ma). They identified several faunal turnover events associated with an increase or decrease in the Antarctic assemblage from the late middle Eocene to late Oligocene and linked these events to a northward or southward migration of the AAPF. Latest research suggests that the ACC was not developed until ~30 Ma, together with the establishment of an AAPF (Scher et al. 2015), when the Tasmanian gateway aligned with the westerly wind flow. From the middle to late Eocene, a westward Antarctic Slope Current is inferred to have flown across the gateway, driven by the polar easterlies (Bijl et al. 2013; Scher et al. 2015).

In this paper, we document variation in radiolarian assemblages and foraminiferal oxygen and carbon stable isotopes from the middle Eocene-to-early Oligocene interval (~40 to 30 Ma) at DSDP Site 277

and relate these variations to radiolarian assemblage changes at DSDP Sites 280, 281, 283 and ODP Site 1172. DSDP Site 277 provides a unique record of pelagic sedimentation in the Southwest Pacific from the late Paleocene to Oligocene times and the first Eocene benthic $\delta^{18}\text{O}$ record was generated from this site (Shackleton and Kennett, 1975).

Although Lazarus et al.'s (2008) study included all above mentioned DSDP sections, this new work i) provides a re-analysis of radiolarian taxonomy at the Southwest Pacific sites, ii) presents the integration of oxygen and carbon isotopes and radiolarian fauna data and iii) investigates if tropical-subtropical conditions persisted in the Southwest Pacific until at least the late Eocene. Our results will help to identify the timing and nature of the development of a distinctive Southern Ocean fauna and discuss implications for the oceanographic history of the SW Pacific from the middle Eocene to early Oligocene.

Comment on biogeographic assignments: *A second substantial criticism is the assignment of individual radiolarian species to biogeographic categories, e.g. Antarctic, Tropical, etc. Paleogene radiolarian biogeography unfortunately is not at all well known for most species, in contrast to the more extensively studied, and far less diverse groups like foraminifera and calcareous nannofossils. The early synthesis by Lazarus and Caulet was based primarily on the subjective but extensive experience of the two authors (Lazarus for the Neogene, Caulet for the Paleogene) as there were at the time no methods available to easily synthesise the scattered primary literature. Many tools are now available which in principle allow a more rigorous, objective basis for biogeographic interpretation, and I had hoped that this ms would provide this as a new, better foundation for current and future research. The authors unfortunately do not provide any details as to how biogeographic assignments were done for individual species, nor is this available from the SOM or the other papers cited. This is a missed opportunity at the least. The ms needs to provide (in the SOM) a brief but sufficient explanation as to why a given species is assigned to a biogeographic category. Funakawa and Nishi's (2008) study gives a good example of how this can be presented - a set of sites with radiolarian faunas from the time interval, marked by either presence-absence or relative abundance symbols. The authors have available to them the materials (including the MRC collections used by Funakawa and Nishi, one of which is housed at their institution) and if desired, access to global published occurrence data, either via formal databases such as the NSB system or simple searches of community shared pdf literature archives. Hopefully the authors have in fact done something similar already and only need to provide the documentation.*

Response: We acknowledge this shortcoming in the SOM. In fact, we have followed the approach recommended by the reviewer in most instances. However, we wish to emphasize that this current work is part of an on-going project that will consist of a set of publications. The assignment of biogeographic affinities in this manuscript is based on an intensive and critical taxonomic literature review of radiolarian occurrences from the Southwest Pacific, Southern Ocean and other sites. Because of the challenges in ensuring taxonomic names have been applied consistently, we have not yet undertaken the same scrutiny of lower latitude records. However, we accept that we could have made greater use of resources such as the NSB database to check the occurrences of relatively well-known species.

Unfortunately, this database lacks many Paleogene radiolarians, and occurrence data are not always robust and still need to be cross-checked with the DSDP/ODP reports. Also we observed that presence/absence data are not always a reliable guide to biogeographic affinity. For instance, *Lithomelissa ehrenbergi* (Buetschli 1882) was described from Barbados, so one might consider this species as tropical or cosmopolitan. However, the species is far more abundant at high-latitude sites,

and only rarely recorded at low-latitude sites. Moreover, Haeckel (1887) found recent *L. ehrenbergi* from deep-water samples at low latitudes. Therefore, we interpret this species as a cold-water indicator, commonly found in high-latitude samples and sometimes found in deep-water samples in low latitudes. We revised Table 1 (below) and provide an additional table in the supplementary material with information on the biogeographic affinity of each species. Furthermore, we provide the paleolatitudes of all sites for certain age-ranges, that we derived from www.paleolatitude.org (van Hindsbergen et al. 2015).

Comment on specific assignments (*L. minor*, *A. murrayanum*, *A. proluxum*): Nor are the biogeographic assignments given always plausible. For example, *Lithelius minor* is definitely cosmopolitan, although it does seem to be less common in tropical than temperate sections in the late Neogene. Also problematic are the two species (*A. murrayanum* and *A. proluxum*) which are the basis in the ms for inferring a tropical water conditions extending into polar regions in the Eocene. Both these species are reported in the literature in a wide variety of locations in the Paleogene: the Russian platform, Poland, Kamchatka, the northern Atlantic, Argentina and even well south of the Pascher study region, from the Kerguelen Plateau. Liu et al. (2011, Palaeoworld) explicitly challenge the claim that these species are tropical indicators.

Response: Although *L. minor* gr. seems to be more common in colder waters than in warmer, we agree that we cannot assign it to the high-latitude group. We assign this taxon to the cosmopolitan group, although we still want to single it out on revised Figures 6 and 7, as it is very abundant in the Southwest Pacific. The biogeographic affinities of *Amphicraspedum murrayanum* and *A. proluxum* group warrant some discussion. These taxa are widely reported in early and middle Eocene sediments but occur in greater abundance in the SW Pacific at times of global warmth (Hollis, 2006). The criticism raised by Liu et al. (2011) was based on the assumption that SW Pacific and North Atlantic Ocean conditions would have been similar in the Eocene. The assumption was said to be supported by an ocean circulation model (i.e. Huber et al. 2004), when in fact this model shows nothing of the sort (cf. Huber et al. 2003). The model indicates that oceanic conditions for the North Atlantic and the Southwest Pacific are substantially different: the North Atlantic is bathed in warm currents of ~25°C moving northwards (Figure 1 below), while the SW Pacific is influenced by a strong cyclonic gyre preventing warm waters from penetrating southwards, except during times of extreme global warmth (see Figure 2 and Hollis et al. 2012). Thus, the occurrence of warm water indicators throughout the Paleocene-Eocene interval in the mid-latitude North Atlantic is consistent with both the GCM results and our interpretation of influxes of *Amphicraspedum* as being indicative of warming. The significance of occurrences of this genus in other high-latitude regions still needs to be assessed with reference to its abundance and the timing of its occurrence.

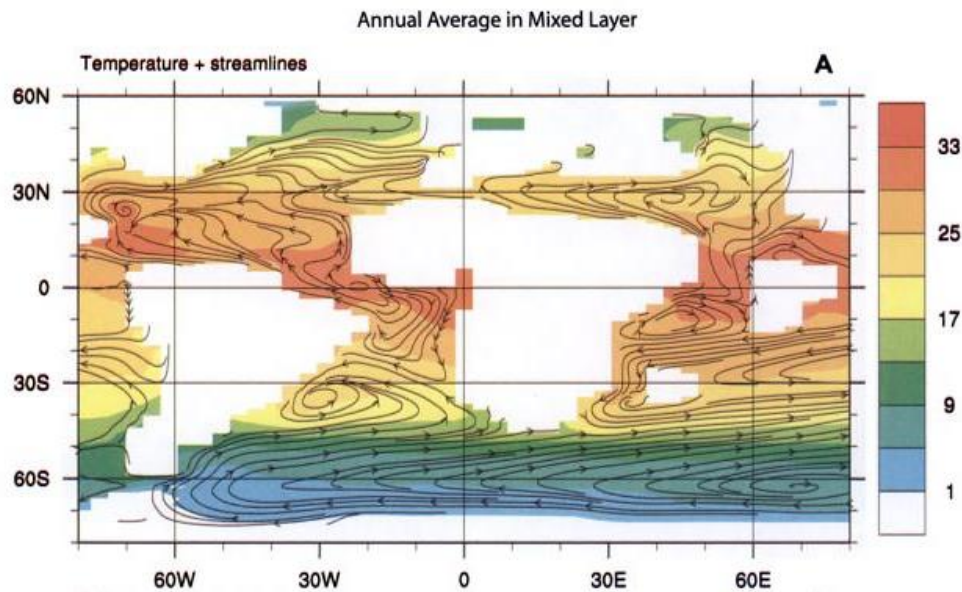


Fig. 1 from Huber et al. (2003) showing annual average temperatures in mixed layer.

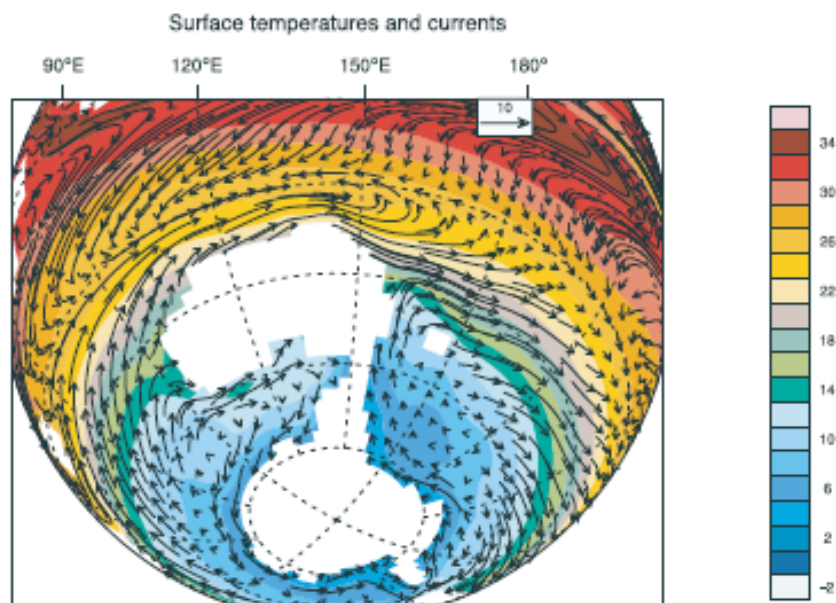


Fig. 2 from Huber et al. (2004), modelled sea surface temperatures and velocity results.

In order to gain more insight into how assemblages at Site 277 changed in response to short-lived warming events, we have examined 5 additional samples (core 23R-1, 100cm, 23R-2, 22cm, 23R-2, 100cm, 23R-3, 20cm and 23R-3, 100cm) that lie within a late Eocene warming event based on the stable isotope record. We included these samples in revised versions of Figures 4, 6, 7 and 8. Within this interval, high-latitude taxa drop, *Lithomelissa* spp. and *Larcopyle* spp. are rare or absent. At the same time, cosmopolitan taxa increase (e.g. *Lychnocanium* spp.) and *Thyrsocyrtis pinguisoides*, that we now assign to the low-latitude group, is abundant. Interestingly, Artostrobiidae are completely absent, but are very abundant directly before and after this event.

Comment on data analysis and biogeographic affinities: *Another issue is the data analysis. I do not see anything in it that, if done differently is likely to completely change the interpretations, but nonetheless there are some weaknesses that could be improved, and which might well also improve the clarity of the results. The most important here is the use of percent values for biogeographic categories that include the most common category of 'unknown'. This makes the patterns, e.g. the time series changes particularly sensitive to the amount of unknowns. This is problematic because the percent unknown is partially a function of preservation/ abundance in the sediment, as can be seen in Figure 6 - taxic richness correlates with % unknown throughout the lower half of the main data series in Site 277, and taxic richness in this interval is certainly a function of abundance since the sample count values are very low (see the spread sheet in the SOM - a plot of species richness vs total count [attached - not fully kosher as it is not one sample, but at least all from one site] gives a typical sampling curve where true richness values are only seen for counts in excess of ca 2,000 specimens). The specific mechanism linking this to % unknown can only be guessed at but probably reflects poorer preservation increasing the number of individuals not identifiable to species level. I suggest recalculating the biogeographic affinities to % of individuals that have been assigned to a biogeographic category only. I suspect that the resulting plots will show the trends claimed in the paper even better than the current figures do.*

Response: We removed the “Unknown” group from Figs. 6 and 7, showing biogeographic affinities. As suggested by the reviewer, the observed patterns are now more clearly identifiable. Furthermore, we changed the colour for *L. minor* gr. to green (cosmopolitan group). We still think it is important to single this group out as it makes a large percentage of the assemblages. Since Figs. 6+7 now show only the species assigned to a biogeographic affinity group, we will recalculate Table 2 accordingly with the % of high-latitude taxa from the number of taxa assigned to one of the three groups (high-latitude, cosmopolitan, low-latitude).

Comment on diversity measurements: *Also, given the fully typical dependence of raw species richness on sample size, if the authors wish to mention diversity in any other sense than as a synonym for abundance (which is the current state of the ms) they should use some sort of subsampling procedure, as is long standard in other areas of biology-paleontology. Simple rarefaction might be adequate in this material. I would only include species level identifications in this.*

Response: We recognize that the lower the counts, the less reliable diversity measurements are. Indeed, the low abundance counts at Site 277 correlate with preservation, resulting in diversity measures and taxic richness being overall underestimated. Following the reviewer's recommendation, we applied an 'Individual rarefaction' analysis for taxic richness with PAST which allows to compare taxonomical diversity in samples of different size. We added the derived taxic richness for Site 277 in Figure 4, and used the Fisher alpha diversity measure in Figure 7 for all sites instead of taxic richness. For site 277 we show the calculated taxic richness for 100, 200, 300 and 500 counts, respectively (Figure 4 revised). Our study shows that counts of at least 300 specimens are required to get a reliable measure of diversity and richness. Thus, diversity measures are considered unreliable where counts are < 300 and diversity is underestimated. However, a sample size of 100 specimens shows the observed trends as well. It was not always possible to achieve this minimum value in our sparse samples (9 samples less than 100 specimens). We therefore removed all samples that have less than 100 specimens from Figure 6 and 7 for Site 277.

Although not commented upon by the reviewer, we also calculated the range-through taxic richness after subsampling for Site 277 with R (www.r-project.org) (Figure 4 revised) to see if the diversity drop between 230-290 mbsf is a preservational artefact or a real temporary absence. We have chosen a sample size of 100 and 300, respectively, which show a similar pattern (both with a subsampling of 1000). According to this analysis, taxic richness is higher as observed from samples of Core-26 to Core 32 (~235-292 mbsf). Chert nodules are present from 246 mbsf downcore, so the absence of species in the interval between 246–350 mbsf seems to be an artefact of diagenesis. However, during

the MECO, taxic richness increases. The results also show the increase in taxa related to the PrOM event around ~225 mbsf, but do not show the observed decrease of taxa during the late Eocene warming event, but instead a slight increase. In conclusion, derived range-through taxic richness can be a helpful tool in determining the presence/absence of taxa due to diagenesis or real temporary absence. But to distinguish between these two scenarios, it is essential to analyse the nature of the sediment (e.g. chert nodules) as well as the nature of faunal assemblages (e.g. presence/absence of high-latitude/low-latitude taxa).

Comment on ODP 1172 data: *There is an issue with the Site 1172 data, which forms a significant part of the analysis. Unlike the other data this is not in the SOM or cited publications - the 2009 Suzuki paper is just a taxonomic survey. It would be better to have this data in the SOM, and Suzuki added as a junior author for the ms.*

Response: The census counts for Site 1172 formed part of a Master's project by Kentaro Chiba and was provided to us by Noritoshi Suzuki. At the time of submitting this article, we were not sure of Mr Chiba's plans for publication. After further discussion with Dr Suzuki, we have very willingly agreed to add Suzuki and Chiba as co-authors to this paper. The census data are now provided in the SOM.

Comment on isotopes: *Lastly, a comment on the isotopes. I am not very convinced by the correlations shown - the only feature of the new data that seems clear is the oxygen isotope shift equivalent to the E-O boundary. It might be better to show each Site's age models (in the SOM) and plot the isotope data for both 277 and the reference site 689 vs age, adding correlation lines based on biostrat events. This might make the claimed correlations of the very gappy data in 277 to 689 more plausible.*

Response: We agree that Figure 2 needs some improvements in correlation (revised Figure 2 below). We enlarged the isotope plot for Site 689 so the three events (EOT, PrOM and MECO) are approximately on the same level to Site 277, which makes it easier to compare. We have chosen not to develop an age model for Site 277 because there are significant uncertainties relating to sampling gaps and over the age of some bioevents. However, we recognise the benefit of showing how key bioevents support the correlation of isotope records between Sites 277 and 689. The isotope record at Site 689 and the bioevents at Site 277 are both calibrated to the 2012 geological timescale (Gradstein et al., 2012; Raine et al., 2015). We recognized that the MECO is a very thick interval at Site 277. However, this is due to the poor core recovery and especially the core gaps of about 10m between cores 32 and 33, 33 and 34, and 34 and 35, respectively. The onset of the MECO is clearly identifiable, however due to the incomplete record, the top of the event is uncertain. The same holds for the PrOM event, the base is clearly identifiable; however the top of the event is uncertain due to the incomplete record.

Further comments on the manuscript by David Lazarus

Comment p. 2981: *to point (i) previously documented in Lazarus et al 2008. OK to question this and thus wish to test but please explain reasons for doubt.* (text in ms: We use these data to test if i) a distinct Southern Ocean fauna was established prior to the major shift in oxygen isotopes in the earliest Oligocene)

Response: We don't question the general results of Lazarus et al. (2008). However, we wanted to see if the timing of the establishment of a Southern Ocean fauna in the SW Pacific could be refined. Indeed our results show that the turnover is not as sudden as that indicated by Lazarus et al. (2008), as high-latitude taxa increase from the middle Eocene. However, the major increase happens in the late Eocene and we are able to tie this change to the PrOM event. The major outcome of our work is the re-analysis of the Southwest Pacific sites and the integration with stable isotopes.

We revised the final part of the introduction to the following:

Although Lazarus et al.'s (2008) study included all above mentioned DSDP sections, this new work i) provides a re-analysis of radiolarian taxonomy at the Southwest Pacific sites, ii) presents the integration of oxygen and carbon isotopes and radiolarian fauna data and iii) investigates if tropical-subtropical conditions persisted in the Southwest Pacific until at least the late Eocene. Our results will help to identify the timing and nature of the development of a distinctive Southern Ocean fauna and discuss implications for the oceanographic history of the SW Pacific from the middle Eocene to early Oligocene.

Comment: P. 2981: please comment on rotary disturbance

Response: We have analysed the scientific report of DSDP Leg 29 on core disturbance, and include this information in the supplementary data file for each site and sample. We categorized disturbance as 'intact' (I), 'blocks' (B), 'disturbed' (D) with occurring 'slurry' (s) or 'breccia' (b) features and added that information in the SOM. However, in addition to the large gaps between cores 32–35, the degree of disturbance is very variable throughout a core on cm-scale (according to core photographs of DSDP Site 277 report). Cores are mainly intact and coherent between core 15 and 25, the sediment changing to 'blocks' in the remaining cores, with breccia or slurry deformation.

Comment: P. 2984 Need to clarify depth habitat for these taxa - which is benthic, planktic.

Response: We updated the manuscript with the following:

At the University of California Santa Cruz (UCSC) and the University of Southampton (UoS), stable oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) isotope ratios were determined for bulk carbonate, *Cibicidoides* spp. (benthic species), *Subbotina* spp. (planktic, mixed layer) (Core 277-34R (332.62 mbsf) to 18R (159.88 mbsf) and *Globigerinatheka index* (planktic, uppermost surface waters) (Core 277-34R (332.62 mbsf) up to its last occurrence in Core 277-21R (188.58 mbsf))

Comment: P. 2985: more detail on preservation helpful as Paleogene diagenetic biases are common even in superficially well preserved specimens.

Response: There is no reason to suspect a large diagenetic bias as a normal gradient exists between benthic, subsurface and surface dwelling planktic isotopic values (revised Figure 3). However, as benthic values are more reliable than planktics, we focused our interpretation on benthic isotopes.

Comment: P.2995: This appears to have been pulled out of thin air. Please explain how a quantitative temperature estimate is made from what we know of Paleogene radiolarian temperature correlations.

Response: We have revised the text to the following:

The persistence of high-latitude taxa and the variety of cosmopolitan species at both sites suggests a warm-temperate climate of (15–20°C, Nelson and Cooke, 2001), in contrast to geochemical proxies suggesting a tropical climate (> 25°C) for the MECO at Site 1172 (Bijl et al., 2010) and ~27°C for the late Eocene at Site 277 (Liu et al., 2009).

The important message is that the temperatures were not tropical in the middle to late Eocene in the SW Pacific at the investigated sites, because low-latitude radiolarians are only present in rare numbers, and typical taxa encountered in low-latitude sites (*Podocyrthis*, *Thyrsoyrthis*) are missing. Based on the stable isotopes and the radiolarian fauna, we are able to identify the late Eocene warming event ~36.4Ma (Bohaty and Zachos 2003), with a common presence of *Thyrsoyrthis pinguicoides*, which we consider to be a warm-water indicator. The absence of other low-latitude taxa suggests modest warming, possibly to subtropical conditions.

Comment: *P. 2997: The ca 20 m interval is also where rad abundance is extremely low, which is most likely indeed a preservation artifact, if not a diagenetic one.*

Response: We replaced “artefact of preservation” on p. 2997, line 1 with “artefact of diagenesis”.

Comment: *P. 3018: site 283 seems plotted at wrong age map.*

Response: We have changed the maps, due to referee two. Please see below (revised Figure 8).

Response to anonymous referee

Comment: *The authors mention, almost in passing, that their faunal and geochemical results are in conflict with the geochemical records of Bijl et al., 2010 and Liu et al., 2009. The authors should at least attempt an explanation of why this discrepancy exists.*

Response: We agree with this comment. We will expand this section in the manuscript. We can address this issue now in more detail as we have obtained 5 samples within the late Eocene warming interval.

Comment: *My biggest issue with the manuscript is the tectonic reconstruction and inferred circulation patterns shown in Fig. 8.*

Response: We apologize for not having given enough explanation and details about the tectonic reconstructions used in the previous manuscript. We now include information from a recent publication by van Hinsbergen et al. (2015) and are now using the following reconstructions:

Tectonic reconstructions of the Australia-Antarctica-Pacific plate circuit were undertaken in GPlates (Boyden et al. 2011) using finite poles of rotation for the relative motions between: Australia-East Antarctica from Cande & Stock (2004) (0-38.13 Ma) and East Antarctica-West Antarctica from Granot et al. (2013) (30.94-40.13 Ma) and West Antarctica-Pacific from Croon et al. (2008) (0-47.54 Ma). Relative motions of the Australia-Antarctica-Pacific plate circuit were tied to the Australian paleomagnetic apparent polar wander path of Torsvik et al. (2012) to provide an estimate of paleolatitude appropriate for paleoclimate studies (van Hinsbergen et al., 2015). The 2000 m isobath from the GEBCO bathymetric grid was used to approximate continental boundaries. The continental/oceanic boundaries of Bird (2003) are also shown (dashed lines in Figure 1 and 8) for reference for regions where extension has significantly thinned continental crust. DSDP/ODP sites have been assigned to the appropriate plate for reconstruction.

The overlap of the North and South Islands of New Zealand is a consequence of the finite poles of rotation from the Adare Trough of Granot et al. (2013) describing the motion of East and West Antarctica between 40 and 30 Ma. These new poles result in a poor fit (significant overlap) of continental crust between the two islands that is not supported by geological data. These issues were not addressed in a recent publication by Matthews et al. (2015). The discrepancy between geological and paleomagnetic data could be reconciled with the use of seafloor spreading data from the Emerald basin (e.g. Keller, 2003), which describes Australia-Pacific relative motions (Sutherland, 1995) between 40 to 30 Ma, and the Adare Trough. No published reconciliation is presently known to the authors.

Comment: *Also the authors need to clarify what they mean in reference to the Tasmanian Gateway being fully open (example is line 15 page 24). Fully open meaning to deep waters? The geophysics of the COB and tectonic reconstructions allow for fairly explicit ages for a deep connection. A deep connection was established 33.5 +/- 1.5 Ma. I would also like the authors to consider that water mass*

reconstructions of Scher et al., 2015 support the hypothesis by Bijl et al., 2013 that the first current to flow through the gateway flowed westward (from Pacific to Indian), probably under the influence of the polar easterlies, as the gateway was in a more southerly position. I do not think that the flow regime described by Scher et al., 2015 is inconsistent with the faunal and geochemical results presented here, though the authors should consider this. The above flow regime persisted until 30-29 Ma, when the northern margin of the gateway appears to have crossed into the westerlies. The arrow currently drawn through the gateway in the reconstructions in Fig. 8 is not consistent with the recent water mass reconstructions (Scher et al., 2015). I also think that the label ACC should be removed from panel D. The large scale homogenization of water mass tracers throughout the Southern Ocean, pointing to establishment of the ACC, does not occur until after 29 Ma.

Response: We have updated Figure 8 accordingly. We will revise the text in the manuscript.

We have revised Fig. 8B in showing the early late Eocene interval (~38–37 Ma), that includes the PrOM event for Site 277 and have added a Subtropical Front (STF) across the Tasman Sea, which seemed to have been a high-productive upwelling region. According to Nelson and Cooke (2001), the STF was the first that had established. We have also added the westward flowing Antarctic Slope Current (ASC) according to Bijl et al. (2013) and Scher et al. (2015).

Furthermore, we have added Figure 8C for showing the late Eocene warming event (~36 Ma), which is evident at Site 283 and 277 by an influx of low-latitude taxa. We interpret this as short more southward shift of the East Australian Current (EAC) and a weakening of the Ross gyre. However, the STF shifted southward along the Campbell Plateau and Site 277 did not experience high-productivity.

Figure 8D shows the latest Eocene-earliest Oligocene interval (~35–32 Ma), with widespread non-deposition across the Tasman region and a high productive area at Site 277. A strong Ross gyre created upwelling and a northward shift of the STF on the Campbell Plateau. In the South, Site 280 has an earliest Oligocene record only, showing a high-productive diatom-rich endemic radiolarian assemblage.

Finally the early Oligocene map 8E shows a strong high-latitude assemblage for Site 1172 and 277. We infer from Site 277, that this condition is similar to today's, an oligotrophic, cold-water environment on the Campbell Plateau, which resulted in a decrease in radiolarian abundance. Both Site 1172 and 277 show the dominant high-latitude species *Axoprunum irregularis*. We interpret this scenario as the start of the Antarctic Circumpolar Current (ACC) around ~30 Ma, adapted from Carter et al. (2004), with the Tasmanian Gateway situated at about 60°S.

References

- Bird, P.: An updated digital model of plate boundaries, *Geochemistry, Geophysics, Geosystems*, 4, 2003.
- Bohaty, S. M., and Zachos, J. C.: Significant Southern Ocean warming event in the late middle Eocene, *Geology*, 31, 1017-1020, 2003.
- Boyden, J. A., Müller, R. D., Gurnis, M., Torsvik, T. H., Clark, J. A., Turner, M., Ivey-Law, H., Watson, R. J., and Cannon, J. S.: Next-generation plate-tectonic reconstructions using GPlates, *Geoinformatics: cyberinfrastructure for the solid earth sciences*, 95-114, 2011.
- Cande, S. C., and Stock, J. M.: Pacific—Antarctic—Australia motion and the formation of the Macquarie Plate, *Geophysical Journal International*, 157, 399-414, 2004.

- Carter, L., Carter, R., and McCave, I.: Evolution of the sedimentary system beneath the deep Pacific inflow off eastern New Zealand, *Marine Geology*, 205, 9-27, 2004.
- Croon, M. B., Cande, S. C., and Stock, J. M.: Revised Pacific-Antarctic plate motions and geophysics of the Menard Fracture Zone, *Geochemistry, Geophysics, Geosystems*, 9, 2008.
- Edwards, A. R., 1991. The Oamaru Diatomite. New Zealand Geological Survey Paleontological Bulletin, 64. 260pp.
- Gradstein, F., Ogg, J., Schmitz, M., and Ogg, G.: The geologic time scale 2012, vol. 2, Elsevier New York, 2012.
- Granot, R., Cande, S., Stock, J., and Damaske, D.: Revised Eocene-Oligocene kinematics for the West Antarctic rift system, *Geophysical Research Letters*, 40, 279-284, 2013.
- Hollis, C. J.: Radiolarian faunal turnover through the Paleocene-eocene transition, Mead Stream, New Zealand, in: *Radiolaria*, Springer, 79-99, 2006.
- Huber, M., Sloan, L. C., and Shellito, C.: Early Paleogene oceans and climate: A fully coupled modeling approach using the NCAR CCSM, *Geological Society of America Special Papers*, 369, 25-47, 2003.
- Huber, M., Brinkhuis, H., Stickley, C. E., Döös, K., Sluijs, A., Warnaar, J., Schellenberg, S. A., and Williams, G. L.: Eocene circulation of the Southern Ocean: Was Antarctica kept warm by subtropical waters?, *Paleoceanography*, 19, PA4026, doi:10.1029/2004PA001014, 2004.
- Keller, W.R., 2003. Cenozoic plate tectonic reconstructions and plate boundary processes in the Southwest Pacific. Unpub. PhD Thesis: California Institute of Technology. Pasadena.
- Liu, J., Aitchison, J. C., and Ali, J. R.: Upper Paleocene radiolarians from DSDP Sites 549 and 550, Goban Spur, NE Atlantic, *Palaeoworld*, 20, 218-231, 2011.
- Matthews, K. J., Williams, S. E., Whittaker, J. M., Müller, R. D., Seton, M., and Clarke, G. L.: Geologic and kinematic constraints on Late Cretaceous to mid Eocene plate boundaries in the southwest Pacific, *Earth-Science Reviews*, 140, 72-107, 2015.
- Nelson, C. S., and Cooke, P. J.: History of oceanic front development in the New Zealand sector of the Southern Ocean during the Cenozoic—a synthesis, *New. Zeal. J. Geol. Geop.*, 44, 535-553, 2001.
- Nishimura, A.: Cenozoic Radiolaria in the western North Atlantic, Site 603, Leg 93 of the Deep Sea Drilling Project, in: Van Hinte, J.E. Wise, S.W.Jr. et al., *Initial Reports of the Deep Sea Drilling Project*, Vol. 93, U.S. Government Printing Office, Washington, D.C., 713-737, 1987.
- Pearson, P.N., Olsson, R.K., Huber, B.T., Hemleben, C. and Berggren, W.A. (2006) *Atlas of Eocene Planktonic Foraminifera*, Cushman Foundation Special Publication no. 41. Cushman Foundation, Washington DC, p. 514.
- Raine, J. I., Beu, A. G., Boyes, A. F., Campbell, H. J., Cooper, R. A., Crampton, J. S., Crundwell, M. P., Hollis, C. J., and Morgans, H. E. G.: Revised calibration of the New Zealand Geological Timescale : NZGT2015/1, Lower Hutt, N.Z.: GNS Science. GNS Science report 2012/39. 53 p, 2015.

Riedel, W. R., and Sanfilippo, A.: Cenozoic Radiolaria from the Caribbean, Deep Sea Drilling Project, Leg 15, in: Edgar, N.T., Saunders, J.B. et al.: Initial Reports of the Deep Sea Drilling Project, U.S. Government Printing Office, Washington, D.C., 705-751, 1973.

Sutherland, R.: The Australia-Pacific boundary and Cenozoic plate motions in the SW Pacific: Some constraints from Geosat data, *Tectonics*, 14, 819-831, 1995.

Torsvik, T. H., Van der Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P. V., van Hinsbergen, D. J., Domeier, M., Gaina, C., and Tohver, E.: Phanerozoic polar wander, palaeogeography and dynamics, *Earth-Science Reviews*, 114, 325-368, 2012.

van Hinsbergen, D. J., de Groot, L. V., van Schaik, S. J., Spakman, W., Bijl, P. K., Sluijs, A., Langereis, C. G., and Brinkhuis, H.: A Paleolatitude Calculator for Paleoclimate Studies, *PloS one*, 10, e0126946, 2015.

Table 1 revised. Summary of species encountered at sites 277, 280, 281, and 283, and 1172 their biogeographic affinities (H=high-latitude, B=bipolar ($>45^{\circ}\text{N/S}$), L=low-latitude ($<25^{\circ}\text{N/S}$) and C=cosmopolitan), and location on plates for selected species. Additional information on biogeographic affinity of species can be found in the supplementary material.

Taxa	Biogeogr. affinity	Site 277	Site 280	Site 281	Site 283	ODP 1172	Plate
<i>Actinommidae</i> sp. A sensu Hollis		x					Pl. 1, Fig. 1
<i>Amphicentria</i> sp. 1 sensu Suzuki	H	x		x	x	x	Pl. 2, Fig. 1
<i>Amphicraspedum murrayanum</i> Haeckel	L	x					Pl. 1, Fig. 14
<i>Amphicraspedum prolixum</i> Sanfilippo and Riedel gr.	L	x	x				Pl. 1, Fig. 15-17
<i>Amphisphaera</i> aff. <i>radiosa</i> (Ehrenberg)		x					Pl. 1, Fig. 4a,b
<i>Amphisphaera coronata</i> (Ehrenberg) gr.	C	x			x	x	Pl. 1, Fig. 2
<i>Amphisphaera radiosa</i> (Ehrenberg)		x					Pl. 1, Fig. 3
<i>Amphisphaera spinulosa</i> (Ehrenberg)	C	x			x		Pl. 1, Fig. 5
<i>Amphisphaera</i> ? <i>megapora</i> (Ehrenberg)		x	x	x	x		Pl. 1, Fig. 6
<i>Amphymenium splendiamatum</i> Clark and Campbell	C	x	x	x	x		Pl. 1, Fig. 18,19
<i>Anomalocantha dentata</i> (Mast)		x	x	x	x	x	
<i>Antarctissa cylindrica</i> Petrushevskaya	H		x				
<i>Antarctissa robusta</i> Petrushevskaya	H		x				
<i>Aphetocyrtis bianulus</i> (O'Connor)	H	x			x	x	Pl. 5, Fig. 1
<i>Aphetocyrtis gnomabax</i> Sanfilippo and Caulet	H	x	x	x	x		Pl. 5, Fig. 2-7
<i>Aphetocyrtis rossi</i> Sanfilippo and Caulet	H	x	x		x		Pl. 5, Fig. 8-11
<i>Archipilium macropus</i> (Haeckel)		x			x		
<i>Artobotrys auriculaleporis</i> (Clark and Campbell)	C	x				x	
<i>Artobotrys titanothericeraos</i> (Clark and Campbell)		x		x		x	
<i>Artostrobos annulatus</i> (Bailey)	B	x			x		
<i>Artostrobos</i> cf. <i>pretabulatus</i> Petrushevskaya	H	x					Pl. 3, Fig. 13
<i>Aspis</i> sp. A sensu Hollis	H	x	x		x		Pl. 3, Fig. 14-16
<i>Axoprunum bispiculum</i> (Popofsky)	H	x			x		
<i>Axoprunum pierinae</i> (Clark and Campbell) gr.	C	x	x	x	x	x	Pl. 1, Fig. 10,11
<i>Axoprunum</i> ? <i>irregularis</i> Takemura	H	x				x	Pl. 1, Fig. 12
<i>Botryocella</i> ? sp A sensu Apel			x				Pl. 3, Fig. 1-4
<i>Buryella granulata</i> (Petrushevskaya)	H	x				x	
<i>Callimitra</i> ? aff. <i>atavia</i> Goll		x					Pl. 2, Fig. 2
<i>Calocycloma ampulla</i> (Ehrenberg)		x					
<i>Ceratocyrtis</i> spp.	B	x	x		x	x	Pl. 2, Fig. 3-5
<i>Cinclopyramis circumtexta</i> (Haeckel)	C	x	x	x	x	x	
<i>Cladoscenum ancoratum</i> Haeckel			x		x		
<i>Clathrocyclas universa</i> Clark and Campbell	C	x		x	x	x	
<i>Clinorhabdus anantomus</i> Sanfilippo and Caulet	H	x		x	x		Pl. 5, Fig. 12,13
<i>Cornutella profunda</i> Ehrenberg	C	x	x	x	x	x	
<i>Corythomelissa adunca</i> (Sanfilippo and Riedel)					x	x	
<i>Cryptocarpium bussonii</i> (Carnevale) gr.	C	x	x	x	x	x	Pl. 5, Fig. 25a,b, 26a,b
<i>Cryptocarpium ornatum</i> (Ehrenberg)	C	x			x		
<i>Cycladophora cosma cosma</i> Lombardi and Lazarus	H		x				Pl. 3, Fig. 17
<i>Cycladophora humerus</i> (Petrushevskaya)	H		x	x	x		Pl. 3, Fig. 18
<i>Cycladophora</i> spp.	H	x		x	x		
<i>Cymaetron sinolampas</i> Caulet			x		x		
<i>Cyrtolagena laguncula</i> Haeckel	C	x			x		
<i>Dictyophimus</i> ? aff. <i>constrictus</i> O'Connor			x				Pl. 4, Fig. 9, 10
<i>Dictyophimus pocillum</i> Ehrenberg	C	x					
<i>Dictyophimus</i> ? aff. <i>archipilium</i> Petrushevskaya	H	x		x	x		Pl. 4, Fig. 3a,b-8
<i>Dictyophimus</i> ? <i>archipilium</i> Petrushevskaya	H	x	x		x		Pl. 4, Fig. 1a,b, 2
<i>Eucyrtidium antiquum</i> Caulet	H	x	x			x	Pl. 3, Fig. 19
<i>Eucyrtidium mariae</i> Caulet	H	x					
<i>Eucyrtidium microporum</i> Ehrenberg					x		
<i>Eucyrtidium nishimurae</i> Takemura and Ling	H			x	x	x	Pl. 3, Fig. 20a, b
<i>Eucyrtidium spinosum</i> Takemura	H	x		x	x	x	Pl. 3, Fig. 21
<i>Eucyrtidium</i> spp.	H				x		
<i>Eucyrtidium montiparum</i> Ehrenberg	C	x			x		Pl. 3, Fig. 22
<i>Eurystomoskevos cauleti</i> O'Connor	H	x	x	x	x		Pl. 3, Fig. 23a, b
<i>Eurystomoskevos petrushevskae</i> Caulet	H	x	x	x	x	x	Pl. 3, Fig. 24
<i>Eusyringium fistuligerum</i> (Ehrenberg)	C	x				x	Pl. 3, Fig. 25
<i>Eusyringium lagena</i> (Ehrenberg)	C				x		
<i>Glycobotrys nasuta</i> (Ehrenberg) gr.	C	x	x	x	x	x	Pl. 3, Fig. 5-7
<i>Heliodiscus inca</i> Clark and Campbell		x			x		
<i>Lamprocyclas particolis</i> O'Connor	H	x	x	x	x		Pl. 5, Fig. 27
<i>Larcopele</i> cf. <i>pylomaticus</i> (Riedel)	H		x	x			Pl. 1, Fig. 25a, b

<i>Larcopele frakesi</i> (Chen)	H		x				Pl. 1, Fig. 20
<i>Larcopele hayesi</i> (Chen)	H	x	x	x	x		Pl. 1, Fig. 21
<i>Larcopele labyrinthosa</i> Lazarus	H		x				Pl. 1, Fig. 22
<i>Larcopele polyacantha</i> (Campbell and Clark) gr.	H	x	x	x	x		Pl. 1, Fig. 23, 24
<i>Larcopele</i> spp.	H	x	x	x			
<i>Lithelius</i> (?) <i>foremanae</i> Sanfilippo and Riedel		x					
<i>Lithelius minor</i> Jörgensen gr.	C	x	x	x	x	x	Pl. 1, Fig. 26-28
<i>Lithomelissa</i> cf. <i>challengeriae</i> Chen		x					Pl. 2, Fig. 9
<i>Lithomelissa</i> cf. <i>haeckeli</i> Bütschli		x			x		Pl. 2, Fig. 14
<i>Lithomelissa challengeriae</i> Chen	H		x				Pl. 2, Fig. 6-8
<i>Lithomelissa ehrenbergi</i> Bütschli	H	x	x	x	x	x	Pl. 2, Fig. 10, 11
<i>Lithomelissa gelasinus</i> O'Connor	H	x	x	x	x		Pl. 2, Fig. 12, 13
<i>Lithomelissa macroptera</i> Ehrenberg					x		Pl. 2, Fig. 15a, b
<i>Lithomelissa robusta</i> Chen	H		x		x		Pl. 2, Fig. 16
<i>Lithomelissa sphaerocephalis</i> Chen	H	x	x	x	x		Pl. 2, Fig. 17
<i>Lithomelissa</i> spp.	H	x	x	x	x		
<i>Lithomelissa tricornis</i>	H	x	x	x	x		Pl. 2, Fig. 18
<i>Lithomelissa</i> ? <i>sakai</i> O'Connor	H		x				Pl. 2, Fig. 19
<i>Lophocyrtis</i> (Apoplanius) <i>aspera</i> (Ehrenberg)	H	x		x	x		Pl. 5, Fig. 14a, b-16
<i>Lophocyrtis</i> (Apoplanius) <i>keraspera</i> Sanfilippo and Caulet	H	x			x	x	Pl. 5, Fig. 17-19
<i>Lophocyrtis</i> (Lophocyrtis) <i>jacchia hapsis</i> Sanfilippo and Caulet	H	x			x		Pl. 5, Fig. 20-22
<i>Lophocyrtis</i> (Paralampterium) <i>dumitricai</i> Sanfilippo	C	x				x	
<i>Lophocyrtis</i> (Paralampterium) <i>longiventer</i> (Chen)	H	x	x	x	x	x	Pl. 5, Fig. 23, 24
<i>Lophocyrtis</i> spp.	H				x		
<i>Lophophaena capito</i> Ehrenberg	C	x		x	x		
<i>Lophophaena simplex</i> Funakawa			x		x		
<i>Lychnocanium</i> aff. <i>carinatum</i> Ehrenberg		x					Pl. 4, Fig. 17
<i>Lychnocanium amphitrite</i> (Foreman)	C	x			x	x	Pl. 4, Fig. 11a, b, c, 12
<i>Lychnocanium babylonis</i> (Clark and Campbell)	C	x			x		Pl. 4, Fig. 13a, b, 14
<i>Lychnocanium bellum</i> Clark and Campbell	C	x			x	x	Pl. 4, Fig. 15, 16
<i>Lychnocanium conicum</i> Clark and Campbell	C	x					
<i>Lychnocanium continuum</i> Ehrenberg					x		
<i>Lychnocanium tetrapodium</i> Ehrenberg		x					Pl. 4, Fig. 18a, b
<i>Lychnocanium waiakeia</i> O'Connor		x			x		
<i>Perichlamydidium limbatum</i> Ehrenberg			x				
<i>Periphaena decora</i> Ehrenberg	C	x	x	x	x	x	
<i>Periphaena heliastericus</i> (Clark and Campbell)	C	x	x	x	x	x	
<i>Phormocyrtis striata striata</i> Brandt		x					
<i>Plectodiscus circularis</i> (Clark and Campbell)	C	x	x	x	x	x	
<i>Pseudodictyophimus galeatus</i> Caulet	H		x				Pl. 2, Fig. 20
<i>Pseudodictyophimus gracilipes</i> (Bailey) gr.	B	x	x	x	x		Pl. 2, Fig. 21-23
<i>Pseudodictyophimus</i> spp.	H		x				Pl. 2, Fig. 24-27
<i>Pterocodon apis</i> Ehrenberg					x		Pl. 4, Fig. 19, 20a, b
<i>Pteropilium</i> aff. <i>contiguum</i> (Ehrenberg)		x					Pl. 4, Fig. 21
<i>Saturnalis circularis</i> Haeckel					x		
<i>Sethocyrtis chrysallis</i> Sanfilippo and Blome	C	x					Pl. 3, Fig. 26a, b
<i>Siphocampe lineata</i> (Ehrenberg)		x					
<i>Siphocampe nodosaria</i> (Haeckel)	C	x		x	x	x	
<i>Siphocampe quadrata</i> (Petrushevskaya and Kozlova)	C	x		x	x	x	
<i>Siphocampe</i> ? <i>acephala</i> (Ehrenberg) gr.		x			x	x	Pl. 3, Fig. 8-10
<i>Siphocampe</i> ? <i>amygdala</i> (Shilov)	C	x			x		Pl. 3, Fig. 11, 12
<i>Sphaeropyle tetrapila</i> (Hays)	H	x					Pl. 1, Fig. 29
<i>Spirocyrtis greeni</i> O'Connor		x		x	x		
<i>Spirocyrtis joides</i> (Petrushevskaya)	C	x	x	x	x		
<i>Spongatractus pachystylus</i> (Ehrenberg)		x					
<i>Spongodiscus craticulatus</i> (Stöhr)				x			
<i>Spongodiscus cruciferus</i> (Clark and Campbell)	C	x		x		x	
<i>Spongodiscus festivus</i> (Clark and Campbell)	C	x				x	
<i>Spongopyle osculosa</i> Dreyer	B	x	x	x	x	x	Pl. 1, Fig. 13
<i>Spongurus bilobatus</i> Clark and Campbell	C	x		x	x	x	
<i>Stichopilium</i> cf. <i>bicorne</i> (Haeckel)		x	x	x	x		Pl. 5, Fig. 28a, b, 29a, b
<i>Stylosphaera minor</i> Clark and Campbell gr.	C	x	x		x	x	Pl. 1, Fig. 7
<i>Theocampe amphora</i> (Haeckel)	C	x					
<i>Theocampe urceolus</i> (Haeckel)	C	x	x	x	x		
<i>Theocyrtis tuberosa</i> Riedel	L	x			x		Pl. 5, Fig. 30
<i>Thyrsocyrtis pinguisicoides</i> O'Connor	L	x			x		Pl. 3, Fig. 27
<i>Tripodiscinus clavipes</i> (Clark and Campbell)	C	x		x	x		
<i>Zealithapium mitra</i> (Ehrenberg)	C	x			x		Pl. 1, Fig. 8
<i>Zygocircus bütschli</i> Haeckel		x			x		

Revised Figures

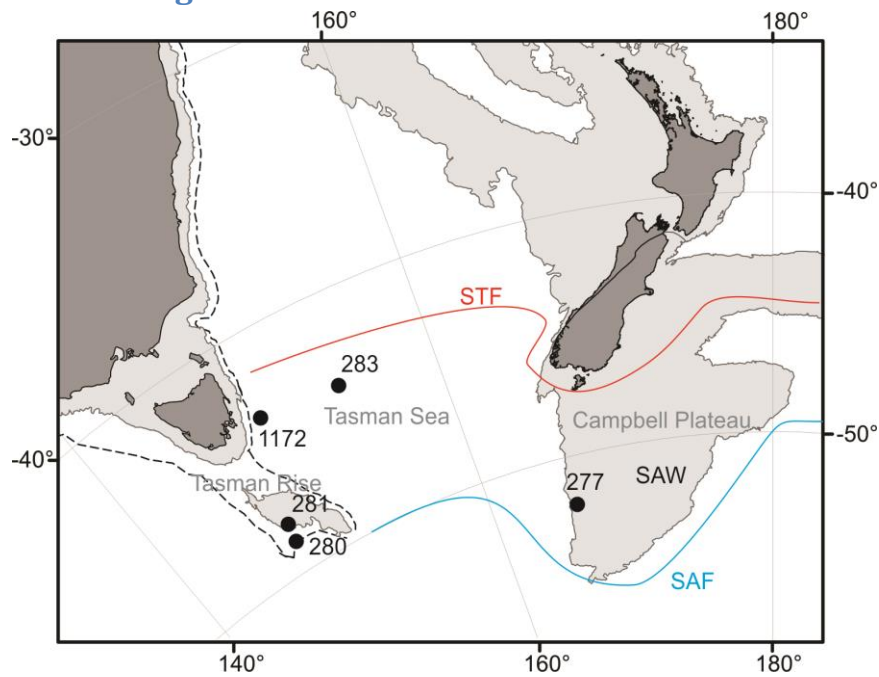


Figure 1 revised. Modern location of DSDP and ODP study sites in the Southwest Pacific; dark grey=coastline, light grey=2000m isobath of the continental/ocean boundary (derived from GEBCO, www.gebco.net), STF=Subtropical Front, SAF=Subantarctic Front, SAW=Subantarctic Water. Dashed line represents the continental/ocean boundary of Bird (2003).

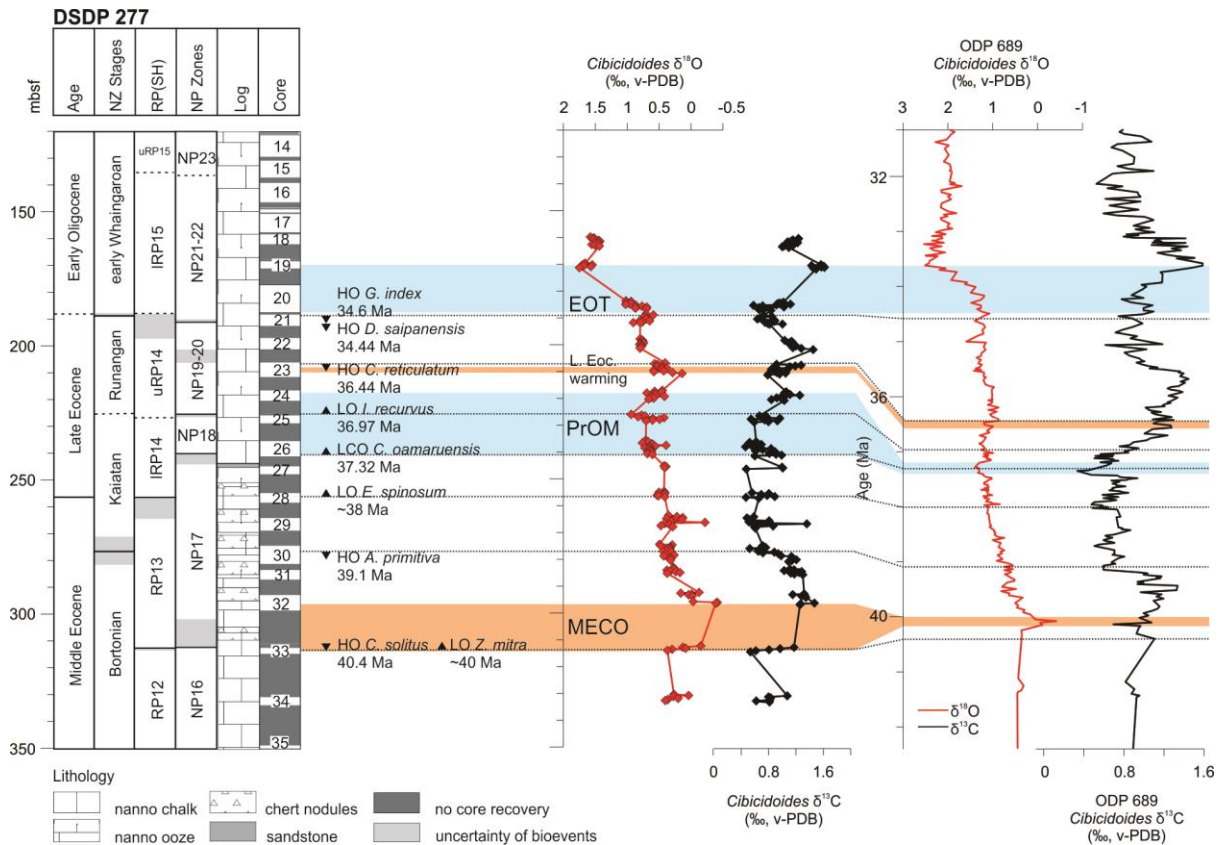


Figure 2 revised. DSDP Site 277 stratigraphy, NZ Stages (Raine et al. (2015), Southern Ocean radiolarian zones (RP), nannofossil zones (NP), lithology, core recovery, selected bioevents (ages calibrated to the 2012 geological timescale (Gradstein et al., 2012; Raine et al., 2015)) and benthic stable oxygen and carbon isotope data of DSDP Site 277. The dashed lines correlate Site 277 based on the ages of the bioevents to Southern Ocean *Cibicidoides* isotopes of ODP Site 689 Hole B (Maud Rise) (Diester-Haass and Zahn, 1996) calibrated to the GTS2012 timescale using the magnetostratigraphy data of Florindo and Roberts (2005) and Spiess (1990). LO=lowest occurrence; LCO=lowest common occurrence; HO=highest occurrence.

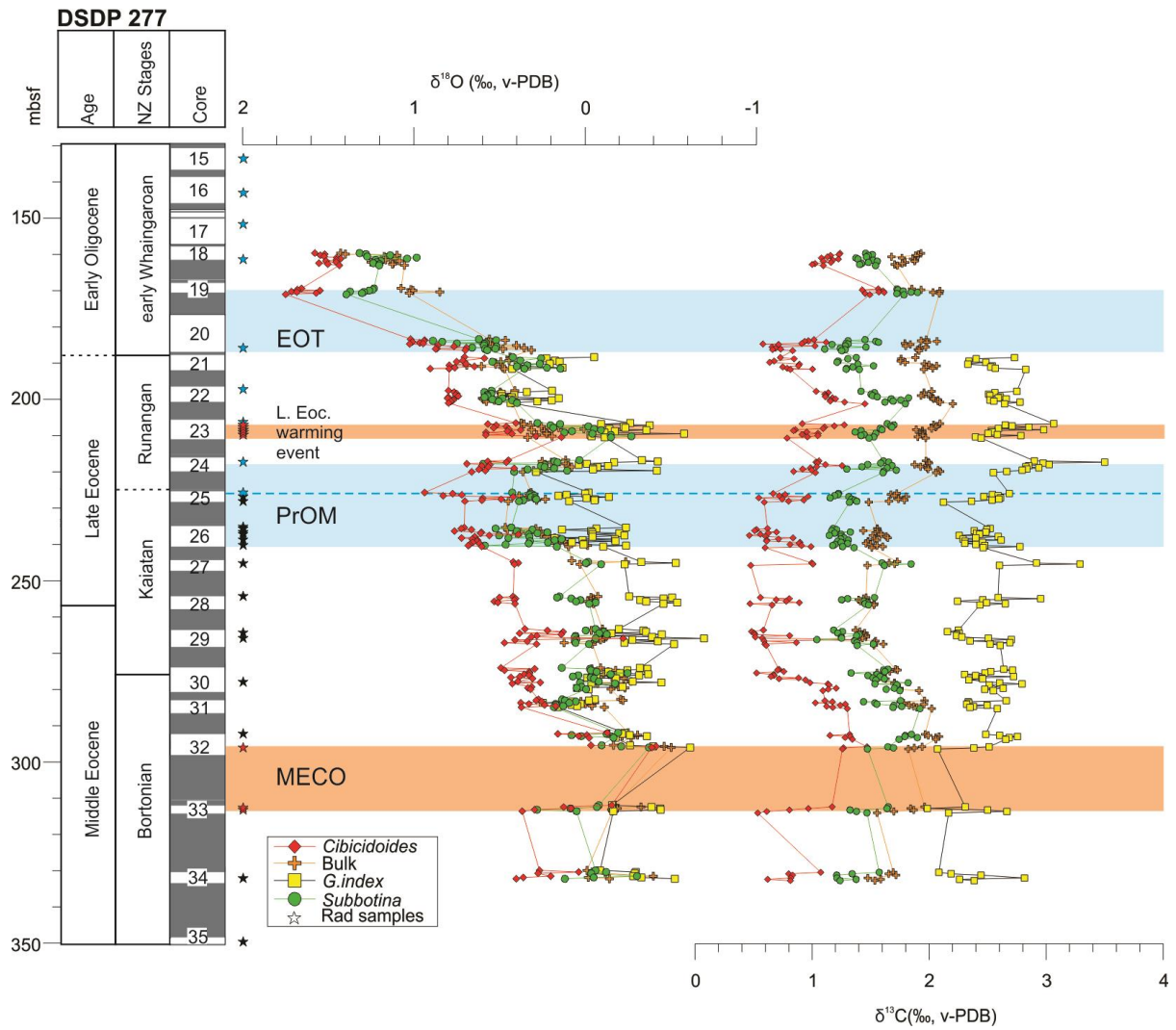


Figure 3 revised. DSDP Site 277 oxygen and carbon stable isotope records and position of studied radiolarian samples within the MECO and the late Eocene warming interval (red stars), and the radiolarian-rich late Eocene-Oligocene interval (blue stars).

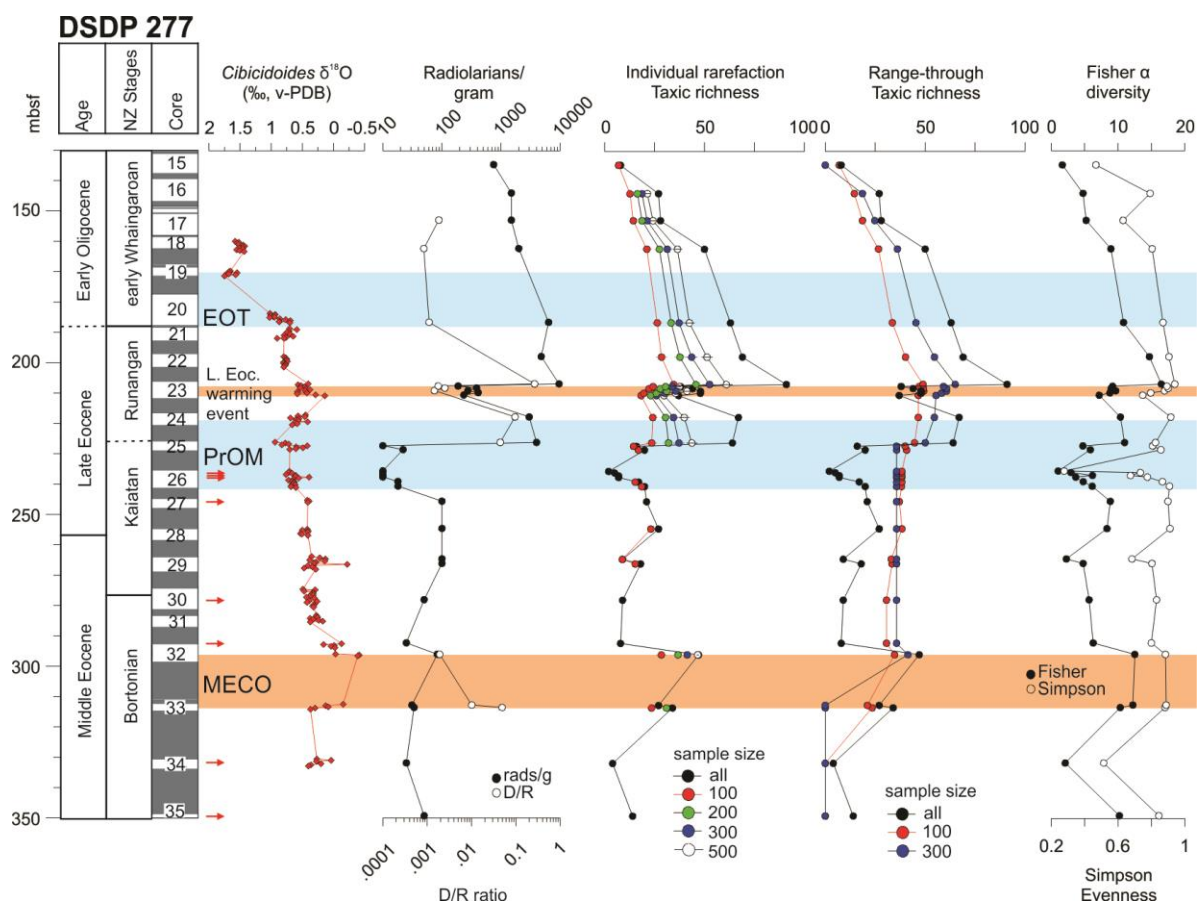


Figure 4 revised. DSDP Site 277 benthic $\delta^{18}\text{O}$ record; radiolarian abundance and Diatom/Radiolarian (D/R) ratio; Taxic richness (number of taxa) derived from individual rarefaction and range-through analyses for different sample sizes; Fisher α diversity Index and Simpson Evenness Index for radiolarian assemblages. Red arrows indicate samples with total specimen counts less than 100, which are statistical insignificant but are included here for the sake of completeness.

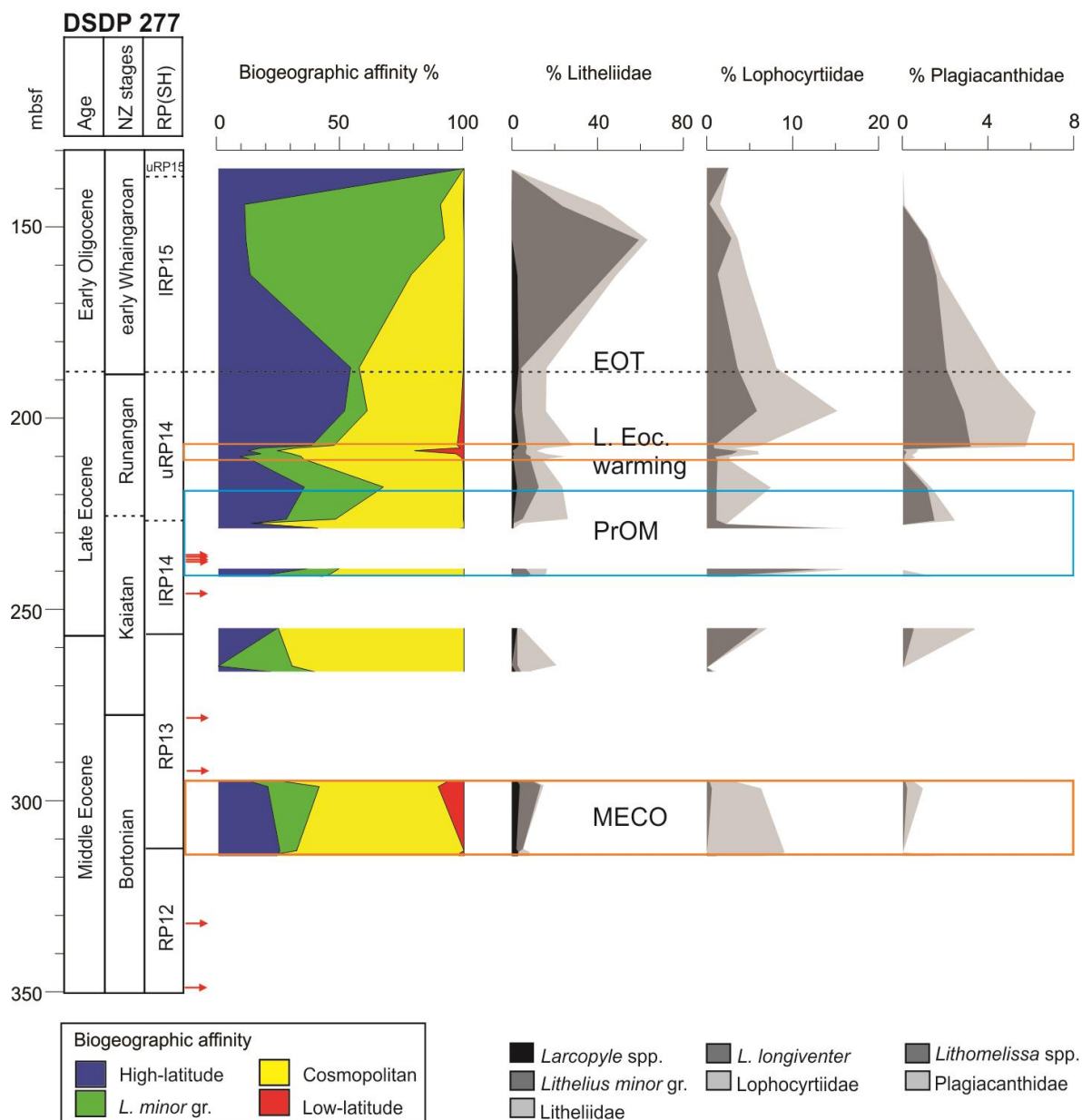


Figure 6 revised. Biogeographic affinities of radiolarian assemblages at DSDP Site 277 and most abundant families with high-latitude affinity (except *Lithelius minor* gr., which is cosmopolitan). Red arrows indicate samples with less than 100 specimens that have been removed here.

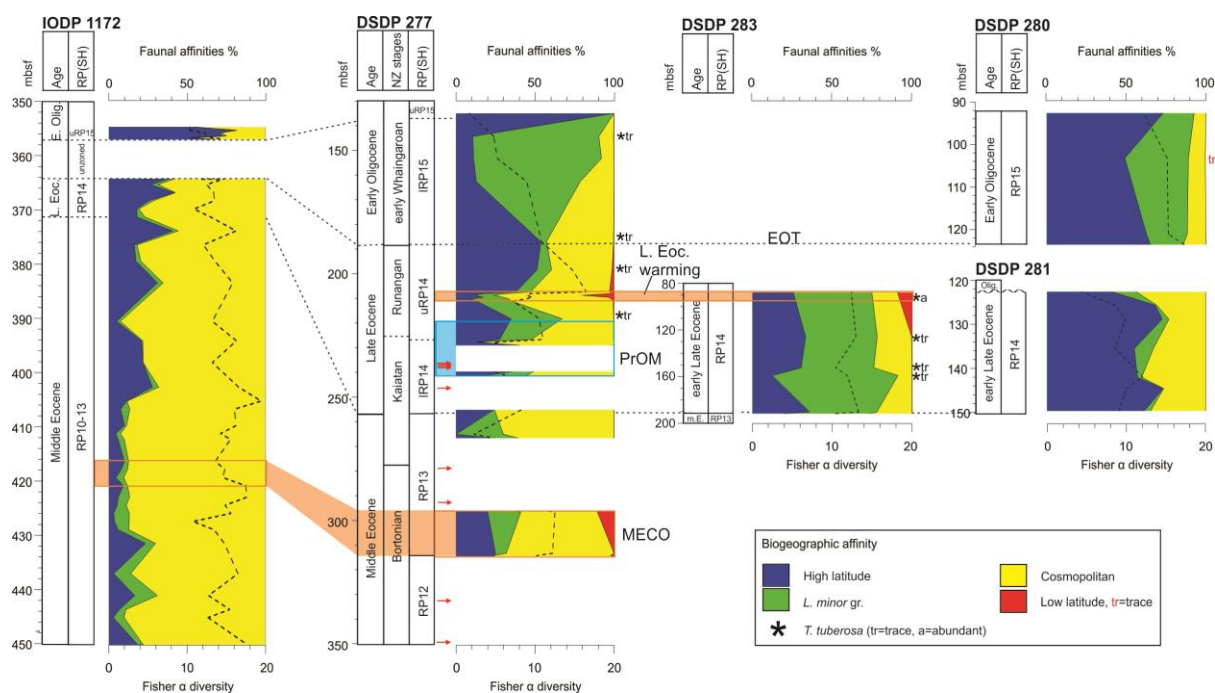


Figure 7 revised. Variation in faunal affinities for radiolarian assemblages at all sites. Dashed black lines indicate correlation between sites, which is hampered by hiatuses and poorly defined ages, respectively. The location of the MECO at Site 1172 is adapted from Bijl et al. (2010). Red arrows at Site 277 records shows removed samples with less than 100 specimens.

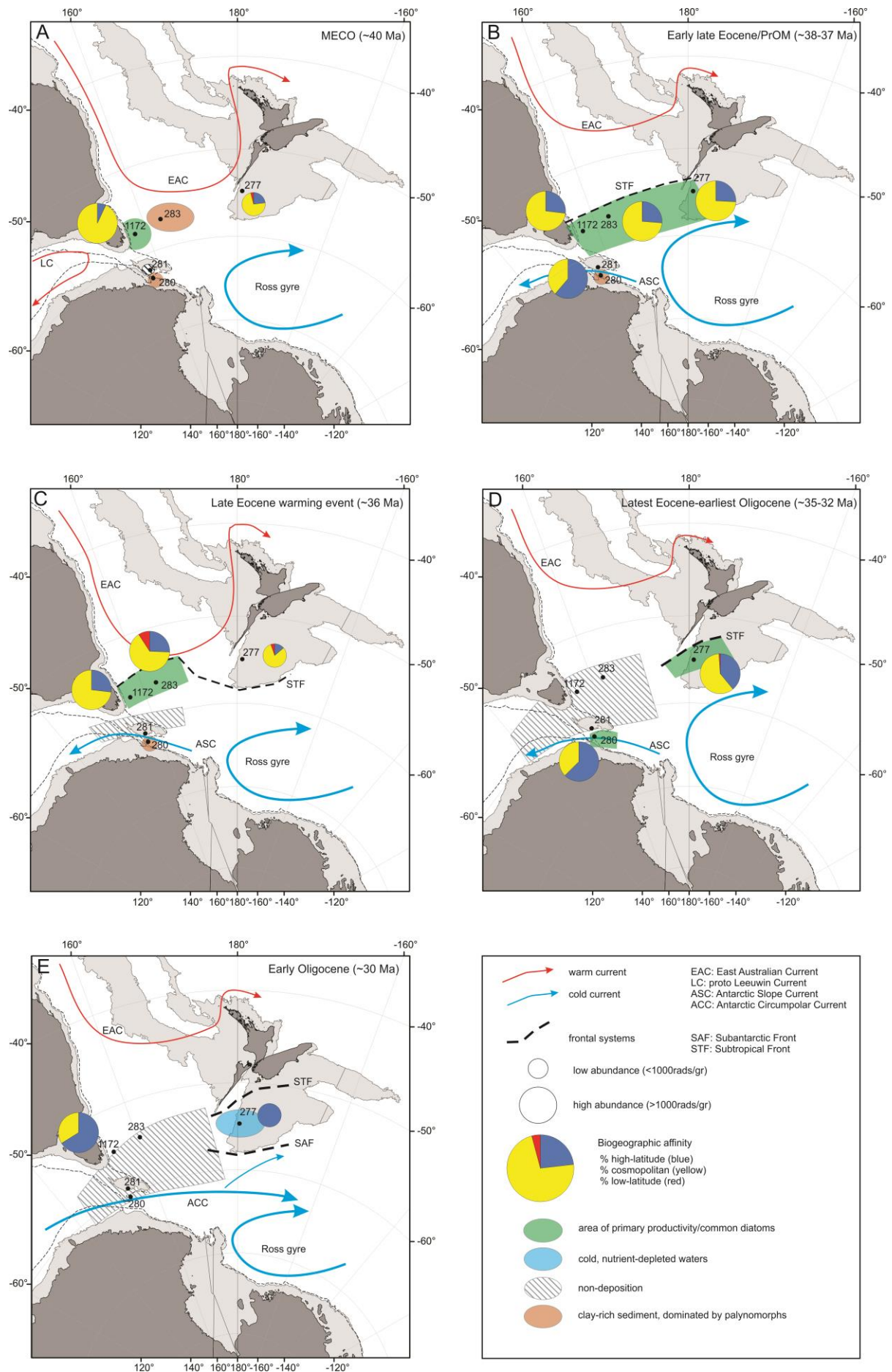


Figure 8 revised. Paleogeographic reconstructions and biogeographic affinities at investigated sites during the MECO (~40 Ma), early late Eocene/PrOM (~38–37 Ma), late Eocene warming event (~36 Ma), latest Eocene-earliest Oligocene (~35–32 Ma), and early Oligocene (~32–30 Ma). The 2000 m isobath from the GEBCO (www.gebco.net) bathymetric grid was used to approximate continental boundaries (light grey). The continental/oceanic boundaries of Bird (2003) are also shown for reference (dashed lines); continents with present day shorelines are in dark grey. The late Eocene average is plotted for Site 1172 in map B and C.