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Long eccentricity cycle in Pliocene oceanic carbon reservoir: A comparison between the Mediterranean and the South China Sea

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ABSTRACT

As quantitative paleoclimate time series extend deeper into the geological past, growing evidence indicates the extensive occurrence of the 400-kyr long eccentricity cycle in geological records. The long cycles are best manifested in the marine carbon isotope as a series of δ^{13}Cmax, which correspond to the long eccentricity's minima; however, it remains unclear how eccentricity affects the oceanic carbon reservoir. To determine what processes are involved in generating the 400-kyr cycles, one long eccentricity cycle in the Late Pliocene from 3.2 Myr to 2.8 Myr was examined in two sections, respectively, from the Mediterranean and the South China Sea. The results indicate that the Mediterranean section displays distinct precession cycles in all of the studied proxy time series, and their amplitudes are modulated by eccentricity, whereas the precession cycles and the eccentricity modulation are much weaker in the proxy sequences from the South China Sea. The difference is attributed to the fact that African monsoon was overwhelmingly dominated by precessional forcing, and the Mediterranean basin was isolated from glacial-induced reorganizations of the global ocean, whereas totally different conditions existed in the South China Sea. It may be inferred from the comparison that the δ^{13}Cmax originated largely from the global ocean and was unlikely caused by local basin factors. At the long-eccentricity maximum, summer insolation reached a maximum at low latitudes, and the intensified global monsoon changed the ocean carbon reservoir and the δ^{13}C value. Because of the long residence time of carbon in the ocean, δ^{13}C changes in the global oceanic reservoir primarily occur on a 10^5-yr time scale with a smoothing effect in the lower frequencies. The 400-kyr long eccentricity was pervasive at least in the Cenozoic Ocean, but its expression was subject to spatio-temporal variations, particularly under the influence of the ice-sheet development.

1. Introduction

The astronomical forcing of climate change, known as the Milankovitch theory, was discovered in the geological record of the Late Quaternary and has been used to interpret the rhythmic occurrence of glaciations (Hays et al., 1976). With the extension of quantitative paleoclimate records to the deeper geological past, longer orbital cycles at 10^5–10^6 year time scales in paleoclimate sequences have been recognized. The long cycles are most prominent in marine carbon cycles, indicating the modulation periods of precession (e.g. Herbert, 1997; Galeotti et al., 2010; Boulila et al., 2012), and the 400-kyr long cycle of eccentricity has been most widely reported (Wang et al., 2010). Clear 400-kyr periodicities have been found from the Neogene to the Paleogene (e.g., Zachos et al., 2001; Holbourn et al., 2005) and have even been traced back to the Mesozoic and Paleozoic (e.g., Giorgioni et al., 2012; De Vleeschouwer et al., 2013). The 400-kyr cycle is considered to be "the tuning fork of geological time" because of its temporal stability (Matthews and Froelich, 2002) and has been likened to the Earth's "heartbeat" because of its climate significance (Pälike et al., 2006).

The idea that marine core records show long-term cycles superimposed on glacial cycles is not new. "Supercycles" have been repeatedly reported in paleontological, lithological and geochemical sequences for at least the past 40 years (see Wang et al., 2004, for a review). The most explicit record, however, was found in the inorganic carbon isotope. Because of the long residence time ($\geq 10^5$ yr) of carbon in the ocean–atmosphere–biosphere reservoir, marine carbon cycling is best manifested in the 400-kyr long eccentricity and longer orbital cycles, with a smoothing effect in the lower frequencies (Cramer et al., 2003; Katz et al., 2005; Ma et al., 2011). The resulting variations in the ocean carbon reservoir are recorded in the isotope fractionation of inorganic carbon in seawater, which is usually measured in foraminiferal tests. Graphically, the 400-kyr cycles are recognized as a series of heavy δ^{13}C values labeled as δ^{13}Cmax, which

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correspond to the long eccentricity minima (Wang et al., 2010; Ma et al., 2011). Although the origin of the 400-kyr cycles in the oceanic carbon reservoir remains unclear, it is well established that monsoon variability at an orbital scale is predominantly precession driven and that its amplitude is modulated by eccentricity (Kutzbach, 1981; Berger et al., 2006). Both proxy data and modeling results show that monsoon precipitation controls the chemical weathering rate and affects the oceanic carbon cycle (Russon et al., 2010; Ma et al., 2011; Tian et al., 2011). This may imply a monsoon origin of the 400-kyr period in the oceanic carbon reservoir, and δ^{13}Cmax occurs at long eccentricity minima with suppressed monsoonal activity.

However, it is still a matter of debate how eccentricity affects the carbon reservoir. Different hypotheses have been proposed to account for the origin of long term δ^{13}C cycles, including the diatom/coccolith ratio (the “rain ratio” or silica hypothesis; Archer et al., 2000; Harrison, 2000; DeMaster et al., 1995), dissolved organic to inorganic ratio (DOC/DIC, which is the dissolved organic carbon hypothesis; Wang et al., 2014a), or to variations in the size of the ice sheet (the Antarctic hypothesis; de Boer et al., 2014). Obviously, much more work is needed to answer the question, and more detailed data are required to learn which processes are involved in this long-term process. Twenty years ago, a case study was performed to examine the precession forcing in Pliocene carbonate outcrops in Sicily, where one precessional cycle in a rock sequence was analyzed in detail for lithology and geochemistry. The results significantly improved our understanding of how the precession-driven African monsoon contributed to biogeochemical changes and sapropel formation in the Mediterranean Sea (Van Os et al., 1994). The long eccentricity cycle is more complicated than a 20-kyr precession cycle, but a similar case study will throw light on the processes involved in the long-term cycle and be helpful for elucidating its origin.

The present paper focused on a long eccentricity cycle in the late Pliocene from 3.2 Myr to 2.8 Myr, in an attempt to explore what happened to the oceanic carbon reservoir within the 400-kyr period and what role the eccentricity has played in modulating the precession. We begin with the global stratotype in Sicily and subsequently compare it with deep-sea sediments from the South China Sea (SCS).

2. Materials and methods

The 400-kyr long eccentricity from 3.2 to 2.8 Myr in the Late Pliocene is well presented in δ^{13}C records from various oceans (Fig. 1), and the present study focused on the Mediterranean (Fig. 1C) and SCS (Fig. 1A). The Mediterranean Pliocene is considered as the type of astronomical stratigraphy because its sequences are highly sensitive to precession and eccentricity forcing (Lourens et al., 2004). The SCS has become a “hot spot” in paleoceanography in recent years, and ODP Site 1143 was chosen because the site has been the most extensively studied for its long cyclicity (Wang et al., 2003, 2004, 2010; Tian et al., 2011).

In the Mediterranean, we worked on the Punta Piccola section that outcrops on the southern coast of Sicily. As a part of the Global Standard Stratotype Section of the Piacenzian Stage in the Pliocene (Castradori et al., 1998), it forms the upper part of the Capo Rossello composite section and covers a period from 3.7 Myr to 2.7 Myr. This marl section is distinguished by its pronounced cyclic bedding with different amounts of $CaCO_3$ and intercalated sapropel layers (Hilgen, 1991). In 2005, a joint team from Tongji University, China, and Padova University, Italy, sampled the Punta Piccola section at intervals of 6 cm. The samples were then analyzed for δ^{18}O, δ^{13}C, and $CaCO_3$% at the State Key Laboratory of Marine Geology of Tongji University, Shanghai, and for clay minerals and element contents at the IDES Laboratory of University of Paris XI, France. Altogether from the Punta Piccola section, 359 samples were analyzed for stable isotopes, 345 samples were analyzed for $CaCO_3$%, and 332 samples were analyzed for clay mineralogy and elemental geochemistry. This analysis enables a time resolution of approximately 1.4 kyr, using an astronomical calibrated age model based on the δ^{18}O records (Lourens et al., 1996).

In the southern SCS, ODP Site 1143 (9°21′N, 113 °17′E, at a depth of 2772 m) shows a prominent 400–500 kyr cycle in the carbon isotope variations of the past 5 Myr (Wang et al., 2010, 2014a; Tian et al., 2011). Previous studies at this site have established a precise age model for the past 5 Myr by tuning the benthic foraminiferal δ^{18}O to the obliquity and precession using the La2004

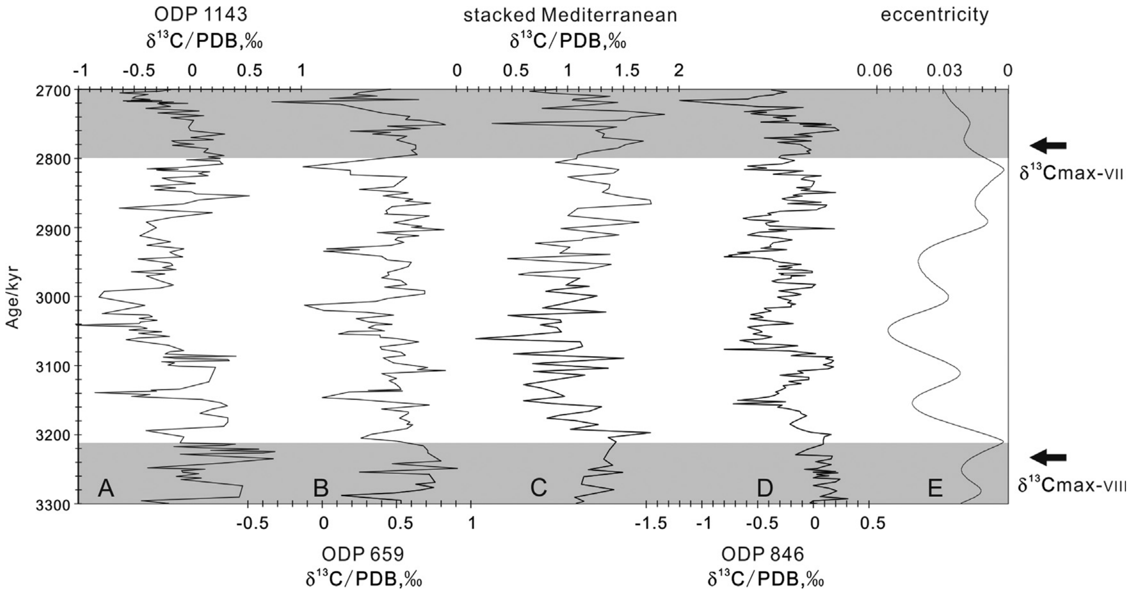

Fig. 1. Foraminiferal δ^{13}C records from various oceans during the past 3.3–2.7 Myr (unshaded area). (A) Benthic δ^{13}C, ODP 1143, South China Sea (Wang et al., 2004); (B) Benthic δ^{13}C, ODP 659, Atlantic (Tiedemann et al., 1994); (C) stacked planktonic δ^{13}C, Mediterranean Sea (Lourens et al., 1996); (D) Benthic δ^{13}C, ODP 846, Pacific (Shackleton et al., 1995); and (E) eccentricity.