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3 **Ross Ice Shelf Displacement and Elastic Plate Waves Induced by Whillans Ice**  
4 **Stream Slip Events**  
5

6 **Douglas A. Wiens<sup>1</sup>, Richard C. Aster<sup>2</sup>, Andrew A. Nyblade<sup>3</sup>, Peter D. Bromirski<sup>4</sup>, Peter**  
7 **Gerstoff<sup>4</sup>, Ralph A. Stephen<sup>5</sup>**

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9 <sup>1</sup>Department of Earth and Planetary Sciences, Washington University, Saint Louis, MO, USA

10 <sup>2</sup>Department of Geosciences and Warner College of Natural Resources, Colorado State  
11 University, Fort Collins, CO, USA

12 <sup>3</sup>Department of Geosciences, Pennsylvania State University, University Park, PA, USA

13 <sup>4</sup>Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA

14 <sup>5</sup>Woods Hole Oceanographic Institution, Woods Hole, MA, USA  
15

16 Corresponding author: Douglas Wiens (doug@wustl.edu)  
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18 **Key Points:**

- 19 • Extensional Lamb waves propagate across the Ross Ice Shelf, radiated from slip events at  
20 the base of the Whillans Ice Stream
- 21 • During the passage of the Lamb waves, the entire ice shelf is displaced about 60 mm,  
22 with a velocity an order of magnitude above its long-term flow rate.
- 23 • The displacement pulses produce a peak dynamic strain of  $10^{-7}$ , suggesting that they  
24 could trigger icequakes in the ice shelf.  
25

## 26 **Abstract**

27 Ice shelves are assumed to flow steadily from their grounding lines to the ice front. We report  
28 the detection of ice-propagating extensional Lamb (plate) waves accompanied by pulses of  
29 permanent ice shelf displacement observed by co-located GNSS receivers and seismographs on  
30 the Ross Ice Shelf. The extensional waves and associated ice shelf displacement are produced by  
31 tidally triggered basal slip events of the Whillans Ice Stream, which flows into the ice shelf. The  
32 propagation velocity of 2800 m/s is intermediate between shear and compressional ice velocities,  
33 with velocity and particle motions consistent with predictions for extensional Lamb waves.  
34 During the passage of the Lamb waves the entire ice shelf is displaced about 60 mm with a  
35 velocity more than an order of magnitude above its long-term flow rate. Observed displacements  
36 indicate a peak dynamic strain of  $10^{-7}$ , comparable to that of earthquake surface waves that  
37 trigger ice quakes.

38

## 39 **Plain Language Summary**

40 Ice shelves normally flow steadily towards their boundaries with the open ocean at the ice front.  
41 However, seismographs and GNSS receivers deployed on the Ross Ice Shelf record guided  
42 elastic plate waves traveling in the ice as well as permanent displacement of the ice shelf. The  
43 elastic waves and ice shelf displacement originate from basal slip events of the Whillans Ice  
44 Stream, which flows into the Ross Ice Shelf. The velocity of the elastic waves is about 2800  
45 m/s, as expected for guided plate waves propagating in an ice shelf. During the passage of the  
46 elastic waves, the entire ice shelf with an area of 500,000 square kilometers is displaced about 60  
47 mm in a direction away from the Whillans Ice Stream. These observations show that the strain  
48 imparted to the ice shelf by the once or twice daily Whillans Ice Stream basal slip events is  
49 sufficient to trigger ice quakes and perhaps enhance the deformation of the ice shelf.

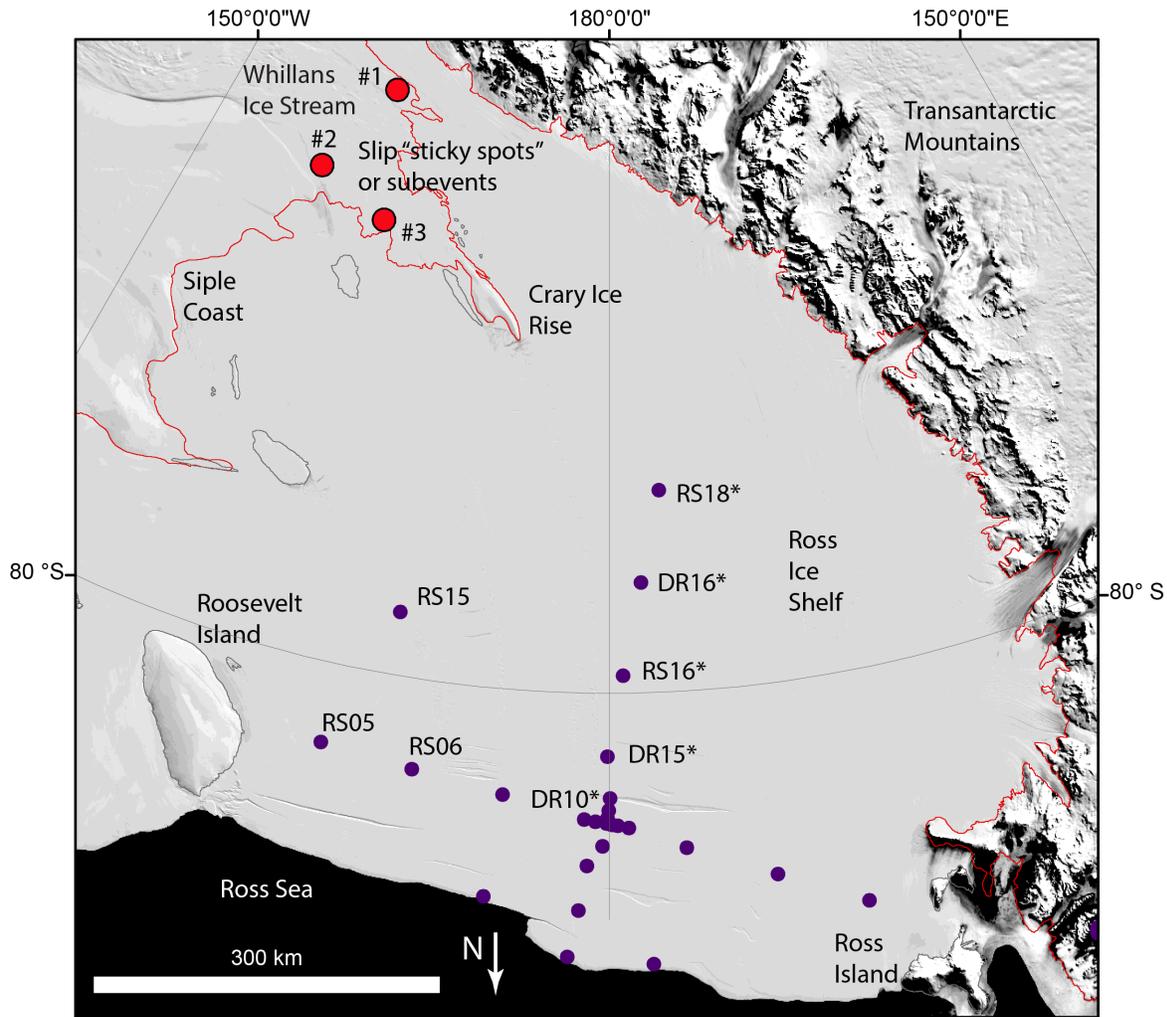
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## 51 **1 Introduction**

52 The interactions between ice streams and ice shelves are highly important for the  
53 dynamics and stability of continental ice sheets and shelves. Ice shelves provide restraining  
54 forces to their associated ice streams and glaciers which act to resist their motion, commonly  
55 referred to as a buttressing effect (Dupont and Alley, 2005; Goldberg et al, 2009). Ice sheet  
56 models show that disintegration of ice shelves increases the velocities of the associated ice  
57 streams and leads to rapid ice sheet thinning and ice mass loss (Joughlin et al, 2012; Martin et al,  
58 2019). Collapse of ice shelves along the Antarctic Peninsula has resulted in increased motion  
59 and thinning of surrounding glaciers (Scambos et al., 2004; Berthier et al., 2012). These  
60 observations have brought increasing attention to the stability of ice shelves and to their  
61 interactions with upstream ice streams and glaciers.

62 Ice streams generally move at a relatively constant velocity over low friction basal  
63 surfaces from the ice sheet interior to their grounding lines, where they often terminate into ice  
64 shelves. Ice shelves similarly move smoothly over the ocean from the grounding lines to the ice  
65 shelf calving front. The motion of both ice streams and ice shelves is modulated by tides, but  
66 this occurs gradually in association with tidal cycles (Anandakrishnan et al, 2003; Brunt et al.,  
67 2010; Klein et al, 2020). The Whillans Ice Stream (WIS) in West Antarctica (Figure 1)

68 represents an exception to this general rule, as it undergoes one or two tidally modulated phases  
 69 of rapid stick-slip motion per day (Bindshadler et al. 2003). During these slip events, the WIS  
 70 moves forward with ice velocities that are about 40 times faster than its average flow rate,  
 71 translating up to 0.4 m over a time interval of about 10 minutes (Pratt et al, 2014; Barcheck et al.,  
 72 2021).



73 **Figure 1.** Geography of the Ross Ice Shelf region with seismic stations shown as blue  
 74 circles. Seismic stations used in this study are labeled, with sites also equipped with GNSS  
 75 receivers denoted by asterisks. The locations of Whillans Ice Stream slip asperities (Pratt et  
 al, 2014) are shown as red circles.

76 As the rupture front of these basal slip events propagates across WIS, it encounters  
 77 multiple regions of higher basal friction and stress, resulting in faster rupture propagation and  
 78 more energetic slip (labeled as #2 and #3 on Figure 1). These “sticky spots” are similar to  
 79 asperities in earthquake rupture mechanics and generate pulses of long period (15–150 s) seismic  
 80 surface waves propagating in the solid earth that are observed at distances of greater than 1000  
 81 km (Wiens et al., 2008). The far-field seismic signature of these slip events is thus characterized

82 by two or three pulses each separated by 10-15 minutes (Pratt et al, 2014). Although the rupture  
83 velocity and thus the relative pulse timing varies from event to event, and the rupture onset is not  
84 always teleseismically observable, the surface wave pulses radiate from the same regions during  
85 all events. The WIS slip events seem to be unique, likely representing a particular phase of ice  
86 stream slowdown for ice streams in the Siple Coast (Winberry et al, 2014). Although stick-slip  
87 behavior has been documented at a small scale on many glaciers (e.g., Graff and Walter, 2021),  
88 there are no other observations of such large-scale stick slip behavior involving entire glaciers or  
89 ice streams.

90       Until now, the effect of transient ice stream or glacier acceleration on downstream ice  
91 shelves has not been documented. In this paper, we use seismic and GNSS data from sensors  
92 deployed on the ice shelf to observe the effects of WIS slip events on the Ross Ice Shelf (RIS).  
93 We find that the WIS slip events produce elastic Lamb waves that propagate as guided waves  
94 within the RIS and are seismically observed on the shelf at distances up to 700 km. A  
95 permanent displacement pulse observed by GNSS receivers also propagates across the RIS in  
96 association with the Lamb waves, translating the entire ice shelf away from WIS. These results  
97 demonstrate that upstream disturbances in ice streams propagate across entire ice shelves, and  
98 could, in the case of large disturbances, produce strain rates that may affect ice shelf fracture and  
99 destabilization.

100

## 101 **2 Seismic and GNSS data**

102       The response of the RIS to WIS slip events was recorded by a network of broadband  
103 seismographs (Baker et al, 2019) and co-located GNSS receivers (Klein et al, 2020) (Figure 1)  
104 deployed on the ice shelf between 2014 and 2016. Twenty-seven broadband seismic stations  
105 were installed on the Ross Ice Shelf in late 2014 and operated continuously until late 2016 during  
106 the coordinated RIS (Mantle Structure and Dynamics of the Ross Sea from a Passive Seismic  
107 Deployment on the Ross Ice Shelf) and DRIS (Dynamic Response of the Ross Ice Shelf to  
108 Wave-Induced Vibrations) projects (Figure 1) (Baker et al., 2019; doi:10.7914/SN/XH\_2014).  
109 Each station consisted of a Nanometrics 120PH posthole sensor buried to a depth of  
110 approximately 2 m below the snow surface, with data recorded at either 100 or 200 Hz by  
111 Quanterra Q330 dataloggers. The instruments were powered by solar panels during the summer  
112 and lithium batteries during the winter, so they recorded year-round. Instrument responses  
113 supplied by the Earthscope data center were deconvolved to provide three-component  
114 displacement or velocity records.

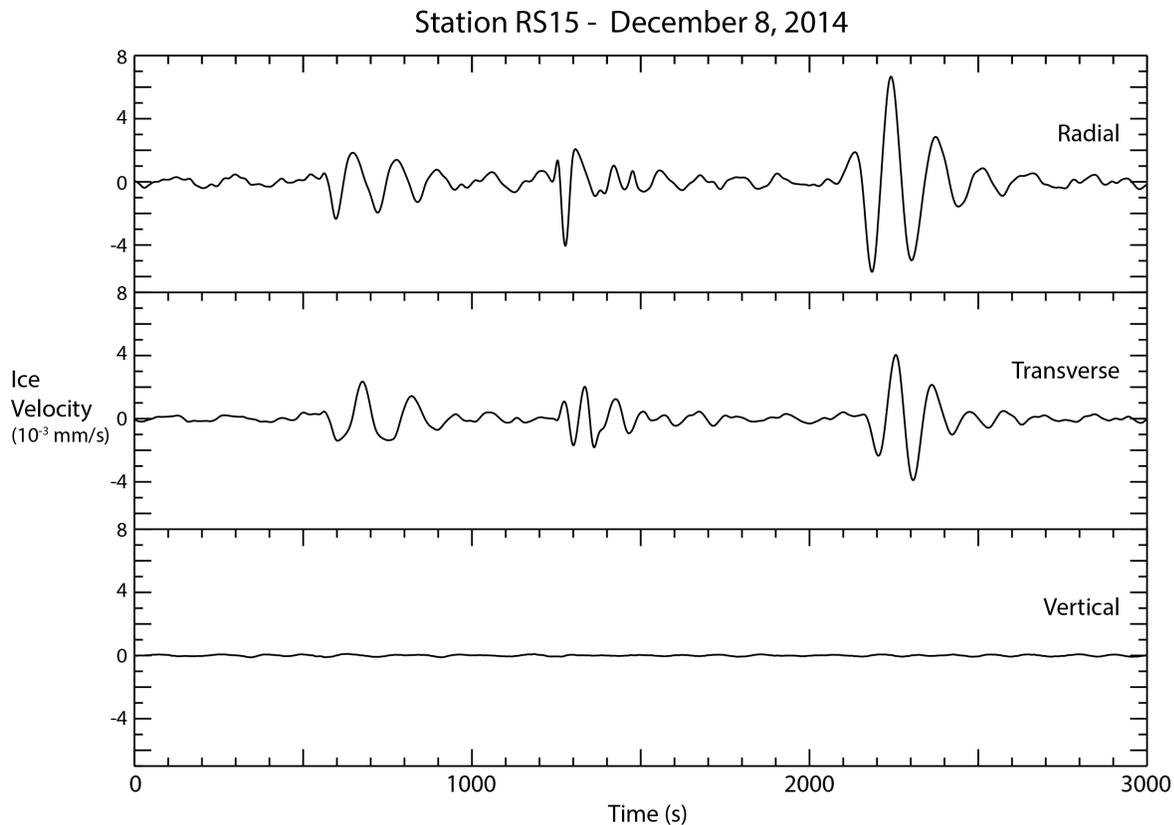
115       Thirteen of the RIS-DRIS stations had co-located GNSS receivers installed in November  
116 2015, which remained in place for 1 year (Klein et al., 2020; doi:10.7283/58E3-GA46). Most of  
117 the receivers were powered by solar panels, so they did not record during the winter months.  
118 The GNSS receivers recorded at 1 Hz and were processed by Klein et al (2020) using a precise  
119 point positioning (PPP) approach (Zumberge et al., 1997) to obtain daily time series for each  
120 station. The 1 Hz time series for each station was down-sampled to 0.0333 Hz to create a time  
121 series spanning the entire observation period.

122

123 **3 Extensional Lamb Waves**

124 The RIS seismographs record clear long-period signals on the horizontal components  
 125 shortly after WIS slip events. We determine the times of WIS slip events independent of any  
 126 signals recorded on the ice shelf by analyzing seismic signals propagating through the solid Earth  
 127 to permanently installed Global Seismographic Network seismic stations in the Dry Valleys  
 128 (VNDA) and at South Pole (QSPA), with known travel times to the WIS source region (Wiens et  
 129 al, 2008; Pratt et al, 2014). The signals recorded by the seismographs on the RIS consist of a  
 130 series of two or three arrivals, separated by 10–15 minutes (Figure 2), with timing that is  
 131 consistent with arrivals observed at the permanent off-shelf seismic stations. The signals at the  
 132 RIS seismic stations, at distances of 350 – 700 km, arrive only a few seconds prior to the signals  
 133 at the permanent seismic station VNDA (distance about 990 km). Previous work identified the  
 134 arrivals at VNDA as primarily fundamental mode Rayleigh waves (Wiens et al, 2008; Pratt et al,  
 135 2014), with elliptical particle motion and the largest amplitude on the vertical component.  
 136 However, the arrivals on the ice shelf are observed only on the horizontal components, and so  
 137 must represent a different seismic phase with a velocity that is slower than the 3000-4000 m/s  
 138 Rayleigh wave group velocity at 20–125 s period in this region (e.g., Shen et al., 2018).

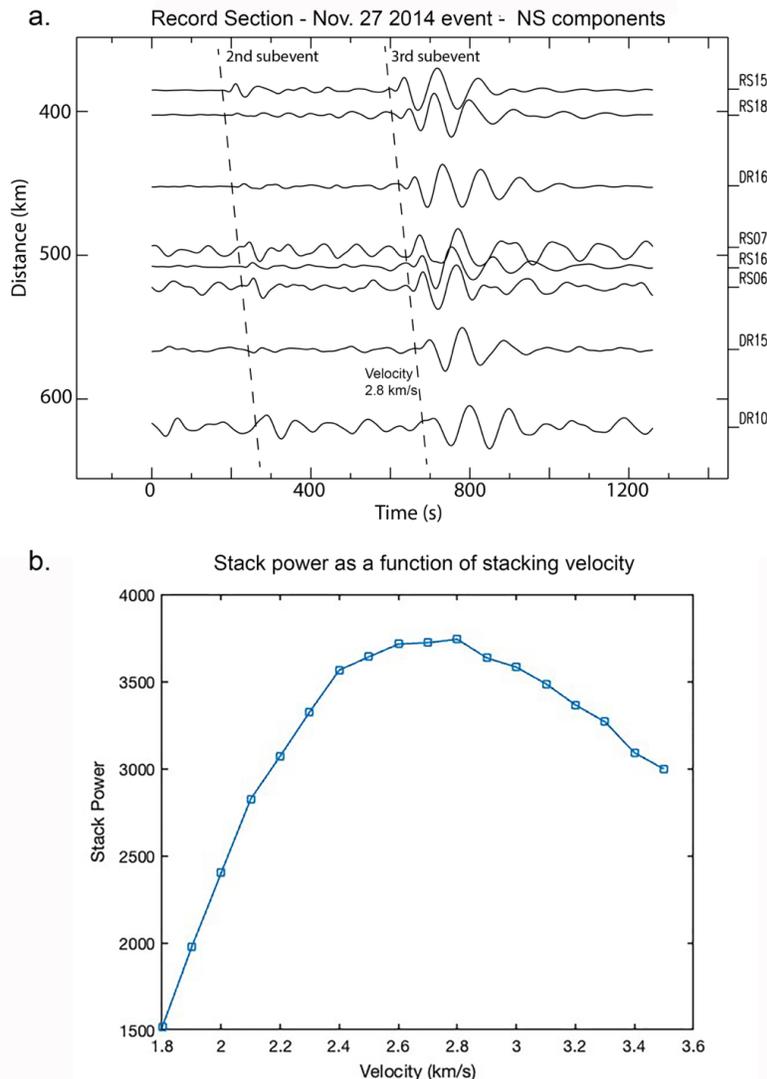
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140

141 **Figure 2.** Broadband three-component seismic record showing extensional Lamb waves  
 142 produced by the Whillans Ice Stream slip event on December 8, 2014 recorded at station RS15  
 (Figure 1), a distance of about 390 km. The instrument response has been deconvolved and  
 filtered to produce velocity from 20 – 125 s.

143 The seismic signals show particle motions that are approximately along the great circle  
 144 path connecting the station and the WIS source region, with first motions oriented radially away  
 145 from WIS. Following the initial arrival, the motion of the pulses become more complex (Figure  
 146 S1). The maximum signal-to-noise ratio is observed at periods between about 20 and 100 s.  
 147 This is because the WIS slip events produce little short period energy and the horizontal  
 148 components of seismic stations on the ice become dominated by large-amplitude ocean-  
 149 propagating infragravity waves at periods longer than several hundred seconds (Bromirski et al,  
 150 2015). To estimate the phase velocity of the arrivals, we computed the power of the stacked  
 151 seismograms assuming different horizontal phase velocities and a source near the WIS (Figure  
 152 3). The estimated velocity of about 2800 m/s is much slower than the P-velocity in ice (~ 3600  
 153 m/s) but much faster than the shear velocity in ice (~ 1900 m/s) or the P-velocity in water (~  
 154 1500 m/s). We also estimated the group velocity, using approximate source times of the pulses  
 155 from the Rayleigh wave arrivals at VNDA and the observed arrival times at stations on the RIS.  
 156 The estimated group velocities are similar to the phase velocities, indicating there is no  
 157 significant dispersion.



**Figure 3.** a) Record section from the November 27, 2014 (19:03) Whillans slip event showing the N-S component from seismographs deployed across the Ross Ice Shelf. Seismograms were filtered with a 20 – 67 s band-pass filter. The first subevent is not visible for this event. b) Slant stack of the NS components for the November 27, 2014 event, showing the stack power as a function of stacking velocity. A velocity of 2800 m/s fits the data best and is also indicated by a dashed line in the upper figure.

159 We identify these arrivals as elastic plate waves, sometimes referred to as Lamb waves,  
 160 propagating as guided waves in the ice shelf (Lamb, 1917). An elastic plate suspended in a  
 161 vacuum gives a solution for longitudinal (extensional) waves with velocity:

$$162 \quad V = 2 V_S (1 - V_S^2/V_P^2)^{1/2} \quad (1)$$

163 where  $V_S$  and  $V_P$  are the S and P wave velocities in the elastic plate. Press and Ewing (1951)  
 164 derived a solution for an elastic plate overlying a liquid layer, arriving at the identical formula  
 165 with a small imaginary term resulting in some attenuation. The equations have been rederived  
 166 by many authors since that time, usually in the wavenumber domain, showing that long-period  
 167 longitudinal waves in this system are a non-dispersive fundamental symmetric mode, often  
 168 designated as  $S_0$  (e.g., Graff, 1991; Chen et al., 2018). The predicted ratio of horizontal to  
 169 vertical particle motion is approximately the ratio of plate thickness to the wavelength. For  
 170 waves with 40 s period and the 350 m thick RIS, this ratio is greater than 300, so this solution  
 171 predicts longitudinal waves with particle motion that are almost perfectly horizontal and are  
 172 radial to the source, consistent with our observations. Using a  $V_P/V_S$  ratio of 1.87 corresponding  
 173 to the ice Poisson's ratio of 0.3 (Squire, 2007), and  $V_S$  of 1695 m/s derived by taking the time-  
 174 weighted average  $V_{sv}$  from the RIS seismic velocity profile of Diez et al, (2016), equation (1)  
 175 predicts a velocity of 2865 m/s for the longitudinal wave speed, which is similar to the 2800 m/s  
 176 that best fits the propagation across the RIS.

177 Longitudinal Lamb waves excited by other processes have been previously observed  
 178 propagating across ice shelves via array analysis in the time, frequency, or wavenumber domain.  
 179 Chen et al. (2018) and Aster et al. (2021) noted that longitudinal Lamb waves were persistently  
 180 excited by swell impinging along the RIS front and used array analysis to estimate the phase  
 181 velocity as 2940 m/s at 0.02 to 0.1 Hz, similar to the velocity observed in this study. Baker  
 182 (2020) also noted that long-period Lamb waves observed in the RIS interior were excited at the  
 183 grounded margins of the RIS by teleseismic shear waves.

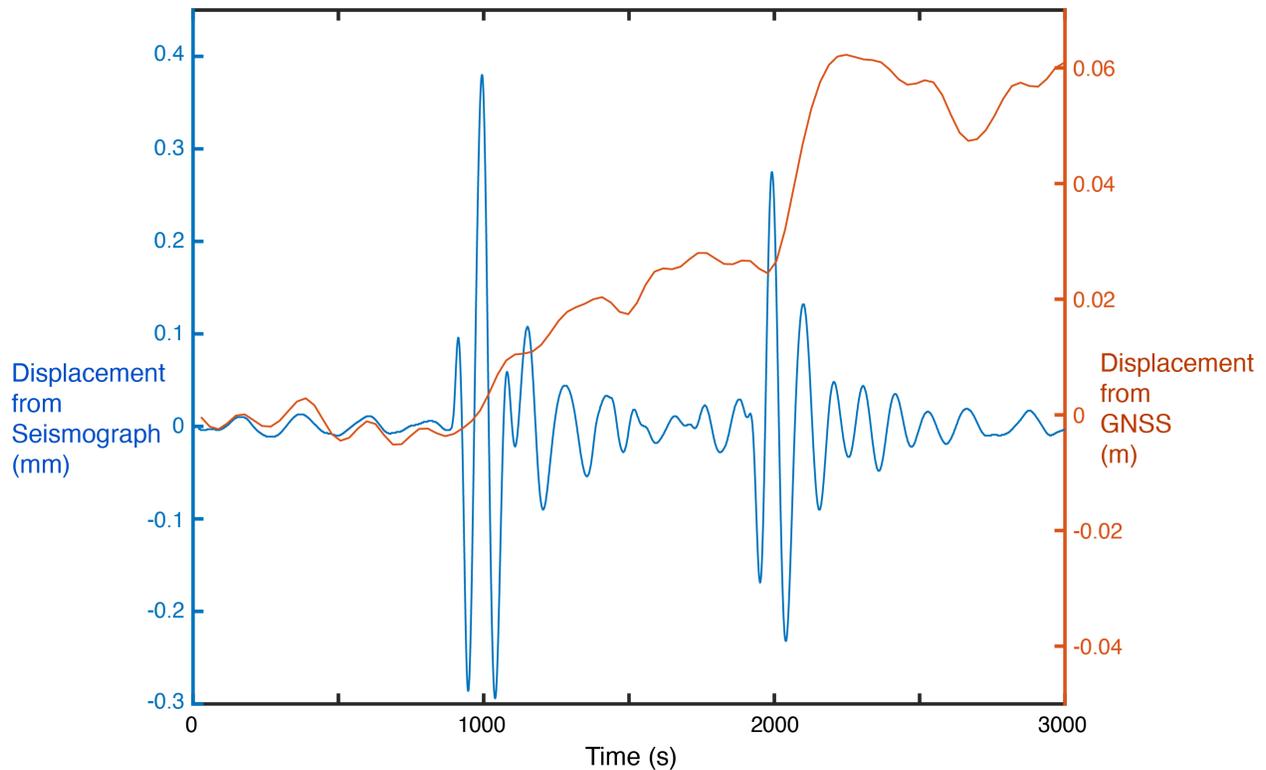
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#### 185 **4 Permanent Ice Shelf Displacement**

186 GNSS receivers located at the seismograph sites during 2015 – 2016 record the  
 187 permanent surface displacement and strain across the RIS. The GNSS signals contain low  
 188 amplitude high frequency noise that precludes determination of the precise onset time of the  
 189 displacement associated with the Whillans slip events, but it initiates simultaneously with or  
 190 shortly after the arrival of the first large amplitude elastic plate wave and continues for 15 to 20  
 191 minutes (e.g., as shown at station RS18 in Figure 4). The total displacement is generally 50 – 60  
 192 mm and the average ice shelf velocity during the displacement episode is about 0.05 mm/s (5  
 193 m/day), compared to the approximate 2 m/day average velocity (Brunt and MacAyeal, 2014) at  
 194 this station. However, the velocities are greater immediately following one of the extensional  
 195 wave arrivals, reaching as high as 0.3 mm/s (26 m/day), or more than ten times the usual ice  
 196 shelf velocity.

197 The displacement is approximately in the direction away from the WIS but varies  
 198 somewhat for the different slip subevents (Figure 5). For example, at station RS18, the first

199 subevent occurring at the southernmost sticky spot produces more northward motion on the  
 200 GNSS displacement record compared to the more southerly third subevent, which produces  
 201 larger westward motions (Fig 5). This is consistent with the first motions from the seismograph  
 202 records, which show the same trend (Figure S1). The ice shelf displacement returns to the  
 203 average flow direction within a few minutes of the final extensional wave arrival. Overall, the  
 204 GNSS records indicate that the WIS slip events displace the entire RIS, with area of about  
 205 500,000 square kilometers and mass of approximately 200,000 Gigatons, by about 60 mm over a  
 206 period of minutes on an almost daily basis.

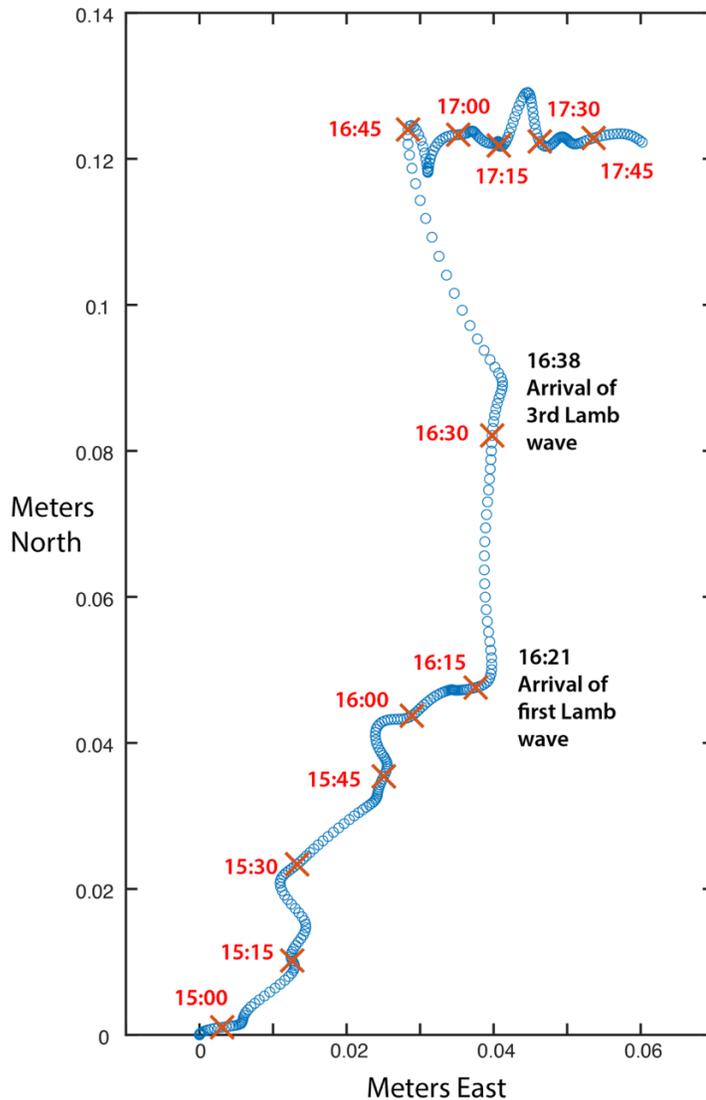


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208 **Figure 4.** Comparison of displacement records of the co-located broadband seismograph  
 209 and GNSS receiver at station RS18 for the Whillans slip event of December 7, 2015  
 210 (16:19). Both records have been rotated into the back-azimuth of the WIS to give radial  
 211 displacement records. Seismic data are filtered with a causal bandpass filter between 0.05  
 212 and 0.008 Hz to remove noise. GNSS data have been detrended to remove the long-term  
 ice flow and filtered with a causal low pass filter at 0.005 Hz. Signals from the first and  
 third subevents are visible on both records; the second subevent is absent at this station  
 due to obstruction by the northernmost extent of WIS and Crary Ice Rise.

213 Ideally, it would be useful to sample the displacement field continuously across the  
 214 seismic spectrum to determine more precisely the relationship between the higher frequency  
 215 elastic wave arrivals and the permanent displacement pulse. However, the seismic sensors  
 216 (Trillium 120 posthole) have reduced sensitivity beyond the 120 s corner period and horizontal  
 217 component signals become dominated by ocean infragravity waves at periods greater than about  
 218 150 s. The displacements recorded by RIS GNSS receivers also have high noise at these periods

219 consistent with the infragravity wave background displacement field, which has rms amplitudes  
 220 of several cm (Bromirski et al, 2015; 2017). Thus, we interpret the seismic and GNSS signals  
 221 separately in high signal-to-noise and relatively band-limited windows of about 20–125 s for the  
 222 seismic data showing the elastic wave propagation, and at very long periods near zero frequency  
 223 for the GNSS data constraining the permanent ice shelf displacement.



224

225 **Figure 5.** Map view of the displacement trajectory of station RS18 (Figure 1) during  
 226 December 7, 2015, determined by GNSS, showing the changes in speed and direction  
 227 caused by Whillans slip events. The displacements have been smoothed using a 900 s  
 228 causal low-pass filter. Open circles denote positions every 30 s. 15-minute time stamps  
 are shown as red x's. The average annual flow velocity determined by Klein et al (2020)  
 has been subtracted from the motion, but some background motion remains due to seasonal  
 and tidal fluctuations.

## 229 5 Discussion and Conclusions

230 These results demonstrate that large-scale stick-slip motion of an ice stream can transmit  
 231 elastic waves and strain pulses across its downstream ice shelf, modifying and briefly dominating  
 232 the motion of an entire ice shelf with lateral dimensions of nearly 1000 km. Ice streams and their  
 233 associated ice shelves thus constitute a single elasto-dynamical system, with persistent ice stream  
 234 events possibly influencing ice shelf stability and deformation. The large number of recorded ice  
 235 stream signals in this data set also show that ice shelf stick-slip events can be easily monitored  
 236 and assessed using instrumentation placed on the ice shelf hundreds of kilometers away.

237 A particularly interesting implication is that dynamic strain from the extensional waves or  
 238 the permanent strain pulse could trigger icequakes, thus facilitating deformation and fracture of  
 239 the ice shelf. We estimate the peak dynamic strain experienced by the ice shelves during passage  
 240 of the extensional waves and the displacement pulse using the relationship:

$$241 \quad |\epsilon_{rr}| \sim (1/V) \partial U_r / \partial t \quad (2)$$

242 Where  $V$  is the phase velocity of the propagating wave and  $U_r$  is the radial particle displacement  
 243 (Gomberg and Agnew, 1996). The stress is given by:

$$244 \quad \sigma_{rr} = E \epsilon_{rr} / (1-\nu) \quad (3)$$

245 Where  $E$  is Young's modulus and  $\nu$  is Poisson's ratio (approximately 10 GPa and 0.3,  
 246 respectively, for ice). The largest WIS-associated ice velocities recorded at the GNSS receivers  
 247 are about 0.3 mm/s, with the largest particle velocities inferred from the band-limited  
 248 seismographs being somewhat smaller. Using the phase velocity of 2800 m/s from the previous  
 249 section gives a peak dynamic strain of about  $10^{-7}$  and a radial normal stress of 1.4 KPa.

250 These dynamic strains and stresses are similar to those observed to trigger seismicity  
 251 during the passage of seismic surface waves from giant earthquakes worldwide. Peak dynamic  
 252 strains on the order of  $10^{-7}$  triggered earthquakes in Alaska following the 2012 Sumatra  
 253 earthquake (Tape et al, 2013), and Fan et al. (2021) observe some triggering in California for  
 254 many teleseisms with peak dynamic strains as low as  $10^{-9}$ . Icequakes are also triggered by  
 255 teleseismic surface waves in the Antarctic ice sheet and on mountain glaciers with peak dynamic  
 256 strains as small as  $10^{-8}$  (Peng et al, 2014; Li et al, 2021).

257 These observations suggest that extensional waves and strain pulses from WIS stick-slip  
 258 events could mobilize fractures in the ice shelf interior and contribute to its destabilization.  
 259 However, up to now there are no documented cases of icequakes in the ice shelf that are clearly  
 260 triggered by WIS slip events. Olinger et al (2019) located more than 2,500 icequakes along rift  
 261 WR4 near the intersection of the two lines of RIS seismic stations (Figure 1) but did not detect  
 262 any greater seismicity during the passage of waves from Whillans slip events. This may be due  
 263 to the fact that rift WR4 is deforming in tension, with icequakes likely confined to the upper few  
 264 meters of snow and ductile deformation at deeper levels (Huang et al, 2022), whereas the strain

265 pulses from the WIS slip events exert dominantly compressional stress across the entire  
266 thickness of the shelf.

267         The WIS is the only location worldwide where such large-scale stick-slip events have  
268 been documented and it is unclear how typical the current activity is over longer time intervals.  
269 The WIS flow rate has been decreasing, likely due to increased friction due to decreased  
270 subglacial meltwater (Stearns et al, 2005). This velocity decrease has resulted in fewer slip  
271 events, with some of the normal twice-daily slip events being skipped and larger slip then  
272 occurring during the next slip event (Winberry et al, 2014). If the dynamics of the slowing ice  
273 stream reach a point where larger slip events occur, it is possible that the extensional waves and  
274 strain pulse from larger slip events could have a greater effect on the deformation and stability of  
275 the RIS.

276

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288

## 289 **Open Research**

290 Seismic data used in this study are available through the Earthscope Data Management Center  
291 under Ross Ice Shelf (RIS) and DRIS network code XH:  
292 [https://www.fdsn.org/networks/detail/XH\\_2014/](https://www.fdsn.org/networks/detail/XH_2014/). Raw GNSS data are archived by the  
293 EarthScope Data Management Center: <https://doi.org/10.7283/58E3-GA46>. Final GNSS  
294 processed data are archived by the Scripps Orbit and Permanent Array Center:  
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