Supplementary Materials

S1. Determining Thresholds for Locatable Glacial Hydraulic Tremor

We closely followed the same methods for the classification of GHT as Vore et al. (2019) and will note instances where we chose to make slight alterations to best suit our study site and dataset.

S1.1 Power Threshold

In order to identify GHT frequency bands throughout the melt season, we determined a power threshold to identify bands that stand out against the median background. This threshold is designed to pick out signals that are likely to be GHT based on their emergence in the spring when melting increases greatly. The continuity, power, and frequencies of the GHT bands depend on conduit geometry and location as well as water flow.

Considering power first, the median power spectral density (the power present within a frequency band) of each station is calculated and manually inspected to identify peaks in power, as described below. First, the median power spectral density of the vertical component per each station is calculated for 20 s windows and averaged over 30 minutes to smooth impulsive, high-power events such as earthquakes, icequakes, electronic noise etc. to allow us to focus on persistent GHT instead. For each daily-averaged median power spectrogram, the power-differences *L*1 and *L*2 between each global power maximum *γ* and neighboring local minima *m*1 and *m*2 are calculated for every frequency *f* (Supplementary Fig. S1). For each month, the 50th percentile of all the *Ln* values is used as a threshold for a power peak, and then the 20th percentile is used as a lower cutoff. Any local minima *m* and maxima *γ* pairs in each daily-average median spectrum that do not differ by the monthly 20th percentile *L20* are ignored in the threshold calculation. For all remaining local minima *m* and maxima *γ* pairs, the average power difference *γavg* of each maximum and its two local minima *m*1 and *m*2 is calculated. If *γavg* added to each local *m*1 and *m*2 both surpass the value of *γavg* plus the monthly 50th percentile of *L50* (as in (S1) and (S2)), it is flagged as a peak in power that may be GHT.

$γ\_{avg}+m\_{1}>γ\_{avg}+L\_{50}$ (S1)

$γ\_{avg}+m\_{2}>γ\_{avg}+L\_{50}$ (S2)

This approach is slightly changed from Vore et al. (2018), who used the 20th and 50th percentile of *Ln*for a time of expected peak GHT activity (mid-July) and applied that to the entire time frame of their data (melt season only). Upon inspecting changes in the 20th and 50th percentile values across the entire year, we discovered that winter values passing the threshold were actually *larger*, despite that winter power spectral density at the same frequencies was generally much lower than in the summer. This could be due to lower median seismic power in the winter allowing small peaks in power to appear more prominent (larger *L* values) above the median power, compared to the summer when high median power allows only substantially larger sources of power to ‘peak’ and exhibit smaller *L* values (Supplementary Fig. S1 B winter and C summer). Therefore, using the approach to power thresholds as in Vore et al. (2019) resulted in winter months being over-inclusive, and we elected to recalculate the power thresholds per each month.

Figure S1 Here.

S1.2 Polarization and Wave Type Thresholds

 GHT may produce multiple polarized and unpolarized wave types, but polarized Rayleigh waves are required to calculate back azimuth angles. The identification and back azimuth angle calculation were developed by Vore et al. (2019), and as used here, are applied to identify polarized Rayleigh waves within the GHT signals on Rhonegletscher. The following is a paraphrase of the methods laid out in Vore et al. (2019) section 3.1.1. We refer readers to the Vore et al. (2019) paper for additional details.

FDPA is used to determine the degree of polarization of each frequency. First, all channels for a seismic station in the time range of interest are windowed into 1-hour segments *x(t)*, and the linear trend is removed. We correct for the instrument response, and then examine overlapping 1-minute windows (50% overlap) with a prolate taper applied to each window for each channel. A fast Fourier Transform (FFT) is calculated per each 1-minute window to transform the seismic dataset *x(t)* into the frequency domain *Xk(f)*, and then a 3x3 spectral covariance matrix *Mk(f)* is calculated by multiplying each row of *Xk(f)* by its conjugate transpose. Finally, the spectral covariance matrices for the 1-minute, 50% overlapping data are binned into 7-minute groups (13 total groups for the original 1-hour segment) labeled *Maj* and an averaged spectral matrix labeled *M*a is calculated by linearly averaging the real and imaginary components of all groups. This average spectral covariance matrix prevents transient events or noise from dominating. A singular value decomposition is then performed to transform *Ma* into components *U*, *D* and *VH* where

$M\_{a}=UDV^{H} U=\left[U\_{1},U\_{2},U\_{3}\right] V^{H}=\left[V\_{1},V\_{2},V\_{3}\right] D=\left[\begin{matrix}d\_{1}&0&0\\0&d\_{2}&0\\0&0&d\_{3}\end{matrix}\right] $ (S3)

The singular values *D* represent the average seismic energy at a given frequency in the plane of motion defined by their eigenvectors. *U* and *VH* are the left and right eigenvectors, respectively. If any singular value is considerably larger than the other two, one plane of motion dominates over the other two (i.e., the wave is polarized). The singular value matrix is sorted so *d*1 is the largest, and magnitude decreases moving down the diagonal; thus, the ratio of *d*1 to *d*2 yields insight on the extent to which the first plane of motion dominates over all other planes (i.e., if the wave field is polarized). By manually inspecting the ratio for each station, we determined a ratio that is not too inclusive or exclusive of peaks (Supplementary Fig. S2). In this study, we selected a threshold of 3.0.

 To determine the wave type for each frequency of a polarized wave (i.e., Rayleigh vs. body waves), information about amplitude and phase is extracted from the singular value decomposition. A polarization vector *Po* is defined as the transpose of the first component of *VH*:

$P\_{o}=V\_{1}^{T}=\left[A\_{Z}e^{-iφ\_{Z}},A\_{N}e^{-iφ\_{N}},A\_{E}e^{-iφ\_{E}}\right]$ (S4)

The phase information is contained in the φ terms, and a horizontal term is determined from the combined north and east channels (for more information, see section 3 of Vore et al., 2019). The vertical phase is subtracted from the horizontal phase, resulting in the delay time between horizontal and vertical motion. For body waves and Love waves, particle motion is rectilinear so the lag should be close to 0°, whereas for Rayleigh waves with elliptical particle motion the absolute value of lag should be around 90°.

To determine what constitutes a GHT ‘peak’ in a wave type, the observed distribution of wave types is compared to a random daily distribution, which regards all possible lags (0° to 90°) as equally probable (as in Vore et al., 2019). We consider lags from 0° to 20° as body and Love waves, which have primarily rectilinear motion, and lags from 70° to 90° as Rayleigh waves, which have primarily elliptical motion. Any lags between 20° and 70° are taken as ‘mixed’ waves. Therefore, the randomly distributed daily probability of body/Love or Rayleigh waves occurring is 22% each with a 56% chance of mixed wave types. For the measured distribution of wave types in a day to have a ‘peak’ of a particular wave type, we require the measured distribution to surpass the random distribution of 22% for body and Rayleigh waves by 85% (hence (1.85\*0.22)\*100 =41%). For mixed waves, the observed distribution must surpass the random distribution of 56% by 70% (hence (1.70\*0.56)\*100=96%). In our study, the requirement of 85% and 70% were chosen after inspecting daily wave type distributions at all stations across the year to ensure the thresholds were not over- or underinclusive.

Figure S2 Here.

S2. Detailed descriptions of the frequency bands identified per each station

S2.1 Identified Frequency bands of Station RA41

 The median power at RA41 in both years was lower than observed at the other two stations. While the seismic record at station RA41 was the only one of the three that did not encompass the entirety of 2018 and 2019 (before and after the melt season), it did encompass the majority of the melt season in both years. The tremor in 2018 at RA41 ended October 29th (day 302). In 2019 the melt season tremor began on June 1st (day 152), though the ending was not captured. There are six frequency bands (around 6.5, 5.5, 4.5, 4, 3, and 2.5 Hz) in the median spectra that surpass the power threshold, appearing more clearly than at the other two stations, possibly because of the lower median power at RA41 than at the other stations. The band around 3 Hz was detected only at RA41. Only three subsections of these frequency bands were detected by the FDPA analysis as locatable GHT (Figs. 2 and 3 B, outlined by boxes of orange, pink and brown, and the back azimuth angles are plotted in similar colors).

The seismic station RA41 was not active at the onset of the 2018 melt season, and in 2019 the end of the season was not captured. The onset and ending of melt were recorded at stations RA42 and RA43, and agree with each other and the available data from RA41. The melt season in 2018 began a month earlier than in 2019, though the season ended only 1 week earlier in 2018 than in 2019.

S2.2 Identified Frequency bands of Station RA42

RA42, which is located ~675 m away from RA41, captured subsets of most of the same frequency bands (6.5, 5.5, 4.5, 4, and 2.5 Hz; Figs. 2 and 3 C). Differences include lack of the RA41 3 Hz band at RA42, lack of the 6.5 Hz band at RA42 in 2019 (although it is present in 2018), and detection of a 1.7 Hz band at RA42 that was absent at RA41. The melt season tremor began at RA42 on May 5th (day 125) in 2018 and June 1st (day 152) in 2019, and ended on October 29th (day 302) and November 5th (day 309), respectively. Of the three stations, FDPA analysis captured the most consistent and continuous locatable GHT as subsets of these bands at RA42 (Figs. 2 and 3 D, outlined by boxes of green, red, purple, and light blue bands, with back azimuth angles plotted in similar colors). In both years (best illustrated in 2018) all bands in RA42 coincided at a similar back azimuth angle (~150°) at the beginning, gradually drifted apart during the melt season, and came together at a similar back azimuth angle again at the end of the season during events with low discharge and power (Figs. 2 and 3 D).

S2.3 Identified Frequency bands of Station RA43

Similar to RA41 and RA42, the melt season tremor began at RA43 on May 5th, 2018 (day 125) and June 1st, 2019 (day 152), and ended around October 29th, 2018 (day 302) and November 5th, 2019 (day 309). RA43 is located ~810 m away from RA41 and ~185 m from RA42. RA43 detected the same bands as RA42 (6.5, 5.5, 4.5, 4, 2.5, and 1.7 Hz), and the FDPA analysis detected the greatest number of locatable GHT sub-bands of all stations (Figs. 2 and 3 F, outlined by boxes of dark blue, yellow, orange, gray, purple, and light blue bands, with back azimuth angles plotted in the same colors). With the exception of the 1.7 Hz band, all bands centered around 135° back azimuth angle (Figs. 2 and 3 E). The 1.7 Hz band, which is present mainly during the peak of the season and is gone by or shortly after the mid-season shift, had a back azimuth angle around 160°. Based only on time and back azimuth, we cannot rule out the possibility that the source is the Furka Pass Road. However, given that occurrences of this band always coincide with periods of high discharge of the subglacial stream, it seems likely that this band is related to GHT and is not an anthropogenic artifact.

In the back azimuth angles across 1.5 to 7 Hz in RA43 (Fig. 4), there is a notable band each year around 3.4 Hz that was not identified as polarized Rayleigh wave GHT by our FDPA analysis. This band has a clear back azimuth angle towards the glacier center, similar to the 3 Hz band at RA41. Median power in this band consistently surpasses our threshold before and after the melt season (Figs. 2 and 3 E), so we cannot conclusively identify this band as being related to GHT.

S3. Additional Discussion Figure

Figure S3 Here.