Reply to Debroas et al.'s comment

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Bull. Soc. géol. France, 2013, t. 184, n° 6, pp. 631-632

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We thank Debroas *et al*. for their comments and we are ready to pay attention to their concerns. Any positive input and constructive remarks that would improve our model will be appreciated. We are well aware that our article may include some points of discussion and that our model integrates conceptual parts. However, since our study is based on the results of a detailed field analysis, we feel confident that the rock-types and lithological contours stated in our article account for the proper geology of the study area.

MAP SIGNIFICANCE OF THE BRECCIAS

We completely agree that our map is « only lithological », as it presents the composition, location, and spatial distribution of the different types of breccias. All the « missing details » (polarity, dips, extent of facies, genetic relationships...) are not reported either because we don't have sufficient observations (see following section below) or just because it's not the purpose of this « *only lithological* » map. However, we believe that such a map is of high relevance for the understanding of the origin of the breccias in the mapped area because the bounding surfaces of the lithological units are sharp and the facies changes across these surfaces are major. In addition, the facies attributes of these units point to their sedimentary origin, so that we may consider the unit map as a geological map.

Namely, our map reports numerous metric to hectometric lenses of dismembered lherzolite. Small lenses are angular or sub-circular, and larger lenses are more elongated. As noted by Monchoux [1970], these lenses are globally elongated in a WNW direction, and are aligned with other lenses in the neighboring valleys. In detail, the lenses could have a more variable orientation, and isolated metric or sub metric lherzolite fragments are observed within the marble breccia at various distances from lherzolitic lenses throughout the mapped area, that is between the Trois-Seigneur Massif and the Axial Zone.

The irregular geometry of the contact between lherzolite-rich sediment bodies and the surounding breccia, the absence of any feature indicative of ductile and/or brittle deformation (fault, striation, dissolution...), and the overall map pattern of dispersed lherzolitic lenses of various shape and size all across the whole area, clearly argue for a sedimentary mixing process of lherzolitic and calcareous clasts at origin of most, if not all the breccias in the mapped area. The clastic origin of the marble breccia was evidenced on polished outcrops [Clerc *et al*., 2012]. In our view, and as a consequence, most of the Aulus basin-fill is dominated by margin rafts and olistostromes, comparable in size with those reported on other steep margins supplied by mass-wasting of carbonate platforms [e.g. Mulder *et al*., 2012].

In our opinion, we did not miss important outcrops that would have led us to a lack of key-observations. Furthermore, we think that going back again to a more detailed discussion around very detailed field observations should make this reply boring for most of the readers. Since Clerc *et al.* [2012] provided a detailed map plus precisely located field observations, and Debroas *et al*. [2013] provided localized field observations, geologists are now able to make their own opinion in the field.

To make a final note on this topic, we do not « ignore the presence of subcircular brecciated bodies » initially mapped by Monchoux [1970], as we have located and mapped them. Moreover, we note that Monchoux wrote « dans la plupart des cas, les gisements ne sont manifestement pas affectés de failles bordières » (which could be translated as « in most cases, the lherzolites are obviously not surrounded by border faults »), and this especially in our studied area [Monchoux, 1970, p. 11].

INTERNAL GEOMETRY AND FACIES OF THE BRECCIAS

Our model of a sedimentary mixing process within a tectonically active environment is in accordance with the poorly-defined internal geometry of the breccias. Both the non-lherzolitic and lherzolitic clasts (different type of marbles, lherzolites...) are poorly sorted and texturally immature (mixed angular or rounded clasts). Although large-scale bedding is very scarce, the lherzolite-rich litharenite matrix of the lherzolite-rich breccia is commonly laminated between the larger clasts, which indicates a dominant bedload transport at origin of (or triggered by) the deposit.

We admit that, in some instances, such a fabric could be compared with that of endokarstic sediments but there is no evidence of included clay or oxide minerals that commonly concentrate in karsts. Also the interbedding of the lherzolite-rich breccia lenses is an issue in the karstic interpretation. Furthermore, the mafic minerals of the lherzolite would rather be weathered through karstic processes and not concentrated within the endokarstic deposit. Still, we may admit that some of the breccias at the outcrop can be

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Manuscript accepted on June 2, 2013

reworked by surface processes related to a post-Cretaceous story.

Debroas *et al.* [2013] claim that the bedding of the lherzolite-rich breccias is horizontal throughout the area, which would indicate a mostly post-pyrenean age. In many outcrops, however, we have reported highgly dipping stratification planes trending alongstrike the mapped hectometric lenses [Lagabrielle and Bodinier, 2008; Clerc *et al*., 2012]. Furthermore, no stratal relationship between the beds within the lenses and the encasing breccia can be significant at the outcrop scale. In our interpretation, most lenses may have channelized bases [by the way, one could see a channel in Fig. 1 of Debroas *et al*., 2013], and therefore the lherzolite-rich breccia beds would likely locally onlap the channel walls cut within the marble breccia. At the scale of the whole deposit, this onlap has not the value of an unconformity and one may consider the lherzolite-rich lenses interbedded within the marble breccia.

FRONTING MODELS OF THE BRECCIA FORMATION

As opposed to Debroas *et al*. [2013], we must say that we never observed thick cataclastic formations (tectonic breccias) within the area mapped in detail in Ravin de Paumères. By contrast, again, both the marble- and lherzolite-rich breccias observed in this area are thought to be sedimentary in origin. In several other publications, we have explained that these sedimentary deposits were emplaced as olistostromes or slope margin rafts by gravity on the footwall of a detatchment fault during the extensional stage in the Pyrenees [Lagabrielle and Bodinier, 2008; Lagabrielle *et al*., 2010]. To date, this model is the only one explaining why the lherzolite can be supplied to the basin and mixed with sediments derived from erosion and collapse of the supra-Permian Mesozoic cover with only very rare contribution of lower parts of the lithologic pile to the sediment supply [Lagabrielle and Bodinier, 2008, cf. outcrop in Plate C, 4].

Assuming the interpretation that most of the Lherz breccias represent cataclastic breccias, Debroas *et al.* [2013] should now provide a tectonic model taking into account this major geological feature. This model should answer the following questions: How and when did the tectonic breccias formed? How carbonates and lherzolites mixed together? Why are breccias also characterized by the scarcity of basement clasts? How can be the fault-damaged zone as thick as the whole Aulus basin breccia? What is its lateral extent? How do the tectonic breccias connect to the major thrusts surrounding the Aulus basin? To our opinion, this is not explained by the cartoons of Debroas *et al.* [2013, Fig. 7].

It is worth noting that the expected tectonic model should also take into account some stratigraphical constraints. We have already stressed on the absence of Paleozoic and basement rocks within the breccias. In their comment, Debroas *et al.* [2013] claim that the Coumettes Breccias were deposited after the Upper Senonian tectonic inversion and emersion of the Aulus basin, probably during the interval between the end-Cretaceous and the present day. There are frequent occurrences of graded-bedded and laminated ultramafic sandstones, reworked as clasts within the carbonate breccia formation itself, that is within the so-called cataclastites of Debroas *et al.* [2013]. These clasts do not show a systematic subhorizontal bedding. We found that this is a major and highly significant observation. Therefore, we provided a photograph of such type of clasts in our article [Figure 6 in Clerc *et al*., 2012]. In our opinion, this indicates that some of the laminated ultramafic sandstones cannot represent syn- or post-inversion deposits.

Moreover, assuming a deposition within vertical conduits through the cataclastic pile, how to explain that the Coumettes Breccias never include clasts from the Upper Cretaceous Flysch?

THE TECTONIC SCENARIO AT THE SCALE OF THE PYRÉNÉES

Our work aims to link mountain belts and their pre-orogenic analogues such as passive margins. In this respect, we have some concerns with the evolutionary diagrams of figure 7 by Debroas *et al*. [2013] since they do not fit to any model of crustal extension proposed in modern literature. In particular:

– what is the process that brings mantle rocks (L) to be part of the « thinned crust »?

– why are the boundaries of the Aulus basin vertical?

– what is the amount of extension and/or shortening between each stages?

– how the S1 schistosity and associated syn-metamorphic deformation was formed during the post-rift stage (middle Cenomanien – Turonian – Coniacian), that is before the onset of inversion [around 85 Ma, Debroas and Azambre, 2012]?

– what connections can be traced between the vertical faults in figure 7 and the thrusts imaged by the ECORS profile?

To conclude, we maintain that Debroas *et al.* [2013] fail to explain the formation of a polymictic breccia consisting of a mixture of clasts of millimetric to kilometric size, at a lower temperature than the metamorphism and serpentinization, but emplaced during the North-Pyrenean syn-rift phase, as attested by paleotemperatures and geochronological ages obtained on the breccias. Similar observations were made around other lherzolite outcrops [Lagabrielle *et al*., 2010], particularly east of Lherz (Vicdessos and Bestiac-Caussou-Prades area; St Blanquat *et al*., in prep.), so this is not a local process. The formation of these breccias imply the fragmentation of the mantle at or near the surface and its sedimentary mixing with the already deformed and metamorphosed Mesozoic cover. Mantle exhumation in narrow intracontinental basins suffering extreme crustal thinning is a process, which could explain all these observations.

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