Opposite response modes of NADW dynamics to obliquity forcing during the late Paleogene

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Although the responses of North Atlantic Deep Water (NADW) is deeply connected to orbital rhythms, those under different tectonic and atmospheric boundary conditions remain unknown. Here, we report suborbitally resolved benthic foraminiferal stable isotope data from J-anomaly Ridge in the North Atlantic from ca. 26.4–26.0 Ma. Our results indicate that the formation of NADW during that time interval was increased during the obliquity-paced interglacial periods, similar to in the Plio-Pleistocene. During the late Oligocene, the interglacial poleward shifts of the stronger westerlies in the southern hemisphere, which occurred due to the higher thermal contrasts near the upper limit of the troposphere, reinforced the Antarctic Circumpolar Current (ACC) and, in turn, the Atlantic meridional overturning circulation (AMOC). However, such a response mode in deep ocean circulation did not occur during the middle Eocene because of different tectonic boundary conditions and the immature states of the ACC. Instead, the middle Eocene interglacial conditions weakened the formation of the proto-type NADW due to less heat loss rate in high-latitude regions of the North Atlantic during high obliquity periods. Our findings highlight the different responses of deep ocean circulation to orbital forcing and show that climate feedbacks can be largely sensitive to boundary conditions.
sedimentary layer, caused by the NADW strengthening that occurred after the Oligocene could minimize early diagenetic effects on the calcium carbonate (CaCO₃) sediments. These geological features of the drilling site allow us to shed new light on orbital-scale variations of NADW during the Paleogene in the mid-latitude North Atlantic Ocean.

In this study, we report suborbital-scale benthic foraminiferal isotope records with additional proxy data during the late Oligocene from IODP Site U1406. Ultimately, these records are compared to previous results from the same area during the middle Eocene, to delineate orbital-scale NADW dynamics before and after the ACC.

Results

Based on the preexisting age models, the ages of study interval (146.72–158.73 m) were calculated to be 26.02–26.43 Ma (Supplementary Fig. S1; see methods). Our benthic foraminiferal δ¹⁸O record revealed a long-term gradual decrease of 0.4‰ between ca. 26.25 Ma (154.3 m) and 26.02 Ma (Fig. 2). The δ¹³C values also gradually decreased by 0.5‰ between 26.25 and 26.12 Ma (150.0 m), and then recovered. The onset of long-term changes in both isotope records coincides with the boundary between the Mid Oligocene Glacial Interval (MOGI; 26.3 to 28.0 Ma by Ref. 16) and the Late Oligocene Warming (LOW; 23.7 to 26.3 Ma by Ref. 16). The long-term patterns of both δ¹⁸O and δ¹³C are in accordance with those of other Atlantic and Pacific sites during the same period, and they are considered to be related to ~405-kyr eccentricity cycles. Short-term fluctuations of 0.5–1.0‰, with prominent quasi-periodicities, are superimposed on the long-term trends of the δ¹⁸O and δ¹³C records.

These isotopic periodicities correlate very well with additional proxy records, such as foraminiferal test size and CaCO₃ contents data, with only a few discordant peaks (Fig. 2). In this study, the onboard color reflectance data (L*), which are considered useful for estimating relative changes in CaCO₃ contents, were used to verify the periodicity based on the relatively low-resolution CaCO₃ content data. The results of spectral analyses of the δ¹⁸O, δ¹³C, L*, and O. umbonatus test size data indicate similar periodicities of 0.95, 1.15, 0.95, and 1.0 m, respectively (Supplementary Fig. S2).
Discussion

The concordance of the periodicities among all of proxy records may indicate that a single paleoceanographic factor ultimately caused the short-term fluctuation in each proxy record from 26.02–26.43 Ma. Considering an average sedimentation rate of 2.95 cm/kyr, the periodicity of our proxy records can be considered as approximately
33 kyr (0.95 m) to 39 kyr (1.15 m), which corresponds to obliquity-related periodicities (29–55 kys; Ref.5,19) (Supplementary Fig. S2). These periodicities were previously reported in the same area (IODP Site U1410) for the middle Eocene (43.5–46.0 Ma). Based on the results of spectral analysis of the L* data for the entire LOW period (24.0–26.5 Ma)12, the periodicity of 0.92 m still fell within the obliquity cycle of 45 kyrs (Supplementary Fig. S3), even when the age model is more robust for the longer time period. Thus, our suborbital-scale records support previous results showing that periodical changes in paleoceanographic conditions in the NADW pathway were mainly controlled by the obliquity cycles. Obliquity-paced paleoceanographic changes during the late Oligocene were also identified in other North Atlantic and Pacific sites, and interpreted as glacial–interglacial cycles. We estimated an average temperature change of ~ 1.7 °C between the glacial and interglacial cycles, based on comparison with a previous result from the high-latitude Southern Ocean site showing minor temperature variations (see supplementary materials).

Our proxy data clearly illustrate that the late Oligocene NADW was strengthened during the interglacial periods, as shown by the lower δ18O values. This is because the lower δ18O values (an average value of ~ 2.3‰) coincided with higher δ13C values (an average value of ~ 0.7‰), O. umbonatus test sizes (an average value of ~ 708.2 μm), and CaCO3 contents (an average value of ~ 46.1 wt%), which can be interpreted as synchronous increases in the supply of younger water, the oxygen level of deep water, and the concentration of CO3²⁻ ions, respectively (Fig. 2). The higher δ13C values indicate younger deep water due to its shorter reaction time with organic matter, where this process could reduce carbonate dissolution in the area. In addition, the stronger NADW likely supplied more oxygenated water to site U1406. Because oxygen in the deep sea is supplied by deep water circulation, we can refer to the test sizes of the benthic foraminifera O. umbonatus to trace past

Figure 3. Comparison of the proxy records from the same study area for a ~ 400-kyr period between the late Oligocene (this study) and the middle Eocene. Note that the δ18O (red) and δ13C (blue) data are detrended to remove long-term trends. Test sizes of O. umbonatus and Ca/Fe are depicted along with five-point moving-averaged data, represented by black and pink lines, respectively. The δ18O values and both proxy records (δ13C and test sizes) for the North Atlantic Deep Water (NADW) production rate for the late Oligocene show the anti-phase relationship, while those in the middle Eocene show the in-phase relationship.
Changes in deep water circulation, where *O. umbonatus* is known to precipitate larger tests in an oxygen-enriched environment\(^{25}\). These sequential interpretations of our proxy data largely accord with those for NADW dynamics in the Plio-Pleistocene e.g.\(^{2,3}\).

Most interestingly, the relationship between the late Oligocene glacial-interglacial cycles and the relative production rate of NADW was opposite to that seen at the study site during the middle Eocene (Fig. 3). Previous researchers proposed that, based on middle Eocene Ca/Fe data from site U1410, the antecedent of the NADW (the Northern Component Water; NCW) circulation was stronger during glacial periods coinciding with obliquity periodicities\(^{6}\). They observed that the δ\(^{13}\)C record shows an in-phase pattern with the δ\(^{18}\)O record during the period (Fig. 3), and the changes in δ\(^{13}\)C values were interpreted as arising from the variability in the supply rate of the nutrient-depleted water mass originating from the tropical surface area. As a result, during middle Eocene glacial periods with higher δ\(^{18}\)O values, the higher δ\(^{13}\)C values in the deep water are compatible with the vigorous NADW, which is supported by the fact that lower Ca/Fe values indicate higher rates of NADW production.

Why do NADW dynamics respond oppositely to the same obliquity-paced glacial–interglacial cycles in the study area during different time periods in the late Paleogene? This phenomenon can be explained by the maturation of the AMOC with the Greenland-Scotland Ridge (GSR) subduction\(^{26}\), and the opening of ocean gateways e.g.\(^{27,28}\) between the middle Eocene and the late Oligocene (Supplementary Fig. S4). These major tectonic events eventually permitted completion of the ACC and strengthening of the NADW\(^{7,29,30}\) (Fig. 4). During the late Oligocene, the mature AMOC was more likely to amplify the effect of deep water reaction time on δ\(^{13}\)C variability compared to the supply rate of the nutrient-depleted water although both the controlling factors on δ\(^{13}\)C values could show same results eventually.

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**Figure 4.** Schematic representations of the different modes of AMOC during the middle Eocene and late Oligocene. The basal structure of AMOC is based on Ref.\(^{7}\). (A) The obliquity-paced glacial (upper) and interglacial (lower) modes of AMOC during the middle Eocene without the ACC, Antarctic ice sheets, or GSR subduction. Note that the formation of NCW was more vigorous during the glacial period\(^{6}\). (B) The obliquity-paced glacial (upper) and interglacial (lower) modes of AMOC during the late Oligocene with the ACC, Antarctic ice sheets, and GSR subduction. Note that the NADW was more vigorous due to the poleward movement of westerly wind currents during the interglacial period. At the same time, the formation of the Antarctic bottom water (AABW) was relatively decreased by shrinkage of the Antarctic ice sheets and sea ice\(^{33,48}\). AABW, Antarctic Bottom Water; AAIW, Antarctic Intermediate Water; ACC, Antarctic Circumpolar Current; NADW, North Atlantic Deep Water; NCW, Northern Component Water; GSR, Greenland-Scotland Ridge.
Based on our supporting evidence, the obliquity-paced glacial–interglacial cycles during the late Oligocene were very likely to affect NADW dynamics e.g.31. The sufficiently deepened ACC during the late Oligocene promoted the AMOC32. The strength of the modern ACC is controlled by the intensity and position of the southern westerly winds33. Thus, we argue that, at the late Oligocene obliquity maxima (interglacial periods), the poleward movement of the westerly wind field enhanced the upwelling of deep water originating from the NADW in the high-latitude Southern Ocean, which could have strengthened the AMOC (Fig. 4). The vigorous upwelling of CO₂-rich deep water might have created a positive feedback loop between greenhouse gases and deep ocean circulation, because the increases in atmospheric CO₂ concentrations could move the westerly wind field further to the south34. In addition, the proxy data from IODP Site U1356, off-shore of the Wilkes Land margin, shows the more vigorous upwelling of the North Atlantic sourced deep water for the obliquity-paced interglacial periods during the late Oligocene (~ 26.0–25.0 Ma)35. Warmer and saltier surface currents for the subduction of NADW in the high-latitude North Atlantic during interglacial periods could be induced by the weakening of the zonal flow in the northern polar gyre, and by expansion of the subtropical gyre36,37.

On the other hand, it is plausible that the middle Eocene AMOC behaved differently during the commensurable obliquity-paced glacial–interglacial cycles. Insufficient extension of ocean gateways during that time period limited the ACC flow to shallower depths than the threshold depth for regulating the AMOC e.g.38, although there are conflicts among the many simulation results regarding the exact threshold depth of the ACC30,32. A recent result suggested that the ACC occurred after 30.0 Ma39. Under these tectonic and oceanic conditions, the southward shift of southern westerly winds could not promote NADW formation during the middle Eocene obliquity maxima (interglacial periods) (Fig. 4). Instead, the most plausible explanation is that the Arctic cooling and partial glaciation e.g.39 facilitated more active formation of NADW during the middle Eocene obliquity minima (glacial periods), as suggested by Ref.40.

In summary, our records indicate a more vigorous NADW during the late Oligocene obliquity maxima (interglacial periods) relative to the middle Eocene. Our findings emphasize that large-scale deep ocean circulation may respond oppositely depending on the tectonic boundary conditions, in spite of equable orbital forcing.

**Methods**

**Age model.** The ages in this study were adjusted to the Geological Time Scale 2012 (GTS 201240) by linear interpolation between paleomagnetostratigraphic and biostratigraphic records20,41, based on the recently revised composite depth scale of Ref.42. The boundaries between paleomagnetic polarity reversals are C8r/C9n (158.45 m; 26.420 Ma) and C8n.2n/C8r (145.52 m; 25.987 Ma) (Supplementary Table S1). In addition, the last appearance datum (LAD) of Areoligerida semicirculata and Saturnodinium pansum dinocysts indicates 26.3 Ma (155.89 m), while that of Emmeadocyctea pectiniformis dinocysts indicates 26.7 Ma (165.59 m) (Supplementary Table S1). Based on the sedimentation rates, the age range in this study is the ~400-kyr period from 26.02–26.43 Ma (146.72–158.73 m) (Supplementary Fig. S1). This is almost coincident with a paleomagnetic age range of C8r, and covers the transition period from the MOGI to the earliest LOW.

**Stable isotope analysis and interspecies verifications.** In this study, we reconstructed suborbital-scale (~2 kyr) stable isotope records (δ¹⁸O and δ¹³C) of benthic foraminifera. For stable isotope analysis, hand-picked tests (>250 µm) of shallow infaunal (Ortidoalas umbonatus) and epifaunal (Cibicidoids spp.) benthic foraminiferal assemblages were crushed and rinsed with methanol. After washing, dehydrated samples were analyzed using a gas-ratio mass spectrometer (Finnigan MAT 252) coupled to an automated carbonate device (KIEL-III) at the Environmental Isotope Laboratory of the University of Arizona. The results are expressed relative to Vienna PeeDee Belemnite (VPDB), and the one-sigma precision is ±0.1‰ for δ¹⁸O and ±0.08‰ for δ¹³C. We analyzed both of O. umbonatus and Cibicidoids spp. in samples including both species to verify interspecies offsets. Based on the results, we added 0.14‰ and 1.19‰ to the original O. umbonatus δ¹⁸O and δ¹³C values, respectively, for compatibility with the 0.64‰-adjusted Cibicidoids spp. values (converted due to the vital effect)43 (Supplementary Fig. S5, Tables S2 and S3). These interspecies offsets are exactly coincident with the results of Ref.43,44.

**Calcium carbonate contents and foraminiferal test sizes.** For estimating CaCO₃ contents of 71 samples (Supplementary Table S4), we used the difference in weight between the original samples and CaCO₃-dissolved samples. At first, we weighed the bulk sediments dried at 40 °C for 48 h, and then removed CaCO₃ components in all samples by using 10% hydrochloric acid. After the CaCO₃ dissolution, each residue was dried at same temperature for 48 h and weighed. Finally, we determined CaCO₃ contents by subtracting the weight of CaCO₃-dissolved samples from that of the original samples; the contents are presented in weight percent (wt%).

In our previous research, we determined the diameter of a single species of O. umbonatus, existing in the almost whole study interval (218 samples in total), under the stereoscopic microscope by using NIS-Elements software48 (Supplementary Table S5). According to the method of Ref.49, the largest O. umbonatus specimen in each sample was used to avoid the effect of juvenile foraminifera.

**Statistical analysis.** To identify orbital periodicities from our unevenly spaced proxy records, we performed spectral analyses on the detrended stable isotope, O. umbonatus test size and the L* data using the open-source software REDFIT46 (Fig. S2). This software was devised to estimate the true spectrum of a time series without the overestimated low-frequency components by interpolation in the time domain. Thus, we can use this program to test if peaks in the spectrum of a time series are significant against the red-noise (a continuous decrease of spectral amplitude with increasing frequency) background from a first-order autoregressive (AR1)
References

1. Raymo, M. E., Hodell, D. & Jansen, E. Response of deep ocean circulation to initiation of Northern Hemisphere glaciation (3–2 Ma). Palaeogeography, 7, 645–672 (1992).

2. Boyle, E. A. Cadmium in benthic foraminifera abyssal hydrography: Evidence for a 41 kyr obliquity cycle. Geophys. Monog. Ser. 29, 360–368 (1984).

3. Cronin, T. M., Raymo, M. E., & Kyle, K. P. Pliocene (3.2–2.4 Ma) ostracode faunal cycles and deep ocean circulation, North Atlantic Ocean. Geology 24, 695–698 (1996).

4. Pälike, H., Frazier, J. & Zachos, J. C. Extended orbitally forced paleoclimatic records from the equatorial Atlantic Ceara Rise. Quat. Sci. Rev. 25, 3138–3149 (2006).

5. Pälike, H. et al. The heartbeat of the Oligocene climate system. Science 314, 1894–1898 (2006).

6. Vahlenkamp, M. et al. Astronomically paced changes in deep-water circulation in the western North Atlantic during the middle Eocene. Earth Planet. Sci. Lett. 484, 329–340 (2018).

7. Borrelli, C., Cramer, B. S. & Katz, M. E. Bipolar Atlantic deepwater circulation in the middle-late Eocene: effects of Southern Ocean gateway openings. Palaeogeography, https://doi.org/10.1002/2012PA002444 (2014).

8. Pekar, S. F., Deconto, R. M. & Harwood, D. M. Resolving a late Oligocene conundrum: deep-sea warming and Antarctic glaciation. Palaeogeogr. Palaeoclim. Palaeoecol. 231, 29–40 (2006).

9. Hauptvogel, D. W., Pekar, S. F. & Pincay, V. Evidence for a heavily glaciated Antarctica during the late Oligocene “warming” (27.8–24.5 Ma): Stable isotope records from ODP Site 690. Palaeogeography, 32, 384–396 (2017).

10. Toggweiler, J. R. & Samuels, B. Effect of Drake Passage on the global thermohaline circulation. Deep Sea Res. Part I Oceanogr. Res. Pap. 42, 477–500 (1995).

11. Toggweiler, J. R. & Samuels, B. On the Ocean’s Large-scale circulation near the limit of no vertical mixing. J. Phys. Oceanogr. 28, 1832–1852 (1998).

12. Expedition 342 Scientists. Paleogene Newfoundland sediment drifts. IODP Prel. Rept. 342. https://doi.org/10.2204/iodp.pr.342.2012 (2012).

13. Boyle, P. R. et al. Cenozoic North Atlantic deep circulation history recorded in contourite drifts, offshore Newfoundland, Canada. Mar. Geol. 385, 185–203 (2017).

14. Pearson, P. N. et al. Warm tropical sea surface temperatures in the late Cretaceous and Eocene epochs. Nature 413, 481–487 (2001).

15. Sexton, P. F., Wilson, P. A. & Pearson, P. N. Microstructural and geochemical perspectives on planktic foraminiferal preservation: “Glassy versus “Frosty”. Geochem. Geophys. Geosys. https://doi.org/10.1029/2006GC001291 (2006).

16. Liebrand, D. E. et al. Evolution of the early Antarctic ice ages. Proc. Natl. Acad. Sci. USA 114, 3867–3872. https://doi.org/10.1073/ pnas.1615440114 (2017).

17. Liebrand, D. et al. Cyclostratigraphy and eccentricity tuning of the early Oligocene through early Miocene (30.1–17.1 Ma): Cibicides mundus stable oxygen and carbon isotope records from Walvis Ridge Site 1264. Earth Planet. Sci. Lett. 450, 392–405 (2016).

18. Balsam, W. L., Deaton, B. C. & Damuth, J. E. Evaluating optical lightness as a proxy for carbonate content in marine sediment cores. Mar. Geol. 161, 141–153 (1999).

19. Laskar, J. et al. A long-term numerical solution for the insolation quantities of the Earth. Astron. Astrophys. 428, 261–285. https://doi.org/10.1051/0004-6361:20041335 (2004).

20. Norris, R. D. et al. Site U1406. In Norris, R. D., Wilson, P. A., Blum, P., and the Expedition 342 Scientists. Proc. IODP 342, College Station, Texas. https://doi.org/10.2204/iodp.proc.342.107.2014 (2014).

21. Flower, B. P., Zachos, J. C., & Paul, H. Milankovitch-scale climate variability recorded near the Oligocene/Miocene boundary. In Shackleton, N. J., Curry, W. B., Richter, C., and Bralower, T. J. (Eds.). Proc. ODP, Sci. Results 154, College Station, Texas (1997).

22. Gröger, M., Henrich, R. & Bickert, T. Glacial-interglacial variability in lower North Atlantic deep water: inference from silty grain-size analysis and carbonate preservation in the western equatorial Atlantic. Mar. Geol. 201, 321–332. https://doi.org/10.1016/S0037-0606(03)00263-9 (2003).

23. Kaiho, K. Global changes of Paleogene aerobic/anaerobic benthic foraminifera and deep-sea circulation. Palaeogeogr. Palaeoclim. Palaeoecol. 83, 65–85 (1991).

24. Schmitz, A., Gallistra, E. D., Hostetler, S. W., Pedersen, T. F. & Zhang, R. Large fluctuations of dissolved oxygen in the Indian and Pacific oceans during Dansgaard–Oeschger oscillations caused by variations of North Atlantic Deep Water subduction. Palaeoceanography 22, PA3027. https://doi.org/10.1029/2006PA001384 (2007).

25. KaHo, K., Takeda, K., Petrizio, M. R. & Zachos, J. C. Anomalous shifts in tropical Pacific planktonic and benthic foraminiferal test size during the Paleocene–Eocene thermal maximum. Palaeogeogr. Palaeoclim. Palaeoecol. 237, 456–464 (2006).

26. Abelson, M., Agraon, A. & Almogi-Labin, A. Indications for control of the Iceland plume on the Eocene–Oligocene “greenhouse-icehouse” climate transition. Earth Planet. Sci. Lett. 265, 33–48 (2008).

27. Livermore, R., Hillenbrand, C. D., Meredith, M. & Eagles, G. Drake passage and cenozoic climate: an open and shut case? Geochim. Geophys. Geochem. 8, Q10015. https://doi.org/10.1029/2005GC001224 (2007).

28. Scher, H. D. et al. Onset of antarctic circumpolar current 30 million years ago as tasmanian gateway aligned with westerlies. Nature 523, 580–583 (2015).

29. Katz, M. E. et al. Impact of Antarctic circumpolar current development on late paleogene ocean structure. Science 332, 1076–1079 (2011).

30. Lee, H., & Jo, K.-n. Oligocene paleoceanographic changes based on an interbasinal comparison of Cibicidoides spp. δ18O records and a new compilation of data. Palaeogeogr. Palaeoclim. Palaeoecol. 514, 800–812 (2019).

31. Naish, T. et al. Obliquity-paved Pliocene West Antarctic ice sheet oscillations. Nature 458, 322–328. https://doi.org/10.1038/nature07867 (2009).

32. Sip, W. P. & England, M. H. Effect of the drake passage throughflow on global climate. J. Phys. Oceanogr. 34, 1254–1266 (2004).

33. Toggweiler, J. R. & Russell, J. L. Ocean circulation in a warming climate. Nature 451, 286–288. https://doi.org/10.1038/nature06590 (2008).
34. Toggweiler, J. R., Russell, J. L. & Carson, S. R. Midlatitude westerlies, atmospheric CO2, and climate change during the ice ages. *Paleoceanography* [https://doi.org/10.1029/2003PA001054] (2006).
35. Salabarnada, A. et al. Paleoceanography and ice sheet variability offshore Wilkes Land, Antarctica—part 1: insights from late Oligocene astronomically paced contourite sedimentation. *Clim. Past.* 14, 991–1014. [https://doi.org/10.5194/cp-14-991-2018] (2018).
36. Chapman, M. R. & Maslin, M. A. Low-latitude forcing of meridional temperature and salinity gradients in the subpolar North Atlantic and the growth of glacial ice sheets. *Geology* 27, 875–878 (1999).
37. Liu, Z. et al. Transient temperature asymmetry between hemispheres in the Palaeogene Atlantic Ocean. *Nat. Geosci.* 11, 656–660. [https://doi.org/10.1038/s41561-018-0182-9] (2018).
38. Scher, H. D. & Martin, E. E. Timing and climatic consequences of the opening of Drake Passage. *Science* 312, 428–430 (2006).
39. Stickley, C. et al. Evidence for middle Eocene Arctic sea ice from diatoms and ice-rafted debris. *Nature* 460, 376–379. [https://doi.org/10.1038/nature08163] (2009).
40. Gradstein, F. M., Ogg, J. G. & Hilgen, F. J. On the geologic time scale. *Newsl. Stratigr.* 45, 171–188. [https://doi.org/10.1127/0078-0421/2012/0020] (2012).
41. Egger, L. M. et al. Magnetostratigraphically-calibrated dinoflagellate cyst bioevents for the uppermost Eocene to lowermost Miocene of the western North Atlantic (IODP Expedition 342, Paleogene Newfoundland sediments drifts). *Rev. Palaeobot. Palynol.* 234, 159–185. [https://doi.org/10.1016/j.revpalbo.2016.08.002] (2016).
42. Van Peer, T. E. et al. Data report: revised composite depth scale and splice for IODP Site U1406. In Norris, R. D., Wilson, P. A., Blum, P., and the Expedition 342 Scientists (Eds.), *Proc. IODP* 342, College Station, Texas (2017).
43. Shackleton, N. J., Hall, M. A., & Noersma, A. Oxygen and carbon isotope data from Leg 74 foraminifers. In Moore, T. C., Jr., Rabinowitz, P. D., et al. *Init. Repts. DSDP* 74, Washington (1984).
44. Billups, K., Channell, J. E. T. & Zachos, J. C. Late Oligocene to early Miocene geochronology and paleoceanography from the subantarctic South Atlantic. *Paleoceanography* [https://doi.org/10.1029/2000PA000568] (2002).
45. Lee, H., Jo, K.-N. & Lim, J. The strengthening of North Atlantic Deep Water during the late Oligocene based on the benthic foraminiferal species *Oridorsalis umbonatus*. *J. Geol. Soc. Korea.* 54, 489–499 (2018) (in Korean with English abstract).
46. Schulz, M. & Mudelsee, M. REDFIT: estimating red-noise spectra directly from unevenly spaced paleoclimate time series. *Earth-Sci. Rev.* 28, 421–426 (2002).
47. Seton, M. et al. Global continental and ocean basin reconstructions since 200 Ma. *Earth-Sci. Rev.* 113, 212–270 (2012).
48. Schmittner, A. Southern Ocean sea ice and radiocarbon ages of glacial bottom waters. *Earth Planet. Sci. Lett.* 213, 53–62. [https://doi.org/10.1016/S0012-821X(03)00291-7] (2003).

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**Author contributions**

H.L. collected all the information and wrote the first draft of the manuscript. K.J. has initiated this study and improved first draft. S.H. contributed to initial interpretations and provided a part of data.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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