Estuaries beneath ice sheets

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ABSTRACT

Interactions between subglacial hydrology and the ocean make the existence of estuaries at the grounding zones of ice sheets likely. Here we present geophysical observations of an estuary at the downstream end of the hydrologic system that links the active subglacial lakes beneath Whillans Ice Stream to the ocean beneath the Ross Ice Shelf, Antarctica. This subglacial estuary consists of a hydropotential low upstream of the grounding zone, which is linked to the ocean by a hydropotential trough and a large subglacial channel. This subglacial channel, which is imaged using active source seismic methods, has an apparent width of 1 km and a maximum depth of 7 m. The hydropotential trough continues upstream of the grounding zone and results from an along-flow depression in surface elevations. Pressure differences along the trough axis are within a range that can be overcome by tidally induced processes, making the interaction of subglacial and ocean water likely.

INTRODUCTION

Some subaerial streams enter the sea from waterfalls over rocky coasts, with essentially no marine influence inland. Far more commonly, rivers and oceans interact in a complex estuarine zone, where often surprising and important processes occur. In estuaries, the mixture of fresh and saline waters results in a biologically rich transition zone between oceans and inland waterways. Along with hydrologic processes and biological abundance, estuaries are further characterized by unique sedimentary deposition. Geologists and glaciologists have long known the possibility of complex interactions at grounding zones, where ice sheets go afloat, but available data have motivated the more common "waterfall" view of independent systems beneath ice sheets meeting the sea with little or no interaction. Many lines of evidence have supported this view, including the submersible observations of Powell et al. (1996) that showed a relatively sharp grounding zone at McKay Glacier (Victoria Land, Antarctica), and the observations of a relatively sharp downstep in surface elevation at the Siple Coast grounding zone (Horgan and Anandakrishnan, 2006) that would produce a hydropotential gradient somewhat like a subaerial waterfall.

Several recent observations, however, renew the questions about important interactions at grounding zones. Subglacial lakes are widespread beneath modern (Siegert et al., 2005) and paleo ice sheets (Christoffersen et al., 2008), and a retreating grounding line during deglaciation should at some point establish a connection between subglacial and proglacial water, generating a system somewhat akin to a tidal lagoon. Different stages of this progression are observed in modern ice sheets. The ungrounding of Helheim Glacier (Greenland; Joughin et al., 2008) appears to have produced flotation behind a bedrock high, and on the Whillans Ice Stream (Antarctica), the largest subglacial lake volume changes (Fricker et al., 2007) occur in close proximity to a region of grounding zone retreat (Bindschadler and Vornberger, 1998). On the Antarctic Peninsula, the loss of the Larsen B ice shelf led to the rapid drawdown of an inland subglacial lake (Scambos et al., 2011). This spectrum of subglacial and proglacial linkage is also produced in models (e.g., Parizek et al., 2013). Therefore, there is probably a continuum between subglacial water isolated from ocean water, through weakly and strongly interacting subglacial and proglacial water bodies, to fully marine conditions with isolated grounding points beneath a floating ice shelf.

Other interactions across the grounding zone are possible. Although subglacial hydrology has often been referenced to the ice-marginal boundary condition (e.g., Rothlisberger, 1972), the most common models reference local subglacial water pressure to the weight of the overlying ice (Shreve, 1972). Water localized in regions may have slightly lower pressure owing to flow over bedrock irregularities, melting from the heat generated by flowing water, or transient bridging stresses from overpressurization during rising supply (e.g., Clarke, 2005). Subglacial water that is at a pressure slightly less than ice overburden cannot discharge to the ice front where a lake or ocean is floating the ice margin, implying that in these cases the lake or ocean influences the upstream subglacial hydrology. Mechanisms to aid the transport of water upstream of the grounding zone exist. For an ice cliff just at flotation, the pressure in the ice exceeds that in the water except at the base, with the difference increasing upward, creating a torque that rotates the upper part of the cliff forward and raises the ice off the bed just behind the grounding zone (Reeh, 1968), lowering the pressure there. This is amplified by the tidal flexure of ice shelves, which raises the inland ice a few ice thicknesses inland of a grounding zone. This produces a drop in the subglacial water pressure more than the ocean pressure is dropped by the tide, pumping water inland (Walker et al., 2013). Just as a subaerial estuary receiving water from a stream and from a tidal inlet can achieve mass balance through slight asymmetries of the incoming and outgoing flows, so should a tidally pumped subglacial system be able to receive water from, and discharge to, the sea.

Hydrologic pathways across the grounding zone of ice sheets can exist as channels or canals in the ice or the bed. Any channel or cavity at the ice-bed interface that is transported toward the grounding line offers a conduit for inland water flow during a rising tide, providing it is not closed by ice flow. Because ocean water is almost everywhere warmer than the melting point of ice in grounding zones (e.g., Rignot and Jacobs, 2002), tidal flow up a basal conduit would assist in expanding it, helping to counter ice closure. For relatively rapid ice flow and initially small drainage channels and flow rates, this is unlikely to be an important process; the channels will be closed by ice creep or carried out to sea by the moving ice before they can be expanded significantly by the tidal melting. However, in cases of slower ice flow with large channels, tidal melting may be more important. In the case of channels in the bed, and in the presence of the deformable till found beneath ice streams, fluvial removal must outpace the inward creeping till (Walder and Fountain, 1994). Tidal currents probably interact with these sedimentary processes in the estuarine zone, with increased flow leading to increased erosion.

Regardless of the nature of subglacial conduits across the grounding zone, the rate of discharge of subglacial melt water is important for channel generation and maintenance. Drainage of supraglacial (Das et al., 2008) or subglacial (Fricker et al., 2007) lakes may make extensive and large channels, which could then be enlarged by tidal flow. Coarse temporal-resolution

GEOLOGY, November 2013; v. 41; no. 11; p. 1159–1162 | doi:10.1130/G34654.1 | Published online 6 September 2013

observations show Antarctic subglacial lakes filling and draining at multiyear time scales (Smith et al., 2009); however, additional evidence shows drainage events occurring at time scales of weeks (Gray et al., 2005) and minutes (Winberry et al., 2009). Beneath the Whillans Ice Stream (Fig. 1), subglacial water is routed toward the grounding zone, where discharge is hypothesized to concentrate in grounding zone embayments (Carter and Fricker, 2012).

In summary, pathways between subglacial and proglacial water bodies exist and will in some cases accommodate water flow in both directions, leading to estuarine zones. Ice bottom and sediment-interface channels, which may enable estuarine development, are likely to be enhanced by tidal processes.

WHILLANS ICE STREAM

To investigate the interaction of subglacial water and the ocean, we acquired radio echo

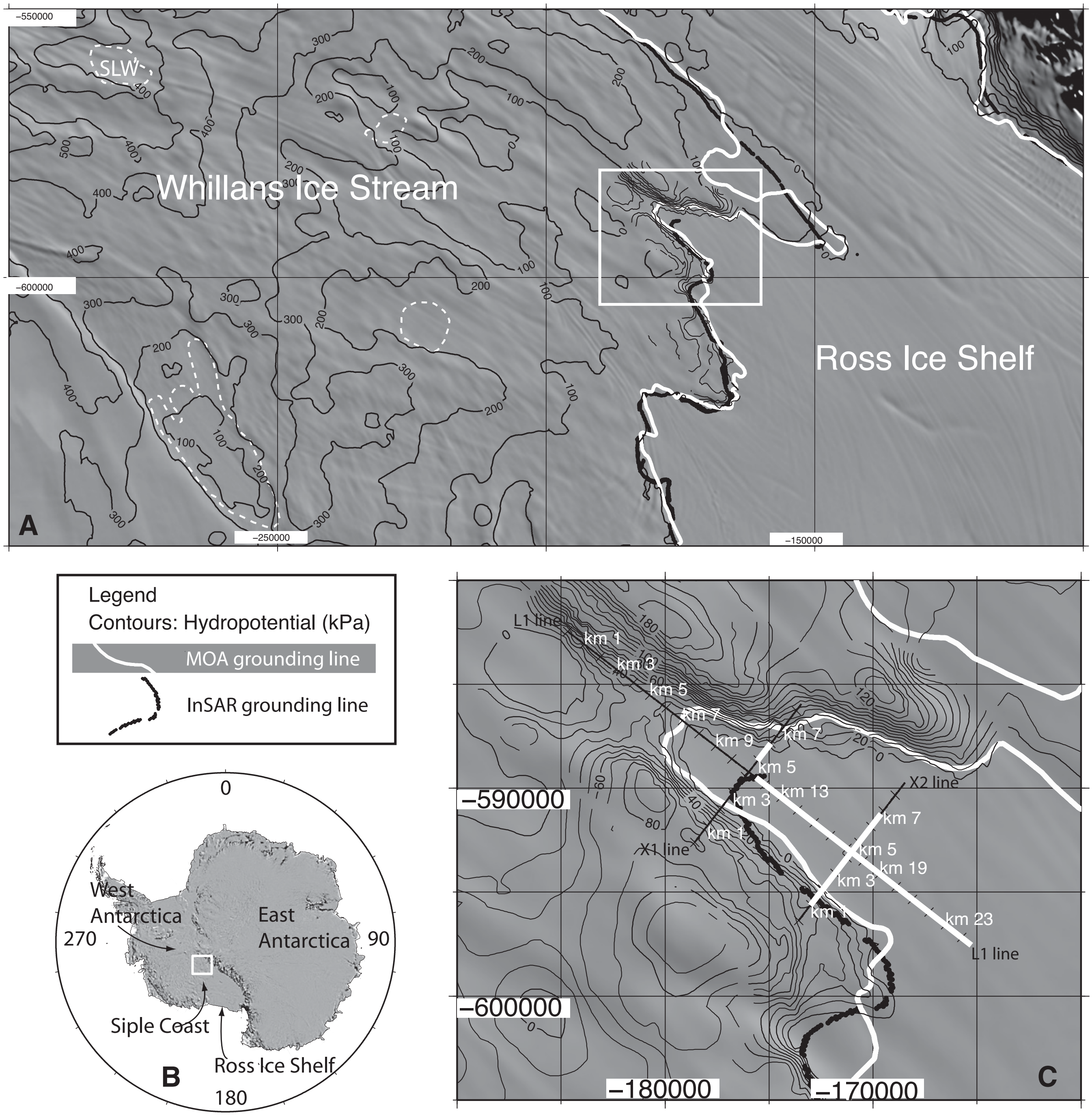

Figure 1. A: Whillans Ice Stream, West Antarctica. Background imagery from MODIS MOA (Moderate Resolution Imaging Spectroradiometer Mosaic of Antarctica; Haran et al., 2005). Dashed white lines denote active subglacial lakes (Fricker et al., 2007). Thick white line denotes MOA grounding zone (Haran et al., 2005). Discontinuous thick black line denotes grounding zone of Rignot et al. (2011). Hydropotential contour intervals are 100 kPa where ICESat (Ice Cloud and Land Elevation Satellite) and BEDMAP2 are used and 20 kPa where GPS and radio echo sounding (RES) are also used. White box shows region covered in C. InSAR—interferometric synthetic aperture radar; SLW—subglacial Lake Whillans. B: Overview map showing location of A in West Antarctica. C: Close-up of study region. Grounding zones and hydropotential are as in A, but with contour interval of 10 kPa where GPS and RES are used. Seismic profiles are shown in black and white, where white denotes imaged water column.

sounding (RES), kinematic GPS, and active source seismic observations at an embayment in the Siple Coast grounding zone where subglacial water is suspected to drain (Fig. 1).

To provide an estimate of where subglacial water is likely to flow and pool, we calculate hydropotential following the method of Shreve (1972). For surface elevations we use data from the Ice Cloud and Land Elevation Satellite (ICESat GLA12, release 531; http://nsidc.org/data/icesat/past_releases.html), processed following Smith et al. (2009). We supplement these elevations with newly acquired kinematic GPS data. For bed elevations we use BEDMAP2 (Bed Topography of the Antarctic; Fretwell et al., 2013) and newly acquired RES data. Kinematic GPS and RES data were acquired on a nominal 1 km grid, and processed following the methods of Christianson et al. (2012). We calculate hydropotential of the ice sole using an ice density of 917 kg m^{-3} and a water density of 1030 kg m^{-3}. We also subtract a constant of 140 kPa to set the grounding zone hydropotential to 0 kPa. Surface elevation data show a broad low that continues upstream of the grounding zone embayment. This elevation low results in a hydropotential trough, ~3 km wide, bounded by steep hydropotential gradients (Fig. 1). Upstream of the grounding zone a hydropotential saddle of 20–30 kPa separates the ocean from a hydropotential basin and the wider subglacial hydrologic system.

The high acoustic-impedance contrast between ice and water makes active-source seismology ideal for imaging elements of subglacial hydrology (e.g., Horgan et al., 2012). We acquired one along-flow and two across-flow seismic profiles in the grounding zone embayment (Figs. 1 and 2). Seismic data acquisition and processing followed the methods of Horgan et al. (2012). Active-source seismic data image the top and bottom of the grounding zone ocean cavity (Figs. 1 and 2). (Our quarter-wavelength resolution, which determines our ability to resolve the top and bottom of the water column, is ~2 m.) We also image a channel in the substrate, which crosses the grounding zone (Fig. 2) with an apparent width of ~1 km and a maximum water column thickness of ~7 m. Elsewhere in the embayment the cavity widens and the water column deepens gradually, reaching a maximum depth of ~12 m. We also interpret the presence of thinner bodies of water below the quarter-wavelength resolution of our data based on high-amplitude negative polarity returns. Notably, we interpret water on the L1 line between kilometers 2.5 and 3.3, which is to one side of the hydropotential low upstream of the grounding zone and upstream of the hydropotential saddle. Together the observations of a hydropotential basin that is connected to the ocean cavity by a hydropotential trough and an imaged channel provide evidence for a subglacial estuary at the grounding zone of Whillans Ice Stream.

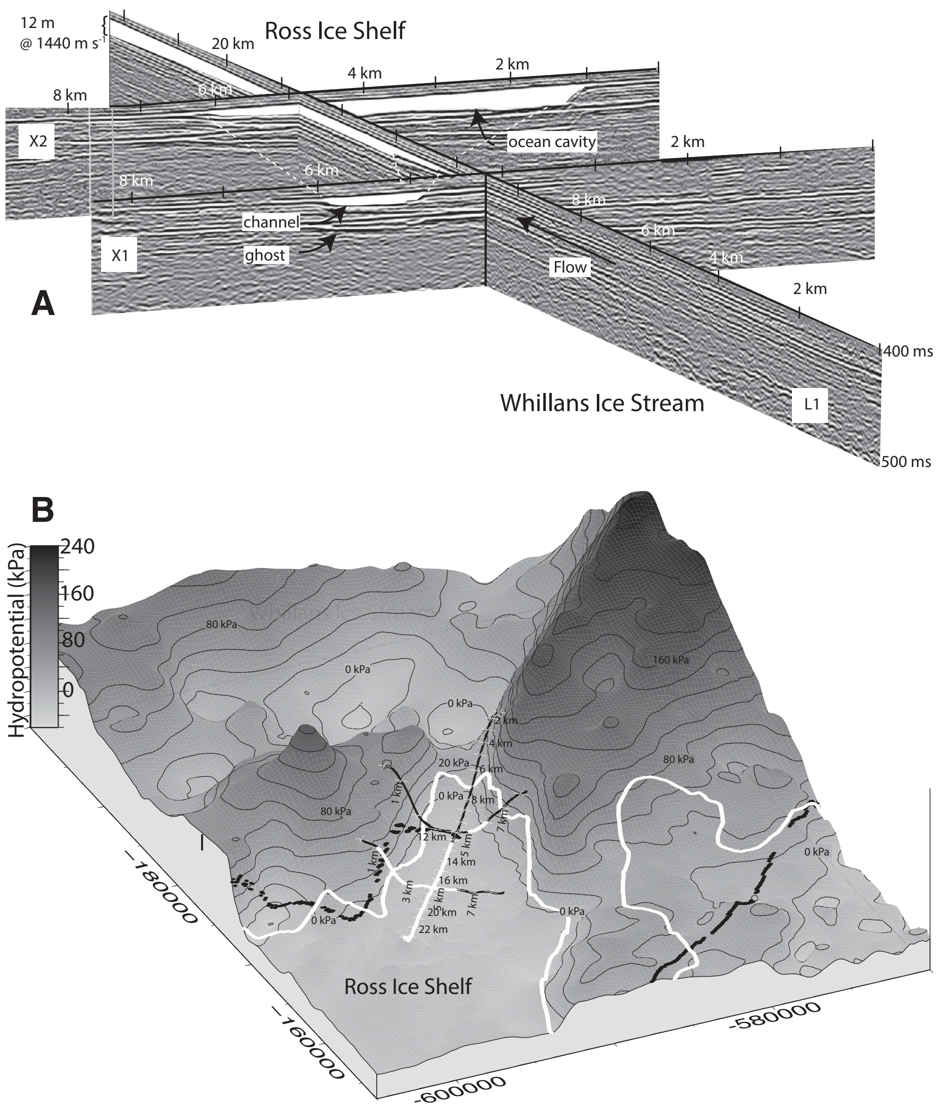

Figure 2. A: Perspective view showing active source seismic data in embayment (West Antarctica). Viewpoint is from upstream, looking downstream and across flow. Area in white denotes imaged water column. Note that primary return is underlain by short-path (ghost) multiple return. Annotated tick marks denote distance along seismic lines (in km). White overlay on seismic lines denotes regions where top and bottom of water column are imaged. B: Perspective view of hydropotential surface. Viewpoint is from downstream looking upstream. Grounding zones as in Figure 1.

DISCUSSION AND CONCLUSION

Our geophysical observations provide an example of an estuary beneath the West Antarctic Ice Sheet. We suggest two mechanisms for the development of estuaries beneath ice sheets. In the first, a retreating grounding zone intercepts a subglacial water body, such as a subglacial lake. In the second, a subglacial outlet channel, resulting either from steady-state melt water flow or more likely from the episodic drainage of subglacial (or supraglacial) lakes, crosses the grounding zone and is enlarged by ocean-driven melt or tidally driven flow. To truly develop an estuarine environment the exchange of water and sediment across the grounding zone is required. Beneath ice sheets this exchange is likely to be assisted by the pressure difference induced by viscoelastic flexure across the grounding zone in response to tidal forcing. [For example, Walker et al. (2013) modeled a 51.5 kPa pressure drop 600 m inland of a 1 m tidal deflection for a 1-km-thick ice sheet.) These viscoelastic processes are probably important at our study site on the Whillans Ice Stream, where a 20–30 kPa saddle separates the ocean from an upstream hydropotential low.

The channel we image (Fig. 2) is incised in the underlying bed and is too large to be generated by steady-state subglacial discharge, which is estimated to be only ~60 m^3 s^{-1} for the entire Siple Coast (Carter and Fricker, 2012). However, drainage beneath ice sheets is known to be strongly nonsteady (e.g., Smith et al., 2009), and greater discharges are likely to be revealed by observations at higher sampling rates over longer time frames. Basal melting of Whillans Ice Stream and its catchment generates 0.53 km^3 yr^{-1} of water (Joughin et al., 2004). Assuming a channel length sufficient to link the hydrologic basin to the ocean (5 km) with a cross-sectional area equal to the imaged channel (1 km wide by 7 m deep) gives a channel volume of 0.035 km^3. Development of a channel of this volume would require large drainage events over short time intervals, such as those suggested by the passive seismic observations of Winberry et al. (2009).

We image a channel incised in the bed, where erosion is outpacing sediment deposition. In other cases where channels in the base of the ice cross the grounding zone, melting by ocean water introduced by tides and aided by flexurally driven pumping would assist in keeping the channel open, and potentially enlarge it. Oceanographic modeling shows that thin ocean cavities, such as the one we observe, should result in vigorous tidal mixing and tidal front formation, which could serve to buffer the grounding zone against plume-driven melt (Holland, 2008). However, additional freshwater drainage across the grounding zone should enhance melt in this zone if stratification can be preserved (Jenkins, 2011).

There is an obvious need for direct oceanic and subglacial observations at the grounding zone. The interplay between the ocean and the subglacial hydrologic system in these zones certainly supports some processes found in subaerial estuarine environments, and likely introduces unforeseen phenomena particular to the cryosphere. We note that our data suggest more inferences than we can currently substantiate, further highlighting the need for subglacial access programs guided by comprehensive geophysical surveying.

ACKNOWLEDGMENTS

This study was supported by the National Science Foundation (grants OPP-0838763, OPP-0838855, and OPP-0424589) and the National Aeronautics and Space Administration (NNX-09-AV94G and NNX-10-AI04G). We thank Matthew Hill, Rory Hart, and Benjamin Petersen for assistance in the field, Ruzica Dadic for useful discussions, and the New York Air National Guard for field deployment.

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Manuscript received 17 April 2013
Revised manuscript received 19 June 2013
Manuscript accepted 1 July 2013

Printed in USA