Recent retreat of Columbia Glacier, Alaska: Millennial context

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ABSTRACT

Columbia Glacier in Prince William Sound, Alaska, has retreated ~20 km in the past three decades. We use marine sediment records to document the Columbia Glacier advance and retreat history over the past 1.6 k.y. in an effort to place its recent retreat in the context of the Common Era (C.E.). A change in magnetic mineralogy coincided with a shift in sediment geochemistry ca. 0.9 ka. This provenance change documents the advance of Columbia Glacier across a fault, resulting in glacial erosion of mafic rocks near the coast; this agrees with the timing of ice advance reconstructed using dendrochronology. Our marine provenance records show that Columbia Glacier remained advanced south of this fault into the 21st century. Columbia Glacier has now retreated north of this fault, making its recent retreat unprecedented since before ca. 0.9 ka. Southern Alaska temperatures have now warmed to pre-0.9 ka levels, based on tree-ring and reanalysis data. We show with glacier model simulations that the warming between C.E. 1910 and 1980, that includes anthropogenic forcing, was sufficient to trigger the recent retreat of Columbia Glacier from its extended position of the past 0.9 k.y., consistent with our data-driven assessment of the relationship between regional climate change and glacier extent. We conclude that the recent retreat of Columbia Glacier is a response to climate change rather than part of a natural internal tidewater-glacier oscillation.

INTRODUCTION

Many Alaskan tidewater glaciers are currently retreating, and are the largest contributors to global mean sea-level rise from the cryosphere other than ice masses in Greenland and Antarctica (Berthier et al., 2010). However, some Alaskan tidewater glaciers are advancing or remaining at extended positions (Meier, 1987; Post et al., 2011; McNabb and Hock, 2014) despite a warming southern Alaskan climate over the past century (Hartmann et al., 2013). Other Alaskan tidewater glaciers began their retreat well before the beginning of the last century (Barclay et al., 2009), when southern Alaska climate had yet to begin to warm significantly (Wiles et al., 2014). Tidewater glaciers are known to undergo cyclic behavior of slow advance and rapid retreat in decades after ice-margin destabilization (Post, 1975; Meier, 1987; Post et al., 2011). Post et al. (2011) noted that understanding the cause of this tidewater stability-instability transition is of critical importance for predicting future tidewater-glacier behavior.

Columbia Glacier in Prince William Sound (southern Alaska) is undergoing one of the most dramatic and best-documented retreats of a tidewater glacier in the past three decades (Fig. 1) (Meier, 1987; McNabb and Hock, 2014), and is the largest Alaskan glacier contributor to sea-level rise over this time interval (Berthier et al., 2010). Placing the recent behavior of Columbia Glacier in the context of past fluctuations in its extent during periods of minimal anthropogenic influence on climate could shed light on the trigger of its rapid retreat. Although numerous tree-ring and 14C chronologies exist for glaciers of southern Alaska (e.g., Barclay et al., 2009), relatively little is known about the prehistoric record of Columbia Glacier and its relationship to climate change (Barclay et al., 2009). Here we present the first continuous sediment discharge record for Columbia Glacier that documents its late-Holocene extent, placing its current retreat in the perspective of the past ~1.6 k.y.

METHODS

To track the extent of Columbia Glacier, we use changes in bulk sediment geochemistry and magnetic grain size in marine jumbo piston core EW0408–951C/TC and multicore EW0408–94MC (60.66°N, 147.71°W, 744 m water depth; RV Maurice Ewing cruise EW0408) in Prince William Sound that are dated by 14C and 210Pb, respectively (Fig. 1B; Table DR1 in the GSA Data Repository1). The summer through fall regional ocean circulation pattern (Musgrave et al., 2013) transports sediment from Columbia Glacier to the core site during the summer ablation season (Fig. 1B) over the course of a few years to a few decades (Jaeger and Koppe, 2016).

Anhysteretic remanent magnetization (ARM), expressed as susceptibility of ARM (kARM) and magnetic susceptibility (k), and bulk sediment geochemistry were measured. We relate the change in bulk sediment, kARM, k, the ratio of the two (a well-known magnetic grain-size proxy), and geochemistry in the cores to changes in sediment source, most notably, the Contact fault, which extends along the north side of Prince William Sound (Figs. 1B and 1C). South of the fault, the bedrock contains Paleogene–Miocene mafic, mainly extrusive, crystalline rocks in addition to marine sedimentary rocks; north of the fault, the bedrock is mainly uplifted Cretaceous marine sedimentary rocks (Wilson and Hults, 2012). Therefore, glacially eroded sediments from north of the fault should have magnetic and geochemical signatures distinctly different from those of glacially eroded sediments from south of the fault.

To determine sediment provenance, we collected glacial sediment samples from the historical moraines of Columbia and Shoup Glaciers (Fig. 1B; Table DR2). The Columbia Glacier moraine contains the con-flated geochemistry and magnetic properties of sediment eroded from both sides of the Contact fault, whereas the Shoup Glacier moraine is sediment eroded only from north of the Contact fault.

We used 3020 glacier model simulations (Colgan et al., 2012) that forced Columbia Glacier with different rates and magnitude of climate warming. We binned the simulation results that destabilized the glacier to compare rate of warming versus magnitude of warming against our data-driven observations. (See the Data Repository for methods, dendrochronology, and glacier modeling.)

GSA Data Repository item 2017175, methods, dendrochronology, and glacier modeling, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

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RESULTS

Foraminiferal 14C ages indicate that the 17.5 m EW0408–95JC core extends back to ca. 1.6 ka, with sedimentation rates of >1 cm a⁻¹ (Fig. 2F). The 14C ages are in stratigraphic order with the exception of age reversals between 554 cm and 1052 cm below the seafloor (Fig. DR1); foraminifera dates are anomalously old (Table DR1); physical sediment structure in the core (Fig. DR1) supports interpretation of this interval as a gravity flow containing reworked foraminifera (Jaeger and Koppes, 2016). The gravity flow deposit separates a bioturbated section above and below (Fig. DR1), where foraminifera dates are anomalously old (Table DR1); physical sediment structure in the core (Fig. DR1) supports interpretation of this interval as a gravity flow containing reworked foraminifera (Jaeger and Koppes, 2016). The gravity flow deposit separates a bioturbated section above from a laminated section below (Fig. DR1); the laminated section probably reflects hypoxic or anoxic conditions in Prince William Sound. The magnetic records have two distinct periods: the earlier is characterized by high variability, and low k, kARM, and kARM/k before ca. 1.0 ka, shifting to reduced variability, higher k, kARM, and kARM/k ca. 0.9 ka (Figs. 2A–2C). Sediment geochemical changes mimic magnetic grain-size changes, with a decrease in Si relative to Fe and Ca concentration ca. 0.9 ka (Figs. 2D and 2E).

Bulk elemental analysis of the glacial sediments shows a distinct change in geochemistry; Columbia Glacier sediment has higher Fe and Ca concentrations and lower Si/Ca and Si/Fe than Shoup Glacier sediment (Table DR2). We find a significant difference in magnetic properties between these two terranes. Sediments from south of the Contact fault have higher k, kARM, and kARM/k (a higher concentration of finer magnetic grain sizes) than sediments north of the fault (Table DR2).

The glacier model simulations show that faster rates of warming require a shorter duration of warming to destabilize Columbia Glacier (Fig. 3).

DISCUSSION

The magnetic and geochemical data show a change in sediment provenance ca. 0.9 ka. The shift in kARM and k to higher values concurrent with increased kARM/k (Fig. 2A) is consistent with a source shift to a lithology that is substantially more magnetic with a consistently fine-grained magnetic mineralogy after ca. 0.9 ka, such as the extrusive mafic rocks from south of the Contact fault (Wilson and Hults, 2012). The decrease in Si/Fe and Si/Ca ca. 0.9 ka (Figs. 2D and 2E) also indicates a new sediment source enriched in elements consistent with mafic rocks that are found south of the Contact fault (Wilson and Hults, 2012). Because of the counterclockwise summer to fall ocean circulation pattern in Prince William Sound (Musgrave et al., 2013), three tidewater glaciers, Columbia, Meares, and Shoup, could be major contributors of sediment to the core site during the ablation season (Fig. 1B). However, only Columbia Glacier advanced south of the Contact fault in the late Holocene (Post, 1975; Post and Viens, 2000; Molnia, 2008) (Fig. 1B), and thus would be the only marine-terminating glacier to overlie and erode highly magnetic mafic extrusive rocks with a homogeneous fine-grained magnetic mineralogy, as identified by the glacial sediment provenance data.

We compared the marine sediment record with calendar tree-ring dates on overrun mountain hemlock forests (Tsuga mertensiana) killed during late-Holocene Columbia Glacier advance (Table DR3). The dendrochronology shows that Columbia Glacier advanced south of the Contact fault ca. 0.9 ka (Figs. 1C and 2G). This timing is in agreement with the observed marine sedimentary shifts in magnetic properties and geochemical provenance ca. 0.9 ka. This advance is consistent with other southern Alaska

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and Coast Range glaciers that began to expand toward their late Holocene maxima ca. 1 ka (Barclay et al., 2009). We attribute increased variability in magnetic parameters and geochemistry before ca. 1.0 ka to more active glaciers in Prince William Sound eroding heterogeneous sedimentary source material from behind the Contact fault (Wilson and Hults, 2012).

The dendrochronologic record, based on calendar-dated trees overrun at the glacier margin, documents the general advance of Columbia Glacier to its maximum extent at C.E. 1808. The dense tree-ring network dates ice advance, but does not constrain possible intervals of ice-margin retreat, as could be implied by the gap in kill ages of 0.6–0.3 ka (Figs. 1C and 2G). However, given the high sedimentation rates (Figs. 2F and 4D) and a sediment transport time from glacier margin to the outer fjord and

Figure 2. Columbia Glacier (southern Alaska) change and core EW0408–95JC/TC data (RV Maurice Ewing cruise EW0408) (in A–F, red is trigger core; blue is jumbo piston core). A–C: Ratio of susceptibility of anhysteretic remanent magnetization (kARM) to magnetic susceptibility (k) kARM/k, kARM, and k. D, E: Si/Ca and Si/Fe. F: Age-depth relationship with 95% confidence interval. G: Columbia Glacier length from dendrochronology (squares; lines indicate life span of glacier-killed trees) and observations (circles) (Post, 1975; McNabb and Hock, 2014). H: Decadal change in tree-ring February–August surface air temperature (SAT, brown line; annual shown in tan) for southern Alaska (Wiles et al., 2014) and summer SAT from reanalysis data (purple line) at the Columbia Glacier equilibrium line (Colgan et al., 2012), both relative to the C.E. 1870–1890 mean. Dashed line is the summer SAT at the time of Columbia Glacier retreat onset in mid–C.E. 1980. PWS—Prince William Sound. Vertical yellow bar is the gravity flow.

Figure 4. Columbia Glacier (southern Alaska) change of the past century. A: Observations of Columbia Glacier length (Post, 1975; McNabb and Hock, 2014); the Contact fault is indicated. B: Si/Ca from core EW0408–94MC (RV Maurice Ewing cruise EW0408). C: Si/Fe. D: 210Pb sedimentation rate in EW0408–94MC with 95% confidence interval on a log scale. E: Decadal change in surface air temperature (SAT) from Figure 2H. Dashed line is the summer SAT at the time of onset of Columbia Glacier retreat. PWS—Prince William Sound. Vertical yellow bar is onset of Columbia Glacier retreat.
continental shelf of a few years to decades (Jaeger and Koppes, 2016), it is very likely that any retreat of Columbia Glacier north of the Contact fault would be recorded as a decrease in kARM/k and an increase in Si/Fe-Si/Ca to pre-0.9 ka levels. The input of high kARM/k and low Si/Fe and Si/Ca sediments to the site through to the core sediment-water interface, reflecting the collection year of C.E. 2004 (Figs. 2 and 4), indicates the continual presence of Columbia Glacier south of the Contact fault (Fig. 1C) since ca. 0.9 ka. The records from EW0408–94MC show increased sediment accumulation with increased input of Fe and Ca relative to Si (Figs. 4B–4D) when Columbia Glacier began northward retreat in mid-1980, consistent with increased sediment discharge during tidewater-glacier retreat (Jaeger and Koppes, 2016). The observational record has Columbia Glacier south of the Contact fault for all of the 20th century, with the glacier retreating north of this geologic boundary in C.E. 2002 (Fig. 4A) (Post, 1975; McNabb and Hock, 2014), two years before EW0408 core collection. Based on the marine sedimentary record, this retracted position has not occurred since before ca. 0.9 ka, meaning that the current retreat of Columbia Glacier is unprecedented with respect to the last millennium.

Because the marine sediment record indicates that Columbia Glacier has not retreated to its modern position at any point in the last millennium, we argue that an external forcing may be the trigger of the current instability, consistent with tidewater glacier theory (Post, 1975; Meier, 1987; Post et al., 2011). Southern Alaska tree-ring surface air temperature (SAT) reconstructions indicate that February–August SAT was colder than the late 20th century for the past ~0.9 k.y. (Wiles et al., 2014) (Fig. 2H). The last time southern Alaska SAT approached late 20th century levels was prior to ca. 1.0 ka, when southern Alaska SAT was +1.0 °C relative to the late C.E. 1800s (Fig. 2H), during which time the marine sediment record indicates that Columbia Glacier terminated north of the Contact fault. The subsequent Columbia Glacier advance corresponds with cooling below this +1.0 °C threshold. Southern Alaska winter precipitation has increased in the past few centuries (Osterberg et al., 2014); this should support glacier expansion. We therefore suggest that climate warming over the past century thinned the lower Columbia Glacier to the point of destabilization in the decade of C.E. 1980–1990, when SAT warmed above +1.0 °C (Fig. 2H), which then led to the observed catastrophic terminus retreat.

The observed April–September warming of +1.2 °C over 70 yr (0.017 °C a−1) at the Columbia Glacier equilibrium line (Fig. 4E), attributed largely to anthropogenic greenhouse gas emissions (Hartmann et al., 2013), agrees well with the glacier model simulated rate and duration of warming necessary to trigger Columbia Glacier instability (Colgan et al., 2012) (Fig. 3). Furthermore, the simulated cumulative warming to trigger Columbia Glacier instability of 1.1 ± 0.2 °C also agrees with the +1.0 °C of warming indicated by the paleodata as necessary to trigger Columbia Glacier retreat.

CONCLUSIONS

We conclude that atmospheric warming of southern Alaska over the 20th century triggered the Columbia Glacier retreat of the last few decades. Columbia Glacier retreat is consequently a response to climate change that includes anthropogenic inputs, rather than a natural tidewater-glacier cyclic oscillation. More broadly, our diagnostic analysis supports the emerging notion, largely derived from prognostic modeling, that air temperature increases of <2 °C can result in the loss of ice masses in a fashion that is irreversible on millennial time scales (e.g., Robinson et al., 2012).

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