Response to the Review

of

Wojciech Gajek, 07 Oct 2024

Title. consider modification of title to better point the reader to scope of your paper, maybe include Stress already

- I changed the title accordingly to "Understanding Seismic Anisotropy in the Rotondo Granite: Investigating Stress as a Potential Source".

Table 1. Reading through, I am not fully certain if the boreholes are totally straight. Please mention it somewhere

- It is right that the boreholes are totally straight. I added this information in the text, see **line 129**.

Table 2. information about sampling frequency should be provided somewhere

- We sampled the data with the highest possible sampling frequency of 48kHz. The information is added in the text in **line 149**.

Table 2. Please help us to understand which was finally used. I am confused. If all, then I think it's fine as it is.

- The results shown in the main part of the paper are based on the first two surveys, while the last survey is added in the appendix for completeness. I highlighted the used surveys in **Table 2** for more clarity.

Line 154. what is your picking method?

- The travel times used in this study are all picked by hand. This ensures precise and reliable picks without mixing the different wave types. I added a short description of the picking method in **line 194**.

Line 228 and 229. "slightly" not informative

- These expressions in section **line 274 – 279** have been corrected.

Figure 5. some figures are lacking panel descriptions (a,b,c etc) like here. The SWS data in panel c does not help much in the interpretation. Also it lacks the colorbar. I propose to include it as a separate chart or resign from it (or at least add the colorbar)

- I reviewed all figures and added the panel descriptions accordingly. The SWS data were removed from Fig. 5 and are now added in the **new Fig. 6**.

Figure 6. if the colorscale is clipped (from text I conclude it must be please indicate it in the caption)

- The colorbar in this plot is clipped to avoid a distortion of the plot by single outliers. I added this information in the **figure description of Fig. 7.**

Line 347. It is discussed but was not introduced before. Consider mentioning what is it before.

- I now introduce this symmetry earlier in the paper in **Sect. 2, line 58**.

A discussion of the bigger picture of stress-induced anisotropy is added in the introduction (see **lines 18 – 20 and 29 – 33**).

Response to the Review

of

Leon Thomsen, 03 Nov 2024

Line 46. This statement is probably not true, and in any case should be supported with references. A better statement would be, “A commonly studied type of seismic anisotropy...”

- This statement got corrected as suggested to “The commonly studied type of anisotropy …” and referenced by Aminzadeh et al., 2022; Horne, 2013 (**line 55**).

Line 55. It should be specified here that Cij is measured in the principal coordinate system of the medium, not the survey coordinate system.

- This information is added in **line 67**, to point out that the elastic tensor is measured in another coordinate system than the survey coordinate system.

Line 57. These phase velocities are correct, but the data measure group (ray) arrival times, hence group (ray) velocities, at ray angles, not phase angles. The authors should discuss these issues, referring e.g. to Thomsen (1986).

- I added a section, pointing out this important difference between the two velocity types in anisotropic medium in **line 87 – 92**. Additionally, I describe in **line 93 – 96**, why it is still valid in our case of a homogeneous, weak anisotropic medium, to work with the equations of the phase velocities.

Line 70. The reference here should not be “near-vertical”, but rather “close to the symmetry axis”, which differs from the vertical in TTI media.

- I changed the description of δ to “controlling parameter for rays subparallel to the symmetry axis” (**line 81**).

Line 102. It appears from Fig. 1 that the boreholes all lie in or close to the vertical plane beneath the tunnel. It would be useful to rotate the inset in Fig. 1 to align with that plane, thus showing the deviations (if any) from the plane. If the data are all co-planar, that reduces their ability to describe tilted orthorhombic symmetry.

- A new subplot is added to **Fig. 1**. The subplot (1d) shows the boreholes used in the survey and exemplary rays from the top, aligned with the vertical plane.

Line 124. This claim needs a reference.

- I added a more explicit description of the P-wave sparker, based on Ellis and Singer (2007) and Geotomographie GmbH, in **lines 143 -148**. The sparker is described as a “monopole source discharging energy through two adjacent electrodes in a water-filled borehole. This energy discharge generates a pressure pulse, which initially spreads isotropically in the water and therefore also excites the borehole wall isotropically.”

Line 127. This “explanation” is misleading. A better explanation would be, “This can be explained by P-S conversion at the borehole wall near to the source..”

- I incorporated this explanation in **line 153**.

LINE 134. This 3C orientation issue results in a MAJOR limitation in the analysis. The geophones may be oriented from the data itself, assuming vector fidelity (c.f. Gaiser, 2007, Geophysics, 72(3), p. V67–

V77). For each geophone-source pair: a) Rotate (3D) the 3C data such that the energy in the P-wave window is maximized on the new x3 axis, which is now aligned with the incoming P-wave polarization, which is close to the P-wave propagation vector. (If this is not pointing back at the source, then either the medium is not uniform (as assumed), or the data are not vector-faithful (as assumed).) b) Rotate about the new x3 axis such that the cross-correlation of the x1 and x2 traces is maximized, with a cross-correlation lag. The geophone is now aligned (3D) in the principal coordinate system, with the three modes separated onto the three axes. c) If you assume (as you apparently do below), that S1 is the SH mode, then this specifies the new x1 axis as lying in the TTI plane of symmetry, which by assumption is the same for all geophones, and is determined absolutely from the P-wave velocities as you describe. d) These rotations, run backwards, determine the original orientation of the geophone. e) The same operation, with the same geophone but different source, should yield the same geophone orientation and the same orientation of the principal coordinate system; if not you can minimize the misfit, or use the differences to refine the assumptions. f) With the 3C data now fully specified, your analysis is more robust, including analysis of shear-wave polarizations.

- We highly appreciate your input on the analysis of the 3C geophone data. The proposed approach could indeed help to use the measured data for an advanced analysis, especially of the S-wave arrivals. Unfortunately, we have to conclude that the available data quality does not allow such an analysis. Even the first step, aligning the x3 component with the incoming energy, is not reliably possible. There are various reasons that prevent this analysis:
  - The quality of the 3C geophone data is in general very weak. About 25% of the measurement points cannot be used because at least one channel per measurement point is either too noisy or dead.
  - The original orientation of the components perpendicular to the borehole (x1, x2) are not known so that the rotation angle around the x3-component along the borehole cannot be interpreted.
  - In a considerable amount of source-receiver pairs a tube- or reflection wave is recorded in addition to the direct waves. These waves are polarized differently than the P- and S-waves and therefore appears even after the rotation on several components and overlays the signal of interest.
  - After the first rotation step (maximizing the P-wave energy on one component), most of the sensors show a maximized energy direction in the horizontal plane, independent of the source or receiver position. However, we do not assume that this describes the actual incoming wave direction, as no pattern with the measurement geometry can be found. We rather assume that this is due to the poor coupling of the sensor with the rock. This reduces the directional dependency of the sensors.

  The sensors used in this study were the only available and reasonably usable sensors under the given conditions. The sensors were “clamped” on the borehole wall by an inflatable bike tube, strongly influencing the data quality. We assume that this clamping mechanism is damping incoming waves from one side and also reduces the sensitivity of the vertical component, along the borehole.

  Even though that the proposed analysis did not work, the 3C geophone data are still helpful to identify the recorded signals as S-waves. Fig. A1 of the manuscript shows that the different wave types (here, P- and S1 wave) appear even in the unrotated case on different components, proving the different polarization directions of the waves. This knowledge proves the appearance of the different wave types in the measurements.

LINE 203, Table 3. This table shows the result that $\varepsilon<\delta$, which results in unusual SV-wave propagation (cf. Tsvankin and Thomsen, 1994, Geophysics, 59(8), 1290-1340). If this result survives the more robust 3C analysis described above, the authors should comment.

- This result is discussed in section **line 247 – 252**. Other studies on comparable rocks, such as Boese et al. (2021), Doetsch et al. (2020) or Motra et al. (2018), show the same trend of $\varepsilon<\delta$, so that our results are considered realistic. We also mention that the absolute values of the Thomsen parameters are sensitive to parameters such as pressure, temperature or mineral compositions, so that a comparison between different studies is challenging.

Line 226. Here the authors assume that S1=SH. This should be discussed.

- This observation is discussed in section **line 316 – 321** and **Fig. 6**. The picked apparent velocities are plotted against the angle between the straight ray and the symmetry axis. A clear separation between the different S-waves is observed in the data, verifying the assumption that one S-wave type is constantly faster. The velocity of the faster S1-wave is constantly increasing for increasing angles, with its maximum perpendicular to the symmetry axis. This verifies that the S1-wave is horizontally polarized with respect to the symmetry axis (=SH-wave).

Line 265. This is a strange result. Authors should show how the measured VS2 compare with VSV for their preferred model, as a function of angle.

- This result is also shown in **Fig. 6** and a discussion of this issue is added in **line 310 – 315**. The picked and the predicted apparent velocities of all three wave types are plotted as a function of the angle with the symmetry axis. This analysis shows that the optimized model can explain the pattern of all wave types, including the weak variation of the S2-wave.

Line 324. The logging data undersample near-vertical fractures.

- I address this observation in the section in **lines 380 - 385**. Studies such as Terzaghi (1965) state that fractures, which are (sub-)parallel to a borehole are undersampled. **Fig. A5** visualizes the undersampled directions for each borehole and the tunnel wall. It shows that a combined interpretation of all four data sets (SB2.1, SB2.2, SB2.3 and the tunnel wall) ensures that no fracture direction is undersampled in our analysis.

Line 228-331. These borehole methods estimate the stress in the immediate vicinity of the borehole, whereas the overburden load varies along the ray paths. Authors should discuss the issue of stress heterogeneity.

- A discussion of the stress heterogeneity is added in **lines 397 – 404**. The vertical stress component increases with increasing source or receiver depth, while the horizontal stress component is assumed to be uncorrelated with the measurement depth. Additionally, the effect of the measurement depth on the P-wave velocity is shown in **Fig. 9**. It shows, that the increase in velocity due to the ray direction is stronger than the effect due to the measurement depth.

Line 456. Authors: provide the name of the university for this Ph. D. thesis.

- The corresponding reference is corrected in the **reference list** and available online under https://doi.org/10.3929/ethz-b-000710435.

In addition, minor improvements were made to the manuscript with regard to individual formulations or spelling mistakes. These changes can be found in the track-changes file.