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Seismic observations of transient subglacial water-flow beneath MacAyeal Ice Stream, West Antarctica

J. Paul Winberry,[1,2] Sridhar Anandakrishnan,[2] and Richard B. Alley[2]

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[1] New seismic observations of harmonic tremors beneath MacAyeal Ice Stream, West Antarctica are reported. Each of the two tremor events that we recorded during a six week period had sustained arrival of 3 Hz energy for approximately 10 minutes. During that time the source location migrated a few kilometers. The harmonic nature of the tremors is interpreted as the result of resonance in subglacial water-filled cracks and conduits. The duration, monochromatic nature, and movement of the tremor indicate that the source mechanism is likely flow in the subglacial water system resulting from the discharge from a small subglacial lake. Our results suggest that the subglacial water system produces repeated, small outburst floods, with possible implications for ice-stream dynamics.

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1. Introduction

[2] The dynamics of West Antarctic ice streams are of interest because of their role in the mass balance of the West Antarctic Ice Sheet (WAIS). These ice streams flow at relatively high speeds (few hundred meters per year) because of an abundance of subglacial water in and above soft sediment [*Alley et al.*, 1986; *Blankenship et al.*, 1986; *Kamb*, 2000], which allows sliding at the ice-bed interface or deformation of a water-saturated till layer beneath. Thus, understanding the subglacial water system is key to interpreting the past and modeling the future behavior of ice streams. Recent studies have highlighted the complexity of the subglacial water-system. Localized patterns of surface-elevation change, with "bulls-eye" lowering coupled to similar inflation downstream, are interpreted to indicate rapid drainage events (outburst floods) over months, weeks or less [*Fricker et al.*, 2007; *Gray et al.*, 2005; *Wingham et al.*, 2006] that have the potential to affect ice dynamics [*Stearns et al.*, 2008]. Here we document two newly-observed, monochromatic 3-Hz harmonic-tremor events that migrated kilometers downstream beneath MacAyeal Ice Stream, West Antarctica (MacIS, which was formerly known as Ice Stream E). We interpret these events as indicating repeated outburst floods, draining from one small lake to another during a period of approximately 10 minutes. Such repeatable events offer a natural target for understanding tremor generation and outburst-flood influence on ice flow and sedimentary processes.

[1]Department Geological Sciences, Central Washington University, Ellensburg, Washington, USA.

[2]Center for Remote Sensing of Ice Sheets, Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania, USA.

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2. Seismic Observations of Glacial Tremor

[3] During the austral summer of 2005–2006, early December through mid-January, we deployed a network of 12 passive seismometers 30 km upstream of the grounding line on MacIS, one of the major outlets that discharges ice from the WAIS into the Ross Ice Shelf (Figure 1). Seismic data from three-component seismometers (with a frequency band of 1 Hz to approximately 125 Hz) were recorded continuously at 250 samples per second. At the study area the ice sheet is approximately 900 meters thick [*Luyendyk and Wilson*, 2003] and is moving at 500 *m/a*, determined from collocated Global Positioning System observations. The array was deployed to record basal seismicity associated with tidally induced variations in ice-stream velocity [*Anandakrishnan et al.*, 2003].

[4] In addition to impulsive events that are typically recorded on ice streams [*Anandakrishnan and Bentley*, 1993; *Smith*, 2006], we recorded two events, which we refer to as harmonic-tremor events, of a type that has not been previously reported from Antarctica (Figures 2a and 2b). The events occurred two weeks apart (on days 348 and 365 of 2005), and are distinguished by: 1) durations of approximately 10 minutes, and 2) nearly monochromatic energy centered at a frequency of 3 Hz (Figure 2). Even though the tremors are ten-minute-long sequences, they consist of individually distinct and recognizable subevents that correlate from station to station; the time offsets between stations change monotonically for successive subevents during each whole event, indicating unidirectional migration of the tremor source, clearly seen in beam-forming results (Figure 3) [*Rost and Thomas*, 2002]. The beam-forming results also show that the wavefront moves across the array at a velocity of $\approx$1.6 *km/s* (slowness of $\approx$0.6 *s/km*) consistent with the particle motion of the waves (not shown) that indicate they are traveling as Rayleigh waves. In an attempt to measure the propagation velocity, we also located the source location through time by measuring the relative arrivals of the wavefront across the array via cross-correlation. However, due to the restricted aperture of our array, we have limited ability to resolve the location of the tremor, so our estimate of downstream propagation velocity (calculated by dividing estimated source migration by the tremor duration) spans the range of 1–20 *m/s* (Figure 1).

3. Source Mechanism

[5] Several characteristics of the tremors are diagnostic of the source mechanism: relatively long duration (compared

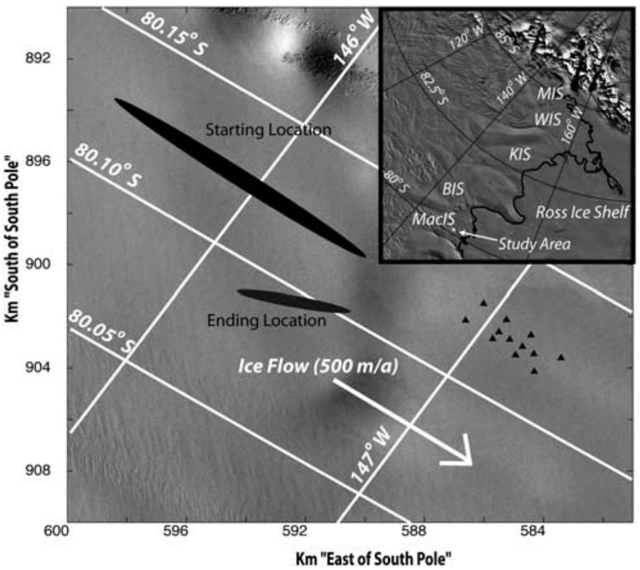

Figure 1. Location of our study, with triangles marking the seismometers overlain on a LANDSAT image (lima.usgs.gov). Ice flow is from the upper-left to lower-right at a speed of approximately 500 m/a. Black ellipses show the approximate starting and ending locations of the tremors. Grid is polar stereographic. Inset shows MODIS mosaic (nsidc.org/data/moa) of the Siple Coast region of West Antarctica. Major ice streams are labeled: Mercer Ice Stream (MIS), Whillans Ice Stream (WIS), Kamb Ice Stream (KIS), Bindschadler Ice Stream (BIS), and MacAyeal Ice Stream (MacIS). Thick black line shows the grounding line [*Horgan and Anandakrishnan*, 2006].

to basal microearthquakes or tectonic events); monochromatic content (frequency of 3 ± 0.2 Hz) (Figure 2c) that does not vary with time (Figures 2a and 2b); migration of the source during the event (Figures 1 and 3); and, the pulsed nature of the subevents (Figures 2a and 2b). As we argue below, a subglacial outburst flood that drained from one lake to a second lake can explain these phenomena. Subglacial icequakes that are generated by stick-slip basal motion produce impulsive broadband signals [*Anandakrishnan and Bentley*, 1993], and ordinary crevassing events are also broadband sources [*Deichmann et al.*, 2000], both inconsistent with the observed tremors. In contrast, the long-duration monochromatic nature of the MacIS tremors is similar to harmonic tremors observed in volcanic settings that originate from the resonance of magma-filled conduits [*Chouet et al.*, 1994; *Julian*, 1994]. A similar effect for mountain glaciers was first proposed by *St. Lawrence and Qamar* [1979], and has been applied to explain seismic observations on a variety of small glaciers [*Métaxian et al.*, 2003; *O'Neel and Pfeffer*, 2007; *Stuart et al.*, 2005].

3.1. Resonance of a Water-Ice Conduit

[6] To test the hypothesis that episodic water flow caused the MacIS tremors, we follow a methodology similar to that proposed by *Métaxian et al.* [2003]. The harmonic oscillation of a fluid-filled conduit is controlled by three variables: the conduit geometry, the physical properties of the wall material, and the physical properties of the fluid. However, the characteristic damping of a resonating conduit, Q, is a function solely of the physical properties of the wall and fluid, and not of the conduit dimensions. We calculate the theoretical value of Q for a subglacial conduit using the expression $Q = \pi \cdot \ln[(Z + 1/Z + 1)]^{-1}$ [*Aki*, 1984; *Métaxian et al.*, 2003], where is Z is the impedance contrast between ice and water given by $Z = \rho_{ice}/\rho_{water} \cdot V_{ice}/V_{water}$, where ρ_{ice} is the density of ice (920 kg/m^3), ρ_{water} is the density of water (1000 kg/m^3), V_{ice} is the seismic velocity of ice (3800 m/s), and V_{water}, is the seismic velocity of water (1500 m/s), resulting in a theoretical value of 3.4 for Q in a ice-water system. We estimate Q for the MacIS tremors by $Q = f/\Delta f$, where f is the center frequency and Δf is the width of the spectral peak measured at one-half the peak amplitude [*Aki and Richards*, 1980]. We average the spectrograms for all stations to improve the signal-to-noise ratio, and measure f = 3 Hz and Δf = 1 Hz, resulting in Q = 3 (Figure 2c). This is consistent with the theoretical quality factor for the ideal ice-water system calculated above; thus, we conclude that a source mechanism involving the resonance of a water-filled conduit is a viable possibility. Numerous other models (e.g., air in ice, till in ice) can be rejected with high confidence because they would give notably different Q values.

[7] Given the temperature regime of the WAIS [*Engelhardt*, 2005], the subglacial environment is the only

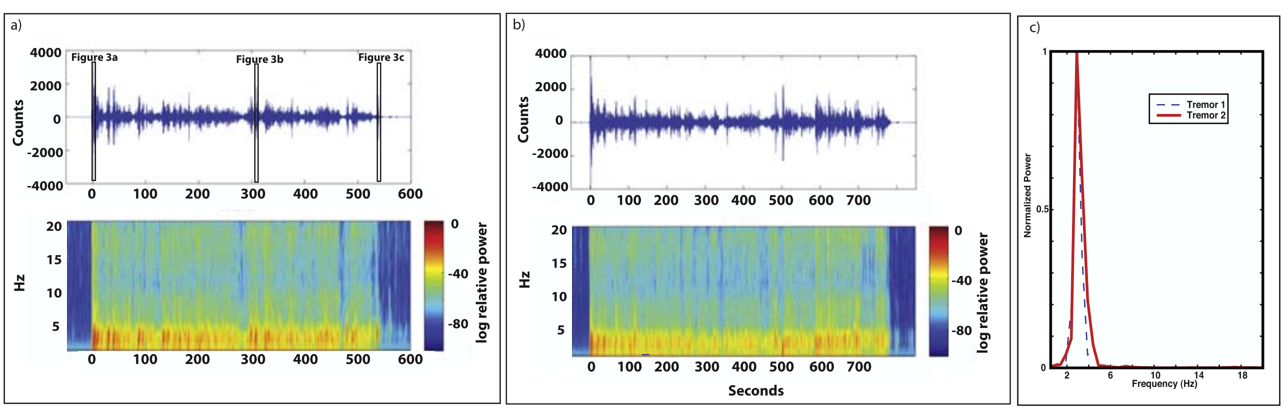

Figure 2. (a and b) The waveforms and spectrograms for the two tremors at a single station. Note the pulsed arrival of energy in the seismograms, and the nearly monochromatic nature of the energy at 3 Hz. The three sections of the first tremor shown in Figure 3 are outlined. (c) Normalized power spectrums for each tremor produced by stacking all stations.

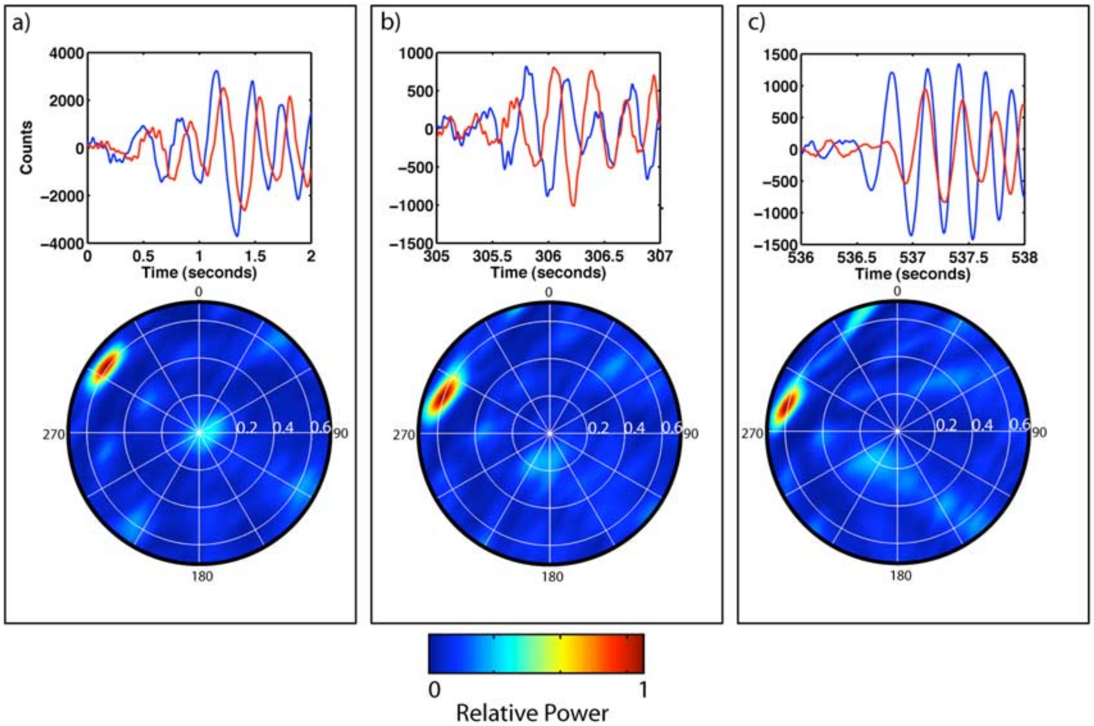

Figure 3. Array beam-forming at three different times during the first tremor, (a) early, (b) middle, and (c) late, shows that the source rotates counter-clockwise relative to the array. (top) The red and blue curves are vertical component seismograms for two stations 900m apart during those times. (bottom) Array beam-forming for each of the three time-periods produced by time shifting and summing all energy recorded by the array for combinations of azimuth and slowness (inverse velocity). Data are scaled to the maximum power at each time step. Radial lines indicate grid azimuth, and concentric circles indicate slowness (s/km).

viable location for free water. For this reason, we assume that the source of the tremors is a subglacial water-system of the ice stream rather than a supraglacial lake/moulin system as is possible in Greenland or in Alpine glaciers. We note that a soft-sediment bed has essentially the same acoustic impedance as ice [*Blankenship et al.*, 1986], so a conduit between ice and sediment is consistent with the estimated Q value. A conduit completely within soft sediments would collapse [*Walder and Fowler*, 1994], and so is not considered further.

3.2. Conduit Geometry and Source Migration

[8] The geometry of the conduit will determine the resonance characteristics of the system. Numerous conduit geometries have been proposed to accommodate water-flow beneath glaciers and ice-sheets, including channels cut into the ice [*Röthlisberger*, 1972], cut into the substrate [*Nye*, 1976], or a combination of the two [*Walder and Fowler*, 1994], a system of linked cavities [*Kamb et al.*, 1985], and thin sheets and films [*Weertman*, 1972] (see *Paterson* [1994] for a review). Notably, all of these possibilities, and others, can be represented by one of two major resonance models: a circular pipe, or a crack. The resonance frequency f of a perfectly cylindrical pipe of length L is $f = a/4L$, where a is the wave speed in the fluid modified by fluid-wall interaction (1100 m/s) [*St. Lawrence and Qamar*, 1979]. This holds for all pipe radii r, so long as $L \gg r$. For our data, $f = 3$ Hz, and therefore $L = 90$ m. Alternatively, the resonant subglacial system can be represented as a crack of constant thickness d (in the direction normal to the bed) and length L (parallel to the bed). Values of L, d, and the ratio $p = L/d$ consistent with the observed $f = 3$ Hz signal can be estimated from numerical results [*Chouet et al.*, 1994] (see *Métaxian et al.* [2003] for a detailed description applied to a glacial setting). Glaciologically viable solutions likely lie between $p = 85$, with $L = 60$ m, $d = 70$ cm, and $p = 2000$, with $L = 20$ m, $d = 2$ cm. Significantly lower values of p would suggest thicknesses $d \geq 1$ m, which is unlikely under large ice sheets, and which might require so much uplift that it would fracture the ice and produce broadband sources that we do not detect. Higher values of p would require cracks so small that we consider them unlikely to serve as viable acoustic sources. With the channel model yielding a resonating cavity of $L = 90$ m, and the crack models indicating resonant cavities in the range of $L = 20$ to 60 m, the resonating cavity has one horizontal dimension of order tens of meters.

[9] Additional consideration of the subglacial environment and of our seismic data suggests that the observed resonance is from a crack tens of meters wide (measured transverse to ice and water flow) that originates from and remains connected to a lake upstream during propagation, possibly as a flood wave or sheet similar to those inferred for certain jökulhlaups in Iceland [e.g., *Bjornsson*, 2003; *Flowers et al.*, 2004]. Following *Engelhardt and Kamb* [1997], if the propagating water mass is unconnected to a lake upstream (a drop of water released from the source), the water overpressure required for downstream propagation would drive water flow in all directions (including the transverse and upstream directions), changing the "drop"

size and thus changing the resonant frequency. Continued connection of the crack to a lake upstream would at least partially stabilize the overpressure driving crack-tip propagation, thus stabilizing crack-tip geometry and the resonant frequency, because of competing physical effects. The enhanced hydrologic conductivity along the crack compared to the preexisting drainage system would raise the overpressure at the crack tip as it propagated downstream, but the head drop from drainage of the lake would lower the crack-tip overpressure. If the resonance occurred along the flow direction, then our inference of a kilometers-or-longer connection to the upstream lake would require that the propagating crack maintained a notable change in thickness along flow to isolate the resonance in a propagating region a few tens of meters long just behind the crack tip. Resonance within the head of a comet or a tadpole connected to a thinner, non-resonant tail may be a useful analogy. However, the monochromatic nature of the events would then suggest a "comet head" either much wider or much narrower than tens of meters so as not to excite a second transverse resonance (or coincidentally almost exactly equant at all times), which we consider unlikely. Some uncertainty remains, however, our favored hypothesis, pending further data collection, is that the resonance most likely occurred transverse to water and ice flow, in a crack tens of meters wide that remained connected at the upstream end to a subglacial lake.

4. Discussion

[10] We thus propose that two drainage events from a small subglacial lake beneath MacIS generated the two observed tremors, with the drainage events terminating at a second, downstream lake. In the absence of the inferred second lake, we expect that the events would have continued propagating downstream, or that disconnection of the propagating cracks from the upstream lake would have changed the hydrologic conditions and thus the resonant frequency before event termination, neither of which is observed. This model explains both the common origin point and the common migration path for each of the two tremors. Our estimate of tremor migration rates (1–20 *m/s*) is faster than the speed of subglacial water pulses (0.2 *m/s*) observed in borehole-injection experiments on Whillans Ice Stream, in which the water injected beneath the ice was hypothesized to have opened a crack between the ice and substrate as the pressure-pulse spread [*Engelhardt and Kamb*, 1997]. However, the site of the injection borehole on Whillans Ice Stream was not chosen to access a naturally preferred water-flow path, whereas the MacIS events follow a preferred flow path and thus may experience less difficulty in propagating. The seismograms we have recorded on MacIS show that the arrival of energy is grouped into individual pulses, which we interpret as the episodic expansion of the conduit down-gradient. This unsteady propagation along an interface with some strength would have provided the transient pressure needed to maintain excitation of the seismic waves for the duration of the tremor.

[11] Existing altimetric data are too sparse in space and time to have detected these lake-drainage events. Larger lake-drainage events previously identified based on altimetric data [*Fricker et al.*, 2007; *Gray et al.*, 2005], such as one just 20 km upstream of our observations [*Fricker et al.*, 2007], lack seismic monitoring to constrain channel dimensions and propagation velocities. Repeated altimetric, seismic and velocity data coordinated with ice-flow and water-flow modeling should reveal the volume of lake drainage during a flood as well as the effect of the water release on ice flow speeds. This would allow assessment of the importance of these events to the transport of ice, water and sediment along the ice streams.

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R. B. Alley and S. Anandakrishnan, Center for Remote Sensing of Ice Sheets, Department of Geosciences, 442 Deike Building, Pennsylvania State University, University Park, PA 16802, USA.

J. P. Winberry, Department Geological Sciences, Central Washington University, 400 East University Way, Ellensburg, WA 98926, USA. (winberry@geology.cwu.edu)