

Investigating Subglacial Water-filled Cavities by Spectral Analysis of Ambient Seismic Noise: Results on the Polythermal Tête-Rousse Glacier (Mont Blanc, France)

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Antoine Guillemot, N Bontemps, E Larose, D Teodor, S Faller, et al.. Investigating Subglacial Water-filled Cavities by Spectral Analysis of Ambient Seismic Noise: Results on the Polythermal Tête-Rousse Glacier (Mont Blanc, France). Geophysical Research Letters, 2024, 51 (4), 10.1029/2023GL105038. hal-04361323

HAL Id: hal-04361323 https://hal.science/hal-04361323

Submitted on 26 Dec 2023

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1	Investigating Subglacial Water-filled Cavities by Spectral Analysis of
2	Ambient Seismic Noise: Results on the Polythermal Tête-Rousse Glacier
3	(Mont Blanc, France)
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13	Key Points:
14	• Spectral analysis from ambient seismic noise is complementary to other geophysical
15	methods for investigating glaciers at depth
16	• Results suggest that the vertical-to-horizontal spectral ratio (VHSR) is a reliable proxy to
17	locate subglacial cavities

• Experimental results were confirmed using a simplified numerical model

19 Abstract

Polythermal glaciers can trap considerable volumes of liquid water with the potential to generate 20 21 devastating outburst floods. This study aims to identify water-filled subglacial reservoirs from ambient seismic noise collected by moderate-cost surveys. The horizontal-to-vertical spectral ratio 22 23 (HVSR) technique is highly sensitive to impedance contrasts at interfaces, thus commonly used to estimate glacier thickness. Here, we focus on the inverse ratio, i.e., the V/H spectral ratio (VHSR), 24 whose high values indicate a low impedance volume beneath the surface, suggesting subglacial 25 cavities. We analyze VHSR peaks from a seismic array of 60 nodes installed on the Tête-Rousse 26 Glacier (Mont Blanc massif, French Alps); data were gathered over 15 days. Mapping the VHSR 27 amplitude over the free surface reveals the main cavity locations and the basal areas affected by 28 melting within the glacier. Results obtained in the field are supported by a conceptual model based 29 on 3D finite-element simulations. 30

31

32 Plain Language Summary

Considerable volumes of liquid water may be trapped within cavities in polythermal glaciers. If 33 these cavities rupture, the resulting outburst flood has the potential to cause devastation in 34 populated mountain areas. With the aim of testing methods to locate such cavities, we installed 60 35 small 3-component seismic sensors on the Tête-Rousse Glacier (Mont Blanc massif, French Alps), 36 which is known to contain such cavities. We used these sensors to test a detection method based 37 on ambient seismic noise. For 3 weeks, the sensors recorded vibrations within the glacier. On a 38 glacier without cavities, these vibrations ought to be predominantly in the horizontal direction. In 39 40 the presence of a cavity, we expect the ice above the cavity to vibrate mostly vertically - like a bridge. In this paper, we highlight areas on the glacier where vertical vibrations were stronger than 41 horizontal vibrations. These areas fit well with the locations of the main known cavities in this 42 glacier, and with areas affected by basal melting. We supported our field observations with 43 44 modeling based on 3D simulations, paving the way to a new method to locate water-filled cavities within glaciers. 45

46 **1 Introduction**

47 Subglacial cavities may trap a considerable liquid water content. Within glaciers meltwater 48 reservoirs can be created by a number of factors, such as topographical traps, heterogeneous

thermal flux regimes, variability of seasonal meteorological conditions and, consequently, 49 hydraulic pressure gradients (Björnsson, 1998; Vincent et al., 2010). An unexpected and 50 instantaneous release of water from intraglacial or subglacial cavities (Haeberli et al., 1989; 51 Vincent et al., 2010), known as a glacial outburst flood, often causes avalanches of ice and debris 52 flows (Breien et al., 2008; Cenderelli et al., 2003; Kattelmann et al., 2003; Kershaw et al., 2005; 53 Vilimek et al., 2005), leading to devastating damages in densely populated mountain areas (e.g., 54 Haeberli, 1983). Excavation and drainage processes to evacuate subglacial water-filled cavities 55 56 remain under-studied (Fountain & Walder, 1998; Boon & Sharp, 2003; Roberts, 2005; Vincent et al., 2010). 57

Several studies have attempted to identify intraglacial cavities early during their formation 58 (Haeberli et al., 2001, 2002; Vincent et al., 2010; Werder et al., 2010; Gagliardini et al., 2011) 59 60 with the aim of preventing and mitigating the related hazards. Both active and passive geophysical methods have been deployed to investigate the glacier-bedrock interface and to characterize the 61 physics of glaciers (e.g., Petrenko & Whitworth, 2002). Some commonly used active methods are 62 Ground Penetrating Radar (GPR), seismic refraction, and borehole measurements. In addition, 63 passive seismic techniques can provide a reliable estimation of the seismic properties linked to 64 glacier morphology by measuring ambient seismic noise. By using efficient survey logistics, these 65 passive seismic measurements come at a contained cost (Sergeant et al., 2020). Ambient noise 66 studies have also been successfully used to reveal water flow activity (e.g., Björnsson, 1998; 67 Harper et al., 2010; Helmstetter et al., 2015 a, b; Gimbert et al., 2021; Nanni et al., 2021, 2022). 68

The horizontal-to-vertical-spectral ratio (HVSR) technique, first applied to ambient noise 69 recordings by Nogoshi & Igarashi (1971) and Nakamura (1989), is based on the analysis of H/V 70 frequency content, obtained by dividing the vectorial sum of the horizontal components by the 71 vertical components of the Fourier amplitude for the recorded wavefield. When impedance 72 73 contrasts exist at interfaces (e.g., a soft layer over a hard bedrock), incident body waves (P-waves, 74 horizontal and vertical S-waves) generate surface (Rayleigh and Love) waves that remain trapped within the shallow layer. When the wavelengths of the incident waves are comparable to the layer's 75 thickness, resonance effects occur. Consequently, the resulting surface waves may have a much 76 larger amplitude than the incident waves (e.g., Picotti et al., 2017). In most cases where a 1D soft 77 layer is underlying a stiffer one, the shape of HVSR curve is primarily determined by the 78 fundamental-mode Rayleigh wave (Konno & Ohmachi, 1998). Under reasonable assumptions, the 79

first HVSR natural peak gives a reliable estimation of the S-wave resonance frequency of a horizontally layered subsurface (Lachetl & Bard, 1994). Other spectral peaks correspond to a superposition of higher Rayleigh-wave, Love-wave, and S-wave resonance modes (Bonnefoy-Claudet et al., 2008).

The HVSR technique is commonly used to retrieve the site amplification function and its 84 resonance frequency in shallow geological layers (e.g. Lachetl & Bard, 1994; Ibs-von Seht & 85 Wohlenberg, 1999; Fäh et al., 2001, 2008; Bonnefoy-Claudet et al., 2006; Tuan et al., 2011; 86 Panzera et al., 2018; Panzera et al., 2022) and Alpine valleys (Panzera et al. (2022)). It is also 87 deployed to map soft sediment layers and estimate glacier thickness (e.g., Barnaba et al., 2010; 88 Picotti et al., 2017; Preiswerk et al., 2019; Molnar et al., 2022; Seivane et al., 2022). Picotti et al. 89 (2017) applied the HVSR method to five glaciers in the Alpine chain and the west Antarctic ice 90 91 stream. Their results show how well the resonance frequency in the HVSR spectra correlates with the local bedrock depth over a wide range of ice thicknesses – from a few tens of meters to more 92 93 than 800 meters. The authors validated their results using other methods, such as GPR, geoelectrical, and active seismic techniques. The limitations of the HVSR method and its reliability 94 95 for glacier characterization have been addressed in various studies, as reviewed by Picotti et al. (2017) and Molnar et al. (2022). Both groups identify coupling of the sensors with the glacier and 96 97 the basal impedance contrast as the main controlling factors. Preiswerk et al. (2019) investigated how the glacier's geometry influences the seismic wavefield and reported an azimuth dependence 98 99 of the HVSR curves' shape. They relate such directivity to higher-order resonance effects caused by the glacier's morphology (like bedrock irregularities). On glaciers, Carcione et al. (2017) 100 demonstrated that attenuation and bedrock deformability affect both frequency and amplitude of 101 HVSR peaks. Moreover, Saenger et al. (2006, 2009) used the HVSR method to extract 102 103 hydrocarbon maps, focusing on HVSR troughs (or peaks of the inverse - Vertical-to-Horizontal -104 spectral ratio, noted VHSR) to detect impedance anomalies. Specifically, they reported a peak in the VHSR (typically, values above 1: i.e., vertical energy higher than horizontal energy) at a 105 specific frequency detected by seismic sensors placed above hydrocarbon reservoirs. Similarly, 106 Antunes et al. (2022) noticed that VHSR peaks provides information about seismic energy 107 anomalies generated by fluids in reservoirs since the wavefield is mainly polarized in the vertical 108 direction. They identified a link between the location of the VHSR peak amplitude and the 109 presence of mud and gas inside a volcanic conduit; they also noticed a spatial correlation between 110

high VHSR anomalies and low resistivity anomalies in geoelectric profiles, corresponding to
 dome-like reservoirs and associated with high-salinity fluids.

Here, we analyze spectral ratios from ambient seismic noise measured for the Tête-Rousse 113 Glacier (Mont Blanc massif) with the aim of locating potential cavities or areas containing melting 114 water within the glacier. We first present the study area and the seismic data experiment in the 115 field, we next detail the results of spectral analysis obtained from our dense, temporary seismic 116 array. We interpret horizontal polarization of seismic noise around 9 Hz detected by HVSR peaks 117 as the fundamental mode for the whole glacier. Vertical polarization anomalies at higher 118 frequencies detected by HVSR troughs (i.e, more intuitive, VHSR peaks) are considered to reflect 119 reduced basal impedance due to the presence of a cavity or a local anomalous basal response in 120 some areas of the glacier. Results obtained in the field are supported by a proof-of-concept 121 122 simulation based on the 3D finite-element method.

123 **2 Experimental site and setup**

The Tête-Rousse Glacier is located in the Mont Blanc massif in the French Alps (Figure 125 1*a*), along one of the classic ascension routes (Figure 1b), making it a very popular site among 126 mountaineers. Fed by avalanches in its upper part, this glacier is approximately 450 m long and 150 m wide, with a maximum depth of 80 m, and its surface topography extends from 3100 to 128 3300 m elevation. There is at least one subglacial water-filled cavity under the central part of the 129 glacier (Vincent et al., 2012), known as the main cavity of this glacier.

In 1892 (July 11), an outburst flood originated from the Tête-Rousse Glacier following 130 131 collapse of an intraglacial cavity. Around 200 000 m³ of water and ice were released, dragging about 800 000 m³ of sediments (boulders, soil, and mud) into the village of Saint Gervais – Le 132 Fayet. The catastrophic event caused 175 fatalities and damaged multiple large infrastructures 133 (Vincent et al., 2010). The mechanism controlling formation and growth of the subglacial cavity 134 has been clearly identified and is probably related to the glacier's thermal regime. According to 135 Vincent et al., 2010), the cold tongue acts as a thermal barrier to water flow. At the time of the 136 outburst flood, factors combined to cause the collapse of the terminal tongue – due to a change in 137 thermal regime (from cold to temperate) or a positive anomaly of the mass balance. 138

Between 2009 and 2010, data were acquired on the Tête-Rousse Glacier from dense GPR
and Surface Nuclear Magnetic Resonance (SNMR) acquisitions. Their analysis revealed a new

subglacial water-filled reservoir measuring 55 000 m³ (+/- 10 000 m³) located at a depth of 40 m inside the glacier (Vincent et al., 2012; Legchenko et al., 2014). To prevent another potential outburst flood, the reservoir has been drained artificially (downhole pumps) several times – in 2010, 2011, and 2012 – to prevent the cavity filling up again. In 2013, a large crevasse almost reaching the surface was detected, corresponding to the former cavity roof that collapsed during a pump in 2012. The other few crevasses present on the glacier seem to be the main channel via which water runs into the cavity (Garambois et al., 2016).

From SNMR surveys conducted in 2015 and 2018, no increase in the water content in the main cavity was detected. However, liquid water was detected at several points spread over the upper part of the glacier. These signals could be linked to a water-filled crevasse located upstream from the cavity together with a diffusive zone, revealed using GPR by Garambois et al. (2016) (see Figure S6). These observations suggest a zone where basal partial melting occurs (Gilbert et al., 2012). The glacier is thus in an unsteady state that requires to monitor both its water content and the cavity's geometry.

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Figure 1: a) Mont Blanc massif in the Alps, the red star indicates the position of the Tête-Rousse Glacier. b) outline of the glacier
 and where it crosses the Mont Blanc Normal route. c) 2022 seismic sensor layout.

The seismic acquisition presented in this paper was performed in 2022, from May 4 to 22. We deployed 60 SmartSolo® three-component (3C) 5Hz seismic nodes, in a grid pattern with approximately 30 m by 25 m spacing (Figure 1c). In addition, three 3C Trilium Compact PostHole ® 20s seismometers were installed (named C1 to C3, red dots in Figure 1c), forming a transversal profile, hence crossing the area above the expected main subglacial cavity (see Supporting
Information S1 and Figure S1 for further experimental details).

165 **3 Data analysis and experimental results**

We first performed a statistical analysis in the frequency domain for all the signals recorded 166 by the seismic stations over the twenty days of experiment. Results show that the horizontal 167 spectral components have a higher amplitude than the vertical component between 5 Hz and 168 30 Hz. This is the case over almost the entire seismic array, as expected for glaciers (Preiswerk et 169 al., 2019). HVSR peaks (see Fig. 2a) are expected to reveal the glacier's vibration modes, as 170 reported previously (Picotti et al., 2017; Preiswerk et al., 2019). Additional examples of power 171 density spectrum (PSDs) plots for several sensors can be found in Supporting Information S2 (Fig. 172 S2 and S3). Interestingly, the amplitude of the vertical component is higher than the amplitude of 173 174 the horizontal component for some seismic sensors at specific frequencies, including sensor C2 located in the central part of the glacier above the expected main cavity (Fig. 2b). Regions where 175 176 the vertical component dominated (VHSR peaks above 1) are indicative of unusual impedance contrasts at depth, suggesting for instance the presence of cavities or ice/water-related contrasts. 177

The first HVSR peak recorded by the C2 sensor and most of the nodes is at about 9 Hz 178 179 (Figure 2a), whereas the first VHSR peak is at about 15 Hz (Figure 2b). We then analyzed how the seismic noise is polarized at these frequencies (see Supporting Information S3 for details). We 180 derived the polarization attributes from singular value decompositions by applying Flinn's method, 181 using the seismic post-processing package Obspy. Our first-pass analysis, between 8 Hz and 182 183 10 Hz, encompasses the first mode observed in the HVSR peak (see Figure S4). This analysis reveals high incidence values (often between 75° and 90°), thus horizontal motion of the particle 184 located in C2 in this frequency band. The corresponding azimuth values mostly ranges between 185 70° and 120° (E-W direction), indicating a longitudinally-oriented horizontal particle motion, in 186 agreement with the directivity of the HVSR peak near 9 Hz (Figure 2a) and the geometry of the 187 glacier. HVSR peak frequency for all other sensors is close to 9 Hz (see Figure S5), with small 188 variability mainly controlled by bedrock depth (Picotti et al., 2017). The azimuth's temporal 189 variability is low, and is probably related to the natural variability of the wavefield propagating in 190 191 the glacier.

We then looked at the polarization attributes of the data encompassing the first VHSR peak 192 (or HVSR trough) observed - between 14 Hz and 16 Hz (Figure 2a). The seismic signal exhibits a 193 mostly vertical motion of the particle located in C2 (highly variable but with a low incidence value, 194 often between 10° and 50°). The corresponding azimuth values covered all directions, with 195 consistently vertical polarization. The polarization analysis thus confirms our first observations 196 from spectral analysis: the first HVSR peak around 9 Hz corresponds to a horizontal vibration 197 mode along the glacier's main longitudinal axis, whereas the peak around 15 Hz revealed by 198 VHSR peak is mostly in vertical mode. Polarization was stable throughout the duration of 199 recording, adding support to our interpretation that these spectral peaks reflect natural vibration 200 modes of the Tête-Rousse Glacier. These conclusions were further corroborated by the 3D 201 mechanical modeling developed below. 202

To better locate areas of vertical resonance all over the glacier, we computed the VHSR 203 for each station over the whole time interval, from May 5 to May 21, using a modification of the 204 hvsrpy Python tool (Vantassel et al., 2022). We then picked the maximum amplitude averaged 205 over the azimuth within the 2 Hz to 30 Hz frequency range, so as to focus only on first natural 206 modes. Finally, using the ordinary-kriging method (based on a Matern model and a Matheron 207 estimator), we interpolated the VHSR peak amplitude over the whole area covered by the seismic 208 network (Figure 3). This analysis reveals a VHSR below 0.8 for most of the lower part of the 209 glacier, whereas above the fourth line of nodes (see Figure 1c), the VHSR is slightly over 0.8. 210 Moreover, two areas of the glacier were associated with VHSR peaks significantly exceeding 1 211 (around sensors C2 and 4.1). These areas are consistent with the location of the main subglacial 212 cavity identified in 2010. 213

In the following section, we describe how we built a simple mechanical 3D model of the glacier to reproduce these resonance modes and their polarization (vertical and horizontal).

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218 Figure 2: a) Azimuth-dependent HVSR amplitude from seismometer C2 with time-averaging over the whole period of the 219 experiment in May 2022. b) HVSR amplitude from some nodes along a longitudinal line at the center of the glacier, with time- and 220 azimuth- averaging mean amplitude (dots) and standard deviation (errorbars) over the whole period of the experiment in May 221 2022.



Nodes 3C (SmartSolo) •

224 Figure 3: VHSR peak amplitude for the Tête-Rousse Glacier, computed with time- and azimuth-averaging over the whole period of 225 experiment and interpolated by kriging. The cavity outline is deduced from Gagliardini et al. (2011).

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4 Numerical validation of results
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We performed direct numerical modeling based on finite-element analysis (FEA) to 227 visualize vibrating modes in the Tête-Rousse Glacier and to reconstruct the resonance frequencies 228 along with their modal polarization. We used COMSOL Multiphysics software (Comsol, 2023) 229 for two purposes: 1) to perform modal analysis (MA) of the glacier, solving eigenfrequencies of 230 the 3D object to reproduce the fundamental mode of the whole glacier, and 2) to determine the 231

²²⁶

frequency response function (FRF) of a 2D axisymmetric model of a local area of the glacier, retrieving the vertical displacements related to the presence of a cavity.

234

4.1 3D modeling of the horizontal glacier mode

MA computes numerical eigenfrequencies of a solid structure and requires well-235 constrained structural knowledge of the vibrating object. By combining all GPR and borehole 236 measurements, Garambois et al. (2016) produced a well-resolved estimation of the ice-bedrock 237 interface's topography (see Figure S6). For our model, we simplified the 3D geometry of the 238 239 glacier to an ellipsoid-shaped ice block with dimensions matching the field observations, lying on a rigid bedrock. Our modeled solid is composed of 94 000 quadratic tetrahedral finite elements, 240 with a maximum dimension of 15 m. We applied consistent boundary conditions to mimic the 241 configuration of the site: embedding the sides of the stable bedrock far from the glacier body, and 242 243 leaving the upper surface free. The mechanical parameters of both glacier and bedrock were estimated from the literature for ice and fractured moraine (Sergeant et al., 2020; Table S1). For 244 245 the sake of simplicity, the properties of both glacier and bedrock were assumed to be homogeneous. 246

247 We found the first eigenfrequency, corresponding to the fundamental mode, to be at 9.42 Hz (Figure 4a), close to the experimental HVSR peak measured at most nodes - at around 248 249 9 Hz (Figure 2a). This first mode is a flexural mode polarized along the longest axis of the glacier (the longitudinal direction). The polarization of this first numerical mode is consistent with the 250 251 observed directivity of the 9 Hz HVSR peak measured by most of the seismic sensors around the 100° azimuth. We noted that observed HVSR peak frequencies show a spatial variability over the 252 glacier (Figure S5 in Supplementary Materials), mainly depending on the local bedrock interface 253 depth and crevasses. We actually measured local "pseudo-modes" of compartments of the glacier, 254 rather than a global resonance of the whole glacier, due to the attenuation on the glacier that could 255 256 not be addressed by the model. Nevertheless, this 3D model suggests a longitudinal resonance around 9 Hz, similar to local horizontal modes detected by HVSR peaks. 257

Overall, this MA validates to the first order the mechanical parameters set of the ice and the bedrock and our interpretation of horizontal modes detected by HVSR. Then, a 2D modeling is needed to accurately interpretate local vertical resonance modes detected by VHSR peaks.

4.2 2D modeling of the cavity mode

We then focused on the presence of a subglacial cavity to assess its effects on spectral 262 263 analysis. For simplicity, we used a 2D geometry with vertical axial symmetry, focusing on the central part of the glacier. We assumed the simulated subglacial water-filled cavity to be elliptical, 264 with realistic dimensions. We only constrained the bedrock depth at 75 m and the location of the 265 top of the cavity at around 35 m depth, in line with GPR measurements obtained in 2022 (Figure 266 4b). Our 2D solid model was composed of 12 000 quadratic tetrahedral finite elements, with a 267 maximum size of 3 m side. A mesh refinement provided greater than 1% precision for all the 268 mechanical fields computed below 30 Hz (minimum of 20 elements per wavelength). 269 Acoustoelastic coupling between liquid water and ice was implemented by imposing continuous 270 normal acceleration at the cavity interface. We simulated ambient seismic sources by applying a 271 linear harmonic loading between 5 Hz and 20 Hz along a horizontal line crossing the geometry. 272 After computing the FRF, we retrieved the corresponding frequency-dependent response 273 displacement in the vertical direction at several points on the surface (closely reproducing the 274 positions at which seismic recordings were made by a vertical seismometer). 275

We compared the vertical displacements (along the Z-axis) obtained with and without the subglacial cavity in Figure 4c. For a simulated sensor placed right above it, vertical vibrations has a clearly larger amplitude when the cavity is present. In these conditions, the peak amplitude was two-fold that measured without the cavity, and has a slightly different frequency.



Figure 4: Fundamental mode of the glacier, based on the MA of the mechanical model applying simple elliptic geometry adapted
 from a). The main direction of displacement is depicted by the red arrow. (b) Vertical displacement of the 2D axisymmetric
 mechanical model at 12.8 Hz, showing the location of points 1, 2, and 3 at the glacier's surface. (c) Vertical displacement
 occurring at points 1, 2, and 3, recorded between 5 and 20 Hz with the cavity (continuous lines) and without the cavity (dashed
 lines), as outputs of FRF.

286 **5 Discussion**

The aim of this study was to analyze ambient noise data from the Tête-Rousse Glacier to verify 287 whether it could be used to detect and monitor subglacial cavities. Findings were confirmed by 288 289 modeling. The results presented in Figure 3 identify two hotspots with high (above 1.1) VHSR amplitude peaks in the central part of the glacier. The first hotspot (centered around the C2 sensor) 290 corresponds to the center of the main cavity first detected in 2010, and confirmed in 2018 using 291 GPR and by borehole drilling (Figure S6). The second one was measured only by node 4.1, which 292 293 corresponds to the area above the 2010 cavity, but with a more limited lateral extension. This sensor was also the closest to a transversal crevasse identified on the glacier's right bank, known 294 as the former roof of the cavity that collapsed in 2012 (Garambois et al., 2016). Note that this 295 crevasse cannot explain the VHSR amplitude peak, since we expect an exacerbated horizontal 296

energy increase at the border of the subvertical crack, due to shear vibration modes. However, this

crevasse was previously shown to feed the cavity with surface water (Garambois et al., 2016).

These recent observations may then result from a reshaping of the central cavity into two (or more) independent smaller cavities. Additional geophysical observations will be required to confirm this

301 hypothesis.

Downward from the cavity line, the VHSR amplitude is always lower than 0.8 (Figure 3). This area corresponds to the cold part of the glacier (Gilbert et al., 2012; Garambois et al., 2016), where the basal ice temperature is always much lower than that of the melting point, so that the ice layer sticks to the underlying bedrock and no basal melting water is expected.

Upward from the cavity line, the VHSR amplitude generally stands between 0.8 and 1.1. This area 306 is very well spatially correlated with the temperate area of the glacier (Gilbert et al., 2012; 307 308 Garambois et al., 2016), where the basal ice temperature remains at the fusion point, allowing liquid water to emerge at the ice-bedrock interface, and some detachments to occur locally. 309 310 Moreover, within the temperate ice, a large amount of liquid water was detected by SNMR (Figure S6). No large cavity containing liquid water has been revealed by GPR up to now, but small diffuse 311 312 cavities filled with liquid water, or wet patches, may exist within this volume, generating slight vertical vibrations. These results confirm the general basal conditions of the glacier, as already 313 314 suggested by GPR and SNMR surveys.

The interpretation of VHSR amplitude has to be performed carefully, mainly due to the temporal variability of the seismic noise, the presence of body and surface waves in the wavefield, and local 2D or 3D resonance effects. In this study, threshold values delineating melting areas have been set with the help of prior information on Tête-Rousse Glacier. Hence, it is worth noting than VHSR amplitude values are site-dependent, and conclusions based on this proxy should not yet be definitive without additional information.

It should also be noted that this seismic experiment was probably oversized: a shorter-lived, less intensive survey could have provided similar results. Statistical analysis of the temporal variability of the measurements will be the subject of further work, but at this point we estimate that only a few days of ambient noise data is required to conduct this type of experiment on glaciers. This duration might be decreased to a few hours through optimization of the data processing procedure. Among other advanced techniques, the extraction of Rayleigh wave ellipticity by DOP-E method (Berbellini et al., 2019; Jones et al., 2023) and its inversion may significantly improve the identification of englacial features (see Supporting Information S6 and Figure S7 for furtherdetails).

330 6 Conclusion

The spectral analysis performed on continuous seismic records acquired at the surface of the Tête-331 Rousse Glacier exhibits both a HVSR frequency peak and a polarization that corresponds to the 332 first longitudinal mode of the glacier, confirming the elastic parameters of ice and bedrock. The 333 VHSR exhibits a clear positive anomaly indicating the presence of a subglacial cavity (areas where 334 VHSR > 1.1) at a location that is consistent with the known position of the cavity. However, the 335 VHSR mapping suggests that the cavity's geometry had been modified since previous 336 observations, dating from 2010 and 2018. In addition, the upper part of the glacier, known to be 337 composed of temperate ice, shows VHSR values close to 1, indicating a possible role for diffuse 338 339 liquid water content and/or local detachment of the basal ice from the bedrock. These results indicate that ambient seismic noise-based spectral analysis of data collected by sensors at the 340 341 surface can be used to map the presence of potential cavities in glaciers. Computing VHSR amplitude peaks is very straightforward, making this method accessible and rapid. But the level at 342 343 which VHSR can detect cavities depends on the impedance contrast between the ice and the underlying layer (fractured or intact bedrock, sediments), and will need further investigation to be 344 345 applicable on glaciers without prior information on their subglacial conditions.

346

347 Acknowledgments

The authors wish to thank Sisprobe for renting their SmartSolo nodes and for assistance with data management. The three Centaur & Trillium PH sensors were from the CNRS-INSU-SISMOB pool. The authors gratefully acknowledge experimental help from Simon Bonin, Baptiste Camus, and Agnès Helmstetter. This work was partially funded by the French Ministère de la Transition écologique et de la Cohésion des territoires (Ministry for Ecological Transition and Territorial Cohesion) through its DGPR ROGP program, by the French national research agency (ANR) through its "Plan de Relance" program, and by the Engineering-Consultancy Bureau Géolithe.

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356 **Open Research**

- Data from seismic stations C1. C2. and C3 available RESIF 357 are on (https://seismology.resif.fr/networks/#/YZ 2022). 358
- Seismic data from nodes are temporarily available on ScienceDB through this link 359
- (https://www.scidb.cn/s/faUZf2), before being available permanently on RESIF. 360
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