# Author responses to review 1 of: Seismic attenuation in Antarctic firn

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## 1 Introduction

First of all, we would like to thank the reviewer for the valuable and constructive comments on our manuscript!
Reviewer's comments are indicated in italic font in this letter. Moreover, new and revised paragraphs which were included in the main manuscript are indicated by the respective line numbers.
According to the points raised below, we made some improvements to the computation of velocities and quality factors (sections 4.1 and 4.2). Furthermore, we added some paragraphs to the Introduction and Conclusions, to better explain the main purposes of our paper and possible new applications of the described menthodology.

## 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 im-*

*portant 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.*

I 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 the following paragraph at the end of the Introduction (starting from Line 61), in order to better explain the main purposes of our paper:

"In the case of Antarctic firn, attenuation of seismic waves cannot be explained by adopting a simple porous model consisting of a rigid ice structure and a pore space filled with air. Such a basic ice-air model underestimates seismic attenuation by orders of magnitude. Therefore, the fluid saturating the pore space in this case is assumed to be fluidized snow, a mixture of snow particles and air (Mellor, 1974; Maeno and Nishimura, 1979; Nishimura, 1996). In this study we show that replacing air with fluidized snow in the pores leads to higher attenuation, and to quality factor values comparable with those obtained from the seismic data. To our knowledge, this is the first attempt to use the concept of fluidized snow as a pore fluid in Biot-theory to model wave attenuation in firn."

We also added the following paragraph at the end of the Conclusions:

"Knowledge of seismic velocity and attenuation is also important because they could allow, at least theoretically, to obtain the porosity profile of polar firn by means of surface seismic or borehole experiments. Therefore, borehole logging in cheap hot water drill holes could replace costly core drills."

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 Section 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. We changed the Lines 206-209 as follows:

"Calculating the maximum penetration depth of the ray emerging at 6 m offset, we estimated the thickness of this layer to be about 1.6 m thick. Moreover, the estimated source dominant frequency and variance are $f_S$= 496 Hz and $\sigma_S$= 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 223-224 as follows:

"The second plot (Fig. 9) exhibit a moderate increase of $Q_S$, from the previously computed minimum value of 1.9±0.5 close to the surface, to an average maximum value of about 210±77, which remains almost constant at depths larger than 35 m."

We also changed the Line 283 in the Conclusions as follows:

"The resulting experimental quality factors range from values as low as 5 at the surface to approximately 300 and 200 at about 60 m depth, for P and S-waves respectively."

In order to improve the theoretical model, we modified the assumptions on the Poisson ratio of the layers. We changed the Lines 241-245 as follows:

"The physical properties of the firn layer are derived from the density model using functions of porosity that have been shown to be suitable for snow. The density profile as a function of depth is obtained by using the following empirical relationship

$$\rho(z) = 0.917\left[1+\left(\frac{V_{P,ice}-V_P(z)}{2250}\right)^{1.22}\right]^{-1}, \tag{1}$$

Kohnen (1972), where $V_P(z)$ is the vertical P-wave velocity displayed in Fig. 4 (a), and $V_{P,ice}$ = 3864 m/s is the ice P-wave velocity, which we assume equal to the maximum computed P-wave velocity.
The porosity obtained from the experimental density (1) is

$$\phi(z) = \frac{\rho_s - \rho(z)}{\rho_s - \rho_f}. \tag{2}$$

Fig. 11 shows the experimental density (a) and porosity (b) as a function of depth. These quantities increase monotonically with depth, mainly due to compaction.

⟨⟨ Figure 11 ⟩⟩

Then, for each layer, the dry-rock bulk modulus which best fits the data of Johnson (1982) is

$$K_m = K_s(1-\phi)^{30.85/(7.76-\phi)}. \tag{3}$$

The dry-rock shear modulus is

$$\mu = \frac{3}{2}\frac{1-2\nu}{1+\nu}K_m, \quad \nu = 0.38 - 0.36\phi, \tag{4}$$

where $\nu$ is the Poisson ratio. For $\phi \leq 6$ % ($\rho \geq 870$ kg/m$^3$) the medium is almost ice, and the Poisson ratio is better approximated from the inverted wave velocities as follows

$$\nu = \frac{{V_P}^2 - 2{V_S}^2}{2\left({V_P}^2 - {V_S}^2\right)} \approx 0.32, \tag{5}$$

(Mavko et al., 2009), where $V_P$ and $V_S$ are the P- and S-wave velocities displayed in Fig. 4(a), respectively."

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 also improved, in particular for the S waves. The new figures 4(a) and 13 are shown below. As requested by the reviewer, we added a second abscissa on the top of each figure, to represent the density corresponding to the depths shown at the bottom abscissa.

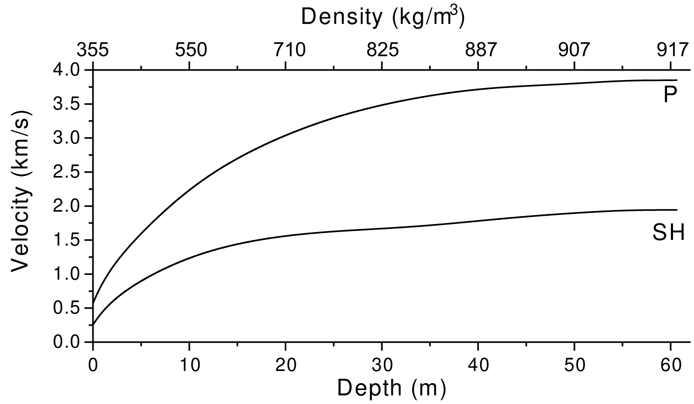


**Figure 1.** P-wave and S-wave velocity profiles versus depth, obtained using the Hergloz-Wiechert traveltime inversion method. The velocity curves are also represented versus density, obtained using equation (1), proposed by Kohnen (1972).

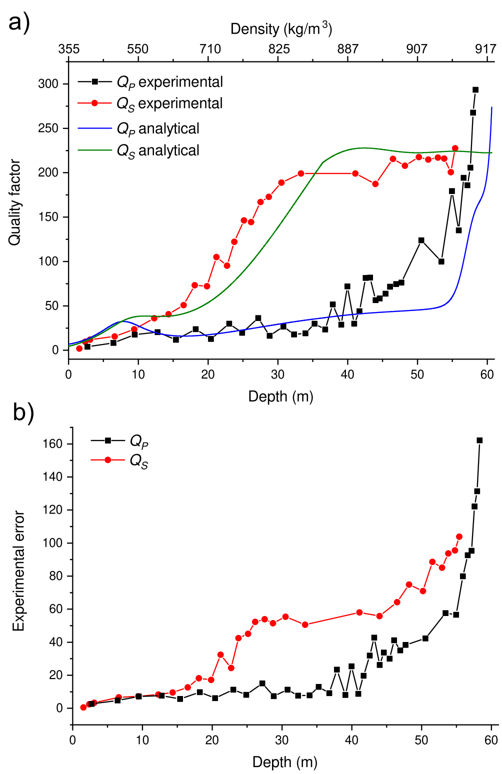


**Figure 2.** Comparison between the experimental (symbols) and theoretical (solid lines) P- and S-wave quality factors (a) as a function of depth. The quality factors are also represented versus density, obtained using equation (1), proposed by Kohnen (1972). Experimental errors (b) in the computation of $Q_P$ and $Q_S$ from the layer-stripping frequency-shift method.

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.*

It is important for this study to measure the properties of the fluidized snow phase. This task can be performed in drilled cores of firn samples as indicated in Nishimura (1991). The main apparatus consists of two parts: fluidized snow feeder and inclined chute, where snow can be kept in disintegrated and fluidized conditions. The measurements are carried out at a temperature of $-15$ °C to avoid the effects of adhesion between snow particles. In this context, bulk density, elastic velocity and viscosity can be measured.

We added this paragraph at Line 245, and 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).

4. *Line 250: "depth depth"*.

Corrected.