Introduction

The application of geophysical techniques on glaciers can be very useful to study the overall impact of climate changes on the terrestrial cryosphere. The multichannel seismic and GPR (ground penetrating radar) methods are the most popular and widely geophysical techniques used in glaciology. Besides enabling to monitor the glacier thickness and then the ice mass balance, these methods can provide useful information on the basal sediment properties, which influence the overall glacier flow. However, these methods require considerable economic and operational efforts, and can be used only where the logistical difficulties are easily overcome.

Passive seismics can help to solve this problem, by using broadband seismometers and the HVSR method. Microtremor measurements and the Nakamura's HVSR (Horizontal to vertical spectral ratio) technique, generally used for site-effect studies as well as to determine the thickness of soft sediment layers, can be effectively used to map the thickness of glaciers. The application of the HVSR technique on glaciers, requiring less economic and operational efforts, may allow to avoid most of the logistical difficulties characterizing the active seismic and GPR methods in these extreme environments. The great advantage of passive seismic tools, in addition to the reduced size and weight, is that there is no need of an active source of elastic waves. In fact, taking advantage of the ambient noise, they does not require the use of artificial sources such as explosives, which are usually detonated in boreholes to be drilled using hot water.

Here we present the results of some tests regarding the reliability of the HVSR method on ice, which have been successfully carried out on some Alpine glaciers

Methods and Theory

We used different analytical techniques for the different methodology adopted to image the glacier bottom and validate the ice thickness obtained from the HVSR technique. In particular, for the active seismic method, the traveltime inversion of P and S diving waves in the firn allowed us to determine the vertical velocity gradient down to approximately 10 m depth, where the medium is pure ice. Below the firn, an iterative imaging technique involving P-wave velocity analysis, tomography and pre-stack depth migration (Yilmaz, 2001) has been used to produce a vertical seismic section of the glacier, basal sediments and bedrock.

The horizontal to vertical spectral ratio (HVSR) method was originally introduced by Nogoshi and Igarashi (1971) and first applied by Nakamura (1989). The method is based on the frequency spectrum obtained by dividing the horizontal component by the vertical component, either displacement, particle velocity or acceleration, since the results are equivalent. The source can be ambient noise, earthquakes or active sources of different nature. It has been shown that for Rayleigh waves propagating in a layer over a half space, the methods yields the fundamental resonance frequency and the related amplitude. In general, the HVSR peak corresponds to Rayleigh-wave, Love-wave and/or S-wave resonances (Bonnefoy-Claudet et al., 2008). Other investigations suggest that the H/V ratio provides the site S-wave transfer function.

2D resonance is caused by the trapping of body waves in soft layered media overlying a solid bedrock. The fundamental S-(body) wave resonance frequencies corresponding to a 2D basin of half-width *w* and thickness *h* are

$$f_{SH} = f_0\sqrt{1+\left(\frac{h}{w}\right)^2}, \qquad (1)$$

$$f_{SV} = f_0\sqrt{1+2.9\left(\frac{h}{w}\right)^2} \qquad (2)$$

(Bard and Bouchon, 1985), where v_S is the low-frequency S-wave velocity and $f_0 = v_S / 4h$. The half-width is defined as the length over which the local soft layer thickness is greater than half the maximum thickness. In the case of an infinite horizontal extent of the basin (1D approximation), $w \to \infty$ and $f_{SH} = f_{SV} = f_0$. In the case of several soft layers over bedrock, the S-wave velocity is the average obtained with the time-average equation.

Examples

The multichannel seismic and GPR methods, generally used to explore the subglacial environments, are here applied to validate the HVSR technique on ice. We selected some target alpine glaciers, in order to validate the technique in a wide range of thicknesses, from tens of meters to over 800 m. The chosen glaciers are the following: the Pian di Neve glacier on the Adamello massif (Italy), the Forni glacier in the Ortles/Cevedale massif (Italy) and the Aletsch glacier (Switzerland).

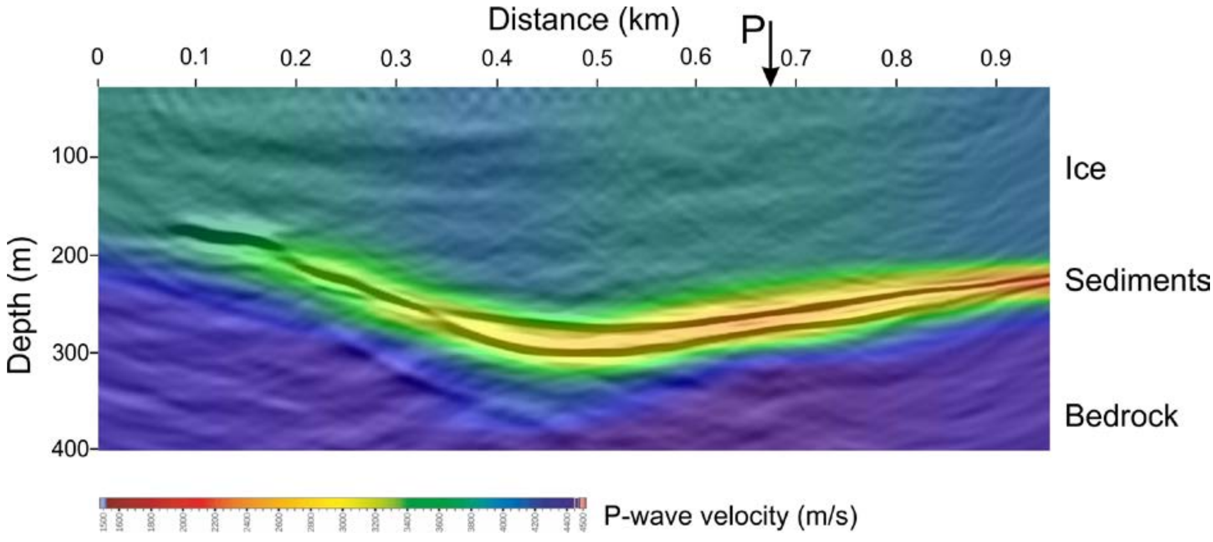

Figure 1 *Pre-stack depth migration of the seismic data acquired on the Pian di Neve glacier (Adamello massif), superimposed to the final interval velocity section obtained using the imaging procedure. The vertical arrow indicates the location (P) of the passive seismic measurements.*

In order to validate the HVSR technique in the three sites, active multichannel (P and S) seismic and GPR data were acquired on the Pian di Neve and on the Forni glaciers, respectively. Figure 1 shows the Pre-stack depth migration of the seismic data acquired on the Pian di Neve glacier, superimposed to the final interval P-wave velocity section obtained using the imaging procedure. A layer is evident between the Ice and the Bedrock, whose average P-wave velocity (2600 m/s) is compatible with consolidated sediments. The average and maximum ice thickness in the section is about 240 m and 270 m, respectively, while the average sedimentary layer thickness is about 20 m. Traveltime inversion of S diving waves allowed to infer the shallow firn velocity gradient. The maximum S-wave velocity, reached at about 10m depth, is v_S = 1907±20 m/s. Figure 2 shows the H/V spectra obtained from the passive seismic measurements at the location P in the section of Figure 1. These measurements were carried out in different periods and using different broadband seismometers (Guralp CMT 30s, Lennartz 5s and Trillium 20s), in order to evaluate the repeatability of the experiment. The H/V spectra clearly show that the measured resonance frequency, considering the experimental errors, is almost invariable. Considering that the lateral extension of the Pian di Neve glacier is much larger than the ice thickness, in this case the 1D approximation holds. Therefore, using the average measured fundamental resonance frequency f_0 = 1.83±0.13 Hz, the average ice thickness obtained from the HVSR method is h = 260±20 m. This value represents the average ice thickness in a circular area with center P and radius $\lambda_0/4$. The average ice thickness computed from the seismic section of Figure 1, within a distance of $\lambda_0/4$ from P, is h = 250±5 m. This example shows a very good agreement between the results obtained from the passive and active seismic methods.

Also on the Forni glacier we obtained a good comparison, using a Trillium 20s sensor. In this case, the resonance frequency is higher, f_0 = 6±1 Hz, giving an ice thickness of 80 ±12 m, while the ice thickness obtained from the GPR data varies between 60 m and 70 m.

Conversely, in the Aletsch glacier, using a Trillium 20s sensor we obtained quite lower resonance frequencies (see the H/V spectra of Figure 3), ranging from f_0 = 1.06±0.09 Hz outside the Konkordiaplatz, down to an average frequency of f_0 = 0.91 ± 0.09 Hz in the Konkordiaplatz. Previous active seismic experiments (Thyssen and Ahmad, 1969), and glaciological drilling and instrumentation in the late 1990s (Hock et al., 1999), evidenced an overdeepening zone in the Konkordiaplatz, with ice thicknesses exceeding 800 m depth (one of the wells reached 904 m depth). In this case, the glacier thickness is comparable to the valley half-width *w*=700 m, and the 1D approximation is no more valid. We found a good agreement with these data using the equation (1), obtaining a thickness of 600±90 m outside the Konkordiaplatz, and 820±120 m in the Konkordiaplatz. Therefore, in this case the resonance seems to be due to Love waves or body SH waves.

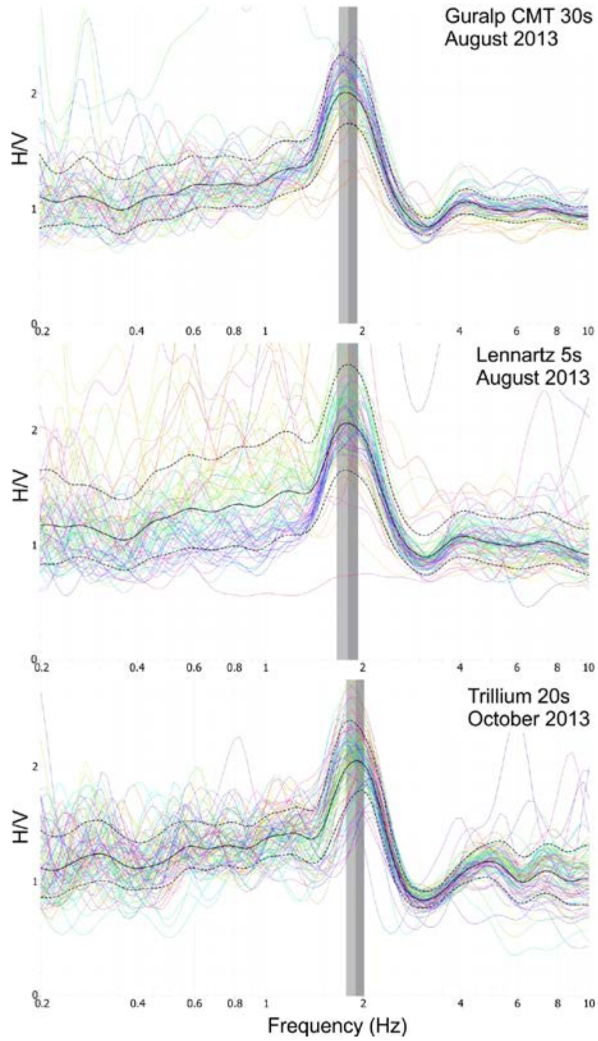

Figure 2 *H/V spectra obtained from the passive seismic measurements at the location P (see Figure 1) on the Pian di Neve glacier (Adamello massif). Even though the measurements were carried out in different periods and using different sensors, the spectra show the same resonance frequency.*

Conclusions

The multichannel seismic and GPR methods, widely used in exploration geophysics, are here applied to validate the HVSR technique on some alpine glaciers: the Pian di Neve glacier on the Adamello massif (Italy), the Forni glacier in the Ortles/Cevedale massif (Italy) and the Aletsch glacier (Switzerland). The comparison of the results obtained from the different methods clearly shows that the resonance frequency in the HVSR spectra can be well correlated with the ice thickness at the site, in a wide range from tens of meters to over 800 m. These results show that the application of passive seismics to glaciers is effective, and may allow mass balance studies also in extreme environments (e.g., Himalaya and Karakorum glaciers), where the multichannel seismic and GPR methods cannot be applied.

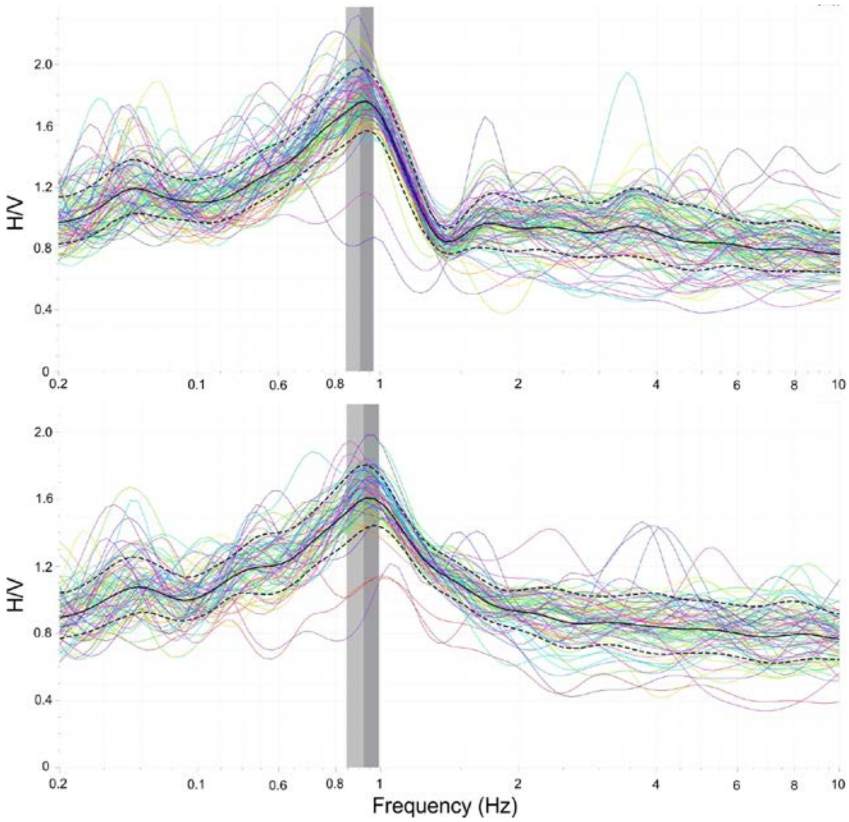

Figure 3 *H/V spectra obtained from passive seismic measurements in the Konkordiaplatz (Aletsch glacier, Switzerland, 2014) using a Trillium 20s sensor. The measurements were carried out in two different locations of the Konkordiaplatz, and the spectra show almost the same resonance frequency.*

Acknowledgements

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