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J. Paul Winberry

Sridhar Anandakrishnan

Douglas A. Wiens

Richard B. Alley

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Nucleation and seismic tremor associated with the glacial earthquakes of Whillans Ice Stream, Antarctica

J. Paul Winberry,[1] Sridhar Anandakrishnan,[2] Douglas A. Wiens,[3] and Richard B. Alley[2]

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[1] The ability to monitor transient motion along faults is critical to improving our ability to understand many natural phenomena such as landslides and earthquakes. Here, we usedata from a GPS and seismometer network that were deployed to monitor the regularly repeating glacial earthquakes of Whillans Ice Stream, West Antarctica to show that a unique pattern of precursory slip precedes complete rupture along the bed of the ice stream. Additionally, we show that rupture can be independently tracked by increased levels of microseismic activity, including harmonic tremor, that are coincident with the onset of slip at any location, thus providing a remote means of monitoring stress and rupture propagation during the glacial earthquakes.
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1. Introduction

[2] Vigorous observational campaigns integrating seismic and GPS techniques have illuminated a range of complex behaviors along tectonic faults [*Gomberg*, 2010; *Peng and Gomberg*, 2010], with similar features as well as novel processes found in glacial settings [*Ekström et al.*, 2003; *Wiens et al.*, 2008]. Perhaps the most predictable macro-scale stick-slip naturally-occurring system known is on Whillans Ice Stream (WIS) in West Antarctica [*Bindschadler*, 2003]. This 800 m thick ice stream produces tidally paced ~M_w 7 slow glacial earthquakes twice per day, when the 150 km downstream portion lurches forward by ~0.4 m during a ~30 min period (Figure 1), generating low-frequency seismic waves that can be detected at teleseismic distances [*Wiens et al.*, 2008]. WIS ice flow into this region from farther inland is relatively smooth, as is the flow of the floating Ross Ice Shelf downstream, although both respond to some degree to the behavior of the stick-slip region.

[3] The rupture kinematics of WIS earthquakes [*Winberry et al.*, 2011] is intermediate between traditional "fast" earthquakes and slow earthquakes such as those of Cascadia subduction zone [*Bartlow et al.*, 2011; *Beroza*, 2011]. However, physical understanding indicates that similar processes, such as dilatancy affecting shear strength through porosity change, regulate slip in all of these settings, suggesting that knowledge learned in one setting may aid understanding of others [*Peng and Gomberg*, 2010].

[4] Direct observations of sliding in tectonic settings are limited due to the difficulty of placing and maintaining sufficiently dense GPS networks and of relating surface displacements to motion on faults that are often deeply buried in geologically complex regions. As a result, naturally occurring seismic emissions are often used to interrogate both the spatial and temporal variability in sliding in these settings. For example, seismic emissions have been used to track the rupture of slow-slip events [*Bartlow et al.*, 2011] and to infer precursory slip of large earthquakes [*Nadeau and Guilhem*, 2009; *Shelly*, 2009; *Bouchon et al.*, 2011]. In contrast, both GPS and seismic observations are straightforward almost everywhere above the seismic zone of the relatively homogeneous Whillans Ice Stream, which is cut only sparsely by near-vertical crevasses, and otherwise is among the geologically simplest terrains on the planet. In this contribution, we show, with coupled geodetic and seismic observations, an example of how naturally occurring seismic events can be used to track the multi-stage rupture of glacial earthquakes.

2. Observations of Slip Nucleation and Microseismicity

[5] Similar to a tectonic earthquake, the WIS stick-slip cycle is driven by the accumulation and release of elastic strain that periodically results in sliding along a fault (Figure 1). In the case of WIS, the elastic strain is stored primarily within the ice, and motion is concentrated just beneath in a narrow (<10 m) fault zone of unconsolidated sediments (functionally and genetically a fault gouge). Borehole data from nearby [*Kamb*, 2001] indicate that the base of the ice is debris laden, and active-seismic data [*Rooney et al.*, 1987] suggest that the fault gouge may be locally discontinuous, exposing consolidated sediments to the debris-laden ice.

[6] To better understand the nature of WIS motion, we deployed a network of Global Position Systems (GPS) and seismometers near the epicenter of the WIS glacial earthquakes during December 2010–January 2011 and again during December 2011. Figure 1 shows the location of our collocated GPS and seismic installations during December 2011; all units were powered by the combination of a solar panel and battery. GPS stations consisted of geodetic quality Trimble receivers sampling every 15 s with the antennas affixed to metal conduit. Seismic stations consisted of Nanometrics T120 seismometers recording at 500 Hz. The seismometers were placed on a tile block in vaults ~0.5m beneath

[1]Department of Geological Sciences, Central Washington University, Ellensburg, Washington, USA.
[2]Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania, USA.
[3]Department of Earth and Planetary Sciences, Washington University in Saint Louis, St. Louis, Missouri, USA.

Corresponding author: J. Paul Winberry, Department of Geological Sciences, Central Washington University, Ellensburg, WA 98926, USA. (winberry@geology.cwu.edu)

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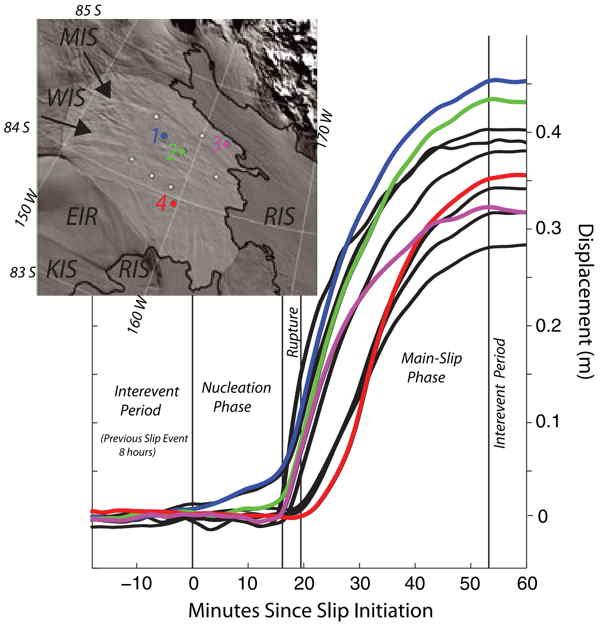

Figure 1. Map showing study area and all displacement records for a single WIS glacial earthquake. Distinct phases of the WIS stick-slip cycle are noted. Dots indicate GPS and seismic stations occupied during December 2011 field campaign. Highlighted region demarcates the approximate boundary of grounded ice that contributes to the WIS glacial earthquakes. Colored dots (labeled 1–4) in map correspond to colored displacement records. Labels indicate Kamb Ice Stream (KIS), Ross Ice Shelf (RIS), Engelhardt Ice Ridge (EIR), and Mercer Ice Stream (MIS). Thick black line is the grounding line, and background image is the MODIS mosaic of Antarctica [*Scambos et al.*, 2007].

the surface. In this paper, we focus on the geodetic and microseismic signals, observed during a single slip event during the 2011 season, that exhibit several ubiquitous features of the WIS glacial earthquakes not previously recognized.

[7] First, our new data show that the transition from slow to fast slip velocities during a WIS glacial earthquake begin with a 5–20 min period that we term the nucleation phase. The onset of the nucleation phase is marked by an increase in velocity to ~5–10 m/day over ~10% of the total stick-slip area. This velocity is intermediate between that of the inter-event period (<1 m/day) and that of the main slip phase (>30 m/day). The relatively small spatial extent of the nucleation zone requires relatively dense stations near the nucleation zone to observe this behavior, thus explaining the lack of detection by previous experiments. Following this nucleation phase, onset of the main "fast" slip phase (velocities > 10 m/day) commences with a rupture front propagating outwards across the remainder of the ice stream at high speeds (>500 m/s) as the remainder of the ice stream transitions to its fast moving mode [*Wiens et al.*, 2008; *Winberry et al.*, 2011]. We define the end of the rupture phase to terminate when fast motion has begun at all of the stations, indicating the rupture front has propagated across the entire ice stream, this transition occurs at ~19 min during the example shown in Figure 1. Following the rupture phase, the ice stream typically continues to move for ~30 min, which we term the main slip-phase, before coming rest.

[8] Our new seismic observations reveal that the motion during WIS glacial earthquakes radiates high-frequency (>10 Hz) seismic energy, in addition to the previously recognized long-period seismic waves observed at distant sites [*Wiens et al.*, 2008]. The relatively small amplitudes and high-frequency nature of these arrivals requires the in situ installation of seismometers to detect these emissions. Likewise, the spacing of our seismometers did not allow most events to be observed by multiple stations, precluding precise source locations to be determined. Where present, microseismic activity increases with the onset of slip at a site and decreases near the termination of slip (Figure 2). Additionally, when the onset of slip is sufficiently gradual, such as within the nucleation zone (station 1), the associated increase in seismic activity is often discernible prior to the geodetic signature of slip initiation. The lack of surface crevassing in the region, and the fact that the first high-frequency seismic arrivals and the onset of motion at a location coincide with each other, suggests that these arrivals are associated with motion near the base of the ice stream. We suggest that stations recording no microseismic energy are underlain by a combination of thicker or more continuous fault gouge and higher pore-water pressures making these regions especially well lubricated, as inferred for tectonic faults.

[9] Further inspection reveals that each microseismically active region is consistently associated with one of two distinctive styles. The first style is characterized by discrete events (Figure 2, stations 1 and 3) [*Anandakrishnan and Bentley*, 1993]. During a slip event, fewer than a hundred to several thousand distinct events may be recorded (Figure 2). Seismicity rate typically tracks with the ice stream velocity measured by the collocated GPS. The relative timing of *P* and *S* wave arrivals is consistent with an origin near the base of the ice stream, the most likely source given the lack of crevassing in this region. At station 1, the waveforms of separate events often exhibit a strong degree of similarity, indicating a similar hypocenter and repeated rupture of a small sticky spot (or asperity) [*Smith*, 2006]. The events, thus can be grouped into families (Figure 3), with anywhere from a few to a few hundred occurring in a family during each slip event, with the same event families being present in subsequent slip events indicating the temporal stability of sub-glacial asperities. The events at station 2 are typically characterized by lower frequencies (<40 Hz), suggesting a larger source than those observed at station 1.

[10] The second style of seismicity is emergent tremor, with distinct events not being clearly discernible (Figure 2, stations 2 and 4). The spectrogram of the seismic tremor reveals the presence of gliding spectral lines, coherent bands of energy whose frequencies vary throughout the slip event. This variation in frequency is largely correlated with the surface speed of the ice stream as determined by the collocated GPS, although with interesting complexity (Figure 2). Similar, signals have been observed in both volcanic [*Jousset et al.*, 2003] and iceberg [*MacAyeal et al.*, 2008; *Martin et al.*, 2010] settings. Periodic stick-slip failure of a single small asperity may produce such spectral peaks, with the fundamental frequency identical to the event repeat rate [*Powell and Neuberg*, 2003]. Additionally, seismic energy during the tremors is concentrated on the horizontal components, consistent with the radiation of shear energy from a source associated with sliding near the ice-bed interface. Gliding will

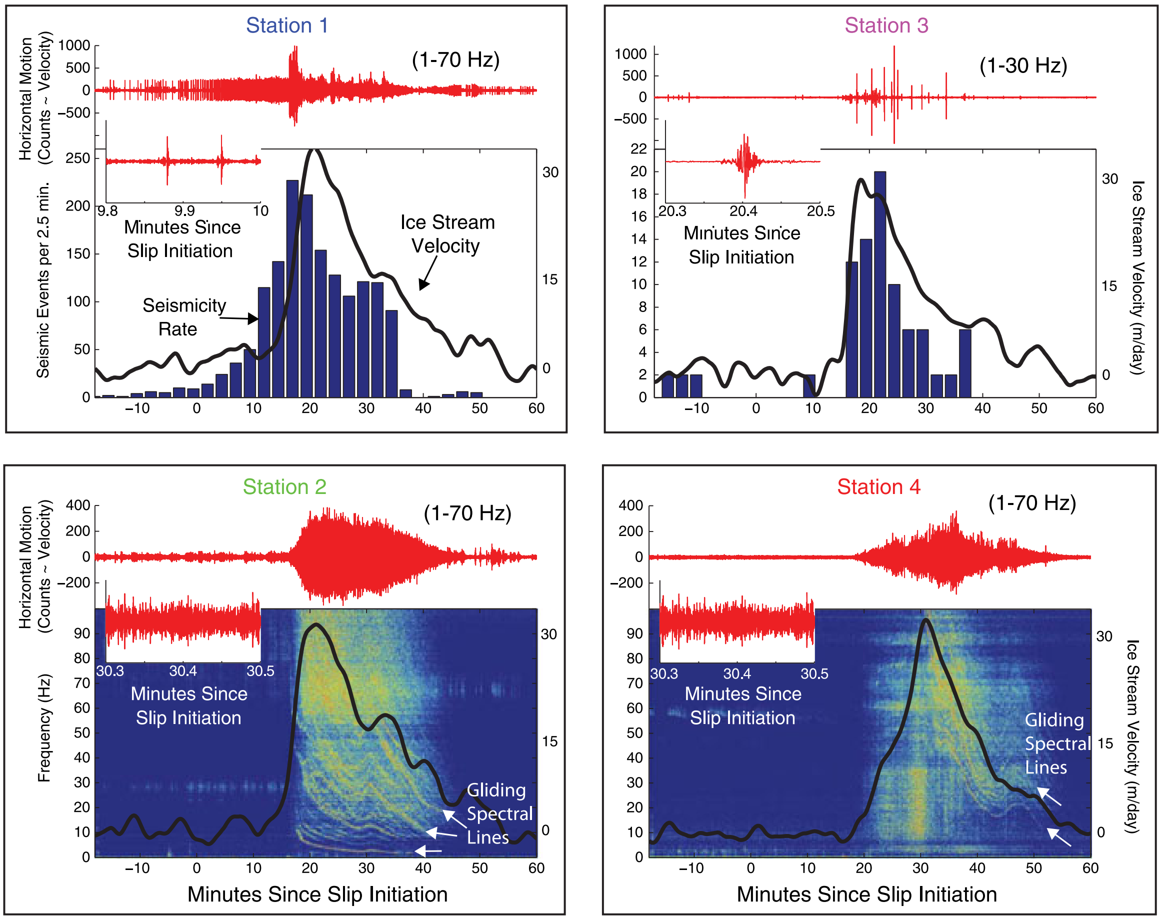

Figure 2. Seismic activity observed at four stations for the event shown on Figure 1. Upper panels show filtered seismic traces with an inset showing 20 s of data. The black line in the lower panels is the GPS observed ice stream velocity (with a 200 s low-pass filter applied) obtained by differentiating the displacement time series shown in Figure 1. Note that due to relatively high-noise in the GPS derived velocity time series (~5 m/day), the nucleation phase is not well represented in the velocity time-series. For stations 1 and 3, histograms of seismicity rate are also plotted in the lower panels. For stations 2 and 4, lower panels also show the spectrogram of the unfiltered seismic trace. White arrows point toward the termination of several examples of gliding spectral lines.

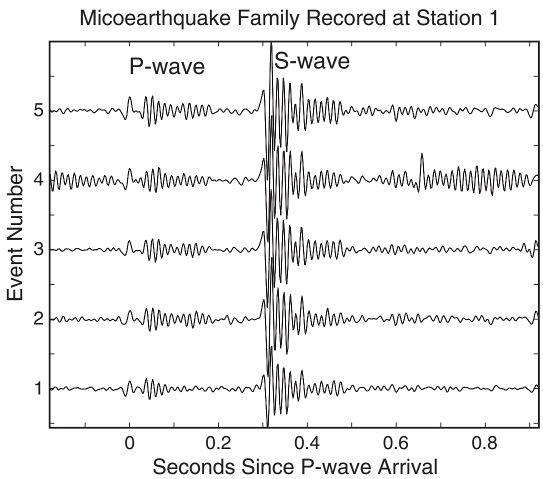

Figure 3. A subset of events associated with a single family composed of 250 events observed at station 1 during the slip event as recorded by the vertical channel. The arrival of the P and S waves is labeled.

result as the periodicity of the source slowly changes through time. In the case of WIS, motion of the ice stream is a primary control on the stressing rate of sub-glacial asperities and thus the time between failures that release seismic energy. Closer inspection reveals that many of the spectral bands appear to be integer harmonic overtones, consistent with a repetitive source [*Powell and Neuberg*, 2003]; however, spectral lines may also diverge and/or converge upon one another suggesting several unique sources. Thus, we propose that the WIS tremor may be generated by the repeated failure of several small sub-glacial asperities with a periodicity modulated the velocity of the ice stream, although deviations from a strictly linear relationship between the gliding of frequencies and observed velocity reveal spatio-temporal complexity in the basal stressing rate.

3. Summary

[11] Our new observations show that the glacial earthquakes of WIS initiate with a nucleation phase prior to

complete rupture. We observe that the complex temporal and spatial pattern of motion during the glacial earthquakes of WIS radiates a range of microseismic emissions, including seismic tremor, that are likely associated with the failure of small-scale (<10 m) asperities at the base of the ice stream. While several differences exist between our setting and most seismogenic faults, such as the relatively low normal stress on our sliding interface, we believe that the rich and clean data set made possible by the ice-stream setting provides insights that are complementary to those from laboratory [*Byerlee*, 1966] and other field studies. The full complement of stick-slip events and associated seismicity with tremor has recently been observed accurately in the laboratory setting [*Zigone et al*., 2011], but our results may provide the clearest coupled geodetic and seismic observations yet obtained of acceleration in a natural stick-slip system. Thus, the highly repeatable WIS system can be used to explore the relationship between driving forces and the spatio-temporal patterns of slip and microseismicty at a detail not possible in tectonic settings, providing a unique environment to study the nucleation of unstable slip associated with the stick-slip motion and associated geophysical phenomena.

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