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The effects of tunnel channel formation on the Green Bay Lobe, Wisconsin, USA

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ABSTRACT

Subglacial water drainage plays a significant role in glacier flow dynamics. Various forms of subglacial drainage have been observed beneath modern ice sheets, and the same forms of drainage likely occurred beneath paleo-ice sheets, such as the Laurentide Ice Sheet. Records of paleo drainage are occasionally preserved in the geomorphic record and can serve as a widespread and easily accessible means to investigate aspects of subglacial drainage that are difficult to directly study on modern-day glaciers. Linear surface depressions that extend tens of kilometers inward from the margin of Laurentide lobes are found throughout the Midwest of North America and are hypothesized to form from incision by channelized subglacial water flow. Here we estimate the subglacial hydropotential and its gradient along the western margin of the Marine Isotope Stage 2 Laurentide Ice Sheet's Green Bay Lobe to identify potential locations for subglacial water pooling. We find that linear surface depressions correlate well with areas where subglacial water likely pooled. We use a combination of active and passive seismic analyses to estimate the actual size of an incised subglacial channel in Waushara County, Wisconsin, that was subsequently infilled with sediment after the formation. We find that the channel incised ca. 65 m into the surrounding unlithified material, which is 6 times greater than the modern surface expression, and has a width of 450 m, which is nearly equal to the width of the surface expression. We estimate the channel would have taken ca. 60 days of water flow to form and that the flow of pore water from the surrounding till into the low-pressure channel could have increased the strength of the till by as much as 140 kPa following a single drainage by as much as 175 kPa in a smaller region following a series of 15-day-long drainage events. Till strengthening could have been a factor of 7 to 25× greater than predrainage strength values.

1. Introduction

Modern-day glaciers and ice sheets demonstrate a wide range of subglacial drainage forms where subtle changes in water transport can result in significant alterations in glacier dynamics and flow speed (Flowers, 2015). In Antarctica, subglacial lakes fill over years then discharge their water over several months (e.g., Fricker et al., 2007; Stearns et al., 2008; Siegfried et al., 2016), while in Greenland supraglacial lakes form from summer meltwater and rapidly drain to the glacier base once a conduit forms (e.g., Alley et al., 2005; Das et al., 2008). In both instances substantial volumes of water drain along the bed and impact glacier flow dynamics (e.g., Stearns et al., 2008; Andrews et al., 2014). The onset of sudden drainage often coincides with a rapid increase in ice velocity as subglacial water pressure initially rises causing sliding rates to increase. Subsequently, the subglacial drainage network adjusts to handle the increased discharge reducing subglacial water pressure and sliding speed, often below predrainage velocities (e.g., Tedstone et al., 2013; Hoffman et al., 2016). Alternatively, temporally continuous channels with modest subglacial discharge and high water pressures result in constant fast sliding (Engelhardt et al., 1990; Engelhardt and Kamb, 1997; Kamb, 2001). These end members of subglacial drainage have different effects on glacier dynamics. In situ observations of subglacial drainage characteristics are limited because directly accessing the glacier bed is difficult (Andrews et al., 2014). In addition, techniques that directly access the bed (e.g., borehole) can alter the drainage network, making observations difficult to interpret. However, glacial geomorphic features preserved in the geologic record contain a widespread, easily accessible, and undisturbed record of subglacial conditions that can inform processes active in modern and paleosubglacial environments when analyzed through the framework provided by modern-day subglacial hydrology observations. One area where geomorphic evidence of large subglacial drainage events is well preserved is the western margin of the Laurentide Ice Sheet's Marine Isotope Stage 2 (MIS2) Green Bay Lobe (GBL) in central Wisconsin (Clayton et al., 1999).

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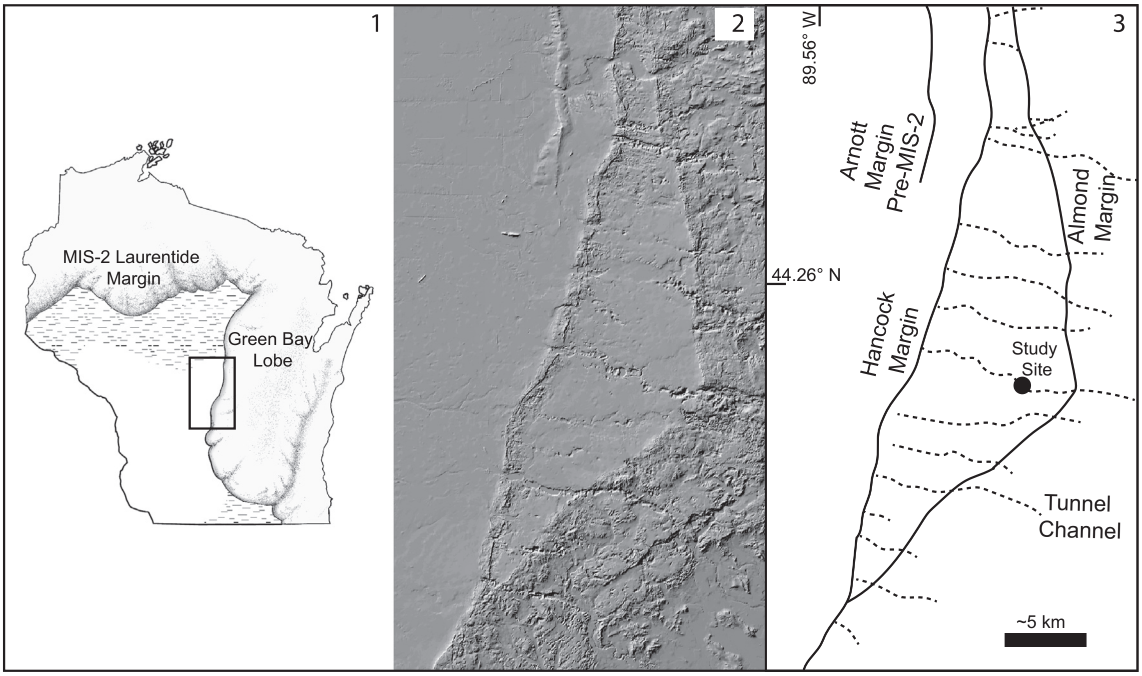

Fig. 1. Map of field locations. Panel 1 represents the MIS2 ice advance in Wisconsin that is indicated by the light gray region. The hatched lines are regions where older glacial deposits are located. The field area shown in the second and third panels is denoted by the black rectangle in the first panel. Panel 2 is a hillshade map from SRTM data of the study region. The linear east-west trending collapse features seen in panel 2 are a series of TCs. The linear features in the second panel correspond to surficial evidence of TC locations, which are shown in panel 3 as dashed lines (panels 2 and 3 are of the same region). The solid lines are the moraines of the region. The black circle denotes the location of the geophysical surveys.

The terminal moraine along the western margin of the GBL is dissected by as many as 70 linear surface depressions that are approximately perpendicular to the moraine (Clayton et al., 1999) (Fig. 1). These depressions often extend ca. 15 km into the interior of the lobe, cutting through several recessional moraines (Clayton et al., 1999). Similar surface features have been observed along the Laurentide MIS2 margin in several locations in North America (Kehew et al., 2012, 2013; Livingstone and Clark, 2016) and have been commonly attributed to fluvial erosion from channelized subglacial water flow. We follow the terminology of Clayton et al. (1999) where these landforms have often been termed *Tunnel Channels* and *Tunnel Valleys*. The term *Tunnel Valleys* generally denotes a landform produced from lateral planation of a subglacial river narrower than the valley. The term *Tunnel Channels* (TC) denotes a landform produced by short-lived (weeks to months) drainage of a subglacial river with bank-to-bank flow (Clayton et al., 1999). The geologic and geomorphic evidence suggest that the features found along the western margin of the GBL were formed by large drainage events, but questions still remain about the origin of the water release, the location of the stored water, and the duration of water flow that led to TC formation (Cutler et al., 2002).

Here we use the TC geologic record and geophysical observations to evaluate the duration of the drainage events and the impact a large-volume subglacial drainage event would have had on glacial dynamics of the Green Bay Lobe. We estimate the impacts on glacial dynamics by first evaluating the source of waters that formed the TC, then estimate the size of the TC with geophysical imaging and drilling. Finally, we use those observations to estimate drainage duration of the TC and what effect their drainage would have had on the surrounding subglacial processes.

2. Regional setting

Late in the Wisconsin Glaciation (late in MIS2) the GBL of the Laurentide Ice Sheet advanced southward along the northward draining Fox River lowland in eastern Wisconsin (Fig. 1). The western flank of the GBL flowed up the regional slope, reaching its maximum extent near the drainage divide with the Wisconsin River basin to the west. The maximum extent of the MIS2 GBL and the location of recessional and readvance ice-margin positions (Fig. 1) are marked by nearly continuous north-south trending moraines composed of sandy till and debris-flow sediment that is included in the Horicon Member of the Holy Hill Formation (Syverson et al., 2011) and heads-of-outwash (Clayton and Haskins-Grahn, 1986; Mickelson, 1987; Attig and Muldoon, 1989). The exact timing of glacial events along the west side of the GBL is poorly constrained, but regional reconstructions of ice-margin positions indicate the ice reached its maximum extent by about 25,000 years ago and began to recede by about 21,000 years ago (Clayton and Moran, 1982; Mickelson et al., 1983; Attig et al., 1985; Mickelson and Attig, 2016).

Previous work along the western margin of the GBL suggested that TCs resulted from at least one large outburst flood and that permafrost played a key role in the formation of subglacial water ponding that subsequently drained through TCs (Attig et al., 1989; Cutler et al., 2002). Through analysis of sediments found in proglacial fans at the mouths of TCs, Cutler et al. (2002) determined that the GBL TCs were formed by large discharges of water flowing at the base of the glacier that eroded the surrounding material and transported sediment toward the margin rapidly. Once the sediment-laden water breached the glacier's margin, the water velocity decreased and material was deposited in a fining-upward sequence in the fans. Cutler et al. (2002) observed numerous boulders 2 m in diameter in the fans that were rolled up the local bed slope (local bed slope is toward the center of the lobe) before being deposited in the fans. Analysis of stratigraphic sections from numerous pits indicated that at least one large drainage event occurred in the formation of each fan but multiple drainages were likely. Based on geologic data, Cutler et al. (2002) estimated that the mean paleo flow velocity as 1.8 m s^{-1}, the mean discharge Q_w as ca. 1000 m^3 s^{-1}, the mean density of transported sediment as 2650 kg m^{-3}, and a grain size distribution with $D_{15} = 0.025$, $D_{50} = 0.08$, and $D_{84} = 0.44$ m. The fans studied by Cutler et al. (2002) that contained coarse sediments were located north of the TC that is the focus of this work. Any fan associated with drainage of the TC that is