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Comment on se-2021-56

M. R. Handy (Referee)

Referee comment on "Two subduction-related heterogeneities beneath the Eastern Alps and the Bohemian Massif imaged by high-resolution P-wave tomography" by Jaroslava Plomerová et al., Solid Earth Discuss., https://doi.org/10.5194/se-2021-56-RC1, 2021

Reviewer Comments on se-2021-56

Mark R. Handy

Black – lines and text from Plomerova et al.

Red – my comments

This paper provides readers with new insight of seismological P-wave anomalies beneath the Alps and their eastern foreland. It employs AlpArray data as well as data from the EASI "swath" experiment across the Eastern and Southern Alps. As such it is a welcome contribution to the growing wealth of literature from these ambitious projects.

As a tectonist, I have concentrated on structural aspects of the authors' interpretation, leaving an assessment of seismological aspects to other qualified reviewers and the topical editor. My main criticisms pertain to the authors' interpretation/understanding of tectonic models, to their nomenclature and to the clarity of their text and figures. I have grouped my comments under headings that pertain to the main themes in the manuscript. My comments follow immediately on the pertinent lines in the manuscript.

Introduction:

Lines 31-32: “The classical concept assumed the European lithospheric slab subducted south-eastward/southward along the entire Alpine chain (Mueller, 1982) without any fragmentation.” I would specify “Alps” rather than “the entire Alpine chain” because Mueller was referring only to the Alps sensu stricto, not to other parts of the Alpine chain which also includes the Apennines and Carpathians. The latter involve subduction of Adriatic lithosphere. It would also be appropriate to cite colleagues who previously proposed lithospheric subduction in the Alps (e.g., Laubscher 1970) inspired by the much earlier “classical” work of Ampferer and Argand.

Line 40: “…reversed polarity…” Here, I would recommend using the descriptive term “opposite dip” rather than “reverse polarity”. The latter is more interpretative and pre-supposes a change in the direction of subduction.

Line 43: “….with a gap between the two Alpine keels…” Please define what you mean by “keel”. You probably mean slabs. Note that Mitterbauer et al. (2011) preferred an interpretation in which there is no slab gap between the Central and Eastern Alps.

Line 58: Nomenclature – “the south-eastern part of the BM (referred to as HV-BM throughout the paper)…” Please keep things simple by using BM = Bohemian Massif. Or, if you really need this long abbreviation (HV-BM), then write it out completely to make your usage clear.

Resolution tests:

Lines 201-205: "The above performed synthetic tests corroborate that the data from the AlpArray and EASI networks are able to image two separate northward dipping sub-parallel slabs beneath the E. Alps and southern rim of the BM. The two slabs are separate from each other, and the northern one is not connected with the shallow parts of the lithosphere (above ~100km). The flip of the subduction polarity beneath the E. Alps relative to the W. Alps is undoubtedly real and it is not produced by potential smearing due to ray geometry." I would distinguish between slab dip (the direction that the slab is presently slanted) and subduction polarity (the original direction of subduction). The steep northward dip of the slab beneath the Eastern Alps is a robust feature of all models so far, but the original direction of subduction is debatable (see comments below). For comparison of end-member models with different slab dips, e.g., resolution tests of Paffrath et al. (in rev.).

Connection of surface to subsurface dynamics:

Lines 226-229: "The uplift rates in the W. and C. Alps exhibit at least 50% contribution by convective processes (due to slab detachment) and dynamic contributions (due to the sub-lithospheric mantle flow), while isostatic response due to ice unloading during deglaciations dominates in the E. Alps (Sternai, 2019)." There are other modelling studies that differ from those of Sternai 2019 in both their approach and their conclusions; they warrant reading and citation in this context (e.g., Champognac et al. 2007, Fox et al. 2015, Mey et al. 2016).

Slab polarity and the boundary between the Eastern and Central Alps:

Lines. 222-224: "In recent studies, Paffrath et al. (2020) suggest the reversed slab polarity relative to the Western Alps already in the Central Alps, as opposed to the formerly documented polarity reversal further to the east - beneath the E. Alps (e.g., Babuška et al., 1990, Lippitsch 2003; Zhao et al., 2016)." This is a misunderstanding/misreading, because Paffrath et al. don't claim that there was a reversal in slab polarity below the Central Alps! Please read carefully. Rather, they refer to the part of the slab beneath the Eastern Alps when they write „The new model does not require a slab polarity switch due to the detachment from the crust and the nearly vertical dip of the eastern Alpine slab. Tectonic arguments (in Handy et al., in rev. with Solid Earth) rather suggest a European provenance of the slab".

Lines 224-226: "Mock et al. (2020) pointed out the discordance between the slab geometry at depth and the boundary between the Eastern and Central Alps observed in the surface geology and, similarly to Rosenberg et al. (2018), shift the boundary between the E. and C. Alps further to the east, at the Giudicare-Brenner fault system." The authors cited do not redefine the boundary between Eastern and Central Alps, they merely note a discordance between the slab geometry at depth and the boundary between the Eastern and Central Alps observed at the surface. The boundary between the E. and C. Alps is defined at the surface in map view by the western edge of the continuous Austroalpine nappe stack located in Eastern Switzerland. This traditional definition does not take into account the effect of erosion which removed Austroalpine nappes originally exposed somewhat further to the west. The former existance of these nappes to the west is supported by the provenance of components in the Molasse Basin and by the Austroalpine Klippe in the Central Alps. Regarding the Alpine slab, the boundary between the central and eastern slab segments (as defined either by a slab gap or a change in dip direction of the slab) coincides generally with the Giudicarie-Brenner faults. In light of recent evidence for a laterally continuous Alpine slab with a change in dip (Handy et al., in review with SE), it would be clearer to avoid relating surface and subsurface boundaries between Central and Eastern Alps.

Lines 238-241: "Later tomography of the upper mantle which included the E. Alps from data of regional passive experiments (Dando et al., 2011; Mitterbauer et al., 2011; Karousová et al., 2013) also retrieved the northward dipping high-velocity heterogeneity of similar geometries (Fig. 5) and associated it mostly with the Adria plate subduction." It is important to avoid equating a switch in the dip direction (polarity) of the Alpine slab with a gap in this slab. In the interpretation of Handy et al. (in rev. with Solid Earth), the slab changes its dip direction along strike without evidence for lateral separation into two segments. Rather, the along-strike change in dip direction of the slab coincides generally with an eastward transition in its degree of detachment from the orogenic lithosphere.

Lines 241-246: "….suggested three main phases in building the E. Alps keel: (1) NW translation of the Adria and its thrusting over the (subducting?) European plate in the W. Alps, (2) fragmentation of northern Adria along a deep-seated fault (possibly the Giudicarie Fault, or at least a spatially nearby structure) and (3) counter-clockwise rotation of the Adria and its subduction beneath the European plate in the Eastern Alps, with a triple-junction of three crustal terranes in its eastern rim proposed by BruÌ□ckl et al. (2010), although the deformation style between the E. Alps and the Pannonian Basin is usually considered diffuse on the surface.” Two points need clarification here: (1) Based on recent P-wave tomography from the newest Alp Array data (Paffrath et al. in rev), the length of slab beneath the Eastern Alps, irrespective of its dip direction, far exceeds the amount of shortening in the eastern Southern Alps. This precludes a primarily Adriatic origin of this slab, as discussed in Handy et al. in rev, Solid Earth; (2) there is no unequivocal evidence at the surface or at depth to support the idea of three “crustal terrains” with distinct Moho boundaries near the transition from E. Alps to the Pannonian Basin. Rather, the Pannonian Basin is underlain by thinned European and Adriatic crust and lithosphere that acquired their reduced thicknesses in Miocene time (e.g., Ustaszewski et al. 2008). The decrease in Moho depth going from the Eastern Alps to the Pannonian Basin is gradual, not abrupt (e.g., Horvath et al. 2015), indicating extensional flow of the lower crust and upper mantle.

Lines 267-277: “The north oriented dip of the EA subduction, imaged in early tomography studies…..Most of them agree in interpreting it being of Adriatic plate origin (Dando et al., 2011; Karousová et al., 2013). However, Mitterbauer et al. (2011), and similarly in recent tomography by Paffrath et al., (2021 this issue), the positive perturbations are associated with a delaminated EU slab. Kästle et al. (2020) relate the HV-EA mainly with the European plate subductions as well, and leave no or only minor role to the Adriatic subduction. The authors explain the northward subduction modelled beneath the E. Alps by imaging a combination of the short Adriatic and deep delaminated, potentially overturned European slabs.” Here, the authors should mention that recent P-wave tomography based on the newest Alp Array data (Paffrath et al. in rev) supports a primarily European origin of the north-dipping slab beneath the Eastern Alps (see discussion in Handy et al., in rev. with Solid Earth). This conclusion is based on the length of imaged slab beneath the Eastern Alps (several hundred km) which far exceeds the amount of shortening (c. 50 km) in the overlying crust of the eastern Southern Alps. In this interpretation, the steep northward dip of the slab segment beneath the E. Alps is attributed to asthenospheric flow during or after Adriatic indentation (Handy et al., rev.).

Lines 401-402: “The northward-dipping lithosphere keel is imaged down to ~200-250 km, without signs of delamination, and we associate it with the Adriatic plate subduction.” As above, it is unclear what the authors mean by “keel”. It appears to mean slab, but this should be clarified.

Interpretations of anomalies beneath the Bohemian Massif:

Lines 281-285: "To understand the positive perturbations beneath the southern BM, we compare it with results from the large-scale Paffrath et al. (20201) tomography and with the regional tomography of the BM (Karousová et al., 2013) of similar resolution to ours (Fig. 6). The strongest positive perturbations related to that heterogeneity overlap in the models, though they are of unrealistically large extent in the Paffrath's et al. model (2021, this issue)." Why is this extent in the Paffrath et al. model unrealistic? "There, they include also the ER with the thinnest BM lithosphere, well imaged by negative perturbations in the EASI-AA and in BOHEMA models (Karousová et al., 2013)."

Lines 308-311: "The role of applying proper crustal corrections is significant in teleseismic regional tomography. Not applying any crustal corrections or applying inadequate ones can strongly affect velocity perturbations within the upper ~100 km of the upper mantle (e.g., Karousová et al., 2013), which is the zone, where the models discussed above differ. From this point of view, developing a uniform detailed and reliable model of the European crust is urgently needed." I agree and find the comparison of models in this chapter valuable. I've sent the authors some PPT slides of a recent talk showing the correspondence between models regarding the degree of connectivity of slabs with their orogenic lithosphere. Both the recent P-wave tomography employing 3D crustal models (Paffrath et al. in rev.) and the surface wave models of Kaestle et al. (2018, 2020) indicate slab detachment in the Western and Eastern Alps, with local slab attachment only in the western Central Alps. This coincidence of images with different methods suggests that the crustal correction of the P-wave model of Paffrath et al. is robust.

Lines 332-333: "The simplest explanation would be to consider it as a fragment of the delaminated part of the European plate subductions, as suggested in Handy et al. (2015) (Fig.7a)." This appears to be a misunderstanding: The +Vp anomaly below the BM is not the anomaly referred to in Handy et al. 2015 (their Fig. 11a), which was a European slab hanging directly below the Eastern Alps in Miocene time. Note that Handy et al. 2015 never considered a +Vp anomaly below the BM in their model. Instead, the Miocene +Vp anomaly below the Eastern Alps in their figure is torn European lithosphere that sank and no longer exists. The model of Handy et al. 2015 is actually consistent with the statement in Line 338 that "Therefore, an association of the HV-BM with the delaminated fragment of the EU subduction is not likely."

Points pertaining to rock physics:

Lines 347-348: "The Phanerozoic continental mantle lithosphere, composed of originally lighter rocks than those in the asthenosphere (Mantle lithosphere is generally denser rather than lighter than asthenospheric mantle) and becomes denser due to metamorphic phase changes as it subducts" (reference?)

Lines 360-363: "The roll-back subduction of the Carpathians, accompanied by a substantial asthenospheric flow, could open a space between the E. Alpine and Carpathian slabs for the northwestward "transportation" of a purely oceanic lithosphere or a mix of oceanic and continental lithosphere fragment into the mantle beneath the BM." No reason or mechanism is provided here to explain why oceanic or mixed ocean-continent lithosphere should be "transported" northward. Please elaborate.

Lines 380-396: The authors emphasize the importance of accounting for seismic anisotropy when interpreting body-wave tomography: "Ignoring seismic anisotropy and assuming isotropic wave propagation or considering only azimuthal and/or radial anisotropy leads to significant isotropic and anisotropic imaging artefacts that may lead to spurious interpretations (Vanderbeek and Faccenda, 2021)." The reader is left without a clear explanation of how anisotropy would change the images of +Vp anomalies which are the basis for interpretations. It would be helpful to discuss this more specifically instead of making vague references to future studies in Lines 392-395.

Figures and Captions: These need significant improvement.

Fig. 1 (right side): Label the main faults and use transparent colour to mark the Alps between the Northern and Southern Alpine Fronts.

Fig. 2 (right panel): Label the Southern Alpine Front (SAF), use transparent colour to mark the Alps between the Northern and Southern Alpine Fronts. It would help to mark the outlines of the Tauern Window (TW). I would eliminate the triple junction, because there is no structural evidence for a Pannonian Plate sensu Brückl et al. (see comments above).

Fig. 3: Label the Southern Alpine Front (SAF) on all cross sections. In the caption, indicate what DF means (this is not included in any of the earlier captions). Indicate the traces of all cross sections on a map or inset map. Include coordinates of the endpoints in the caption or directly on the figures. This is important for others who wish to compare their results with the authors'.

Fig. 4: Label all the faults shown in the other cross sections. Include coordinates of the endpoints in caption or directly on the figures. Again, this is important for others who wish to compare their results with the authors'.

Fig. 5: The labelling of the cross sections should be made clearer. Label each section only once so it corresponds to the letters of the traces on the map. The orogen-parallel cross section in a) should have the longitudinal degrees correspond to the longitudinal units on the map on the lower right.

Fig. 6: Add Variscan unit boundaries on the main horizontal slice of Paffrath to enable better comparison with the other slices shown. Distinguish Alpine and Variscan boundaries, either by using lines with different thicknesses (Alps thick, Variscan thin) or colours.

Fig. 7: Check the position of the cross sections with respect to the seismic anomalies, because they look misaligned. The northern tip of the delaminated EU slab in a) is too far to the north in b) with respect to the Northern Alpine Front (NAF). Handy et al. 2015 proposed that this slab sank beneath the core of the Alps, not that it migrated to the north with respect to the front. However, if this is your idea (meaning the authors of this text), then please state this clearly.

Fig. 8: Show the end points of the cross sections on an inset map so that the location of the. anomalies and unit boundaries can be compared, otherwise the model can't be compared with other data and the reader is helplessly lost. In b), please also consider other interpretations of Late Devonian to late Carboniferous paleogeography and subduction directions of the Rheic Ocean, e.g., Schulmann et al. 2009, 2014, Ballevre et al. (2009), Zeh & Will (2011) or in Franke et al. (2000). What effect do these scenarios have on your interpretation of the 3% positive Vp anomaly beneath the Moldanubikum?

Please also note the supplement to this comment:
https://se.copernicus.org/preprints/se-2021-56/se-2021-56-RC1-supplement.pdf