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Deep-water Earliest Oligocene Glacial Maximum (EOGM) in South Atlantic

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Abstract **The most prominent cooling event of the Earth surface during Cenozoic in the long-term transition from a non-glaciated planet, or "green-house world", to a polar, glaciated planet, or "ice-house world", is the Earliest Oligocene Glacial Maximum (EOGM) above the Eocene/Oligocene boundary at about 33.7 Ma. Planktonic and benthic foraminiferal oxygen and carbon isotopes, carbonate content, and coarse fraction, along with high-resolution color reflectance and magnetic susceptibility records during 35—30 Ma, from deep-water Sites 1262 and 1265, Ocean Drilling Program (ODP) Leg 208 in South Atlantic, reveal the global cooling event occurring in both surface and deep oceans. The results show that the earliest Oligocene δ^{18}O values during 33.5—33.1 Ma represent the magnitude of continental ice sheets on east Antarctica and indicate the large decrease in both surface and deep water temperatures of worldwide oceans. The δ^{13}C records show the large excursion during the period of EOGM event and indicate some types of shift in global carbon reservoir, probably demonstrating the sudden increase in organic carbon burial rates and the changes in the distribution and timing of production. At the same time, lithologic composition, carbonate content, color reflectance, and coarse fraction brought about significant changes close to the Eocene/Oligocene boundary, reflecting the abrupt deepening in the carbonate compensation depth (CCD). Changes in carbonate content were revealed from the color reflectance identify periodicities associated with eccentricity of the Earth's orbit (100 and 400 ka), further indicating orbitally forced global climate variations in the Early Oligocene.**

Keywords: Earliest Oligocene Glacial Maximum (EOGM), Eocene/ Oligocene boundary, South Atlantic, stable isotopes, Ocean Drilling Program (ODP).

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Since the beginning of Cenozoic, Earth's climate has undergone the continuous cooling evolution with various extremes of cold with massive continental ice-sheets, from a non-glaciated planet, or "green-house world", to a polar, glaciated planet, or "ice-house world". The long-term transition from "green-house" to "ice-house" conditions occurred during the middle Eocene to early Oligocene. Although this interval encompasses as long as 18 Ma, the most prominent cooling event happened close to the Eocene/Oligocene boundary at 33.7 Ma. This event is called the significant phase of the global climate shift in the Earth's history[1]. Recent high-resolution benthic foraminiferal isotope records in worldwide oceans indicate that the rapid δ^{18}O increase of 1.4‰ in the earliest Oligocene (33.6 Ma), occurring within ~400 ka, marks the rapid expansion of permanent continental ice sheets on east Antarctica and a minimum of 3—4℃ of cooling of bottom waters. This period with the first appearance of permanent ice sheets on Antarctica was called the Earliest Oligocene Glacial Maximum (EOGM) or Oi-1 event[2].

Along with the occurrence of global EOGM event, critical components of the Earth system including sea level, atmospheric CO_2, land/sea surface coverage, continental weathering rates, and ocean chemistry, each of which has the potential to trigger large-scale physical and geochemical feedbacks, changed significantly[3,4]. Moreover, the EOGM event is the rapid climate change, which has closed relationship to instantaneous changes in atmospheric CO_2. The variation rates are close to the modern atmospheric CO_2 changes caused by human activities[5]. Therefore, the further study on the EOGM event in sediment records will contribute to the understanding of the past global climate change on Earth and to the forecasting of climate change in future.

The best materials to conduct the EOGM event study are continuous, non-disturbed, and diagenesis-ignored deep-sea sediments, which are distributed in worldwide oceans. Those sediments have been collected by cruises of the Deep Sea Drilling Program (DSDP) and Ocean Drilling Program (ODP). Various excellent studies have been performed, including many planktonic and benthic foraminiferal oxygen and carbon isotope records[2—4,6—8]. However, the previous studies were based mainly on sites in high-latitude, near Antarctica and only a few of them dealt with sediments with different water depths at the same/closed sites, especially in low-latitude oceans. In addition, because of drilling technique reasons during earlier DSDP and ODP periods, the core recovery was generally less than 60%—70%[9], thus constraining high-resolution study on climate changes.

In 2003, the ODP Leg 208, titled "Early Cenozoic Extreme Climates", collected early Cenozoic sediments from six sites with water depths between 2500 and 4700 m on the northeast Walvis Ridge in South Atlantic. Five of all sites used the triple Advanced Hydraulic Piston Corer (APC) to retrieve the EOGM sediments and ensure the ignored drilling disturbance and the 100% recovery[10]. Based mainly upon oxygen and carbon stable isotopes of planktonic foraminiferal fragments, carbonate content, coarse fraction, color reflectance, and magnetic susceptibility of ODP Leg 208 Site 1262 (4755 m in water depth) and on associated benthic foraminiferal oxygen and carbon stable isotope records of Site 1265 (3060 m in water depth), this study reveals the global climate changes during the Eocene-Oligocene transition (35—30 Ma) in deep-water South Atlantic Ocean.

1 Materials and methods

Site 1262 (27º11.15′S, 1º34.62′E) is situated in the Angola Basin, northwestward the Walvis Ridge in South Atlantic Ocean (Fig. 1), with a water depth of 4755 m, which is close to the modern carbonate compensation depth (CCD) of about 5.0 km in the eastern Atlantic. The CCD is a significant sedimentary boundary in deep sea from calcareous to non-calcareous sediment distributions. Above the depth, the amount of carbonate sediments deposited from overlaid water column keep a balance with dissolved carbonate; whilst below the depth, carbonate contents are generally <10% and even dissolved completely[11]. The CCD in South Atlantic holds at such depth for most of the Cenozoic[12]. Site 1265 (28º50.10′S, 2º38.35′E) with a water depth of 3060 m is located on the Walvis Ridge (Fig. 1). Along with Site 1262, they constitute a deep-sea transact.

Total 134 samples were collected between 68.84 and 87.64 mcd (composite depth meters) from Site 1262. The average 7.5 cm sampling interval for most part of the section (72.98—80.95 mcd) yields a temporal resolution of 42 ka, with a higher temporal resolution of 10—20 ka during 33.0—33.6 Ma interval. The Eocene/Oligocene boundary is located at 78.87 mcd. The site records abrupt lithologic changes over a <10-cm interval in the uppermost Eocene and lowermost Oligocene, from brown clay below to light gray foraminifer-bearing nannofossil ooze above. Carbonate content of the Oligocene interval is around 70%—90%, but mainly consists of calcareous nannofossil and fragments of foraminifers. Because the water depth of this site during the Eocene-Oligocene transition period is much close to the CCD, the content of foraminifers, especially benthic species, is very low and the planktonic species mainly consists of fragments, which theoretically belong to anti-dissolution species. It is impossible for most of them to be further identified. The carbonate content of the Eocene interval is generally <5% and almost no calcareous foraminifer exists in sediments[10]. Therefore, fragments of planktonic foraminifers in the Oligocene interval (68.86—78.87 mcd) are measured for oxygen and carbon stable isotopes. Fragments with sizes of >150 μm were selected randomly to yield average isotope compositions of anti-dissolution planktonic foraminifers and to avoid specific isotopic vital effects. The isotope compositions obtained from this method are generally not as good as to results from single species, but much better than those of bulk samples, while the latter is usually used in the international paleoceanography[13].

Total 122 samples were collected between 167.03 and 199.96 mcd from Site 1265, with a depth resolution of 27 cm and a temporal resolution of 50 ka. The Eocene/Oligocene boundary is located at 191.88 mcd. The site records gradual changes over a 40-cm interval from yellow-brown clay-bearing nannofossil ooze in the uppermost Eocene to gray foraminifer-bearing nannofossil ooze in the lowermost Oligocene. Carbonate content throughout the studied interval is around 85%—92%[10]. They mainly consist of abundant foraminifers and calcareous nannofossil and ensure the measurement of foraminiferal oxygen and carbon isotopes.

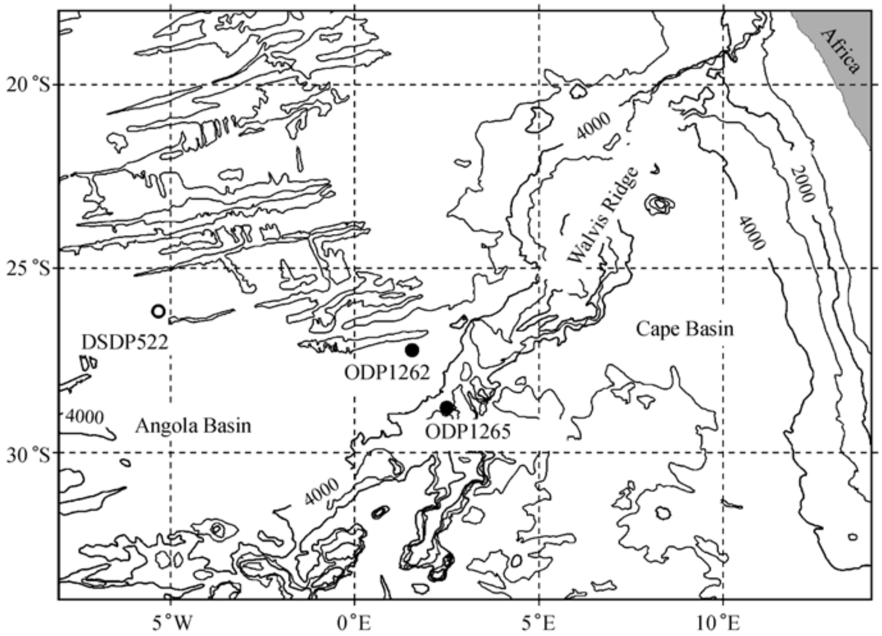

Fig. 1. Bathymetric chart (in meters) of Walvis Ridge in South Atlantic Ocean, showing locations of Sites 1262 and 1265.

Fragments (>150 μm) of planktonic foraminifers from Site 1262 and benthic foraminifer *C. mundulus* (>150 μm) from Site 1265 were selected and cleared. Their oxygen and carbon isotope analysis was conducted using a Finnigan MAT 252 mass spectrometer at the Laboratory of Marine Geology, Tongji University. Data were reported relative to the Pee Dee belemnite standard with an external error of less than ±0.08‰. Carbonate content was determined using the gasometric techniques[14], which have a precision of better than ±2‰. Statistics of coarse fraction was taken from the ratio of coarse particles (>63 μm) with bulk sample to reflect various preservation[15]. Magnetic susceptibility and color reflectance (lightness, L*) were measured by onboard automatic-controlled Bartington MS2 magnetic susceptometer and Minolta CM-2002 spectrometer, with a resolution of 2.5 cm, respectively[10]. We select the Morlet as a wavelet function[16] to conduct the wavelet analysis after the linear interpolation of original magnetic susceptibility data and to discuss potential Earth's orbital cyclicity.

We use the preliminary age-depth model decided after the cruise (Fig. 2)[10]. The model was determined by the onboard calcareous nannofossil and foraminifer stratigraphies, combined with the magnetic stratigraphy, with an average age error of ±20 ka. Based upon the age-depth model, the average sedimentation rate for the 35—30 Ma interval is 0.26 cm/ka for Site 1262 and 0.57 cm/ka for Site 1265, respectively.

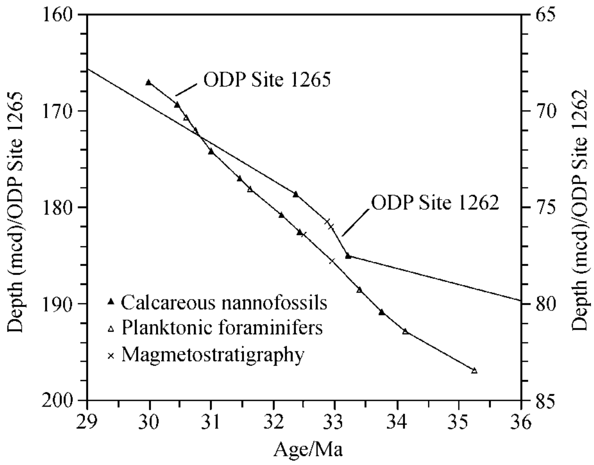

Fig. 2. Age-depth models of Sites 1262 and 1265[10].

2 Results and discussion

(ⅰ) Foraminiferal oxygen and carbon stable isotopic stratigraphies. The Site 1262 records in the early Oligocene interval show obvious trends of oxygen and carbon stable isotopes that are revealed by fragments of planktonic foraminifers (Figs. 3 and 4). The δ^{18}O values vary in the range of 0.5‰—1.4‰ and display two maximal peaks with increases of 0.7‰—0.8‰ in the early Oligocene 33.1—33.5 Ma interval. The δ^{13}C values vary between 0.7‰ and 2.2‰ and reach a maximal peak with an increase 0.9‰ at ~33.4 Ma in the early Oligocene. Those features coincide with the global information revealed by other planktonic foraminifers[17]. The Site 1265 displays complete δ^{18}O and δ^{13}C records for the 35—30 Ma interval, revealed by the benthic foraminifer *C. mundulus*. The Eocene/Oligocene boundary at 33.7 Ma and the short EOGM event are obviously displayed (Figs. 3 and 4). The δ^{18}O values vary in the range of 0.6‰—2.4‰ and increase rapidly from 1.2‰ to 2.4‰ within <20 ka at 33.6 Ma. The δ^{13}C values vary between 0.1‰ and 1.9‰ and reach maximal values during the EOGM event interval.

We selected similar δ^{18}O and δ^{13}C records of the benthic foraminifer *Cibicidoides* spp. at DSDP Site 522 (26º6.84′S, 5º7.78′W, 4441 m water depth, Fig. 1) in the Angola Basin[2], which is close to Site 1262, to compare with our results. A good linear correlation for the uppermost Eocene to lowermost Oligocene interval is obtained, i.e. higher values of the benthic foraminiferal δ^{18}O and δ^{13}C of Site 522 correspond to higher δ^{18}O and δ^{13}C values of Sites 1262 and 1265, respectively, especially during the EOGM event interval (Fig. 4).

The abrupt increase in δ^{18}O values just above the Eocene/Oligocene boundary are recorded in world-wide pelagic sediments. The excursion in high δ^{18}O values has been designated as Oi-1 or EOGM event[2,18]. The Sites 1262 and 1265 records provide the same important aspects of the event, the duration of roughly 400 ka and the profile structure with two pronounced peaks of 0.7‰—0.8‰ magnitude of increase, which keep the length of 100—150 ka and are separated by a 150-ka minima (Fig. 4). The two δ^{18}O climax values, designated as Oi-1a and Oi-1b events, may represent the upper limit of the ice volume effect on seawater during the early Oligocene, or an ice sheet size limit set by accommodation space of east Antarctica[2]. The relatively low values between the two climaxes may represent the "interglacial" stage ice volumes for that period. The termination of Oi-1 event occurred more slowly than its initiation. The post-Oi-1 decline in isotopic values initiated at 33.2 Ma and continued to 32.9 Ma with several brief cooling events. After the termination, there was about 2-Ma period (31.0—32.9 Ma) for the slow recovery (Fig. 4). Previous studies mainly based on single site or single water site[2—4], but this study reveals the global cooling climate event from both the deep-ocean floor, whose water depth is close to the CCD, and the ocean surface in South Atlantic, based upon a transect at the same location with different water depths.

The similarities in timing and magnitude of the Oi-1a/b δ^{18}O excursion of planktonic and benthic foraminifers at Sites 1262, 1265, and 522 suggest that these events represent some sort of global change in both deep and surface waters, i.e. an increase in ice volume and/or a drop in sea-water temperature. Using the seawater/calcite

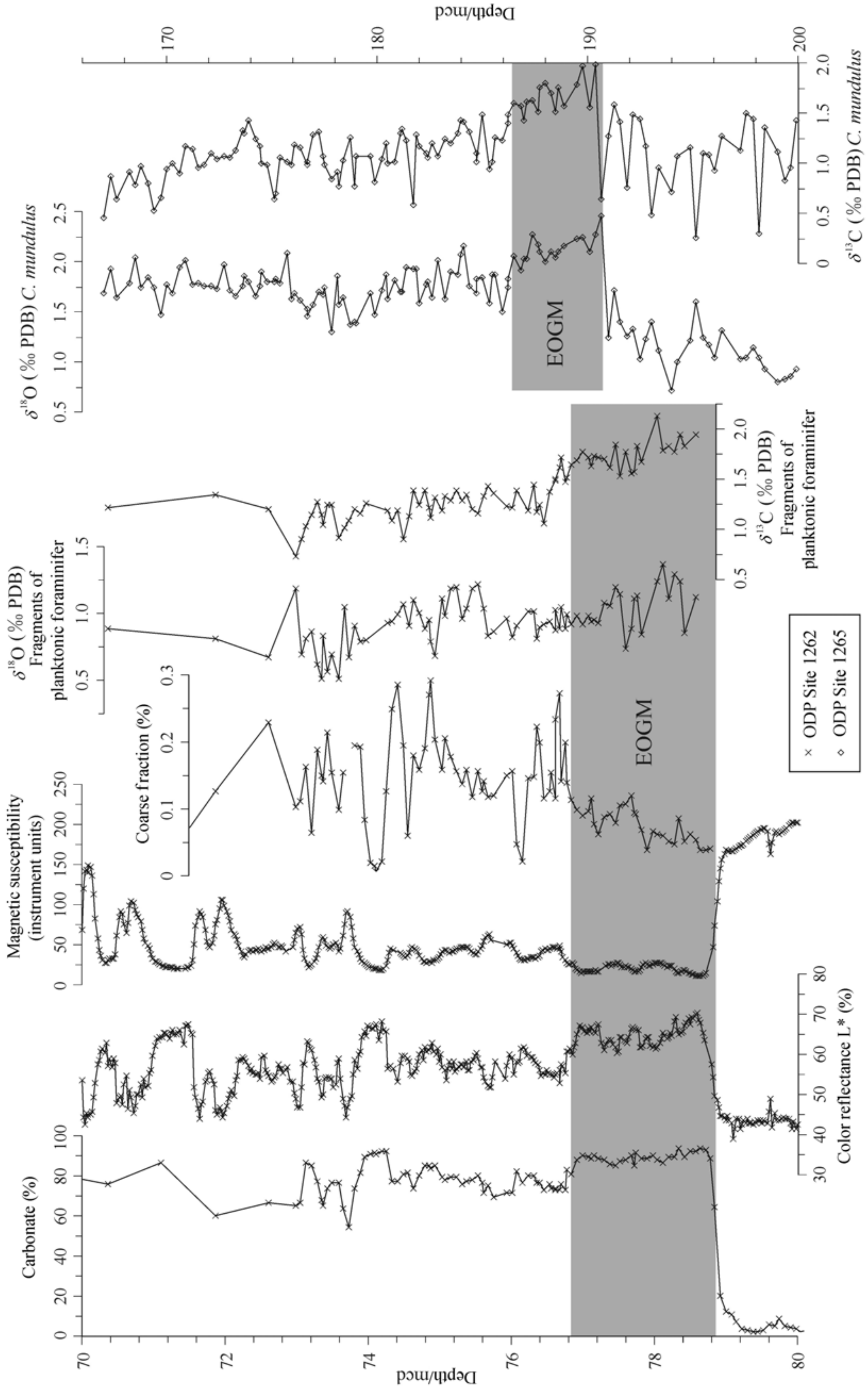

Fig. 3. Oxygen and carbon stable isotope records of fragments of planktonic foraminifers, carbonate content, coarse fraction, color reflectance (lightness, L*), and magnetic susceptibility of Site 1262, and oxygen and carbon stable isotope records of benthic foraminifer of Site 1265 plotted versus depth.

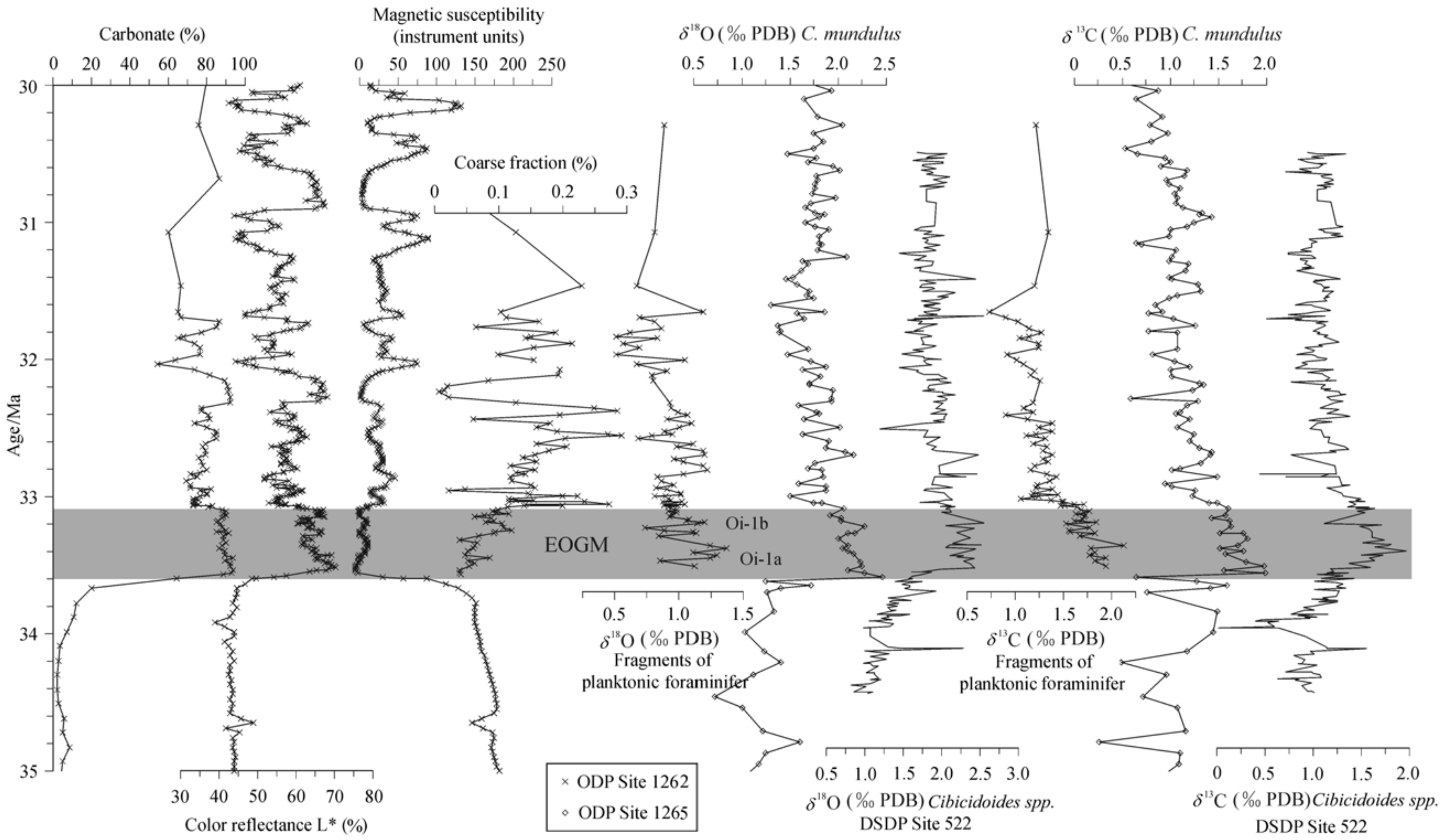

Fig. 4. Oxygen and carbon stable isotope records of fragments of planktonic foraminifers, carbonate content, coarse fraction, color reflectance (lightness, L*), and magnetic susceptibility of Site 1262, and oxygen and carbon stable isotope records of benthic foraminifer of Site 1265 plotted versus age for the 35—30 Ma interval. Oxygen and carbon stable isotope records of benthic foraminifer *Cibicidoides* spp. at Site 522 in the Angola Basin of South Atlantic[2] were selected for their correlation.

equilibrium $\delta^{18}O$ equation[19], Zachos et al. (1996)[2] obtained a decline in bottom-water temperatures of approximately 3—4℃ for the Oi-1 event at Site 522, while surface-water temperatures in world oceans decrease by around 6—8℃.

(ii) Early Oligocene carbon isotope excursion and global carbon cycle. The carbon isotope records from planktonic foraminifer fragments of Site 1262 and benthic foraminifera of Site 1265 show nearly identical long-term trends with those of Site 522 (Fig. 4). The most prominent feature common to both records is the large excursion during the Oi-1 event, specially the maxima between 33.5 and 33.4 Ma, where values rapidly increase by 1.4‰. Thus earliest Oligocene $\delta^{13}C$ excursion appears to be global in scale, supported by both benthic and planktonic records from the Pacific, Atlantic, and Indian Oceans[20—22]. The excursion may increase as high as the maximal value of 2.0‰[23]. The occurrence of $\delta^{13}C$ excursion coincides with the Oi-1 event. Our study further suggests a cause and effect relationship.

Changes in the ocean $\delta^{13}C$ composition of such magnitude indicate a significant shift in the global carbon storage rates. On these timescales, the exchange of carbon with the organic and carbonate carbon reservoirs is among the most important fluxes balancing the carbon isotope budget[2]. Because fractionation of carbon to the organic reservoir is large (~–22.7‰), a change in the flux of carbon to this reservoir could make ocean $\delta^{13}C$ higher. Why would Corg production/burial rates suddenly change during the Oi-1 climate transition? Zachos et al. (1996)[2] suggested two potential reasons. One is that marine fertility had shifted in response to a dramatic change in ocean and atmospheric circulation. As the planetary temperature gradient steepened and an ice sheet appeared on Antarctica during the earliest Oligocene, termohaline and atmospheric circulation should have intensified leading to higher rates of oceanic turnover[24]. In the southern oceans, the strength and persistence of the polar winds would have increased, thereby enhancing the vigor of surface circulation and upwelling and the supply of abundant nutrients, particularly iron[2,25]. The other is that changes in the distribution and timing of production would have further enhanced Corg burial rates. Because a greater percentage of detrital organic matter escapes from oxidation regions easily, burial rates would have increased as the balance of production shifted toward upwelling regions[26]. Similarly, with cooling, production should have become more seasonal or bloomlike, thus increasing the size of organic aggregates and accelerating the sinking rates of particles from the surface.

(iii) CCD changes during late Eocene to early Oligocene transition. The carbonate contents at Site 1262 are very low during the late Eocene, generally <5%, but abruptly increase to 70%—90% during the early Oligocene, and especially reach a maximum of ~90% during the period of the EOGM event (Fig. 4). The color reflectance L* also increases from ~44% in the late Eocene to 50%—70% in the early Oligocene, with a positive linear correlation with variations in the carbonate contents, thus suggesting the color reflectance can be served as an indirect proxy for the carbonate contents[27]. Variations in magnetic susceptibility values, representing clay mineral contents, indicate an opposite relationship to both the color reflectance and the carbonate content, from ~200 instrument units in the late Eocene to ~50 instrument units in the early Oligocene (Fig. 4). The coarse fractions at Site 1262 consist mainly of fragments of planktonic foraminifers. The values are close to zero in the late Eocene and increase during the EOGM event period and reach its maximum of ~0.3% at ~33.0 Ma (Fig. 4).

The Eocene/Oligocene boundary is marked by one of the largest known shifts at the level of the CCD during the Cenozoic. During that time, the CCD deepened by as much as 1 km in the equatorial Pacific and by about 0.5 km in the Atlantic and Indian Oceans[28,29]. The paleodepth of Site 1262 was very close to the modem CCD in the eastern Atlantic and could have been particularly sensitive to the rapid deepening of the CCD. Lithology changes from brown clay in the late Eocene to light gray foraminifer-bearing nannofossil ooze in the early Oligocene, indicating that the paleodepth of Site 1262 during the late Eocene was deeper than the paleo-CCD. Considering the strong dissolution of foraminifers during the early Oligocene and the composition of planktonic foraminiferal fragments, we deduce that the paleodepth of Site 1262 during the early Oligocene is shallower then, but very close to the paleo-CCD, suggesting the rapid deepening of the CCD across the Eocene/Oligocene boundary. At Site 1265, although an amount of clay minerals are included during the late Eocene, the carbonate contents keep a range of 85%—92%, and therefore, the site reflects the CCD changes are obviously less than the Site 1262.

The coarse fraction at Site 1262 can be served as a quantitative indicator for the foraminifer preservation[15]. Variations in the coarse fraction during the early Oligocene do not appear to be immediate with rapid deepening of the CCD; however, they lag behind about 0.5 Ma and show a maximum until 30.0 Ma (Fig. 4). This temporal relationship suggests that the shift in carbonate preservation was triggered by changes in climate. Globally, ocean carbonate chemistry may have been adjusting to an increase in continental weathering fluxes due to glacial erosion and the corresponding drop in sea level. Because the response to changes in burial ratios, productivity, and circulation-driven changes in chemistry should be almost immediate, we suspect that the gradual increase in the coarse fraction at Site 1262 has a close relationship with continental weathering rates[2].

(iv) Orbitally forced variations in global climate

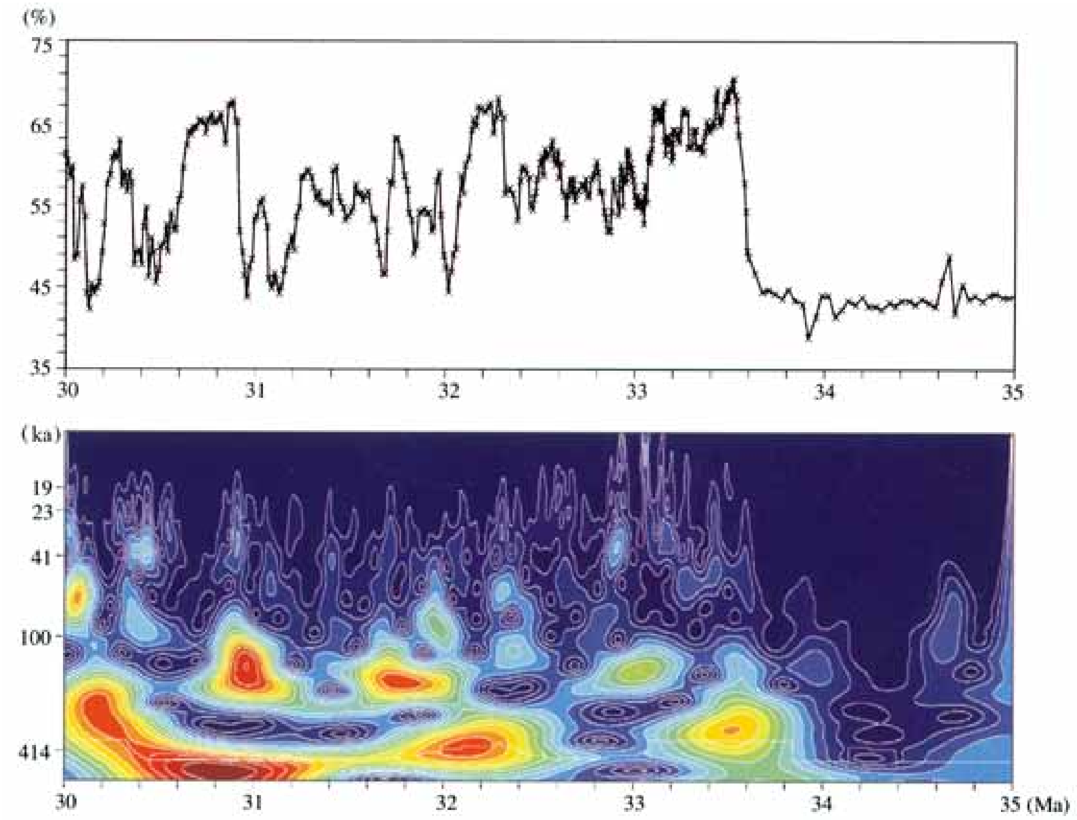

Fig. 5. Color reflectance L* (up) and wavelet analysis spectra (down) during 35—30 Ma at Site 1262.

during the early Oligocene. High-resolution studies of magnetic susceptibility and oxygen stable isotope during the Eocene-Oligocene transition at Site 522 documented cyclic variations with periods near those associated with Milankovitch orbital forcing of climate change[2,30]. Those orbitally forced variations are also recorded in other oceans[8]. Because the lithology at Site 1262 during the late Eocene consists almost of clay, it is difficult to recognize any climate cyclicity relative to variations in the carbon cycle. For the early Oligocene, however, we can retrieve the periodicity of carbonate content variations recorded by the high-resolution color reflectance.

The wavelet analysis of the color reflectance during 34—30 Ma at Site 1262 indicates the periodicities associated with eccentricity of the Earth's orbit, 100 and 400 ka, respectively (Fig. 5). The 100-ka eccentricity period of the carbonate variations was also found from other areas[2], and was suggested to have close relationship with the ice volume in high latitudes[2]. While the 400-ka eccentricity period was previously reported from the carbon isotope records in the South China Sea[31] and was interpreted as the characteristic process in low latitudes. Though these periods need further study in future, our work confirms the orbitally forced variations in global climate during the early Oligocene.

3 Conclusions

Planktonic and benthic foraminiferal oxygen and carbon isotopes, carbonate content, and coarse fraction, along with high-resolution color reflectance and magnetic susceptibility records during the Eocene-Oligocene transition (35—30 Ma) at Sites 1262 and 1265, Ocean Drilling Program (ODP) Leg 208 in South Atlantic, reveal the global climate change occurring near the Eocene/Oligocene boundary. The earliest Oligocene $\delta^{18}O$ values during the EOGM event (33.5—33.1 Ma) represent the magnitude of continental ice sheets on east Antarctica and indicate the large decrease in both surface and deep water temperature of South Atlantic. The $\delta^{13}C$ records show the large excursion during the period of EOGM event and indicate some type of shift in global carbon reservoir, probably demonstrating the sudden increase in organic carbon burial rates and the changes in the distribution and timing of production. At the same time, lithologic composition, carbonate content, color reflectance, and coarse fraction at Site 1262, combined with lithology and carbonate content at Site 1265, brought about significant changes near the Eocene/Oligocene boundary, reflecting the abrupt deepening in the CCD level. Changes in carbonate content revealed from the color reflectance identify the periodicities associated with eccentricity of the Earth's orbit (100 and 400 ka), further indicating orbitally forced global climate variations in early Oligocene.

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