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Late Cretaceous seasonal palaeoclimatology and diatom palaeoecology from laminated sediments

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A B S T R A C T

Laminated diatom-rich marine sediments from California and the Arctic Ocean provide a window into the seasonal climate and oceanography of the mid- and high-latitude Late Cretaceous. These remarkable shallow-buried sediments constitute palaeo-sediment traps that record exceptionally well-preserved sequential biogenic and lithogenic flux events. Many of the diatom laminae are composed of a few dominant taxa, and we use a species-based approach for palaeoecological interpretation. Contrary to many earlier interpretations, results indicate that both sites preserve a major flux of taxa adapted to exploit a strongly stratified ocean. The uppermost Maastrichtian Marca Shale of California records a seasonal cycle initiated with a spring bloom flux of diatom resting spores followed by a summer lithogenic sediment input likely driven by monsoonal storms providing river runoff and aeolian input. This is followed by a dominant diatom flux of species that thrived in the summer stratification in deep chlorophyll maxima and were sedimented in the fall when this stratification broke down. Dominant taxa comprising this group include *Hemiaulus*, *Stephanopyxis*, *Stellarima* and *Rhizosolenia*. The uppermost Campanian CESAR 6 core from the Arctic Alpha Ridge, records a spring bloom flux of resting spores followed by a more dominant summer and fall flux of diatom vegetative cells which were likely concentrated in subsurface summer blooms that generated a "summer export pulse" and by the breakdown of stratification in the fall that gave massive flux of deep chlorophyll maxima species in the fall dump. The dominance and diversity of *Hemiaulus* in the CESAR 6 core together with widespread evidence of N_2-fixation may indicate that some diatom blooms were powered by intracellular N_2-fixing cyanobacteria as in the modern oligotrophic ocean. Thin lenses of fine lithogenic sediment that occur mostly in the spring layer represent rafting by winter sea ice and support other evidence that suggests intermittent winter freezing in the Late Cretaceous Arctic.

1. Introduction

Laminated pelagic and hemipelagic marine sediments often constitute "palaeo-sediment traps" that preserve sequential flux events from which the ancient seasonal flux cycle may be reconstructed. They commonly preserve both the biogenic flux events from surface ocean productivity and also the terrigenous sediment input common in hemipelagic or marginal settings. Within rare, exceptionally well-preserved Cretaceous sediments, fossil diatom algae record the seasonal cycle of marine production and flux to the sea bed. In the modern ocean diatom algae are the dominant, bloom-forming phytoplankton in many environments and are key players in the marine biological carbon pump. The relative contribution of diatoms to total primary production has been estimated to range from 35% in the oligotrophic oceans to 75% in the coastal zone and in the Antarctic (Nelson et al., 1995), while their contribution to export production (the downward flux of organic carbon from the euphotic zone) is proportionately even greater, due to their propensity for rapid sinking (Smetacek, 1999; Smetacek, 2000; Agusti et al., 2015). Ecological studies of diatoms, developed primarily from the coastal zone, have conventionally associated diatom blooms and subsequent export with the spring bloom or with upwelling environments (Guillard and Kilham, 1978; Margalef, 1978). Palaeoenvironmental interpretations have commonly followed this maxim and ascribed an upwelling origin to ancient diatomaceous sediment (Kitchell and Clark, 1982).

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However, new insights from water column and sediment trap sampling and from ancient laminated sediments, have demonstrated that key diatom species that are adapted to stratified conditions may contribute significantly to production and export (Sancetta et al., 1991; Kemp et al., 2000; Davies et al., 2009; Villareal et al., 2011; Karl et al., 2012). There is now, therefore, an opportunity, using a species-based approach, to develop new perspectives on the palaeoecology of ancient diatomaceous deposits and their palaeoceanographic and palaeoclimatic significance. In this paper we report the analysis of two laminated diatomites of Late Cretaceous age. The analysis of around 6400 years of palaeo-sediment trap data is reported from two contrasting Late Cretaceous palaeoenvironments, the mid-latitude Marca Shale of California and the CESAR 6 core from the Alpha Ridge of the Arctic Ocean (Fig. 1).

The Cretaceous period saw the burgeoning of the diatom fossil record from isolated windows of preservation in early Cretaceous clastic deposits to the first significant diatomites in the Late Cretaceous. Following a major diatom radiation after the Cenomanian–Turonian anoxic event (Harwood and Nikolaev, 1995; Sinninghe Damsté et al., 2004), the development of the first extensive diatomites after 90 Ma provides the earliest widespread geological evidence for the rise to prominence of diatoms in ocean biogeochemistry (Harwood et al., 2007). Studies of Earth system behaviour in the greenhouse Cretaceous climates are especially topical since such warm, high CO_2 periods of the past are often invoked as potential analogues for present warming trends. In this context, the development of an enhanced understanding of the dominant phytoplankton that operate the marine biological carbon pump in warm stratified waters analogous to future projections is especially important. In earlier publications we reported the main elements of the Late Cretaceous seasonal cycle and the results of time series analysis of inter-annual to decadal scale climate variability (Davies et al., 2009; Davies et al., 2011; Davies et al., 2012). In this contribution we report the complete floral compositions of the two sections together with more detailed species-based diatom ecological interpretations and place these in a palaeoceanographic and palaeoclimatic context that complements recent palaeoecological studies of the Late Cretaceous from shallower coastal water environments of the Canadian Arctic (Chin et al., 2008; Witkowski et al., 2011).

2. Palaeogeographic settings and biostratigraphy

Two sites containing some of the best preserved Late Cretaceous diatoms are analysed in this study; that of the mid-latitude upper Maastrichtian Marca Shale and the high-latitude upper Campanian CESAR 6 Core from the Alpha Ridge, Arctic Ocean (Figs 1, 2).

2.1. Marca Shale of California

The Marca Shale member of the Moreno Formation, crops out along the Panoche Hills, on the western flank of the San Joaquin valley, central California, and represents the topmost unit of the Cretaceous Great Valley Sequence of California (Fig. 3A and Supplementary Fig. 1). Palaeontological data from planktonic and benthic foraminifers, dinoflagellates and radiolarians place the Marca Shale in the uppermost Maastrichtian stage and the top of the unit is marked by the Cretaceous-Tertiary boundary (Fonseca,

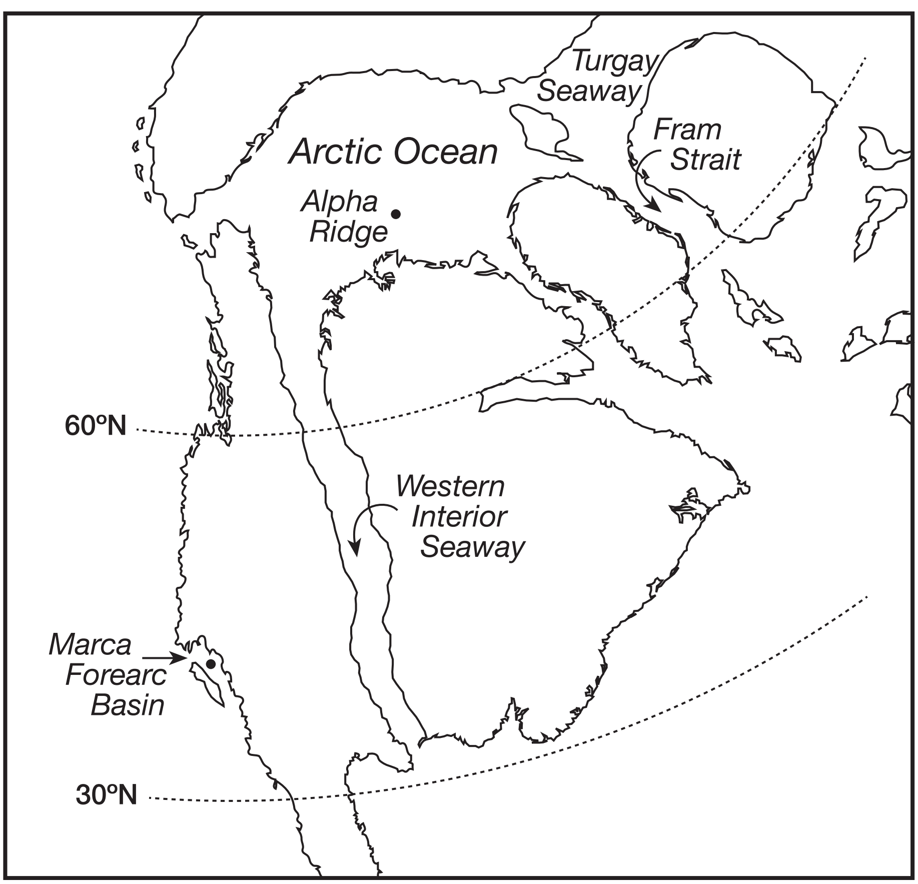

Fig. 1. Late Cretaceous palaeogeography showing settings of the Alpha Ridge Cesar Core location and of the Marca Shale forearc basin. Palaeogeography adapted from Blakey (2011).