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Reply to comment by P. Olivier on "Thermal control on the modes of crustal thinning leading to mantle exhumation: Insight from the Cretaceous Pyrenean hot paleomargins"

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We thank Philippe Olivier for the great attention he paid in reading our work and for the discussion he initiated. P. Olivier has been alarmed by our proposition that some Pyrenean granulites might have been (re)granulitized during the Cretaceous rifting event. In a rigorous scientific approach, this hypothesis has to be envisioned. However, in the paper, we proposed two alternative scenarios: one involving a Cretaceous (re)granulitization and another one implying a succession of metamorphic events with a first Paleozoic High Temperature (HT) metamorphism event responsible for the granulitization, followed by a second HT metamorphism event during the Cretaceous. Our main point here was to put in relation the strikingly similar fields of metamorphisms responsible for the granulitization of the crystalline basement and for the HT metamorphism of the prerift and synrift Mesozoic sedimentary cover. In other words: with temperatures up to 600°C in the metasedimentary cover, we would expect temperatures at least as high as 600°C in the basement. If not, it would mean that the continental crustal basement was already withdrawn from the metamorphic domain at that point. This scenario corresponds in fact to the concept of lateral extraction of the continental crust that we retained from our field constraints and that we defend here.

In the following, we try to answer point by point the comments by P. Olivier.

For P. Olivier, "…the Aptian, Albian and Lower Cenomanian sediments were very likely deposited in a unique basin…" This point was already raised in the discussion between *Olivier* [2013] and *Vauchez et al*. [2013b]. It may be difficult to argue for continuity between the St. Paul-de-Fenouillet unmetamorphosed syncline and the strongly metamorphosed Boucheville syncline. Furthermore, these basins are today separated by several major tectonic contacts along which are found the mantle peridotites of Salvezines. This observation suggests that the two domains where initially probably far from each other and separated by a domain of hyperextended continental crust.

P. Olivier argues that within the Agly massif, the systematic increase in metamorphic grade toward the domain of exhumed mantle does not necessarily imply a tilting because "the deepest gneissic unit (Caramany unit) is horizontal". However, as stated by the author, "the overlying units […] dip to the north in the northern part and to the east in the eastern part" which, if we believe the Oxford English dictionary, is in agreement with the definition of the word "tilt" ("to move into a sloping position" http://www.oxforddictionaries.com).

Furthermore, in *Olivier et al*. [2004], the author himself writes: "Steepened foliations and lineations observed on the northern border of the massif may correspond to such tilting to the north, linked to the formation of the large synclines made up of Cretaceous strata which enclose the massif to the north and to the south. Some reactivation of the mylonitic bands might have happened at that time." In 2008 the author restated "such relationships between the metamorphic country-rocks and the pluton imply a northward tilt after its emplacement" [*Olivier et al*., 2008].

"The lherzolites […] are considered by the authors as remnants of the subcontinental mantle contemporaneous with the Black flysch deposition (Middle Albian-Early Cenomanian)."

We would like to draw the attention of P. Olivier to Figure 6 and its caption, which states "models for the Cenomanian architecture…" Hence, we do not present a model involving exhumation of the peridotites contemporaneous with the Black Flysch deposition. We are, however, aware that this misunderstanding might be due to our representation of the Cenomanian situation in several figures throughout the manuscript.

Indeed, for simplification, we decided not to represent the Cenomanian post-Black Flysch sediments while they were being deposited.

According to P. Olivier, the publication of *Vauchez et al*. [2013a] does not report robust observations in favor "of the (re)activation of mylonitic extensional faults and shear zones during the Cretaceous." We are aware that P. Olivier was not convinced by Vauchez et al.'s work [*Olivier*, 2013]. However, *Vauchez et al*. [2013a] are not the only ones advocating Cretaceous reactivation: in section 5.3, we also cite and discuss the work of [*Passchier*, 1984; *St Blanquat et al*., 1986; *Costa and Maluski*, 1988; *St Blanquat et al*., 1990; *Paquet and Mansy*, 1991].

We made the observation that "high-grade Paleozoic material is overrepresented in the North Pyrenean Zone (NPZ) in regard to the Axial Zone." The proposition of P. Olivier stating that there is less erosion in the Axial Zone (the highest reliefs of the belt, constituted of exhumed crystalline basement) than in the sedimentary basins of the NPZ is interesting and deserves a dedicated communication.

"Hydrothermal phenomena are not "generalized" but localized along faults which have acted until the Eocene time." We considered the outcrops of metasomatic albitites, albitized rock, and talc to be sufficiently numerous in the Pyrenean belt that the hydrothermal phenomena can be termed "generalized." Therefore, using the term generalized is not an exaggeration when the specialists of the topic describe it as a "Regional-scale Cretaceous albitization" [*Poujol et al*., 2010], "widespread process" [*Boulvais et al*., 2006], "extensive albitization", "Albitization occurs throughout the massif" [*Boulvais et al*., 2007], etc.

Using various radiogenic dating methods, the same authors determined Cretaceous radiogenic ages for the activity of the hydrothermal circulations responsible for these mineralizations.

We agree with P. Olivier that the nature and origin of the post Albian-early Cenomanian sedimentary cover allowing an increase of the temperatures up to 600° in the black shales is an important issue that has to be addressed.

Most of the drawings in *Clerc and Lagabrielle* [2014] propose a restored situation during the Cenomanian. For simplicity we never draw the Cenomanian sediments as they were being deposited above the Black Flysch. This may be a mistake because in our proposed model, these sediments played a major role as they act as a thermal blanket over the black shales [*Clerc et al*., 2015]. Concerning Figure 4a, we thank P. Olivier for pointing out to our mistake: instead of "Cenomanian" in the legend, we should have written "Cenomanian to Campanian."

We thank P. Olivier for drawing our attention toward the mylonitic shear zones of the Axial Zone; however, the topic of our manuscript was focused on the NPZ.

We agree with P. Olivier that reverse faults could have been represented in the Agly basement of Figure 4c. However, the purpose of this figure is not to illustrate the deformation of the basement but rather to show the tectonic style and the basal truncations already noticed in the Mesozoic cover by *Durand-Delga* [1964].

We agree with P. Olivier that our use of the term "Cenomanian flysch" is too imprecise. In page 7 the term "Albian-Cenomanian flysch" refers to the Black Flysch, while in page 6, the Cenomanian flysch refers to the Cenomanian to Turonian flysch.

We have to agree on the rather subjective and imprecise definition of the term "early." As stated by P. Olivier, the sedimentary reworking cannot be so early because the marbles were metamorphosed prior to the reworking. However, this does not preclude an early juxtaposition of the sedimentary cover over exhumed peridotites at depth as soon as the Albian Lower Cenomanian.

We agree with P. Olivier that the hypothesis of a Cretaceous (re)granulitization is not strongly supported by data and might appear questionable. However, we wanted to propose this hypothesis (among others) to point to the fact that the HT-LP metamorphism that affected so strongly the Mesozoic sediments may also have had strong impacts on the Paleozoic basement. Whereas it is now clearly established that the mantle peridotites were exhumed during the Cretaceous, how is it possible to put mantle and cover together in a HT-LP metamorphic context without affecting the basement? What happened to the basement during Cretaceous times? This is our main concern. For the moment only little data are available; however, in addition of the generalized metasomatism affecting the North Pyrenean Massifs, it is established that radiogenic chronometers in the Paleozoic basement have been reset during Cretaceous times [e.g., *Costa and Maluski*, 1988;

St Blanquat et al., 1990], which is indicative of general heating of the NPZ. Cretaceous ages have been also reported in mylonitized granitoids from the Axial Zone in the Eastern Pyrenees [*Monié et al*., 1994].

Page 6, we wrote "The internal structure of the North Pyrenean massifs reveals a condensed crust, passing in a few kilometers from low-grade Carboniferous sediments to migmatitic and granulitic basement considered as exhumed middle to lower crust [*Vielzeuf and Kornprobst*, 1984]. This rapid transition may result from late-variscan extension [*Bouhallier et al*., 1991; *St Blanquat*, 1993] but is also the consequence of the (re)activation of mylonitic extensional faults and shear zones during the Cretaceous [*Passchier*, 1984; *St Blanquat et al*., 1986; *Costa and Maluski*, 1988; *St Blanquat et al*., 1990; *Paquet and Mansy*, 1991; *Vauchez et al*., 2013a]." In agreement with P. Olivier, we do not refer to one single detachment, but to "numerous mylonitic bands accounting for distributed thinning throughout almost all the series" [*Olivier et al*., 2004].

We are very sensitive to the remark of P. Olivier that if the migmatites and granulites observed in the NPZ were Cretaceous in age, we should find Cretaceous plutonic rocks. This supports the hypothesis of the Paleozoïc granulitization commonly admitted and illustrated in our Figure 9b.

1. "If most authors admit that the continental crust of the North Pyrenean Zone suffered an extension from the late Aptian onwards, many points are still poorly understood, especially […] the age of the metamorphism of the Albian-Lower Cenomanian series: Middle Cenomanian or latter"Until now, a very large amount of the radiogenic ages obtained for the HT-LP Cretaceous metamorphism range from the Albian to the Coniacian [*Montigny et al*., 1986; *Albarède and Michard-Vitrac*, 1978; *Clerc et al*., 2015].
2. P. Olivier seems to remain unconvinced by the recent, though abundant literature concerning the mechanism of exhumation of the peridotites [*Lagabrielle and Bodinier*, 2008; *Jammes et al*., 2010a; *Clerc et al*., 2012, 2013], the structure of the Cretaceous rift system [*Jammes et al*., 2009, 2010b; *Lagabrielle et al*., 2010; *Vauchez et al*., 2013a; *Masini et al*., 2014; *Tugend et al*., 2014; *Mouthereau et al*., 2014].
3. The unroofing of the North Pyrenean Massifs [*Filleaudeau et al*., 2011; *Vacherat et al*., 2014]. As an example of this abundant literature, we would like to cite the title of the publication by *Debroas et al*. [2010] "The Urdach Breccias evidence the exhumation of the Pyrenean mantle in a Vraconnian to Lower Cenomanian fault scarp (North Pyrenean zone, Pyrénées-Atlantiques, France)" which clearly states that the peridotites where exhumed and reworked during the Upper Albian-Lower Cenomanian, which means, contemporaneously with the HT metamorphic event.

Finally, in the frame of our hypothesis of mid-Cretaceous mantle exhumation: if we consider that the Paleozoic basement did not undergo HT metamorphism during the cretaceous this implies that the continental crust was removed early enough so that it never reached the HT: this is a fact that has to be outlined. This reinforces our model of crustal boudinage during the Albian-Cenomanian period.

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