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Interaction between climate, volcanism, and isostatic rebound in Southeast Alaska during the last deglaciation

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ABSTRACT

Observations of enhanced volcanic frequency during the last deglaciation have led to the hypothesis that ice unloading in glaciated volcanic terrains can promote volcanism through decompression melting in the shallow mantle or a reduction in crustal magma storage time. However, a direct link between regional climate change, isostatic adjustment, and the initiation of volcanism remains to be demonstrated due to the difficulty of obtaining high-resolution well-dated records that capture short-term climate and volcanic variability traced to a particular source region. Here we present an exceptionally resolved record of 19 tephra layers paired with foraminiferal oxygen isotopes and alkenone paleotemperatures from marine sediment cores along the Southeast Alaska margin spanning the last deglacial transition. Major element compositions of the tephras indicate a predominant source from the nearby Mt. Edgecumbe Volcanic Field (MEVF). We constrain the timing of this regional eruptive sequence to 14.6–13.1 ka. The sudden increase in volcanic activity from the MEVF coincides with the onset of Bølling–Allerød interstadial warmth, the disappearance of ice-rafted detritus, and rapid vertical land motion associated with modeled regional isostatic rebound in response to glacier retreat. These data support the hypothesis that regional deglaciation can rapidly trigger volcanic activity. Rapid sea surface temperature fluctuations and an increase in local salinity (i.e., $\delta^{18}O_{sw}$) variability are associated with the interval of intense volcanic activity, consistent with a two-way interaction between climate and volcanism in which rapid volcanic response to ice unloading may in turn enhance short-term melting of the glaciers, plausibly via albedo effects on glacier ablation zones.

1. Introduction

Volcanism may induce short-term (sub-decadal) atmospheric cooling, deplete ozone, and affect the hydrologic and carbon cycles (McCormick et al., 1995; Robock, 2000, 2002). On longer timescales of centuries to millennia, global episodes of enhanced volcanism have been associated with deglaciation, hypothetically in response to gravitational unloading during high latitude ice loss (Hammer et al., 1980; Zielinski et al., 1997; Maclennan et al., 2002; Huybers and Langmuir, 2009; Kutteroff et al., 2013). Debate continues on the magnitude of this effect (Huybers and Langmuir, 2009; Watt et al., 2013), and on the response time of volcanism to isostatic triggering, ranging from nearly instantaneous (Maclennan et al., 2002) to several thousand years (Kutteroff et al., 2013; Watt et al., 2013; Rawson et al., 2016). Most studies have cataloged global or hemispheric averages of eruptive events; these have a statistical advantage of integrating many individual events but a disadvantage of greater uncertainty in the timing of ice unloading for various source regions, making it difficult to assess the triggers and mechanisms responsible for enhanced frequency of deglacial eruptions.

The climatic response to volcanism is similarly complex and difficult to predict, with the potential for global warming related to enhanced CO_2 emissions (Huybers and Langmuir, 2009) or regional lowering of albedo from tephra deposition on snow or ice (Conway et al., 1996), and for regional or hemispheric cooling due to aerosol

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radiative effects in the atmosphere (Robock, 2000) or global cooling by tephra-fertilized marine CO_2 drawdown (Langmann et al., 2010). Each of these processes occurs with its own characteristic timescale, and the type and degree of climate response is likely sensitive to the location, magnitude, composition, and climatic context of a given eruption. Furthermore, the relatively limited spatial extent of macro-tephra fallout and the short-term nature of these events make it difficult to identify and link a geologic record of a climate response to a given volcanic eruption. Nevertheless, it is likely that volcanism may be an important source of abrupt climate forcing, which may help to trigger instabilities in the climate system.

Ice cores preserve a detailed record of climate changes in conjunction with fine-scale tephra and sulfate layers that can record distant eruptions. For example, the GISP2 ice core in Greenland documents enhanced volcanic sulfate deposition during the last deglaciation (17–6 ka) relative to the last 100,000 yrs (Zielinski et al., 1996, 1997). Some of these sulfate peaks have been linked to eruptions from Iceland (Mortensen et al., 2005), which show enhancement of volcanic frequency of up to 50 times modern levels during the last deglaciation (12–10 ka) (Maclennan et al., 2002). While the Greenland record may be biased towards Icelandic volcanism (for example; Bourne et al., 2015) the GISP2 volcanic sulfate record documents an increase in volcanism commencing earlier than peak volcanism on Iceland, leaving the sources of this early deglacial volcanism poorly constrained. Many of the tephra deposits that have been analyzed in Greenland ice cores have compositions distinct from Icelandic volcanoes, suggesting more distal sources such as Japan, Kamchatka, the Cascades of the US Pacific Northwest, or volcanic systems of mainland Alaska or the Aleutian Arc (Mortensen et al., 2005; Abbott and Davies, 2012; Coulter et al., 2012; Jensen et al., 2014; Bourne et al., 2016). Resolving regional volcanic histories and tephra stratigraphies will not only help to constrain the timing and magnitude of the response of distinct volcanic systems to deglacial processes, but could also identify the source regions of volcanic activity recorded in distal archives.

A sequence of at least 12 postglacial tephra deposits from the Mt. Edgecumbe Volcanic Field (MEVF) have been previously identified in terrestrial outcrops, lake sediment cores, and peat cores from Southeast Alaska (Riehle et al., 1992a, 1992b; Beget and Motyka, 1998). A maximum of 28 tephra beds in a terrestrial outcrop have been identified, although the lack of sediment deposition between layers makes it difficult to determine how many of these beds were distinct eruptions as opposed to multiple eruptive phases of a single event. A number of tephras have also been detected in proximal marine sediment cores, some of which have been correlated to the MEVF deposits (Addison et al., 2010).

The postglacial eruptive sequence from the MEVF encompasses a wide compositional range from early basalt flows to rhyolitic tephras later in the sequence; whole-rock geochemistry from previously identified post-glacial MEVF deposits range from basaltic (∼49.5 SiO_2 wt%) to rhyolite (∼72 SiO_2 wt%) (Riehle et al., 1992b, 1994). Although mafic non-MEVF vents have been identified throughout Southeast Alaska, both terrestrially (Eberlein and Churkin, 1970) and in the submarine environment (Greene et al., 2011), many of these deposits have poor associated age control, limited geochemistry, and all are over 100 km distant (Riehle et al., 1992b). A distinctive dacitic tephra from Mt. Edgecumbe (MEd) dated to near the Pleistocene–Holocene boundary has been well dated on land at 13.13 ± 0.09 ka cal based on ^{14}C dates of 11.25 ± 0.05 ka, Beget and Motyka (1998), recalibrated here using INTCAL13 (Reimer et al., 2013). However, the initiation and duration of the entire MEVF deglacial eruptive sequence is not fully constrained because the land records generally lack good age controls.

Here we utilize rapidly accumulating marine sediments from the Southeast Alaska continental margin to construct a stratigraphically complete and precisely-dated record of the deglacial eruptive sequence from the Southeast Alaska volcanic province at multidecadal resolution, paired with climate proxies in the same samples. These records provide the highest resolution deglacial multiproxy climate history of the high-latitude North Pacific to date, and allow for an in-depth evaluation of the interactions among regional climate, glaciation, and volcanism.

2. Methods

2.1. Stratigraphy

Two nearby marine sediment cores were used to form a high-resolution composite record of planktonic oxygen isotopes spanning the late glacial to Holocene period (18.2–4.3 ka) (Praetorius and Mix, 2014). These sediment cores, EW0408-66JC (58.87°N, 137.10°W, 426 m) and EW0408-26JC (56.96°N, 136.43°W, 1623 m) are located in proximity to the MEVF (Fig. 1) and record a combined sequence of ∼22 tephras during the deglacial period. Core EW0408-26JC spans 18.2–13.5 ka and records 15 tephra layers in non-bioturbated sediments with high sedimentation rates (100–800 cm/kyr) (Fig. 2). Visual evidence for bioturbation is present in the upper 27 cm of this core, making detection of discrete tephra layers difficult, but rhyolitic tephra shards are present in the sediments. The 48 cm trigger core from site EW0408-26TC is used to extend the record into the Holocene, but low sedimentation rates and bioturbation in these uppermost sediments preclude a well-constrained age stratigraphy. Two tephras were analyzed from core EW0408-26TC at depths of 6–7 cm and 47–48 cm. Core EW0408-66JC spans 13.5–4.3 ka, with sedimentation rates ranging from 200–2000 cm/kyr during the deglacial period and 10 cm/kyr during the Holocene, and is thus used to extend the regional climate and tephra history into the mid Holocene. Two tephras were analyzed from core EW0408-66JC at depths of 858–860 cm and 1374–1376 cm.

2.2. Age model

The age model for these cores (Praetorius and Mix, 2014) consists of 28 radiocarbon dates on mixed planktonic foraminifera (predominantly *Neogloboquadrina pachyderma* (Nps) and *Globigerina bulloides* (Gb)) picked from the >150 μm size fraction (Fig. 2). Calendar corrections were made using the Calib 7.0 calibration software with the Marine13 calibration curve (Reimer et al., 2013). A tephra layer in core EW0408-66JC is matched (based on major element chemistry and stratigraphy; Fig. S3) to a terrestrial tephra layer from Mt. Edgecumbe. This provides an additional age control and an estimate of the marine reservoir correction in core EW0408-66JC during the deglacial interval. A surface–ocean marine reservoir correction of 595 ± 50 yrs (i.e., $\Delta R = 190 \pm 50$ yr in CALIB 7.0/Marine13) was applied to core EW0408-66JC based on the difference between the terrestrial radiocarbon age for the Mt. Edgecumbe dacite deposit and the planktonic foraminifera radiocarbon ages bracketing the dacite deposit in EW0408-66JC (Fig. 2). A marine reservoir correction of 735 ± 50 yrs (i.e., $\Delta R = 330 \pm 50$ yr in CALIB 7.0/Marine13) was applied to core EW0408-26JC based on the average age difference between terrestrial plant material and marine bivalves from a nearby core site (Addison et al., 2010).

An alternative age model was produced by correlating the oxygen isotope changes in the GOA record to the NGRIP chronology to allow for small changes in the marine reservoir age (Praetorius and Mix, 2014). This tuned age model preserves 15 of the original radiocarbon dates, the age control provided by the MEd correlation, and includes 5 adjusted tie points within the time period from 13.5–11.7 ka that result in only minor (<200 yrs) changes to