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Supporting Information for

Seismic Moulin Tremor

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Introduction

This supporting information consists of two figures with a figure caption and one sections of text that is supported with a figure. The first supporting information contains the time series of spectrograms for the entire duration of the seismic field campaign including the spectrogram and waveforms recorded at two different seismic stations (FX01 and FX06) in comparison with the concurrent moulin water.

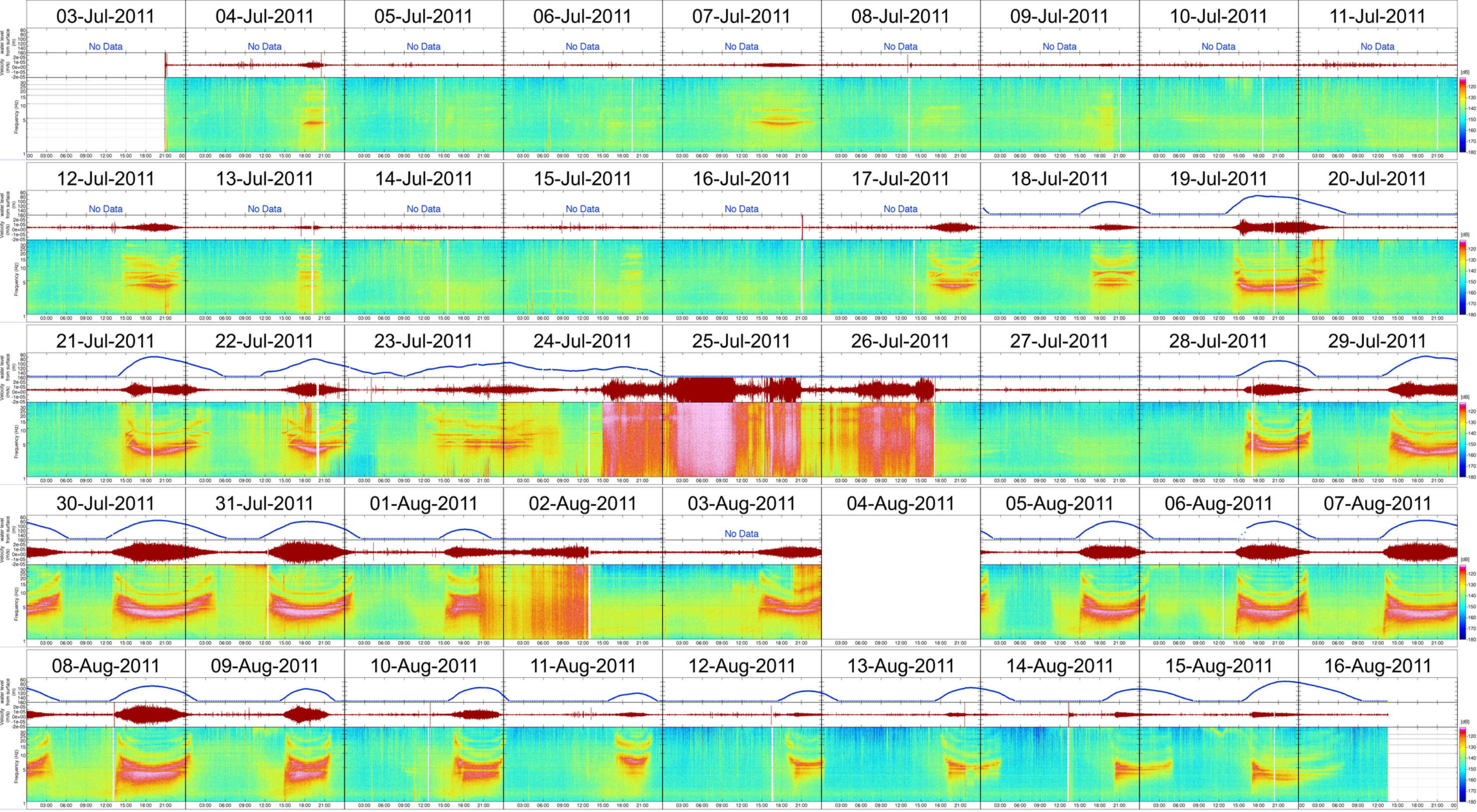
The second supporting information contains the detailed procedure of the manual picking of the beginning and end of each tremor episode and its comparison with the moulin water level.

Caption S1.

The two images show spectrograms for the entire measurement period observed at seismic station FX01 (closest to the moulin) and FX06 (second closest).

- Upper panels (blue line): moulin water level measured from ice surface, dashed lines show that water level dropped below the sensor (data gap).
- Middle panels (red line): seismic waveform Butterworth bandpass filtered (2-pole) between 2 and 5 Hz.
- Lower panels: spectrogram in logarithmic scale for the frequency content between 1 and 35 Hz. The moulin tremor is characterized by red and pink "smileys". Vertical red or pink lines denote times of high noise mostly caused by a tilted seismic sensor. Vertical blue or white lines denote data gaps during station maintenance.

Tremor started normally in the early afternoon and lasted between 4 and 16 hours in duration. The tremor was active on most of the days and when the water level rose above a certain height with an average duration of 6 hours.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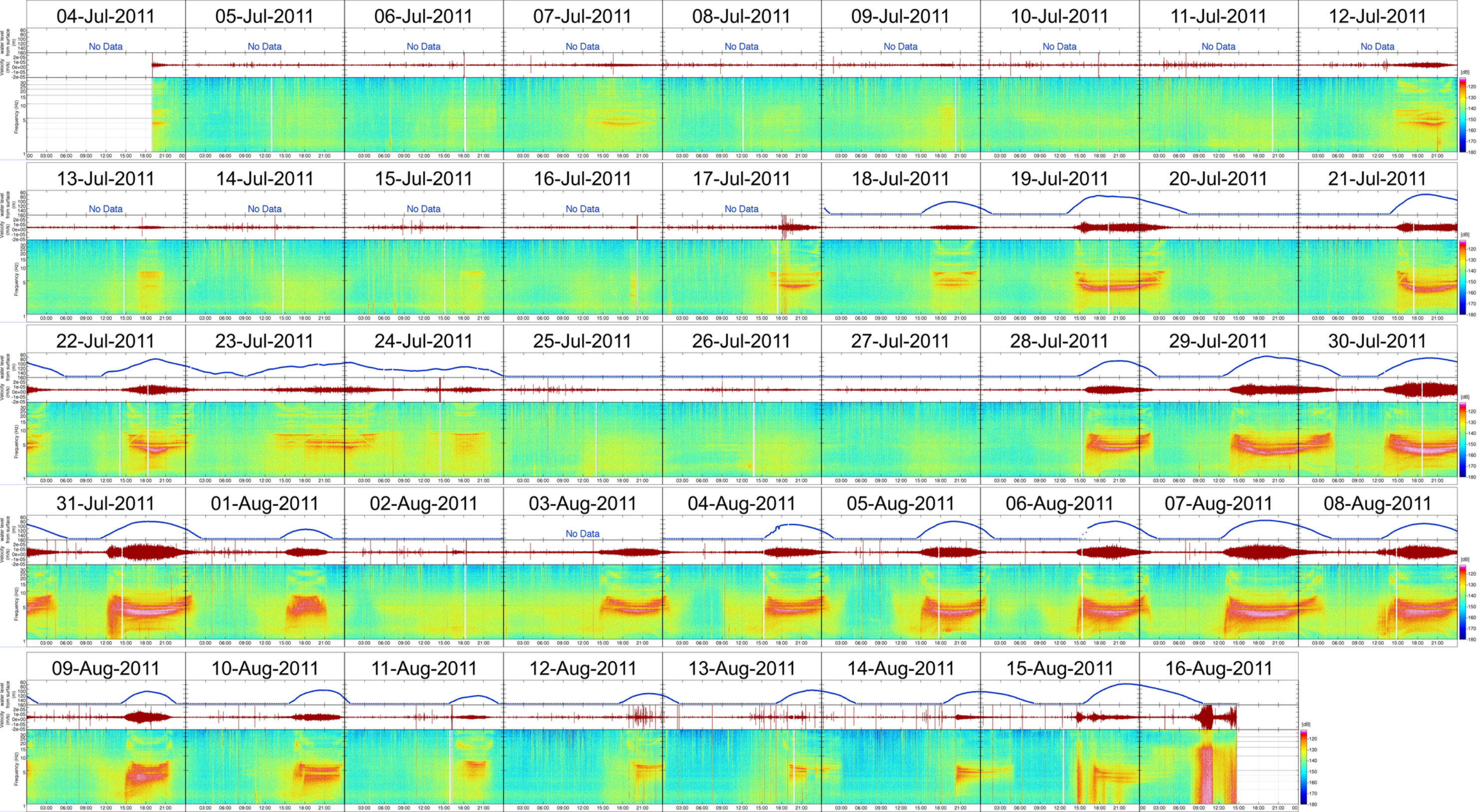
No Data
Velocity
water level from surface (m)
Frequency (Hz)
[dB]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13-Aug-2011
14-Aug-2011
15-Aug-2011
16-Aug-2011
No Data
Velocity
water level from surface (m)
Frequency (Hz)
[dB]

Text S2.

The emergent characteristic of the tremor beginning results in high uncertainties for waveform picking. Therefore, we use the highest degree of waveform coherency in order to define the beginning and end of the tremor. A sudden change in coherency, indicated with the cross-correlation factor for station pairs, was used. We calculated the cross-correlation factor for a station pair for the entire period of measurements with sliding time windows of 1min and an overlap of 50%. Cross-correlation factors for three different station pairs for one day are shown in Figure S2A. The beginning of the tremor is visible with a sudden jump in cross-correlation factor with about 0.4 with high fluctuations to 0.8-0.9 with less fluctuation for all three station pairs. The sudden short drops of the cross-correlation factor during the tremor episode are caused by several high amplitude icequakes related to surface crevasses located northwest from the network.

We manually picked the onset of the tremor at the beginning of increase of the correlation factor and assigned uncertainties to the picks (Figure S2A1). The end of a tremor is again characterized with a drop in cross-correlation coefficient; however, due to a lower signal-to-noise ratio (SNR), mostly less distinct than the beginning, hence error bars are larger (Figure S2A2). The picks and uncertainty levels were then compared to the concurrent moulin water level. Note that the moulin water level measurements were recorded with a sampling rate of 5min and a resolution of 1m with no measurements when the water level dropped more than 163m below the ice surface.

The comparison between the picked onset and concurrent moulin water level (Figure S2B) shows a temporal evolution that can be divided into three parts: from beginning until 23 July, between 28 July and 10 August and between 11 August and 16 August 2011. The three time windows could be correlated with changes in tremor characteristic that we see on the spectrograms (see the time series of spectrograms in the electronic supplement S1). Note that the tremors in the first and last part of the observation period have lower amplitudes and a lower SNR that might affect the detection capability hence a later picking of the beginning resulting in an overestimation of moulin water level (closer to the surface).

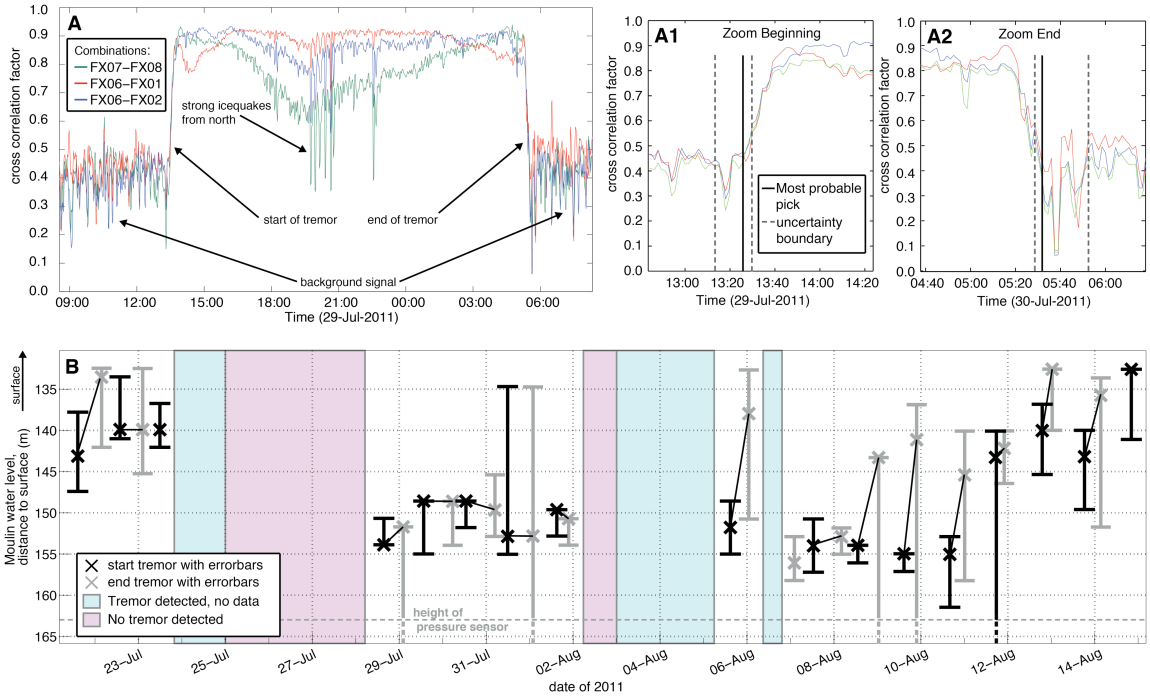

Figure S2. Evaluation of the moulin water level at the beginning and end of each tremor episode. A: Example of a tremor episode with the cross-correlation coefficient calculated for three station pairs, with a sudden increase in correlation factor when tremor begins. B: Zoom into the beginning and end of the tremor episode shown in panel A. The manual picks of the most probable beginning of the tremor and uncertainty boundaries are drawn with vertical lines. C: Time series of the comparison between beginning (black) and end (grey) of the moulin tremor with the water level inside the moulin. The error bars denote water height considering the picked uncertainty levels. An open ended error bar correspond to a tremor episode with high uncertainties and to a pick of the latest pick when the water level were dropped below the pressure sensor (no data). Purple and blue colors mark time windows without moulin tremor occurrence and sensor outage, respectively.