RESEARCH FOCUS

A new breath of life for anoxia

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The middle of the Cretaceous (120–80 Ma) was one of the warmest periods of the past 300 m.y., with tropical sea-surface temperatures well over 30 °C (Pucéat et al., 2007; Forster et al., 2007a) and atmospheric CO_2 levels much higher than today. Therefore this period can give us crucial information on the mechanisms governing the climatic system in a context of extreme greenhouse conditions. Within this interval, major perturbations of the carbon cycle occurred around the Cenomanian-Turonian boundary (93.5 Ma), evidenced by worldwide deposition of organic-rich (black) shales in the oceans, and a large positive carbon isotope excursion reflecting enhanced burial of ^{13}C-depleted organic carbon. Such episodes of extensive organic-matter burial are known as oceanic anoxic events (OAEs) and are thought to have an impact on global climate through atmospheric CO_2 draw-down (Forster et al., 2007b). Both increased primary productivity leading to higher fluxes of organic carbon to the seafloor, and better preservation of organic matter due to anoxic conditions have been invoked to explain enhanced organic-matter burial (Arthur et al., 1990). Although sluggish ocean circulation is often called upon to explain widespread ocean anoxia, we actually know very little about the global circulation system during the Cretaceous. Apart from numerical simulations, few studies treat paleocirculation, and existing data on ocean structure remain very scarce for this period (Barrera et al., 1997; Pucéat et al., 2005; Soudry et al., 2006). In this issue of *Geology*, MacLeod et al. (p. 811–814) present new paleoceanographic data based on neodymium isotopes for the Late Cretaceous period, and they track circulation changes in the southern North Atlantic across the oceanic anoxic event of the Cenomanian-Turonian (OAE2), one of the most prominent OAEs.

Seawater neodymium isotopic ratios (represented by $\varepsilon_{Nd}(0) = \{[(^{143}Nd/^{144}Nd)_{sample}/(^{143}Nd/^{144}Nd)_{CHUR}] - 1\} \times 10^4$, and expressed in ε units; CHUR is the chondritic uniform reservoir) are a good tracer of oceanic circulation because Nd has a short residence time (500 yr; Tachikawa et al., 2003) relative to oceanic mixing (~1500 yr; Broeker et al., 1960), and because the relative contributions of Nd from ancient continental-versus-young volcanogenic materials differ in the various basins. At present, the unradiogenic signature of North Atlantic Deep Water ($\varepsilon_{Nd} = -13.5$) derives from the contribution of Nd from old continental rocks such as those surrounding Baffin Bay and the Labrador Sea (Stordal and Wasserburg, 1986). By contrast, the Pacific Ocean has a more radiogenic composition ($\varepsilon_{Nd} = 0$ to -5) derived from the weathering of island arc material (Piepgras and Jacobsen, 1988).

Using the Nd isotope composition of fish debris, MacLeod et al. reconstructed the Late Cretaceous ε_{Nd} evolution of bottom seawater at the Demerara Rise (~10°N during the Late Cretaceous). Given the paleodepths of the studied sites (>1000 m for the deepest Ocean Drilling Program [ODP] site 1258), these waters can be defined as intermediate water masses. The first remarkable result of this work is the very unradiogenic signature of these waters (−14 to −16.5) during most of the Late Cretaceous. These values are the lowest reported for Cretaceous bathyal ocean sites, and are very close to ε_{Nd} values of the Davis Strait seawater, at the mouth of Baffin Bay (typically −15 to −16 ε units; Stordal and Wasserburg, 1986). Although this feature cannot be uniquely interpreted yet, warm bottom water temperatures reported in the southern North Atlantic (Friedrich et al., 2008) and the similarity of the Nd signature at three ODP sites separated by over 1000 m of depth at the Demerara Rise have logically led MacLeod et al. to propose the existence of a locally derived water mass, named “Demerara bottom water mass.” Local exchange with aeolian or riverine particles weathered from the nearby Precambrian Guyana Shield would indeed have imprinted surface waters in the region with a very unradiogenic signature. This signature would then be carried by surface waters as they sink to greater depth. As these intermediate waters derive from a low-latitude area, they have to be very saline to be dense enough to sink in spite of their warm temperatures. Because the ε_{Nd} values of bottom waters at the Demerara Rise remain very unradiogenic except during OAE2, MacLeod et al. suggest that the Demerara bottom water mass was present in this area during most of the Late Cretaceous.

Production of warm, saline intermediate water has already been suggested in low- to mid-latitude evaporative seas for the Cretaceous and Eocene period (Brass et al., 1982). This issue is, however, highly debated as most recent circulation model experiments point to a high-latitude source of deep waters, which would have been warmer than today due to greenhouse forcing (Otto-Bliesner et al., 2002). In a recent study, Friedrich et al. (2008) identify the existence of an interval of higher $\delta^{18}O$ values in benthic foraminifera lasting ~1.5 m.y., prior to OAE2, at the Demerara Rise (Fig. 1). These authors interpret the higher $\delta^{18}O$ values as evidence of an incursion of warm and highly saline intermediate water at the Demerara Rise. Although they both support the existence of such a water mass, the work of MacLeod et al., based on an oceanic circulation tracer, contrasts to that of Friedrich et al. (2008), as it points to a persistence of these intermediate waters at the Demerara Rise during most of the Late Cretaceous. Yet, if ε_{Nd} values remain consistently low except during OAE2, which argues in favor of a dominant local source for the Demerara bottom water, it is interesting to note that moderate variations in the ε_{Nd} record occur within this very unradiogenic range prior to OAE2 (Fig. 1). Could these fluctuations reflect variations in

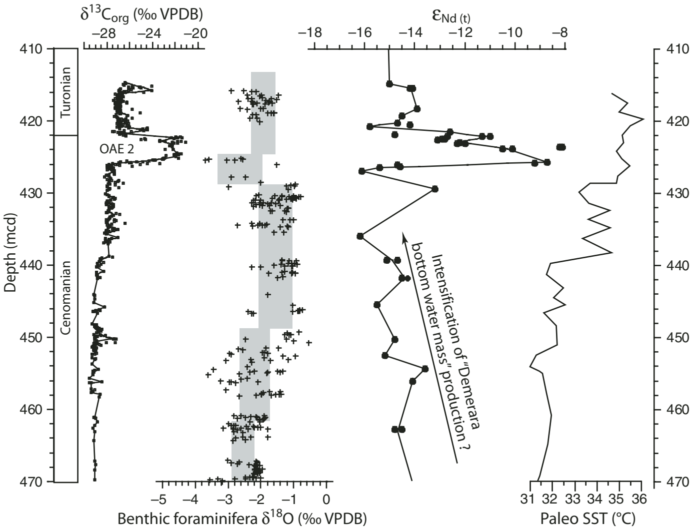

Figure 1. Organic matter $\delta^{13}C$ ($\delta^{13}C_{org}$, black squares; Friedrich et al., 2008), benthic foraminifera $\delta^{18}O$ (black crosses; Friedrich et al., 2008), ε_{Nd} (black circles; MacLeod et al., 2008), and sea-surface temperatures (SST; Forster et al., 2007a) as a function of core depth (mcd—meter composite depth) at Ocean Drilling Program site 1258, Demerara Rise.

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the intensity of intermediate water production in the southern North Atlantic prior to OAE2, which might then reconcile the benthic foraminifera $\delta^{18}O$ record of Friedrich et al. (2008) with ε_{Nd} values? The decrease, with oscillation, of ~1.5 ε units in the 3 m.y. that precede OAE2 may indeed reflect an increasing contribution of a warm, highly saline (high $\delta^{18}O$) and locally derived (low ε_{Nd}) water mass. At any rate, more ε_{Nd} data from this interval are needed to further discuss this issue and the intriguing short-term 3 ε unit positive excursion recorded just before the beginning of OAE2.

Nevertheless, these ε_{Nd} variations appear limited when compared to the very large positive excursion of 8 ε units detected during OAE2. Again, as acknowledged by MacLeod et al., this excursion cannot be uniquely interpreted, and the influence of radiogenic Nd derived from Caribbean large igneous province eruptions cannot be totally excluded. A significant contribution of Nd from hydrothermal sources would, however, require an Nd budget in the oceans markedly different than today's. Yet, if the Demerara bottom water mass model is correct, as MacLeod et al. suggest, evolution of intermediate water Nd isotope composition toward less negative values can be interpreted as a temporary interruption of intermediate water sinking in the southern North Atlantic. If waters from Tethyan and other North Atlantic sites had a more radiogenic composition during the Mid-Cretaceous (typically −10/−5 ε units), we do not yet know the isotopic signature of South Atlantic waters during this period. Discussions about possible sources of intermediate waters replacing the Demerara bottom water mass during OAE2 would therefore remain very speculative, given the present state of knowledge about the Nd isotope composition of Cretaceous water masses. Nevertheless, the work of MacLeod et al. points to changes in water mass pathways, and the location of deep water production sites during OAE2, even if more ε_{Nd} data from other bathyal sites are needed to clarify the exact nature and spatial extent of these changes. Therefore, these results have important implications for our understanding of the processes that lead to extensive black shale deposition. If it is still difficult to define whether an ε_{Nd} increase precedes or follows the beginning of the $\delta^{13}C$ excursion marking OAE2, the decrease of ε_{Nd} values clearly begins before the return of $\delta^{13}C$ to pre-excursion values. This could indicate a causal role of ocean circulation in worldwide black shale formation, either through bottom water oxygenation or through nutrient concentrations at the depth tapped by upwellings. The exact nature of this role, and its link with rapid climate variations inferred from sea surface temperature changes (Forster et al., 2007b; Fig. 1), and with large-scale magmatic activity (Turgeon and Creaser, 2008), which may have affected oceanic patterns by displacement of seawater during plateau formation, still remain to be determined.

Many of the uncertainties concerning the interpretation of ε_{Nd} records of specific water masses come from the scarcity of existing ε_{Nd} data relevant to the Cretaceous oceans. The work of MacLeod et al. provides a valuable ε_{Nd} record of intermediate water masses in the tropical North Atlantic during the Late Cretaceous. It is essential that the Nd isotope signatures of potential sites of deep water formation be characterized, in order to be able to track the origin of deep water masses bathing the Cretaceous oceans. Hopefully the work of MacLeod et al. will spur more effort to generate such Nd isotope records, which will help to constrain ocean structure and circulation patterns during the Cretaceous.

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