Response to reviews and comments on the MS: **"Evolution of the Iberian Massif as deduced from its crustal thickness and geometry of a mid-crustal (Conrad) discontinuity"**, by Ayarza et al.

Reviewer 2: Prof. Rob Butler

Ahead, we provide answers to the comments on our paper presented by reviewer 2.

Are there descriptions of any sensitivity analysis in the various migration and attribute enhancements available?

Not at this point

I think the narrative would flow better if the seismic reflector patterns were described first and then interpreted.

Although that is our usual way of presenting and discussing vertical incidence seismic profiles, the high number of datasets presented in this paper and the fact that they have all been previously interpreted geared us to find a more agile way of presenting the data and we prefer to keep it this way. However, we are going to add more information in the figure captions and modify labelling so it is more uniform and valid for all figures (e.g., M: Moho, C: Mid-crustal Discontinuity (Conrad)). In addition, labels will be described in figure captions as well..

The paper would benefit if the authors' preferred interpretation strategy and expectations were laid out explicitly at the outset. The introductory preamble is useful but maybe presents a rather optimistic view of the relationship between a seismic image and deformation structures in the crystalline crust.

This paper tries to make a joint interpretation of all Iberian Massif vertical incidence datasets acquired to date. Where there is a gap, seismic interferometry based on natural source seismic data (noise) is used. The seismic upper crust of every profile has already been interpreted and correlated with surface geology. Cites are given. Our contribution is to interpret the entire dataset on the light of new models that emphasize 1) the lateral extent of late Variscan extensional tectonics, identified after 2003 and which relevance is being found on field and geophysical data 2) the depth extent at which crustal melting has taken place in the NW quadrant of the Iberian Massif 3) the effect that this late tectonic processes had in the Alpine reworking of the Iberian crust. This task is made through the study of the geometry of two interfaces: 1) a mid-crustal detachment, addressed to the Conrad discontinuity, whose character is later discussed and 2) the Moho. The introduction will be modified so the goal of this paper is clearer.

There are two distinct parts to this. The discussion assumes that the reflectivity in the, rather transparent, upper part of the profiles (less than 4-5 s TWT) is from faults/shear zones which therefore have a very simply form. This expectation is despite the complex geology and structural geology reported from outcrop. I think the interpretation of apparently continuous inclined (and locally apparently listric) reflectors in the top 5 seconds to be faults is at least open to debate. While cartoons of idealised imbricate thrust systems show such structures, they are pretty rare in my experience in nature!

We agree with the reviewer on the fact that the geometry of faults/thrusts is complicated. It is also our personal opinion that trusts themselves do not need to be very reflective unless they follow a detachment level characterized by contrasting lithologies. But the surface correlation between reflectors and mapped thrusts forced us, and cited authors, to interpret the former as thrusts. Besides, they have the geometry given for these features in cartoons. Finally, all sections are migrated, so we are reasonably confident about the geometry of reflections. If listric reflectors are not faults/thrust, what could they be instead? The reflectivity itself might be produced by contrasting lithologies, but in the Iberian Massif, mappable thrusts (detachments) are often identified to coincide with important lithological boundaries.

Second, the authors expect the continental crust to have a long-distance layered character with geophysically distinct “upper”, “middle” and “lower” crust. Where this tripartite structure is obscure in their images they infer “missing middle crust”. Of course there is middle crust present – there’s not a void between deep crust and upper crust layers! So presumably they mean that the interval between say 4-8 s TWT does not match their expectations.

From a seismic point of view what we and most of the authors working in these data have seen is reflectors in the ‘seismic’ upper and lower crust merging in a mid-crustal discontinuity. Of course there is a middle crust, and there is a part in the discussion referring to what a metamorphic middle crust means. But these petrologically-speaking mid crustal rocks and even lower crustal rocks are, sometimes, emplaced in the surface by thrusts and/or extensional faults. Thus we find that seismically there is only upper and lower crust separated by a discontinuity often coinciding with a detachment. Furthermore, between 4 and 8 s TWT sometimes we find a layered and very reflective lower crust (ALCUDIA profile) and sometimes a fairly transparent upper crust (ESCIN-3.2 profile). So it is not a matter of depth or travel time. It is a matter of rheology of the crust and how the later accommodates deformation.

Certainly, it is interesting that the transect shows a consistently reflective seismic “lower” crust (i.e. c 5-11 s TWT) – though it may be better to say that there is a consistently near-transparent shallow crust (1-5 s TWT).

Surprisingly, reviewer 1 argues that the upper crust is not very transparent in the ALCUDIA section, where hardly any upper crustal reflections are found. However, we agree with reviewer 2 in interpreting a fairly transparent upper crust.

Personally I’d make more of the sub-Moho reflectors – perhaps referencing other such features imaged elsewhere in the world (e.g. the Flannan “event” in BIRPS images). If the authors are correct in their interpretation that the Iberian crust has been stacked by thrusts, then long-range layering might not be expected. . . unless it over-prints the Variscan structures. . .. in which case how much of the image relates to Variscan tec-tonics at all?

In our opinion, lower crustal layering is partly pre-Variscan, and partly overprinted by Variscan structures, especially by late-Variscan extensional ones. Sub-Moho reflections represent, in some cases, preserved Variscan crust/mantle imbrications. Their interpretation does not represent the main goal of the paper, but following this comment and another one made by reviewer 1, they will be dealt with in the revised version. In this regard, W dipping mantle reflections found in profile

ESCIN3-2 will be interpreted as result of Variscan shortening and crustal imbrication and underthrusting, as observed in profile ESCIN-3.3 and in the upper crust.

The points made above indicate that I found the rolling discussions on the tectonic interpretation rather confusing. This may reflect the difficulties in reconciling competing views amongst the extensive authorship!

The first author is the only contributor that has been part of all the experiments and most publications regarding the presented extensive dataset. It is her model which is presented here, with the agreement of co-authors. However, we will try to clarify the tectonic interpretation

The Geological Setting notes are useful but quite involved, detailed and dense. The only illustration that accompanies the text is the geo-tectonic map of Iberia. As such it is very difficult to follow. How much of this do I, as a reader, need to retain to pick up the story...? For example, is the timing and delay of anatexis (line 132) really needed for the interpretation of the seismic data later?

We think that the Geological setting contains what is necessary to understand our interpretation, and yes, there are way too many things to retain. Many of the data described there will find support in the geological sections that we are going to add to each profile. In addition, we consider that timing of late Variscan extension (and anatexis) is important as it overprints pre-and early Variscan features and erases, in places, the mid-crustal detachment, with the corresponding consequences.

The message I get from the "Geological Setting" is that the structure of the present-day near surface is complex. . . including folds – that include deformed thrusts and thrust sheets (e.g. lines 150-157; line 187) – which is not conducive to their seismic imaging. . . For readers not familiar with region, some kind of palaeotectonic framework diagram could help to reinforcing the content. Likewise, some simple diagrams illustrating the competing models and interpretations of crustal structure would be useful – and these could then allow the seismic interpretations of the composite profile to be reframed as tests against these models.

We agree with the reviewer that geology is extremely complex. But entering on paleo-tectonic (plate-dynamics?) considerations is outside the scope of the paper and will make it even more complicated. Our goal is to make a joint interpretation of the entire dataset, understanding the role of observed reflectors in the context of the Iberian Massif, which implies the collision between Gondwana and Laurussia (Avalonia). Accordingly, geological cross-sections are going to be added to all seismic profiles.

Line 770 etc alludes to important ambiguities resulting from the interpretation of out-ofplane and migration artifacts. More could be made of this in discussion of interpretation uncertainties.

Comments on the uncertainties of the interpretation on the edge of the profiles and in areas with 3D reflectivity will be added

The interpretation is interwoven with basic description of seismic character. I think the narrative would flow better if the seismic reflector patterns were described first and then interpreted. The

narrative would benefit from a simple statement of assumptions and the preferred model at the outset (see above) – as much of the discussion here takes much of this as read.

As indicated above, we prefer to keep this structure as it is more agile, but we are going to add extra information in the figure captions to help in the interpretation

For example – line 461 and on states that the variations in the thickness (in TWT) of the reflective layer ("lower crust") imply differential thinning– extension: But why? Could it not be that the reflectivity was developed heterogeneously? Or that the thicker portions have been thickened, rather than the thinner ones thinned?

The thinned portions of the lower crust appear in the areas where late Variscan extension has been described by metamorphic offsets, existence of gneiss domes and pervasive crustal melting. Where these processes have not been identified, the lower crust is thicker. In our opinion, these facts allow to make the interpretation we have presented

Section 3.3 Is called a description of the seismic sections. It would be better indeed if this was what it was.. In fact, the section interlaces basic description of the seismic character with geological interpretation. In my view, the narrative would flow better if these two aspects were decoupled – so that first order description ("observations") are separated from the interpretation. So describe reflection dips…Then say you infer that these track shear zone/thrust zone trajectories. Therefore where they go sub-horizontal then you deduce regional floor thrust positions

We hope the reviewer allows us to keep the present structure, adding information on the figure captions and cross-sections on top of the seismic profiles to ease the interpretation. Also, we will change the name of section 3.3. The reasons to do this are explained above.

Section 4.3 There are not many places in the world, away from Cenozoic orogens and basins, where continental crust is not underlain by a largely sub-horizontal Moho. Whether this represents gravitation flow of deep crust or simply differential isostatic rebound and concomitant erosion is debatable. Just how much upper crustal extension is there (stretching factors) from place to place?

Extension is the late tectonic dominant process in areas where high degree rocks crop out (migmatites and granites), i.e, NW Iberian Massif. Isostatic balance must be the dominant process elsewhere (S-SW Iberian Massif). We don't have absolute control about extension since crustal melting has erased much of this information. But in places, metamorphic offsets related to extension have been estimated (e.g., chlorite to sillimanite in Central Iberia; Díez Balda et al., 1995). The minimum offset of some normal faults and extensional detachments has also been estimated (e.g., Viveiro fault, 14 km by thermobarometry, chlorite zone to sillimanite zone: e.g., Martínez et al., 1996). But these zones do not necessarily coincide with locations sampled by the seismic profiles. Nevertheless, we will include these data.

In settings like the Variscan – is the Moho a passive pre-orogenic marker – or is it a (partly magmatic or metamorphic) construct? There are interesting points in this discussions – many further references could be added

In our opinion the Moho is a modified pre-orogenic marker and a detachment along most of the profile. However, it has been redefined in areas of severe extension (ESCIN3-2), and where Alpine reworking has affected the lower crust (CIMDEF). That implies that along the Variscan Massif the Moho has a varying character depending on the tectonic evolution.

> Section 4.4 I found the premise here confusing. Metamorphic units are notoriously metastable – after all we get granulites and eclogites at the Earth's surface. Only if the metamorphism was in equilibrium and therefore over-printed previous assemblage salong modern (sub-horizontal) isotherms would the crustal seismic structure be as discussed here. But if so -the tectonic structure would (presumably) be hard to resolve– the intensities of reflectivity in the profiles could simply chart metamorphic (thermal) structure – not intensities of deformation as assumed here). : You allude to this (line 761-2). But if so – when is the layering established? Presumably post-tectonically (after thermal re-equilibration)

The discussion is intended to show that a petrological subdivision of the crust would yield an extremely complex crustal section, as the same rocks may have passed through the upper, middle and even lower crust and then be back to upper crustal levels. Conversely, a subdivision can be made on the basis of seismic profiling which reflects the present state of the crust and is (perhaps surprisingly) much simpler as depends on crustal rheology at the timing of deformation. This is the goal of the paper.

> In the final discussion on the mid-crustal structure – description of the geophysical character is continuously intermingled with interpretation as a tectonic discontinuity. I would find it helpful if these two distinct aspects were separated. By all means set up the discussion in terms of Conrad – which is a geophysical construct. But make this distinct from its geo-tectonic interpretation.

We will make the necessary changes to separate these two points in the discussion

> Personally, I find the continual use of acronyms distracting – especially short ones. It is easier for readers if you use Cantabrian Zone rather than CZ for example.

We will make an acronyms list where the reader can refer to easily

> Line 57 – more complete than what? Better to say Our aim here is the present a composite seismic profile that integrates results from two new experiments (CIMDEF and ALCUDIA WA) with existing data-sets (specify).

We'll do it

> Line 60 – "Later on" makes it sound like it is another paper. "Here we continue to…"or some such might be clearer…continuing…We revisit interpretations of crustal extension and a possible mid-crustal discontinuity. We discuss mid-crustal reflectivity, the so-called "Conrad Discontinuity" of classical continental seismology (Conrad 1921), in the light of long-running debates as to its tectonic significance (REFS).

We'll change it

Line 87 – strictly the correlation does "support" the affinity – it is consistent with it ..

We'll change it

Line 88 etc "Evidences" - the plural of evidence in this context is "evidence" (no "s", like sheep).

We'll change it

Line 95 – "in the surface" – do you mean at outcrop?

Yes, we will rephrase it

Line 98 – what is "it"? The structure of the Iberian Massif along a N-S transect?

The diachronous deformation of the Iberian Massif

Line 139 and Line 140 etc. Be consistent with the verb….– is it "crop out" or "outcropping"..

According to reviewer 1, we will change it to outcropping

Line 183-184. Statements like this are key….mid crustal reflectivity can be explained by intrusions: But what evidence is there that they were controlled by shear zones?

The relation between reflectivity, intrusions and shear zones has been brought up by Schmelzbach et al., 2007 and mostly 2008 (line 494) and it is supported by surface geology (Simancas et al., 2003).

Why does reflectivity necessarily track deformation?

Because it follows the pattern of faults and thrusts in cross sections. But event though reflectivity follows the geometry of these features, it is probably due to the fact that thrusts often follow the boundaries between lithologies. The later will be added on the top of the seismic sections

Line 229 etc. a plural of a date has no apostrophe – it's 1990s

We'll change it

Line 237 – kind of experiment (no need for plural).

We'll change it

Line 285-287. Please reference explicitly these primary sources for the seismic processing. Hopefully these are peer-reviewed, formal publications!

We will do it

Line 305 (and many other places). Interpretation is presented as fact. So "W-dipping reflections that represent the Variscan imbrication" – is highly interpretative. First it would help if this statement is justified…. How explicitly does the reflectivity match to outcrop structure?

In relation to this point, the addition of cross sections in the top of seismic profiles will ease the interpretation

Line 312 – Interesting – but when thin-skinned interpretations were provided by (eg) COCORP Appalachians from 1970s– they tied reflectivity to underthrust sediments that could be traced down from outcrop….

Yes, often thrusts follow lithological boundaries that feature a high impedance contrast. This point will be considered throughout the text

Line 448 etc. I'd avoid using the phase "is related to" when discussing the seismic expression with respect to the surface geology. A better basic phrase is – "coincides with" – as this avoids associating description with interpreted causation….

We'll do it

Line 459 – Can you exclude the "cross-cutting" relationships are in-plane migration (or out of plane) artifacts?

They have the geometry of Variscan structures and since the profile is perpendicular to the latter, we think they are in plane reflections. In addition, they migrate as they are expected for 2D structures.

Line 477 "Mantle" reflectivity – what evidence is there to support the notion of crust mantle imbrication? Could this not be intra-mantle structure?

This reflection is related to a crocodile structure well identified in the lower crust. The most likely explanation is that the reflectivity into the mantle is part of this structure, i.e., crust imbricated into the mantle. The geological context does not suggest the existence of a shear zone in the mantle, which, in addition, might not have this high reflectivity.

Line 707 – which author? Meissner??

Yes, Meissner, 1989. We will change it to 'the later author'