AGU100 ADVANCING EARTH AND SPACE SCIENCE

Tectonics

COMMENT

10.1029/2018TC005129

This article is a comment on Pedrera et al. (2017), https://doi.org/10.1002/2017TC004716.

Key Points:

- The crustal model proposed by Pedrera et al. (2017) is not supported by the available deep seismic data set
- The gravity model is built upon inaccurately retrieved residual gravity anomalies and uses inappropriate density values
- The sequential restoration shows geometric-structural inconsistencies, mechanical difficulties, and problematic isostatic and kinematic implications

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Citation:
Pedreira, D., Pulgar, J. A., Díaz, J., Alonso, J. L., Gallastegui, J., & Teixell, A. (2018). Comment on "Reconstruction of the exhumed mantle across the North Iberian Margin by crustal-scale 3-D gravity inversion and geological cross section" by Pedrera et al. *Tectonics*, *37*, 4338–4345. https://doi.org/10.1029/2018TC005129

Received 8 MAY 2018
Accepted 22 OCT 2018
Accepted article online 6 NOV 2018
Published online 20 NOV 2018

Comment on "Reconstruction of the Exhumed Mantle Across the North Iberian Margin by Crustal-Scale 3-D Gravity Inversion and Geological Cross Section" by Pedrera et al.

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1. Introduction

Pedrera et al. (2017) presented a new tectonic model for the Basque-Cantabrian Basin in the Pyrenean-Cantabrian belt, based on a geological cross section and the results of a 3-D gravity modeling that presumably "demands the presence of a high-density mantle body placed within the crust in order to justify the observed anomalies." Other authors have discussed before the possibility that the strong gravimetric (and magnetic) anomalies observed over the area could be explained, totally or partially, by bodies of mantle rocks located at shallow depths beneath the sediments of the Basque-Cantabrian Basin (e.g., Pedreira et al., 2007; Roca et al., 2011; Tugend et al., 2014). However, the contribution by Pedrera et al. (2017) is novel in that it suggested that the present-day crustal-scale structure retains largely the morphology of the hyperextended Mesozoic basin and is only slightly modified by the Cenozoic Pyrenean orogeny. In their model, the continental crust is totally removed at present beneath the Cretaceous sediments of the northern part of the Basque-Cantabrian Basin, so that these sediments are resting on top of the mantle, with the asthenosphere at only ~15-km depth. The modeled upper surface of the mantle extends laterally to the central Pyrenees, always reaching "shallow crustal levels also locally attaining the topographic surface." That is to say that in those places of the Pyrenees, there is supposedly only mantle from the topographic surface to the Earth's core, at ~2,900-km depth.

New and provocative ideas, especially when implying paradigmatic changes, should be particularly convincing in their presentation. These presentations should ideally provide detailed justifications for the decision adopted in the course of the research and take into consideration all the available results from previous studies, or a reinterpretation of them, adding full discussions regarding their implications. The contribution by Pedrera et al. (2017) failed in this attempt. It used inadequate procedures and unrealistic parameter values in the course of the modeling, leading to a final structural model with clear geological inconsistences and contradictions with several geophysical observations. In the following, we briefly describe some of these problems, hoping that Pedrera et al. can clarify them and provide additional arguments in support of their work.

2. Modeling Rationale

The core of the new interpretation by Pedrera et al. (2017) lies in 3-D gravity inversion results, and therefore, the way this inversion is performed is crucial to the discussion. The geophysical inversion inherently provides no unique solution. This limitation is particularly acute when dealing with potential field modeling, as widely discussed in the literature (e.g., Michel & Fokas, 2008). In the work by Pedrera et al. (2017), it is not true that "3-D lithospheric-scale gravity inversion demands the presence of a high-density mantle body placed within the crust in order to justify the observed anomalies," as stated in the abstract. First, the inversion can only demand a high-density body, not a "high-density mantle body" (whether this dense body is mantle or not is a matter of interpretation). Second, it is not that the inversion demands it; it is just that the inversion was designed to demand it. In fact, rather than an inversion, the modeling presented by Pedrera et al. (2017) can be seen as a forward modeling *polished* by inversion. They constructed several 2-D forward gravity models along parallel sections in which the shape of the exhumed mantle was delineated according to a preconceived model (inspired in the recent proposal by Wang et al., 2016, for the western Pyrenees). The interpolated surface delimiting the mantle was modified by the 3-D inversion, refining the fitting of anomalies but "preserving the geometry" that resulted from the previous step.

Although we do not have concerns with the practice of designing models to test hypotheses, we consider that the way Pedrera et al. (2017) described their results is somewhat biased: not only did they invoke the shallow presence of the mantle as a demand of the inversion but they also avoided a proper scientific discussion about alternative ways of explaining the gravity anomalies. These alternatives are just mentioned very briefly at the beginning of their section 4.2: "High-density, high-velocity bodies have been previously identified along the Basque-Cantabrian Basin and the Pyrenees and interpreted either as exhumed lower crust material … or as mantle rock …. The high-density body derived from our gravity inversion … is connected to the mantle in agreement with Wang et al. (2016), which constituted a main difference with previous models (e.g., Muñoz, 1992; Pedreira et al., 2003, 2007; Quintana et al., 2015; Teixell, 1998)." The lack of discussion on this crucial discrepancy is surprising considering the large number of previous gravimetric models proposed for the Pyrenean-Cantabrian belt and fails to provide the readers with strong arguments in favor of the new model over the previous ones.

3. Problems With the Isolation of the Residual Gravity Anomaly

Before performing the inversion, Pedrera et al. (2017) calculated the gravity effect of a reference model that simulates a *normal* crust for the area. Then, they subtracted this effect from the Bouguer anomaly map to isolate the residual gravity anomaly that they use to model the geometry of the exhumed mantle body. This reference model is composed of Cenozoic and Mesozoic sediments on top of a crystalline crust that extends downward to depths estimated by receiver function data (Mancilla & Diaz, 2015).

The accurate determination of layer thicknesses and densities in the reference model is crucial to correctly isolate the residual gravity anomaly. However, the information provided by Pedrera et al. (2017) is very limited. For example, regarding sediment thicknesses, the only mention is: "The thickness of Tertiary and Mesozoic sedimentary deposits has been estimated with deep boreholes and seismic data (Arenillas-González et al., 2014)." No information is provided about the resolution and accuracy of these determinations. For example, how many boreholes reach the basement? How evenly are they distributed? Moreover, the reference by Arenillas-González et al. (2014) applies exclusively to the Spanish mainland side of the study area. What sources of information were used for the French side and the Bay of Biscay? Neither have we found justification for the density values used. Are they determined from rock samples? Are they converted from seismic velocities?

Regarding the Moho depth map, we must recall that the receiver function (RF) technique can only give a "smooth crustal thickness map of the area" (quoting Mancilla & Diaz, 2015) because RF averages the results over zones comprising a few tens of kilometers around each station. Note that the deployment of seismic stations in the contribution of Mancilla and Diaz (2015) provides an ~60×60 km coverage, which is insufficient to correctly retrieve the abrupt Moho depth variations present in the area investigated by Pedrera et al. (2017). There are other contributions presenting more detailed RF studies that were not considered, including a profile running from the Iberian Range to the Basque Massifs (Díaz et al., 2003) and a 2-D survey covering the western Pyrenees and eastern Cantabrian Mountains (Díaz et al., 2012). Also, the H-κ technique used by Mancilla and Diaz (2015) may provide very complex solutions that are difficult to interpret in the case of overlapping Mohos (e.g. Díaz et al., 2012), a feature that was revealed by deep seismic sounding profiles (DSSPs) in the Pyrenean-Cantabrian belt (e.g., Pedreira et al., 2003; Teixell, 1998). In fact, considering these limitations, it is surprising that the authors did not use the information from the DSSPs, which have good coverage in the area, with Moho depths compiled by Díaz and Gallart (2009) and Diaz et al. (2016). Moreover, these compilations also provided Moho depth information for the Bay of Biscay, whereas the RF results of Mancilla and Diaz (2015) did not. How did Pedrera and coauthors fix the offshore Moho in their model? Nothing is said in the text.

The density distribution within the reference crust is also problematic. The authors state that "a linear depth-density variation from 2.67 at surface to 2.95 g/cm^3 at 50 km was assumed during 3-D forward modeling based on already published seismic data (e.g., Pedreira et al., 2015; Torne et al., 2015)." However, the published seismic data, especially the velocity-depth profiles (Pedreira et al., 2003), show that the crustal structure of the area is incompatible with this simplicity at the scale of the modeling performed by Pedrera et al.

Actually, strong lateral and vertical heterogeneities in seismic velocities (and hence densities) are evidenced, as well as significant changes in layer thicknesses. These heterogeneities include the presence of discontinuous high-velocity bodies within the crust (interpreted to be sections of the European-Cantabrian lower crust indented into the thicker and overall less dense Iberian crust), implying also negative velocity (and density) contrasts at depth.

In summary, the excessive oversimplification of the crustal structure and its internal density distribution makes the residual gravity anomaly map of little significance. As proof, once the inversion to retrieve the exhumed mantle geometry is completed, "The difference between the observed and calculated gravity, called 'gravity error,' displays small amplitude anomalies, between –5 and 5 mGal, in the area that corresponds to the assumed location of the high density body, whereas outside that area, the "gravity error" displays high amplitude anomalies (between −40 and 25 mGal) that can be attributed to lateral density variations within the crust that were not taken into account when defining the density of the crust in step 2." If there are high-amplitude errors in the crustal area where no exhumed mantle was modeled, the reference model used to retrieve the residual anomaly is clearly inaccurate.

4. Misuse of Constraints

One of the main incoherencies of the paper by Pedrera et al. (2017) is that the authors first use RF-derived Moho depth maps to build a reference crustal model, but in the final model they violate these constraints to place the Moho at much shallower depths along most of the investigated area. Disregarding the limitations of the RF technique to resolve small-scale Moho depth variations, the results of Mancilla and Diaz (2015) showed that the crustal thickness inferred in all the stations of the western Pyrenees and the Basque-Cantabrian Basin ranges from 35 to 49 km. These results are remarkably consistent with the information provided by a significant number of DSSPs acquired in the past 40 years (e.g. Diaz et al., 2016, and references therein), revealing a continuous crustal root with variable depth extension beneath the Pyrenean-Cantabrian belt. The exceptional knowledge of the crustal thickness variations resulting from such a wealth of seismic data of different types and interpreted with different methodologies cannot simply be ignored; this is one of our major criticisms to this contribution. Just to mention a very illustrative example, all the seismic data available (RFs and DSSPs) in the Biscay Synclinorium show a thickened crust beneath it, averaging ~40- to 45-km depth (Diaz et al., 2016; Mancilla & Diaz, 2015; Pedreira et al., 2003), whereas in the final model presented by Pedrera et al. (2017) the Moho is located at only ~5-km depth. Of course, seismic data can also be reinterpreted, but this was not done. Since Pedrera and coauthors propose a near-surface Moho with a strong impedance contrast (according to their gravity model), how can they explain that this shallow Moho was not identified in the preceding seismic studies and, conversely, how can they explain the nature of the seismic reflector/conversor located at approximately 40- to 45-km depth that they considered to be a reliable Moho in their reference model? These very relevant issues were not discussed in their contribution.

5. Problems With the Density of the Exhumed Mantle

Pedrera et al. (2017) used a density of 2.9 g/cm^3 for the exhumed mantle in their gravity model, with no explanation to justify such an unusual value. This is incomprehensible because 2.9 g/cm^3 is a value more typical (almost diagnostic) of the lower crust (e.g. Rudnick & Fountain, 1995). The authors themselves used a value of 3.3 g/cm^3 for the mantle outside this exhumed mantle body. In the context of a long-lived discussion on the lower crust versus mantle origin for the dense bodies originating the Pyrenean gravity and magnetic anomalies, the proposal of a new model using lower crustal densities but claiming a mantle origin is disconcerting. The only way we can explain such a low density for the mantle is to assume that it is approximately 50% serpentinized (e.g., Carlson & Miller, 2003; Christensen, 2004), but this possibility was not mentioned in the text. Even considering the effect of serpentinization, the density of the altered rocks would hardly be constant. Since serpentinization requires water availability and temperatures below ~500 °C (e.g., Mével, 2003), it usually decreases with depth as less water is able to enter into deeper parts of the mantle. This induces strong gradients in both the seismic velocity and the density of the exhumed mantle (e.g., Skelton et al., 2005). Actually, density can vary from ~2.5 g/cm^3 (for 100% serpentinization) to ~3.3 g/cm^3 (the typical fresh mantle density) at depth (Carlson & Miller, 2003; Christensen, 2004).

Moreover, Pedrera et al. (2017) showed a large map of aeromagnetic anomalies (their Figure 4b), whose only mention in the text is: "Prominent magnetic anomalies (Figure 4b) accompany the high-density body along all of its paths." Since peridotites are essentially paramagnetic (e.g., Oufi et al., 2002, and references therein), how do they explain the magnetic anomalies? Again, serpentinization of the uppermost mantle could be a potential explanation, but the formation of magnetite by means of these reactions is only significant at serpentinization levels higher than 60–75% (Bach et al., 2006; Oufi et al., 2002), thus implying densities below ~2.8 g/cm^3 (Bach et al., 2006; Carlson & Miller, 2003).

We must recall again that Pedrera et al. (2017) never mentioned serpentinization as an explanation for the density and magnetization values of the exhumed mantle body. But even considering this process, and that 2.9 g/cm^3 could be a reasonable density average for a mantle body with variable serpentinization (from ~100% at the top to 0% at ~40-km depth), the use of such a constant density average for the whole depth range is an oversimplification that cannot be assumed. This is because the shape of the calculated anomaly would be totally different. A body of density 2.9 g/cm^3 near the surface in the model by Pedrera et al. (2017) generates a strong, short wavelength positive anomaly, whereas a body of ~2.5–2.6 g/cm^3 would create a short wavelength negative anomaly. And conversely, a body of density 2.9 g/cm^3 at lower crustal depths barely creates a noticeable anomaly in their model, whereas a body of ~3.3 g/cm^3 would generate a positive anomaly of very long wavelength.

6. Problems With the Geometry of the Exhumed Mantle

Pedrera et al. (2017) showed a depth-contour map of the top of the exhumed mantle at present, from the Basque-Cantabrian Basin to the Central Pyrenees, after the results of their gravity inversion. The shape of the exhumed mantle varies along strike, but it overall reflects the effect of the Cretaceous lithospheric extension, with little disruption during the Pyrenean orogeny, something that we find unrealistic. According to the authors, the top of this mantle body reflects the southward deepening of the top extensional detachment in the 2-D Basque-Cantabrian sections (L1 to L3) and the northward deepening of the detachment in the western Pyrenees sections (L5 and L6). However, sections L7, L8, and L9 show very narrow and almost vertical contours for which no explanation was given: "the high-density body becomes narrow (~15 km wide) and extends vertically to levels near to the topographic surface." These particular geometries are hardly compatible with the crustal structure expected after an episode of intense horizontal stretching, alleged to remain after the orogenesis in the other sections. And how do all these geometries fit with the well-constrained crustal structure and tectonic evolution along the ECORS seismic reflection profiles? How can the abrupt lateral change between the geometries of sections L6 and L7 be explained?

Regarding the geometry of the Cretaceous detachment in the Basque-Cantabrian Basin, Pedrera et al. mentioned in section 6.1 that "The activity of the Gernika-Leitza detachment determines the dissimilar margins of the Basque-Cantabrian Basin and the observed asymmetry in the exhumed mantle, which reaches the shallowest crustal levels along the Biscay synclinorium, close to the north basin boundary (Figures 7 and 11). The crustal-scale geometry of the rift described above notably differs from recent models (Roca et al., 2011; Tugend et al., 2014). Here we propose that the basin developed in the hanging wall of a major north-dipping detachment." Apart from the mistake in the final sentence (*north dipping* instead of *south dipping* detachment), the writing suggests that Pedrera et al. (2017) are the first authors to propose such a Mesozoic south dipping detachment in the Basque-Cantabrian basin. However, the general south dipping geometry of the Mesozoic detachment had already been proposed at least by Quintana et al. (2015) and DeFelipe et al. (2017), contributions quoted elsewhere in the text by Pedrera et al. (2017) but not mentioned in this discussion.

7. Isostatic and Thermal Implications

There are also important isostatic implications in the present-day crustal configuration proposed by Pedrera et al. (2017) that are not addressed in their article. The thicknesses and densities of the different layers of the lithospheric column in the Basque-Cantabrian Basin do not differ too much between the Late Cretaceous and the present-day stages (with the mantle still at ~5-km depth). However, in the Late Cretaceous this area was a rapidly subsiding flysch trough, while at present it is a mountainous region with elevations up to ~1,500 m above sea level. Therefore, their model is incompatible with local (Airy-type) isostatic compensation.

Flexural rigidity of the lithosphere would hardly contribute to support the orogenic topography at a regional scale in their model, because the lithosphere is considered to be extremely thin, and therefore hot and weak (with the asthenosphere located at minimum depths of only ~15 km) from the Paleocene to the latest Oligocene (their Figure 12). This also implies very high and rather constant geothermal gradients during the whole orogenic process, something that is unrealistic and contrary to the findings of thermal studies in the basin (e.g., Arostegui et al., 2006; Gómez et al., 2002). This spatial and temporal evolution is also incompatible with a hypothetical support of the topography by hot asthenospheric upwelling (i.e., *dynamic topography*) acting only since the Eocene and up to the present, a mechanism for which there is no evidence.

8. Inconsistencies of the Crustal-Scale Restoration

The crustal-scale sequential restoration proposed by Pedrera et al. (2017) in their Figure 11 presents several geometric, structural, and mechanical problems that put into question the proposed evolution. One of the most obvious is the progressive disappearance of the lower crust in the central part of the section, between the two conjugate shear zones in the time lapse between the Barriasian-Valanginian (their Figure 11F) and the early Cenomanian (their Figure 11C). The only explanation we can find in the text is that "At lower crustal levels, the crust was completely attenuated in ductile conditions with a presumably pure shear component induced by upward displacement of the asthenosphere." However, ductile flow cannot erase material. Out-of-plane flow is possible, but, if considered, it must be discussed and justified.

There are also several minor-scale structural inconsistencies in the reconstruction by Pedrera et al. (2017). For example, it is surprising that a large syncline developed south of the Bilbao Anticline during the extensional period (Albian and Cenomanian stages), but it unfolded after the contractional deformation (present-day reconstruction). Also, the fault bounding the syncline to the south shows an offset in the top of the basement that is much smaller than the increase in thickness of the synrift sediments accumulated in the hanging wall. We must recall that the use of a computer software like Move Suite© to restore a section does not guarantee that the results are correct.

The whole description of the tectonic inversion stage and the development of the structures proposed by Pedrera et al. (2017) starts with the assumption that the exhumed mantle domain acts as a rigid and strong block: "Strong near-surface heterogeneity produced by the exhumed mantle lithosphere acts as a rigid buttress. Under contraction, weaker continental material is expulsed outward and upward by thrusting forming two crustal triangle zones at the boundaries of the exhumed mantle." However, a thin, hot mantle lithosphere (as considered in their model) would be weak, not strong, and the shallowest part is expected to be highly serpentinized and therefore weaker still. The presence of only 10% serpentinite drastically reduces the strength of the altered peridotite, making it as weak as nearly pure serpentinite (Escartín et al., 2001). It is difficult to understand from a mechanical point of view why the inherited weak detachment is not largely reactivated during inversion, as documented for other segments of the Pyrenean orogen (e.g., Teixell et al., 2016), but instead, completely new inverse faults are formed cutting the whole lithosphere (Pedrera et al., 2017, Figure 12).

One of the consequences of preserving the Mesozoic exhumed mantle domain in the present-day crustal section across the Basque-Cantabrian Basin proposed by Pedrera et al. (2017) is that their sequential restoration implies a total shortening of only 34 km since the Late Cretaceous. This is 2.5 to 5 times smaller than the shortening predicted by different plate kinematic models or deduced from geological reconstructions by other authors in a wide range of sections along the Pyrenean-Cantabrian belt (e.g., Macchiavelli et al., 2017; Rosenbaum et al., 2002; Teixell et al., 2018, and references therein; Vissers & Meijer, 2012). Although it is possible that those kinematic models and other reconstructions might have overestimated the orogenic shortening, it is hardly acceptable to present such a divergent result while restricting the discussion to this failed argument: "Such lower shortening rates across the eastern part of the Cantabrian Mountains were possibly caused by the coeval inversion of the Cameros Basin, caused by the thrust front of the Iberian Chain. Therefore, a far-field contraction is accommodated in a much broader sector (eastern Cantabrian Mountains and Cameros) than in the Pyrenees. The boundary between these two strain rate domains is the aforementioned Pamplona transfer fault that also represents a compartmental fault zone during the orogenesis." The argument fails because the inverted Cameros Basin is not limited by the Pamplona Fault (see Figure 1 in Pedrera et al., 2017) and represents a small part of the greater Iberian Range, which extends in NW-SE direction all the way to the Catalan Coastal Ranges, where it also accommodates far-field contraction to the south of the Pyrenees (in the same way that part of the contraction to the south of the central-western Cantabrian Mountains is accommodated in the Spanish Central System).

9. Concluding Remarks

The idea of revisiting the Basque-Cantabrian Basin in light of recent advances in the study of hyperextended basins is timely, and similar exercises have been undertaken in other segments of the Pyrenees. It is now generally accepted that during the mid-Cretaceous the mantle was exhumed to the base of the Mesozoic basins or even to the seafloor as a consequence of the extensional deformation that occurred between Iberia and Eurasia (e.g., DeFelipe et al., 2017; Jammes et al., 2009; Lagabrielle & Bodinier, 2008; Lagabrielle et al., 2010; Masini et al., 2014; Teixell et al., 2016, 2018). This certainly makes mantle rocks good candidates to explain, at least partially, the strong positive gravity anomalies observed between the Western Pyrenees and the Basque-Cantabrian region. However, the Mesozoic architecture of these hyperextended basins and the deep crust and upper mantle beneath them were deeply modified by the Pyrenean orogenic event. Different types of geological and geophysical observations revealing the deep crustal structure must be honored by any proposed model. In particular, a variety of seismic studies using both passive and active sources are consistent in revealing the existence, from the Central Pyrenees to the Cantabrian Mountains, of a thickened crust that the model by Pedrera et al. (2017) ignored.

As stated in the introduction to this comment, we are convinced that the first requirement to accept a new and provocative model is to discuss its consistency with the available data and results, eventually providing arguments against the validity of such previous results. The gravity inversion presented by Pedrera et al. (2017) was designed to refine a forward model that fails to accomplish this requirement with regard to the seismic constraints. Quoting the words of Sambridge (2006): "inverse problems are as much about asking the right questions of a data set than building a model that fits it." And as Gallagher and Ketcham (2018) add: "the inverse modelling process involves selecting an appropriate model structure and finding values for the parameters in that model structure that can explain the observed data to varying degrees." In the work of Pedrera et al. (2017), we find that both the model structure and the parameter values are inappropriate, especially the misuse of constraints and the model density assigned to the upper mantle. In addition, the model was constructed to fit inaccurate residual gravity anomalies and ignores the magnetic anomalies, which add complexity to the interpretation based on the presence of mantle rocks at shallow depths, because mantle rocks can only be strongly magnetized when they are so intensely serpentinized that they can no longer account for significant positive gravity anomalies. Neither do the authors take into consideration the problematic isostatic and thermal implications of their model. This type of discussion is lacking in the proposal by Pedrera et al. (2017), a deficiency that is accompanied by other shortcomings present in their sequential restoration of the Basque-Cantabrian crustal transect, such as geometrical-structural and mechanical inconsistencies.

Acknowledgments
We thank Editor John Geissman and reviewers Antonio Azor and Josep Anton Muñoz for their helpful remarks on the original version of this comment. We acknowledge support from project CGL2013-48601-C2 (Spanish Ministry of Economy and Competitiveness).

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