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DISCUSSION

Comment on González-Acebrón et al. Criteria for the recognition of localization and timing of multiple events of hydrothermal alteration in sandstones illustrated by petrographic, fluid inclusion, and isotopic analysis of the Tera Group, Northern Spain Int J Earth Sciences (2011) 100:1811–1826

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The paper by González-Acebrón et al. (2011) deals with both regional and methodological problems about the timing of thermal events in one of the best-known and controversial basins in the Iberian microplate: the Late Jurassic–Early Cretaceous Cameros Basin. The aforementioned paper contains invaluable data about the thermal evolution of the basin, and it is an important contribution to the understanding of the post-sedimentary, pre-inversion processes in this strongly subsiding basin. It will undoubtedly add new evidence to the knowledge of hydrothermal processes in general and particularly to the paleothermal evolution of the basin.

However, in our opinion, there are some problems involving important matters within the paper, namely (1) the interpretation of the data obtained, which are too constrained within a univocal line of thinking without considering other simpler and more viable options that in the discussed paper are aprioristically rejected. (2) The second problem deals with referencing to previous papers and acknowledgement of previous works by other authors. We must say that this aspect does not refer to this paper alone, but it is recently becoming a commonplace for many scientific papers in this field.

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On the side of the references to previous works, it must be stated that:

1. Up to date, the only thorough studies of the small-scale extensional structures (namely tension gashes and microfaults) at the basin scale within the Cameros Basin have been carried out by Guiraud and Séguret (1984). The study of these extensional structures is considered, together with other data, by Mas et al. (1993), and Guimerà et al. (1995) who in fact provide a re-representation of data from Guiraud and Séguret (1984). This kind of errors can be misleading when the authorship of previous works is to be considered.
2. In our opinion, the reference to the "flaws" existing in some of the previous basin models is confusing. The discussed paper states that there is a mechanical flaw that invalidates the hypothesis of the synclinal basin model for the Cameros syn-rift stage… In fact, this "mechanical flaw" was proposed by Guimerà et al. (1995) and Mas et al. (1993) considering not actually the hypothesis of the syncline basin but the hypothesis of "tectonic erosion" proposed by Guiraud and Séguret (1984) to explain the continuity (we will return to this matter later on) of the marine Jurassic sequence along the northern border of the Cameros basin. Thus, the "syncline basin" model cannot be discarded according to this argument, as González-Acebrón et al. (2011) seem to suggest.
3. The third problem is related to a misinterpretation and application of the term hydrothermal metamorphism.

We consider that an apparent misunderstanding is arising from a rather unclear use of the term hydrothermal metamorphism *vs* hydrothermal processes, this later being a more accurate term. The term hydrothermal metamorphism is commonly used for the formation of metamorphic minerals resulting from the interaction of a rock with hot circulating fluids and is commonly used to define the low-grade alteration of oceanic crust (Alt 1999 and references therein). The term hydrothermal alteration and metamorphism can be therefore used in the same way in oceanic crust, but caution must be taken in sedimentary sequences where tectonics, faulting, and other processes can be active and significant. Casquet et al. (1992) suggested the term hydrothermal metamorphism to explain the low-grade metamorphism in the Cameros Basin, based on local observations on centimeter tension gashes located in the Urbión group. This term has been used by Barrenechea et al. (1995), Alonso-Azcárate et al. (1999), Mantilla-Figueroa et al. (2002), Ochoa et al. (2007), and González-Acebrón et al. (2011) to offer an explanation for the high heat flow and therefore to uphold the model of the basin proposed by Mas et al. (1993).

In the following paragraphs, we arise the main points concerning the paper that we think must be clarified when considering the aforementioned topics and the interpretation of data.

In our opinion, the main problem of the paper by González-Acebrón et al. (2011) is related to the one-sided consideration of basin models and some previous data and the aprioristical rejection of the syncline basin model without considering published data. In fact, as we will discuss later, the use of a syncline model basin simplifies interpretations and explains many of the problems arisen in this study, many of them difficult to interpret considering a lateral juxtaposition of sedimentary bodies. In addition, the authors consider only preliminary previous geochronological models for the timing of the metamorphic peak and ignore the intermediate deformational stages. The main deficiencies in the paper considering different sources of data that should be considered in this kind of study before plainly defining a basin model are the following:

1. Consideration of previous studies dealing with the thermal and chemical evolution of the Cameros Basin: Villalaín et al. (2003) and Casas et al. (2009) published a large enough amount of good-quality paleomagnetic data that unequivocally indicate the dip of beds at the moment of a pre-inversion remagnetization and indicate a syncline basin geometry during Albian-Cenomanian times. This basin geometry, corroborated from paleomagnetic data, was formerly proposed from other sources, such as the study of cleavage–bedding relationships in the Cameros basin (Casas-Sainz and Gil-Imaz 1998). Remagnetization of the whole syn-rift sequence is also an interesting matter that can be related to basin geometry and evolution. Remagnetization, which can be associated with the thermal-chemical evolution of the basin (probably one of the hydrothermal stages interpreted by González-Acebrón et al. 2011), is not linked to a specific structure or basin sector (what could be expected from a hydrothermal event linked to fault-fluid circulation) but to the whole Eastern Cameros Basin, where anchizone-epizone parageneses occur.
2. Mineral assemblages and fluid inclusion data: Previous studies (Mata et al. 2001) already indicated the close relationship between paleotemperatures and the position within the stratigraphic sequences (prograde sequence). This is corroborated in the paper by González-Acebrón et al. (2011). These authors study the older part of the stratigraphic series that underwent the highest thermal conditions within the basin. Note that from Fig. 1 in the paper by González-Acebrón et al., the areas where thermal metamorphism occurred are precisely the deepest parts of the basin exposed at surface after inversion of the basin (but only if the syncline basin model is assumed!), in a similar way as the maximum temperature isotherms delineated by Del Río (2009) on the basis of independent zircon fission track cooling ages. In this way, we plainly reject the considerations of González-Acebrón et al. (2011) about the position of their studied samples within the basin (grey star in their Figure 12). These samples have been located in a NNE-SSW cross-section (their Fig. 12) that does not correspond at all with the structure of the basin in the area presented in the paper, neither after the Tertiary tectonic inversion nor at the extensional, basinal stage. The authors may argue that the construction of the cross-sections in this area was not one of the objectives of the paper, but there are several reconstructions by other authors (in both Spanish and English publications, see e.g., Gil Imaz and Pocoví Juan 1994; Guimerà et al. 2004) that could be useful to this purpose and that are closer to the structure of the studied than the cross-section used in Fig. 12.
3. Geothermal gradients and hydrothermal events: This is the principal merit of the paper and justifies its main objectives and the good data presented. We think that they are very valuable and that under a proper vision and interpretation, they can help to unravel a good part of the history of the Cameros Basin and some of the apparent contradictions found in previous works (Mata et al. 2001). However, some of the interpretations

Table 1 Implications of the two end-member basin models for different data sources

Evidence	Extensional ramp basin geometry (lateral superposition of sedimentary bodies)	Syncline basin geometry (vertical superposition of sedimentary bodies)
Geothermal gradient	Partly depth dependent but necessarily based on other sources. Maximum 276 °C/km	Depth-dependent geothermal gradient according to position within the stratigraphic sequence. Between 30 and 70°/km
Total thickness of syn-rift sediments	Not stratigraphically constrained About 5 km	Stratigraphically constrained in the basin depocenter (minimum 8 km). Not in other areas
Continuity of the pre-rift sequence	Continuous	Discontinuous
Amount of horizontal extension	30 km	Less than 10 km
Thickness distribution for each sedimentary unit	Depocenter at the northern basin border (progressively moving south during the rifting stage)	Depocenter for all the units near the basin axis.
Influence of the detachment, Upper Triassic level	Not especially relevant during extension. Important during the inversion stage	Important both during extension and compression
Dip of the syn-rift sequence	North during the basinal stage. Changing to south during the inversion stage in the northern basin border	Steer's head geometry, centripetal during the basinal stage
Low-grade metamorphism	Only hydrothermal (because of low sedimentary thickness)	A prograde sequence with syn- to retrograde hydrothermal events

about geothermal gradients based on a extremely thin sedimentary sequence (in this case, it seems admissible for the authors to consider sedimentary bodies to be superimposed in the vertical) of only a few hundreds of meters are not sound and cannot be considered as representative. Even less reliable are the changes of gradient interpreted in the two studied outcrops. Why? Because there is a strong horizontal variability that depends on the assumed geometry of the basin and the variation of thermal properties in the sedimentary sequence (thermal diffusivity and conductivity, Del Río 2009) that allow for the gradient to change strongly along the sequence. We do not criticize González-Acebrón for not taking into account this factor within their interpretation, since the determination of thermal properties comes from a PhD and unpublished data (Del Río 2009), but future interpretations should consider these constraints.

4. Seismic reflection data unequivocally indicate a thickening of the stratigraphic sequence from the northern basin border toward the South. This constraint on basin geometry has been published at least twice, both in English and in Spanish (Casas-Sainz and Gil-Imaz 1998; Casas et al. 2009). Together with paleomagnetic data, this suggests a syncline basin geometry for the extensional stage.
5. Concerning the scale of fluid flow and regional metamorphism, Alonso-Azcárate et al. (1999) showed interesting and accurate data of the metamorphic/hydrothermal processes related to the genesis of the pyrite ore, pointing to a local circulation of fluids, in the order of hundreds of meters along highly permeable sandstone aquifers. Although evident local features of hydrothermal processes as tension gashes and pyrite ores are observed, the genesis of the higher-grade mineralogical assemblage (quartz—muscovite—paragonite—chloritoid—chlorite) found in the deepest part of the basin has not to be necessarily fluid-related. The higher-grade mineral paragenesis is observed in a large area close and far away from tension gashes, ore deposits, or faults as described by Guiraud (1983) and Guiraud and Séguret (1984). Mata et al. (2001, 2004) did not propose a strictly burial sequence, as González-Acebrón et al. (2011) stated, but a low-grade prograde sequence overprinted by syn- to retrograde hydrothermal events. Neither a pure burial-prograde sequence as the Gulf Coast and the Welsh Basin sequences (Merriman and Peacor 1999) nor the hydrothermal alteration of oceanic crust (Alt 1999) is necessary to explain the mineral assemblages found in the Cameros Basin.

Why then González-Acebrón et al. (2011) are not by any means willing to consider a syncline basin geometry? We think that there are some a priori assumptions influencing the interpretation of basin from different sets of data (Table 1; Fig. 1):

1. Eight kilometer of thickness for the syn-rift sequence is a priori considered as excessive for sedimentary bodies to be superimposed in the vertical in an intracontinental

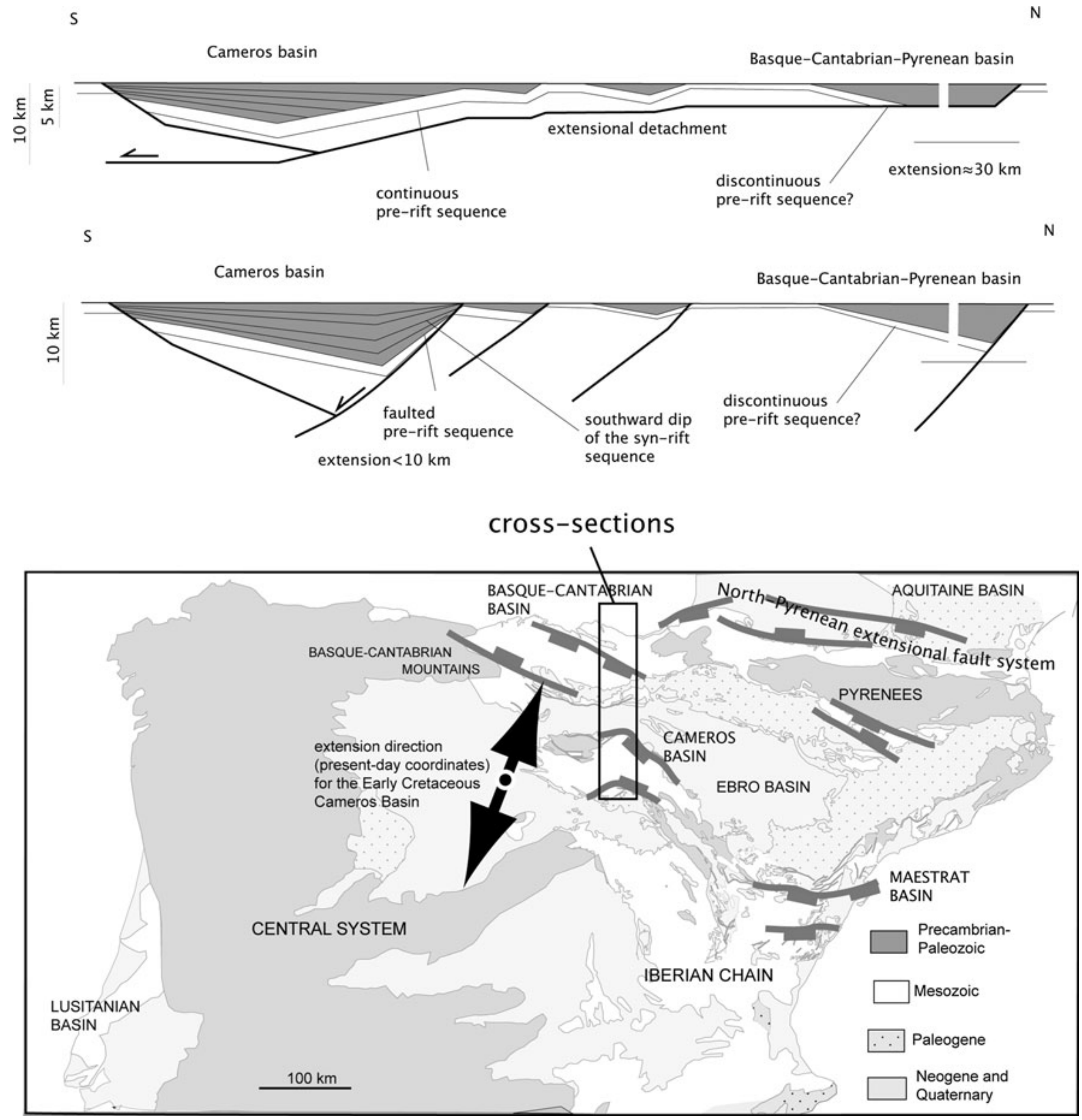

Fig. 1 Sketch showing the two end-member models proposed for extension in the Cameros Basin and adjacent areas. The upper cross-section shows the sag basin model associated with a step in a mid-crustal detachment level. The lower cross-section corresponds to the syncline basin interpretation associated with crustal-scale normal faults. The approximate position of the interpretative cross section is shown in the map

basin. This leads the authors to propose other hypotheses with lateral and not vertical superimposition of sedimentary bodies. However, other basin histories in the Iberian plate and the European rift system indicate that this figure is not exceptional for a vertical superposition to occur.

2. The existence of continuous outcrops of the syn-rift sequence all along the northern basin border (at present the hangingwall of the Cameros thrust after inversion). This assumption is not actually true since there are areas where the pre-rift post-detachment sequence is present and other areas where it does not crop out, because of syn-rift faulting. The existence of a detachment level below the pre-rift sequence (marine Jurassic) strongly controls the geometry of extensional structures (see Soto et al. 2007 and references therein).
3. The amount of extension and its relationships with other basins in the northern border of the Iberian plate (see Fig. 1). In the case of an extensional ramp basin (sag basin associated with a flat-ramp-flat geometry), assumed by González-Acebrón et al. (2011), either two strike-slip transfer zones with 30 km of differential displacement at both sides of the basin and therefore in the basement of the Tertiary Ebro basin or a whole

displacement of the upper part of the continental crust toward the South must be invoked. This kind of transfer structures has not been recognized from geophysical or geological evidence and is probably one of the main kinematic flaws for the proposed model.

In summary, we consider that many of the data shown by González-Acebrón et al. (2011) are of great interest and can be interpreted according to a syncline basin model, therefore considering that the samples were taken in the deepest part of the basin now exposed at surface, with at least 8,000 m (probably more considering fission track data from Del Río et al. (2009b), because samples from the youngest syn-rift unit are reset for AFT even outside the "hydrothermal-involved" area) of sediments overlying this part of the sequence. If we consider Figure 1 from González-Acebrón et al. (2011), it is self-evident that the areas with low-grade hydrothermal metamorphism are the areas that would be deeper within the basin in a synclinal basin model. Evidently, lithological constraints must also be considered because this kind of metamorphism has a strong chemical control. When the whole series is considered in both A and B areas (González-Acebrón et al. 2011, figure 1), the first stage of thermal metamorphism can be easily explained. The second stage can be related to hydrothermal metamorphism and the increase in gradient throughout the basin, probably related to the remagnetization event (a thermal-chemical event at plate-scale cannot be discarded, according to data from Juárez et al. 1998; Gong et al. 2009; Soto et al. 2008), what can also help to constrain its age. And finally, the third hydrothermal event interpreted by González-Acebrón et al. (2011) opens new possibilities in the interpretation of foliation development in the Cameros Basin (a shortening stage not very much dealt with in works concerned with hydrothermal events, see González-Acebrón et al. 2011; Mantilla-Figueroa et al. 2002) or even basin geometry (Mas et al. 1993; Guimerà et al. 1995).

A large record of sequences that have undergone a complex history of active metamorphism and hydrothermal alteration in response to recent volcanism and active faulting can be found in the literature (Pirajno 2009 and references therein). In the Cameros Basin, a mineral prograde sequence, from deep diagenesis to epizone, has been described (Guiraud 1983; Alonso-Azcárate et al. 1999; Barrenechea et al. 1995; Mata et al. 2001), but only a detailed textural study for the whole sequence (made of thousands of meters) would indicate whether mineral reactions are heat or fluid flow driven or both and the timing for hydrothermal processes. Although González-Acebrón et al. (2011) present an excellent and detailed fluid inclusion and petrographic study, detailed data showing textural relations and reaction progress in clays at reticular scale are also necessary to constrain metamorphic/hydrothermal/tectonic processes and retrograde reactions in low-grade environments (Merriman and Peacor 1999; Nieto et al. 2005). Furthermore, dating is insufficient and scarce, and there is no direct, in situ dating related to hydrothermal or cleavage processes. First attempts were made by Goldberg et al. (1988) by Ar39 ± Ar40 isotope analysis in what they called phengites, the high pressure term of mica (Velde 1965), but later studies have shown that the authigenic illite crystals are muscovitic (low-pressure terms), so a probable detrital component was present in Goldberg et al.'s measurements. A second attempt was made by K ± Ar analysis on fine-grained illite (Casquet et al. 1992), and a last try was done by Del Río et al. (2009a) on in situ U–Pb SHRIMP analysis on authigenic monazite crystals, giving so far the most accurate dating of authigenic minerals in the Cameros Basin. Many previous references claim to chlorite geothermometry to determine the temperature reached for the matrix of the rock in this sequence. We want to state that chlorite geothermometry has been rejected as a reliable geothermometer since the early 1990s, as activity composition relation is not accurately known (Essene and Peacor 1995). The only accurate thermometric data now existing for two areas and events are the metamorphic conditions based on mineral reactions calculated with the program THERMOCALC and the database of Holland et al. (1998) based on EMPA analysis of chlorite and chloritoid (Mata et al. 2001) for metapelites matrix and the temperature calculated by Alonso-Azcárate et al. (1999) on the basis of anhydrite-pyrite geothermometry. The lack of consistent geothermometers in low-grade metamorphism is another drawback for the right interpretation of basin evolution, so caution has to be taken when comparing and interpreting fluid inclusion data of veins or hydrothermal events with the whole rock or matrix temperatures when no equilibrium has been attained.

All the assumptions in González-Acebrón et al. (2011) and previous papers have been made on the basis of textural relations frequently disregarding the timing and meaning of the present cleavage described in detail by the aforementioned authors. Furthermore, fluid circulation along fractures and dissolution-precipitation processes are compatible with a sequence with a prograde temperature increase. Dating, detailed microstructural features of phyllosilicates, and geothermochronology are still the main flaws to achieve the full evolution of this basin.

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