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Interactive comment on "Influence of basement rocks on fluid evolution during multiphase deformation: the example of the Estamariu thrust in the Pyrenean Axial Zone" *by* Daniel Muñoz-López et al.

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Review of the paper "Influence of basement rocks on fluid evolution during multiphase deformation: the example of the Estamariu thrust in the Pyrenean Axial Zone" by Daniel Muñoz-López, Gemma Alías, David Cruset, Irene Cantarero, Cédric M. Jonh, Anna Travé

"This paper by Munoz-Lopez et al. reports structural and geochemical evidence of several multi-phase fluid-flow along the Estamariu thrust located in the Pyrenean Axial

Zone combining detailed structural and microstructural observation to O, C, Sr and $\Delta47$ isotopes. The techniques employed here are adequate and I'm glad to see application of $\Delta47$ thermometry in the Axial zone. The dataset is sound, and the conclusions are reasonable. The authors document a complex fluid-flow history along the thrust during Alpine compression and Neogene extension involving different sources of fluid at different temperatures. This paper should be published as it is an important regional contribution. As stated by the authors, there is a long list of works studying the fluid-flow along thrust faults affecting the sedimentary cover (e.g. Southern Pyrenean zone), but just a few focuses on the basement from the Axial Zone."

We thank the referee for his positive comments and detailed reviews.

"Although this work should be published, there are several points that need to be addressed/commented during revision.

1. The structural analysis and description are very detailed but somehow confusing. Here are some suggestions that could clarify the description:

- Adding sub-titles such as 4.1.1. Adding sub-title such as Hanging wall, Main Thrust, and Footwall would help a lot."

Sub-titles have been added to clarify the text. (i.e., 4.1.1. Hanging wall; 4.1.2. Thrust zone and 4.1.3. Footwall).

- "I would also recommend adding a general schema synthetizing all the relationship between the observed structures and microstructures. The current Figure 3 does that, but it is still confusing."

As pointed by the reviewer, Fig. 3 represents a general sketch that summarizes the relationships between the observed structures. We have modified this figure in order to avoid confusion. For this, we simplified the terminology used to describe the different structures (see for instance the answer to the following comment) and added arrows to match such structures with their correspondent stereoplots.

- “Also, I found the adopted typologies for structures “Sr, Sm, Ssp, SD, etc. . .” confusing and did not catch up what the subscript letter (‘r’ and ‘m’) refer to. What about calling these foliations the same way (unless they are associated to different tectonic phases) and just describe them (morphologies, intensity, orientation) in the sub-section. This would simplify understanding of the numerous stereoplots presented in Figure 3. I also noticed that some of these foliation typologies are not called in the text. For example in line 199: “The foliation within the thrust zone affecting the Devonian hanging wall strikes NW-SE and dips 40 – 50o NE, similar to the regional foliation in the protolith, but it is more closely spaced, generally between 0.2 and 1 cm (Fig. 6A, B).” Specify in the text if this foliation corresponds to “Sr”. The same comment is applicable for all the section 4.1.”

We changed and simplified the shorthand used to describe the observed structures. For regional foliation we now use S1 (instead of Sr). The foliation associated with the thrust (i.e., the thrust zone foliation) is now called the same way (S2), even if it affects the thrust zone deforming the hanging wall or the footwall (we use S2 instead of SD or SSP). We do not use shorthand for layering magmatic anymore (i.e., we removed the shorthand Sm) because layering magmatic is an inherited fluidal structure that is not discussed in detail.

All foliation typologies are clearer and better described in section 4.1.

- “You mentioned pressure solution surfaces e1 and e2 but it was not clear on which basis they were differentiated. Is there any cross-cutting feature? The orientation of these features (if any) are not presented on stereoplots.”

These stylolites were only observed locally at microscopic scale and therefore, their orientations are given according to more relevant structures (i.e, they trend subparallel to the thrust zone foliation). This is stated in the text.

We could not find crosscutting relationships between these structures, however, we differentiated them according to their spacing and crosscutting relations with veins V1a.

Stylolites e1 are less spaced and are always crosscut by veins V1a, whereas, stylolites e2 are more abundant and postdate V1a (as they developed as sutured areas between the host rock and veins V1a). This has been clarified in the new text.

2. “The authors report warm temperature fluid-flow event (up to 200°C), presumably hydrothermal fluid for the CC3 and CC4 calcite phases. As you know, $\Delta47$ composition of carbonate may be altered by $\Delta47$-reordering when carbonate experienced temperature in excess of 200°C (maybe lower temperature). Although, I’m convinced that these hydrothermal events did not altered previous carbonate phases (cc1, cc2), I would like to see the authors discussing potential (or not) $\Delta47$-reordering and how it could be ruled out. Here are some ways to discuss that: - Is there some metamorphic/Fluid Inclusion/chronology work in the same area reporting temperature-time relationship of this hydrothermal event? If this hydrothermal event if short, the solid-state $\Delta47$ probably did not occur; - Is the thermal history of the area constrained by other studies? If it is the case, the authors could use re-ordering models (e.g. Stolper and Eiler 2015; Lloyd et al., 2017) to see if the $\Delta47$ composition of the different calcite phases may experience re-ordering. - Alternatively, the authors may acknowledge that further re-ordering is possible but unlikely due to the short time.”

We agree that clumped isotopes may potentially be altered due to the relatively high temperatures. However, as suggested by the reviewer, we also consider that this is unlikely because of the relative short time of hydrothermal fluid migration in the study area and because there is no evidence of calcite recrystallization and/or solid-state reactions. We have explained this in the new manuscript, in section 5.3 of discussion.

3. “I have noticed few poorly constructed sentences. I would suggest the English to be checked before re-submission. I won’t make any comment on that as I’m myself always struggling with English.”

The English grammar has been revised and improved.

Minor comments:

“l. 28: Deformation associated with crustal shortening is mainly accommodated by thrust faulting and related fault zone structures: Add references.”

References added (Mouthereau et al., 2014; Muñoz, 1992a; Sibson, 1994).

“l. 30: “The reactivation of faults may produce changes in the hydraulic. . ..”: Add References.”

References added (Arndt et al., 2014; Barker and Cox, 2011; Cantarero et al., 2018; Cruset et al., 2018a; Lacroix et al., 2018; Travé et al., 2007a).

“l. 174: Which fractionation curve is used to calculate the oxygen isotope composition of water?”

The fractionation equation used to calculate the oxygen isotope composition of water is the one from Friedman and O’Neil (1977). This is stated in the new text.

“l.180 – 181: “The main slip plane is undulose, producing changes in the strike direction and dip, and generates a 2 – 3 m thick thrust zone, which is thicker in the hanging wall, up to 2.5 m thick”: Do you mean the thrust fault consists to a deformation zone affecting both hanging wall and footwall, with deformation zone thicker in the HW?”

Exactly! The thrust zone affects both the footwall and hanging wall. This has been specified in the new text.

“l.187: “In the studied outcrops, the Devonian Rueda Formation from the hanging wall is characterized by a well-bedded alternation of dark to light grey limestones with dark grey shales”: Does this refer to S0, Sr, Sd? Please specify.”

It refers to S0 (bedding). It has been better explained in the text.

“l.190-192: “Deformation in the Devonian protolith (i.e., outside the thrust zone) corresponds to a decametric anticline (Fig. 2B), which has associated an axial plane pervasive regional foliation (Sr) concentrated in the pelitic intervals (Fig. 5B)”: looking at the stereoplot from Fig. 3, the bedding (S0) seems to define a fold oriented E-W

(although only based on 3 measurements). In contrast the Sr does not seem parallel to the axial plane and is more or less oriented N-S (even slightly folded). How can you explain this?”

As observed in Fig. 2, the fold in the hanging wall corresponds to a tight and SW verging anticline. Looking at the stereoplot (Devonian protolith), the observed planes define the fold limbs, which are approximately oriented WNW-ESE and NE-SW. The intersection between these planes (through the bisector angle) defines the axial surface, which is oriented ~NNW-SSE, similar to the regional foliation. This has been explained in the new text.

“l. 203-204: “When present, these stylolites are very systematic with densities between 5 and 8 stylolites/cm.” Should the intensity be given in number/cm2?”

This is a rough estimation because stylolites e1 are only locally observed at microscopic scale. Therefore, in the new manuscript, we give the stylolites intensity by means of their spacing, this is, they are 1 – 2 mm spaced (Fig. 6C).

“l. 201 – 202: “At mesoscale, SD has related shear surfaces (Ci) defining centimetric S-C-type structures, again indicating reverse kinematics (Fig. 6A).”: Do you have a closer view of the C-S relationship?”

We improved the quality of the picture showing S-C structures. The S-C relationships is better seen now.

“l.220-222: “The vein cement (Cc2) is milky white in hand sample and consists of up to 3 mm blocky to elongated blocky crystals (Fig. 6G) with a dull to bright orange luminescence (Fig. 6H).”: To me, e2 and V1b are clearly cogenetic as their crosscutting relationship are ambiguous (as stated by the authors). It is also interesting to see that V1b is extensional (Mode I) but also show mode II with conjugate opening (Fig. 6F). In any case all these structures formed under the same field stress and can be assumed contemporaneous.”

We totally agree with the reviewer and, as it is explained in the text, these observations indicate that these structures developed coevally.

"l.226: "They are parallel or locally branch off cutting the foliation planes in the subsidiary thrust zone": What are the textures of these veins? They seem to show interdigitated texture in agreement with extension opening. These are important as they give indication of the opening regime and stress field."

As explained in the text, although veins V3 locally branch off, they are mainly parallel to the foliation planes and therefore, we could not observe geometrical features (in the field) indicative of the stress regime. However, the fibrous texture of the calcite crystals, growing perpendicular to the vein walls and to the foliation planes, indicates their extensional character. This extensional opening postdates the thrust zone foliation and is compatible with the Neogene extension. On the other hand, the vein cement (Cc3) has a similar geochemical composition to the cement present in the Neogene normal faults (Cc4). This observation seems to indicate precipitation during the same tectonic event and associated with the same fluid regime. This has been stated in the new text.

"l.246: You state here v4 for fault. However, you previously used V labels for veins. It is confusing even if we expect slickenside onto these faults."

We use V labels (V1 to V5) as a shorthand for calcite veins instead of the related structure type (opening fracture or fault). This has been clarified in the new text.

"l.252-253: "Shear fractures (V5) are locally mineralized with a greyish microsparite calcite cement (Cc5).": Any Figure to document?"

We added two images of these veins, a field image of the vein and a microphotograph of the vein-related cement.

"l. 400: Huyghe et al. (2018): "Impact of topography, climate and moisture sources on isotopic composition (δ18O & δD) of rivers in the Pyrenees: Implications for topographic

reconstructions in small orogens" reported new isotope lapse rates for the Pyrenees. This study should be cited here as it supports very well you high elevation hypothesis. The authors could even use these lapse rates to document the paleo-elevation."

This reference has been added because, as suggested by the reviewer, this study supports our interpretations. The paleo-elevation have not been calculated because according to Huyghe et al., 2018 the relationship between the isotopic composition and the elevation is not clear in the Southern Pyrenees. According to these authors, the elevation does not seem to be the only parameter controlling the isotopic composition in this part of the belt.

"Figure 11: This figure is really good!"

We are glad that the reviewer likes this figure.

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