Author's responses to the reviewers 1 & 2. Seismic attenuation in Antarctic firn

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1 Introduction

We thank the reviewers for the valuable and constructive comments on our manuscript. The reviewer's comments are indicated in italics throughout this letter. New and revised paragraphs that have been included in the main manuscript are indicated by their line numbers.

Based on the points raised below, we have made some improvements to the calculation of velocities and quality factors (Sections 4.1 and 4.2). Moreover, we added a Discussion (Sections 5) to explain in detail the importance of this model for studies related to the physical properties of the firn and the characterization of subglacial materials using amplitude variations with offset (AVO) analysis. Furthermore, we have added a few paragraphs to the Introduction and to the Conclusions, to better explain the main purposes of our work and the possible new applications of the described methodology.

2 Reviewer 1

1. *The study derives phase velocities and attenuation of P- and S-waves in polar firn from seismic experiments using an inversion algorithm. The basic model of the inversion is a stack of homogeneous layers. The attenuation of each layer is obtained from the phase shift between the reference wavelet and the first break wavelet at the corresponding offset. The reference e.g. source wavelet is obtained from receivers placed close to the source. Parameters for the Biot model are derived from the density model using functions of the porosity that have been shown to be functional in snow. The study shows, that wave velocities in firn can not be explained by a basic porous model consisting of a rigid ice structure and a pore space consisting simply of air. Such a basic ice-air model underestimates the P-wave attenuation by at least two orders of magnitude. The authors therefore use a porous model with the pore space filled with so called 'fluidized snow'. Fluidized snow is a mixture of snow particles and air. The difference between the soft air and the relatively rigid snow leads to higher attenuation as of higher friction of the rigid phase and the larger slip due to the soft phase being squeezed. The mechanism and the orders of magnitude of the attenuation is similar to a pore fluid consisting of air and water in melting snow. To my knowledge, the concept of fluidized snow as a pore fluid in Biot-theory to express wave*

velocity and attenuation in firn is new and has not been applied before this study. As described in the introduction of the manuscript, only little information of wave velocity and attenuation of firn is present today. Such information is important as it could be used, for example, to obtain porosity of firn with seismic borehole experiments. As such, borehole logging in cheap hot water drill holes could replace costly core drills. Knowledge of the wave attenuation in the firn layer of ice sheets is also important to seismic surveys obtaining geological information of the underlying geological structures.

We would like to thank the reviewer for the clear synthesis of our work.
We agree with the reviewer that "seismic attenuation in firn can not be explained by a basic porous model consisting of a rigid ice structure and a pore space consisting simply of air". According to the above reviewer comments, we added a paragraph at the end of the Introduction (Lines 69–76) and Conclusions (Lines 429–433), in order to better explain the main purposes of our paper.

2. *In the manuscript the attenuation and velocities are only shown versus depth in the firn deposits. For the use in further investigation and to compare with alternative theoretical models it is crucial to have the velocities and attenuation as a function of density and/or porosity. I would therefore highly recommend to add such figures to the manuscript.*

We made some improvements to the computation of velocities and quality factors. As explained in Sections 3.3 and 4.1, the quality factor profiles obtained using the layer-stripping method, strongly depend on the thickness and seismic properties of the shallowest layer. While these properties are well constrained for the Q_P profile, it was not possible to properly constrain the thickness of the shallowest layer related to the Q_S profile. This is due to the fact that the S-wave velocity close to the surface is too low. Therefore, we revised the S-wave velocity curve computed by Picotti et al. (2015), obtaining higher velocities in the first 15 m below the surface. In the new version of Fig. 4a (now Fig.5a), errors of velocity versus depth are also represented, for both P and S waves. We changed the Lines 230–233 as follows:

"By calculating the maximum penetration depth of the emerging ray at an offset of 6 m, we estimated the thickness of this layer to be about 1.6 m. Furthermore, the estimated dominant frequency and variance of the source are f_S= 496 Hz and σ_S= 146 Hz, respectively."

As expected, after these corrections the shape of the Q_S profile changed, showing lower quality factors in the deeper parts of the firn. We changed the Lines 262–264 as follows:

"The second graph (Fig. 10) shows a moderate increase of Q_S, from the previously calculated minimum value of 1.9±0.4 near the surface, to an average maximum value of about 250±90, which remains almost constant at depths greater than about 40 m."

We also changed the Lines 419–420 in the Conclusions as follows:

"The resulting experimental quality factors range from values lower than 5 at the surface to approximately 300 and 250 at about 60 m depth, for P and S waves, respectively."

In order to improve the theoretical model below the pore close-off depth, we modified the assumptions on the Poisson ratio (Lines 304–307). We reorganized the paragraphs between Lines 285–311.

We added the following reference to the bibliography:

Mavko, G., T. Mukerji, and J. Dvorkin, 2009, The rock physics handbook: tools for seismic analysis in porous media, Cambridge Univ. Press.

Being these assumptions more realistic, the comparison between the experimental and theoretical quality factors improved, in particular for the S waves (see Fig. 14). As requested by the reviewer, we added a second abscissa on the top of Fig. 5a and Fig. 14, to represent the density corresponding to the depths shown at the bottom abscissa.

3. *For the theoretical model, fluidized snow is assumed to fill half the available pore space. Where the available pore space is a function of density. Given the results of the study this is a good approximation. It is, however, not so clear, how the fluidized snow phase can be measured in firn samples as for example in drilled ice cores. This is not a flaw of the study, but rather a question, that arrises from the results of the study.*

We added at Lines 285–289 the following paragraph:

"For this study it is important to measure the properties of the fluidized phase of the snow. This task can be performed in coring of firn samples as indicated in Nishimura (1991). The main apparatus consists of two parts: fluidized snow feeder and inclined chute, where it is possible to store the disintegrated snow in fluidized conditions. Measurements are made at a temperature of -15 °C to avoid adhesion effects between snow particles. In this context, bulk density, elastic velocity and viscosity can be measured."

We also added the following reference to the bibliography:

Nishimura, K., 1991, Studies on the fluidized snow dynamics. Contributions from the Institute of Low Temperature Science, Ser. A, No. 37, pp. 1–55 (Doctor Thesis, Hokkaido University).

3 Reviewer 2

1. *The manuscript "Seismic attenuation in Antarctic firn" submitted by Picotti et al. presents a relevant study addressing the attenuation of seismic P- and S-waves in Antarctic firn. In particular, the authors develop a model based on novel combination of the Biot theory with the concept of fluidized snow filling the pore space. The results shown in the manuscript demonstrate the validity of the proposed approach and its importance for investigations of Antarctic subsurface structures and properties using seismic methods. Accordingly, the study is particularly relevant for the readership of this journal, and thus should be considered for publication after a thorough revision of the manuscript.*

   We thank the reviewer for the clear summary of our work.

2. *In the current version, the objective is indirectly obvious as from the current literature only sparse information regarding seismic wave velocity and attenuation in firn is available. The introduction should clearly state the objective of this study.*

   We have modified a paragraph at the beginning of the Introduction (see Lines 23–42), to better explain that tools for quantifying the depth dependence of attenuation in ice sheets need to be further developed.

   Moreover, we added two paragraphs at the end of the Introduction (Lines 69–76 and 82–87), in order to better explain the main purposes of our paper.

3. *The authors should be more critical about the uncertainty associated with their results especially with respect to the seismic/mechanical properties of the first (shallowest) layer. How does this rather large standard deviation affect the application of the layer-stripping method?*

   We have made some improvements to the calculation of velocities and quality factors. As explained in Sections 3.3 and 4.1, the quality factor profiles obtained using the layer stripping method strongly depend on the thickness and seismic properties of the topmost layer. While these properties are well constrained for the Q_P profile, it was difficult to correctly constrain the topmost layer thickness for the Q_S profile. This is because the velocity of the S-wave near the surface was too low. Therefore, we revised the S-wave velocity curve calculated by Picotti et al. (2015), obtaining an improved version. In this new version (Fig. 5a), errors of velocity versus depth are also represented, for both P and S waves. We have changed the paragraph on lines 244–250, to explain these improvements.

   Then, we modified the text in lines 230–233:

"By calculating the maximum penetration depth of the emerging ray at an offset of 6 m, we estimated the thickness of this layer to be about 1.6 m. Furthermore, the estimated dominant frequency and variance of the source are f_S= 496 Hz and σ_S= 146 Hz, respectively."

As expected, after these corrections the shape of the Q_S profile changed, showing lower quality factors in the deeper parts of the firn. We changed the Lines 262–264 as follows:

"The second graph (Fig. 10) shows a moderate increase of Q_S, from the previously calculated minimum value of 1.9±0.4 near the surface, to an average maximum value of about 250±90, which remains almost constant at depths greater than about 40 m."

We also changed the Lines 419–420 in the Conclusions as follows:

"The resulting experimental quality factors range from values lower than 5 at the surface to approximately 300 and 250 at about 60 m depth, for P and S waves, respectively."

Regarding the computation of uncertainties, we added two new paragraphs at lines 234–239 and 251–256.

In order to improve the theoretical model below the pore close-off depth, we modified some assumptions on the Poisson ratio at Lines 304–307. Being these assumptions more realistic, the comparison between the experimental and theoretical quality factors also improved, in particular for the S waves (see new Fig. 13, now Fig. 14). We reorganized the paragraphs between Lines 290–311, adding the corresponding new cites.

4. *These values were obtained as the average and the standard deviation of the Q factors obtained for traces recorded at 7, 8, 9 and 10 m offset from the source (point)? How does this rather large standard deviation affect the application of the layer-stripping method?*

As explained above, we made some improvements to the computation of velocities and quality factors (and corresponding errors). In the new version (lines 223–224 and 230) it is now specified that, together with the average of the quality factors of the shallowest layer, we computed also the standard deviations, both for Q_P and Q_S. In the old version it was indicated an incorrect value of the error for Q_P. In the new version we indicated the correct value: Q_P = 4.1±1.3. The effects of these errors on the application of the layer-stripping method, both for P and S waves, are described in point 3 above.

5. *In the current version, the manuscript does not provide a detailed discussion of the obtained results as reflected by the manuscript structure, which does not include a Discussion section yet solely a section presenting the results.*

A Discussion section has been included (Lines 330–411), to explain in detail the importance of this model for studies related to the physical properties of the firn and the characterization of subglacial materials using amplitude variations with offset (AVO) analysis.

To support the discussion, new data have been included in the paper. These data are displayed in the new Fig. 3. This plot is described in the manuscript at Lines 110–118.

6. *The conclusion is a mere summary of the main points of the manuscript, yet it does not interpret the main findings in a broader sense and does not relate them to the objectives stated in the Introduction.*

We added more details to the Conclusions, and two new paragraphs in lines 421–424 and 429–433.

7. *Throughout the manuscript the authors use rather qualitative formulations to describe their results (e.g., "very low/high"). Considering the strong mathematical and physical background of this study such formulations should be avoided by providing a more quantitative interpretation of results or presentation of findings/values reported in the existing literature. Further (more detailed) comments and suggested (technical) corrections can be found in the annotated manuscript file attached here.*

We accepted most comments and suggested corrections (technical) found in the annotated manuscript. Many qualitative formulations have been eliminated or replaced with quantitative ones. We would like to point out that many of these expressions were already supported by quantitative explanations.

8. *Lines 235–240: The grains (ice) have the properties K_s = 10 GPa, μ_s = 5 GPa (shear modulus) and ρ_s = 917 kg/m^3 in both layers. The fluid saturating the pores is assumed to be fluidized snow, which is defined as a mixture of snow particles and air, like powder, having zero rigidity modulus. We considerK_f = 571 MPa, ρ_f = 200 kg/m^3 and η = 0.1 Pa s. Reference for these values?*

   Lines 250–261: The squirt-flow model has the following values of the parameters: h/R = 0.015, ϕ_c = 0.0002, $K_h = 1.38K_m$, where K_m is the bulk modulus with the grain contacts and cracks open, C = 0.012 kg^2/m^4

Regarding the grain (ice) properties, we cite Gurevich and Carcione (2023) (Line 281).

Regarding the squirt-flow model properties, we cite Carcione and Gurevich (2011) (Line 314).

Regarding the properties of fluidized snow (K_f, ρ_f and η), there is already a sentence specifying the references in Lines 283–284. Moreover, we added a paragraph (lines 285–289), and a new reference (Nishimura, 1991).

Regarding the constant C in the permeability equation, there are already two references in Line 310: Sidler (2015) and

Gurevich and Carcione (2023).

9. *Line 264: "softer layer with much higher porosity". What is "softer" and "much higher", respectively?*

At the beginning of Section 3.2 we state that "Firn is assumed to be a deposition of two porous media, one layer snow-like with high porosity and the other ice-like with low porosity.". Therefore, the term "softer" refers to the layer with higher porosity.

10. *Line 266–267: "strong peak", a strong peak in what? "lower frequencies", quantify.*

We specified "strong relaxation peak (high attenuation)..." (Line 319).

11. *Line 280: "amplitude-versus-offset (AVO)". Why was this not mentioned before?*

As indicated in point 2 above, we evidenced the importance of this study for AVO in a specific paragraph at the end of the introduction. Moreover, in the new version of the paper we have added a Discussion section detailing the utility of this model for AVO inversion.