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Tectonically restricted deep-ocean circulation at the end of the Cretaceous greenhouse

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ABSTRACT

The evolution of global ocean circulation toward deep-water production in the high southern latitudes is thought to have been closely linked to the transition from extreme mid-Cretaceous warmth to the cooler Cenozoic climate. The relative influences of climate cooling and the opening and closure of oceanic gateways on the mode of deep-ocean circulation are, however, still unresolved. Here we reconstruct intermediate- to deep-water circulation for the latest Cretaceous based on new high-resolution radiogenic neodymium (Nd) isotope data from several sites and for different water depths in the South Atlantic, Southern Ocean, and proto-Indian Ocean. Our data document the presence of markedly different intermediate water Nd-isotopic compositions in the South Atlantic and Southern Ocean. In particular, a water mass with a highly radiogenic Nd isotope signature most likely originating from intense hotspot-related volcanic activity bathed the crest of Walvis Ridge between 71 and 69 Ma, which formed a barrier that prevented deep-water exchange between the Southern Ocean and the North Atlantic basins. We suggest that the Cenozoic mode of global deep-ocean circulation was still suppressed by tectonic barriers in the latest Cretaceous, and that numerous, mostly regionally-formed and sourced intermediate to deep waters supplied the deep ocean prior to 68 million yr ago.

1. Introduction

The formation of oceanic deep-water masses is the key process for heat transport in the modern ocean-climate system. For the Cretaceous greenhouse world, however, the role of oceanic poleward heat transport as a main driver of long-term climate change has been questioned. Instead, heat transport is thought to have responded to high-latitude cooling due to atmospheric CO_2 reduction (Robinson and Vance, 2012; Robinson et al., 2010). The relationship between the climatic state of the Earth and deep-ocean circulation was in addition affected by the plate tectonic configuration. Due to plate-tectonic limitations and the lack of open seaways between major ocean basins, the formation and circulation of deep-water masses occurred individually in restricted, relatively small oceanic basins over long periods of time in the middle Cretaceous (120–80 Ma; Friedrich et al., 2008; MacLeod et al. 2008, 2011). It is widely assumed that the ongoing opening of the South Atlantic Ocean has connected all major oceanic basins from the early Campanian (~83 Ma) onwards, thus causing a marked change of global ocean circulation (MacLeod et al., 2011; Martin et al., 2012; Murphy and Thomas, 2012; Robinson et al., 2010). The underlying driving mechanisms and source regions of deep-water masses are, however, controversial. It has been suggested that deep waters formed in the North Atlantic (Northern Component Water, NCW) played a significant role in Late Cretaceous ocean circulation (Frank and Arthur, 1999; MacLeod et al., 2011; Martin et al., 2012). Alternatively, the South Atlantic and Indian Ocean domain has been invoked as the main region of deep-water formation, with the sinking of Southern Component Water (SCW) having been a result of early Campanian climate cooling (Brady et al., 1998; Huber et al., 1995; Murphy and Thomas, 2012; Robinson and Vance, 2012; Robinson et al., 2010). Both scenarios imply a transition towards an early Cenozoic mode of deep-ocean circulation mainly driven by sinking of cool waters at high latitudes. In contrast, an alternative hypothesis suggests vertical oceanic mixing at numerous sites via local eddies, which formed as the consequence of weak or missing oceanic fronts related to the lack of permanent polar ice, low hemispheric temperature gradients and weakly developed westerly winds (Hay, 2011).

To resolve the potential influence of different ocean basins during the waning greenhouse climate of the latest Cretaceous, we present new, high-resolution radiogenic Nd isotope records obtained from sedimentary ferromanganese-oxide coatings of three sites in the South Atlantic, the Southern Ocean, and the proto-Indian Ocean (Fig. 1). Nd isotopes can be used as geochemical

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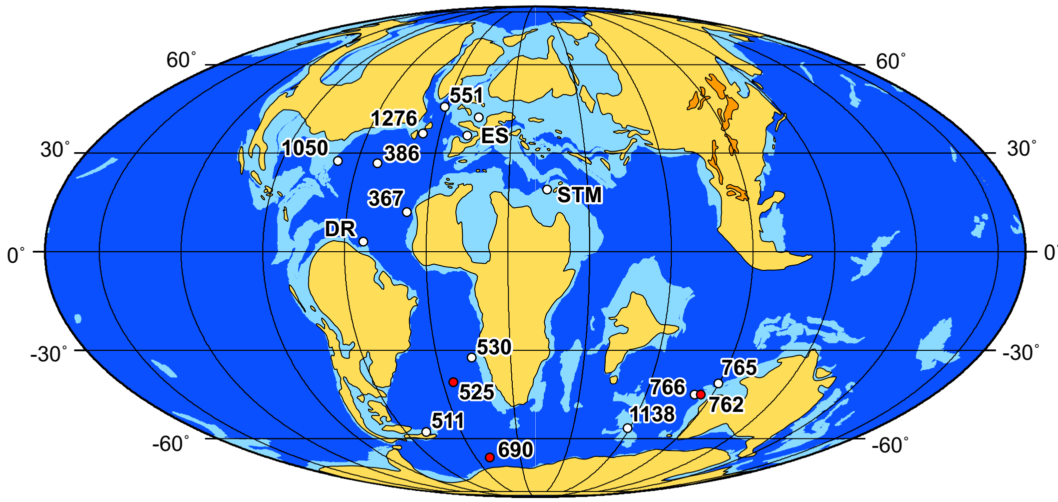

Fig. 1. Palaeogeographic reconstruction at 70 Ma, showing the distribution of shallow shelf seas and ocean basins (map modified from Hay et al. (1999)). The location of DSDP and ODP sites studied here and for which published $\varepsilon_{Nd(t)}$ data exist are indicated with red and white dots, respectively. Abbreviations: DR—Demerara Rise, ES—European shelf, and STM—Southern Tethys margin.

tracer to reconstruct past ocean circulation. The Nd isotope composition of continental rocks is a function of rock type and age, and weathering processes release the Nd to the ocean either via riverine and aeolian input or through exchange processes with shelf sediments (Lacan and Jeandel, 2005). Therefore, water masses are labelled with distinct Nd-isotope compositions in their source regions. Because the oceanic residence time of Nd and the global mixing time of the ocean are similar (e.g. Frank, 2002), the isotopic composition of Nd in seawater, expressed as $\varepsilon_{Nd(t)}$, has been shown to behave quasi-conservatively and thus serves as a tracer for water-mass mixing in the past. Nd isotope signatures of ferromanganese-oxide coatings allow the reconstruction of past deep-water masses at a significantly higher spatial and temporal resolution than commonly achieved by fossil fish debris. Both archives have been shown to generally yield indistinguishable Nd isotope signatures (Martin et al., 2010, 2012). Our Campanian to Maastrichtian Nd isotope data set is augmented by literature data to reconstruct latest Cretaceous (66–76 Ma; Campanian to Maastrichtian) intermediate- to deep-water mass circulation and mixing.

2. Materials and methods

Nd-isotope data have been obtained from three sites in the South Atlantic (Deep Sea Drilling Project [DSDP] Site 525, Walvis Ridge), the Southern Ocean (Ocean Drilling Program [ODP] Site 690, Maud Rise), and the proto-Indian Ocean (ODP Site 762, Exmouth Plateau) (Fig. 1). DSDP Hole 525A is located on top of Walvis Ridge, a volcanic ridge between Africa and the Mid-Atlantic Ridge. During the Maastrichtian, it was situated at 36°S palaeolatitude at a water depth of approximately 1000–1500 m (Li and Keller, 1999; Moore et al., 1984). Maastrichtian stratigraphy of Site 525 is well constrained by palaeomagnetic data (Chave, 1984), as well as by zonations with planktic foraminifera (Li and Keller, 1998) and calcareous nannofossils (Manivit, 1984). Ages of geomagnetic reversals are used as tie-points for the age model (GTS04; Gradstein et al., 2004). In addition, carbon-isotope records of benthic foraminifera (Friedrich et al., 2009; Li and Keller, 1998), globally correlated to other Maastrichtian sites (Voigt et al., 2012), enable a high temporal resolution of inter-site correlation (Fig. 2). The analyzed samples cover the interval of upper chron C32 and chron C31 (488.80–528.57 mbsf, core sections: 44-1/70-71 to 48-2/97-98).

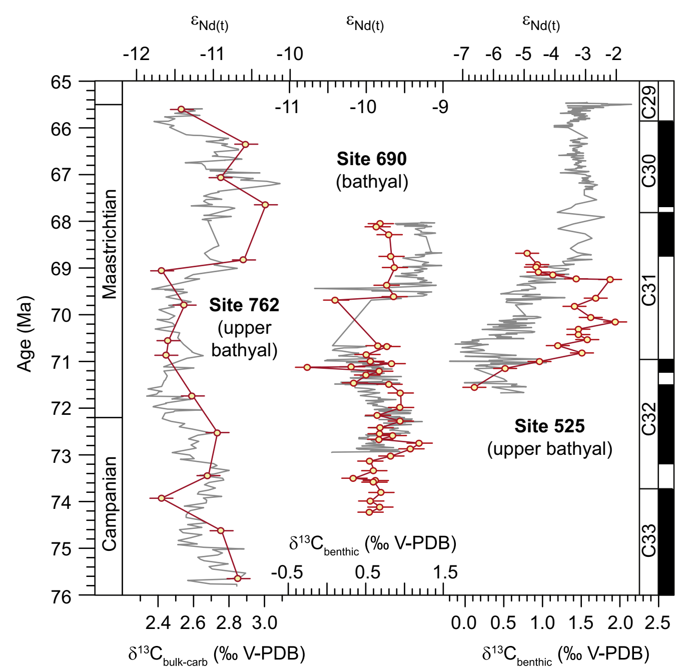

Fig. 2. Radiogenic Nd isotope data obtained from DSDP Site 525 and ODP Sites 762 and 690 (red) relative to carbon isotope variations (grey; Friedrich et al., 2009; Li and Keller, 1998; Thibault et al., 2012). The timescale is the GTS04. The age model is based on biostratigraphically calibrated carbon-isotope correlation (Voigt et al., 2012). Neodymium isotope data are expressed in the $\varepsilon_{Nd(t)}$ notation, which represents the deviation of the measured $^{143}Nd/^{144}Nd$ from that of the Chondritic Uniform Reservoir (Jacobsen and Wasserburg, 1980) in parts per 10,000 and which has been corrected for in-situ production of ^{143}Nd. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ODP Hole 690C recovered uppermost Campanian to Maastrichtian calcareous chalks and oozes on the southwestern flank of Maud Rise, a volcanic ridge located in the eastern Weddell Sea (Barker et al., 1990; Barrera and Savin, 1999) (Fig. 1). The succession was deposited at a palaeolatitude of about 65°S in an estimated water depth of 1800 m (Huber, 1990; Thomas, 1990). The stratigraphy is based on planktonic foraminifera, calcareous nannofossils (Barrera and Huber, 1990; Huber, 1990; Pospichal and Wise, 1990), and palaeomagnetic data (Hamilton, 1990). Ages of geomagnetic reversals are used as tie-points for the age model (GTS04, Gradstein et al., 2004).