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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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"Muñoz-López and co-authors document evolving fluid sources and conditions during multiple stages of deformation through a combination of field, petrographic, and geochemical analysis of an exhumed thrust in the Pyrenees. The manuscript is generally well written, with only minor grammatical or stylistic edits, and the quality of the work is robust. I do think that the manuscript could be improved with relatively minor edits, specifically with regards to motivation, descriptions of geologic units, and inclusion of a better synthesis figure".

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We thank the referee for his constructive comments, which greatly helped to improve the quality of the manuscript.

General Comments:

“The motivation for the study should be stated clearly and much earlier in the document. The clearest iteration that I found was on page 13, the first sentence of section 5.4. It would be helpful for this type of statement to appear in the abstract, and in the introduction”.

The main objectives of this contribution were already stated in the text. However, clearer sentences explaining the purpose and objectives of this paper are now included in the abstract and the introduction section.

“For all the discussion of basement, the age, lithology, and metamorphic grade were only briefly discussed, and relatively late in the text. It would be helpful to expand and highlight the section on the basement geology, and specifically previously published geochemistry, instead of the broader regional tectonism. It is particularly confusing because you repeatedly refer to “crystalline basement” but we learn that the basement is composed of Paleozoic slates, phyllites, sandstone, mudstone, limestone, conglomerate, and shale in Figure 11 and at the very end of the background geology, and if these are not the basement rocks then I’m completely lost. This is perhaps relevant because the Sr data is really more about interaction with older rocks with a different radiogenic signature, not rocks that are “crystalline” or not, correct? “

We expanded the description of basement rocks in the geological setting describing the age, lithology, metamorphic grade and involved tectonic event.

We agree with the reviewer that the Sr data from the basement is likely related to the interaction between vein-forming fluids and older rocks with a higher radiogenic signature. Therefore, we removed the phrase “crystalline rocks” as it was not properly used. Instead, we now refer to “basement rocks”.

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“I would like to see a figure of chemistry/temperature/source and deformation/tectonic events through time, rather than the 3D block diagram. The source and direction of infiltration and upwelling are rather speculative, but putting your observations into a more linear, temporal framework would be really helpful for me (see for instance my quick quick sketch). Similarly, annotating the figures showing geochemistry with some additional information about the inferred timing of cements, or associated structures, would be very helpful.”

We combined the final 3D diagram with a temporal framework summarizing the tectonic and geochemical evolution of the area through time, similar to the sketch suggested by the reviewer.

All figures showing geochemistry have new information about the structure related to each calcite cement. We also added arrows to better observe the relative timing of all cements in the graphs. Therefore, with this new information it is easier to observe the geochemical evolution over time.

“What you meant by “timing” was a little misleading. At first, I assumed you were talking about relative timing from cross cutting relationships, but then you mention radiogenic ages, but then you acknowledge that you did not get ages. . . I think it would be better to be more specific, and upfront, about these being relative ages that are broadly linked to specific styles of tectonism”.

We firstly stablished the chronological order of the observed structures based on cross-cutting relationships of (micro)structures. Then, we attempted to validate our interpretations by means of U/Pb geochronology. However, as we did not obtain absolute ages from U/Pb data, we use relative ages instead of absolute ages for discussion. To better clarify this, we explained in the results section that we did not get absolute ages and therefore, we are discussing with relative ages. In addition, we now use the term “relative timing” throughout the manuscript.

“This was originally a specific comment, but I think it applies to the whole manuscript:

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Many hydrothermal systems are ultimately derived from meteoric fluids, and I agree that there is a clear and reasonable distinction between your cooler, younger fluids and hotter fluids, but a short sentence relating the importance of fluid-rock reaction and chemical evolution at higher temperatures and longer times would be helpful, because I think you are really making the point that you can track fluids because of that residence time at depth, not their ultimate source".

We added a paragraph at the end of the discussion section 5.3 in which we summarize the geochemical evolution of cements Cc1a to Cc5 and its implication with water-rock interactions and with changes in the fluid regime (upward vs. downward fluid migration). This geochemical evolution through time is clearer in the new final sketch (Fig. 13).

Specific Comments:

"Line 13: "timing" is a bit vague here. Because absolute age in faults and fractures is such a hot topic, I think it is important to specifically describe relative ages throughout."

Changed. We have specified that we refer to relative timing of fluid migration and vein formation.

"Lines 17-21: Crystalline basement is vague, especially in light of the abundance of low grade and unmetamorphosed rocks you show in later figures. Also, the distinction between deeply circulated meteoric and hydrothermal fluids... Is this just a matter of temperature or chemical evolution?"

We removed "crystalline basement rocks" as it was confusing and we now describe only "basement rocks" or "basement lithologies". The distinction between deeply circulated meteoric and hydrothermal fluids is based on both, chemical evolution and temperature. For instance, the clearest evidence of the presence of meteoric fluids (which precipitated cements Cc1a and Cc2) comes from the δ18Ofluid (yielding typical meteoric values between -6.4 and -0.3‰). By contrast, the clearest evidence of

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the presence of hydrothermal fluids (which precipitated Cc3 and Cc4) comes from the relative high temperatures (up to 208°C) in comparison to the burial depths (probably less than 1 km). In both cases, the high 87Sr/86Sr ratios point to deep circulation and interaction with basement lithologies.

“Line 33: I’m not sure how understanding past fluid flow helps use understand the current configuration of a mountain belt. Perhaps it informs the factors leading to the current configuration? Additionally, I think there is a missing comma after “through time”

We agree with the reviewer and the paragraph has been changed accordingly. The missing comma has been added.

“Line 51: You say only a few, but cite 7 papers working on similar topics. Also, “On the other hand” does not seem necessary here.”

Seven papers work in similar topics in the Pyrenean basement, but all are focused on the same thrust system. This has been specified in the text.

“On the other hand” has been removed.

“Line 100: These are the crystalline basement rocks? I think the geologic background should be more clear about rock types much earlier.”

We agree with the reviewer, “crystalline rocks” was incorrectly used and we now use “basement rocks” instead. Also, as said in a previous comment, we expanded the geology of the basement rocks and deleted the word “crystalline” in order to avoid misunderstandings.

“Line 105: I’d like to see a short description of why samples were selected before launching into all the analysis, i.e. the field methods component, which is well documented in your figures. You include a lot of structural context in “Results” but it is difficult to evaluate whether 35, 12, or 8 samples is enough without some description of the structures that are present.”

We firstly stablished the different vein generations observed in all fracture sets and fault-related deformation. Then, we selected representative samples of all these vein generations and related host rocks. This is now explained in the text.

“Line 121: Extra comma in “then, they”

The extra comma has been removed.

“Line 138: Extra comma in “one, keeping”

The extra comma has been removed.

“Line 162: First mention of U-Pb geochronology. So is this about absolute age?”

As said before, we did not get U-Pb data and therefore, our interpretations are based on relative timing. This has been specified in the new manuscript.

“Line 191: I understand the shorthand for regional foliation being Sr, but it is unfortunate that this paper also discusses strontium. Perhaps use Sr?”

We do agree with the reviewer and we have changed the shorthand for regional foliation (we now use S1 instead of Sr). Also, in order to simplify, we have changed the shorthand for thrust zone foliation affecting the hanging wall and footwall (we now use S2 instead of SD and SSP).

“Line 241: Perhaps “steeply” dipping?”

Exactly, it has been changed.

“Line 246: “frequently affect”? Commonly may be a better choice; frequent implies some element of time.”

Changed. We now use commonly instead of frequently.

“Lines 225-253: It may be imbedded in the figures, or I may have been tired at this point, but I felt like the cross cutting relations or structural context for sequencing was a bit week with veins and cements 3-5.”

Veins V3 to V5 are located in different structural positions (e.g., Fig. 3). Therefore, we could not observe crosscutting relationships between them in the field. However, these veins postdate the thrust-related structures and their formation is compatible with the Neogene extension (as explained in the discussion section). In the case of veins V3 and V4, their related calcite cements Cc3 and Cc4, have a similar geochemistry (Fig. 9 – 12). This supports precipitation of these cements during the same tectonic phase and associated with the same fluid flow event (i.e., although they precipitated in different structures, they are probably contemporaneous). Veins V5, as specified in the text, probably precipitated during the latest stages of extension, when the fluid regime changed from upward fluid migration to downward percolation of fluids, similar to models proposed in similar settings (e.g., Cantarero et al., 2014b).

“Lines 262-266: This could go in a table.”

This information is already on table 1. In this part of the text, we describe the isotopic results and the observed isotopic tendencies.

“Line 301: Oh, there is NOT absolute geochronology. This passage should appear much earlier.”

This passage has been moved to the results section. There, we also explain that we are dealing with relative timing and not with absolute timing.

“Line 304: An example of the basement lithologies and ages being clearly and simply defined.”

As suggested by the reviewer in another comment, we added a similar description in the geological setting in order to better describe the basement geology, linking lithologies, ages and tectonic events.

“Line 330. Capitalize “Calcite. . .”

Done.

"Lines 355-361: Emphasis on channelized is a little confusing, because you also say that cements in different structural positions precipitated from the same fluids, which then begs the questions How wide are the fluid flow channels? Do you have samples from inside and outside of these channels? I think this invites a lot of extra scrutiny, and as it is written it is too vague."

Preferential fluid circulation along the thrust is evidenced by the exclusive presence of calcite cements (Cc1a and Cc2) within the thrust zone. As these cements (Cc1a and Cc2) precipitated during the same tectonic event but in different structural positions within the thrust zone, they likely precipitated from the same fluids, progressively increasing the fluid-rock interaction from the thrust plane (Cc2) towards the hanging wall (Cc1a). We have explained this in the text and the word "channelized" has been removed in order to avoid confusion.

"Lines 385-390: I think you do a good job defending your interpretation of fluid sources here."

We are glad to hear that from the reviewer.

"Line 393: replace "than" with "as"?

Replaced.

"Line 402: Probably the clearest statement of purpose in the manuscript."

We added a similar statement of purpose in the abstract and in the introduction. In the 5.4 subsection, we specified that we are assessing the influence of basement rocks on fluid chemistry.

"Line 464: "Common reservoir" implies a system in hydrologic or pressure communication. I don't think this is necessarily supported. Rather, you could claim that fluids are sourced or resided in similar basement rocks."

We agree! In the new manuscript we state that these fluids are sourced and/or inter-

acted with similar basement rocks.

“Lines 469-470: Great Basin and Basin and Range Province are not necessarily synonymous, but they are in this case and therefore redundant.”

Changed. We now use only Great Basin in the text and the two references have been merged.

“Line 495: Although you do include a caveat, I think the phrase “long-term” implies persistence, which is not necessarily true. I think places in the text that you describe long term fluid flow should be revisited.”

We removed the term “long-term” as we have no evidence of the persistence of fluid flow. Instead, we state that hydrothermal fluids migrated in Neogene times and in present times and that the circulation of these fluids could be continuous through time or related to different pulses of fluid flow.

“Line 790 (Table 1): alignment issue after sample C6.II in some columns impacts readability. Also check on reason for differences in significant digits for reported values of the same quantity (for instance, see d18O and d13C columns).”

The alignment issue has been corrected and the significant digits have been revised.

“Line 800 (Table 2): check grammar “when is darker”. A scale bar for color might be useful so we know what is considered high or low or how divisions were made (are they quartiles, or relative to some standard?).”

The grammar has been checked. In table 2, for each element, the darkest green points qualitatively to the highest concentration and vice versa. This has been explained in the text and a scale bar has been provided.

“Line 805 (Figure 1): Including generic rock types instead of or in addition to ages would be helpful, see generic comment about describing the lithology of the basement rocks.”

We added generic rock types in addition to ages of the map performed in the study area.

“Line 855 (Figure 9): The relative timing of cements can be inferred from their order, but perhaps arrows on the graph showing fluid evolution over time, or some other way to relate these to types of structures or tectonic events would be useful. See general comment about a timeline figure.”

Arrows have been drawn in the graph to show the geochemical evolution of calcite cements over time. In addition, the structure related to each calcite cement has also been provided.

“Line 865 (Figure 10): Again, this could be combined with a figure showing fluid evolution in the context of other events or structures, rather than leaving it to the reader to relate samples and setting. Add more text on the graphs to help guide me.”

A graph showing the structure related to each calcite cement and their evolution over time has also been provided.

“Line 874 (Figure 11). Shales and mudstones don’t seem particularly “crystalline”, but you refer to crystalline basement a few times in the manuscript. I can understand why dilatant crystalline rocks may be geothermal reservoirs, but why these low grade rocks? Is it just that these rocks exist at deeper, hotter depths? Brown line seems a bit high (it cuts off a few basement values), how it was chosen?”

As previously stated, the term “crystalline rocks” has been removed, we refer now to “basement rocks”.

The hydrothermal character of the fluids is inferred from their high temperatures (up to 208°C), which are higher than values expected by normal geothermal gradients (if we consider < 1km burial depths, according to Saura, 2004). Therefore, the involved fluids probably warmed at greater depths and then migrated upwards through Neogene faults, flowing fast enough to maintain their high temperatures or at least, to be in

thermal disequilibrium with the surrounding rocks. This has been better explained in the new manuscript.

We selected the limit between basement and cover values taking into account both the previous contributions and our own results. As shown in Fig. 11, all calcite cements precipitated from fluids that have circulated through cover rocks have 87Sr/86Sr ratios clearly lower than 0.710. By contrasts, all calcite cements precipitated from fluids that have circulated through basement rocks have 87Sr/86Sr ratios greater than 0.710 (i.e., these calcites reflect a higher radiogenic signature, similar to that reported for basement rocks). The only exception is observed in reference 14 and reference 16 (Fig. 11). Reference 14 is located in Plan de Larri, at the transition between basement and cover structures. In this location, the lowest 87Sr/86Sr values (<0.710) are found in relatively undeformed Cretaceous carbonates, which are lithologies widely exposed in the Pyrenean cover (in the Southern Pyrenees). This explains the little overlap between these lowest values and those of the sedimentary cover. On the other hand, as explained in the manuscript, authors from reference 14 (McCaig et al.,1995) used the same limit (i.e., 87Sr/86Sr = 0.710) to differentiate between values derived from the unaltered limestone protolith and the thrust-related carbonate mylonite affected by a fluid carrying radiogenic Sr. Values of reference 16 belongs to low grade metamorphic rocks. Although the lowest values of this reference overlaps those of the sedimentary cover, no information about synkinematic veins have been provided, which is the focus of the comparison in this contribution.

“Line 885 (Figure 12). Again, I’d rather follow the changes over time, so instead of looking at changes in Mg, then Fe, then Mn... plot these values in the context of other events and features and then we could see what was happening with Mg when Sr goes up, for instance.”

We have modified this figure according to the reviewer comment. Now it is easier to follow changes in the elemental composition over time.

“Line 890 (Figure 13). This is a fine figure, but I don’t know that it adds a great deal to the story, other than showing what you have already described fairly well in the text. If you do keep it, I think showing warmer colors for hotter fluids may be more intuitive.”

As said before, we added a sketch summarizing both the tectonic and geochemical evolution of the studied area. We also changed colors of the arrows that indicate fluid migration, that is, we now use red and orange colors for warm fluids and green colors for cold fluids.

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