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Coccolithophore productivity response to greenhouse event of the Paleocene–Eocene Thermal Maximum

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Abstract

During the Paleocene–Eocene Thermal Maximum (PETM), rapid release of isotopically light C to the ocean–atmosphere system elevated the greenhouse effect and warmed temperatures by 5–7 °C for 10^5 yr. The response of the planktic ecosystems and productivity to the dramatic climate changes of the PETM may represent a significant feedback to the carbon cycle changes, but has been difficult to document. We examine Sr/Ca ratios in calcareous nannofossils in sediments spanning the PETM in three open ocean sites as a new approach to examine productivity and ecological shifts in calcifying plankton. The large heterogeneity in Sr/Ca among different nannofossil genera indicates that nannofossil Sr/Ca reflects primary productivity-driven geochemical signals and not diagenetic overprinting. Elevated Sr/Ca ratios in several genera and constant ratios in other genera suggest increased overall productivity in the Atlantic sector of the Southern Ocean during the PETM. Dominant nannofossil genera in tropical Atlantic and Pacific sites show Sr/Ca variations during the PETM which are comparable to background variability prior to the PETM. Despite acidification of the ocean there was not a productivity crisis among calcifying phytoplankton. We use the Pandora ocean box model to explore possible mechanisms for PETM productivity change. If independent proxy evidence for more stratified conditions in the Southern Ocean during the PETM is robust, then maintenance of stable or increased productivity there likely reflects increased nutrient inventories of the ocean. Increased nutrient inventories could have resulted from climatically enhanced weathering and would have important implications for burial rates of organic carbon and stabilization of climate and the carbon cycle.

Keywords: Paleocene–Eocene Thermal Maximum; productivity; coccolith; Sr/Ca

1. Introduction

A prominent negative carbon isotopic excursion in marine and terrestrial sediments at the end of the Paleocene epoch [1,2] records a large rapid (<20 ky) release of >1500 Gt of isotopically light carbon to the ocean–atmosphere system from seafloor methane hydrate [3] or

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organic carbon [4]. Global temperatures warmed 5–7 °C in response to increased concentrations of atmospheric greenhouse gases [5,6]. A 20–30% increase in continental weathering rates, likely from warmer PETM temperatures and more humid climates in previously weathering-limited regions, is inferred from Os isotopic proxy data [7], and is consistent with theoretical models of climate-weathering feedbacks which yield 10–30% increase in silicate weathering rate from PETM temperature increases [8]. Because continental weathering is the principal source of limiting nutrients like P as well as alkalinity to the ocean, such changes may have influenced the strength of the biological pump and burial rates of organic carbon and carbonate, modulating the degree of warming during the event and the rapid recovery to pre-PETM climates within about 100 ky [9,6]. Interpretation of marine productivity records during the PETM has been controversial. Changes in the assemblages of planktic foraminifera [10] and calcareous nannofossils [11,12] at many sites suggest changes in ecological strategies and potentially productivity in response to environmental changes during the PETM. The pronounced dissolution event accompanying the PETM complicates inferences of biogenic carbonate production based on sediment mass accumulation rates, and may also have affected some calcareous microfossil assemblages. Increased abundance of infaunal benthic foraminiferal communities during the PETM may reflect increased food supply from higher production and organic carbon export [13], or substrate disturbance from carbonate dissolution. Increased barite accumulation rates in some open ocean sites during the PETM may reflect higher productivity [9], but could also result from changes in the marine cycle of Ba [14].

A new approach reported here to document the response of calcareous nannoplankton productivity to the warming event of the PETM is based on determinations of Sr/Ca ratios of nannofossils and circumvents potentially adverse effects of dissolution and preservation on estimating export production. Calcareous nannoplankton is one of the most widely preserved of all primary producers, and was the dominant carbon exporter among marine phytoplankton during the warm climates of the Mesozoic and Late Paleocene until diatoms gained dominance beginning 33 Ma [15].

Consistent positive relationships exist between coccolith Sr/Ca ratios and nutrient-stimulated changes in coccolithophore productivity in culture, sediment core top, and sediment trap studies [16–18] (Fig. 1). Nutrient limitation in coccolithophores appears to trigger carbon dumping of extracellular polysaccharides which preferentially bind extracellular Sr and reduce the Sr/Ca ratio taken into the calcifying vesicle, depressing coccolith Sr/Ca ratios [19]. Downcore records demonstrate that this relationship remains valid through changes in surface ocean pH, atmospheric CO_2, and temperature, over glacial–interglacial transitions (Fig. 1). In other Quaternary sediments, coccolith Sr/Ca correlates with Ba/Al and Ba/Ti ratios which track biogenic Ba export and are hence linked to total export production [20,21]. Correlation may arise because coccolithophore calcification and presumably growth is positively correlated to total productivity in the modern ocean [22]. The timescale over which this consistent relationship between coccolith Sr/Ca and productivity forcing is observed is comparable to that of the Paleocene–Eocene Thermal Maximum. Assuming that the biochemical and physiological processes that regulate uptake of Sr in modern coccoliths are similar to those of their ancestors, as is typically assumed for elemental and isotopic chemistry of foraminifera [6], coccolith Sr/Ca can be used as an indicator of ecosystems response to environmental changes in the geologic past. That seawater Sr/Ca ratios vary by less than 2% in the surface and deep ocean [23] and temporal changes in seawater Sr/Ca are small on timescales $<10^6$ yr because of the long (10^6 yr) residence time of Sr and Ca in the ocean support the idea. Because different genera of coccoliths have different absolute Sr/Ca ratios [18], productivity-driven Sr/Ca variations must be extracted from monogeneric samples.

We present monogeneric Sr/Ca records from the dominant calcareous nannofossils in three different open ocean sites spanning the PETM to ascertain spatial and ecological patterns of productivity response to the environmental changes of the PETM. These data were collected using a new technique of picking individual nannofossils for ion probe analysis. The new approach allows isolation of signals from many coexisting genera not possible with previous techniques for species separation [24], permitting the independent assessment of the productivity responses among ecologically-distinct groups and thus providing greater insight in mechanisms of productivity change. We use the Pandora model of ocean nutrient cycling to explore potential mechanisms for productivity change during the PETM.

2. Sediments and methods

Sediments used in this study were collected by the Ocean Drilling Program in the Weddell Sea in the Southern Ocean (ODP 690B), the tropical Pacific (ODP 1209C), and tropical Atlantic (ODP 1258A; locations given in Table 1). Sediments consist of