Replies to Reviewer #2

Review of reviewer #2:
Dear Editor, Dear Authors,
the manuscript entitled "Gravity modelling of the Alpine lithosphere affected by magmatism based on seismic tomography" provides a very interesting and promising approach to model the density distribution in the Alpine crust. It makes a lot of sense to use existing seismic models as starting point to determine the density structure as they deliver reasonable constraints on Moho depth and principal crustal structures. However, I would like to see a more thorough discussion on the influence of the chosen starting model and of the 1D reference density model on the final result. This doubt is related to the observation that the Bouguer gravity anomaly (Fig. 3c) and the gravity anomalies after correction with the model obtained from seismic data (Fig. 7b) have a similar absolute range of values. Would your inversion results be drastically different if you simply used the 1D density model as starting model instead of the more complex Vs model? Many of the other comments listed below are related to the clarity of the manuscript, I would recommend a thorough revision to improve the English of the manuscript. Many local names of faults and regions in northern Italy are used in the manuscript. It would certainly be easier for the reader if these regions were marked somewhere in the maps. The manuscript is well structured and the methods are properly explained. I would recommend the manuscript for publication in SE after a major revision that addresses the points listed in the supplement.
Please also note the supplement to this comment:
https://se.copernicus.org/preprints/se-2020-101/se-2020-101-RC2-supplement.pdf
Interactive comment on Solid Earth Discuss., https://doi.org/10.5194/se-2020-101, 2020.

Replies to the review:

Dear Editor, dear Reviewer,

We thank the reviewer for the time dedicated to reviewing our manuscript and for appreciating the fact that our work is "a very interesting and promising approach to model the density distribution in the Alpine crust".

Comment "It makes a lot of sense to use existing seismic models as starting point to determine the density structure as they deliver reasonable constraints on Moho depth and principal crustal structures. However, I would like to see a more thorough discussion on the influence of the chosen starting model and of the 1D reference density model on the final result"

Reply: we fully agree that the use of the existing seismic model is an excellent approach to model the crustal density, due to the inherent ambiguity in the solutions that satisfy the potential field. Limited constraints on the depth of the source are theoretically present from the wavelength of the gravity signal (e.g. Blakely, 2009; Braitenberg, 2020; Tsuboi, 1983), but the inversion of the density distribution requires constraints on depth and density. For instance, one solution could be formulated by a mass distribution of fixed thickness and fixed depth, with varying density. The sheet mass distribution would reproduce the gravity, but the density that would be obtained would be incompatible with the rock densities, since the real density distribution exists throughout the lithosphere and mantle. When transferring the entire source-mass to one fixed layer leads to densities that do not comply with the experimentally known in situ densities of rocks in crust, mantle lithosphere and mantle, although the potential field is satisfied. For this reason, it is necessary to set some constraints on the density distribution, which we do using the seismic velocity model both for mantle and lithosphere, and the relations that tie density to velocity.

In the case that the seismic model is available, as in the case of the Alps, we have opted for the strategy to use it as constraint for the density modeling. Given the relation between velocity and density, in theory it could be sufficient to apply the conversion and obtain at once the correct density model. This would be true, if there were no density bounds on each velocity value. The density bounds are due to the fact that the same velocity is obtained for different rock compositions, but not the density, so that there is a spread in the attributable density values, given a velocity value. The gravity field is used as a constrain, to fix the density values inside the acceptable bounds, given a certain velocity.

The 1D reference model is needed, because the gravity anomaly field is obtained from the absolute gravity values from which the gravity field of the reference ellipsoid is subtracted, analogous to the operation which is done in seismology, where the velocity slices are sometimes referred as percentage velocity variation respect to a 1D standard velocity model. Since density has a linear relation to gravity, the 1D density model has the effect of subtracting a constant gravity value from the modelled gravity values. A change in the 1 D reference model inducing a variation in the integrated mass column, has the effect of shifting the modelled gravity upward or downward, so over our study area competes with the very long wavelengths of the gravity field, that originates in the sublithospheric mantle densities. We opt for a 1 D density model which is a standard global Earth model, as it facilitates the future comparison of models from other authors with ours, since the reference model does not depend on our specific modeling. It further allows comparison of the Alpine analysis with a density model in other parts of the world, in case the same standard reference model is used. Using a coherent standard reference model maintains all information contained in the gravity data. The use of a reference model is a standard procedure in gravity modeling, and is a step which is needed and not optional. We publish the density values in term of absolute densities, so the 1 D reference model does not affect the final crustal density model. A different choice of reference model can in minor way only affect the final density values of the mantle.

Comment: “This doubt is related to the observation that the Bouguer gravity anomaly (Fig. 3c) and the gravity anomalies after correction with the model obtained from seismic data (Fig. 7b) have a similar absolute range of values. Would your inversion results be drastically different if you simply used the 1D density model as starting model instead of the more complex Vs model?”

Reply: As explained above, the results would be different, if we used a 1D starting model instead of the seismic model, due to the mandatory choice of the constraints needed for solving the inherent ambiguity. The results would not be drastically different by using another 1D reference model, since this would only affect the longest wavelength of the modelled gravity field, stemming from the mantle. Some widely used softwares, as Geosoft, when modeling the crust, subtract a constant from the observed gravity, instead of introducing a 1D reference model, and restrict the model to the superficial structures. In our view, the use of a 1D model is closer to reality, because the 1D model is based on world-wide averaging of crustal, subcrustal lithosphere and sublithospheric mantle densities. Neglecting the existing Vs model as constraint, would be equivalent to blindly neglecting existing constraints on the density structure, which to our view makes no sense, since this information is available and the closest model to the real world is the one which fits more than one observable, linked through the existing physical relations between the modelled parameters.
The gravity values, after subtracting the first model obtained from the seismic data, change the values from the starting range of 360 mGal to a range of 270 mGal, which is considerably different. Furthermore, the biggest large scale anomalies are largely reduced, leaving a residual field that is

dominated by smaller scale gravity anomalies. The large scale Bouguer lows are not seen any more (see Fig. 7b). Dividing the mantle contribution from the crustal contribution shows that the high amplitude of the residual comes from the mantle (Fig. 9a), with a range of 270 mGal, whereas the crustal contribution is mostly limited to a range of 140 mGal (Fig. 9b) with very located small scale features reaching to a range of 190 mGal.

Comment: Many local names of faults and regions in northern Italy are used in the manuscript. It would certainly be easier for the reader if these regions were marked somewhere in the maps.

Reply: we have now updated the maps to mark the cited local names, faults and regions.

Comment: The manuscript is well structured and the methods are properly explained. I would recommend the manuscript for publication in SE after a major revision that addresses the points listed in the supplement

Reply: We thank the reviewer for the appreciation of a well-structured manuscript, with well-explained methodology. We have addressed the points listed in the manuscript.

Comments from the supplementary:
General comments
In the following, the comment of the reviewer is in black, our reply in green.

l. 31 It would be good to highlight this region on the map in Fig. 1 and refer to Fig. 1 in this paragraph.
Ok, done.

l. 35 All maps are cut in the west at 8 degrees, part of the western Alps and the Ivrea body are thus missing. So it is not the entire Alpine arc.
Ok, Changed to Central and Eastern Alps.

l. 38-43 The sentences are repetitive. Please rephrase for more clarity.
Ok, cancelled repetition and rephrased: We use the most recent terrestrial-satellite derived gravity model, and apply the global correction for terrain, which leads to very different Bouguer gravity values compared to the classical local correction up to the 167 km Hayford radius, but is more realistic. The global fields require special attention, because of the far field effect of topography, and we include a dedicated chapter which explains how to deal with this problem, in order to use the fields in the regional density modeling. The Alpine gravity field has been modelled before (Ebbing et al., 2006; Spooner et al., 2019), novel in our study is the use of the Bouguer field corrected for the global topography.

it is also not clear to me what is meant by "we include a dedicated study".
Ok, changed to: The global fields require special attention, because of the far field effect of topography, and we include a dedicated chapter which explains how to deal with this problem, in order to use the fields in the regional density modeling.
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l. 55 A hypothesis should not be a question. I would recommend to write something like "We address the question whether..." or "The working hypothesis is that the above mentioned..."
Ok. Changed to: The working hypothesis is that the above mentioned gravity high could be related to the different magmatic events that have affected the study area at different times, and to the consequent crustal densification and/or juvenile crust formation in underplating.

l. 65 I am not sure whether the three faults/lineaments you name here can be classified as "tectonic systems". What is meant by tectonic system? Please rephrase to clarify.

Definition: A system is a group of individual yet interdependent components that interact to form a unified entity and are under the influence of related forces. A tectonic system consists of individual faults that are under the influence of an overarching stress field. They move individually, so as to bring the system into equilibrium in response to the applied stress field.
For the definition of a system see for instance the Introduction to tectonics lecture of Prof. Jean-Pierre Burg, ETH Zurich. http://www.files.ethz.ch/structuralgeology/JPB/files/English/1Introtecto.pdf

We have changed to fault systems, which is more specific to our case (Viganò et al., 2013).
Revised text: The central South-Alpine realms are characterized by three principal fault systems: the Val Sugana line, the Giudicarie line, and the Schio-Vicenza line, all active in the late Permian (Viganò et al., 2013). A fault system consists of individual faults, that are under the influence of an overarching stress field. They move individually, so as to bring the system into equilibrium in response to the applied stress field.

l. 63 Please give a reference for the Permian activity.
Reply: The reference is (Viganò et al., 2013), added in the text.

l. 65 What does "first Eocene" mean? Maybe the beginning of the Eocene?
Ok, changed to early Eocene.

l. 78 What is meant with "frame" here? Maybe not the right word?
Ok, changed to setting.

l. 90 What is meant with "confined with"? Maybe "was confined to"? But then I do not understand how a continental area can be confined to the oceanic domain of the western Tethys.
Changed to: which at the time bordered the western Tethys

l. 118 This is not exactly correct. The inversion includes the dataset of Ekstroem, 2011 which is a global dataset of phase-velocity measurements which is used to constrain the long-period velocity field, but it's not a starting model.
Changed to: The tomography inversion includes the global dataset of phase-velocity measurements of Ekström (2011) which is used to constrain the long-period velocity field.

l. 123-125 The numbers are not giving the resolution of the model in the sense of capability of resolving structures of that size. They only give the grid spacing of the model. The resolution is lower than the grid spacing and varies strongly across the model depending on station density, data quality and period. I would recommend to replace resolution with grid spacing in this sentence.
Ok, done.

l. 160 You should define all variables that haven't been defined before (r, GM, R, phi, ...).
Ok, done: G is the gravitational constant, M is the Earth mass, n,l are the degree and order of the spherical harmonic expansion, N is the maximum degree of the expansion, and r, λ, φ are the three spherical coordinates radius, longitude and latitude.

l. 168 "regional Bouguer values", meaning Bouguer values obtained with the local correction up to the Hayford radius?
Yes. Replaced with: obtained with the Hayford radius

l. 184 It is not clear to me which of the gravity models you chose to fit? The Bouguer gravity disturbance corrected with topography model RET2014 shown in Fig. 3a or the one in Fig. 3c? What exactly is the model shown in Fig. 3c? Is it the the one where you apply the Hayford radius correction?

Or is it the one where you use only the band-limited models? Please clarify in the text and in the Figure caption.

Ok, changed text and it should be clear now: The non-band-limited Bouguer field (Fig. 3a), the non-band-limited effect of topography (Fig. 3b) and the band-limited Bouguer field (Fig. 3c) are displayed in the respective maps. The band-limited Bouguer map (Fig. 3c) obtained for degrees $10 < N \leq 2190$ (EIGEN 6c4 and RET2014) has the same features as the non-band-limited map (Fig. 3a), with the difference that now the bounds of the Bouguer anomalies are more similar to those of the regional topographic reduction obtained with the Hayford radius (e.g. Braitenberg et al., 2013; Ebbing et al., 2006; Spooner et al., 2019; Zanolla et al., 2006).

l. 266 How important is the choice of the reference co-PREM model for your results? Your gravity measurements are corrected using a reference ellipsoid, the densities are translated into an anomaly by comparing it to a simple 1D model. Could that introduce a bias?

Maybe there is a misunderstanding, the 1D model is thought as a 1D density variation with depth, inside the ellipsoid. So it is not a simplification of the ellipsoid, but instead of using a homogeneous fluid mass with an average density of 5532.2 kg/m^3, which is the density of the ellipsoid, a more realistic density stratification is used. This is a standard procedure, as it is not possible to model the gravity anomalies without subtracting a reference model from the absolute densities. The reference model is equivalent to subtracting a constant value from the modelled gravity values, since gravity has a linear relation to density. For the crustal model a different choice of the reference model will not alter the results, because the constant gravity value will be absorbed in the mantle gravity residual field. Therefore, it could give some effect on the density variations in the mantle. Assuming a difference in the gravity field of the reference model of 10 mGal or 50 mGal, there would be an upward bias in the mantle densities of about 8 kg/m^3 or 40 kg/m^3, a very small value compared with the mantle densities of close to 3500 kg/m^3.

l. 303 Please show a Figure that illustrates the gravity residual after the last iteration (appendix or main manuscript). How many iterations are needed? I do not understand why the mantle component inversion needs an inner loop and the crustal part doesn't (Figure 8). Please explain. Are there any constraints on how far the density may deviate from the starting value?

Reply: The inner loop is present both in the crust and mantle, we have changed Fig.8 to make it clearer.

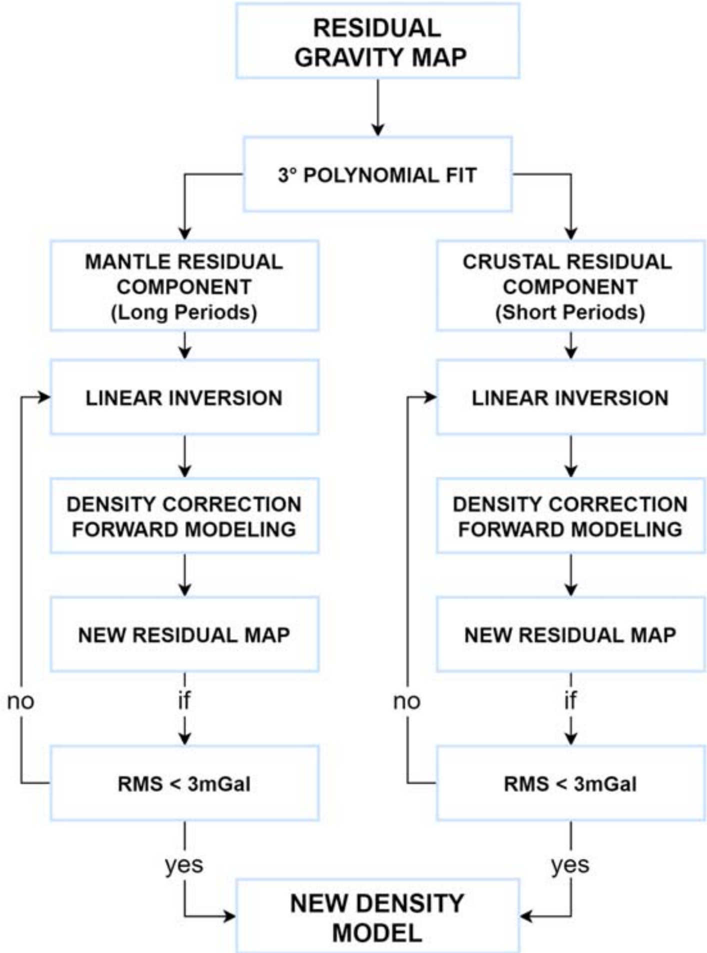

Figure 8 – Flowchart of the linear inversion algorithm

The density is free to vary at the stage of the iterations inside the bounds of acceptable densities in crust and mantle, defined from laboratory measurements. These are as follows: density in crust: 2200 kg/m^3 to 3000 kg/m^3. Mantle: 3000 kg/m^3 to 3500 kg/m^3. The number of iterations were 6 for the crust, and 5 for the mantle. We have added a figure:

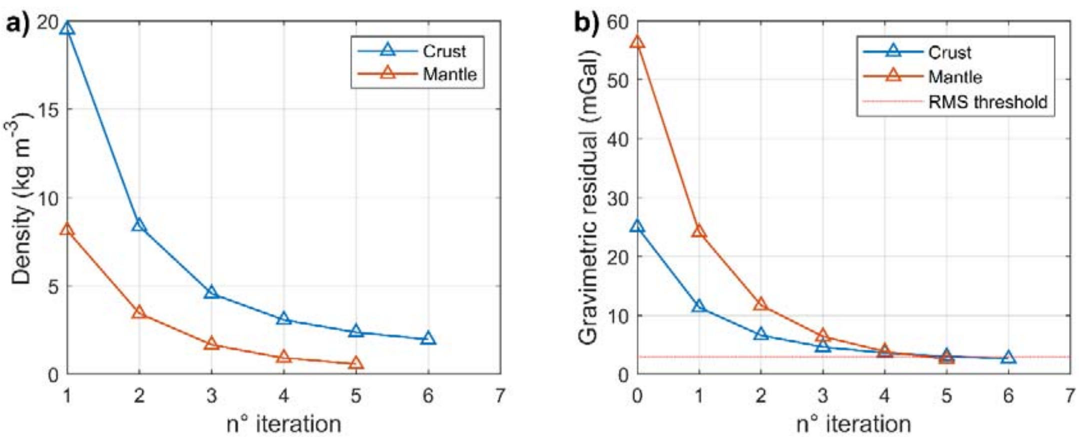

Figure Rv-1: Illustration of the effectiveness of the iteration steps in crust and mantle. A) Root means square density correction over the volume of crust and mantle during iterations. B) Root mean square decrease of the gravity residual, separated for the signal of crust and mantle during iterations. The iterations were stopped when a root mean square residual below 3 mGal was reached.

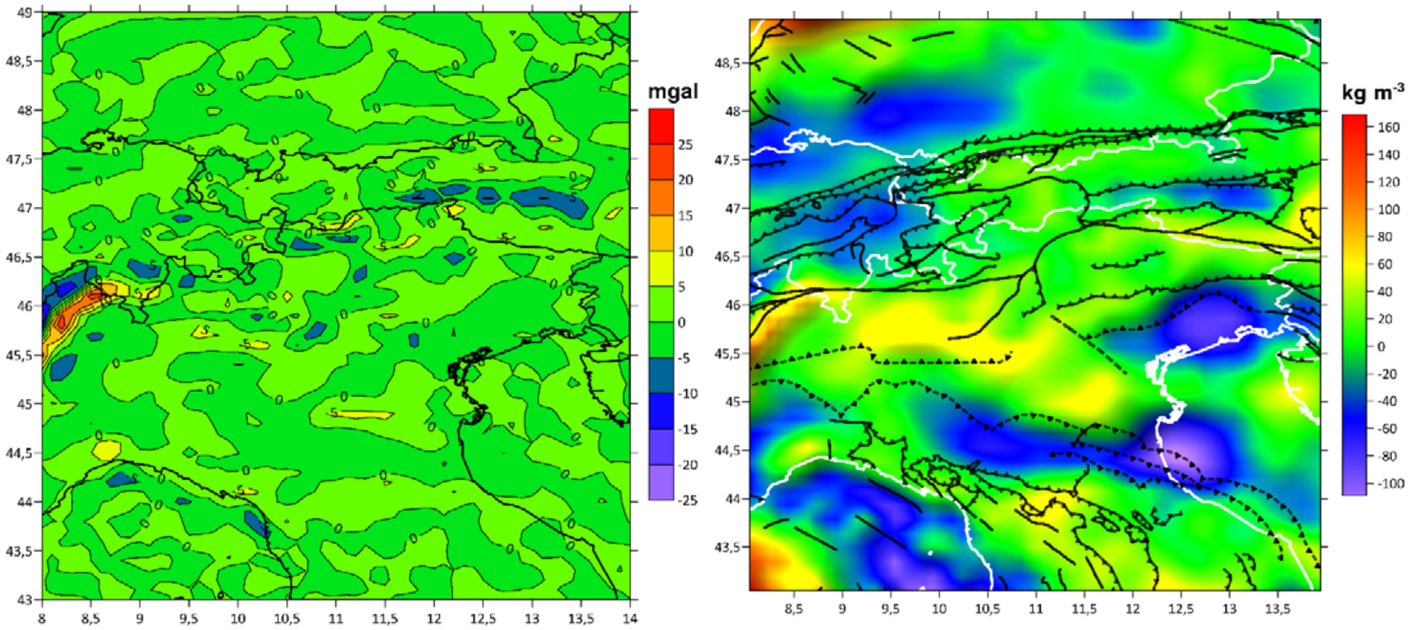

Figure Rv-2 Final gravity residual (left) and density correction (right) in the last step of the iteration for the crustal modelling.

l. 350 Please show a figure that compares the initial density values (in the starting model generated from the Vs model) with the final density model. Elaborate in the text how large the density variations between initial and final models are. Are the final densities still in good agreement with the Vs parameters or do we have regions where Vs and density are so different that there is no rock type that could explain the modelled features?

Reply: The initial density values are exactly on the two curves, of Gardner and Christensen-Mooney by definition. We have added a figure (here Fig. Rv-3) that shows the position of the final density values in the same graph. The upper and lower bounds are the experimental root mean square deviations from the curves, and are added to the graph. The final density values are illustrated by red symbols in the graph, and are seen to remain inside the one rms deviation from the theoretical relations.

In the updated text the paragraph reads: The root mean square density correction over the volume of crust and mantle and the root mean square decrease of the gravity residual, during iterations are shown in Fig. 10. It can be seen how the gravity residual quickly decays in the first iterations, and then remains close to constant when reaching the level of 3 mGal. The final density values in relation to the Vp velocity are shown in Fig.5, as red symbols. It can be seen that the final density values are inside the root mean square experimental deviations from the theoretical relations between density and velocity, and are therefore physically acceptable. The map of the density corrections and the final gravity residual, are displayed in Fig. 11.

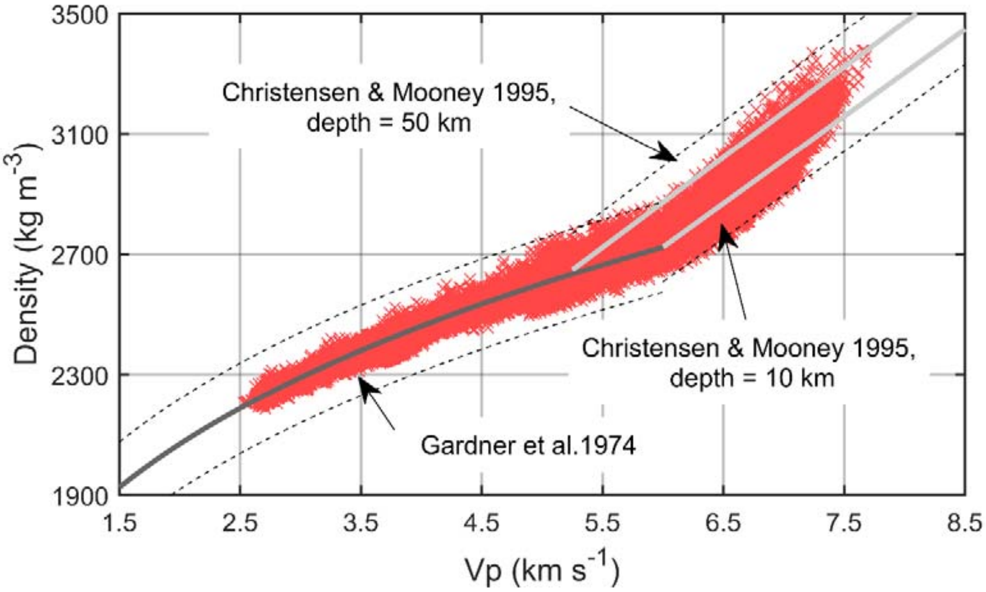

Figure Rv-3: Comparison of published densities versus Vp relations discussed in (Brocher, 2005), dark grey continuous line represents the Gardner's equation, light grey continuous line represents Christensen & Mooney linear regression fit. The relation of Christensen and Mooney has been published for different depth ranges, from 10 to 50 km, and we show the two extreme relations. The stippled curves delimit the upper and lower bounds derived from the root mean square experimental scatter from the lines. The switch from Gardner's equation to the relation of Christensen and Mooney is made at the intersection of the two relations. The red symbols show the final distribution of the density versus velocity values of our final model, at the end of the iterations.

l. 354 What is "the positive gravity anomaly"? Is it the Vicenza-Verona anomaly or the Venetian Volcanic anomaly? Please say so explicitly and mark the anomaly in one of your maps.
Reply: yes, it is the Venetian Volcanic anomaly. Added in text and in Figures 12b) and Figure 3c), as suggested.

l. 356 In profile 1, I cannot really see the high-density plateau (RH). If I take the point marked RH in profile A and go further NW or further SE, the density seems to increase, so why should that point be called adensity high? Maybe in mapview I can see a ridge-like high density feature (please show the profiletraces also in Fig. 12b). But the average density high in map view is more likely to be solely due to theMB1 anomaly directly above RH.
Reply: we have reformulated the description of the increased lower crustal density, to make it clearer: As seen before, between the South-Giudicarie fault (SGF) and the buried Appennines thrust front, there is again the increased density area (RH) situated between 25km and the Moho discontinuity, and extending between 10.8° E up to 11.8° E, with a density of 2900–3000 kg m^{-3}. This increased density in the lower crust can be recognized by an upward shift for instance of the 2900 kg m^{-3} isoline, distancing it from the Moho.

l. 361 What about the density high at about 9.8 deg in profile A? Why is this not categorized as anomaly?
Reply: we have now added a remark to this anomaly, although it is outside our focus area of the magmatic affected crust. We have added a comment:

Although outside our focus area, we mention a density high along profile A which is located NW of the Periadriatic Line (PL) and affects depths of 30 to 10 km. Along profile A it is located at longitude 9.8°

approximately. The recent work of Rosenberg and Kissling (2014) interprets the crustal velocity variations, and notices the upwelling of the velocity lines north of the PL, with a lower effect in the central Alps, and an increase of the effect towards the Central-Western Alps. They interpret it as lower crustal accreted terrain which is deformed and brought to upper crustal levels north of the PL. From our modeling this unit not only has high velocity, but also increased density.

l. 385 Why does the Tauern window show up with lower densities? Often, the Tauern window is described as an area of exhumation after indentation of Adria and uplift of European crust. This would lead to lower/middle crustal material (normally denser) being transported to shallow depths (see for example Fig. 1 in Lüschen et al. 2006, TRANSALP - deep crustal Vibroseis...). Consequently, highly metamorphic, high-density material is found at the surface (e.g. Groß et al. 2020, Crustal-Scale Sheath Folding...). In this context, I would expect higher densities in the Tauern region, but the opposite seems to be the case. Do you have an explanation for this discrepancy?

Reply: Our result of the decreased density is in full agreement with the measured density values, which give a reduced density of the Tauern window with respect to the surrounding areas. For instance in (Ebbing et al., 2006) there is a specific remark: A good example of the effect of near surface structures on the gravity field exists in the area of the Tauern Window. The densities of the upper parts of this structure are known from outcropping rocks measurements (Granser et al., 1989). The central gneiss of the Tauern Window has a low density (2550 kg/m3) and a negative contrast compared to the surrounding nappe structures (>2700 kg/m3).

l. 411 What is lithospheric attenuation? I am not familiar with this term and doubt that it is the proper expression.
Reply: The term can be found in several published papers, as for instance in the title of Spencer (1996). But since it seems to be a problem we changed the text to:
Regarding the geodynamic context, all evidence suggests that this magmatic pulse was induced by post-Variscan lithospheric thinning that produced crust-mantle detachment and large ultra-mafic crustal underplating, together with the development of a Permian basin

Comments that are only related to language/expression (non extensive)
Throughout the manuscript, you change between present tense and past tense. Please stick to one of the two (e.g. l. 68 "develop", l. 70 "developed") and others
ok,, changed to past tense.

"Infact" -> In fact. ok

l. 62 and others "Gudicarie" -> Giudicarie. ok

l. 68 ";" -> : ok

l. 72 and others brackets for inline citations only around the year (In Latex use \citet{...} instead of \citep{...} for inline citations). ok

l. 83 no comma after magmatism. ok

l. 98 "restitic" -> remnants of?
Reply: restitic crust is a term used by petrologists, to indicate the crust that has remained after partial melting and production of magmatic material.

l 109 "Judicarie" -> Giudicarie ok

l. 133 "consists in" -> consists of, better write the model is parameterized in terms of spherical harmonic... ok

l. 136 "The layers building topography" -> The layers describing the topography? ok

l. 160 "to which" -> from which ok

l. 223-225 Not a very nice sentence, maybe write something like: In this work, we combine these two Vp/Vs relations for sedimentary and crystalline rocks by linking them at their intersection point as illustrated in Figure 5. (The following sentence, "The velocity is Vp =..." is not necessary in my opinion). Ok Changed to:
In our work, the sedimentary rocks velocity domain was distinguished from the crystalline domain by the velocity value at which the two curves intersect as seen in Fig. 5 and also in Brocher (2005). For the sedimentary rocks Gardner's rule was used, for the crystalline rocks the linear fits of Christensen and Mooney (1995) were used, which are given for depth ranges from 10 km to 50 km. The intersection velocity is dependent on depth, for the shallower depths of 10km for instance, the velocity is $Vp = 6\ km\ s^{-1}$, at 50 km the intersection is at $Vp = 5.2\ km\ s^{-1}$ (see Fig. 5).

l. 228 "compared with" -> compared to ok

l. 256 "has been argued" -> has been illustrated/described. Ok, changed to: In the previous section the transformation of P-wave velocities to density values was described.

l. 267 "The Fig. 7" -> Fig. 7 ok

l. 283 "with" -> to ok

l. 285 This sentence needs to be rephrased. Ok, done.

l. 299 "represent" -> represents; "belong" -> belonging ok

l. 309 "develops" -> better: stretches/is trending in/.. ok.

l. 310 "straitens" -> straightens/becomes more elongated ok

l. 316 "Always" -> Throughout the region? Changed to: remaining in the first 15 km…

l. 335 "beyond" -> below; "orogens" -> orogen's/orogenic ok

l. 342 "interesting the Po basin" -> ?? changed to highlighting

l. 388 no comma after provinces ok

l. 410 "As regards" -> Regarding, better: Geodynamic evidence suggests that... ok

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