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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, shutdown 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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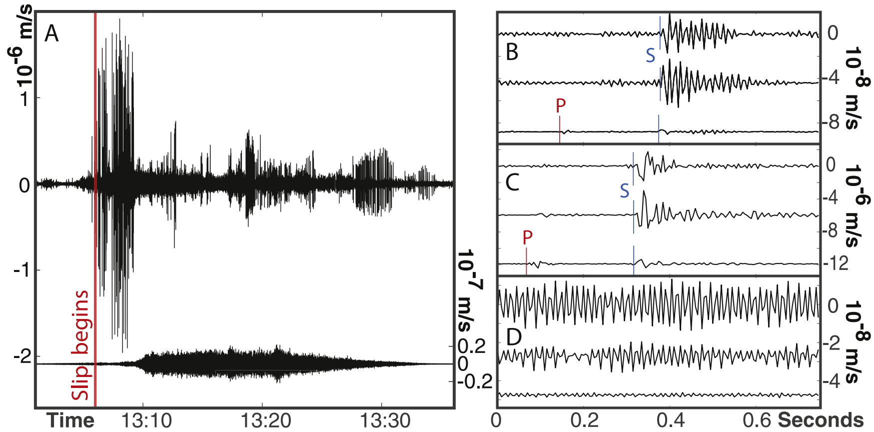

Fig. 1. Example basal earthquake and tremor seismic data. A: Sample east component seismic records of individual basal micro-earthquakes (top) and basal tremor (bottom) at two different sites during the same slip event that begins at the red line. Note the different vertical scales. Slip time is from 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