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Argentière glacier characterization by full waveforms: source inversion as a preliminary step

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Main objectives

The aim of this study is to investigate the performance of Full Waveform Inversion on data from a dense network of sensors deployed on the surface of a glacier, in this case the Argentière glacier. The first step of this work consists in characterizing the spatial location, focal mechanism and temporal signature of the sources at the origin of the recorded signals.

New aspects covered

1. Automatic detection and localization of thousands of icequakes from seismic data recorded on the surface of the Argentière glacier.
2. Systematic moment tensor and time signature waveform based reconstruction for each of these events.
3. Representation of the inverted focal mechanisms distribution on the fundamental lune from moment tensor informations.

Summary

The importance of studying glacier behavior and mechanisms has greatly increased in the context of current climate change. In this study, we process seismic data recorded at the surface of the Argentière glacier to characterize its 3D structure. The first step is to characterize the sources responsible for the recorded signals, most of them being icequakes. We start by using the Matched Field Processing method to detect events in the data and spatially localize the icequakes within the glacier. We then build a 3D model of the glacier's surface topography using digital elevation models. Finally, we invert the focal mechanism and time signature associated with each icequake using an iterative alternating optimization algorithm. The inversion is performed in the elastic approximation and the 3 data components are used. The method is based on a decomposition of the solution of the elastodynamic equations into the derivatives of the Green functions associated with the moment tensor coefficients (characterizing the source mechanism). The results are encouraging: surface waves are generally well reconstructed in the calculated seismograms. Moreover, the estimation of mechanisms yields an interesting result: most icequakes (84%) seem to behave like isotropic sources.

Argentière glacier characterization by full waveforms: source inversion as a preliminary step

Introduction

Glaciers represent almost 70% of the Earth’s drinking water. In the context of current climate change, they are undergoing major modifications, their melting is accelerating and some of them are already beginning to disappear. A better understanding of their behavior and mechanisms is therefore crucial for the years to come. A dense seismic array has been deployed on the Argentière glacier, in the Mont Blanc massif (French Alps), in order to monitor modifications in its structure over time (Gimbert et al., 2021). The sensor array consists in 98 3-component seismic stations (Fairfield ZLand) which have recorded displacements on the glacier surface continuously over 35 days in early spring 2018. During this time of year, the temperature rises and the glacier undergoes major changes, so the sensors captured thousands of events, mostly icequake type events.

We are interested in the high-resolution 3D characterization of the Argentière structure. For this, we are going to apply a full waveform inversion algorithm to the data recorded on the glacier surface. Before proceeding with this step, we need to characterize the sources at the origin of the recorded signals. This includes spatial localization, characterization of their mechanism and temporal signature. This study focuses on this preliminary step towards glacier structure characterization.

Icequake localization by Matched Field Processing (MFP)

In order to spatially localize icequakes in the glacier, we use the Matched Field Processing (MFP) method (Nanni et al., 2021). This method makes it possible to spatially localize a source from signals recorded by different sensors, without prior knowledge of velocity v or emission time t_0 . We apply it to the vertical displacement component of the recorded data. It is based on several assumptions, including the propagation of a single type of wave in the medium: in the current case, Rayleigh wave is considered as it is the most energetic wave on vertical component for near-surface icequakes. Furthermore, the velocity of this single wave type is assumed to be constant in the medium, depending on the propagation frequency.

Let ω be a frequency, let us consider a discretization into K frequency points $(\omega_k)_{k=1,\dots,K}$ of the interval $[\omega - \varepsilon, \omega + \varepsilon]$ with ε small. The optimal velocity v^* is assumed to be constant over the discretized frequency interval. Let us denote \hat{g}_r^k the Fourier coefficient observed at receiver index r ($r = 1, \dots, N$) for frequency ω_k and $\phi_r^k = \text{Arg}[\hat{g}_r^k]$ its phase. Then, by property of the Fourier transform, we have,

$$\phi_r^k = \phi_0^k - 2\pi t_r(\mathbf{x}_s, v^*)\omega_k, \quad \text{with: } t_r(\mathbf{x}_s, v^*) = \frac{\text{dist}(\mathbf{x}_r, \mathbf{x}_s)}{v^*} \quad (1)$$

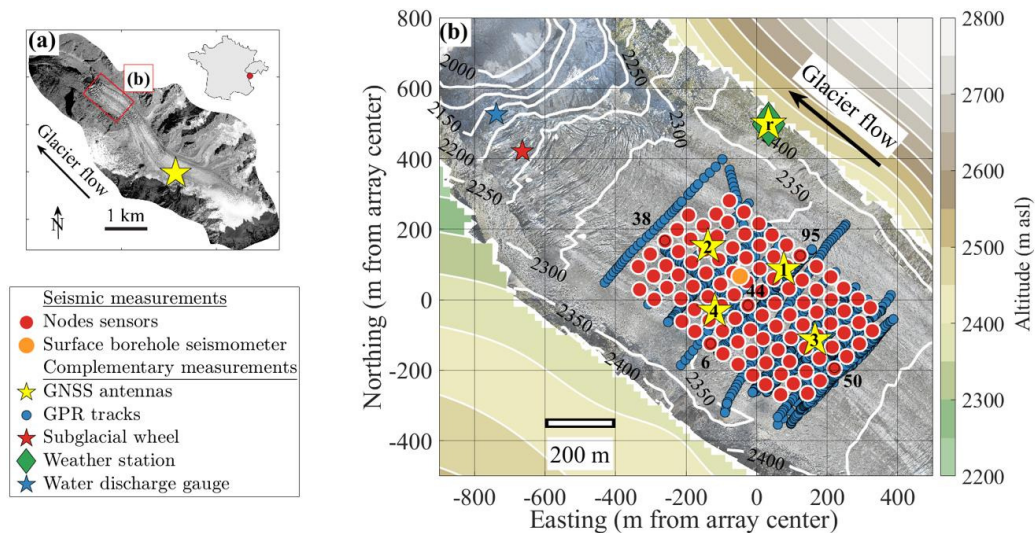


Figure 1 Maps of the Argentière Glacier and of the instruments deployed (see legend for symbols correspondence). (a) Aerial picture of the Argentière Glacier. The red rectangle indicates area shown in (b). (b) Map showing the lower part of the Argentière Glacier along with instrument positions. Red circles correspond to the 98 3-component seismic stations. White contours indicate glacier surface topography and color contours indicate topography outside of the glacier. Figure taken from Gimbert et al. (2021).

where \mathbf{x}_s and \mathbf{x}_r are the spatial positions of the source and receiver of index r , and ϕ_0^k is the absolute phase for frequency ω_k , i.e. $\phi_0^k = \text{Arg}[\hat{f}^k]$ with \hat{f}^k the Fourier coefficient of the source signal for ω_k . The only information we have here is the spatial positions of the receivers $(\mathbf{x}_r)_{r=1,\dots,N}$ and the phases $(\phi_r^k)_{r=1,\dots,N}^{k=1,\dots,K}$. In order to determine the source position \mathbf{x}_s and the optimal velocity v^* , we solve the following maximization problem:

$$\max_{\substack{\mathbf{x} \in \mathbb{R}^3 \\ v \in \mathbb{R}}} F(\mathbf{x}, v) = \frac{1}{N^2 K} \sum_{k=1}^K \left| \sum_{r=1}^N e^{i\phi_r^k} e^{2i\pi t_r(\mathbf{x}, v)\omega_k} \right|^2 \quad (2)$$

Note that the function F has values between 0 and 1, this value being the MFP score. This problem is solved using an implementation of the Nelder-Mead local optimization algorithm, a heuristic method based on the simplex concept. This enables automatic event detection in the raw data over the 35 days of recording. Indeed, the MFP is applied to each 1s time window (with 0.5s overlap) of the data for different frequencies. A MFP value of 1 means a perfect match between the data and the model. Figure 2 shows the 1650 icequakes (red circles), between the surface and bedrock, detected and localized by MFP with a score greater than 0.9 (on at least one frequency) over the 35 days of recording.

Waveform based moment tensor and source time signature inversion

The first step to characterize the mechanism and time signature of the icequakes within the glacier using waveform information is to build a surface topography. We use two different digital elevation models (DEM) to do this: a surface DEM based on a drone geodetic survey, and a bedrock DEM reconstructed by Ground Penetrating Radar (GPR) for the part below the glacier (Gimbert et al., 2021). We focus on a rectangular area of size 1210m by 1140m surrounding the sensor network as shown in Figure 2. The result of the merge between the 2 DEMs is shown by the grey surface in Figure 2(a). For visualization purposes, we superimpose the bedrock DEM on the surface topography reconstructed in Figure 2(b).

Then, we work on characterizing the mechanism and time signature of icequakes. For this, we consider a source point moment tensor in the 3D elastodynamic equations. Let $\mathbf{M}(\mathbf{x}, t; \mathbf{x}_s, 0) \in \mathcal{M}_3(\mathbb{R})$ be the tensor source function triggered at spatial point \mathbf{x}_s at time $t = 0$, we assume it is localized in space, i.e. $M_{ij}(\mathbf{x}, t; \mathbf{x}_s, 0) = \delta(\mathbf{x} - \mathbf{x}_s) m_{ij}(t)$ (for $i, j = 1, 2, 3$) with $\{m_{ij}(t)\}_{1 \leq i, j \leq 3}$ the time coefficients of the tensor. Let us denote $\mathbf{G}_{n,k} = \frac{\partial \mathbf{G}_n}{\partial x_k}$, the spatial derivative of 3-component Green's function \mathbf{G}_n in the k direction. By symmetry of the moment tensor, i.e. $m_{ij}(t) = m_{ji}(t)$, there are 6 independent coefficients which we denote $\{m_I(t)\}_{I=1,\dots,6}$ using Voigt notations. In addition, we have $\mathbf{G}_1 = \mathbf{G}_{1,1}$, $\mathbf{G}_2 = \mathbf{G}_{2,2}$, $\mathbf{G}_3 = \mathbf{G}_{3,3}$, $\mathbf{G}_4 = \mathbf{G}_{2,3} + \mathbf{G}_{3,2}$, $\mathbf{G}_5 = \mathbf{G}_{1,3} + \mathbf{G}_{3,1}$ and $\mathbf{G}_6 = \mathbf{G}_{1,2} + \mathbf{G}_{2,1}$. We assume that the source mechanism does not depend on time, i.e. $\forall I = 1, \dots, 6, m_I(t) = \alpha_I s(t)$ with $\alpha_I \in \mathbb{R}$ constant. Under this assumption, the solution $\mathbf{u}(\mathbf{x}, t)$ of the elastodynamic equations follows,

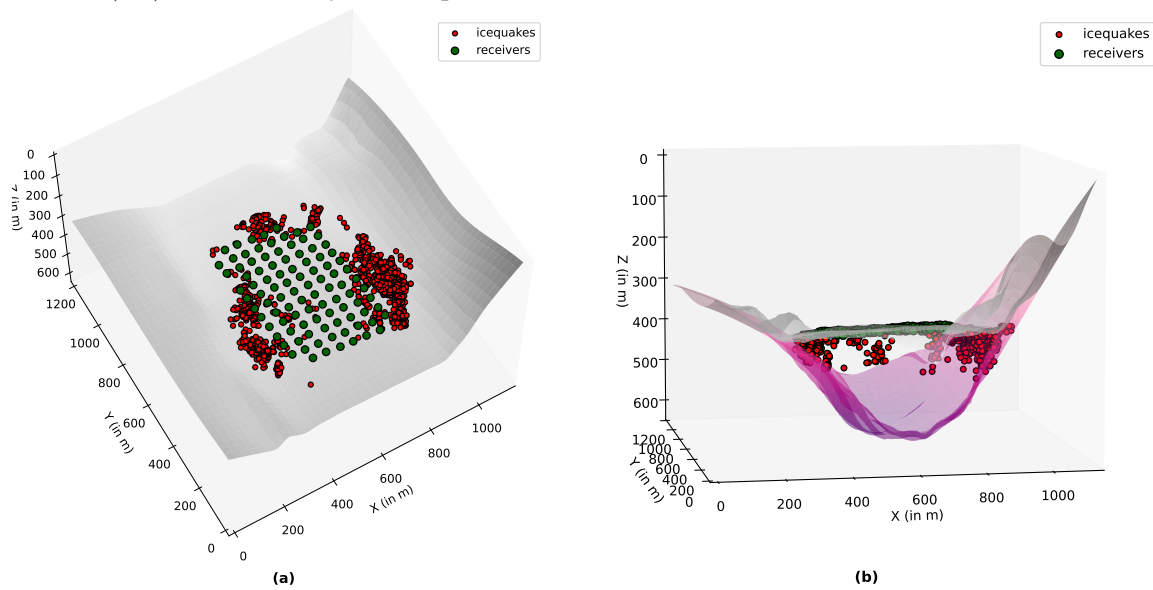


Figure 2 Plot of the surface topography (gray surface) with the sensor network (green circles) placed on it and the icequakes (red circles) estimated by MFP with a score greater than 0.9. (a) Surface seen from above. (b) Side view of the surface topography with bedrock DEM (purple surface).

$$\mathbf{u}(\mathbf{x}, t) = \left[\sum_{I=1}^6 \alpha_I \mathbf{G}_I(\mathbf{x}, t; \mathbf{x}_s, 0) \right] *_t s(t) \quad (3)$$

In order to determine the tensor coefficients $\boldsymbol{\alpha} = \{\alpha_I\}_{I=1,\dots,6}$ and the wavelet $s(t)$ for a given source responsible for the observed data $\mathbf{d}_{obs} \in \mathbb{R}^{3 \times N_{rec} \times N_t}$, we minimize the following problem:

$$\min_{\substack{\boldsymbol{\alpha} \in \mathbb{R}^6 \\ \mathbf{s} \in \mathbb{R}^{N_t}}} F(\boldsymbol{\alpha}, \mathbf{s}) = \frac{1}{2} \left\| \mathbf{d}_{obs} - \left[\sum_{I=1}^6 \alpha_I \mathbf{G}_I \right] *_t \mathbf{s} \right\|^2 \quad (4)$$

where \mathbf{G}_I is a discretization of the derivatives of Green's functions at N_{rec} receivers (spatially) and N_t time steps (temporally). We solve this problem using an alternating minimization algorithm on variables $\boldsymbol{\alpha}$ and \mathbf{s} . Indeed, by fixing $\boldsymbol{\alpha}$, the minimization solution on \mathbf{s} is unique and vice versa. Working in the frequency domain, we can show that for $\boldsymbol{\alpha}$ fixed, the solution $\hat{s}(\omega)$ (Fourier coefficient of \mathbf{s} for frequency ω) of problem 4 is (Pratt, 1999):

$$\hat{s}(\omega) = \frac{\langle \hat{\mathbf{d}}_{obs}(\omega) | \hat{\mathbf{G}}(\omega) \rangle}{\|\hat{\mathbf{G}}(\omega)\|^2} \quad (5)$$

with $\hat{\mathbf{G}}(\omega) = \sum_{I=1}^6 \alpha_I \hat{\mathbf{G}}_I(\omega)$ and $\hat{\mathbf{G}}_I(\omega) \in \mathbb{R}^{3 \times N_{rec}}$ the Fourier coefficients for frequency ω of the Green's functions. On the other hand, if we fix \mathbf{s} , then we can show that $\boldsymbol{\alpha}$ which minimizes problem 4 is the solution of the linear system $\mathbf{A}\boldsymbol{\alpha} = \mathbf{b}$ with $A_{IJ} = \langle \mathbf{G}_I * \mathbf{s} | \mathbf{G}_J * \mathbf{s} \rangle$ and $b_I = \langle \mathbf{G}_I * \mathbf{s} | \mathbf{d}_{obs} \rangle$. The matrix \mathbf{A} is positive definite by property of Gram matrices and the fact that the vectors $\{\mathbf{G}_I * \mathbf{s}\}_{I=1,\dots,6}$ are linearly independent, so the solution to the system exists and is unique. By alternating these 2 linear minimizations, we converge to a local solution for $(\boldsymbol{\alpha}, \mathbf{s})$.

The derivatives of Green's functions $\{\mathbf{G}_I\}_{I=1,\dots,6}$ are computed once for a given velocity model using the SEISCOPE spectral element code SEM46. We use the reciprocity theorem linking strain to displacement for a tensor-type source, which allows us to divide the number of simulations required by more than 30 (in our case with 1650 sources and 98 receivers).

Result analysis

We use a homogeneous velocity model, based on the results presented by Gimbert et al. (2021), to generate the Green's function derivatives. These velocities are $V_p = 3400 \text{m.s}^{-1}$ and $V_s = 1720 \text{m.s}^{-1}$. Figure 3 shows an example of a z-component seismogram obtained from inverted moment tensor and wavelet for an icequake localized by MFP at 5 m below the surface in the northeastern part of the glacier. Note that it is necessary to use the 3 data components for the moment tensor inversion. We compare observed data (Fig. 3(a)) with calculated data (Fig. 3(b)) offset-ordered, as well as observed (Fig. 3(c)) with calculated (Fig. 3(d)) data ordered by sensor lines. P- and Rayleigh waves kinematics and dynamics appear to be correctly reconstructed. The field data show 2 reflections with a slope inverted to that of the surface wave. These are the P and Rayleigh waves reflected by the glacier/bedrock interface at the glacier edges. These reflections are barely visible on the calculated data, as a homogeneous velocity model is used, but the topography makes it possible to start modelling the one linked to the Rayleigh wave.

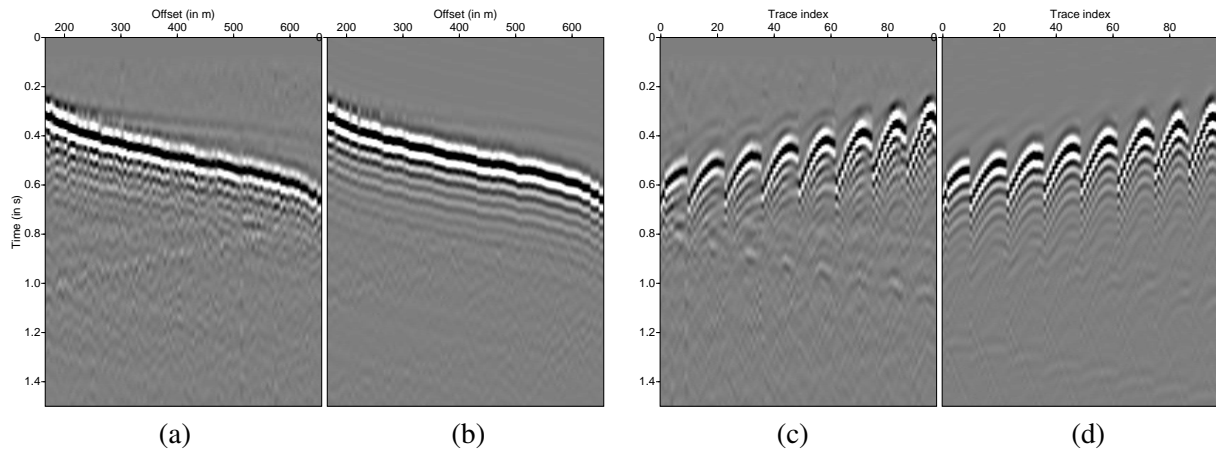


Figure 3 Example of observed and reconstructed data (same amplitude scale) after inversion of the moment tensor and time wavelet. Observed (a) and calculated (b) data ordered by offset. Observed (c) and calculated (d) data ordered by receiver lines.

In order to represent the inverted source-type for the 1650 icequakes detected by MFP, we use the fundamental lune of the unit sphere described by Tape and Tape (2012), which is presented in Figure 4. The moment tensor source type can be represented by its coordinates on the lune, defined by the tensor eigenvalue triples (with $\lambda_1 \geq \lambda_2 \geq \lambda_3$) regardless of its orientation (eigenframe, not considered here). Moreover, we represent all the tensors on the left part of the lune with the aim of only observing the distribution of mechanisms first, with a more isotropic or deviatoric trend. We can see that most icequakes seem to tend towards a (not purely) isotropic source mechanism, with all 3 eigenvalues of the same sign, implying a displacement of the same sign in all directions. Indeed, over 84% of them lie to the left of the $\lambda_3 = 0$ curve on the fundamental lune (all positive eigenvalues).

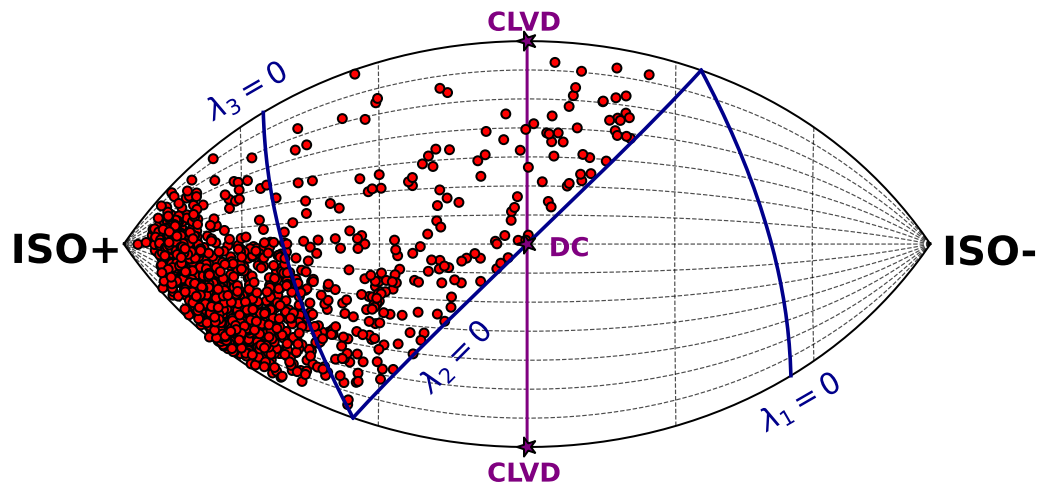


Figure 4 Representation of the inverted moment tensors for the 1650 icequakes on the fundamental lune of the unit sphere (Tape and Tape, 2012). Only the left side of the lune has been considered here, in order to study the distribution of source mechanisms between isotropic and deviatoric.

Conclusions and Perspectives

In this study, we present an approach for spatially, mechanically and temporally characterizing the icequake sources responsible for the displacement recorded on the surface of the Argentière glacier. The icequakes are detected in the data and localized in the glacier by MFP. Then, using the reconstructed 3D surface topography their focal mechanism and temporal signature are estimated using an alternating minimization algorithm. Our results show that we are able to correctly reconstruct the surface wave in the data. Furthermore, we show that a large proportion of the icequakes (84%) appear to behave as an isotropic source. The next step in this work is the 3D inversion of the glacier structure by full waveform, using the source characterization already performed.

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