Reviewer 1

- It would be worthy to provide some kind of sensitivity analysis about the impact of subtle changes in density and/or density domains boundaries geometries on the gravity response of the model. Such sensitivity analysis could further support and reinforce your interpretations and conclusions and contribute to reduce the inherent ambiguity of the gravity method.

- You should discuss the causes and/or possible origin of the differences observed between the densities you calculated for each modelled body from P wave velocities and the densities you finally used, which are shown in Table 1. Particularly when considerable differences exist (e.g. Upper Crust North East Adria, Lower Crust Northern Adria) and when opposite tendencies arose (e.g. Lithospheric Mantle Less Dense vs. Lithospheric Mantle More Dense).

- You should also provide possible explanations or at least discuss the fact that very low densities had to be assigned to lower crustal bodies (Lower Crust Europe, Lower Crust Northern Adria) corresponding to some sectors of the European and Adriatic plates, in order to fit observed and calculated gravity anomalies. Mostly, considering that such very low densities are more typical of the upper than of the lower crust.

We thank the reviewer for these suggestions and have added an additional figure to the manuscript and some new paragraphs to address these topics collectively. The new Fig. 9, shows the results of a model that has been run with lower crustal densities indicated from P-wave velocity to density conversions in regions where the misfit between the densities indicated from P-wave velocity and those used in our final model are greatest (Europe and North Adria). The effect that these alterations have on the calculated and residual gravity fields of the model is then addressed in the paragraphs from line 343 – 363. Model sensitivity, the origin of differences between P-wave velocity to density values and modelled values, and causes for the regions of low density lower crust are also discussed.

- Language should be polished. Some sentences are too long. Wording and phrasing should be improved.

We thank the reviewer for the extensively annotated copy of the manuscript that they provided and have implemented all the corrections they have made to the text along with all suggestions on improvement of sentence structure and brevity. Additionally we have also made our own changes to portions of the text in an attempt to further deal with the point raised.

- Please, show in Figure 1a or in a new figure the limits/boundaries of showing the different plates, blocks and terrains, particularly showing the limits of the European and Adriatic plates, the Vosges, Black Forest and Bohemian massifs, the Po and Molasse Basins, the Upper Rhine Graben, the Veneto-Friuli plain, the Ivrea Zone, and Moldanubia and Saxothuringia. Where is the Ligurian Sea located? You should refer to a figure in the Introduction showing the terrains, blocks, plates mentioned in Introduction section.

We thank the reviewer for their helpful suggestions and have altered Figure 1 significantly to incorporate all of the limits and boundaries you have suggested. In addition the labelling of important tectonic features on all other figures has also been edited to include your suggestions. A sentence has also been added to line 38 of the manuscript indicating that the all tectonic features mentioned in the introduction can be seen in Fig. 1a. Figure captions have also been altered to reflect these changes.

- Please, show clearly in a map and in the section presented in figure 3 the location, extension and boundaries of the European and Adriatic plates and the location of Central Alps.

We thank the reviewer for suggesting how to add clarity to the figure and have implemented these changes.

- Line 73 - seismic reflection heights?..what do you mean with heights?..please clarify

We thank the reviewer for pointing out this ambiguous meaning. We have changes the word heights at line 76 to depths, as we are referring the depths below the surface of seismic reflections.

- Line 78 - Please, briefly describe how these authors obtained the LAB (which methodology did they use), as the LAB is one of the sufaces constituting your model.

We thank the author for pointing out this omission and have added that the LAB was obtained by S receiver functions of teleseismic events in the sentence at line 81.

- Line 172 - Do you mean "upper crust" or whole crust?

The sentence was referring to the whole crust and has now been changed to reflect as such at line 170. We thank the reviewer for noting this.

- Line 179-182 You should use a different word. The word "modelled" is confusing, as you previously said that you did not modify layers thicknesses (which were defined from constraining data) during gravity modelling with IGMAS+.
We thank the reviewer for pointing out the confusing wording and have updated the sentences at lines 178-181 to say the word 'used' instead of modelled.

-Line 185 – 188 Please, define European Upper crust, Adriatic Upper Crust and Adriatic Sea. Which bodies of the ones listed in Table 1 are supposed to compose them? Does Adriatic Sea correspond to bodies 15 and 17 in Table 1?
We thank the reviewer for pointing out the lack of clarity here and have made a number of changes to rectify this. The upper crust density domains that Europe (domains 7-11) and Adria (domains 14, 15 and 17) are composed of have been added at lines 184 and 185 respectively so that it is clear when viewing either Figure 4 or Table 1. The Adriatic Sea is now labelled in Figure 1a to make clearer where it is on the modelled area.

Line 195 – 196 Why are European and adreatic (Bodies 23 and 24?) average crust densities given different to those in table 1. Please explain.
We thank the reviewer for pointing out the lack of clarity here. The densities given are an average of the density domains that comprise it. This clarification has been added to the text at line 186 and we have added the lower crust density domains that Europe and Adria are composed of at lines 196 and 197 respectively so that it is clear when viewing either Figure 4 or Table 1.

Please, check along the whole paper the use of upper case or lowercase letters in the names of terrains, blocks etc. as Brianconais Terrain, Tauern Window, etc. Actually, you are sometimes using upper case and sometimes lowercase.
We thank the reviewer for bringing this to our attention and have checked the manuscript for mistakes such as this and corrected them all.

localisation or localization?. Please check spelling along the whole manuscript.
We thank the reviewer for noticing this and we have rectified the instances that these occurred.

What indicates the line labelled a-a´?. Please, explain it in Figure 1 and 2 caption.
We thank the review for pointing out this mistake. a-a' represents the cross section in Fig. 3. and we have updated the figure captions to reflect this.

Reviewer 2

- Partly comparable results showing differences in thickness and density between the European and Adriatic crust were presented in a previous study, although carried out along a transect (TRANSALP; Ebbing et al., 2006, Tectonophysics) and not presenting a 3D picture. That work, however, should be cited at some stage. We thank the reviewer for noting this omission and have now included it in the references and it is cited at line 59.

- The presentation of the results and the Discussion sections are very essential and could be expanded a little in order to compare the results with other works and to give some hints on the potential implications for the tectonic evolution of the Alps.

We thank the reviewer for mentioning this. We feel that as we have implemented many additional sections to both the Results and Discussion of the manuscript, in response to all issues raised during the review process, that this has been accomplished satisfactorily.

- lines 47-49: modelling indicates that the crust is thinner in the Po and Molasse basins, where sedimentary depocenters are present, and in the Rhine Graben. Whereas crustal thinning occurred in the Rhine Graben in late-post Alpine timing, the Po and Molasse basins are produced by flexure, mainly due to the load of the adjacent mountain belts (Apennines and Alps, respectively). The thickness of the crust is not affected by plate flexure; the crustal thinning should therefore be considered an inherited feature.

- lines 246-248: the Molasse foreland basin originated by flexure of the European plate under the Alpine load, and that was independent from the inherited along-strike difference in crustal density. Present-day vertical motions could represent a post-orogenic isostatic adjustment, but the Austrian sector of the Molasse is an undeformed basin, whereas a detachment connected to a thrust front located north of the basin underlies the western Molasse; an active involvement of the basement has also been suggested in the region of the Jura mountains (e.g., Mock and Herwegh 2017 Tectonics), and this could contribute to positive vertical motion. The authors also mention a difference in the density of sediments between the western and eastern Molasse basin; however, the difference in density between the two sedimentary domains is rather small: is it enough to drive a differential vertical motion?
- lines 295-300: as mentioned before the thickness of the crust underlying the Molasse and Po foreland basins should be taken as unaffected by the load of the mountain belts. The possibility of having a contribution to subsidence driven by crustal extension in the Po Basin, as suggested by the authors, seems highly unlikely and no evidence to support it is present.

We thank the author for pointing out these mistakes and have made several changes to account for the issues raised. In the first instance we have changed the wording of the sentences at lines 47-50 such that references to crustal thinning have been removed, as this section purely deals with the geographical location of the sedimentary depocenters in the region. We agree with the reviewer that our work has not been able to constrain the underlying causes of features such as differential surface uplift in the East and West Molasse Basin and have added sentences reflecting this from lines 320-323. There we have also added mention to your suggestion that the thinned Po Basin crust could also be an inherited feature

- lines 207-208: perhaps some comments on the comparison of the results with previously published Moho maps (e.g., Ziegler and Dezes 2008, Geol. Soc. London; Spada et al., 2013 GJI) could be useful.

We thank the reviewer for pointing out this oversight. We have included a number of sentences from lines 211-216 commenting on the similarity with the trends of the Spada et al. (2013) Moho to our integrated Moho surface, whilst also mentioning why we believe our integrated Moho surface is better for the purpose of a 3D gravity model. We have also updated the references list accordingly.

- lines 217-219: interestingly the two areas of negative residual anomaly in Fig. 6b seem to have some geological relationships. The western one partly follows the Ivrea zone, and the eastern one is over a basement high that existed since Late Permian-Triassic (see Masetti et al., 2012 AAPG). Perhaps the authors have some comments on this fact, that doesn't look random.

We thank the reviewer for pointing out this omission. Indeed we had previously identified the source of these anomalies but neglected to include them in the manuscript. The anomalies are coming from Moho depths that are slightly too high, however as we have fixed surfaces during the modelling work and the anomaly was not coming from crustal densities we deemed it appropriate not to account for them in changes to density in the model. We have explained as such in additional sentences from lines 225- 230.

- lines 231-235: the average density of the crust result from the integration of a column of rocks where different units are stacked one on top of the other; the domains cropping out at surface not always continue at depth, as illustrated in many of the geological cross sections across the Alps (e.g., Schmid et al 2004). The relationship between average density distribution and tectonic domains may not always be straightforward, and this should betaken into account.

We thank the reviewer for their points here that we had not addressed the inaccuracies of constraining the horizontal boundaries of these features due to tectonic features at the surface not occupying the same location as their expression at depth. To address this we have added a new paragraph in the Discussion at lines 273-279, explaining that the density domains of the gravity model define a bulk density for different regions of the model and often correlate to tectonic features at the surface. Additionally, we now stress that caution should be exercised if trying to link the exact location of domain boundaries to features at the surface.

- lines 250-251: the distribution of earthquakes with M>6 and max. horizontal strain is rather limited spatially. They are mostly located at the thrust front of the Southern Alps which represents the active southern boundary of the Alps, as also supported by focal mechanisms (see Serpelloni et al., 2006). The difference in average crustal density observed in the model is expected at such plate boundary. The other few and sparse earthquakes are not very indicative of dynamics at crustal boundaries and likely reflect different tectonic regimes: the earthquake next to BLF is likely related to the Rhine Graben, whereas those in the Swiss Alps reflect a regional trend of extension/strikeslip that characterizes the highest regions of the central Alps, irrespective of tectonic domains.

- Lines 289-290: see also Serpelloni et al 2016 Tectonophysics for distribution of seismicity in central-eastern Alps: crustal seismicity seems to follow the major faults driving the eastward escape of the Eastern Alps .

- lines 282-285: the "boundaries" between different crustal "blocks" is a likely place for the occurrence intraplate earthquakes, that tend to follow pre-existing weakness zones. In the presence of an active plate boundary, like the Alps, the link between different blocks and seismicity is less obvious, as there are plate interfaces, and faults originated by the collisional process are abundant, and often seismically active (e.g., Serpelloni et al., 2016).

- Lines 306-307: see also Serpelloni et al 2016 Tectonophysics for distribution of horizontal velocity and strain rates in central-eastern Alps: the motion of Adria seems mostly accommodated by deformation at the thrust front of the Southern Alps.

We agree with the reviewer here on multiple points. That the large earthquakes away from the plate boundaries likely reflect different tectonic regimes and that the boundaries between different crustal blocks is a likely place for intraplate earthquakes. We have included Serpelloni et al. (2016) as a reference and added some additional points from that work to strengthen our discussion further. We added to the sentence at Line 259 to make it clearer that seismicity is primarily expected at major plate boundaries. And we also added multiple sentences to the paragraph from line 298, that also deals with why we used the sparse M>6 large earthquake dataset. As we only have the ability to describe density contrasts at a coarse resolution in the crust we felt it suitable. As mentioned before we do not have the ability to provide causal relationships from the correlation with earthquakes, hence we don't use a high resolution dataset. And we also lack the ability to provide causes for noted correlations as this will be interrogated in future works as is pointed out in the manuscript from line 364-369.

- line 312-316: the authors assume that the evidence for a thinner and denser crust in eastern Adria supports its subduction underneath the European plate, as originally inferred by Lippitsch et al. However, it should be considered that the long term evolution of the Alps, including the Eastern Alps, is consistent with a subduction of the the European plate below Adria. And this is certainly true until the last 20 Myr. Therefore, density alone does not justify a supposed change in the polarity of subduction along the strike of the Alpine orogen. Moreover, shortening of the Adriatic plate in the eastern Southern Alps is rather limited, as also pointed out by Kastle et al. (2019 SE), and is not enough to explain the extent of the slab observed in Lippitsch's tomography.

We thank the reviewers for pointing out the shortcomings of how we have addressed this topic in the text and have made changes to rectify accordingly, by adding additional sentences to the paragraph at line 339-342. We mention that there is no consistent plate model of the Alps, but that our findings in this work (bulk densities of the crust and lithospheric mantle of Europe and Adria) could help to reach this stage in the future.

- Figure 2. It would be useful to have also a simplified geological map of the Alps (e.g., taken from Schmid et al 2004) to give a better link between geophysical and geological data.

We thank the reviewer for this suggestion and have tried to implement accordingly. Overlays of additional tectonic features mentioned in the rest of the manuscript, such as the Ivrea zone, the Vosges, Black Forest and Bohemian Massifs have been added to the figure to complement the already labelled Alpine domains. We hope that the reviewer agrees this indicates a simplified version of the geological features in both the Alps and their forelands, and is an acceptable solution.

- Figure 3: A simplified geological cross section, plotted at the same scale of the profile in Fig. 3, would be useful to give a better feeling of the relationships between density domains and geological units. I am not aware of a geological cross section running along the same direction of the profile in Fig. 3, but perhaps the TRANSALP cross section, with appropriate comments, could be indicative enough (after Pfiffner 2014, Geology of the Aps; or Schmid et al 2004)

We thank the reviewer for this suggestion, but having looked into it we have decided against making any changes here. The location of the cross section used originally was chosen so that it represents most of the tectonic features within the region such as the European, Adriatic and Apennine plates, the Mollasse and Po basins and 2 different density domains within the Alps, thus giving a concise indicative view of our model, rather than multiple cross sections to achieve the same effect. As no geologic section exists of our chosen cross section we have been unable to implement a simplified geologic section next to it for reference. In an attempt to deal with this however we have labelled the extents of the European, Adriatic and Apennine plates in order to make interpretation of our cross section simpler.

- Technical corrections line 13: "orogenies" instead of "orogenys" line 43: "More recent" instead of "Newer" line 79: sufficient; however (insert semicolon) Line 127: "before" instead of "prior" line 185: "... thicker, but with a similar..." line 191: "Apennine belt" instead of "Apennine plate" line 204: "respectively, " instead of "respectively" (insert comma) line 218: "exceeds that value." instead of "exceeds that." line 297: "before" instead of "prior" Line 303: "however" can be removed line 489: before listing the labels of key tectonic features add that a-a' is the cross section in Fig. 3. line 499: add that a-a' is the cross section in Fig. 1a line 500: location is marked in Figs 1a, 2 and 4 to 6. line 508: "depth to the Moho" instead of "depth to top surface of the Moho" line 508: "... required within the lithospheric mantle..." instead of "...required within the layer..."

We thank the reviewer for noticing these mistakes and have implemented all of these changes into the manuscript.

Density distribution across the Alpine lithosphere constrained by 3D gravity modelling and relation to seismicity and deformation

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Abstract. The Alpine Orogen formed as a result of the collision between the Adriatic and European plates. Significant crustal heterogeneity exists within the region due to the long history of interplay between these plates, other continental and oceanic blocks in the region, and inherited crustal features from earlier orogenies. Deformation relating to the collision continues to the present day. Here, a seismically constrained, 3D structural and density model of the lithosphere of the Alps and their respective forelands, derived from integrating numerous geoscientific datasets, was adjusted to match the observed gravity field. It is shown that the distribution of seismicity and deformation within the region correlates well to thickness and density changes within the crust, and that the present day Adriatic crust is both thinner and denser (22.5 km, 2800 kg/m3) than the European crust (27.5 km, 2750 kg/m3). Alpine crust derived from each respective plate is found to show the same trend with zones of Adriatic provenance (Austro-Alpine and Southern Alps) found to be denser and those of European provenance (Helvetic Zone and Tauern Window) to be less dense. This suggests that the respective plates and related terranes had similar crustal properties to the present day ones prior to orogenesis. The model generated here is available for open access use to further discussions about the crust in the region.

1 Introduction

The Alps are one of the best studied mountain ranges in the world, yet significant unknowns remain regarding their crustal structure and links that may exist between the localisation of deformation and seismicity in the region and crustal heterogeneity. Significant amounts of seismicity and deformation correspond to plate dynamics, such as at the convergence of the European and Adriatic plates in North-East Italy (Restivo et al., 2016) where the Adriatic plate is observed to act as a rigid indenter, moving northwards and rotating counter-clockwise against the weaker European plate (Nocquet and Calais, 2004; Vrabec and Fodor, 2006; Serpelloni et al., 2016). However, numerous large historic seismic events (Fäh et al., 2011; Stucchi et al., 2012; Grünthal et al., 2013), such as the Magnitude 6.6 Basel earthquake in 1356 AD, lie substantially intra-plate in areas with low amounts of horizontal surface strain (Sánchez et al., 2018) suggesting that possible inherited features within the crust are also significant factors to their localisation.

Crustal heterogeneities in the European plate, constituting the northern foreland of the Alps, principally derive from different terranes that collided during the Carboniferous age Variscan orogeny (Franke, 2000). Collision during orogenesis resulted in the juxtaposition of crustal domains with differing properties next to one another, such as Moldanubia and Saxothuringia, (Babuška and Plomerová, 1992; Freymark at al., 2016) and also resulted in the creation of the Vosges, Black Forest and Bohemian massifs. The locations of all relevant tectonic features within the region can be found in Fig. 1a.

As a consequence of the collision of the Adriatic plate with the European plate from the Cretaceous until the present (Handy et al., 2010), heterogeneity within the Alpine orogen is also very pronounced, however different interpretations exist on the plate provenance of some features. Traditionally, the Alps have been split into distinct zones according to their plate of origin and metamorphic history, such as the Adriatic derived Austro-Alpine and Southern Alps, the European derived Helvetic Alps and the Penninic zone representing distal margin units and slivers of oceanic crust (Schmid et al., 1989). The Briançonnais crustal block that lies within the Penninic zone derives from the Iberian plate (Frisch, 1979). More recent works examining the plate provenance of Alpine zones have reinterpreted some features such as the Tauern Window from Penninic origin to European plate origin (Schmid et al., 2004).

Density distribution throughout the lithosphere of the region is also affected by mantle features and sedimentary depocentres. The three main depocentres within the region are the Po Basin of the southern foreland, the Molasse Basin of the northern foreland and the Upper Rhine Graben, also within the northern foreland, that formed as part of the European Cenozoic Rift System in the Eocene (Dèzes at el., 2004). Anomalously high densities within the crust are present in the Western Alps, in the Ivrea Zone and along its sub-surface continuation to the South to the Ligurian Sea, as a result of a South East dipping mantle wedge, where mantle and lower crustal rocks are present at upper crustal depths (Zingg et al., 1990) and even at the surface (Pistone et al., 2017 and therein).

Previous published interpretations of crustal features within the orogen have been primarily based upon 2D seismic sections (e.g Brückl et al., 2007), tending to result in simple models. However, lateral differences in crustal structure have been demonstrated, even at short wavelength, for example through the deployment of parallel seismological profiles, spaced 15 km apart across the Eastern Alps (Hetényi et al. 2018a), indicating the need for more complex models. Studies that have integrated multiple geo-scientific datasets to create 3D models of the region, have either focussed on smaller sub-sections of the Alps (Ebbing, 2002; Ebbing et al., 2006) or included the Alps as part of a much larger study area (E.g. Tesauro et al., 2008). Therefore the generation of a 3D, crustal scale, gravity constrained, structural model of the Alps and their forelands at an appropriate resolution could be used to more accurately describe crustal heterogeneity in the region. The generation of such an Alpine-wide specific model is made possible by the existence of seismological results from numerous published deep seismic surveys (e.g. Zuerich, 1981; Gajewski & Prodehl, 1985; Yan and Mechie, 1989; Ye et al., 1995; Brückl et al., 2007) that have been completed throughout the region, and available high quality global gravity field models (e.g. Förste et al., 2014). Within this current work, such data is integrated in a common frame to give insights into the distribution of densities within the crust as constrained by 3D gravity modelling across the vast majority of the Alpine region and its forelands for the first time, so that questions about the relationship between the distribution of densities within the crust and seismicity and deformation patterns can be addressed.

2 Input Data

Existing geological and geophysical observations from previous published works about the Alps and their respective forelands were used as constraints for the generation of the 3D structural model. Topography and bathymetry were utilised unaltered from ETOPO1 (Amante and Eakins, 2009), as shown in Fig. 1a. The data integrated to constrain sub-surface lithospheric features are shown in Fig. 1b and include: regional scale, gravitationally and seismically constrained models of the TRANSALP study area (Ebbing, 2002), the Molasse Basin (Przybycin et al., 2014) and the Upper Rhine Graben (Freymark et al., 2017); regional scale, seismically constrained models of the Po Basin, such as MAMBo (Turrini at al., 2014; Molinari et al., 2015); and seismic reflection/conversion depths and their associated P wave velocity from projects such as ALP'75, EGT'86, TRANSALP, ALP 2002 and EASI (IESG, 1978; IESG & ETH Zuerich, 1981; Strößenreuther, 1982; Mechie et al., 1983; Zucca, 1984; Gajewski & Prodehl, 1985; Deichmann et al., 1986; Gajewski et al., 1987; Gajewski & Prodehl, 1987; Yan and Mechie, 1989; Zeis et al., 1990; Aichroth et al., 1992; Guterch et al., 1994; Ye et al., 1995; Scarascia and Cassinis, 1997; Enderle et al., 1998; Bleibinhaus & Gebrande, 2006; Brückl et al., 2007; Hetényi et al., 2018a). The Lithosphere-Asthenosphere Boundary (LAB) was utilised unaltered from Geissler (2010), which was obtained by S receiver functions of teleseismic events.

Constraining data coverage for most sub-surface lithospheric features was sufficient; however, thicknesses of unconsolidated sediments were not available across the full modelled region. In regions of less dense data coverage, continental scale, seismically constrained, integrative best fit models, EuCRUST-07 and EPcrust (Tesauro et al., 2008; Molinari and Morelli, 2011) were also used. Both models provided complete coverage of major structural interfaces and P wave velocities over the whole modelled area at a coarse resolution. Detailed values of unconsolidated sediment thicknesses were only available for the Upper Rhine Graben, the Molasse Basin and the Po Basin, as the seismic sections utilised lacked the resolution for shallower features and the continental scale models did not differentiate between sedimentary strata.

The free-air anomaly used was calculated from the global gravity model EIGEN-6C4 (Förste et al., 2014), at a fixed height of 6 km above the datum (Fig. 2, further referred to as observed gravity). As the gravity data source is a hybrid, terrestrial and satellite dataset, the potential exists for it to be lacking some of the short wavelength response that a fully terrestrial dataset would possess. The fixed height of 6 km was utilised to account for this, so that the vertical component of the gravity response from the generated regional structural model (further referred to as calculated gravity) and observed gravity can be directly compared during the gravity modelling process.

3 Method

Data from numerous existing geoscientific datasets (see Input Data section) were integrated to create a gravity constrained, 3D, structural and density model of the lithosphere of the Alps and their respective forelands. The study area of this work, indicated in both Figs. 1a and b, focuses on a region of 660 km x 620 km where the highest density of constraining data coverage was compiled. The vast majority of the Alps and their forelands are included, with the Central and Eastern Alps and the northern foreland being the best covered regions.

The software package Petrel (Schlumberger, 1998) was used for the creation and visualisation of the modelled surfaces in 3D, representing the key structural and density contrasts within the region. These surfaces were: 1. top water; 2. top unconsolidated sediments; 3. top consolidated sediments; 4. top upper crust; 5. top lower crust; 6. top lithospheric mantle; 7. top asthenospheric mantle. All surfaces were generated with a grid resolution of 20 km x 20 km using Petrel's convergent interpolation algorithm. The above mentioned model layers were generated by correlation and integration between data sources, with the exception of the following: 1. The water layer was generated from cropping ETOPO1 to 0 m a.s.l. No freshwater bodies were added as they are too small to be of impact at the model resolution utilised; 2. The top unconsolidated sediment surface used in the modelling corresponds to topography and bathymetry, which is plotted in Fig. 1a; 3. As a result of unconsolidated sediment thicknesses from the data sources only being present in the Upper Rhine Graben, the Molasse Basin and the Po Basin, outside of these regions a thickness of 0 was used. This was deemed acceptable because unconsolidated sediment thicknesses are not large enough as to be of impact at the model resolution, outside these regions; 4. The LAB was used unedited from the data source, in spite of its low resolution as it does not represent a significant density contrast. Alpine nappe stacks were included within the consolidated sediments layer of the model.

During correlation and integration, a hierarchy of data source types was used and in the case of contradiction between the different data sources, those of the highest hierarchy were accepted. The hierarchy was derived from the quality, resolution and consistency of data sources and was as follows: 1. regional scale, gravitationally and seismically constrained models; 2. regional scale, seismically constrained models; 3. individual seismic reflection surfaces and interpreted sections; 4. continental scale, seismically constrained, integrative best fit models.

No subduction interfaces were modelled, as multiple studies within the region have shown that the effect of different subduction polarities as well as the presence or lack of subducting plates is small. Previous 2D gravity modelling across the TRANSALP profile has demonstrated that the differences in gravity response between a model of both different subduction polarities and a model setup with no subducted crust were negligible (Deutsch, 2014). Lowe (2019) showed that the contribution of subducting slabs in the region to the gravity field is relatively small, in the range of 30 mGal).

The 3D gravity modelling software IGMAS+ (Schmidt et al., 2010) was used, which operates by creating triangulated meshes between points on input surfaces and vertical parallel planes, around a body of homogenous density, to calculate their volumetric contribution to the gravity response. Gravity in the model was calculated at 6 km above the datum to be concurrent with the observed gravity. In this way, the short wavelength response of the calculated gravity was not overestimated as mentioned before. The top of the model was also set to a height of 6 km with a density of 0 used to represent the column of air between it and topography. To account for the edge effect of the gravity field, the model was extended by ~50% (330 km) in all horizontal directions of the studied area using the surfaces from EuCrust-07 (Tesauro et al., 2008).

The free-air gravity response was used because this work is focussed on the crustal composition of the Alpine region and considering that up to 4.8 km of crust lies above sea level within the modelled area, removing this from the gravity signal was deemed unacceptable. Additionally, the complex geological setting of the Alps implies that the removal of Alpine topography as a Bouguer slab of homogenous density would potentially introduce errors.

The process of gravity modelling involved the modification of an initial 3D structural model, comprising surface heights and densities, such that through multiple iterations the resulting model produced a gravity field similar to the observed one. Best practice of such an iterative process allows only one input parameter, density or surface heights, to be altered. Here, the surfaces generated as part of the integration work were not modified during the gravity modelling process as they were better constrained than the densities, leaving only density as a free parameter.

For the calculation of the densities used in the initial structural model, P wave velocities from seismic data sources were converted using the experimentally derived empirical relationship detailed in Brocher (2005). In the absence of seismic data, P wave velocities from the continental scale models listed in the Input Data section were used to supplement, giving coverage over the entire study area. Densities of 1025 kg/m3 and 3320 kg/m3 were assigned to the water layer and the asthenospheric mantle, respectively.

The densities derived from the P wave velocity conversions were then used in conjunction with densities from the input regional scale, gravitationally and seismically constrained models, to split the layers of the generated model laterally into domains of different density, to reflect the heterogeneous nature of the crust within the region. During the generation of the model, preference was given to the resolution of major density contrasts. Consequently, units of known differing lithology, age and/or provenance were grouped together, when they appeared to have a similar density to best fit the gravity in the region. An overview of the mean densities of each modelled body, derived from seismic P wave velocities, is presented in Table 1.

To determine how well the structural model fits the gravity field in the region, the calculated gravity was subtracted from observed gravity during interactive modifications of the location of different domains within each layer and their densities, and the result (further referred to as residual anomaly) interrogated. No filtering for specific wavelengths was done during gravity modelling, with the full signal being used. No presumptions were made about which tectonic features would require domains of different density, with their location ultimately derived from the gravity modelling process.

In the case of anomalies in the residual gravity field, the depth of the source was estimated to be half the width of the anomaly wavelength and the density of the body lying at that depth was increased for a positive residual anomaly or decreased for a negative residual anomaly. Successive iterations of the model were then generated by modifying the distribution of densities within the model layers. This was repeated until a 3D structural density model of the region was obtained, that best reproduces the indications of both the seismic data sources and the gravity field.

4 Results

Figure 3 shows a North-South cross section through the generated model illustrating the thickness of all main structural layers, the density domains defined within them and the calculated and observed gravity of the section. The location of the cross section can be seen in Fig. 1a and is also marked on all figures illustrating the setup of the model.

Our model indicates that more heterogeneity is required in the crust, than in other model layers, to replicate the gravity field and that significant differences exist between the crust of the European and Adriatic plates. Sedimentary thicknesses, both unconsolidated and consolidated, are thinner in the Molasse Basin than in the Po Basin and crustal densities and thicknesses also differ between the plates. Beneath the orogen itself, the result of incorporating all Alpine nappes within the consolidated sediment layer can be observed, with higher thicknesses beneath the central Alps. The whole crust is thickest below the central Alps and is compensated by higher thickness and density of the lower crust. The observed gravity along with the calculated gravity of the model can also be observed, showing a good fit.

Figure 4 shows the thicknesses of the layers of the generated model, which were created as a result of the correlation and integration work, with the areal extent of all density domains overlain on top. An overview of the final density of all the bodies composing the model required to fit the gravity field can be found in Table 1.

Both sedimentary layers shown in Fig. 4 reflect trends across the region previously identified along the cross section presented in Fig. 3, with thicker and denser sediments in the Po Basin than in the Molasse Basin, and large thicknesses of consolidated sediments in the central Alps (18 km) representing the Alpine nappe stacks. Maximum thicknesses of 9 km and 12 km were used in the Po Basin for unconsolidated and consolidated sediments respectively, whilst 6 km and 9 km were used in the Molasse Basin. Thicknesses of 3.75 km unconsolidated sediments were used in the deepest part of the Upper Rhine Graben with consolidated sediment thicknesses of up to 3 km. In both of the sedimentary layers, separate density domains were necessary in the Eastern Molasse Basin (2470 kg/m3 and 2680 kg/m3) and the Po Basin (2470 kg/m3 and 2700 kg/m3) that were denser than the sediments in the rest of the region (2450 kg/m3 and 2670 kg/m3).

The European upper crust (domains 7-11 in Fig. 4c and Table 1) is thicker, but has a similar density on average (20 km and 2700 kg/m3), compared to the Adriatic upper crust (12 km and 2700 kg/m3, domains 14, 15 and 17 in Fig. 4c and Table 1). The densities given for the European and Adriatic crusts are averages of the density domains that comprise them. The thickest regions of upper crust can be found around the Bohemian massif in the northern foreland and the Briançonnais Terrane and Tauern Window in the Alps reaching a thickness of up to 30 km, whilst thinned upper crust with thicknesses of only 4 km is found below the Adriatic Sea and the Ivrea Zone. Multiple density domains in the upper crust correspond to known tectonic features in the modelled region such as the Variscan domains of Saxothuringia (2670 kg/m3) and Moldanubia (2700 kg/m3), the massifs of Bohemia (2740 kg/m3) and Vosges/Black Forest (2660 kg/m3) that lie close enough together in the model to be grouped, the Briançonnais Terrane (2790 kg/m3) and the Apennine belt (2720 kg/m3). However, in the Alps and the Adriatic Sea the modelled density domain boundaries do not correspond to specific tectonic features. The Alps are divided roughly

North East (2740 kg/m/3) to South West (2670 kg/m3), being denser in the NE, while the Adriatic Sea is split roughly North (2660 kg/m3) to South (2700 kg/m3), being denser in the south.

The configuration of the European lower crust (domains 19 and 20 in Fig. 4c and Table 1) is of similar thickness, but less dense on average (10 km and 2860 kg/m3) than the Adriatic (10 km and 2910 kg/m3; domains 21, 23 and 24 in Fig. 4c and Table 1). The lower crustal Alpine root is thicker and denser (2950 kg/m3 and 34 km) than in the rest of the region. Density domains within the lower crust show less correspondence with known tectonic features than those in the upper crust. Of the domains in the lower crust only two correspond roughly to tectonic features, one to the Saxothuringian Variscan domain (2920 kg/m3) and the other to the Briançonnais Terrane (3100 kg/m3). A large region of similar density within the lower crust exists, mostly in the European Plate, covering an area including the Moldanubian Variscan domain, the Bohemian Massif and the Western and Eastern Alps (2800 kg/m3). The central Alps and the Western Po Basin are also grouped as a region of similar density (2950 kg/m3). As with the upper crust, the lower crust beneath the Adriatic Sea is split roughly North (2750 kg/m3) to South (3040 kg/m3) with a denser domain in the south. Some lower crustal density domains in the European and Adriatic plates have been modelled as low as 2800 kg/m3 (domain 20 in Fig. 4c and Table 1) and 2750 kg/m3 (domain 23 in Fig. 4c and Table 1) respectively, and although necessary to fit the gravity anomaly, these values are similar to upper crustal density values. The other density domains in the lower crust of the region have values that would be expected for this depth level.

Figure 5 shows the depths of the Moho and LAB used in this work. The Moho is shallowest below the Ligurian Sea (20 km) but also shallow beneath the Ivrea Zone (22.5 km) and below the Upper Rhine Graben (25 km). It reaches its deepest point in the crustal root of the Alps at 55 km. The trends in Moho depth noted here correspond well to trends in the Moho map of Spada et al., (2013). However the minimum (Ivrea Zone: 12 km) and maximum (Alpine crustal root: 60 km) depths of the Spada et al., Moho are more extreme and likely represent more local values than those used in this work. Additionally, our integrated Moho does not contain large vertical steps (28km in the Northern Apennines) between defined plate domains, such as in the Spada et al. (2013) Moho as these would create large density contrasts within the 3D model that would present severe difficulties when trying to fit the observed gravity in the region.

From the gravity modelling process it was found necessary to have variation in the density of the lithospheric mantle, and that the regions of different density correspond to different thicknesses of the lithosphere (Geissler et al., 2010). Broadly, the lithosphere is thinnest and least dense to the North-West of the region (70 km and 3305 kg/m3) whilst being thickest and densest to the South-East (140 km and 3335 kg/m3) below the Adriatic Sea. The shallowing of the LAB below the Alps could correspond to the boundary between the Austro-Alpine and Helvetic/Penninic Alps.

The observed gravity in the modelled region is visible in Fig. 2, while the calculated gravity response is shown in Fig. 6. The residual anomaly can be observed in Fig. 6 demonstrating the good fit achieved by the generated structural model. Almost all of the modelled area reproduces the observed gravity to ± 25 mGal with the exception of a couple of isolated regions where the misfit between observed and calculated gravity slightly exceeds that value. As the polarity of both anomalies indicates less density is required to fit the gravity field, they correspond to Moho highs and their wavelength would suggest the top surface of the Moho as the source of the anomaly, the anomalies likely stem from isolated Moho depths that are slightly too shallow.

As crustal densities were not the source of these anomalies and surface heights remained fixed during the modelling process, no changes were made to account for these anomalies so that a more representative density configuration of the regional crust could be calculated.

The thickness and average density of the modelled crust throughout the region are shown in Fig. 7. The lateral variation in average density is obtained as a weighted average calculated from the thicknesses and densities of the upper crust and the lower crust at every point in the model. Overall the crust is thicker and less dense on average in the European plate (27.5 km and 2750 kg/m3) compared to the Adriatic (22.5 km and 2850 kg/m3). The thickest crust corresponds to the crustal root of the Central Alps (55 km). Areas of thinned crust are found below the sedimentary depocentres of the Po Basin and the Upper Rhine Graben, which can additionally be seen extending South and West of its surface location, however the crust does not appear significantly thinned beneath the Molasse Basin. Whilst the Adriatic crust is denser on average than the European crust, it has more extreme density variations within it, such as a modelled low density crust in the North of the Adriatic indenter that coincides with the Veneto-Friuli plain (2700 kg/m3), immediately adjacent to much denser crust lying to the South below the Adriatic Sea (2900 kg/m3).

Density contrasts within the crust correlate spatially with the locations of some Alpine zone boundaries as defined in the literature (Schmid et al., 1989; Schmid et al., 2004). The Briançonnais Terrane can be seen as a higher density block contrasting with the rest of the zones that surround it. The Southern Alps can also be identified as a dense block, with its borders to the Briançonnais Terrane and the Austro-Alpine zone clearly defined in the East of the modelled region. The Tauern Window can also be clearly identified as a relatively lower density zone within the Austro-Alpine zone.

Figure 8 also shows the thickness and average density of the modelled crust, but additionally shows their correspondence with large earthquakes and ongoing surface deformation. The thickness of the crust is overlain with present day vertical displacement rates (Sternai et al., 2019) in Fig. 8a and the average density of the crust is overlain with present day horizontal surface strain distribution (Sánchez et al., 2018), earthquakes of a moment magnitude of 6 or larger (Fäh et al., 2011; Stucchi et al., 2012; Grünthal et al., 2013) and the location of modelled upper crust domain boundaries in Fig. 8b, so that relationships between crustal features and recent deformation and seismicity can be interrogated.

Within the Alps a strong correlation exists between the thickness of the crust and vertical displacement rates at the surface. Regions of modelled thickened crust correspond to high positive rates of vertical displacement. Regions of thinned crust, such as the Po Basin and the Upper Rhine Graben, were found to correspond to negative vertical displacements. Differing rates of vertical displacement can also be observed in the Western Molasse and Eastern Molasse Basin, with the west uplifting and the east subsiding. The transition between these two behaviours in the Molasse Basin corresponds to the boundary of the modelled density domain boundaries in the sedimentary and upper crustal layers, separating the denser eastern region of the basin and the less dense western portion of the basin.

Among regions with a pronounced change in the density of the crust, such as the plate boundary between Adria and the Southern Alps, there is coincidence with large earthquakes (Fig. 8b). Whilst not every large earthquake corresponds to a contrast in the average density of the crust, they all correspond to the location of density domain boundaries within the upper crust as defined in the generated model. Horizontal surface strain distribution also corresponds to the location of density domain boundaries within the upper crust as defined in the model, with the direction of maximum horizontal strain predominantly perpendicular to the domain boundaries.

5 Discussion

Differing methods of classifying the Alpine zones have been adopted over time, however the results presented here would support works that utilise tectonic reconstructions and constrain zones based on the plate the crust originated from (e.g. Schmid et al., 2004). Crust derived from different terranes could potentially be assumed to have differing properties such as density, and from the model produced in this work that is found to be the case. From the results, correlation can be observed between zones of different density in the model and Alpine zones as defined by tectonic reconstructions and paleogeography, such as the dense Briançonnais Terrane and Southern Alps and the less dense Tauern Window.

As no density domain geometries were pre-defined during the modelling stage, the correlation of these domains within the generated model to known features adds validity to the generated model. However, caution should be exercised with the exact location of domain boundaries due to many geological cross sections (e.g., Schmid et al., 2004) showing that tectonic domains cropping out at the surface are offset or not continuous at depth. As this was not possible to implement during the gravity modelling workflow, an offset is often present between features in the average crustal densities (Fig. 7c) and the location of the associated feature at the surface. Two examples of this are in the North of the Briançonnais Terrane and the Tauern Window, suggesting these features have subsurface geometries that differ from there surface expression. Nevertheless the bulk average densities allow for the location of density distinct tectonic features in the crust.

Additionally, Alpine zones of Adriatic provenance were found, in general, to be denser than those of European provenance, a trend also noted in the present day densities of the Adriatic and European crusts, potentially indicating that prior to orogenesis this was also the case. Alpine zones derived from Adriatic continental crust such as the Austro-Alpine and Southern Alps appear denser, in general, than the European continental crust derived Helvetic zone and Tauern Window. The Briançonnais Terrane derives from neither Europe nor Adria and appears as such in our model, as the region of highest density in the area. These observations are consistent with the interpretation that the provenance of crust within the Alps can potentially be indicated by its properties, such as density, implying that as the Alpine zones were emplaced at different times during orogenesis, the respective plates prior to orogenesis could have had similar crustal properties to the present day ones.

Regions in the generated model exist with similar provenance and differing densities, indicating that factors other than provenance would also influence their densities. This is exemplified by the Helvetic and Penninic Alps, both deriving from the European plate, which possess a boundary between them that corresponds to an average crustal density contrast. Additionally, some expected boundaries between crusts of different provenances are obscured by other elements of the model. The transition from the European, Helvetic and Peninnic, to Adriatic Austro-Alpine units corresponds to the thickest area of the crustal root, where lower crust percentages are much higher than upper crustal ones, creating a region of high density crust in the model that masks the transition from European to Adriatic crust, when looking at average crustal densities.

Correlation between present day horizontal surface deformation and large seismic events with density contrasts within the crust in the generated model would suggest the localisation of deformation along these features. Previous works have also shown correspondence between the localisaton of seismicity at density contrasts within the crust, such as at crustal block boundaries (Dentith and Featherstone, 2003), providing further validity to our model. As we are working with a coarse resolution crustal model to identify major features we found it appropriate to compare to a sparse seismic catalogue comprising only the largest (M>6) events allowing for a first-order identification of this correlation. Due to the complex structural nature of an active orogen it is difficult to relate seismicity purely to density contrasts in the crust at higher spatial resolution, as the interplay of faults and collisional processes play a major role in localising seismicity (Serpelloni et al., 2016), while a non-negligible part of earthquakes occurs away from known faults (Hetényi et al. 2018b). However, due to the inherently different properties of crustal blocks of different provenance, it presents the likelihood that major faults and other structures likely to accommodate seismicity would form at the boundaries between these blocks.

All large seismic events in the region coincide with the modelled location of upper crustal density domain boundaries, however not all correlate to contrasts in the average density of the crust. This fact would suggest that within the Alps upper crustal density contrasts are a more likely location for the localisation of seismicity than lower crustal ones. Observations of the occurrence of seismicity at depth within the Alps have shown that it is predominantly present within the upper crust (Deichmann, 1992; Serpelloni et al., 2016; Wiemer, et al., 2017), supporting interpretations made from the derived model. However, regions exist within the model that have both average crustal density contrasts and upper crustal density domain boundaries that do not coincide with seismic events, indicating that there are additional controlling factors to the localisation of seismicity.

Observations of the correlation between positive vertical displacement at the surface (Sternai et al., 2019) and thickened crust within the modelled region, and negative vertical displacement and thinned crust also strengthen the validity of the model, with this behaviour expected due to isostasy. The crust is significantly thinned beneath the Po Basin of the southern foreland while it is not in the Molasse Basin of the northern foreland, explaining the discrepancy in sedimentary thicknesses noted before. This could also indicate different driving mechanisms for the formation of either basin, with the Molasse Basin potentially lacking significant subsidence due to being formed predominantly through flexure and the Po Basin being formed through both flexural and active extensional processes. Alternatively the thinned crust below the Po basin could purely represent an inherited crustal feature. Deriving the driving processes for the sedimentary basins formation within the region remain outside of the scope of the present work, however the accurate constraint of the thinned crust in these regions through the use of gravity provides the scope for this to be identified in future projects.

The results presented in this work indicate crustal properties that would support observations from previous works (Sternai et al., 2019) on the dynamics of the region. Whilst correlation can be observed between vertical displacement at the surface and thickened or thinned crust, some regions such as the Molasse Basin show a crust of similar thickness throughout but present a change in the polarity of surface vertical motion. The crustal densities of the model generated here would support this change, with the transition occurring at the boundary of density domains in the crust and the denser eastern portion exhibiting subsidence and the less dense western portion exhibiting uplift.

Previous works on the dynamics of the Adriatic plate show that it acts as a more rigid indenter than the European plate as it moves northwards rotating counter-clockwise into it (Nocquet and Calais, 2004; Vrabec and Fodor, 2006; Serpelloni et al., 2016). Our model shows that the Adriatic crust is denser than the European crust and seismic velocities are also higher in the Adriatic crust than in the European crust (e.g. IESG, 1978; IESG & ETH Zuerich, 1981; Strößenreuther, 1982; Scarascia and Cassinis, 1997; Bleibinhaus & Gebrande, 2006; Brückl et al., 2007). Higher densities and velocities indicate an on average more mafic lithology for these domains, potentially suggesting that they may be stronger than the European crust. The properties of the plates, as modelled here, would suggest that in the present day convergence of the Eastern Alps the denser Adriatic crust would subduct under the European crust, which fits with the subduction polarity identified in teleseismic tomographies (Lippitsch et al., 2003) and high-resolution receiver function analysis interpreted with other datasets (Hetényi et al., 2018a). However, as stated by Kästle et al. (2019) there is no consistent model of Alpine subduction, it is a complex system that has evolved over time with more influencing factors than plate densities. Gravity constrained bulk average densities of the crust and lithospheric mantle in the region, however, provide strong constraints for future works to identify the nature of Alpine subduction.

Whilst the densities used in the final best fit model often correspond very closely to those derived from the P wave velocities (Table 1), there are exceptions. In general these are not of concern, such as the opposite tendencies of the more and less dense lithospheric mantles, as the modelled bodies are large volumes of homogenous density that in the real world contain much more heterogeneity. The seismic velocities only provide a fraction of coverage through any of the bodies therefore it is expected that the density indicated by P wave velocity to density conversions will not accurately represent its bulk effect on the gravity field and as such they have been used for initial indications on density and the final densities indicated through gravity constraint.

In the European and North Adriatic domains of the lower crust, however, values are more typical of upper crust, which requires more scrutiny. The sensitivity of the model to density alterations in these crustal has been demonstrated in Fig 9. There, a model run with lower crustal densities in North Adria and Europe derived directly from P wave velocities to density conversions, is shown. The density of the European lower crust has been raised from 2800 to 2890 kg/m3, and the lower crust of North Adria has been raised from 2750 to 2990 kg/m3. Fig 9a shows the residual gravity (calculated – observed) of this altered lower crust model and its difference to the residual of the best fit model is shown in Fig 9b.

The figure indicates that density changes in the lower crust ~ 100-200 kg/m3 can affect the gravity field by up to 100 mGal and that using lower crust densities indicated by the P wave velocity to density conversions in Europe and North Adria causes significant misfit. As mentioned prior, the only free parameter during the gravity modelling phase was density. With these low crustal densities required to fit the gravity field and the P wave velocity to density conversions from the upper crust regions fitting so closely, the likely explanations are that either the lower crust in those regions is in fact of a low density or the lower crust is thinner than in the initial structural model, in turn allowing for a slightly denser lower crust. In either case the average density of the crust as presented in Figure 8 would largely remain unchanged and these regions would still represent regions of low density crust.

Although correlations are noted between lateral variation in density distribution in the crust and observations such as plate dynamics and the localisation of large earthquakes and recent deformation, the causes of these observations must be further investigated. Planned future modelling will look closer at the features of the crust by creating thermal and rheological models to investigate the driving forces behind the observed correlations, and potentially helping to better explain trends noted in this work. Work is also progressing on constraining deeper structures in the region, such as the mantle, allowing for better constraints on crustal features in the future.

Although the generated model fits the observed gravity well across almost all of the modelled region, it represents a simplified version of the geology below the surface that is not able to account for all the complexity of the real world and as such, inaccuracies within the model exist. Additionally, whilst the location of density domains in the model remains a non-unique solution, efforts were made to minimise errors by using seismic data and indications from previous modelling (see Input Data section) to constrain the densities within each layer and density domain boundaries. Although these uncertainties cannot fully be accounted for, by only dealing with features and trends appropriate to the scale of the model they are severely mitigated. At the scale of the Alps and their forelands as described in this work, irrespective of localised changes to surface heights or densities, the overall trends identified would not be altered.

6 Conclusions

By creating the first gravity constrained, 3D structural and density model of the lithosphere focused on the Alps and their respective forelands, insights were gained into the distribution of densities at depth within the crust. The findings suggest that the present day Adriatic crust is both thinner (22.5 km) and denser (2800 kg/m3) than the European crust (27.5km, 2750 kg/m3). Crust derived from different terranes was also found to have significantly different densities with Alpine zones of Adriatic provenance. The Austro-Alpine and Southern Alps were found to be denser and those of European provenance such as the Helvetic Zone and Tauern Window to be less dense, indicating the respective plates prior to orogenesis may be assumed to have had similar crustal properties to the present day.

Our modelled anomaly showed a good fit to the observed gravity with maximum misfits of around ± 25 mGal across the whole region. It was further validated by density domains defined in the model corresponding to known tectonic features, large earthquakes corresponding to crustal density contrasts and surface vertical displacements corresponding to crustal thicknesses. The causes of these observations and correlations cannot be explained solely from the results of this work. Therefore, planned future modelling will generate thermal and rheological models to give further insight into the crustal architecture of the region as well the causes of the localisation of deformation and seismicity.

Author Contributions

Hans-Jürgen Götze and Jörg Ebbing contributed pre-existing gravity models from the region and advised on the gravity modelling workflow and utilisation of the software used to carry it out. György Hetényi contributed seismic data for the work and advised on the interpretation of the crust and Moho in the Eastern Alps. Magdalena Scheck-Wenderoth advised on the entire workflow and the interpretation of results. Cameron Spooner carried out the modelling work and prepared the manuscript with contributions from all co-authors.

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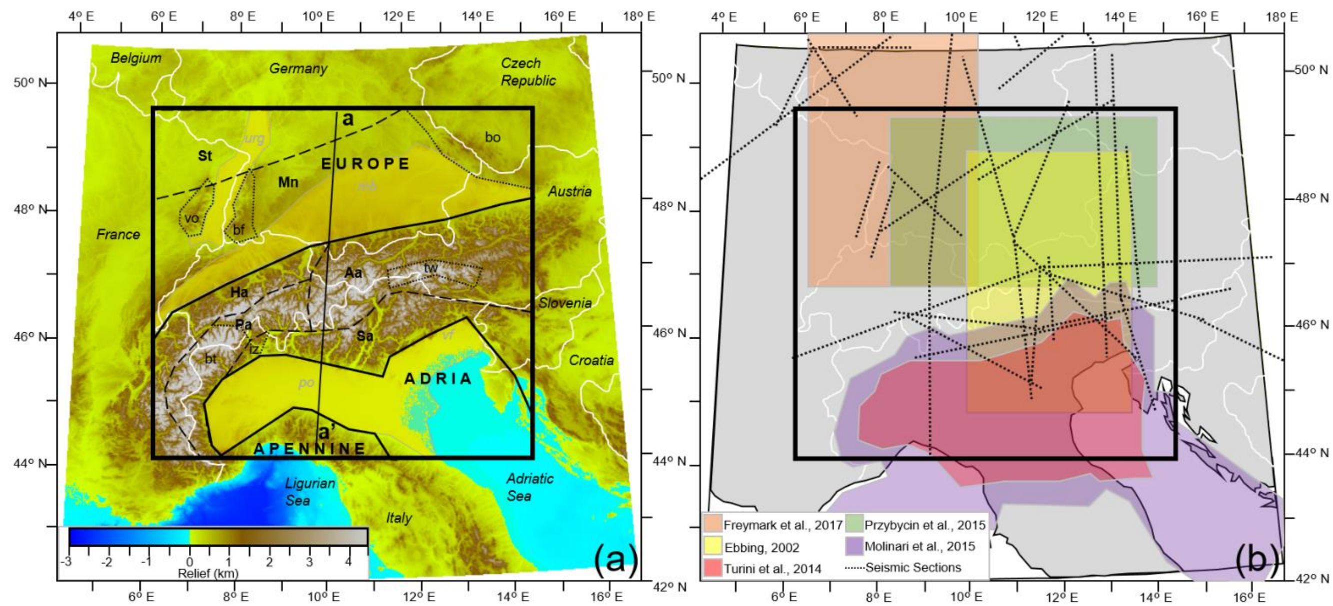
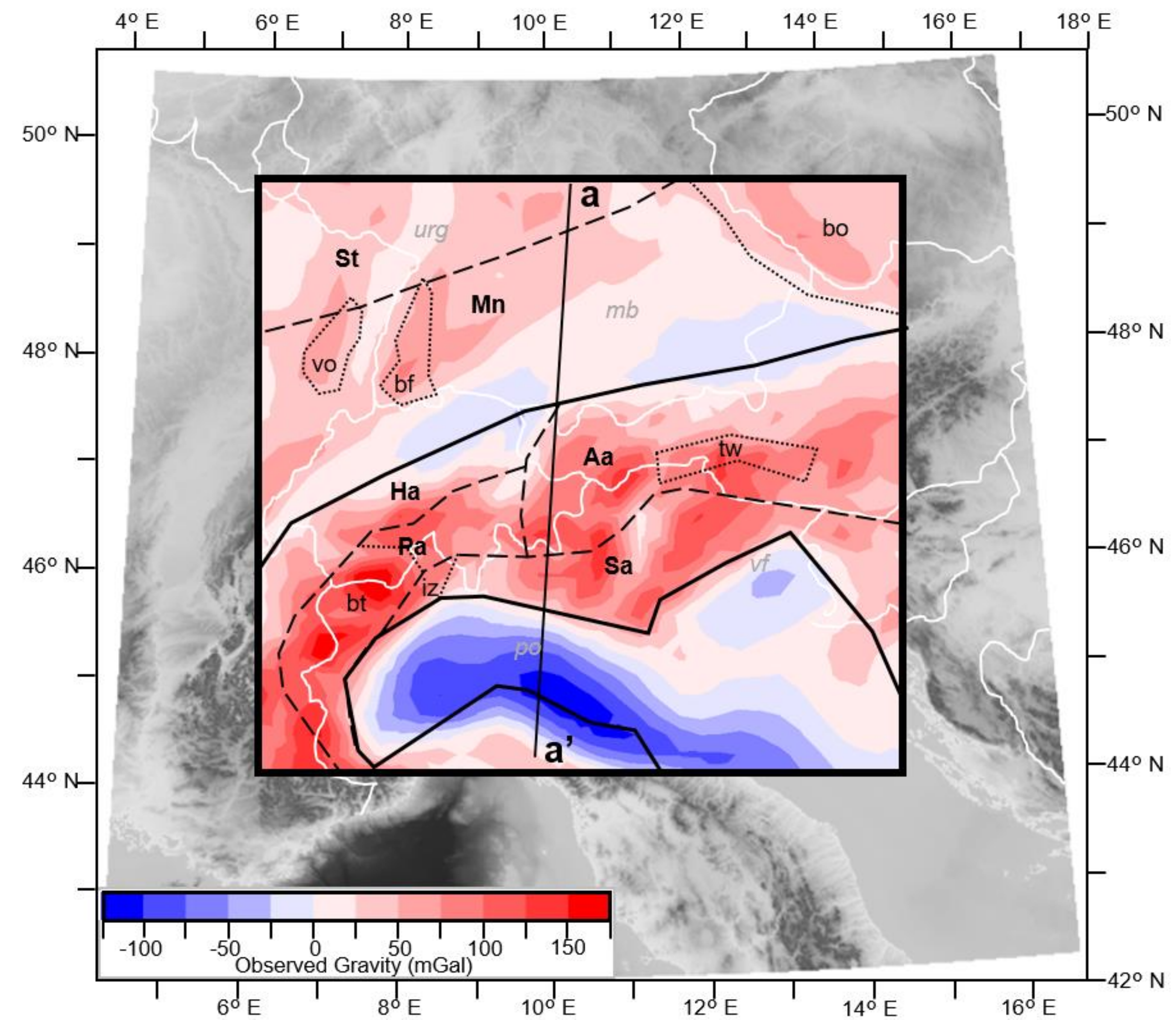
Figures

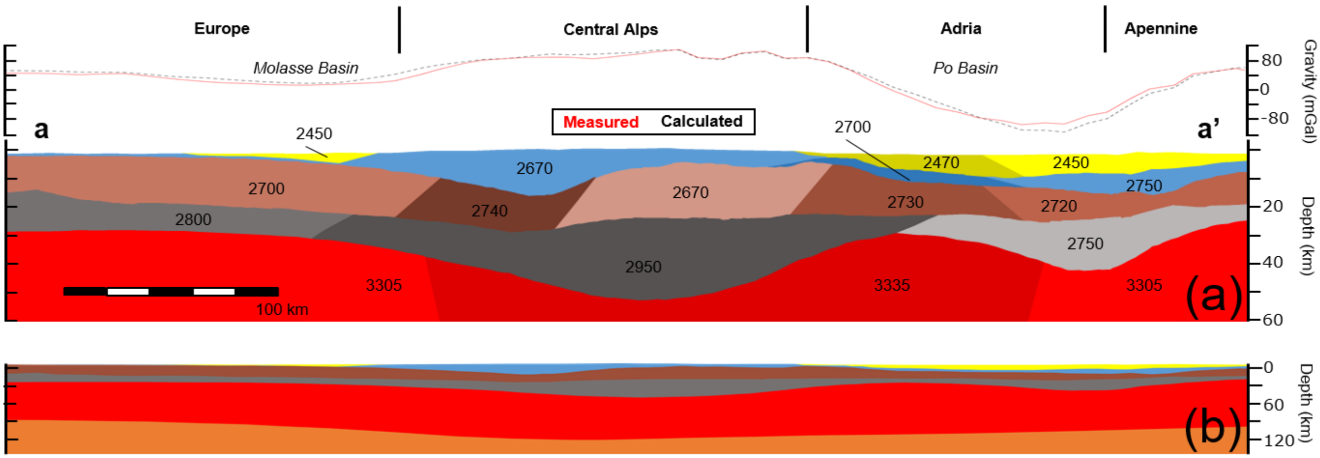
- Figure 1. a) Topography and bathymetry from Etopo 1 (Amante and Eakins, 2009) shown across the Alpine region with the key tectonic features overlain. Study area is indicated with a black box. a-a' represents the cross section in Fig. 3. Solid black lines demark the boundaries of the non-deformed European and Adriatic Plates, the location of the Apennine plate is also marked. Dashed black lines indicate different geological domains (St – Saxothuringian; Mn – Moldanubian; Aa – Austro-Alpine Zone; Ha – Helvetic Alps; Pa – Penninic Alps; Sa – Southern Alps). Dotted black lines indicate the extent of other tectonic features within these domains (bo – Bohemian Massif; vo – Vosges Massif; bf – Black Forest Massif; tw – Tauern Window; bt – Briançonnais Terrane; iz – Ivrea Zone). Yellow areas bound by a solid grey line indicate the extent of sedimentary basins (urg – Upper Rhine Graben; mb – Molasse Basin; po – Po Basin). b) Input data source extents: Upper Rhine Graben gravity constrained model (Freymark et al., 2017); Molasse Basin gravity constrained model (Przybycin et al., 2015); TRANSALP gravity constrained model (Ebbing, 2002); Po Basin seismically constrained models (Turini et al., 2014; Molinari et al., 2015); and Seismic Sections (IESG, 1978; IESG & ETH Zuerich, 1981; Strößenreuther, 1982; Mechie et al., 1983; Zucca, 1984; Gajewski & Prodehl, 1985; Deichmann et al., 1986; Gajewski et al., 1987; Gajewski & Prodehl, 1987; Yan and Mechie, 1989; Zeis et al., 1990; Aichroth et al., 1992; Guterch et al., 1994; Ye et al., 1995; Scarascia and Cassinis, 1997; Enderle et al., 1998; Bleibinhaus & Gebrande, 2006; Brückl et al., 2007; Hetényi et al., 2018).



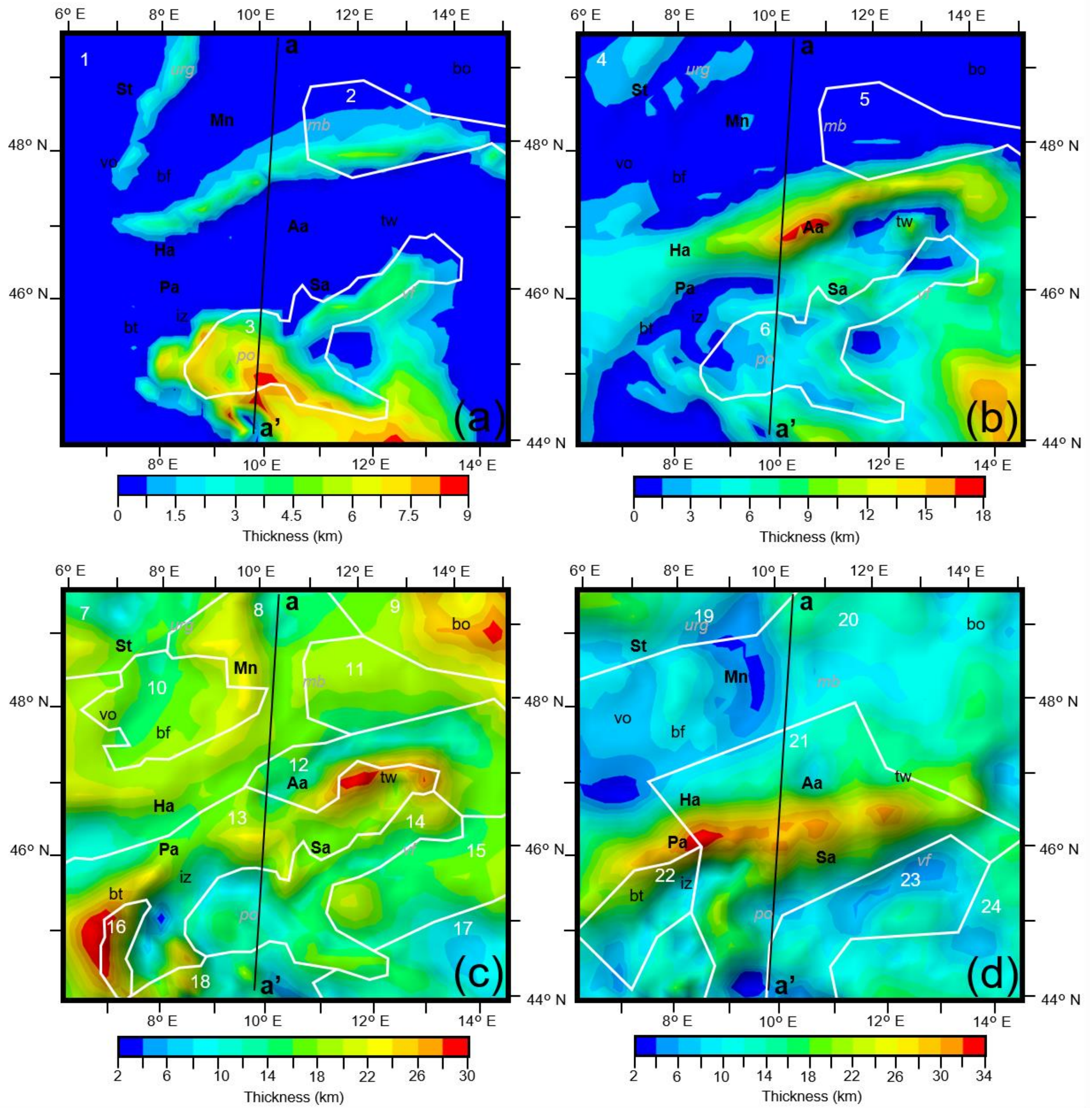
- Figure 2. Observed gravity of the region. Values calculated from a spherical approximation at 6km above datum of EIGEN-6C4 global gravity model (Förste et al., 2014). a-a' represents the cross section in Fig. 3. Locations of key tectonic features are overlain (definitions shown in Fig. 1a caption).



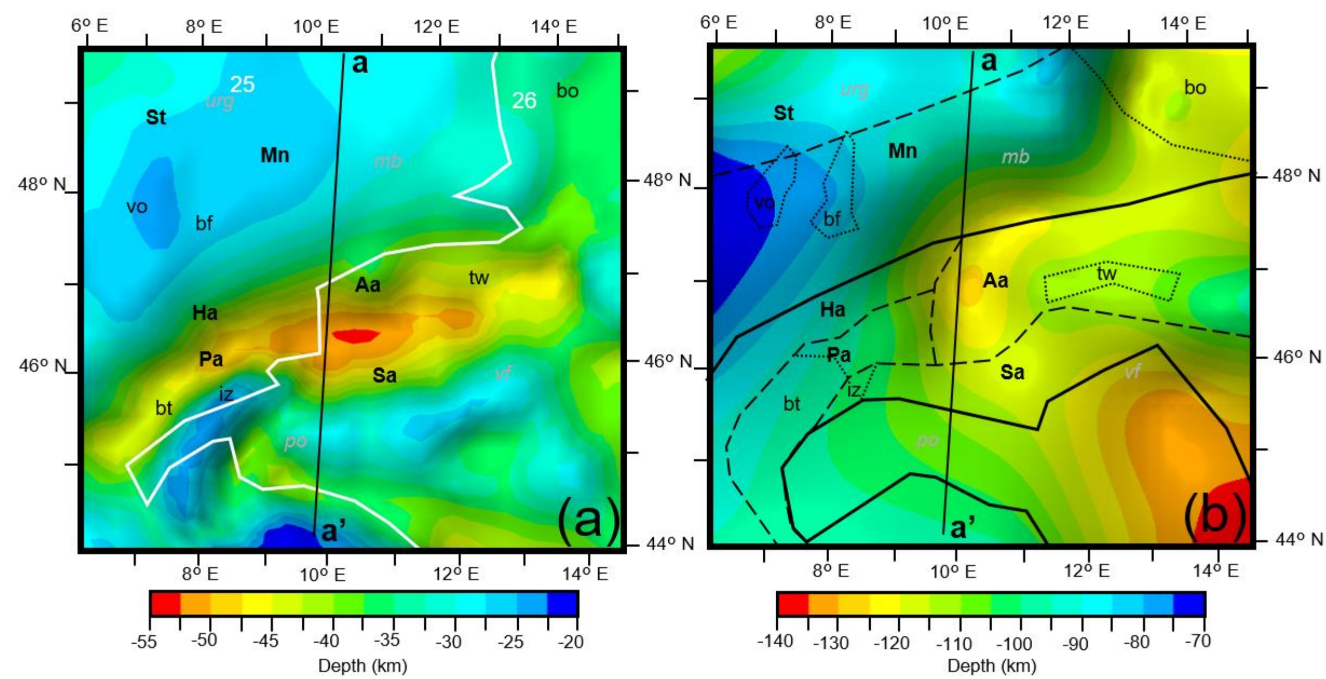
- Figure 3. Cross sections through generated model showing thickness of model layers. Location is marked in Figs 1a, 2 and 4-6 as a-a'. 1a. Lithospheric mantle layer is shown in red, lower crust is shown in grey, upper crust is shown in brown, consolidated sediments are shown in blue and unconsolidated sediments are shown in yellow. In Fig. 3. a) Density domains within each layer are shown as a change of shade and the density of each domain is labelled. On top, the observed and calculated gravity anomalies along the cross section are shown. Fig. b) is scaled to show the thicknesses of all layers down to the asthenospheric mantle, shown in orange.



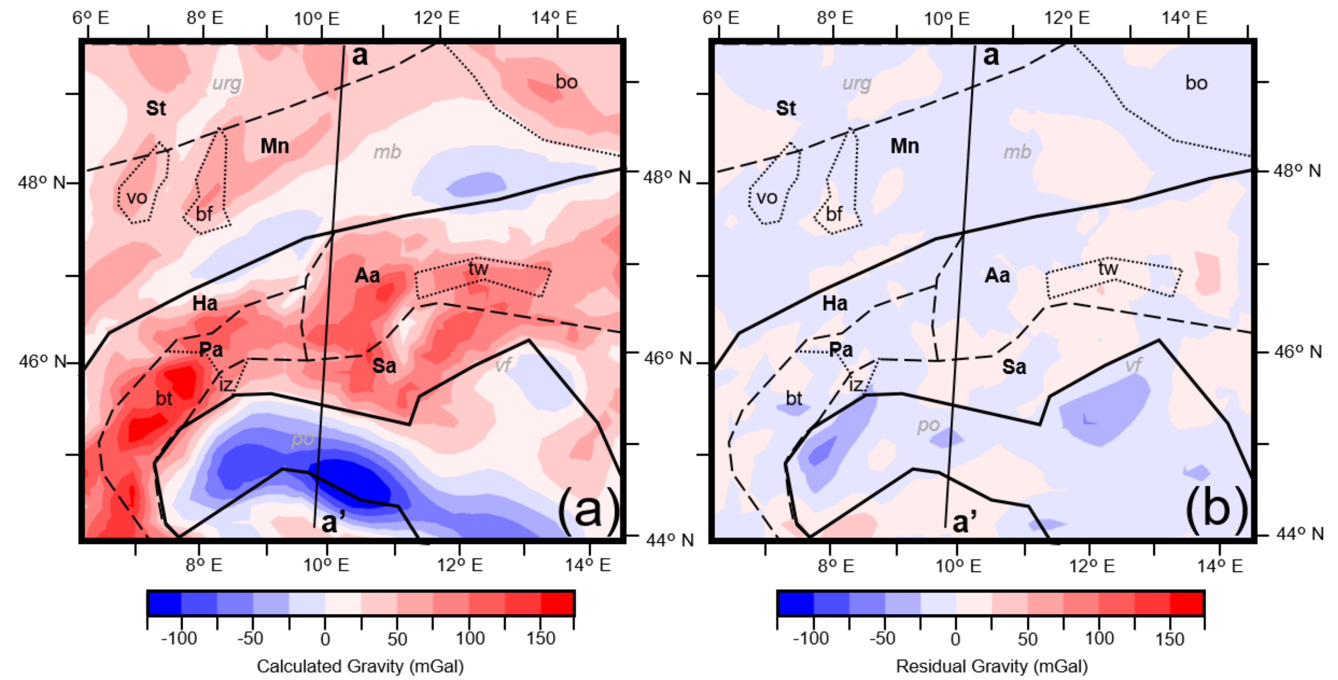
- Figure 4. Thickness of a) unconsolidated sediments, b) consolidated sediments, c) the upper crust and d) the lower crust across the modelled area. Density domains required during modelling within the layer are overlain in white, domain numbers are shown in white and correspond to Table 1. Locations of key tectonic features are overlain (abbreviations shown in Fig. 1a caption).



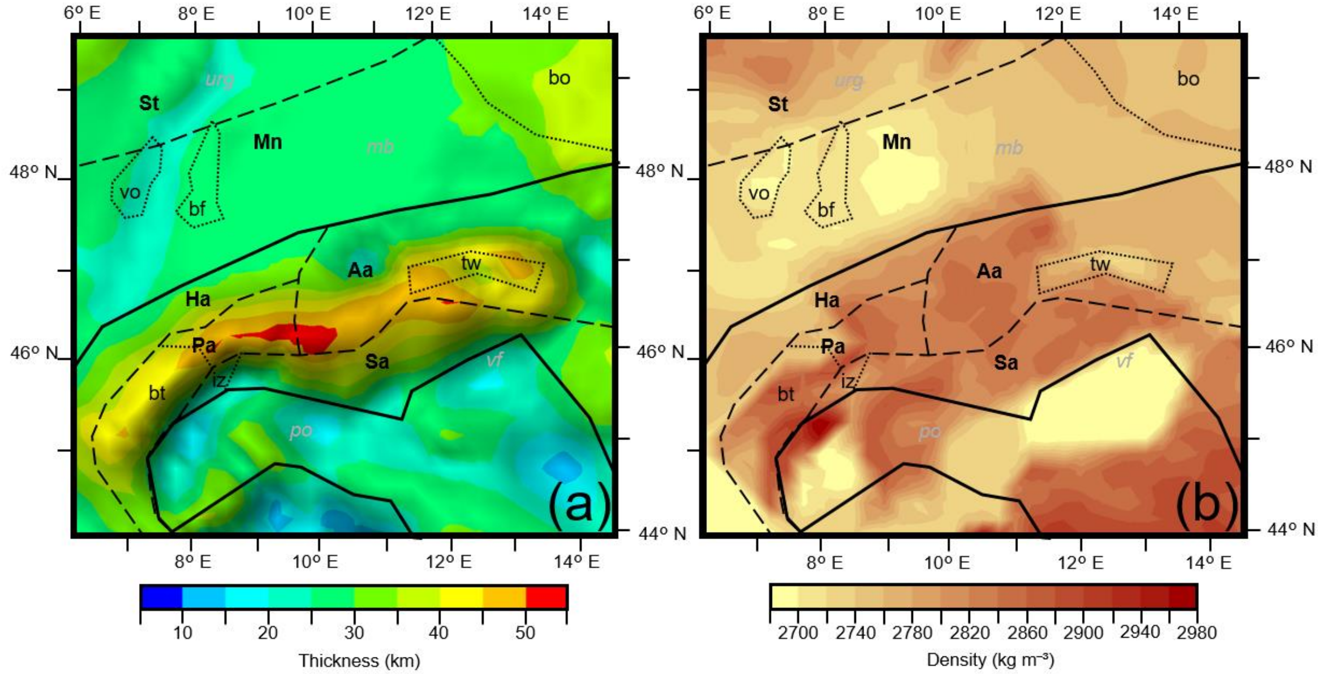
- Figure 5. a) Depth to the Moho across the modelled area. Density domains required during modelling within the lithospheric mantle are overlain in white, domain numbers are shown in white and correspond to Table 1. b) Depth to the LAB from Geissler et al (2010) across the modelled area. Locations of key tectonic features are overlain for both figures (definitions shown in Fig. 1a caption).



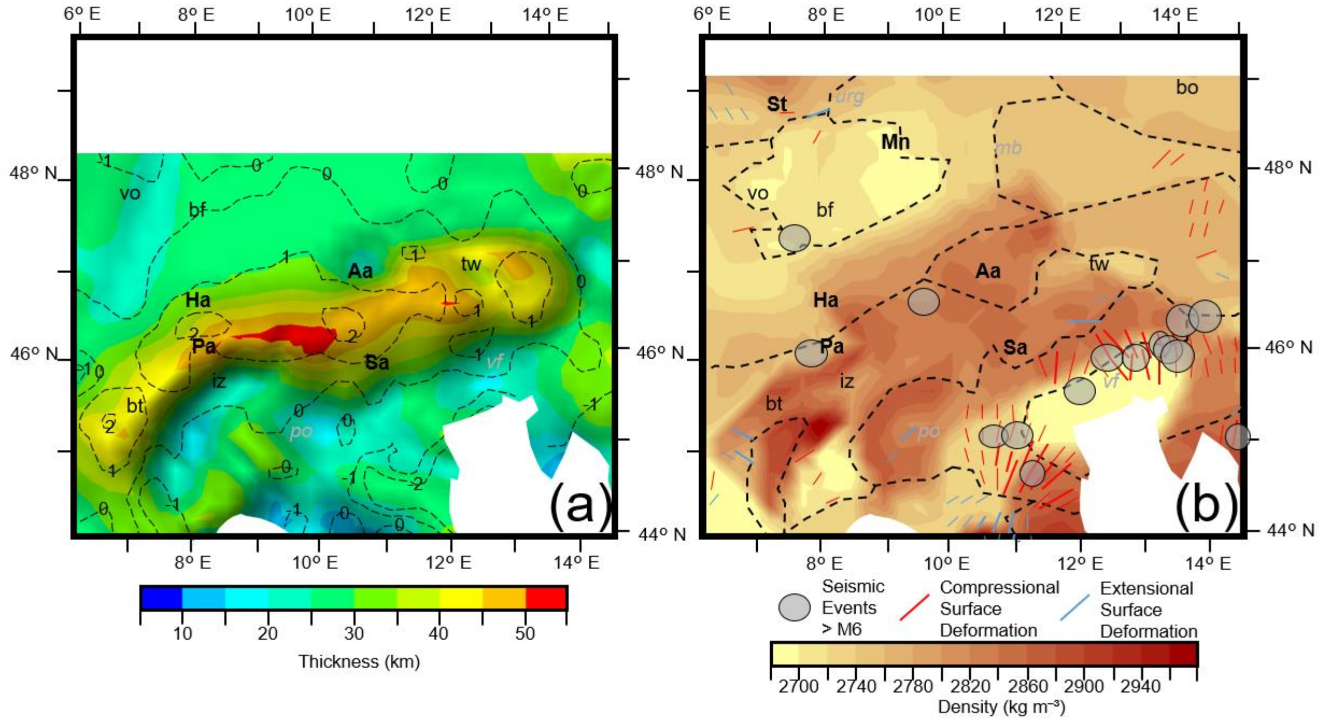
- Figure 6. a) Calculated gravity at 6 km above the datum resulting from the final structural and density model. b) Residual gravity (observed gravity - calculated gravity) of the best fit model. Locations of key tectonic features are overlain for both figures (definitions shown in Fig. 1a caption).



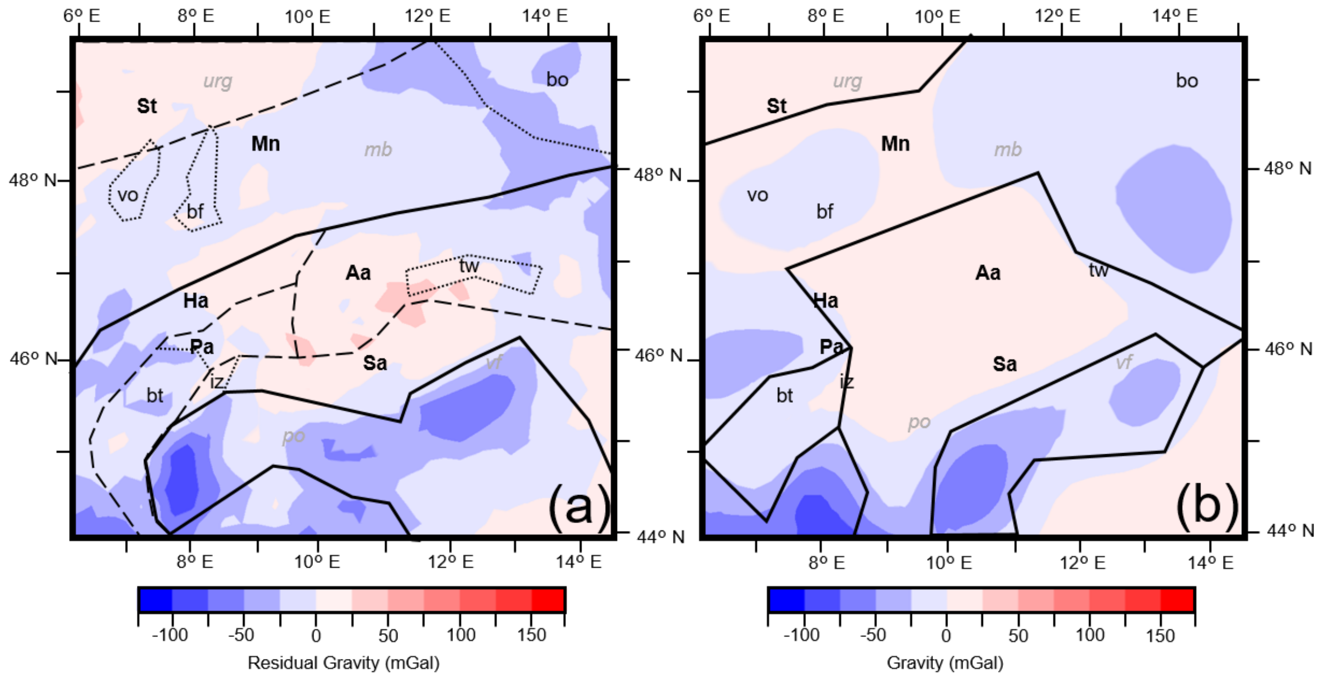
- Figure 7. a) Thickness and b) average density of the entire crust across the modelled area. Solid lines demark the boundaries of Alpine zones, the dotted black lines indicate the extent of the non-accreted Adriatic plate. Locations of key tectonic features are overlain (definitions shown in Fig. 1a caption).



- Figure 8. a) Thickness of the crust across the modelled area overlain with vertical displacement rates (Sternai et al., 2019). Dotted black lines indicate isolines of the vertical displacement rates in mm/yr. b) Average density of the crust across the modelled area overlain with geodetically derived horizontal surface strain distribution (Sánchez et al., 2018) and seismic events of a moment magnitude larger than 6 (Fäh et al., 2011; Stucchi et al., 2012; Grünthal et al., 2013). Bar orientation indicates orientation of maximum surface strain. Dotted black lines indicate the upper crust density domains of the final structural and density model. Regions where the overlain data was not available have been whited out in both figures. Locations of key tectonic features are overlain for both figures (abbreviations shown in Fig. 1a caption).



- Figure 9. a) Residual gravity (observed gravity - calculated gravity) of a test model with lower crust densities for the Europe and Northern Adria domains set to values indicated directly from P wave velocities using conversion suggested by Brocher (2005). b) Difference in gravity residual between the best fit model (Fig. 6b) and the model shown in the Fig. 9a. Lower crustal density domains of the best fit model are overlain in black.



Tables

- Table 1. The density of each domain in the model calculated by converting from its mean P wave velocity using the empirical relationship detailed in Brocher (2005) and the density of all domains used in the final model of the region that best reproduce the indications of both the seismic data sources and the gravity field. Locations of each density domain can be found in Fig. 4.

Unit	Mean Density indicated by P Wave Velocities (Kg/m3)	Density Used in Final Model (Kg/m3)
1. Unconsolidated Sediments	2530	2450
2. Unconsolidated Sediments – East Molasse	2540	2470
3. Unconsolidated Sediments - Po	2610	2470
4. Consolidated Sediments	2680	2670
5. Consolidated Sediments – East Molasse	2670	2680
6. Consolidated Sediments - Po	2700	2700
7. Upper Crust – Saxothuringia	2690	2670
8. Upper Crust – Moldanubia	2710	2700
9. Upper Crust – Bohemia	2720	2740
10. Upper Crust – Vosges and Black Forest	2690	2660
11. Upper Crust – East Molasse	2720	2720
12. Upper Crust – East Alps	2740	2740

13. Upper Crust – West Alps	2740	2670
14. Upper Crust – Po	2740	2730
15. Upper Crust – North East Adria	2780	2660
16. Upper Crust – Ivrea	-	2790
17. Upper Crust – East Adria	2780	2700
18. Upper Crust – Apennine	2770	2720
19. Lower Crust – Saxothuringia	2900	2920
20. Lower Crust – Europe	2890	2800
21. Lower Crust – Alps	2880	2950
22. Lower Crust – Ivrea	-	3100
23. Lower Crust – Northern Adria	2990	2750
24. Lower Crust – East Adria	2950	3040
25. Lithospheric Mantle – Less Dense	3340	3305
26. Lithospheric Mantle – More Dense	3260	3335
Water	-	1025
Asthenospheric Mantle	-	3320