Solid Earth Discussions

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Comment on se-2021-27

Anonymous Referee #3

Referee comment on "Elastic anisotropies of deformed upper crustal rocks in the Alps" by Ruth Keppler et al., Solid Earth Discuss., https://doi.org/10.5194/se-2021-27-RC3, 2021

General Comments

In this study, the authors aim to characterize seismic anisotropy in the upper crust of collisional orogens with focus on the European Alps. The goal is to derive representative elastic properties of an average upper crustal rock as it would be measured by seismic observations which are sensitive only for larger scale structures. They select the Adula Nappe as representative unit for upper crustal deformation. Samples of Ortho- and Paragneisses are analyzed for their composition and CPO. CPO and volume percentages are determined in neutron time-of-flight diffractometer. Based on these measurements and considering single crystal anisotropies from laboratory measurements of previous studies, the anisotropy of the samples is calculated showing large variability. An average upper crustal rock is constructed using the volume percentages of relevant mineral phases, their characteristic CPO and average CPO strength. Thin sections and ultrasonic measurements are used to determine characteristic microcrack structure of the samples. This allowed a quantification of the influence of microcracks on the elastic anisotropy of an average upper crustal rock with depth.

The findings are well prepared and the conclusions reasonable based on the presented results. In particular I think this study is significant for the scientific community as it aims to fill the gap in scale between laboratory and seismic measurements, the approach is efficient, as it provides anisotropy for an effective average rock unit and it considers the change of anisotropy with depth by considering microcracks in the samples. I see only some minor issues, which require a minor revision.

Specific Comments

1) The only major issue, I see in the current manuscript, is the fact, that the influence of structural properties like intrusions or layering on the effective anisotropy measured in seismic experiments is mostly neglected throughout the manuscript with two exceptions in

the discussion (“layering” first occurs at L477). I would suggest spending some thoughts on this feature at earlier parts of the manuscript and revise some statements in view of this extrinsic anisotropy. Generally, this is not a very big issue, as the authors even provide already an idea of how to deal with this feature in the discussion: L628-630. The following 5 comments relate to the layering issue.

1-1) L37-39: Here, the authors are pointing out the limitations of the "average rock" applicability. I would suggest to also mention, that apparent anisotropy from structural larger-scale features like layering is not considered in the "average rock" approximation and needs additional knowledge, when interpreting seismic data sets.

1-2) L50-64: In the introduction, the authors nicely describe the different features to be considered, when measuring seismic anisotropy at rocks. The authors mention CPO and microcrack influence and the issues about scale differences between sample size, variability, and sensitivity of seismic observations. However, this introduction lacks mentioning structural features as layering, which also produces anisotropy. It should be mentioned, that even isotropic structures produce anisotropy when occurring as intrusions or small-scale layers within larger-scale rock units. I know that this is not considered in the average rock characterization, but this is an important limitation of the applicability, that should be consistently taken care of.

1-3) L167-168: Here, the authors mention the interlayers of lenses from different rock types. If I understood the explanation correctly, these lenses and structures are not considered in the average rock. I agree completely that these structures might be far too small to identify them and their properties in seismic methods. However, I assume that they have a significant effect on the measured anisotropy, which would be a result from the layering of these intrusions in the larger gneiss background rock. I would suggest mentioning this possibility in the discussion and refer to the layering which is identified here.

1-4) L369-370: Theoretically also heterogeneities like lenses if they occur regularly in the massif would have to be considered. However, the geometry won't be as equally distributed as the properties considered here, therefore I completely agree with the choice of parameters used for the average rock. Still, the statement here reads as if it is a complete list of important factors, which is not completely true.

1-5) L579-580: I agree here that the CPO of marble might be of no relevance for the anisotropy of the overall unit. However, the lenses itself with their shape oriented and spread over a wider region might very well produce effective anisotropy in seismic measurements. That depends of course on the vertical and horizontal extent in which these lenses occur. I don't want to say, that the assumption here is wrong. It might very well be, that these lenses have no effect at all. But I would assume, that this very much depends on the geometry and frequency of these lenses as there is a considerable difference in isotropic (P-wave) velocities between marble and gneiss.

Not related to layering:

2) L18-19: “This yields difficulties for seismic investigations of tectonic structures at depth since local changes in elastic anisotropy cannot be detected.” > Maybe this is not really the point. I would say it is more important, that the diverse and partially strong upper crustal anisotropy might overprint the signal of anisotropic structures at depth, when observed and interpreted in seismic measurements.

3) L46-48: I would suggest to cite the AlpArray seismic network group, here.
(Hetényi, G., Molinari, I., Clinton, J., Bokelmann, G., Bondár, I., Crawford, W. C., Dessa, J.-X., Doubre, C., Friederich, W., Fuchs, F., et al., 2018a. The AlpArray seismic network: a large-scale European experiment to image the Alpine orogen, Surveys in geophysics, 39(5), 1009–1033.)

4) L103-113: There are a lot more studies looking into the anisotropy of the Alps, which complement the early studies cited here. Below a few recent examples.
Orogen parallel anisotropy:
Bokelmann, G. H. R., Qorbani, E., & Bianchi, I., 2013. Seismic anisotropy and large-scale deformation of the Eastern Alps, Earth and Planetary Science Letters, 383, 1–6, doi: 10.1016/j.epsl.2013.09.019.
Petrescu, L., Pondrelli, S., Salimbeni, S., Faccenda, M., & Group, A. W., 2020. Mantle flow below the central and greater Alpine region: insights from SKS anisotropy analysis at AlpArray and permanent stations, Solid Earth, 11(4), 1275–1290, doi: 10.5194/se-11-1275-2020.
Two-layer anisotropy also from SKS-splitting in the transition to the Eastern Alps (interpreting the two layers as asthenospheric flow above a detached lithospheric slab fragment with frozen in mountain chain parallel CPO):
Qorbani, E., Bianchi, I., & Bokelmann, G., 2015. Slab detachment under the Eastern Alps seen by seismic anisotropy, Earth and Planetary Science Letters, 409(1), 96–108, doi: 10.1016/j.epsl.2014.10.049.
Link, F. & Rümpker, G., 2021. Resolving seismic anisotropy in the lithosphere-asthenosphere in the Central/Eastern Alps beneath the dense SWATH-D network, Front. Earth Sci., provisionally accepted, doi: 10.3389/feart.2021.679887.

5) L114-117: I was a bit irritated by the abrupt change of focus from the general collisional and orogenic setting of the Alps to the very distinct profile, which the measurements and interpretation are based on. Maybe one or two phrases explaining, why this profile is chosen as representative region for the general setting would be nice, that the reader follows the flow of work here.

6) L636-638: It would be nice, if there would be some suggestions on the seismic techniques the authors think are suitable to investigate the upper crustal anisotropy. While receiver function techniques are great to infer seismic anisotropy for a certain depth below a single station, they are only sensitive to azimuthal anisotropy. If I look at the foliation/lineation map, I would assume that the radial anisotropy is much larger than the azimuthal anisotropy. Therefore, surface wave techniques or local earthquake tomography

might be more suitable, while less accurate in lateral and depth resolution.

Technical comments

L17-18: Doubling of the word "very", maybe use "highly".

L27-28: Insert "the" in "of deformed"

L53-54: Remove the first occurrence of "be"

L220: …rocks are discussed in, e.g., (Vasin et al., 2013; Vasin et al., 2017; Lokajicek et al., 2021).
I would suggest removing the braces "()". "…, e.g., Vasin et al. (2013; 2017) and Lokajicek et al. (2021)."