Teleseismic surface waves radiated by stick-slip motion of the Whillans Ice Stream

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Summary Whillans Ice Stream, West Antarctica, regularly undergoes tidally modulated stick-slip episodes with a ~25 minute duration and a total seismic moment equivalent to an Mw 6.5 earthquake. Here we report on simultaneous teleseismic and GPS observations of these slip episodes. Seismic arrivals generally are most prominent at periods of 20-100 seconds and consist of three packets. Time correlation with the GPS observations identifies the first packet with the initial rupture nucleation and the final packet with rupture termination at the grounding line. The seismic amplitudes are correlated with the spring-to-neap tidal cycle and with rupture velocity. We suggest that the Whillans slip events can be monitored using permanent seismic stations allowing us to detect changes over a longer time period than is possible with in-situ measurements. More generally, other glaciers and ice streams can be remotely monitored for fast glacial slip using seismic detection techniques.

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Introduction

The Whillans Ice Stream (WIS, formerly Ice Stream B) undergoes stick slip motion of its ice plain, as determined by GPS geodesy (Bindschadler et al., 2003). The stick slip episodes are tidally modulated, and generally occur twice per day. Each slip event moves a region larger than 200 km x 100 km by up to 70 cm over a period of approximately 25 minutes. A simple calculation shows that this dislocation has a seismic moment equivalent to an Mw 6.5 earthquake. The slip events nucleate near the center of the ice plain and the rupture propagates outwards at velocities of approximately 100-200 m/s.

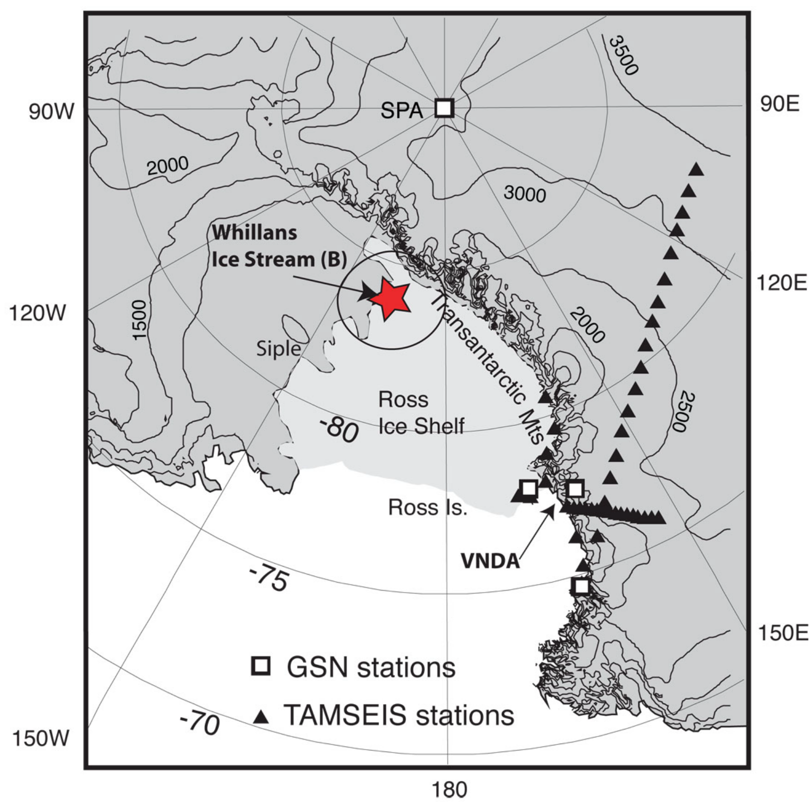

Figure 1. Seismic stations in the vicinity of Whillans Ice Stream. Star shows the location of Whillans Ice Stream events determined from Rayleigh wave arrivals at TAMSEIS stations.

During the 2001-2003 TAMSEIS experiment, a deployment of 43 broadband seismographs from Ross Island to the East Antarctic interior, we detected daily Rayleigh wave arrivals originating from the WIS region that correlated with the expected times of tidally triggered WIS slip events (Figure 1) (Wiens et al., 2006). There are no corresponding GPS data from the ice sheet for 2001-2003 when the TAMSEIS instruments were installed. However, 19 GPS instruments with relatively high sample rates (0.1 sps) were operated on the WIS during 2004 to record the ice stream motion as part of the TIDES project (Joughin et al., 2005). Athough no suitable broadband seismic array was deployed during 2004, the ice stream slip events are well recorded at the borehole seismic station at Vanda (VNDA) in the Dry Valleys at a distance of about 1000 km from WIS. Here we use the joint GPS and seismic observations to study the seismic surface wave excitation of the WIS.

Observations

Nearly all slip events produce seismic Rayleigh waves observed at VNDA, and the stronger events produce Rayleigh and Love wave arrivals at other broadband seismic stations around the Antarctic continent. Typical arrivals at VNDA consist of two or three Rayleigh wave packets during the ~ 25 minute rupture episode (Figure 2) with the best signal to noise at periods of 20-100 s. Correlation of the slip nucleation time at WIS (determined by GPS) with the Rayleigh wave onset times at VNDA (corrected for propagation time between the nucleation site on WIS and VNDA) shows that the first packet originates during the initial slip nucleation; this packet is sometimes of low amplitude and occasionally is missing. The onset time of the last packet is nearly identical with the arrival of the rupture at the WIS grounding line when corrected for propagation; the time between the initiation of rupture and the termination is correlated with the rupture velocity (which is variable from slip to slip). The intermediate packet may correspond with the arrival of the rupture front at the lateral edges of the ice stream. Thus we conclude that the seismic waves are produced by rapid changes in the moment rate of the slip associated with slip onset (at the nucleation site) and termination (at the grounding line of WIS). The first packet represents a "starting phase" and the final packet represents a "stopping phase" of the rupture.

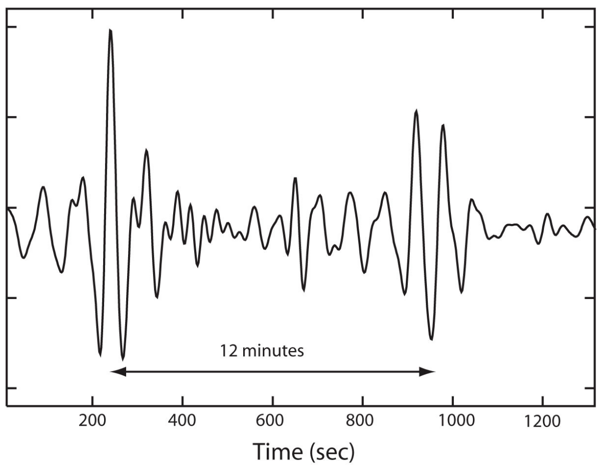

Figure 2. Typical low-pass filtered seismogram of a Whillans slip event recorded in the Dry Valleys region. The seismogram consists of three Rayleigh wave packets.

The character of the seismic signals show consistent variations depending on the part of the tidal cycle and the inter-event time delay. Seismic signal amplitudes are not correlated with the total slip amplitude, but are instead correlated with the average rupture velocity and are largest during spring tide, when the tidal forcing is greatest.

Discussion and summary

We can model the basic characteristics of the first Rayleigh packet as a double-couple rupture initiating on a horizontal interface at very shallow depth (800 m, which is the average thickness of Whillans Ice Stream). The seismograms can also be modeled using a single force formalism, in which a horizontal force is applied at the earth's surface representing the onset of rupture (Eissler and Kanamori, 1987; Kawakatsu, 1989). This is not surprising since the double couple and horizontal single force solutions become identical for very shallow sources (Dahlen, 1993). Seismic amplitudes are weak relative to the total seismic moment of the slip (Mw ~ 6.5) at typical surface wave periods (~ 50 s) due to the extremely slow source process, and are invisible at mode frequencies due to the degenerate nature of a horizontal dislocation at very shallow depth.

The observation of teleseismic surface wave radiation from WIS slip events has a number of important implications. (Ekstrom, et al., 2003) discovered long period seismic sources co-located with outlet glaciers in Greenland using global seismic data and suggested that may represent glacial slip events. (Tsai and Ekstrom, 2007) analyzed these events using a single-force inversion formalism and concluded that the source process of the slip was on the order of 50 s. Our observations show that at least in Antarctica, the seismic packets represent the onset and termination of much longer (~ 25 minutes) slip episodes.

Ekstrom, et al. (2003) found possible glacial seismic sources in Antarctica only at Totten Glacier in Wilkes Land. Our results suggest that regional seismic observations may disclose many additional glacial events in Antarctica, and furthermore suggest that a network of broadband seismographs in Antarctica can efficiently monitor such unusual glacial characteristics.

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