Cordilleran ice-sheet growth fueled primary productivity in the Gulf of Alaska, NE Pacific

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ABSTRACT

Fertilization of the ocean by eolian dust and icebergs is an effective mechanism to enhance primary productivity. In particular, high-nutrient, low-chlorophyll (HNLC) areas where phytoplankton growth is critically iron (Fe)-limited, such as the subarctic Pacific and the Southern Ocean, are proposed to respond to increases in bioavailable Fe-supply with enhanced phytoplankton productivity and carbon export to the seafloor. While Fe-fertilization from dust is widely acknowledged to explain a higher export production during glacial periods in the Southern Ocean, paleoceanographic records supporting links between productivity and eolian dust and/or icebergs in the North Pacific are scarce. By combining independent proxies indicative of ice-sheet dynamics and ocean productivity from a single marine sedimentary record (IODP Site U1417), we present a comprehensive data set of phytoplankton response to different fertilization mechanisms in the subarctic northeast Pacific between 1.5 and 0.5 Ma, including the Mid Pleistocene Transition (MPT). Importantly, the timing of the fertilization events is more strongly controlled by local ice-sheet extent than by glacial-interglacial climate variability. Our findings indicate that fertilization by glacigenic debris results in productivity events in ocean areas adjacent to ice-sheets and that this mechanism may represent an important, yet rarely considered driver of phytoplankton growth.

INTRODUCTION

The stimulation of primary productivity through the addition of Fe to the ocean surface, particularly in HNLC areas, significantly contributes to ocean carbon sequestration (Martin, 1990; Sigman et al., 2010). Field observations and laboratory experiments imply that, in addition to the input of Fe-rich eolian dust (Martin et al., 1989), delivery of macro- as well as micronutrients and vertical mixing processes in the vicinity of icebergs foster phytoplankton growth in high latitude oceans (Duprat et al., 2016; Smith et al., 2007). Such *in situ* measurements and remote sensing data suggest a potentially important role for icebergs and eolian dust in driving primary productivity in HNLC regions, but provide only a snapshot view of modern ocean biogeochemical feedbacks. Paleoreconstructions, in turn, permit an integrated view and evaluation of the role of these fertilization mechanisms on export production. Owing to its proximity to a former major Northern Hemisphere ice-sheet, the Gulf of Alaska (GoA; NE Pacific) is an area with vigorous temperate glacial erosion of Fe-rich rocks (Gulick et al., 2015; Montelli et al., 2017). Here, we present the first reconstruction of phytoplankton productivity in the GoA linked to Fe inputs from glacial debris. We focus on sediments spanning the last important climate transition in Earth's history, the Mid Pleistocene Transition (MPT), when the Northern Cordilleran Ice Sheet (NCIS) experienced a significant expansion (Gulick et al., 2015). Although the exact timing and cause(s) of the MPT are intensely discussed (Clark et al., 2006; Elderfield et al., 2012; Maslin and Brierley, 2015), the potential for biogeochemical feedbacks operating in the high-latitude oceans during this crucial time interval of northern hemisphere ice-sheet growth remains poorly studied. This is the first assessment of (subpolar) Fe-fertilization mechanisms across the MPT from outside the Southern Ocean (Lamy et al., 2014; Martinez-Garcia et al., 2011).

We present a multi-proxy record including geochemical, micropaleontological and sedimentological data obtained from IODP Site U1417 in the GoA (56°57'N, 147°6'W, 4200 m water depth; DR1; Jaeger et al., 2014). Our results record the interactions between sea surface temperature (SST), the input of terrigenous material by both eolian as well as ice rafting processes, and export productivity for multiple glacial-interglacial cycles between 1.5 and 0.5 Ma (Fig. 1). In the absence of eolian dust measurements, elevated contents of land-plant specific long-chain *n*-alkanes (depicted by higher terrigenous-aquatic ratios (TAR); Meyers, 1997; Peters et al., 2004) are used to track terrestrial dust input (Simoneit, 1977). In addition, icebergs may carry high amounts of terrigenous organic matter to distal ocean sites and are considered as a further transport agent of these leaf-wax compounds (Knies, 2005; Stein et al., 2009; Villanueva et al., 1997). Accordingly, at Site U1417, elevated TAR values that coincide with at ice-rafted debris (IRD) maxima suggest an ice rafting of leaf-wax lipids, while maximum TAR values accompanied by IRD minima indicate an airborne transport of these compounds. From the consistent pattern in concurrently high marine productivity indicators and high TAR values, we deduce that enhanced marine productivity was directly related to the input of terrigenous matter. Details on individual analytical methods and the age model are provided as Supplementary Information DR2.

Sea surface conditions and different Fe-fertilization mechanisms in the GoA

An overall consistent relationship applies at U1417, with intervals of lower SSTs and more polar waters (%$C_{37:4}$) coinciding with higher deposition of IRD (e.g., MIS 39, 30, 20), indicating a direct link between GoA sea surface conditions and NCIS dynamics. A distinct variability in diatom abundances, biogenic silica (opal; BSi) content and the Ba/Al ratio is considered to reflect abrupt phytoplankton productivity changes at Site U1417 (Fig. 1). Despite relatively warm SSTs prior to the MPT (> 1.2 Ma), the occurrence of diatoms was confined to short-lived events, and a significant rise in diatom abundance and BSi content occurred only at the onset of the MPT (1.22 Ma, MIS 37; Fig. 1). The association between the biosiliceous signal and SST is not consistent over the entire record and SST changes do not appear to be a primary driver of diatom productivity. However, both diatom and BSi signals are strongly linked to elevated Ba/Al values, recording increased export productivity (Jaccard et al., 2010), and to higher TAR values (Fig. 1). Today, significant amounts of Fe-rich glacial silt are deposited along glacifluvial river banks and at glacier termini along South Alaskan coastal areas and glacial rock flour is transported beyond the continental shelf into Fe-limited pelagic waters during dust storms (Crusius et al., 2011; Muhs et al., 2016). Evidently, the eolian transport of this glacial flour-derived dust via strong northerly winds is an important mechanism for the supply of bioavailable Fe to foster phytoplankton blooms in the GoA (Crusius et al., 2011; Crusius et al., 2017). We hence argue that the TAR peaks coinciding with diatom, BSi and Ba/Al maxima and IRD minima at Site U1417 reflect intervals of enhanced eolian export of leaf-wax lipids together with Fe-rich Alaskan dust, leading to productivity increases in the GoA across the MPT (e.g., at 1.22, 1.15 and 0.99 Ma; Fig. 1; DR3). Similarly, McDonald et al. (1999) proposed that late Pleistocene diatom productivity events at ODP Site 887 could have been promoted by Fe-supply via dust.

In addition to dust-fertilization, we suggest that also ice rafting of glacial Fe-rich debris (transported together with glacially reworked organic matter containing leaf-wax lipids) stimulated productivity at Site U1417. Intervals characterised by enhanced IRD deposition and high TAR, diatom, BSi and Ba/Al values occurred at e.g. 1.05, 0.91, 0.77 and 0.66 Ma (Fig. 1; DR3). Recent observations highlight the importance of Fe-fertilization of pelagic ecosystems from icebergs, accounting for up to 20% of the total carbon export in the Southern Ocean (Duprat et al., 2016; Smith et al., 2007). The coincidence of ice rafting and elevated marine productivity events in the GoA suggests that this mechanism also operated during the MPT in the subpolar NE Pacific. In addition to dust- and iceberg-fertilization, Fe-supply via mesoscale eddies (Crawford et al., 2007) and volcanic ash (Hamme et al., 2010) may have promoted phytoplankton blooms in the GoA. However, we consider these mechanisms of only minor importance at Site U1417 (see DR4 for discussion).

From the early towards the late MPT (ca. 1.2 Ma - 0.6 Ma), we note a decrease in predominantly dust-fertilized productivity pulses, while iceberg-fertilization sustained. This transition could result from an overall reduction in dust export owing to the persistent expansion of the NCIS (sealing central Alaskan dust (loess) deposits) and/or a change in atmospheric circulation diverting Alaskan storm tracks. Deposition of lithic particles by ice rafting, however, does not *per se* relate to a higher export production in the GoA and we argue that additional factors impacted ocean productivity (e.g. nitrate depletion; Galbraith et al., (2008)). Peaks in IRD at 1.27 or 0.82 Ma, for example, do not coincide with higher Ba/Al or opal values but an enhanced abundance of the $C_{37:4}$ alkenone (Fig. 1), pointing to a significantly cooler ocean surface.

Further implications

With regard to the overall environmental evolution in the subpolar NE Pacific, we suggest that the diatom and BSi peaks at 1.22 Ma mark a transition when NCIS growth and, hence, the production and export of glacigenic dust led to an effective Fe-fertilization in the adjacent GoA. Whereas eolian dust-fertilization dominated during intervals of reduced glacier extent (i.e., when coastal plains and glacigenic silt deposits were subaerially exposed; Fig. 2A, B), iceberg-fertilization occurred during intervals of enhanced glaciation when the NCIS terminated on the Alaskan continental shelf and discharged icebergs to Site U1417 (Fig. 2C, D). We note that, during the latter intervals, strong katabatic winds may have sustained an (airborne) export of dust from areas that remained ice-free (DR3).

Interestingly, the higher dust input at Site U1417 at approximately 1.22 Ma coincides with an enormous increase in dust delivery to the subantarctic Atlantic (Martinez-Garcia et al., 2011). Ocean cooling as well as increasing latitudinal temperature gradients are considered to have accounted for an equatorward movement of oceanic fronts and a strengthened atmospheric circulation leading to a higher dust export to the subantarctic Southern Ocean during the MPT (Kemp et al., 2010; Martinez-Garcia et al., 2011; McClymont et al., 2013). We suggest that the expansion of polar waters in the high northern latitudes and the growth of the NCIS (affecting surface albedo and orography) could have induced similar atmospheric shifts promoting dust export events in the GoA at the onset of the MPT. Comparisons between western and eastern records of subpolar North Pacific paleoproductivity, however, reveal that although SSTs in both areas developed in a similar fashion, the patterns of Mid Pleistocene primary productivity did not. While export production generally decreased in the Bering Sea due to an increase in sea ice cover (Kim et al., 2014), the productivity events observed in the

GoA point to an efficient, yet sporadic, ocean fertilization from the input of NCIS-sourced glacigenic terrestrial matter (and Fe) across the MPT.

We note that the productivity pulses at Site U1417 are neither exclusively confined to glacials nor to interglacials. This pattern contrasts to the western subarctic Pacific and the Bering Sea, where BSi production increased primarily during Pleistocene interglacials (Kim et al., 2014). The productivity pulses at Site U1417 may reflect local feedback mechanisms between South Alaskan glacier dynamics (controlling ice-proximal dust production and dispersal), and an immediate response of the marine ecosystem, yet they highlight potentially relevant mechanisms to elucidate hitherto neglected interactions in the land-ocean-atmosphere system during glacial-interglacial transitions. We propose the GoA as a case example of a Pleistocene ice-proximal marine environment where ice-sheet dynamics exhibited a significant control on primary productivity and potentially also CO_2 draw-down. In fact, with the intensification of Pleistocene Northern Hemisphere glaciation and sea-level lowering, extensive sub-aerial pro-glacial (coastal) outwash plains developed not only in South Alaska but also along the Laurentide Ice Sheet and European Ice Sheets, and these areas should be considered as potentially important sources of Fe-bearing glacigenic silt (Bullard et al., 2016) for areas where seasonal Fe-limitation restricts phytoplankton growth (Moore et al., 2006; Nielsdóttir et al., 2009). Further exploration of sedimentary archives from high-latitude ocean areas adjacent to (paleo) ice-sheets that permit correlations between productivity proxies and terrigenous compounds are required to evaluate the potential impacts of glacigenic dust- and iceberg-fertilization on phytoplankton productivity across the MPT and beyond. Importantly, such data would provide for a quantitative assessment of whether these processes could have accounted for an amplification of glacial-interglacial cycles, or if they even contributed to an appreciable CO_2 draw-down during the MPT.

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FIGURE CAPTIONS

Figure 1: Records of phytoplankton productivity (diatom concentration, BSi content, Ba/Al), terrigenous-aquatic ratio (TAR), IRD (3-point running average of wt.% coarse sand grains) deposition, and SST (U^{K}_{37}, U^{K}_{37}', $\%C_{37:4}$) at Site U1417 compared to the $\delta^{18}O$ isotope stack (Lisiecki and Raymo, 2005) over 1.5 - 0.5 Ma. Blue shadings highlight glacial intervals. Filled and hollow circles mark high productivity events stimulated by iceberg- and eolian dust-fertilization, respectively. Gray numbers mark Marine Isotope Stages (MIS).

Figure 2: Site U1417 (56°57’N, 147°6’W) and different Mid Pleistocene environmental settings in the study area and associated fertilization mechanisms. Brown shadings refer to modern Alaskan loess deposits (after Muhs et al., 2016). A, B: Reduced ice-sheet coverage (pale blue shadings) and a predominantly eolian export of glacigenic dust to Site U1417. C, D: Periods of an extended NCIS (2C; after Kaufman et al., 2011) with marine terminating glaciers and ice-rafting of glacigenic debris across the GoA. Green shadings indicate assumed area of dust- and iceberg-fertilized high productivity in the GoA through the MPT.