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Meltwater intensive glacial retreat in polar environments and investigation of associated sediments: example from Pine Island Bay, West Antarctica

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A B S T R A C T

Modern Pine Island and Thwaites Glaciers, which both drain into Pine Island Bay, are among the fastest changing portions of the cryosphere and the least stable ice streams in Antarctica. Here we show that the uppermost sediment unit in Pine Island Bay was deposited from a meltwater plume, a plumite, during the late stages of ice sheet retreat ~7–8.6 k cal yr BP and argue that this deposit records episodes of meltwater intensive sedimentation.

The plumite is a hydraulically sorted, glacially sourced, draping deposit that overlies proximal glacimarine sediments and thickens towards the modern grounding line. The uppermost sediment unit is interpreted as a product of non-steady-state processes in which low background sedimentation in large bedrock-carved basins alternates with episodic purging of sediment-laden water from these basins. The inner part of Pine Island Bay contains several basins that are linked by channels with a storage capacity on the order of 70 km^3 of stagnant water and significant sediment storage capacity. Purging of these basins is caused by changes in hydraulic potential and glacial reorganization. The sediment mobilized by these processes is found here to total 120 km^3.

This study demonstrates that episodes of meltwater-intensive sedimentation in Pine Island Bay occurred at least three times in the Holocene. The most recent episode coincides with rapid retreat of the grounding line in historical time and has an order of magnitude greater flux relative to the entire unit. We note that the final phase of ice stream retreat in Marguerite Bay was marked by a similar sedimentary event and suggest that the modern Thwaites Glacier is poised for an analogous meltwater-intensive phase of retreat.

1. Introduction

The last few decades of Antarctic marine geological research has yielded several examples for diachronous and stepped retreat of ice sheet grounding lines around the Antarctic margin following the Last Glacial Maximum (LGM) (e.g. Anderson et al., 2002, 2013a,b; Ó Cofaigh et al., 2008; Larter et al., 2013; Macintosh et al., 2013; Hillenbrand et al., 2013a,b). The mechanisms that have been put forward for forcing grounding-line retreat include: buoying by sea-level rise (both eustatic and isostatic), thinning from accelerated glacial flow, basal melting from impinging warmer waters, removal of ice shelves through atmospheric and oceanographic warming, and under-pinning by subglacial meltwater. These mechanisms were apparently active at different times and locations throughout the post-LGM retreat, due largely to the highly variable bathymetry of the continental shelf (e.g. Mosola and Anderson, 2006; Heroy and Anderson, 2007; Ó Cofaigh et al., 2008; Kirshner et al., 2012; Livingstone et al., 2012; Anderson et al., 2013a).

Changes in subglacial water volume, flux, and dynamic state are hypothesized to play a critical role in glacial stability by altering basal conditions that control glacial sliding and stability (Kamb et al., 1985; Fowler, 1987; Kamb, 1987; Sharpe, 1988; Alley, 1989; Walder and Fowler, 1994; Anandakrishnan and Alley, 1997; Schoof, 2010). Modern remote sensing measurements have

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yielded evidence for the movement of considerable volumes of water in concentrated and distributed configurations beneath the Antarctic Ice Sheets (Gray, 2005; Wingham et al., 2006; Fricker et al., 2007; Carter et al., 2009; Schroeder et al., 2013). Direct observation on Byrd Glacier documented the movement of water, corresponding to an increase in glacial flow speed (Stearns et al., 2008) and highlights the potential of subglacial hydrology to influence ice sheet dynamics.

Evidence for subglacial water having contributed to past instability of the ice sheet is derived from bathymetric maps of the areas of former ice streams. Extensive, organized subglacial drainage networks consisting of basins linked by channels have been identified using multibeam swath bathymetry in Marguerite Bay (Anderson and Fretwell, 2008), in the western Amundsen Sea Embayment (Smith et al., 2009), and in Pine Island Bay (Lowe and Anderson, 2003; Nitsche et al., 2012). All three areas were occupied by large ice streams during the most recent glacial maximum. Geomorphic evidence for organized meltwater drainage also exists in the Transantarctic Mountains (Sugden et al., 1991; Denton and Sugden, 2005; Lewis et al., 2006), but these drainage networks appear to be much older and more confined than those in Marguerite and Pine Island bays. It is generally believed that these drainage networks evolved over many glacial cycles (Lowe and Anderson, 2003; Anderson and Fretwell, 2008; Smith et al., 2009), but bedrock-carved channels still provide a conduit for the transport of water between subglacial basins and for distributing water beneath ice streams. The general absences of sediment fill within these subglacial channels imply that they may have been active in more recent glacial episodes. However, sampling of these channels has yielded no compelling evidence of recent activity (Lowe and Anderson, 2003; Smith et al., 2009), although the coarse sediments that are expected to fill these channels would be difficult to sample using conventional coring methods.

Here we describe unique sedimentary deposits that, to our knowledge, have been sampled only in Marguerite Bay and Pine Island Bay (PIB) and are inferred to have a meltwater origin followed by dispersal at higher levels in the water column by marine currents (plumites by the nomenclature of Hesse et al., 1997). The meltwater origin of these sediments is based primarily on observed draping seismic character, sorted grain-sizes of terrigenous silt and very fine sand, and a low abundance of microfossils and ice-rafted debris (e.g. Kennedy and Anderson, 1989; Lowe and Anderson, 2003; Smith et al., 2009; Kirshner et al., 2012). We extend this work with a more detailed sedimentological investigation of the PIB plumites and a quantitative geomorphological study of the subglacial basin and channel network. This research also yielded important constraints on the age of deposition, which further enables us to calculate the accumulation rate for plumites as well as sediment flux. We use this information, in conjunction with a reconstructed glacial history for PIB (Kirshner et al., 2012), to assess the feedback between changes in meltwater storage, ice thickness, subglacial hydrological processes and ice stream activity, and gauge the potential magnitude of meltwater discharge and its influence on ice sheet instability.

1.1. Study area

Pine Island Bay is located in the Amundsen Sea Embayment (ASE), West Antarctica, a truly polar regime in which surface melting is minimal and therefore the glacial hydrology is dominated by subglacial processes (Fig. 1). PIB is bounded to the east by the Hudson Mountains and Ellsworth Land and to the south by Marie Byrd Land. Within the bay, Burke Island lies in the northeast and the large Pine Island Trough extends across the continental shelf. Glaciers that drain into the Amundsen Sea Embayment include Pine Island Glacier to the south and Thwaites Glacier to the southwest. Further inland and to the south of Pine Island Glacier is the Bentley Subglacial Trough, and south of the Thwaites Glacier is the Byrd Subglacial Basin (see inset Fig. 1). The Amundsen Sea glaciers drain approximately 25% of outflow from the entire West Antarctic Ice Sheet into Pine Island Bay (Vaughan, 2008). The drainage basin for the Pine Island Glacier is 184,000 km^2 and the Thwaites Glacier is nearly equal in area at 189,000 km^2 (Joughin et al., 2009). The modern glaciers draining into the ASE are thinning and accelerating at unsustainable rates, and Pine Island Glacier is currently in a state of retreat (Rignot et al., 2008; Jenkins et al., 2010; Jacobs et al., 2011; Pritchard et al., 2012). Pine Island Glacier was grounded on a large transverse bedrock ridge as recently as the 1970’s, but has recently uncoupled from this ridge (Bindschadler, 2002; Jenkins et al., 2010).

1.1.1. Geomorphology

Pine Island Bay south of ~73.5°S is characterized by rugged crystalline bedrock, with bathymetric relief of over 400 m (Lowe and Anderson, 2002; Nitsche et al., 2012) (Fig. 1). This region will henceforth be referred to as inner Pine Island Bay, following the nomenclature of Kirshner et al. (2012). The geomorphology of inner PIB has been noted as being indicative of a subglacial drainage system (Lowe and Anderson, 2003; Nitsche et al., 2012), displaying a well-organized, seaward-convergent, channel network sculpted into bedrock. The age of this seascape has yet to be determined, but is thought to have formed over numerous glacial/interglacial cycles (Lowe and Anderson, 2003). Deep channels connect otherwise isolated basins which may have the potential to store considerable volumes of water when beneath an ice sheet (Nitsche et al., 2012). Drumlins and streamlined features at the floor of these depressions are evidence for grounded ice and flowing water in the subglacial environment of inner PIB (Lowe and Anderson, 2003; Nitsche et al., 2012).

North of ~73.5°S, Pine Island Bay has a sedimentary substrate (Lowe and Anderson, 2002). This region will be referred to as Outer Pine Island Bay/Outer Shelf, following the nomenclature from Kirshner et al. (2012). Geomorphic features in Outer PIB/Outer Shelf are indicative of grounded, streaming ice and include grounding zone wedges and mega-scale glacial lineations. Other geomorphic features include plow moraines, corrugation ridges and transverse ridges (Lowe and Anderson, 2002; Graham et al., 2010; Jakobsson et al., 2011, 2012).

1.1.2. Regional oceanography

The Amundsen Sea Embayment contains three primary water masses. These include an upper (~50–100 m) surface layer that is influenced by melting sea ice and icebergs, wind and solar radiation; a middle layer of seasonally modified Ice Shelf Water (ISW) that is a mix of Circumpolar Deep Water (CDW) and ice shelf meltwater; and a lower (below ~ 500 m) water mass composed entirely of CDW. This CDW is warmer (~1 °C), saltier and more dense than ISW (Jacobs et al., 2011; Mankoff et al., 2012). In addition to these water masses, oceanographic measurements have revealed almost undiluted Circumpolar Deep Water impinging onto the continental shelf below the pycnocline through deep submarine troughs (Jacobs et al., 1996; Jenkins et al., 1997; Hellmer et al., 1998; Shepherd et al., 2004).

Positive temperature, salinity and current anomalies have been observed near the modern floating terminus of Pine Island Glacier, revealing a buoyant plume of melt-laden, deep outflow. This outflow becomes entrained and follows the general cyclonic circulation within PIB (Mankoff et al., 2012). Additionally, some of the outflow into PIB introduces a less buoyant plume that is well below the sea surface and unseen by satellites (Hellmer et al., 1998;