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Quantifying the missing sink for global organic carbon burial during a Cretaceous oceanic anoxic event

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ABSTRACT

The Cretaceous experienced numerous global and local climatic perturbations to the ocean–atmosphere system, especially during periods of known widespread organic-carbon burial termed oceanic anoxic events (OAEs). The Cenomanian–Turonian boundary event (∼93.9 Ma), or OAE-2, is the best documented and widespread organic carbon (OC) burial event in Earth history—with more than 170 sections published. Despite the substantial number of locations, the majority is found within the proto-Atlantic Ocean, Tethys Ocean and epicontinental seaways. It has been hypothesized that the pervasive burial of OC during OAE-2 caused the observed positive carbon isotope excursion (2 to 7‰, average ∼3‰). The isotope excursion can help constrain the global burial of OC, even for unstudied portions of the global ocean. This approach can solve for 'missing' OC sinks by comparing model estimates with the known distribution of OAE-2 sediments and their OC contents. Specifically, mapping the known spatial extent of OC burial in terms of mass accumulation rates (MARs), and comparing those results with the prediction using a forward box model to derive the amount of OC burial to reproduce the globally observed positive carbon isotope excursion. The available OC data from outcrop and drill core, with reasonable extrapolation to analogous settings without data, quantifies ∼13% of the total seafloor, mostly from marginal marine and epicontinental/epeiric settings. However, this extrapolation for OC burial, plus using most appropriate MARs to unknown portions of the seafloor, fail to account for the amount of OC burial predicted for a 3‰ positive carbon isotope excursion. This discrepancy remains even when considering additional sinks of organic carbon burial such as coal, lacustrine environments, authigenic carbonate, and the loss of OC associated with hydrocarbon reservoirs. This outcome points to a large reservoir of OC that is not currently constrained, such as highly productive margins and/or equatorial regions, or a small but significant increase deep ocean OC burial. Another possibility is that the carbon fluxes are less than those used in the model which would require less OC burial to explain a ∼3‰ carbon isotope excursion.

1. Introduction

Extensive deposition of organic-rich facies was common throughout the Mesozoic era; in the Cretaceous, these time intervals have aptly been named oceanic anoxic events (OAEs) (Schlanger and Jenkyns, 1976). The Cenomanian–Turonian boundary event (93.9 Ma), or OAE-2, is the most extensively studied of these events, with reports of elevated organic carbon (OC) preservation in multiple ocean basins (Indian, Pacific, Atlantic and Tethys oceans; Fig. 1A) and under various paleo-water depths, paleolatitudes and depositional conditions (Arthur et al., 1987; Jenkyns, 2010; Kuroda and Ohkouchi, 2006; Schlanger et al., 1987; Takashima et al., 2006). Due to the enhanced burial of organic matter, which preferentially sequesters isotopically light carbon, there is a coeval positive carbon isotope (δ^{13}C) excursion (Schlanger et al., 1987; Scholle and Arthur, 1980). Importantly, the positive carbon isotope excursion is observed in all carbon phases: organic-C, carbonate-C and terrestrial OC (as reviewed in Jenkyns, 2010). The magnitude of this excursion recorded in marine organic and carbonate carbon ranges between ∼2 and ∼7‰ with an average of ∼3‰ (Fig. 1B; Erbacher et al., 2005; Jarvis et al., 2006; Schlanger et al., 1987). The larger isotope excursion (∼7‰) for the organic carbon record has been interpreted to reflect a changing net fractionation between organic matter and inorganic C over the course of the event, possibly due to declining atmospheric pCO_2 (Kump and Arthur, 1999). Also, much of the $\delta^{13}C_{organic}$

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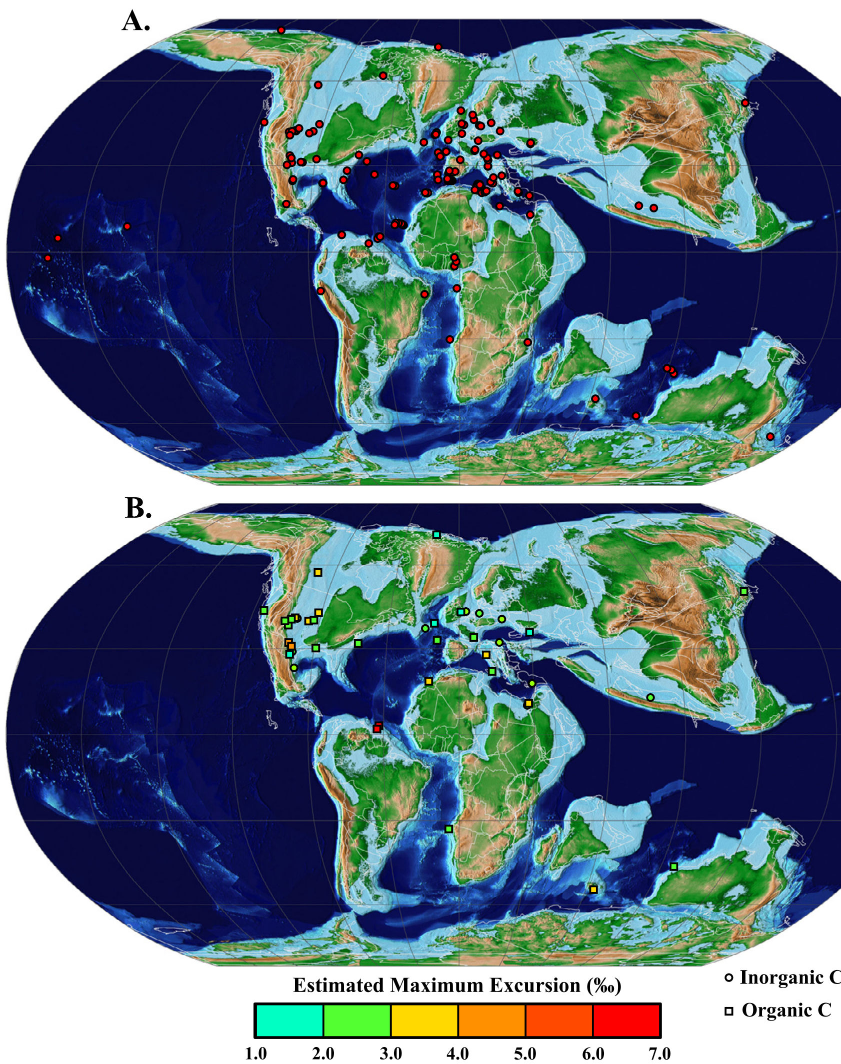

Fig. 1. Fig. 1A shows the localities that have been documented to contain OAE-2 sediments. Fig. 1B documents the maximum carbon isotope excursion globally with squares represent an excursion in organic carbon and circles document inorganic carbon perturbation. This map is adapted from the PALEOMAP Project (Scotese, 2008). (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)

variation recorded globally can be attributed to varying paleo-latitudinal gradients in sea surface temperature, with increased fractionation at lower latitudes (van Bentum et al., 2012). The pervasive OC burial inferred from the isotope excursion during OAE-2 is thought to be the result of either enhanced productivity or preservation, due to increased anoxia, and/or a combination of these two factors (Kuypers et al., 2002; Schlanger et al., 1987; Schlanger and Jenkyns, 1976).

OAE-2 is characterized by an overall warm climate recorded in proxy records for elevated temperatures (Jarvis et al., 2011; Takashima et al., 2006) likely related to high pCO_2 (estimated to be 2–8 times higher than the present level; Barclay et al., 2010; Takashima et al., 2006) and increases in sea level (Jarvis et al., 2001). However, proxy evidence also points to climatic cooling during the OAE, referred to as the Plenus cold event, which has been attributed to the widespread burial of OC and a concomitant decrease in atmospheric pCO_2 (Jarvis et al., 2011; van Bentum et al., 2012). Sustaining enhanced productivity, export and burial of OC throughout the event requires increased delivery of nutrients (e.g., N and P) and bio-essential metals (e.g., Fe) to the surface ocean. Increased seafloor spreading rates (Jones and Jenkyns, 2001), increased weathering (Pogge von Strandmann et al., 2013) and/or enhanced phosphorus regeneration under oxygen-deficient marine conditions (Mort et al., 2007; Van Cappellen and Ingall, 1994) have all been implicated in explaining enhanced availability of nutrients. Various geochemical data point to increased volcanism during OAE-2 associated with the emplacement of large igneous provinces (e.g., Du Vivier et al., 2015; Turgeon and Creaser, 2008), which could explain high pCO_2 values and may have fostered enhanced delivery of bio-essential metals such as iron to the oceans. An important consideration, however, is the difficulty in transporting dissolved and other bioreactive forms of iron in seawater under both oxic and anoxic-sulfidic (euxinic) conditions (Owens et al., 2012).

Traditionally, the widespread distribution of organic-rich sediments has been used to infer regional and even global extents of anoxic deposition, which can enhance preservation and thus burial (Schlanger et al., 1987; Takashima et al., 2006), but is not a direct proxy for marine oxygen content (e.g. Them et al., 2018). Thus, numerous geochemical proxies have been applied to OAEs to independently constrain local anoxia and/or euxinia (Brumsack, 2006; Hetzel et al., 2011; Ostrander et al., 2017; Owens et al., 2017, 2016; van Bentum et al., 2009; Zhou et al., 2017; and additional references within all), including evidence for photic zone euxinia based on organic biomarker data (Kuypers et al., 2002; van Bentum et al., 2009). Nevertheless, the documented global record of local redox conditions remains poor during OAE-2—especially in the Pacific, Indian and Arctic oceans. Recent studies have suggested widespread reducing, low oxygen but non-