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Implications of basal micro-earthquakes and tremor for ice stream mechanics: Stick-slip basal sliding and till erosion

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ABSTRACT

The Whillans Ice Plain (WIP) is unique among Antarctic ice streams because it moves by stick-slip. The conditions allowing stick-slip and its importance in controlling ice dynamics remain uncertain. Local basal seismicity previously observed during unstable slip is a clue to the mechanism of ice stream stick-slip and a window into current basal conditions, but the spatial extent and importance of this basal seismicity are unknown. We analyze data from a 2010–2011 ice-plain-wide seismic and GPS network to show that basal micro-seismicity correlates with large-scale patterns in ice stream slip behavior: Basal seismicity is common where the ice moves the least between unstable slip events, with small discrete basal micro-earthquakes happening within 10s of km of the central stick-slip nucleation area and emergent basal tremor occurring downstream of this area. Basal seismicity is largely absent in surrounding areas, where inter-slip creep rates are high. The large seismically active area suggests that a frictional sliding law that can accommodate stick-slip may be appropriate for ice stream beds on regional scales. Variability in seismic behavior over inter-station distances of 1–10 km indicates heterogeneity in local bed conditions and frictional complexity. WIP unstable slips may nucleate when stick-slip basal earthquake patches fail over a large area. We present a conceptual model in which basal seismicity results from slip-weakening frictional failure of over-consolidated till as it is eroded and mobilized into deforming till.

1. Introduction

Basal conditions that promote or prevent fast ice stream flow are important for determining future stability of the West Antarctic Ice Sheet (e.g., Bennett, 2003). The largely unmapped basal interface of the ice streams that drain the West Antarctic Ice Sheet may be variably resistant, and the extent to which ice sheet models need to account for this complexity is largely unknown. Part of the reason for the lack in understanding of ice stream basal sliding behavior is the difficulty of accessing or imaging the ice base. Increasingly, however, seismicity from the bed of fast-moving glaciers and ice streams is used to inform our understanding of bed conditions and processes that control fast ice flow (e.g., Anandakrishnan and Alley, 1994; Blankenship et al., 1987; Podolskiy and Walter, 2016; Roeoesli et al., 2016; Smith, 2006; Smith et al., 2015) and that affect ice stream contribution to sea-level rise.

Some basal micro-earthquakes near the bottom of ice streams and glaciers occur as double-couple slip between two elastic surfaces in the ice, till, or bedrock (Anandakrishnan and Alley, 1994; Anandakrishnan and Bentley, 1993; Blankenship et al., 1987; Roeoesli et al., 2016; Smith et al., 2015; Zoet et al., 2012). Fundamental controls on the timing, size, and frequency of occurrence of these basal micro-earthquakes remain largely unresolved, and their relevance for broader ice stream dynamics is unknown. Basal micro-earthquakes are common beneath the slow-moving, shut-down portion of the Kamb Ice Stream (KIS), but rare beneath fast-flowing, upstream KIS (Anandakrishnan and Alley, 1997), suggesting a relationship between presence or absence of basal seismicity and ice stream flow regime (stagnant vs. streaming, respectively). Beneath Rutford Ice Stream, areas of the bed with lodged till (embedded in the substrate), as inferred by measurements of seismic impedance (Smith, 1997), have more basal micro-earthquakes than areas of the bed inferred to be actively deforming (Smith, 2006; Smith et al., 2015). These inferences suggest that basal micro-

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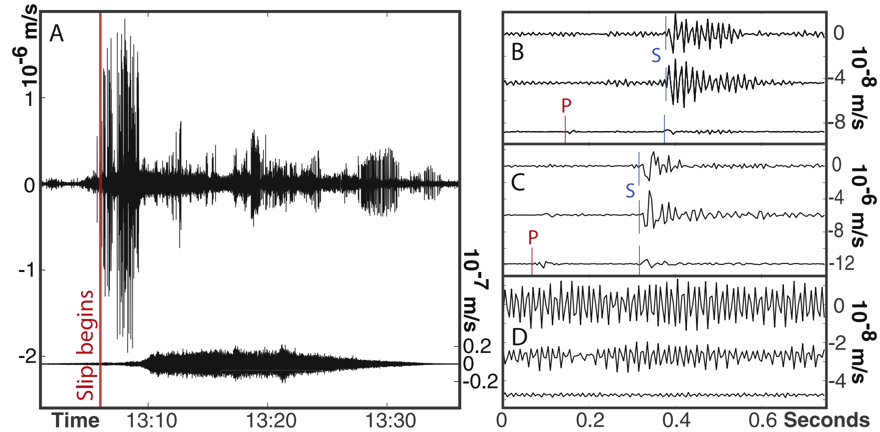

Fig. 1. Example basal earthquake and tremor seismic data. A: Sample east component seismic records of individual basal micro-earthquakes (top) and basal tremor (bottom) at two different sites during the same slip event that begins at the red line. Note the different vertical scales. Slip time is from Pratt et al. (2014). B–C: Example basal micro-earthquakes from two different stations. Channels from top to bottom are E, N, Z. P and S waves are labeled. D: Basal tremor for same amount of time. Tremor seismicity is continuous instead of discrete basal micro-earthquakes. Basal micro-earthquakes are identified by a characteristic P and S wave shape, while tremor is identified as spectral gliding lines (see Fig. S1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

earthquakes may indicate variation in certain bed conditions, for example till properties, that may impact flow velocity. Passive seismic observation of basal micro-earthquakes is therefore a useful technique to infer the spatial and temporal variability of basal conditions and, by extension, basal resistance to fast flow.

The Whillans Ice Plain (WIP), in West Antarctica, is an excellent area to investigate basal seismicity because seismic and GPS data have been collected over the last decade at numerous sites on the ice plain to study its stick-slip cycle (e.g., Bindschadler et al., 2003; Pratt et al., 2014; Siegfried et al., 2016; Walter et al., 2015, 2011; Winberry et al., 2014, 2013, 2011, 2009), its basal hydrologic cycle (e.g., Fricker and Scambos, 2009; Siegfried et al., 2016), and its long-term slowdown and basal strengthening (e.g., Joughin et al., 2005; Beem et al., 2014). Typical stable sliding of the WIP is punctuated once or twice daily by sudden unstable sliding events (accelerations) lasting 20–30 min and displacing the ice 10s of cm (Bindschadler et al., 2003). Unstable slip events nucleate at one of two areas of the WIP, typically but not always depending on Ross Ice Shelf tidal height: the central nucleation area at high tide, or the grounding zone nucleation area at low tide (shown in Fig. 2) (Pratt et al., 2014; Walter et al., 2015). The central nucleation area is thought to be underlain by low-porosity, but deforming, till (Luthra et al., 2016). The current slowdown and positive mass balance of the Whillans Ice Stream is modulated by changes in the frequency of stick-slip events (Winberry et al., 2014).

Basal micro-earthquakes beneath the WIP were previously observed as rapidly repeating nearly identical events during unstable slip events (Winberry et al., 2013), but the spatial extent of basal seismicity is unknown. The earthquakes likely occur within the till or at the ice-till interface, with the preferred plane of rupture sub-parallel to the ice base (Anandakrishnan and Bentley, 1993; Blankenship et al., 1987; Roeoesli et al., 2016; Smith, 2006; Smith et al., 2015). Basal ice may contain significant concentration of debris (Kamb, 2001) and may be locally exposed to sub-till sediment or bedrock material (Rooney et al., 1987), both of which may affect basal sliding. If basal micro-earthquakes involve till or other sediments, then the mechanical behavior of the till or sediment is critically important in the basal micro-earthquake mechanism. Lower porosity till is stronger in shear (Tulaczyk et al., 2000) and may be more likely to exhibit basal seismicity than deforming and high-porosity till that likely deforms aseismically (Smith, 2006, 1997; Smith et al., 2015).

In this paper, we identify areas of the WIP that exhibit basal seismicity by analyzing several seismic datasets recorded during 2010–2011 and originally used to identify the stick-slip nucleation areas (Walter et al., 2015, 2011; Winberry et al., 2014). Basal seismicity (Fig. 1) includes both individual basal micro-earthquakes (e.g., Blankenship et al., 1987; Anandakrishnan and Bentley, 1993; Smith, 2006; Winberry et al., 2013; Smith et al., 2015) and basal tremor, which has been modeled as a seismic signal composed of interfering basal micro-earthquakes (Lipovsky and Dunham, 2016; Winberry et al., 2013). We compare the spatial distribution of basal seismicity from these datasets to the locations where unstable sliding nucleates during the Whillans Ice Plain stick-slip cycle (stars in Fig. 2 from Pratt et al., 2014). We also compare basal seismicity locations with GPS-derived patterns of ice stream slip during and between WIP unstable sliding events.

2. Data and methods: seismic and GPS data

To assess where basal seismicity happens beneath the WIP, broadband seismic data from 55 locations were analyzed visually for presence of basal micro-earthquakes and tremor (Fig. 1) during unstable slips in 2010–2011. Data was collected during three separate deployments of seismometers and GPS, and between 25 and 79 slip events were analyzed for each seismic site depending on deployment length. Our analysis does not discriminate between high and low tide unstable slip events. Additional network details can be found in Supplementary Table S1. Basal micro-earthquakes during unstable slip are visually identified as short-lived repeating seismic events with a distinct characteristic wave shape: *P* energy primarily on the vertical component, *S* energy mostly on the horizontal component, and lack of surface wave energy (Fig. 1B, 1C). *S* minus *P* intervals of ∼0.18–0.4 s indicate a hypocentral distance of ∼650–1440 m ($V_p = 3840$ m/s; $V_s = 1860$ m/s; Luthra et al., 2016), consistent with near-nadir origins at the base of 650–800 m thick ice (Fretwell et al., 2013). In contrast, crevasse-forming events have surface wave energy and a different waveshape and are ignored. Individual basal micro-earthquakes rarely show up at two neighboring seismometers in this dataset, meaning the sources are small and the seismic waves attenuate within a few km. If there are more than ∼10 characteristic repeating basal micro-earthquakes during an unstable slip event, that event is marked as having basal micro-seismicity, though some seismic sites show 1000s of basal micro-earthquakes during a single unstable slip. Basal tremor is identified visually as gliding lines in east component spectrograms of seismic data during unstable slip events (e.g., Supplementary Fig. 1; Lipovsky and Dunham, 2016). Gliding

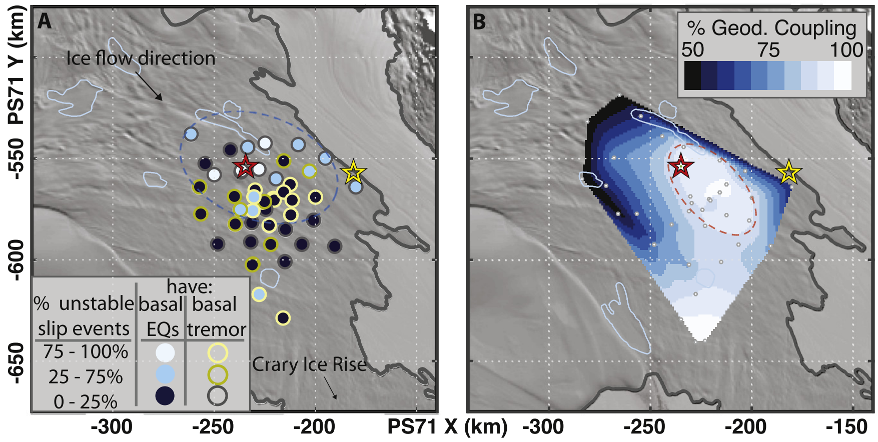

Fig. 2. Results of seismic and GPS analysis. A: Circles are locations of seismometers deployed in 2010–2011. Colors show percentage of unstable slip events in the dataset recording basal micro-earthquakes (circle fill color) and basal tremor (circle outline color). Blue oval outlines main area with basal micro-earthquakes and tremor. B: Interpolated geodetic coupling, or the percent of total ice motion that occurs during unstable sliding. Grey dots are locations of GPS used. Red oval outlines high geodetic coupling patch. Both: red and yellow stars are the central (high tide) and grounding zone (low tide) nucleation areas, respectively (Pratt et al., 2014). Light blue outlines indicate subglacial lakes (Fricker and Scambos, 2009). Thick grey line is the grounding line from Bindschadler et al. (2011). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

lines occur when the seismic signal recorded during basal tremor (Fig. 1D) has a preferred frequency that changes with variations in ice sliding velocity, as shown in Supplementary Fig. S1. These gliding lines are interpreted as the spectral signal of repeating basal micro-earthquakes overlapping in time such that the number of earthquake S-wave arrivals per second becomes the frequency of the recorded seismic signal (Lipovsky and Dunham, 2016). Seismicity results are summarized in Fig. 2A.

WIP downstream motion is partitioned into unstable sliding (resulting from acceleration during slip event) and stable sliding (observed at the surface as ‘creep’ between slip events) in varying amounts across the ice plain. Some sites stagnate between unstable slips and accrue a ‘slip deficit’ relative to nearby sites that continue to creep. This variability is captured with GPS data by the geodetic coupling coefficient (called ‘seismic coupling’ by Winberry et al., 2014), which is the percent of total ice motion accommodated by unstable slip. Sites with the largest slip deficit between unstable slips have the highest geodetic coupling coefficient. These high geodetic coupling sites move little except during unstable slip, because of either locally higher basal drag or stress shielding by the higher basal drag areas. Geodetic coupling is calculated for 39 WIP GPS sites by fitting downstream displacement curves from each unstable slip to a hyperbolic tangent curve, following the method of Larson et al. (2004). Displacement during and before each unstable slip is determined from the fit, and geodetic coupling is the ratio between unstable displacement summed over all slips and all displacement since the previous slip (both stable and unstable) summed over all slips (Fig. 2B; additional details in Supplement).

3. Results

The percent of unstable slip events with basal micro-earthquakes and tremor varies across the WIP (Fig. 2A). Basal micro-earthquakes occur commonly during unstable slip within ∼40 km of the central nucleation area (blue oval, Fig. 2A), though basal micro-earthquake occurrence rates vary significantly over distances of 1s–10s of km within this area. Seismicity is abundant at some of these sites during unstable slip, but individual basal micro-earthquakes are rarely observed at more than one seismometer. Basal micro-earthquakes occur rarely further downstream than ∼40 km from the central nucleation area, except at a site near the Crary Ice Rise and near the grounding zone nucleation area.

Fig. 2A also shows that basal tremor occurs most often at sites slightly downstream from the central nucleation area. As shown in Fig. 1, tremor is generally smaller amplitude than basal micro-earthquakes. Some of the seismic sites have only basal micro-earthquakes or tremor during unstable slip, while other sites have both or neither.

Fig. 2B shows interpolated GPS-determined geodetic coupling. A central patch of high geodetic coupling (>80% of ice motion occurs during unstable slip events) is ∼30 km across and extends ∼50 km downstream of the central nucleation area (red oval, Fig. 2B). This patch corresponds to the Central Sticky Spot of Winberry et al. (2014). The low-tide, grounding zone nucleation area is meanwhile characterized by low geodetic coupling. This area moves 10s of cm between unstable slip events. Geodetic coupling is highest at the two sites upstream of Crary Ice Rise, where ice is effectively stagnant between unstable slip events.

The central high coupling area overlaps with the high basal seismicity area, but it is narrower across flow and offset downstream (Figs. 2, 3A). For all the seismic sites, there is no statistically significant correlation between calculated geodetic coupling and the percent of unstable slips with basal micro-earthquakes or tremor.

4. Discussion

4.1. Spatial patterns in seismicity and geodetic coupling

Sites that most often record distinct basal micro-earthquakes cluster around the central nucleation area, suggesting that conditions that cause stick-slip nucleation are also associated with basal seismicity (Fig. 2A). Within this seismically active area, the frequency of seismicity during unstable slip is variable in space, with seismometers that often record seismicity neighboring seismometers that rarely record seismicity. Bed conditions that cause basal micro-earthquakes, therefore, are highly heterogeneous and vary over length-scales of less than a few km (illustrated in Fig. 3A).

The central nucleation area exhibits clear stick-slip behavior at two length scales: the scale of unstable slip nucleation (<10s of km, Lipovsky and Dunham, 2017; Pratt et al., 2014), and the smaller scale of asperities that generate basal micro-earthquakes. This smaller scale is uncertain but may be approximately 10 m^2 for tremor (Lipovsky and Dunham, 2016) and is certainly less than inter-station distances of ∼1 km. The overlap of these two scales

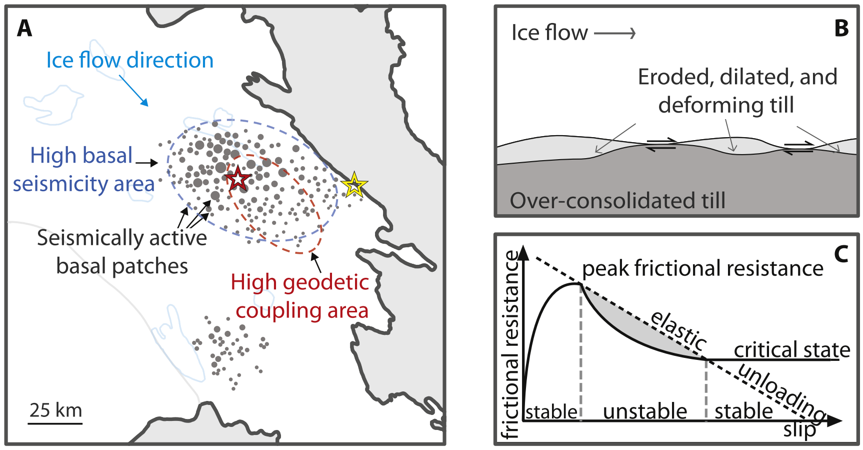

Fig. 3. A: Conceptual model of basal till conditions schematically showing areas of seismogenic stick-slip (grey) and aseismic stable sliding (white) beneath the Whillans Ice Plain. Seismically active areas (grey) may be dominated by over-consolidated till. Ovals are from Fig. 2, showing the approximate area that regularly records basal micro-earthquakes and tremor (blue), and the high geodetic coupling area (red). Unstable slip event nucleation at the central nucleation area (red star) may happen when enough stick-slip basal patches break simultaneously. B: Cross section of ice base showing conceptual model of over-consolidated till outcropping through high-porosity deforming till. Basal micro-earthquakes may occur by a slip-weakening mechanism between over-consolidated till and basal ice. Scale is unknown and intentionally left out. C: Schematic illustration of slip-weakening failure mechanism for basal micro-earthquakes in over-consolidated till. The fault is loaded elastically until peak frictional resistance is reached, after which frictional resistance decreases. In over-consolidated till, this corresponds to elastic loading of till grains in their over-consolidated configuration until frictional grain contacts start failing. Frictional resistance drops as grains move out of an over-consolidated packing and lose some frictional contacts. If the frictional resistance drops faster than the elastic unloading with slip (grey area), the excess elastic stress results in acceleration (unstable sliding) and emission of seismic waves. With continued slip, grains reach a steady state porosity and shear strength (critical state), and unstable sliding due to force imbalance is inhibited. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of stick-slip behavior suggests that the bed conditions that cause basal micro-seismicity may in aggregate be the same conditions that cause nucleation of ice-plain-wide unstable slip. We propose that the central nucleation area sticks between unstable slips because it has higher basal traction, apparent in the high geodetic coupling, and different frictional basal properties than surrounding aseismic areas of the WIP bed. Basal micro-earthquakes may indicate the spatial extent of the higher basal traction and basal till conditions that promote stick-slip. This is consistent with the modeling results of Lipovsky and Dunham (2017), who show that large-scale heterogeneity in frictional properties is required to reproduce the shape of GPS displacement curves during ice-plain-wide unstable sliding.

Subglacial tremor typically occurs in a spatially distinct part of the WIP, in a halo of sites that overlap with but are mainly downstream of the central nucleation area and the sites with basal micro-earthquakes. Seismicity changes from relatively larger amplitude discrete basal micro-earthquakes upstream to smaller amplitude tremor further downstream (Fig. 2A), suggesting that the conditions causing basal seismicity change with distance downstream of the central nucleation area (Lipovsky and Dunham, 2016).

The area with high geodetic coupling is offset downstream of the central nucleation area (Fig. 2B). This offset makes sense if we assume the central nucleation area is an area of higher basal traction. The WIP has very low driving stress because the surface slope is shallow (0.4×10^{-3}) (Bindschadler et al., 1987). If the WIP becomes 'stuck' on the higher basal traction area between unstable slips, the area just downstream is shielded from the longitudinal upstream push. It consequently moves little between unstable slips, and both areas accumulate a comparable slip deficit until pulled by the falling Ross Ice Shelf tide or until the central nucleation area is loaded to failure. This shielded area is observed as the downstream continuation of the high geodetic coupling patch.

Basal micro-earthquakes are also observed at the site nearest the grounding zone nucleation area, though sparse station coverage precludes thorough characterization of seismicity in that area (yellow star, Fig. 2A). The presence of basal micro-earthquakes at sites near the grounding line suggests that the basal conditions causing basal micro-seismicity and stick-slip are present in that region as well. Given the lack of station coverage, we hesitate to interpret basal seismicity near the grounding zone nucleation area further. Surprisingly, there is little strain accumulation near the grounding zone nucleation area between unstable slip events despite the fast acceleration of unstable slip in this area (Pratt et al., 2014; Walter et al., 2015). There may instead be basal stress conditions that are transiently important as local tide falls (Walter et al., 2015) that are not recorded in the sparse geodetic data.

The widespread presence of seismicity, both basal micro-earthquakes and tremor, around the nucleation areas implies that a frictional description of ice-bed interactions that allows stick-slip may be appropriate for large portions of ice stream beds (Fig. 3A). This is consistent with the modeling results of Lipovsky and Dunham (2017), who successfully reproduce the GPS displacement curves of the ice-plain-wide unstable slip events using an ice stream model with rate-and-state friction as a basal sliding law and large-scale heterogeneity in frictional bed properties. However, the specific mechanism for the much smaller basal seismicity remains unclear. We next propose a mechanism for these basal micro-earthquakes and tremor.

4.2. Constraints on a basal micro-earthquake mechanism

Basal micro-earthquakes and tremor have been successfully modeled as shear displacements near the ice-bed interface in several ice stream environments (Anandakrishnan and Bentley, 1993; Blankenship et al., 1987; Lipovsky and Dunham, 2016; Roeoesli et al., 2016; Smith et al., 2015). For seismic energy to be radiated from a shearing fault, friction of the fault surface must be either slip-weakening (frictional resistance decreases as fault slip distance increases) or velocity-weakening (frictional resistance decreases with increased fault slip velocity). In either case, if the frictional resistance decreases (fault weakens) faster than elastic stress is released (elastic unloading), the unbalanced elastic stress causes transient inertial acceleration on the fault. This short-lived acceleration is 'unstable' sliding and can radiate seismic energy (e.g., Scholz, 2002).

Velocity-weakening friction is typically invoked to cause tectonic earthquakes using the framework of rate-and-state friction (e.g., Scholz, 1998), but the limited experimental evidence of till frictional properties suggests conflicting behavior: tills from different environments may be plastic (Kamb, 1991) but velocity-strengthening (Rathbun et al., 2008; Tulaczyk et al., 2000), or velocity-weakening (Iverson et al., 1998; Iverson and Zoet, 2015; Thomason and Iverson, 2008). The most relevant till sample comes from upstream Whillans Ice Stream, and this till exhibits a slight increase in yield strength as strain rate increases, or velocity-strengthening behavior (Tulaczyk et al., 2000). Though the sample comes from 200 km upstream of the ice plain, this result makes simple velocity-weakening an unattractive mechanism for basal seismicity in this till and leads us to search elsewhere besides rate-and-state-friction for a mechanical explanation for basal micro-earthquakes and tremor in till. Ploughing of clasts embedded in the base of the ice through wet low diffusivity till can also cause velocity-weakening behavior (Iverson, 2010; Thomason and Iverson, 2008). We search for other mechanisms, though, because there is evidence of basal micro-seismicity when there is no apparent surface velocity (Winberry et al., 2013), which is inconsistent with the ploughing model, and there is no obvious way ploughing can arrest slip and result in interseismic healing and stress accumulation to produce repeating basal icequakes and tremor.

A clue about the potential mechanism of basal micro-earthquakes in till comes from the Rutford Ice Stream, where Smith (2006) and Smith et al. (2015) showed that basal micro-earthquakes occur in areas of the bed with relatively lower porosity till, as inferred by active-source measurements of seismic impedance. Adopting this interpretative framework, we likewise suggest that the seismically active central nucleation area consists of a heterogeneous bed dominated by till with relatively lower porosity than the surrounding ice plain till, and therefore higher basal traction and greater likelihood to experience stick-slip motion and basal micro-earthquakes. This framework is consistent with the nearby active seismic results of Luthra et al. (2016) showing the till porosity near the stick-slip central nucleation area is lower than that determined for a faster-moving upstream section of the Whillans Ice Stream (Blankenship et al., 1986). Experimental evidence for velocity-strengthening behavior of Whillans Ice Stream till (Tulaczyk et al., 2000), evidence that basal micro-earthquakes happen beneath the Rutford Ice Stream where till porosity is lower (Smith, 2006; Smith et al., 2015), and evidence that the central nucleation area till may indeed have lower porosity than upstream till (Luthra et al., 2016) together point to a basal micro-earthquake mechanism involving low porosity, stiff till that is likely velocity-strengthening.

4.3. A proposed slip-weakening mechanism for ice stream basal micro-earthquakes

We conjecture that the small basal micro-earthquakes and tremor happen during a slip-weakening failure of over-consolidated low porosity till as it is being subglacially eroded and converted into high-porosity, weak till. The higher porosity till may still be velocity-strengthening after dilation, consistent with laboratory tests on samples from upstream Whillans (Tulaczyk et al., 2000). Over-consolidated till will be transiently slip-weakening (Fig. 3C) (Tulaczyk et al., 2000), and velocity-weakening behavior may not be required to generate basal seismicity. An over-consolidated sediment is one that has lower porosity and higher shear resistance than would be reached by compaction under the current effective normal stress. Over-consolidation of till indicates higher effective normal stress in the past, perhaps because of previously lower subglacial water pressure, thicker ice with no change in absolute subglacial water pressure, or erosion into till layers that used to be located deeper in the till package and experienced greater overburden stress due to the combined weight of ice and sediment. Over-consolidation happens because till porosity reduction is largely maintained when effective normal stress decreases again, provided the till is not sheared (Tulaczyk et al., 2000). Importantly, the shear resistance of over-consolidated sediment deformed under a constant effective stress reaches a peak value at failure and then decreases with increasing shear strain towards a critical state value, often referred to as the ultimate shear strength (Fig. 3C) (Jefferies and Been, 2015; Tulaczyk et al., 2000). Just like velocity-weakening, this 'slip-weakening' during post-failure deformation of over-consolidated sediment can cause transient stress imbalances if it happens faster than the elastic unloading of the fault walls, resulting in local accelerations, unstable sliding, and seismic energy radiation (Fig. 3C). This mechanism could also produce basal micro-earthquakes beneath other ice streams and glaciers that do not experience stick-slip at the scale of the Whillans ice-plain-wide unstable slip events.

In a fine-grained, water-saturated till, such as is found beneath the Whillans Ice Stream, slip-weakening during dilation of over-consolidated till may be complicated by dilatant strengthening. Dilatant strengthening occurs in over-consolidated fine-grained sediments when rearrangement of grains during shear causes an increase in shear zone porosity, a corresponding decrease in shear zone pore pressure, and consequent strengthening of the dilating shear zone. This strengthening is transient because it lasts only until ambient pore pressure can diffuse back into the shear band (Moore and Iverson, 2002). Dilatant strengthening does not preclude shear accelerations and unstable slip, though it can arrest them once they begin.

An illustrative example is reported in Moore and Iverson (2002, Fig. 2). The authors use a ring-shear device to experimentally produce a series of brief unstable sliding events in wet over-consolidated till. The unstable slips remain 'slow', and the authors argue they are arrested by dilatant strengthening. These may be analogous to the slip-weakening mechanism that we propose: As the over-consolidated till shears, its shear strength drops due to rearrangement of the tightly packed grain framework attained during over-consolidation. This decrease in shear resistance leads to unbalanced forces that cause acceleration. But the fast slip phase is also associated with rapid dilation, which causes a local drop in pore water pressures and a corresponding increase in effective stress and frictional shear resistance. At some point the dilatant hardening becomes dominant and slip is temporarily arrested or slowed until pore water flows back into the shear zone, eventually allowing another acceleration. As shown in Moore and Iverson (2002), it may require many episodes of shear followed by dilatant hardening for a sediment to reach critical state, which may explain our observations that basal micro-earthquakes and tremor can repeat up to many hundreds of times in the same location during a single ice stream-wide slip event lasting 20–30 min. At the same time, micro-earthquake source locations do not persist for more than a few slips, presumably because the subglacial sediment reaches critical state after many micro-earthquakes.

Slip-weakening friction is thought to be important in other geologic settings, for example the Nankai Subduction zone, though the mechanism is slightly different. The Nankai subduction zone features very low frequency earthquakes, a type of earthquake that is deficient in high frequencies, possibly due to lower rupture velocities. These slow earthquakes typically occur outside of the frictional limit of the seismogenic zone of subduction zones, for example in Nankai (Obara and Ito, 2005) and Costa Rica (Walter et al., 2013). High clay content samples from the Nankai subduction zone exhibit velocity-strengthening behavior when a velocity increase is imposed during laboratory experiments. However, the samples also exhibit weakening over larger slip distances as slip continues after the velocity perturbation(s) (Ikari et al., 2013). The velocity-strengthening behavior of Nankai samples is inconsistent with the seismic observations of very low frequency earthquakes, but the earthquakes may be explained by the slip-weakening over larger slip (Ikari et al., 2013; Ito and Ikari, 2015). Though the slip-weakening of Nankai material beyond the initial velocity-strengthening response is slightly different than slip-weakening of over-consolidated till, the observations from Nankai suggest that slip-weakening may cause seismogenic fault behavior.

4.4. Regional frictional properties and ice-plain-wide stick-slip

Considering our proposed slip-weakening mechanism of basal seismicity, we interpret that our observation of kilometer-scale heterogeneity in basal micro-earthquake and tremor activity results from small, localized, seismically active patches of over-consolidated till deep in the till package exposed by erosion and outcropping through a layer of aseismically deforming, high porosity, weak till. This is similar to a conceptual picture in Alley (1993), and there may be evidence for such outcrops in active seismic results from upstream Whillans Ice Stream (Rooney et al., 1987). Fig. 3B illustrates our conceptual picture of the ice-bed interface: basal micro-earthquakes occur by slip-weakening in the over-consolidated till where it contacts the ice bottom. As this over-consolidated till dilates and erodes, it is transported downstream, becoming part of the aseismically deforming till package. Ice stream motion causes horizontal transport of this high-porosity, aseismic till, estimated to be $< 40\ \mathrm{m}^3\,\mathrm{m}^{-1}\,\mathrm{yr}^{-1}$ beneath the WIP (Hodson et al., 2016). Provided the basal sedimentary environment is erosive, till flux from upstream plus till generation by erosion is less than till advection downstream. Eventually, new over-consolidated till is exposed to maintain locally higher basal tractions and allow the WIP stick-slip cycle and probably basal micro-earthquakes to persist for more than a decade (Bindschadler et al., 2003; Siegfried et al., 2016).

We additionally suggest that the overlap between the central nucleation area and the cluster of sites that most often record distinct basal micro-earthquakes indicates that the conditions that cause basal micro-earthquakes and tremor are the same conditions that nucleate the WIP-wide unstable slip events. Because over-consolidated, lower porosity till has a transiently higher peak shear strength than its normally consolidated equivalent, it can offer locally higher basal resistance to ice motion. If slightly stronger over-consolidated till is continuously exposed by erosion and in contact with the ice base over a large area, the ice stream can become transiently 'stuck' on it with ice-plain-wide unstable slip events initiating when a large enough area of over-consolidated till is loaded to failure and starts to experience weakening. Then, ice-plain-wide unstable slip in surrounding aseismic areas of the ice plain can be sustained by velocity-weakening ploughing of clasts through non-over-consolidated deforming till, or some other velocity-weakening mechanism of till deformation (Iverson, 2010; Lipovsky and Dunham, 2017; Thomason and Iverson, 2008). Thus, the area of the WIP bed that features basal seismicity, the size of the high geodetic coupling patch, and the location of the central stick-slip nucleation area may all be controlled by the spatial distribution of varying till mechanical properties, for example the areal density or size of the outcrops of slip-weakening till that may interact to nucleate the large scale unstable slip.

We also note that Lipovsky and Dunham (2017) successfully model the ice-plain-wide unstable slip events using a rate-and-state frictional constitutive law for basal sliding. This suggests that the aggregate frictional properties of the ice plain at ∼10 km scales may be reproduced by rate-and-state friction, but this does not preclude a non-rate-and-state friction explanation for basal micro-earthquakes happening on localized meter-scale basal faults.

We propose that outcrops of over-consolidated till may be regions that catch on the ice bottom, generate basal micro-earthquakes, and if covering a wide enough area, can generate large scale stick-slip such as is observed for the WIP. If subglacial erosion in the nucleation area exposes larger areas of over-consolidated, stiff till, the WIP bed will continue to strengthen and we may observe changing basal seismicity. Regardless of the mechanism of basal strengthening, conditions that are currently causing basal strengthening and slowdown of the WIP (Beem et al., 2014; Joughin et al., 2005) may become more favorable in the future to form a slow-moving ice ridge in the middle of the ice plain with a narrower Whillans Ice Stream flowing to the north. Seismicity from the bed of an ice stream may therefore be indicative of changing bed properties that can trigger significant re-arrangement of regional ice flow patterns and velocity fields over the coming decades and centuries.

5. Summary

We compare the spatial patterns of basal seismicity, tremor, and geodetic coupling with the inferred nucleation areas of the well-known WIP unstable sliding events. We find that while seismicity rates are heterogeneous between neighboring sites, there are informative regional patterns. Basal micro-earthquakes typically happen at a cluster of sites overlying the central nucleation area and the upstream end of a central highly geodetically coupled patch. Tremor generally occurs downstream of this cluster. The dominant type of seismicity changes from larger amplitude individual basal micro-earthquakes upstream to small amplitude tremor and seismically quiet bed further downstream, indicating changing basal conditions.

These results confirm that the WIP bed is heterogeneous (e.g., Alley, 1993; Rooney et al., 1987) and that ice sliding can be described using a frictional constitutive law at both the large scale of unstable sliding nucleation (Lipovsky and Dunham, 2017) and the small scale of basal-earthquake-generating asperities. We adopt the interpretive framework of Smith (2006) and Smith et al. (2015) in suggesting that basal micro-earthquakes beneath till-bedded ice streams occur in low porosity, stiff till. As a possible mechanism, we propose sudden, slip-weakening till deformation and failure on a plane in over-consolidated till. Because an over-consolidated till has a transiently higher peak shear strength than the same till at critical state, discrete basal micro-earthquakes and tremor in till may indicate areas of higher basal shear strength. This slip-weakening mechanism for small basal seismicity has potential implications for modeling of basal traction in ice sheet models.

The relative abundance or absence of basal micro-earthquakes yields information about the bed conditions and stresses at the bottom of the ice and the spatial extent of low porosity till that is eroding during ice motion. Further study with dense seismometer networks is required to understand the mechanism and relevance of basal seismicity to understanding fast ice flow.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2017.12.046.

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