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A B S T R A C T

Although they are famous among Earth scientists, the Lherz peridotites are exposed within geological formations of the North Pyrenean Zone (NPZ) still lacking detailed investigations. Our study focuses on the metasediments of the Aulus basin hosting the Lherz peridotite body and associated ultramafic fragments of smaller size. The new data set comprises of structural analysis and detailed geological mapping of the massive Mesozoic marbles that form the prerift sequence typical of the NPZ and of the ultramafic-rich clastic breccia formations surrounding the peridotite bodies. The massive marbles display an evolution from hot and ductile to cold and brittle deformation, indicative of an exhumation process ending with the sedimentary reworking of both the deformed Mesozoic metasediments and the exhumed ultramafic rocks. Crystal Preferred Orientations (CPO) measured in the marbles support a deformation mechanism by dislocation creep of calcite, which is dominant between 400 °C and 600 °C; these deformation temperatures are within the range determined earlier by Clerc et al. (2015), using RSCM (Raman Spectroscopy of Carbonaceous Material) geothermometry. As a consequence, we better describe the transition from ductile to brittle deformation in the prerift marbles and clarify the origin of the syn-rift breccias. Due to continuous exhumation along detachments' faults, the brecciated metamorphic carbonates of the prerift NPZ sedimentary cover were passively uplifted towards shallower levels and progressively unroofed, while transported passively on the back of the exhumed ultramafic footwall. These results are consistent with the recent interpretations of the North Pyrenean peridotites as remnants of subcontinental mantle rocks exhumed within the pre-Pyrenean rift system. We emphasize the importance of tectonic decoupling between the Mesozoic sedimentary cover and the Palaeozoic basement, which leads to the juxtaposition of metamorphosed and deformed Mesozoic

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sediments directly on top of exhumed mantle rocks. We favor a model of tectonic denudation of the peridotites below prerift sediments metamorphosed during the extension of the basin floor under high temperatures and in a thermal regime characterized by a very high gradient.

1. Introduction

About forty small fragments of subcontinental, variably serpentinized lherzolites are spread along the Pyrenean chain. They are concentrated in a narrow belt of Mesozoic sediments forming the North Pyrenean Zone (NPZ) parallel to the North Pyrenean Fault (NPF), which represents the major tectonic boundary between the Eurasian and Iberian plates (Choukroune and ECORS Team, 1989; Muñoz, 1992; Roure and Choukroune, 1998; Teixell, 1998). The peridotites are locally associated with tectonic slices of lower crustal material, which exhibit granulitic paragenesis (Vielzeuf, 1984; Vielzeuf and Kornprobst, 1984). The NPZ corresponds to an alignment of inverted basins that deepened during Albian–Cenomanian times in response to the transtensional motion along the future NPF during the counterclockwise rotation of Iberia (Gong et al., 2008; Olivet, 1996; Sibuet et al., 2004). Various models have been proposed to explain the occurrence of small mantle fragments in the NPZ. They involve opposite processes ranging from tectonic intrusions into sediments (Minnigh et al., 1980; Vielzeuf and Kornprobst, 1984) to tectono-sedimentary reworking of previously exhumed mantle rocks (Choukroune, 1973). Recent studies favor a tectono-sedimentary model for the emplacement of the ultramafic rocks and associated breccias (Clerc and Lagabrielle, 2014; Clerc et al., 2012; Jammes et al., 2009, 2010; Lagabrielle and Bodinier, 2008; Lagabrielle et al., 2010; Mouthereau et al., 2014; Saint Blanquat et al., 2016). In these models, the subcontinental Pyrenean mantle has been exhumed along detachment faults and exposed locally on the floor of the narrow NPZ basins during the Mid-Cretaceous rifting period.

Since they recorded crucial events in relation with the Cretaceous extension, the prerift sediments of the NPZ represent important targets for geological investigations related to mantle exhumation processes. This study is aimed at characterizing the metamorphic and deformation history of the Mesozoic sediments of the Aulus basin (Haute-Ariège) in relation with the tectonic processes accompanying mantle exhumation. We investigate the transition from ductile to brittle deformation of metasediments during exhumation and their subsequent brecciation within the Aulus basin on the basis of a new detailed geological mapping of the metasedimentary formations coupled with the first microstructural analysis of the massive deformed carbonates.

2. Geological setting of the Lherz ultramafic bodies

Two major peridotite bodies outcrop in the Aulus basin, at the Étang de Lherz and in the Freychinède forest (Fig. 1). They occur within a narrow band of Mesozoic metasediments pinched and verticalized between two units exposing the Palaeozoic continental crust: the Axial Zone to the south and the Trois Seigneurs massif to the north. The Étang de Lherz subcontinental peridotites derive from the refertilization of an old (~2.5 Ga) harzburgitic lithosphere by mantle-derived melts (Bodinier et al., 1988; Le Roux et al., 2007), possibly during Late Variscan times (Pin and Vielzeuf, 1983). The ultramafic rocks of the Aulus basin are included within a High Temperature–Low Pressure (HT–LP) metamorphic belt that developed between 110 and 85 Ma (Albarède and Michard-Vitrac, 1978; Clerc et al., 2015; Golberg and Maluski, 1988; Montigny et al., 1986) with *P*–*T* conditions estimated at 500–650 °C for 300–400 MPa (Bernus-Maury, 1984; Golberg and Leyreloup, 1990), to 50–150 MPa, in accordance with a maximum stratigraphic thickness of 3–4 km (Goujou et al., 1988).

3. The metasedimentary formations of the Aulus basin

The Mesozoic metasediments of the Aulus basin are massive carbonates, often mylonitic, and monomictic to polymictic carbonate breccias (Choukroune, 1973, 1976; Colchen et al., 1997; Ternet et al., 1997; Fig. 1). Our detailed mapping indicates that the contacts between these two rock types consist alternatively of an abrupt juxtaposition by fault or of a progressive transition, as described further in this section. At the basin scale, the largest units of massive carbonates are found in the eastern and western part of the Aulus basin, whereas the carbonate-ultramafic polymictic breccias are dominant in the core of the basin (Fig. 2).

3.1. The massive carbonates

Despite an important imprint of the HT–LP metamorphism, the overall stratigraphy of the Aulus massive metasediments is well established. The original sedimentary sequence includes dominant Triassic to Aptian carbonates and minor black metapelites. Some fossils are well preserved in Liassic dolostones (Col Dret and Vallon de Saleix: Carez, 1901; Colchen et al., 1997; Ternet et al., 1997). All the metasediments display clear evidence of ductile deformation with bedding-parallel foliation (Fig. 3). The most abundant lithologies are Late Jurassic to Aptian banded marbles with alternating white to bluish-gray centimeter-thick layers, locally stretched, showing millimetric to decametric recumbent folds. Middle Liassic banded metasediments are composed of alternating millimeter-thick layers of brown marbles and metapelites

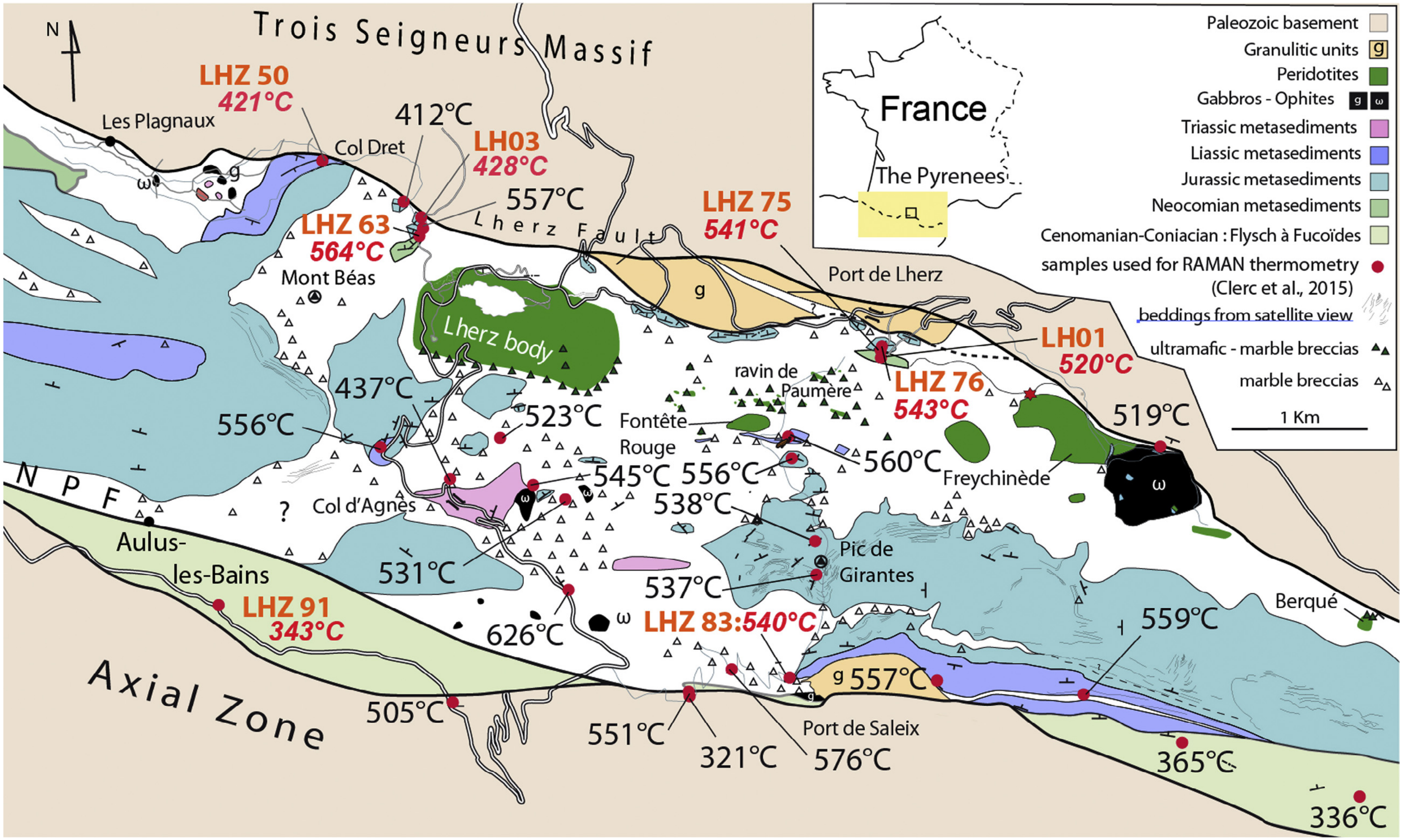

Fig. 1. Geological map of the central part of the Aulus basin based on unpublished field data collected by Y. Lagabrielle (2006–2009) and during the Master and PhD works by C. Clerc (2008–2012). Units of massive carbonates are separated by wide areas of polymictic sedimentary breccias. The ultramafic-bearing breccias are restricted to the central part of the Aulus basin where the peridotite bodies are concentrated. Samples used for CPO calculations are reported (bold orange labels). The peak temperatures obtained by RSCM from the same samples (Clerc et al., 2015) are indicated in red numbers. Additional peak temperatures from the Clerc et al. (2015) study are also reported (red spots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

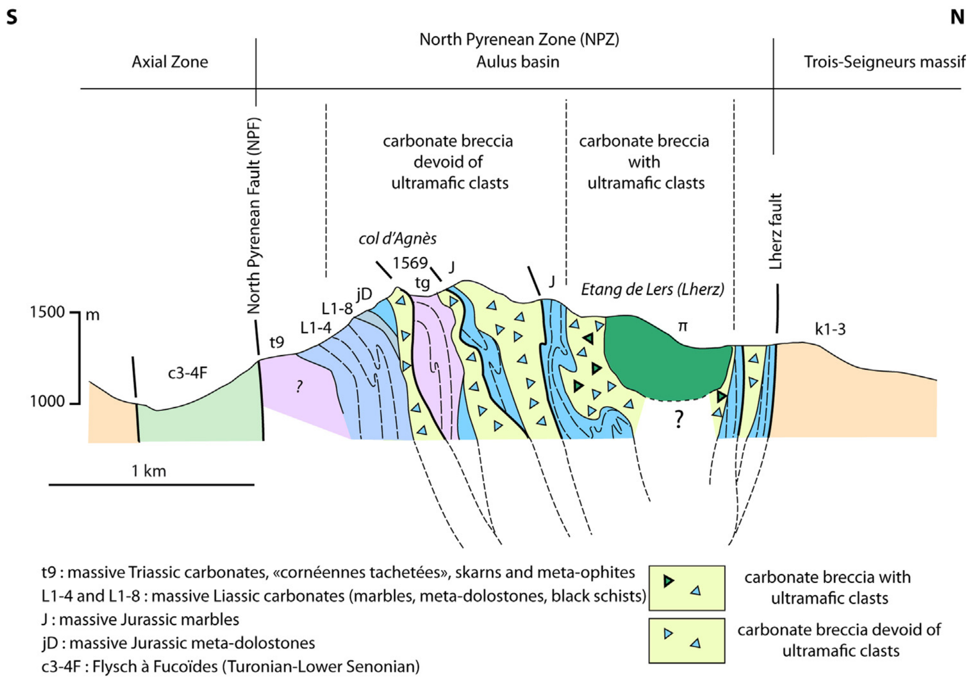

Fig. 2. Interpretative cross-section of the Aulus basin. The southern part is redrawn from Colchen et al. (1997).

showing stretching and boudinage parallel to the sedimentary bedding (S0). Late Liassic black metapelites show a thin pervasive foliation composed of quartz, calcite, chlorite, and white micas layers locally containing retromorphosed scapolites.

As revealed by our mapping, the massive carbonates form cohesive units separated by polymictic breccia intervals (Fig. 2). Hectometric recumbent folds can be recognized within the massive units (Figs. 2 and 6). Tectonic contacts between massive units have been mapped locally. Jurassic marbles are observed (i) against Triassic metasediments and ophites at the col d'Agnes and at Tuc de Pedrous, (ii) against grey and black Berriasian to Hauterivian marbles at the eastern foot of Col Dret and at the Port de Lherz, and (iii) against Liassic metapelites at the southern end of the Ravin de Paumère.

3.2. The carbonate breccias

Attention has been paid recently to the Aulus basin breccias as they provide critical information on the processes of mantle exhumation during the Cretaceous crustal hyperextension (Clerc et al., 2012, 2013; Debroas et al., 2013; Lagabrielle and Bodinier, 2008). In their detailed study east of the Étang de Lherz, Clerc et al. (2012) have proposed that the polymictic breccias are of sedimentary origin, in agreement with some previous interpretations (e.g., Choukroune, 1980). The breccias mostly include fragments of carbonate rocks deriving from the various lithologies of the pre-Albian Mesozoic sequence exposed in the Aulus basin (Fig. 5). The carbonate clasts are dominantly deformed marbles, some of them displaying metamorphic minerals such as scapolites. The carbonate breccias also include peridotite fragments that may form up to 90% of the rock (Fig. 5). Our new geological mapping shows that the ultramafic-bearing carbonate breccias are not present in the southern half of the Aulus basin where pure carbonate polymictic breccias only exist (Fig. 1). They are also lacking north of the Lherz body, such as along the trail to the Col Dret. Therefore, the ultramafic clasts are restricted to a domain close to the main lherzolitic bodies.

3.3. Transition from massive to brecciated carbonates

The significance of the transition between the massive carbonates and the carbonate breccias in the Aulus basin is still an on-going debate (Colchen et al., 1997; Debroas in Ternet et al., 1997). In the frame of this study, a complete transition from a massive protolith to monomictic and polymictic breccias has been observed in many places and a type sequence can been summarized as follows: (1) the original massive rock is affected by increasing veining and fracturing; (2) the veins and the fractures merge progressively so that the marble appears to be broken into numerous centimeter- to decimeter-sized clasts that underwent little displacement, and (3) this in situ breccia passes progressively, in a few meters, to an assemblage of clasts having similar origin, but which experienced more important reworking (Fig. 4). Fracturing crosscuts the metamorphic banding of the marbles, demonstrating that brecciation postdates the development of the HT foliation. A progressive transition between monomictic to polymictic breccias can be observed. In such cases, exotic carbonate clasts are incorporated progressively into the monomictic material

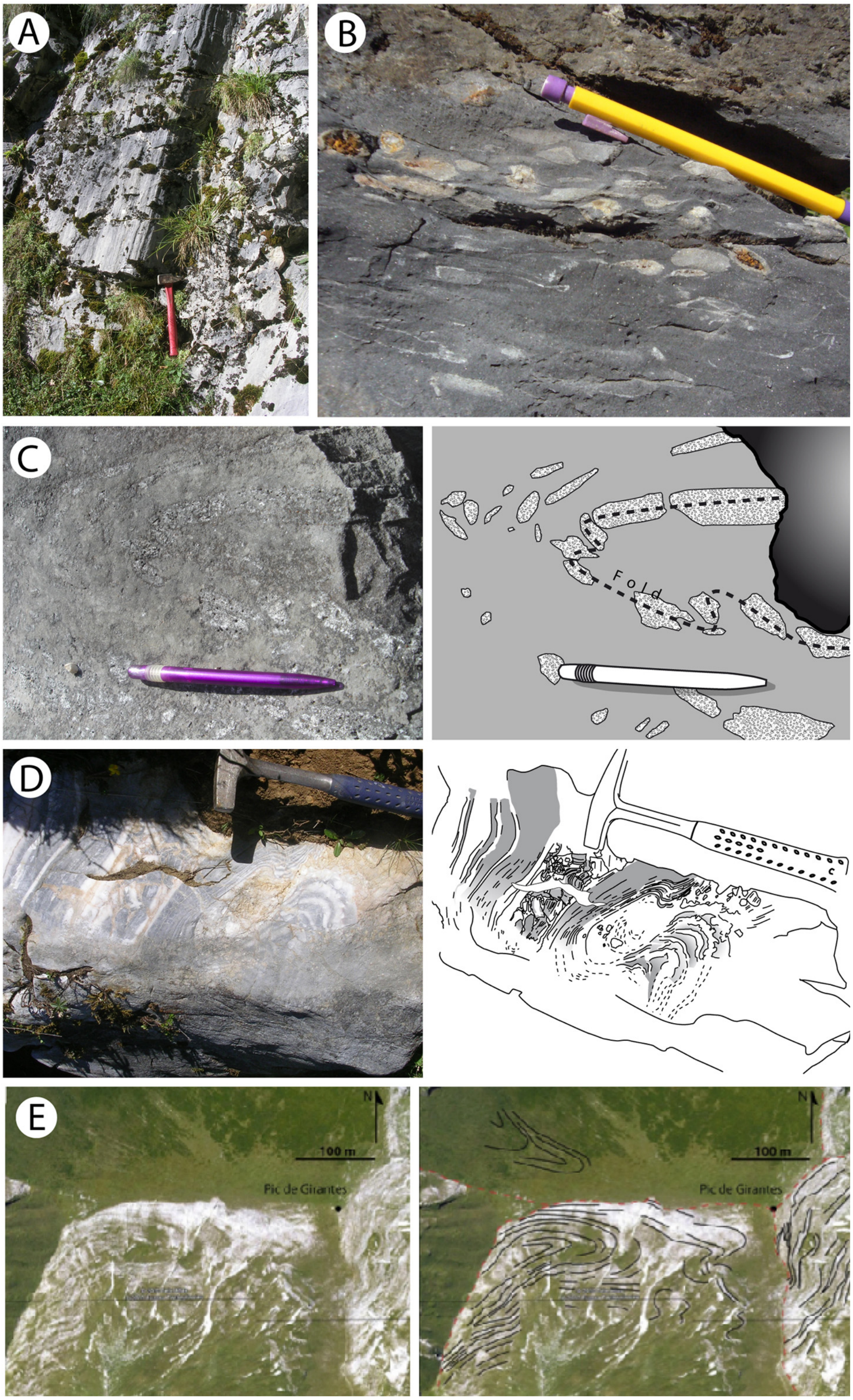

Fig. 3. Some aspects of the ductile deformation of the Mesozoic metasediments of the Aulus basin. (A) Subvertical ductile lineation in mylonitic marbles. (B) Deformed Liassic fossils flattened in the S0/S1 foliation (vallon de Saleix). (C) Boudinage of dolomitic beds in a fold. (D) Ductile folds in marbles. (E) Satellite view of km-scale ductile folds affecting the S0/S1 foliation on the southern flank of the Pic de Girantes.

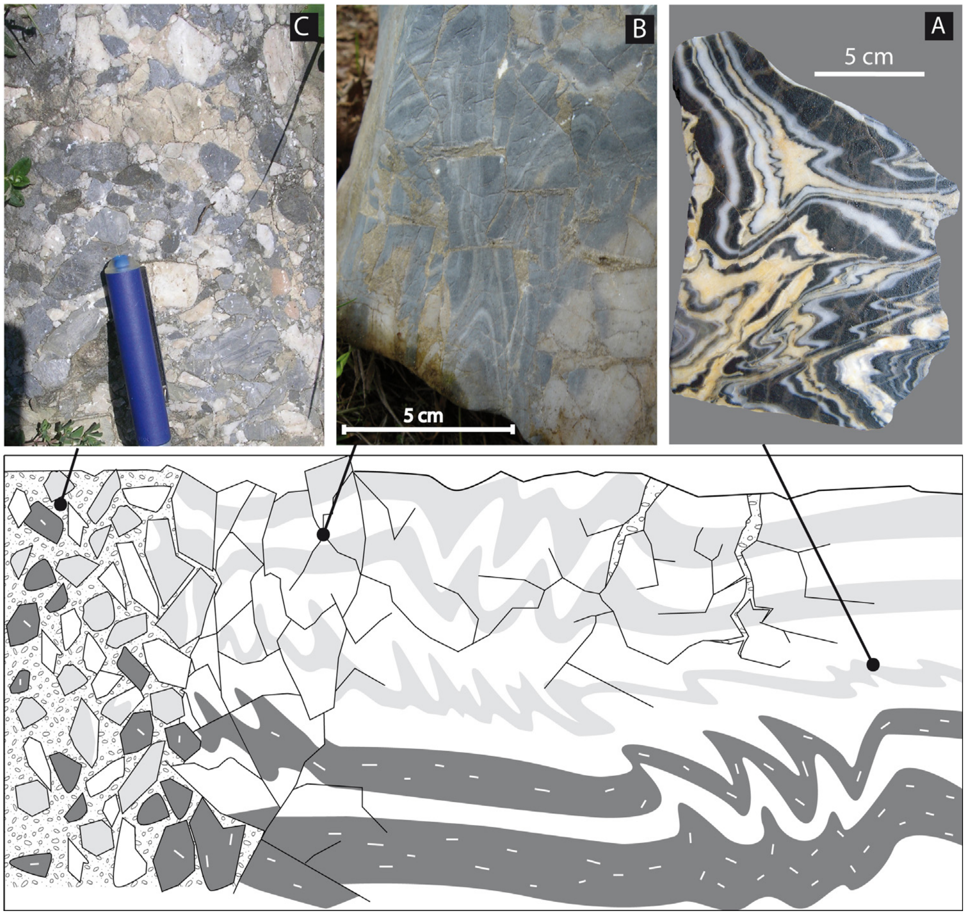

Fig. 4. From ductile to brittle deformation in the mylonitic marbles: a tentative reconstruction of the syn-kinematic cooling history recorded in the prerift metasediments. (A) Ductile deformation, (B) in situ breccias, (C) polymictic breccias.

(Fig. 5). The polymictic carbonate breccias may infill fractures opened in the massive marbles.

4. Deformation of the Aulus metasediments: thermal conditions

4.1. Characters and age of the deformation

In the Aulus basin, deformation in the carbonates is marked by a ductile foliation (S1) parallel to the Lherz fault and to the NPF (Fig. 1). In the most deformed samples, the original sedimentary bedding is completely transposed into this foliation. Even in less deformed outcrops, the S1 foliation systematically parallels the initial S0 bedding. This is well observed in the massive Liassic carbonates on the northern flank of the Port de Saleix, where abundant fossils of lamellibranches are stretched with their long axis contained in the S0–S1 plane (Fig. 3).

The apparent intensity of the deformation varies from place to place. Weak deformation is observed in the Col Dret carbonates, whilst deformation is more intense in the Étang de Lherz and Port de Lherz areas. Some lineations are observed due to extreme stretching in marble fine-grained mylonites and mineral alignments, generally scapolites (Fig. 3). The scapolites are stretched and pinched in situ, indicating pre- to syn-deformation crystal growth. The attitudes of the lineation vary from place to place, being vertical at the eastern foot of the Col Dret, and gently plunging in the Étang de Lherz and Port de Lherz areas. As reported by Clerc et al. (2015), the overall trend of the lineations is NW–SE. Multiscale ductile recumbent folds are common in the marbles (Fig. 4) as well as boudinage of stratigraphic intervals due to rheological heterogeneities between marble and metadolostone or between marble and metapelite (Fig. 3).

In a recent study, Clerc et al. (2015) obtained six new $^{40}Ar/^{39}Ar$ ages on muscovites and amphiboles extracted from the Aulus basin massive marbles. These ages range from 89.5 ± 0.3 Ma to 92.6 ± 1.1 Ma (Late Cenomanian to Turonian), with the exception of one sample for which muscovite has a plateau age of 100.1 ± 1.2 Ma (Albian). This demonstrates that the HT event relates to the opening of the NPZ basins and is not linked to the early compressional stages of the Pyrenean orogeny.

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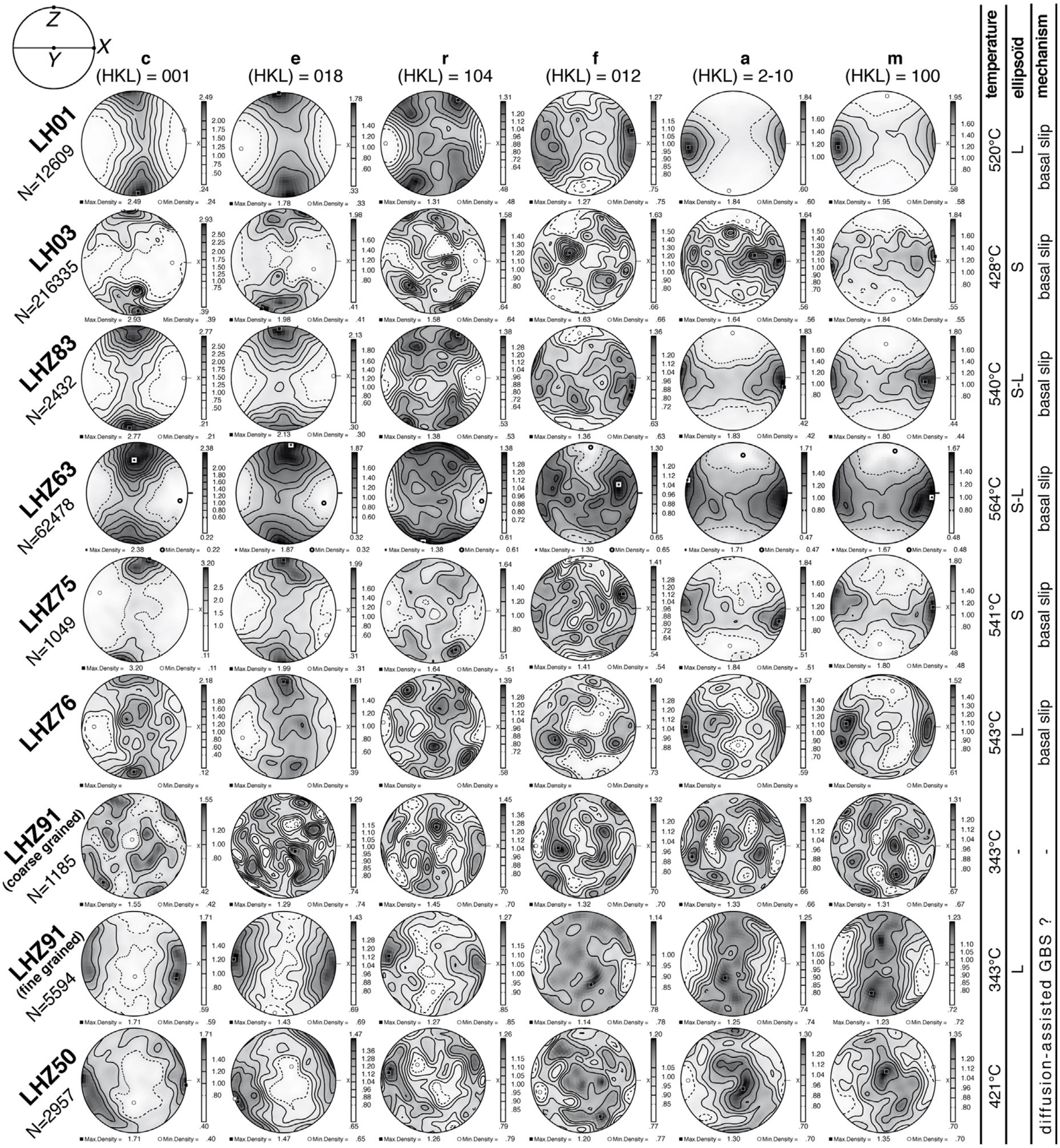

Fig. 5. Stereonets representing the Crystallographic Preferred Orientation (CPO) of calcite in mylonitic marbles from the Aulus basin. All samples display a well-defined although weak CPO. Temperatures are peak temperatures determined using the Raman spectroscopy of carbonaceous material (RSCM) as described in Clerc et al. (2015). Temperatures obtained from additional samples in the Aulus basin are reported in Fig. 1.

4.2. Crystallographic texture of the carbonate mylonites

4.2.1. Principle and method

Samples showing a clear foliation and/or lineation have been used for Crystallographic Preferred Orientation (CPO) measurements. Calcite CPO was measured on polished thin sections using the Electron Back Scattering Diffraction (EBSD) technique. Measurements were performed in automatic mapping mode on a grid basis of 2–40 μm in either a Camscan CrystalProbe X500FE or a JEOL JSM-5600 scanning electron microscope at Geosciences Montpellier (Université de Montpellier). In both cases, the sample is tilted at an angle of 70°, relative to the electron beam producing Kikuchi bands on a phosphorus screen. Diffraction images recorded by high-speed camera are amplified and processed using the Channel 5 software (Oxford Instruments). Each measurement allows determining the nature of the mineral and the orientation of the crystal lattice. Postprocessing of measurements includes data filtering and averaging measurement for each crystal under the Channel 5 software. Pole figures (PF) were computed using the MTEX software (Bachmann et al., 2010; Hielscher and Schaeben, 2008; Mainprice et al., 2011).

4.2.2. *Sample description*

Eight samples of massive carbonates have been selected for the CPO analysis: LH01, LH03, LHZ 50, LHZ63, LHZ75, LHZ76, LHZ83, and LHZ91 (Fig. 1). Peak temperatures of metamorphism by Raman spectroscopy of carbonaceous material (RSCM) were determined on all samples (Clerc et al., 2015) and are reported in Figs. 1 and 5. From macro- and microscopic observations, samples LH01 and LHZ76, have a dominantly linear fabric (prolate-like, L-type, Fig. 5), and the remaining samples have a dominantly planar fabric (oblate-like, S-type, Fig. 5).

4.2.3. *Results*

All studied samples display a weak but well-organized CPO that supports a deformation mechanism involving dislocation creep. Two main different patterns have been obtained. Samples LH01, LH03, LHZ83, LHZ63, LHZ75, and LHZ76 show CPO with a maximum concentration of *c* axes close to the foliation pole and a maximum concentration of *a* axes paralleling the lineation. This fabric is considered as resulting from intracrystalline deformation by dislocation creep on the basal ***c*** planes of calcite. Samples LHZ 51 and LHZ91 yield a different fabric with a maximum of concentration of ***c*** axes close to the lineation and a maximum of concentration of *a* axes perpendicular to the lineation. The calcite crystals show elongation paralleling the lineation with a shape ratio of 3:1. Sample LHZ 91 has been split into two parts: the first one contains large recrystallized calcites (20–100 μm), whereas the second one contains fine-grained calcites (3–10 μm). The fine-grained population shows a shear fabric suggesting low-temperature deformation, but the large-grained population is devoid of crystallographic fabric. Comparable observations are reported from the prerift cover of the

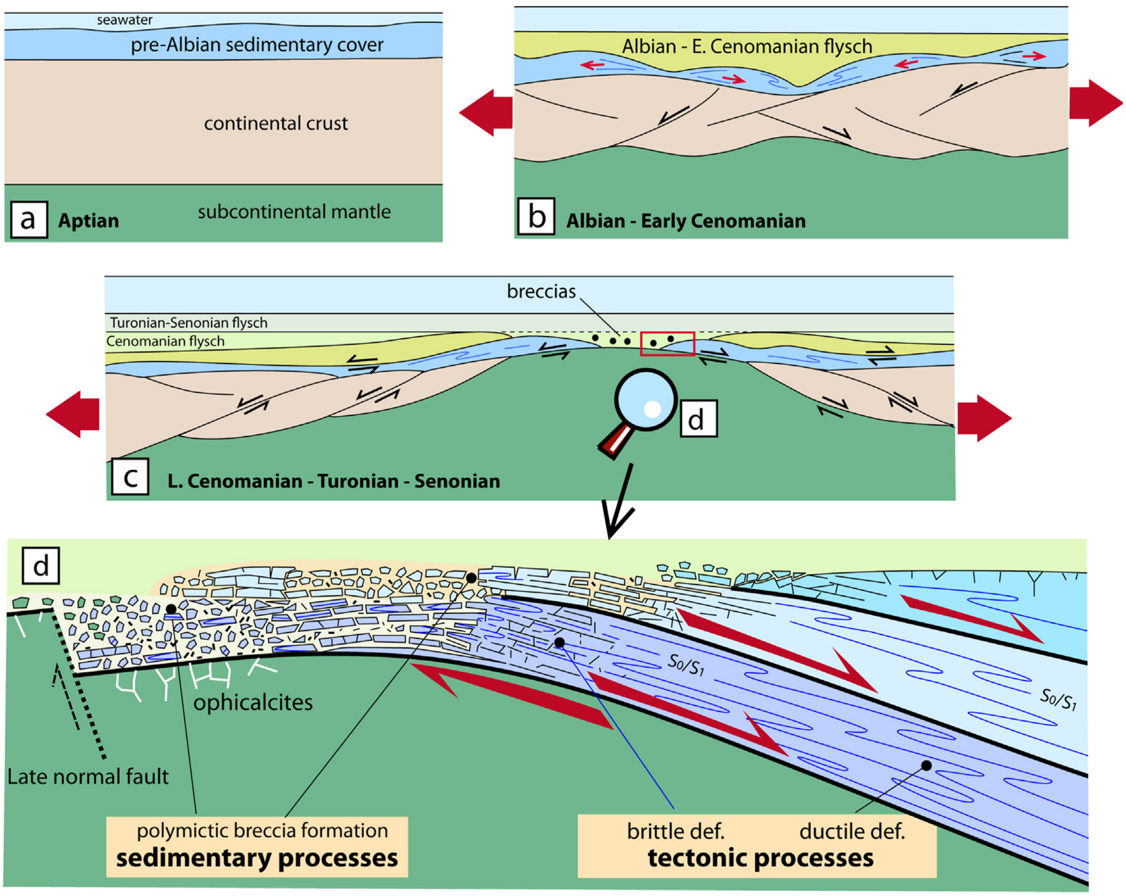

Fig. 6. Model for the ductile–brittle transition affecting the Mesozoic marbles in the frame of major low-angle detachment faults active during mantle exhumation after the lateral extraction of the attenuated continental crust. Cartoons (a) to (c) illustrate the evolution of the Aulus basin during the Cretaceous period of crustal hyperextension. Lateral extraction of the crust requires complete decoupling between the continental basement and the prerift Mesozoic cover. This basin evolution leads to the juxtaposition of metamorphic and ductilely deformed Mesozoic sediments directly on top of the exhumed mantle rocks. The lower cartoon (d) focuses on the transition from the ductile to the brittle behavior of the marbles during their exhumation and to the formation of the sedimentary breccias. The main detachment fault separates the mantle rocks from the marbles and was active during the ductile deformation of the marbles and during the transition from the ductile to the brittle deformation. Forming such types of breccias does not require the disaggregation of steep and high fault walls, since brecciation occurs along a low-angle detachment surface. We have represented a late high-angle normal fault cutting the ultramafic basement. Such faults may account for the local abundance of ultramafic clasts in the polymictic breccias.

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Agly massif, which suffered ductile deformation in a similar setting (Vauchez et al., 2013).

5. Discussion

5.1. High-temperature ductile deformation

Well-defined CPOs are strong evidence of dislocation creep activation. According to experiments on marble (Schmid et al., 1987) and calcite single crystals (De Bresser and Spiers, 1993, 1997), basal slip is likely to be active at relatively high temperatures of deformation. De Bresser and Spiers (1993, 1997) suggest that during experiments this slip system is activated above a temperature of 600 °C. However, since the activation of the different slip systems in calcite is not only coupled with temperature, the observed CPO should be interpreted with caution. Similar CPO was reported in natural mylonites for deformation temperatures of 300–400 °C (Austin et al., 2008; Leiss and Molli, 2003; Oesterling et al., 2007; Trullenque et al., 2006; Vauchez et al., 2013).

Our study provides the following main new results:

- (i) as suggested by macroscopic observation, the carbonate units exposed along the northernmost limit of the Aulus basin underwent mylonitic ductile deformation;
- (ii) this deformation occurred at relatively high temperatures that can be reasonably estimated above 300 °C;
- (iii) comparison with RSCM data (Clerc et al., 2015) confirms the high temperatures reached by the marbles, with the highest value at 564 °C.

Most samples show a relatively planar fabric (oblate-like) with a maximum concentration of c-axes perpendicular to the foliation (Fig. 6). Some samples present a rather fibrous microtexture (prolate-like), with *c*-axes rotated perpendicularly towards the lineation. This is consistent with the macro- and microscopic observations revealing a lineation-dominant aspect in LH01 and LHZ76 samples and a foliation-dominant aspect in the other ones. Such differences can be due to grain size reduction, possibly allowing a change in the deformation mechanism (Vauchez et al., 2013).

The elevated temperatures have to be considered in the frame of the extensional Albian–Cenomanian event, as confirmed by the syn-kinematic character of all the metamorphic assemblages. Therefore, the Aulus basin prerift metasediments share characteristics with the carbonates exposed along the portions of the NPZ in the eastern Pyrenees, showing the highest grades of metamorphism with peak temperatures of 450 °C to more than 550 °C. These regions include the Pays de Sault and Boucheville palaeobasins. There, all the prerift carbonates experienced ductile deformation in the interval between the Mid-Albian and the Coniacian (110–85 Ma), contemporaneous with extreme crustal thinning and mantle exhumation (Clerc et al., 2015; Golberg and Leyreloup, 1990; Vauchez et al., 2013). By contrast, the Mid-Cenomanian, Turonian, and younger metasediments of the NPZ always display metamorphic record (if any) of lower grade with respect to the metasediments they overlie. The Albian–Cenomanian and younger flyschs probably acted as a blanket on the basins, allowing temperature to increase below them.

5.2. From marbles mylonites to cataclastic breccias, then to sedimentary breccias

We have described a frequent progressive transition from massive marble mylonites towards monomictic breccias composed of slightly displaced mylonitic marble clasts, passing in turn into polymictic sedimentary carbonate breccias containing locally ultramafic clasts (Clerc et al., 2013; Lagabrielle and Bodinier, 2008). This reveals a progressive decrease in temperature during deformation of the prerift carbonates that ends with the sedimentary processes. If the mylonitic deformation clearly occurred at depth under high-temperature conditions, the in situ tectonic fracturing results from brittle processes, possibly assisted by fluid circulations, which are typical of shallower crustal levels. Such evolution implies the progressive exhumation of the carbonates from the base of a pile of rocks corresponding to the syn-rift sediments, including the post-Albian flysches. Infilling of fractures opened within the carbonate units with polymictic carbonate breccias and suggests that the marbles were largely exposed on the floor and on the flanks of an actively opening basin, in positions allowing both the production and the reception of carbonate debris. The local abundance of ultramafic clasts mixed with the carbonate clasts indicates that the subcontinental mantle was also exposed on the floor of the basin, thus confirming the complete removal of the continental crust. Owing to the age of the HT metamorphism event, the age of the breccias cannot be older than the Cenomanian–Turonian. In addition, the absence of post-Albian material reworked in the breccias suggests that they were emplaced during the same time interval, thus implying a rapid exhumation process.

Fig. 6 is a tentative representation of the conceptual evolution proposed here. Three main stages have been synthesized. Initiation of crustal extension causes the ductile deformation and boudinage of both the crustal basement and the prerift sediments below an Albian–Early Cenomanian flysch cover (stage b). This stage is followed during the Cenomanian by (i) the lateral extraction of the crust and (ii) the exhumation of the metamorphic cover from below the flysch pile and its brecciation on the ultramafic seafloor. The ongoing sedimentation of the Upper Cretaceous flysches during the Turonian–Santonian allowed in turn the burial of the breccias and their metamorphic evolution (stage c). It is noteworthy that the metamorphic evolution of the pre- and syn-rift cover was continuous during the whole interval away from the exhumation area, implying diachronism of the age of the peak of metamorphism across the basin.

5.3. A contribution to models of mantle exhumation

In this article, we reconstituted the transition from ductile to brittle behavior of the prerift sedimentary cover during the progressive exhumation of the mantle rocks in the Aulus basin during the Albian–early Late Cretaceous interval. As shown in the sketch of Fig. 6, we infer that the exhumation of the massive carbonate units occurred along low-angle detachment faults. These detachment faults include: (i) the underlying detachment that exhumed the mantle, and (ii) one or several overlying detachments that extracted the carbonates from below their cover. Tectonic brecciation is regarded as a major process able to have developed into large portions of the carbonates forming the hanging-wall of the detachment, as they crossed the ductile–brittle transition during exhumation. Due to continuous exhumation along the faults, the tectonic breccias were passively uplifted towards shallower levels, and progressively unroofed while transported passively on the back of the exhumed footwall. As a result, the carbonates that reached the floor of the basin were composed of highly fragmented tectonic breccia. As it was exposed on the basin floor, this fragmented material lost its cohesion and was submitted to gravity forces that triggered sedimentary processes including rockfall, debris flow and subsequent mélanges from various sources.

As outlined by Lagabrielle and Bodinier (2008) and Clerc et al. (2012), the considerable volume of carbonate-ultramafic breccias of the Aulus basin is almost completely devoid of Palaeozoic basement material. This implies that the continental crust has been removed from the edges of the basin, leading to an ultramafic seafloor surrounded by reliefs composed of dominant metasedimentary rocks. Lateral extraction of the crust requires complete decoupling between the continental basement and the prerift Mesozoic cover, as discussed in Lagabrielle et al. (2010) and Clerc and Lagabrielle (2014). Our new data help in completing models of extreme continental thinning. We demonstrate that the Pyrenean margins were affected by a very high thermal gradient during mantle exhumation. Following Clerc and Lagabrielle (2014), we emphasize the peculiarities of the stretching modes of the Pyrenean palaeomargins with respect to various types of Atlantic passive margins. Cold margins, such as the Galicia–Newfounland conjugate margins, do not exhibit marks of high thermicity related to crustal thinning and to mantle exhumation. By contrast, the hot Pyrenean palaeomargin includes a distal region of thinned crust and exhumed mantle bearing ductilely stretched prerift metasediments.

6. Conclusions

In this study, we have determined the thermal conditions that allowed the ductile deformation of the prerift metasediments of one of the most famous basins of the NPZ. CPO measurements in mylonitic texture revealed clear lattice preferred orientations supporting that deformations occurred under temperatures higher than 300 °C, in agreement with the syn-deformational habitus of some scapolite crystals. These results are consistent with the RSCM thermometer indicating high peak temperatures of metamorphism ranging from 400 °C to approximately 600 °C in the same samples (Clerc et al., 2015) as well as with *T* estimates based on mineralogical metamorphic assemblages (Golberg and Leyreloup, 1990). The compilation of all $^{40}Ar/^{39}Ar$ ages obtained so far in the NPZ demonstrate that the HT–BP metamorphic event occurred in the 110–85 Ma interval (Clerc et al., 2015), that is during the opening and the deepening of the NPZ basin, before the onset of the Pyrenean orogeny. Thus, as stressed by previous studies, the peak of the HT metamorphism is linked to the extreme thinning of the continental crust and to the exhumation of the subcontinental mantle.

In addition, we have shown that the metamorphic carbonate units show evidence of a progressive cooling during their exhumation to the basin floor. We describe an original model accounting for the continuum of ductile to brittle deformation followed by intense disaggregation to form the carbonate breccias.

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