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Response of a marine-terminating Greenland outlet glacier to abrupt cooling 8200 and 9300 years ago

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[1] Long-term records of Greenland outlet-glacier change extending beyond the satellite era can inform future predictions of Greenland Ice Sheet behavior. Of particular relevance is elucidating the Greenland Ice Sheet's response to decadal- and centennial-scale climate change. Here, we reconstruct the early Holocene history of Jakobshavn Isbræ, Greenland's largest outlet glacier, using ^{10}Be surface exposure ages and ^{14}C-dated lake sediments. Our chronology of ice-margin change demonstrates that Jakobshavn Isbræ advanced to deposit moraines in response to abrupt cooling recorded in central Greenland ice cores ca. 8,200 and 9,300 years ago. While the rapid, dynamically aided retreat of many Greenland outlet glaciers in response to warming is well documented, these results indicate that marine-terminating outlet glaciers are also able to respond quickly to cooling. We suggest that short lag times of high ice flux margins enable a greater magnitude response of marine-terminating outlets to abrupt climate change compared to their land-terminating counterparts. **Citation:** Young, N. E., J. P. Briner, Y. Axford, B. Csatho, G. S. Babonis, D. H. Rood, and R. C. Finkel (2011), Response of a marine-terminating Greenland outlet glacier to abrupt cooling 8200 and 9300 years ago, *Geophys. Res. Lett.*, *38*, L24701, doi:10.1029/2011GL049639.

1. Introduction

[2] Fast-flowing outlet glaciers disproportionately influence the overall mass balance of ice sheets [*Joughin et al.*, 2004; *Rignot and Kanagaratnam*, 2006]. Satellite-based observations show that outlets of the Greenland Ice Sheet (GrIS) fluctuate rapidly on sub-decadal time scales and highlight the importance of non-climatic (dynamic) processes in dictating outlet-glacier behavior [*Howat et al.*, 2007; *Nick et al.*, 2009]. The relatively short period over which detailed ice-sheet observations have been made, however, has made it difficult to assess the interaction between dynamic and climatic controls on GrIS change and what role these mechanisms play in the GrIS' response to abrupt climate change. Paleo-records of GrIS change extending through the Holocene epoch (the past ~11.7 thousand years (kyr) [*Walker et al.*, 2009]) can place empirical constraints on the timing and magnitude of ice-sheet response to temperature change over timescales longer than those dominated by dynamics, and are key to reducing uncertainties about projections of future ice-sheet retreat and sea-level rise.

[3] Abrupt isotope excursions in Greenland ice cores ca. 8,200 and 9,300 years ago record the most prominent abrupt climatic events of the past 10,000 years [*Alley et al.*, 1997; *Kobashi et al.*, 2007; *Rasmussen et al.*, 2007], likely driven by freshwater outbursts into the North Atlantic Ocean and attendant changes in thermohaline circulation [*Barber et al.*, 1999; *Yu et al.*, 2010]. The 8,200-year event resulted in an estimated drop in annual temperatures of 3.3 ± 1.1°C in Greenland [*Kobashi et al.*, 2007]; similar in amplitude but shorter in duration is the 9,300-year event [*Rasmussen et al.*, 2007]. These proxy records from central Greenland ice cores provide type chronozones for the 8.2 and 9.3 kyr abrupt cooling events, which appear to have influenced climate far beyond Greenland [e.g., *Haug et al.*, 2001; *Alley and Ágústdóttir*, 2005; *Fleitmann et al.*, 2008], yet remarkably there is no definitive evidence indicating that these perturbations influenced GrIS behavior. These events afford an ideal opportunity to assess the sensitivity of the GrIS to short-lived climate change as early Holocene abrupt cooling interrupted climatic baseline conditions that were similar to today [*Alley and Ágústdóttir*, 2005]. Here, we develop a precise glacial chronology for Jakobshavn Isbræ to discern the response, if any, of this major marine-terminating outlet glacier to abrupt climate change.

2. West Greenland and Jakobshavn Isfjord

[4] The Fjord Stade moraine complex located throughout west-central Greenland consists of the older Marrait and younger Tasiussaq moraines (Figure 1) [*Weidick*, 1968; *Weidick and Bennike*, 2007]. It has been hypothesized that Fjord Stade moraine deposition was the result of a climatically driven standstill or advance of the western GrIS during overall deglaciation, perhaps related to the 8.2 kyr cooling event [*Long and Roberts*, 2002]. Dynamics related to topographic controls on ice-sheet position, rather than changes in mass balance, have also been proposed as the cause of moraine deposition [*Long et al.*, 2006]. Bracketing radiocarbon ages broadly constrain deposition of the Fjord Stade moraine complex to sometime between ~10 and 7.9 kyr ago [*Weidick*, 1968; *Long and Roberts*, 2002; *Long et al.*, 2006; *Weidick and Bennike*, 2007]. At Jakobshavn Isfjord (Figure 1), recent ^{10}Be surface exposure ages (herein ^{10}Be

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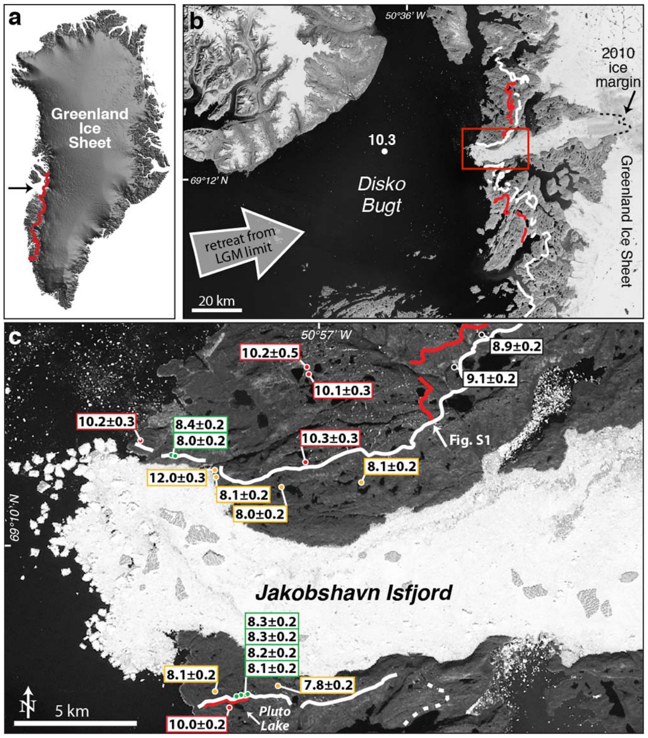

Figure 1. Study area on west Greenland. (a) Latitudinal extent of the Fjord Stade moraines on west Greenland [*Weidick*, 1968; *Funder et al.*, 2011] and the location of Disko Bugt (arrow). (b) Disko Bugt region with generalized Fjord Stade moraines [*Weidick*, 1968]; following a last glacial maximum position on the continental shelf, Jakobshavn Isbræ retreated through Disko Bugt by ca. 10.3 kyr ago [*Lloyd et al.*, 2005] before depositing the Fjord Stade moraines between ca. 10 – 7.9 kyr ago. (c) Marrait (red lines) and Tassiusaq (white lines) moraines at Jakobshavn Isfjord [*Weidick*, 1968; *Young et al.*, 2011]. ^{10}Be ages are presented in kyr at 1σ and in four distinct morphostratigraphic groups: 1) outboard of the Fjord Stade moraines (red), 2) inboard of the Marrait moraine (black), 3) Tasiussaq moraine boulders (green), and 4) directly inboard of the Tasiussaq moraine (orange).

ages), calculated with the northeast North America production rate [*Balco et al.*, 2009; *Briner et al.*, 2011] (see auxiliary material), indicate that the fjordmouth initially deglaciated ~10.2 kyr ago and deglaciation from the Tasiussaq moraine was underway by ~8.0 kyr ago [*Young et al.*, 2011], consistent with bracketing radiocarbon ages [*Briner et al.*, 2011].[1] These ages suggest possible correlations with abrupt climate changes in the early Holocene, but the Fjord Stade moraines remain imprecisely dated and therefore their climatic significance remains debated [*Long and Roberts*, 2002; *Long et al.*, 2006; *Weidick and Bennike*, 2007; *Young et al.*, 2011]. Here we directly date both the Tasiussaq and Marrait moraines for the first time using ^{10}Be ages and ^{14}C-dated lake sediments.

3. Methods and Results

[5] We sampled large boulders resting on the Tasiussaq moraine at Jakobshavn Isfjord (Figure 1). Individual ^{10}Be ages are shown in Figure 1 with 1σ analytical uncertainties and in Tables S1 and S2. ^{10}Be ages from Tasiussaq moraine boulders range from 8.4 ± 0.2 to 8.0 ± 0.2 kyr (n = 6; reduced χ^2 = 0.86), and have a mean exposure age of 8.2 ± 0.4 kyr (error term includes production rate uncertainty). ^{10}Be ages derived from bedrock and erratic boulders [n = 5, excluding one outlier] located just inboard of the Tasiussaq moraine average 8.0 ± 0.4 kyr (reduced χ^2 = 0.43 [*Young et al.*, 2011]). These ^{10}Be ages further constrain the timing of retreat from the Tasiussaq moraine, supporting the 8.2 kyr age of the moraine.

[6] The Marrait moraine contained no boulders suitable for ^{10}Be dating in our field area. To constrain the age of the Marrait moraine, we collected sediment cores from Pluto Lake (informal name; Figures 1 and 2), a threshold lake [e.g., *Briner et al.*, 2010] located directly outboard of the Marrait moraine on the south side of Jakobshavn Isfjord. Pluto Lake is currently dominated by organic sedimentation; however, during emplacement of the Marrait moraine Jakobshavn Isbræ spilled silt-laden meltwater into Pluto Lake, leading to alternating units of organic- (Figure 2, units I and III) and minerogenic-rich sediment (unit II) whose sharp contacts we dated with radiocarbon. The lower organic unit (III) indicates that following initial deglaciation ~10.2 ± 0.5 kyr ago [*Young et al.*, 2011] (see auxiliary material), Jakobshavn Isbræ did not spill silt-laden meltwater into Pluto Lake until emplacement of the Marrait moraine. Two radiocarbon ages from

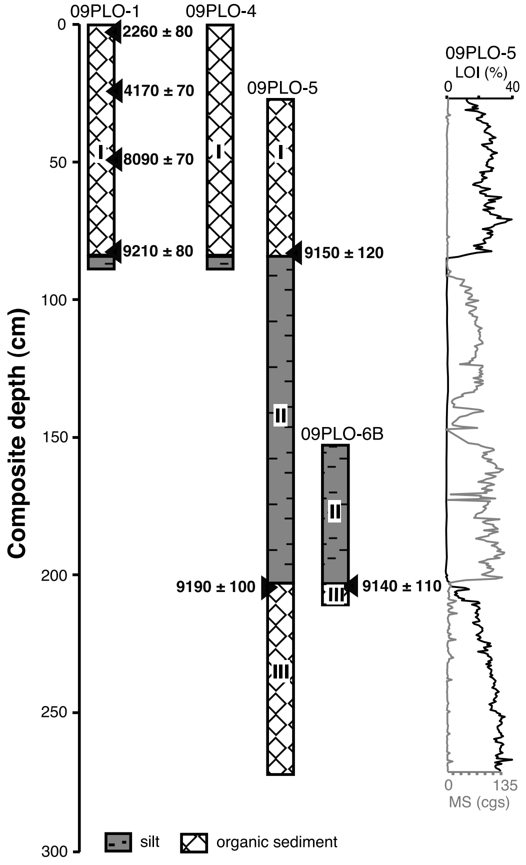

Figure 2. Lithostratigraphy of four sediment cores recovered from Pluto Lake with ^{14}C ages (cal yr BP; 2σ). LOI - loss on ignition; MS - magnetic susceptibility. Detailed radiocarbon information can be found in Table S3. Photograph of Pluto Lake shown in Figure S4.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL049639.

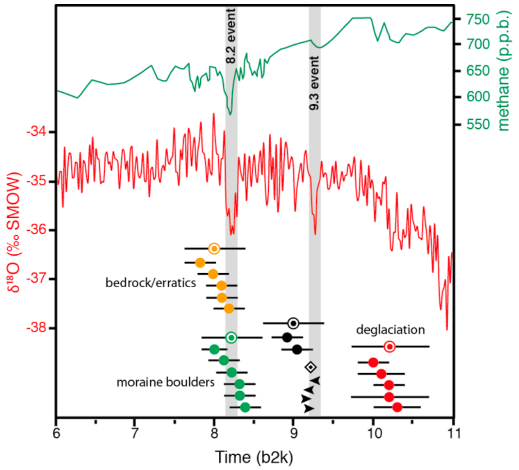

Figure 3. ^{10}Be and radiocarbon ages constraining the Fjord Stade moraines at Jakobshavn Isfjord. We present individual ^{10}Be ages with 1σ analytical uncertainties and the mean ^{10}Be age of each morphostratigraphic group with a ^{10}Be production rate uncertainty of ~5% (bullseyes). Colorway is from Figure 1. Maximum- (left pointing arrows) and minimum-constraining (right pointing arrows) radiocarbon ages are from Pluto Lake. Fifty years has been added to each radiocarbon age to make them compatible with the ice-core chronology (before AD 2000; b2k). Also depicted is the mean radiocarbon age from Pluto Lake (diamond) constraining Marrait moraine deposition to 9,225±45 b2k. ^{10}Be ages constraining the Marrait moraine are located inboard of the moraine and must be younger than the radiocarbon constraints. Results compared to δ^{18}O values from the North Greenland Ice Core Project (NGRIP) ice core [*Rasmussen et al.*, 2007] and methane concentrations from the Greenland Ice Sheet Project Two (GISP2) ice core [*Kobashi et al.*, 2007, and references therein].

macrofossils immediately below the thick minerogenic unit are 9,190 ± 100 and 9,140 ± 110 cal yr BP and provide maximum-limiting ages for moraine deposition. Two radiocarbon ages from just above the minerogenic unit (minimum ages) are 9,210 ± 80 and 9,150 ± 120 cal yr BP. Because all radiocarbon ages overlap at 1σ, we calculate a mean radiocarbon age of 9,175 ± 45 cal yr BP. Consistent with these radiocarbon ages are two ^{10}Be ages from ice-sculpted bedrock of 8.9 ± 0.2 and 9.1 ± 0.2 kyr from just inboard of the Marrait moraine north of Jakobshavn Isfjord (Figure 1). ^{10}Be ages from this surface must be equal to or slightly younger than the age of the Marrait moraine as constrained by the Pluto Lake radiocarbon ages. All maximum- and minimum-constraining radiocarbon and ^{10}Be ages overlap at 1σ indicating nearly instantaneous (i.e., sub-centennial; within dating resolution) deposition of the Marrait moraine ~9.2 kyr ago.

4. Discussion

[7] Taken together, these ^{10}Be and radiocarbon ages, combined with published ^{10}Be ages [*Young et al.*, 2011], indicate that the Tasiussaq and Marrait moraines record advances of Jakobshavn Isbræ in response to abrupt cooling occurring 8.2 and 9.3 kyr ago (Figure 3). Our results reveal that these moraines appear to record changes in GrIS mass balance, although the exact location and preservation of the Fjord Stade moraines at Jakobshavn Isfjord also may be influenced by topography. Pluto Lake's alternating organic- and minerogenic-rich sediment stratigraphy, and the onlap of the Tasiussaq moraine onto the Marrait moraine in some locations (Figure 1 and Figure S1 in the auxiliary material), indicate that both moraines represent readvances rather than standstills of the ice margin. Although glaciological conditions also can trigger short-lived advances of marine-terminating outlet glaciers, our chronology suggests that abrupt coolings, rather than glaciological conditions, drove advances of Jakobshavn Isbræ during the early Holocene.

[8] This precise chronology has implications regarding the response of marine-terminating outlet glaciers to abrupt climate change. It has been proposed, based upon paleo-records and modern observations, that the growth of ice sheets and their outlets may be much slower than their decay, which is linked to dynamically forced positive feedbacks involving the interaction of the calving terminus with fjord bathymetry, interior drainage and oceanographic changes [*Joughin et al.*, 2004; *Holland et al.*, 2008; *Briner et al.*, 2009; *Rignot et al.*, 2010]. In contrast, the coincidence of the age of the Fjord Stade moraines with the 8.2 and 9.3 kyr cooling events implies a rapid response of Jakobshavn Isbrae to decades- to centuries-long cold events. It seems that abrupt climate cooling can drive rapid advances of GrIS outlet glaciers with lag times perhaps similar to high mass-balance-gradient alpine glaciers [e.g., *Oerlemans*, 2005]. Although fresh moraines that fringe the current GrIS, including Jakobshavn Isbræ, record a response of the ice sheet to the Little Ice Age (LIA; i.e., a centennial-scale event), prior to the LIA, the GrIS had already been advancing for several thousand years in response to long-term Neoglacial cooling [*Kelly*, 1980; *Funder et al.*, 2011]. Consequently, LIA moraines were deposited at the culmination of long-term cooling and GrIS advance. In contrast, during the early Holocene, Jakobshavn Isbræ was in retreat following its last glacial maximum position on the western Greenland continental shelf [*Weidick and Bennike*, 2007; *Funder et al.*, 2011]. Thus, the 8.2 and 9.3 kyr event-driven advances of Jakobshavn Isbræ reversed a pattern of overall retreat. In summary, Jakobshavn Isbræ experienced quick retreat during the early Holocene that was punctuated by readvances ~9.2 and 8.2 kyr ago.

[9] Jakobshavn Isbræ and other marine-terminating outlet glaciers are characterized by ice velocities on the order of several km yr^{-1} [*Joughin et al.*, 2004; *Rignot and Kanagaratnam*, 2006] and modern observations show that Jakobshavn Isbræ displays enhanced sensitivity to regional warming compared to the adjacent land-based margin [*Csatho et al.*, 2008]. We suggest that this relationship also applies to phases of outlet-glacier growth. For example, in addition to Jakobshavn Isbræ's quick response to early Holocene abrupt cooling, Jakobshavn Isbræ was also much more extended than the adjacent land-based margin during the LIA [*Weidick*, 1994; *Csatho et al.*, 2008]. We speculate that ice-sheet margins with high ice fluxes display an amplified response to cooling due to much quicker response times than margins with lower ice fluxes. In these high ice flux sectors of the ice sheet, a mass balance shift from negative to positive would be relayed quickly to the margin resulting in an ice-sheet advance.

5. Conclusions

[10] Currently the GrIS is experiencing rapid retreat and accelerated rates of ice loss [*Rignot et al.*, 2011]

influenced by dynamic fluctuations in marine-terminating outlet glaciers, and there is increasing concern that these changes may become irreversible at outlets whose beds sit well below sea level [*Intergovernmental Panel on Climate Change*, 2007; *Pfeffer*, 2007]. Our data suggest that dynamically forced ice-margin retreat is not necessarily irreversible [*O'Cofaigh et al.*, 2008]; Jakobshavn Isbræ overcame rapid retreat twice in the early Holocene in response to centennial-scale cooling events. At the same time, these results reinforce the notion that high-ice-flux outlet glaciers are extremely sensitive to climate change, both warming and cooling, with ice extent having responded rapidly to climate change in the past. As temperatures in the Arctic are expected to continue to increase over the next century, GrIS outlets will likely continue to retreat as evident by the close coupling between temperature and ice-margin change presented here. Ice-margin retreat initially may be largest for marine-based outlets and ice-sheet sectors whose beds are below sea level far inland. However, should warming be reversed or punctuated by a significant cooling episode, widespread retreat could be halted.

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