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ABSTRACT

The Chaînons Béarnais ranges (North-Pyrenean Zone, west-central Pyrenees) display a fold-and-thrust structure involving the Mesozoic sedimentary cover, decoupled from its substratum at the Keuper evaporites level and associated with a few peridotite bodies and scarce Palaeozoic basement lenses. In the western part of the Chaînons Béarnais, the newly described recumbent fold of the Saraillé massif comprises a peridotite body and several lenses of Palaeozoic basement wrapped by the Triassic to Aptian sedimentary cover. This structure represents a remnant of the distal portion of the Pyrenean paleo-rifted margin where mantle rocks have been exhumed during Albian–Cenomanian times. In this paper, we present the first detailed mapping and microstructural analysis of the Saraillé massif, providing new geological basis for reconstructing the evolution of this part of the paleo-margin. Our mapping (i) shows that the pre-rift Mesozoic cover forms a recumbent fold cored by mantle and crustal rocks and (ii) confirms that the prerift cover was detached from its bedrock along a layer of Triassic evaporites and slid onto the exhumed mantle rocks. Sliding of the prerift cover was associated with extreme crustal thinning and mantle exhumation along a major detachment fault, together with intense metasomatism affecting both the continental basement and the sedimentary cover. We show for the first time (1) that the Mesozoic pre-rift sediments experienced syn-metamorphic ductile thinning during mantle exhumation, and (2) that during its extreme attenuation, the continental basement was reduced to tectonic lenses some ten meters thick by ductile shearing.

1. Introduction

Subcontinental mantle rocks are exhumed at the foot of some present-day non volcanic distal passive margins due to extreme thinning of the continental crust. In the deep ocean, the rocks recording the processes of mantle exhumation are of very limited access. Therefore, the study of inverted passive margins exposed in mountain belts is of high interest (Clerc and Lagabrielle, 2014; Mohn et al., 2015; Péron-Pinvidic and Manatschal, 2009; Tugend et al., 2014). Such analogues allow direct sampling of a great variety of rocks in the environment where mantle rocks are exhumed.

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The Pyrenees are an east-west-trending belt resulting from the tectonic inversion of a thinned continental domain opened between the Iberian and European plates during mid-Cretaceous times (Choukroune, 1992). They comprise three main domains, the North-Pyrenean Zone (NPZ), the Axial Zone (AZ) and the South-Pyrenean Zone (SPZ) (Fig. 1a). The NPZ is comprised of a folded Mesozoic sedimentary cover, locally metamorphosed. The eastern and central parts of the NPZ are characterized by the occurrence of massifs of Palaeozoic rocks, the so-called the North-Pyrenean Massifs. The AZ is mostly made of Variscan meta-sediments and granitoids. The SPZ is made of the folded Mesozoic and Cenozoic sedimentary cover detached on the Triassic evaporites. The Cretaceous extension in the Pyrenean realm resulted from the rotational plate motion of Iberia versus Europe, in relation with the opening of the North Atlantic and the Bay of Biscay oceanic domains (e.g., Choukroune and Mattauer, 1978; Gong et al., 2008; Olivet, 1996; Sibuet et al., 2004). So far, several kinematic models have been proposed to describe the Iberia rotation. These models provide different constraints for the age, amount and direction of crustal extension and for the width of the thinned domain (Jammes et al., 2009, 2010; Mouthereau et al., 2014, Teixell et al., 2016; Tugend et al., 2014). However, a general consensus exists on the fact that mantle rocks have been exhumed on the floor of Albian–Cenomanian basins as the result of extreme continental thinning. These basins were inverted by the Pyrenean orogeny from the Late Santonian to Early Miocene times to form the future NPZ (e.g., Mouthereau et al., 2014; Muñoz, 1992; Roure et al., 1989; Vergés et al., 2002; Teixell et al., 2016). As a consequence, the Pyrenean belt is now considered as a relevant analogue of preorogenic passive margins (Clerc et al., 2012, 2013; Jammes et al., 2009, 2010; Lagabrielle and Bodinier, 2008; Lagabrielle et al., 2010; Teixell et al., 2016).

The Iberian and European distal margins are characterised by a regime of hyperextension implying the exhumation of the subcontinental mantle, the tectonic lenticulation of the continental crust and the detachment of the sedimentary Mesozoic cover (Jammes et al., 2010; Lagabrielle et al., 2010). Recently, Clerc and Lagabrielle (2014) have proposed that owing to the high thermal gradient accompanying mantle exhumation, the crustal and sedimentary cover rocks of the distal part of the hyperextended margins behaved in a ductile manner. Therefore, an important issue is to better investigate the significance of the relationships between mantle rocks, continental basement rocks and Mesozoic metasediments that are exposed together in the NPZ. In this paper, we present a new detailed geological study of the Saraillé Massif (Chaînons Béarnais ranges, west-central NPZ; Fig. 1), a key area where mantle rocks, continental basement rocks and pre- and syn-rift sediments are exposed over a restricted area. Despite its importance in unravelling fundamental processes (Lagabrielle et al., 2010), the geology of the Saraillé massif has been little investigated; in particular, a detailed geological map at 1/25,000 scale was lacking. Here, we provide this detailed mapping and we discuss its implications for the processes related to mantle exhumation accompanying extreme continental thinning in the Pyrenean domain.

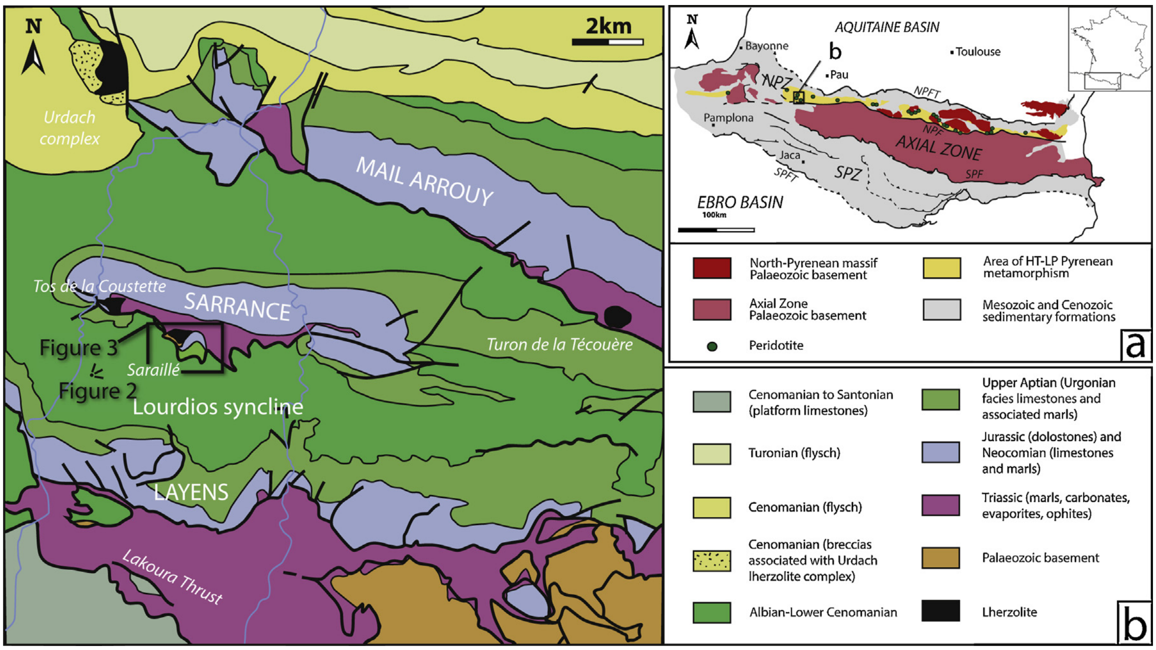

Fig. 1. a. Structural map of the Pyrenees. NPFT: North-Pyrenean Frontal Thrust, NPF: North-Pyrenean Fault, SPF: South-Pyrenean Fault, SPFT: South Pyrenean Frontal Thrust (after Vauchez et al., 2013). b. Structural map of the Chaînons Béarnais region, with location of the panoramic view of Fig. 2 and of map in Fig. 3 (rectangle) (after Castéras, 1970 and Lagabrielle et al., 2010).

2. Geological setting and previous results

2.1. The North-Pyrenean Zone (ZNP)

The NPZ shows three major geological features.

(1) The metamorphic Mesozoic sediments are intimately associated with fragments of subcontinental mantle rocks and with very thin tectonic lenses of continental basement rocks.
(2) The Mesozoic sediments were metamorphosed at low pressure and high- to very high-temperature conditions during the Albo-Cenomanian extension (Albarède and Michard-Vitrac, 1978; Choukroune and Mattauer, 1978; Golberg and Leyreloup, 1990). In the western Pyrenees, the maximal temperature recorded in the metasediments reaches *ca.* 350 °C and was measured in Albian sediments of the Saraillé massif (Clerc et al., 2015). The Cretaceous metamorphism was thus synchronous with extreme continental thinning and mantle unroofing.
(3) The Cretaceous rifting led to the opening of basins filled with flysch-type sediments. Opening started during the Albian with disconnected basins filled with the so-called Flysch Noir; these basins were later connected into a wider trough during the Cenomanian (Debroas et al., 2010). A significant feature is that, during extension, the Triassic to Aptian shallow water prerift sediments were decoupled from their basement and were set in tectonic contact on top of the mantle rocks. Such a decoupling of the sedimentary cover was caused either by (1) gravity sliding of sediment rafts into the basins, or by (2) traction-assisted sliding during lateral extraction of the ductile crust (Clerc and Lagabrielle, 2014).

2.2. The Chaînons Béarnais

The Chaînons Béarnais correspond to a segment of the west-central ZNP, forming a series of E/W-trending fold-thrust structures in the Mesozoic succession, floored by a south-verging Pyrenean décollement in the Triassic evaporites (Teixell et al., 2016). In their western part, the Chaînons Béarnais comprise from north to south: the south-verging Mail Arrouy thrust and the Sarrance anticline and the north-verging Layens anticline (Castéras, 1970) (Fig. 1b). The base of the Mesozoic sequence is represented by the Triassic Keuper facies with shales, evaporites, breccias and ophites, followed by Jurassic to Aptian platform limestones and dolomites, and Upper Jurassic Aptian limestones, with shale intercalations in the Upper Liassic and Lower Aptian. These sediments represent the original prerift cover of the northern Iberian margin (Canérot and Delavaux, 1986; Canérot et al., 1978), now entirely detached from its original Palaeozoic basement (Lagabrielle et al., 2010; Teixell et al., 2016). The syn-rift Albian–Lower Cenomanian Flysch Noir is preserved within the synclines. This sedimentary succession is intimately associated with peridotite (lherzolite) bodies and scarce Palaeozoic basement exposures, most of them located at the base of the Mesozoic sequence (Fig. 1b). The mantle rocks were incorporated during the Cenozoic in the tectonic wedge as the result of the closure of the unroofed mantle domain. As a whole, the Chaînons Béarnais wedge represents the suture between the Iberian and the European plates (Lagabrielle et al., 2010; Masini et al., 2014, Teixell et al., 2016).

Four main lherzolite bodies are exposed in the western Chaînons Béarnais (Fig. 1b): (1) the Saraillé and (2) the Tos de la Coustette bodies in the core of the Sarrance anticline, (3) the Turon de la Técouère body at the base of the Mail Arrouy thrust unit, and (4) the Urdach body at the western end of the Mail Arrouy. In this paper, we report the results of detailed investigations on the Saraillé massif where the most complete collection of lithologies is exposed.

2.3. The Saraillé massif

The Sarrance anticline displays a folded Mesozoic cover and two peridotite bodies associated with tectonic lenses of Palaeozoic rocks, outcropping respectively in the Tos de la Coustette and the Saraillé massif (Castéras, 1970) (Fig. 1b). In the Saraillé massif, the comprehensive association of mantle rocks, Palaeozoic basement rocks and Triassic to Albian metasediments forms a unit, 1 km × 1 km wide, thrust southwards over the Albian Flysch Noir. This unit corresponds to folded Mesozoic metasediments wrapping both mantle and crustal rocks (Fig. 2).

The 1/50 000 scale geological map of Oloron-Sainte-Marie (Castéras, 1970) provides a brief description of the peridotite bodies of the Sarrance anticline with a short interpretation of their geological setting. Following this first description, the peridotite bodies have been the subject of different interpretations:

(1) they have been first regarded as the result of an early exhumation during the Mid-Jurassic times, followed by the deposition of unconformable Mesozoic sediments over a seafloor comprising ultramafic and Palaeozoic crustal rocks (Duée et al., 1984; Fortané et al., 1986);
(2) peridotite uplift along Mesozoic faults and their incorporation with a slice of Palaeozoic rocks into the sedimentary cover during the Cenozoic tectonic inversion of the NPZ has been proposed by Canérot and Delavaux (1986);
(3) the contact between the mantle rocks and the Mesozoic sediments has been attributed to detachment faulting during the Albo-Cenomanian extensional phase, with the Palaeozoic lens corresponding to a remnant of the hyper-extended crust (Lagabrielle et al., 2010).

The peridotites of the Saraillé massif form a 500 m-long and 100 m-thick lens-shaped body overlying 10–20 m-thick tectonic lenses of various continental rocks. Both the mantle body and the continental lenses are in tectonic contact with the Mesozoic sediments. At the top of the lherzolite body, the contact with Jurassic dolostones is outlined by a lenticular, strongly sheared, talc-rich layer up to 15 m thick (Lagabrielle et al., 2010). As discussed below, this layer is thought to be the record of intense fluid

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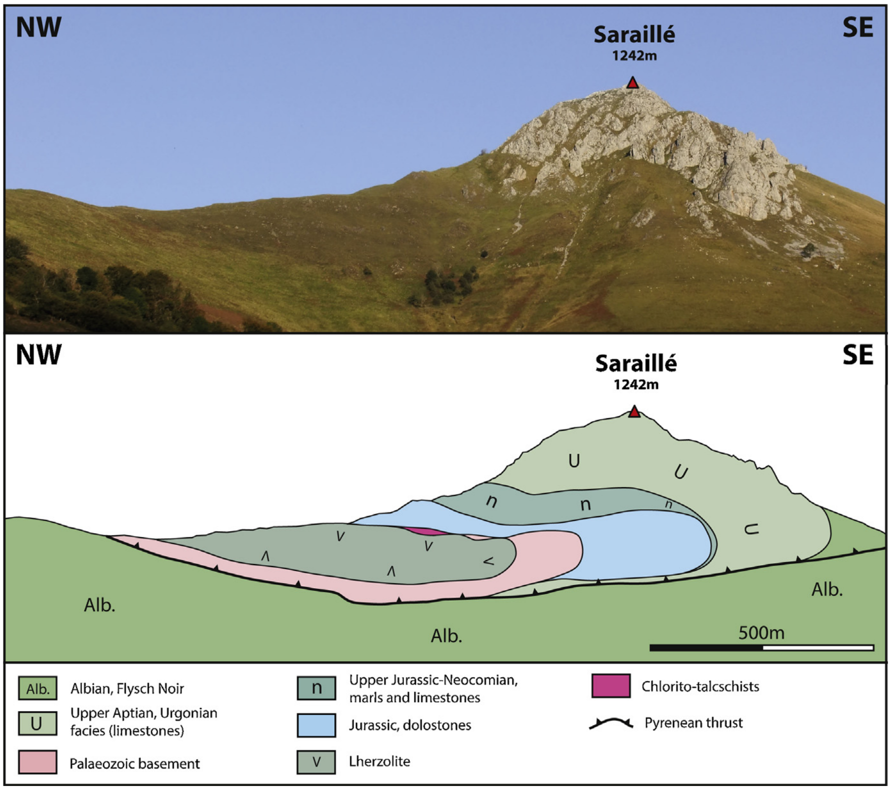

Fig. 2. Interpreted panorama of the Saraillé massif seen from the Lourdios syncline (see Fig. 1).

circulations coeval with mantle exhumation. The Saraillé mantle rocks are made of two types of peridotites: spinel-lherzolites and pyroxenites, mostly websterite. Pyroxenites are represented by numerous centimetre-thick parallel layers within the lherzolite body. These layers are part of an early mantle history of the lherzolite (Gaudichet, 1974) and are associated with refertilisation processes identified in other mantle bodies of the NPZ (Le Roux et al., 2007). Refertilisation by secondary melts, first described in the Lherz mantle body (central NPZ), involves addition of Cpx and dissolution of Ol at the expense of a primary harzburgite. Such a phenomenon is thought to have occurred during the ascent of the mantle in extensional context in lithospheric conditions (Kaczmarek and Müntener, 2010; Le Roux et al., 2007; Müntener and Piccardo, 2003). The Saraillé lherzolites are highly serpentinized with chrysotile and lizardite as dominant (95%) phases (Ferreira, 2013). The temperature of the fluids responsible for the mantle hydration is estimated at *ca.* 175 °C (Ferreira, 2013). In addition, the serpentinites are crosscut by late antigorite veins, resulting from the circulation of metamorphic fluids (Ferreira, 2013).

2.4. Metamorphic evolution of the Saraillé massif

Gaudichet (1974) revealed the presence of a metamorphic mineral association of newly-formed muscovite, chlorite and albite, observed in the whole Mesozoic cover of the Sarrance anticline, including the Albian Flysch Noir. In addition, this author showed that the Albian flysch is characterized by the development of at least two cleavages. The earliest one (S1), parallel to bedding (S0), is underlined by the alignment of syn-kinematic muscovite and chlorite flakes. The metamorphic imprint is homogeneous across the Sarrance anticline and there is no increase of the metamorphic conditions towards the Saraillé lherzolite body. In their first detailed mapping of the Saraillé massif, Fortané et al. (1986) described the foliated talc-rich layer located between the lherzolites and the Mesozoic sediments. They evidenced the presence of talc, clinochlore and pyrite, an association representative of greenschist facies conditions (250–350 °C). Similar temperatures have been obtained recently by Raman spectrometry analysis of organic matter in the Aptian limestones and Albian flysch, the highest temperature being found close to the Saraillé lherzolite (Clerc et al., 2015).

3. Lithology and structure of the Saraillé massif: new results

3.1. General structure

As shown on the panorama in Fig. 2 and on the map and cross-sections in Fig. 3, our field investigations reveal that the structure of the Saraillé massif corresponds to a recumbent fold of Mesozoic sedimentary cover wrapping the main lens-shaped unit of mantle rocks and associated

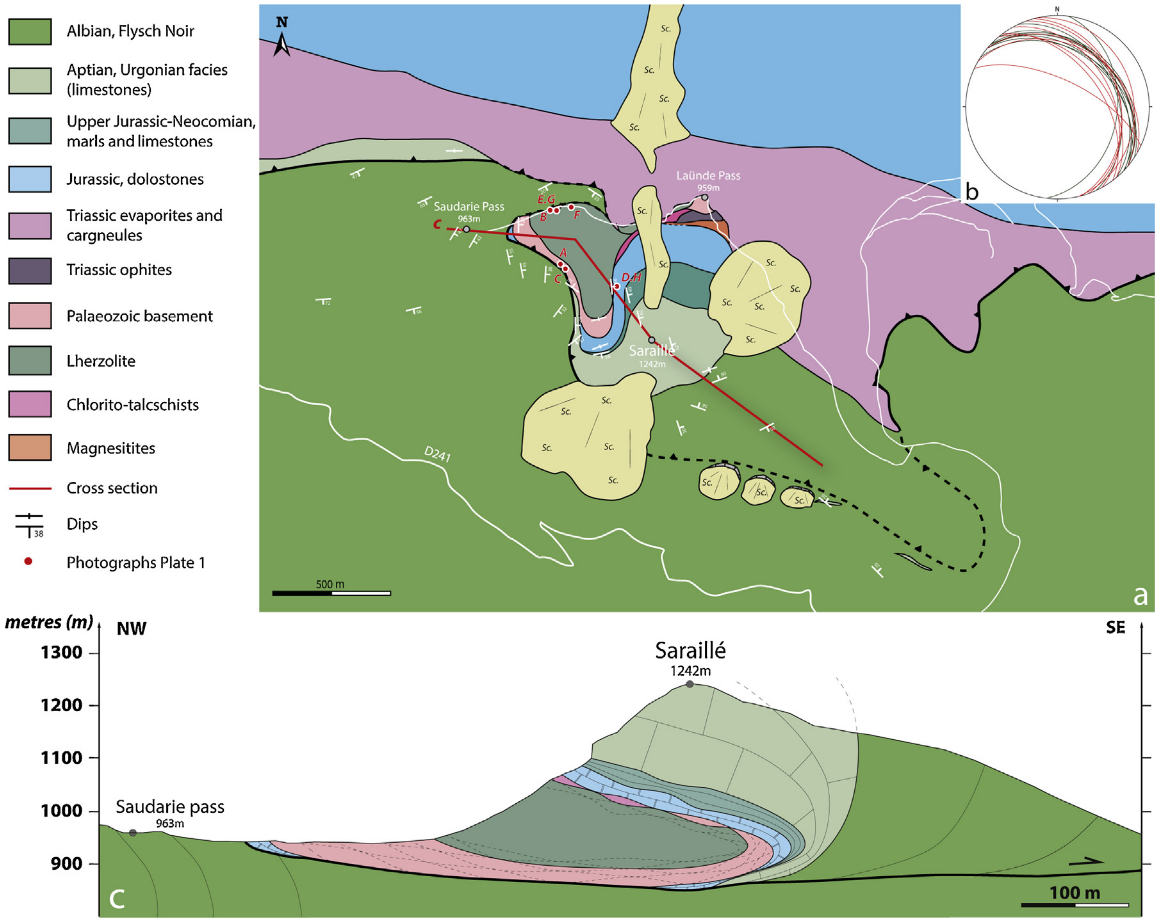

Fig. 3. a. Detailed geological map of the Saraillé massif. b. Stereogram (southern hemisphere) showing the attitude of the pyroxenitic layering in the lherzolites (green lines) and the foliation of the Palaeozoic basement (red lines) along the western boundary of the mantle body. c. NW–SE cross-section along the Saraillé massif. See Fig. 1 for location. Letters: location of photographs shown in Plate 1.

slices of Palaeozoic basement rocks. These Palaeozoic lenses also follow the fold geometry, but are absent at the upper contact of the peridotite body, which is there directly against the sedimentary cover. The geometry of the folded Mesozoic cover exhibits a very strong asymmetry between the normal and the reverse limbs, with stretching of the reverse limb shown by the considerable thickness reduction of the carbonate sequence. Other small lenses of crustal and mantle rocks occur in the northern part of the massif (Laünde Pass; Fig. 3). The mantle rocks, the continental basement rocks and the sedimentary cover are all separated from each other by tectonic contacts.

On its northeastern side, the Saraillé massif rests above brecciated Triassic sediments forming the core of the Sarrance anticline. Both the Saraillé massif and the Triassic sediments are thrust southwards above the Albian Flysch Noir of the Lourdios syncline by a subhorizontal contact (Castéras, 1970; Lagabrielle et al., 2010).

3.2. Basement rocks

Our mapping reveals that various lithologies from the continental crust form thin, elongated tectonic lenses exposed beneath and south of the main mantle body on the western flank of the massif and, to the north, in a poorly exposed area at the Laünde pass (Fig. 3a). The western lenses display a well-developed tectonic foliation (Plate 1A) paralleling the contact with the peridotites (Fig. 3b). We collected twenty-six samples from these crustal lenses for microscope study. Seventeen samples are quartz-rich mylonites or chlorite- and mica-rich mylonites, deriving from Palaeozoic metasediments (Plate 1, B and C). Locally, the mylonitic foliation is crosscut and offset by decametric brittle faults and by cataclastic shear bands. Weakly deformed metasediments are rare: only one sample of quartzite and one sample of folded marble were collected. The remaining nine samples are undeformed quartz-albitites and one sample of granite.

Numerous millimetre-to-centimetre-thick albitite veinlets and veins cross-cut the foliation in mylonites close to the contact with mantle rocks (Plate 1C). In the eastern Pyrenees, albitites are known as a product of fluid/rock interactions during a syn-extension metasomatic event lasting *ca.*15 Ma between 100 and 98 Ma (Boulvais et al., 2007; Fallourd et al., 2014; Poujol et al., 2010).

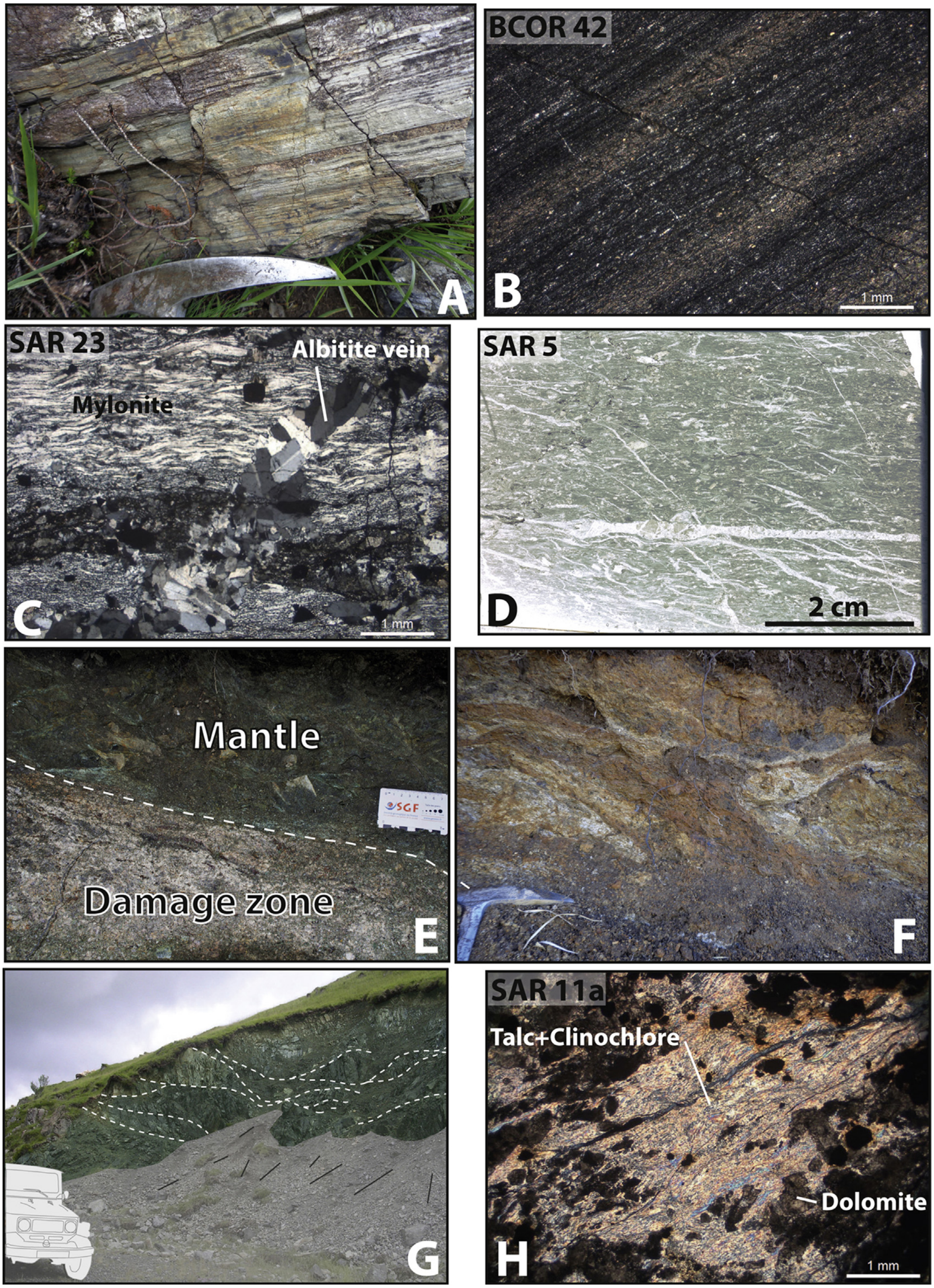

Plate 1. Outcrop pictures of the Saraillé massif and selected thin sections of rocks from the crustal basement, the mantle rocks and the Mesozoic meta-sediments (see Fig. 3 for locations): A. Mylonitic Palaeozoic basement. B. Ultramylonite in Palaeozoic metapelite. C. Mylonitic Palaeozoic felsic rock crosscut by undeformed albitite veinlets. D. Jurassic dolomite showing flattening of various biogenic debris and different populations of carbonate veinlets parallel to or cutting the foliation. E. Detailed view of the basal contact of the peridotite body, showing the cataclastic core zone in its lower part. F. Detail view of the core zone, featuring a cataclastic phacoidal fabric in mixed peridotite and sialic rock fragments. G. Damaged zone of the contact featuring fracture surfaces defining a m-scale phacoidal fabric at the rim of the mantle body, a few metres above the contact. H. Foliated talc-rich zone in Jurassic dolomite in contact with the chlorito-talcschist layer.

3.3. Sedimentary cover

The upper part of the Saraillé massif consists of a Mesozoic sequence including Triassic to Albian metasediments (Fig. 3). The Triassic is poorly exposed north of the massif and seems to be tectonically dismembered. It includes motley calcschists, cellular dolomite, brecciated limestones as well as dolostones and ophites. Ophite is a tholeiitic mafic igneous rock of dolerite type, characteristic of Triassic magmatic events (Castéras, 1970). Above the main peridotite body, the metasedimentary cover is base-missing and begins by a layer of Jurassic dolomite up to one hundred meters thick. This dolomite layer can correspond to the Callovian–Oxfordian, but with a lighter grey colour and a finer grain size than its regional facies. The Kimmeridgian–Neocomian corresponds to an up to 40 m-thick alternation of decimetre-thick beds of dolomite, limestones and phyllite-rich limestone. The thickness of the latter is much lower than the regional thickness (250 m in the northern limb of the Sarrance anticline). The Upper Aptian is represented by Urgonian facies platform limestones largely exposed on the top and southern flank of the Saraillé massif (Fig. 2). The Albian Flysch Noir follows the Urgonian limestones on the south-eastern flank of the massif and lies below the sole thrust of the massif. It comprises an alternation of black marls, silts and limestones.

The Jurassic to Aptian carbonates are strongly recrystallized, as well as the Albian limestones on a local scale. In the entire Mesozoic sequence, a S1 foliation always parallels the stratigraphic bedding (S0). The foliation, of variable intensity, is defined by the flattening of paleontological and sedimentological objects such as macrofossils, microfossils and biogenic clasts, perpendicular to the S0 plane. At the thin-section scale, flattening is not only observed in discrete deformed bands paralleling S0, but it can also affect the entire rock as observed in the carbonates sampled close to the basal contact with the mantle rocks (e.g., SAR 5 Plate 1D). The longest calcite veins observed in the carbonates parallel S0 and therefore also underline the foliation. A striking feature is that these veins are boudinaged, indicating extension in the S0/S1 plane consistent with the overall deformation pattern. Younger small veins cut obliquely to the S0/S1 planes. The Albian limestone beds in the footwall of the thrust also feature prefolding strong boudinage with thick interboudin quartz and calcite veins. As a whole, this deformation pattern suggests an early flattening of the sedimentary pile that occurred during the Albo-Cenomanian extensional phase.

3.4. Nature of the contacts

3.4.1. Contact between mantle rocks and continental basement

The Saraillé massif displays a spectacular tectonic contact between mantle rocks and Palaeozoic basement rocks (Canérot and Debroas, 1988; Canérot and Delavaux, 1986; Duée et al., 1984; Fortané et al., 1986; Lagabrielle et al., 2010). On the northern side of the massif, serpentinites outcropping along the road to the Col de Saudarie overly gneissic granitoids and acidic mylonites lenses. The geometry as a "reversed Moho" results from the folding of an original assemblage where the mantle rocks occurred at the base. The contact is a sharp surface (Plate 1E), but it is included into a deformation zone several tens of metres in thickness. Below the main contact, the metre-thick core zone of the fault is a breccia made of a mixing of ultramafic and sialic grains and featuring decimetre-scale phacoids (Plate 1, E and F). Thin sections in the mantle rocks close to the main contact (Fig. 1E, upper part) show millimetre-scale phacoids composed of cataclastic grains from the mantle rocks (serpentinized olivine, pyroxenes and spinel) cemented by intergrowth of phyllitic material, mostly talc and green to pale chlorite associated with numerous pyrite grains. These newly formed minerals result from fluid circulation in greenschist facies conditions and outline the pervasive foliation. Above the contact, the serpentinites feature a ten-meter thick damage zone with discrete fracture surfaces coated by fibrous serpentinite and forming phacoids at the meter scale (Plate 1G). Hence, the deformation zone is characterized by a phacoidal fabric at various scales and dominant cataclastic deformation mechanisms. The planar fabric of the phacoids is parallel to the main contact and their shape is symmetrical, suggesting deformation in a pure shear rather than in a simple shear regime. Owing to the thickness of the deformation zone, to the development of a metamorphic paragenesis in the foliation planes and to the fact that the NPZ has recorded a HT–BP metamorphism during Albo-Cenomanian times, this deformation can be regarded as a consequence of the exhumation of the mantle rocks during the prealpine stages and not as the simple result of the Pyrenean thrust. A detailed microtectonic and mineralogical analysis of this contact is in progress.

3.4.2. Contact between mantle rocks and prerift metasediments

The contact between the mantle rocks and the prerift metasediments is also a tectonic contact (Lagabrielle et al., 2010). This interface is outlined by a discontinuous layer of reactional rocks that can be followed from the southern to the northern side of the massif at the basis of the Jurassic dolomites (Fig. 3). On the northern side, a tectonic lens of layered brown Mg-rich carbonates overlies a strongly tectonized assemblage of Triassic metabreccias, cataclastic and massive ophites and talc-rich yellow schists, the latter probably deriving from the extreme shearing of mantle rocks. On the southern side, the largest mineralized lens is a 100 m-long-per-10 m-thick body of strongly schistose pink talc-rich rock showing a strong phacoidal fabric similar to the fabric observed along the basal contact of the mantle body. This rock is composed of an association of talc, clinochlore and pyrite showing a pervasive foliation, with rare relicts of cataclastic pyroxenes. Dolomite grains are frequent between the phyllitic minerals (Plate 1, H). Microprobe analyses of chlinochlore from this chlorito-talcschist are available in Fortané et al. (1986). Talc is known to form in greenschist facies conditions by alteration of ultramafic rocks (Abzalov, 1998) and/or dolomites (Blount and Vassiliou, 1980) favoured by an intense contribution of Si-rich fluids. The foliation of the chlorito-talcschist is parallel to the contact between the mantle body and the platform carbonates and bears a north–south lineation. Moreover, as discussed above, the carbonates lack their stratigraphic base and show a pervasive bedding-parallel foliation subparallel to the contact (Plate 1D). As a whole, these features argue that the mantle/sediments contact was a syn-metamorphic extensional shear zone, where extensive fluid circulation and metasomatism at rather high temperature (up to 350 °C) led to the precipitation of newly-formed chlorite-talcschist (Plate 1 H). The upward decrease of dolomitization in the metasedimentary cover (cf. above) may also point to metasomatism related to fluid circulation in the contact. Such a phenomenon has been reported from the metasomatic system of Trimouns/La Porteille (Boulvais et al., 2006), where a thick talc/chlorite rich layer occurs between Palaeozoic micaschists and dolomites.

4. Discussion

4.1. Evolutionary model of the Saraillé Massif

During the Albo-Cenomanian, the NPZ domain underwent extension that led to the formation of passive margins as the result of extreme crustal thinning and unroofing of the subcontinental mantle (Jammes et al., 2009; Lagabrielle et al., 2010; Tugend et al., 2014; Masini et al., 2014, Teixell et al., 2016). The Saraillé massif is unique as it records most of the successive stages of the tectonic processes leading to crustal hyperthinning. Based on field observations and microscopic analyses, our study allows us to reconstruct an evolutionary model for these processes.

Firstly, as revealed by the nature of the contact between mantle rocks and the sialic basement, crustal thinning has been accompanied by the activation of a major ductile detachment fault (Fig. 4). Motion along the detachment led to the individualization of tectonic lenses at all scales, limited by mylonitic shear bands and defining a phacoidal fabric. The important lithological variety of the crustal rocks of the Saraillé massif can be explained by the fact that tectonic lenticulation and extreme thinning of the crust predated mantle denudation. In other words, the crustal rocks have been sampled and left along the detachment during the extensional phase to form a succession of discontinuous lenses above the denudated mantle (Fig. 4). Ultimately, the detachment evolved toward cataclastic deformation due to exhumation processes in the latest stages of rifting (Fig. 1b).

Crustal thinning was synchronous with the sliding of the sedimentary cover towards the distal parts of the margins, the Triassic evaporites playing the role of an efficient detachment layer (Jammes et al., 2010) (Fig. 4). In contrast to the nearby Urdach massif, the Saraillé peridotites never formed the seafloor of the extensional Cretaceous basin; they were only unroofed beneath extremely thinned basement rocks during the Albo-Cenomanian (Lagabrielle et al., 2010). Decoupling of the sedimentary cover from its crustal basement occurred while the continental crust underwent lateral extraction between two convergent detachment faults located respectively at the mantle–basement interface and at the basement–cover interface (Clerc and Lagabrielle, 2014). The prerift sediments are in tectonic contact with the mantle rocks only between the tectonic crustal lenses. Extensional ductile deformation of the sedimentary cover along the detachment fault resulted in the development of subtractive contacts associated with a strong bedding-parallel foliation and a drastic thickness reduction of the stratigraphic pile. The detachment between the mantle rocks and the sedimentary cover has been the locus of intense metasomatic circulations responsible for the mineralization of the talc/chlorite-rich layer (Fig. 4). The foliation of this layer indicates synkinematic development during the Albian-Cenomanian rifting episode. The relatively high temperature allowing the ductile deformation of the sedimentary cover and the talc-chlorite development was possible thanks to two geological processes: (1) the ascent of the subcontinental mantle which caused a steep geothermal gradient; and (2) the synchronous sedimentation of the Albian–Cenomanian flysch that probably acted as a blanket on the basin, facilitating the temperature increase (Clerc et al., 2015).

It still remains an important issue to decipher the timing of folding of the Saraillé massif structure. Folding may have occurred during the extensional phase (Albian–Cenomanian) in relation with salt tectonics (James and Canérot, 1999), or during the compressional phase of the Pyrenean orogeny starting in the Late Santonian.

The Saraillé talc/chlorite-rich layer shares some characteristics with metasomatic layers known in the eastern Pyrenees such as one of the largest deposits of talc ore worldwide, in the Saint-Barthélémy North-Pyrenean massif (Trimouns: Fortuné, 1971; Moine et al., 1989). At Trimouns, the hydrothermal activity responsible for the talc formation has been dated between 112 Ma and 97 Ma (Schärer et al., 1999). It was thus contemporaneous with the opening of the Albian–Cenomanian basins. However, this major ore deposit is located in a pure continental environment in contrast with the Saraillé massif. To our knowledge, the Saraillé massif is the only known example worldwide of a preserved detachment system involving subcontinental mantle, thinned continental basement and prerift metasediments.

4.2. The Saraillé massif: in search of analogues. Comparison with recent passive margins

Nowadays, numerous models of passive margin formation do exist (see review in Huismans and Beaumont, 2011). Recently, Clerc and Lagabrielle (2014) distinguished a cold rifted margin model from a hot rifted margin model. In the first one, the proximal part of the margin is characterized by a system of tilted blocks and the distal part exhibits an exhumed mantle domain partly covered by continental allochthons. The prerift sedimentary cover remains welded on the tilted blocks and on the continental allochthons. A typical example of such a system is represented by the Galicia/Iberia margin (Boillot et al., 1995; Péron-Pinvidic and Manatschal, 2009; Reston, 2007). The hot margin model differs from the cold margin one by its distal part where mantle is exhumed between lenses of crust deformed in a ductile manner. In this case, the prerift sedimentary cover is also affected by a syn-metamorphic ductile deformation.

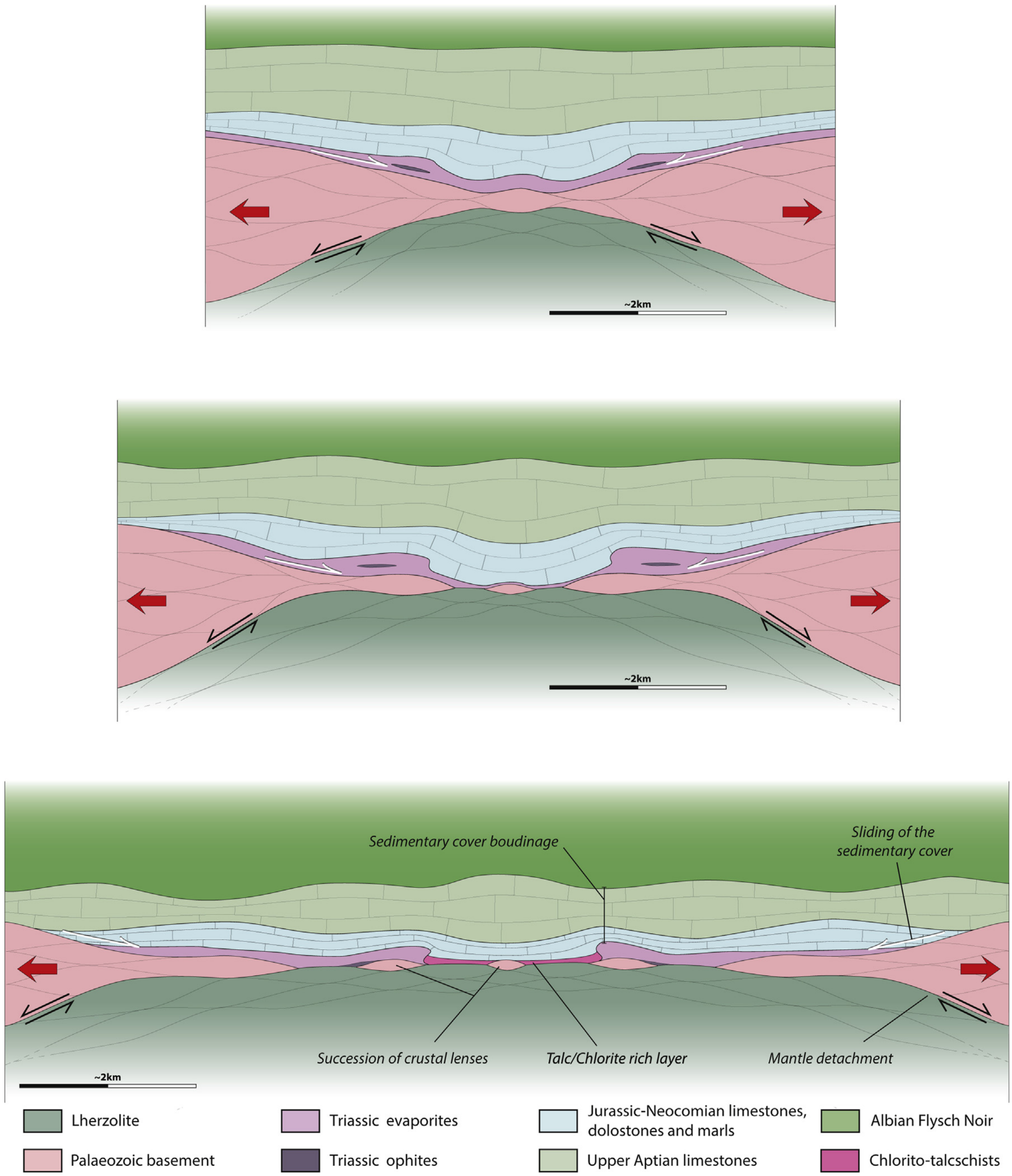

Fig. 4. Conceptual model based on field observations in the Saraillé massif showing the evolution of a distal, hot passive margin with mantle exhumation.

In the Saraillé massif, we observed the following major features consistent with the model of distal, hot passive margins with exhumed mantle rocks proposed by Clerc and Lagabrielle (2014) for the preorogenic Pyrenees: (i) As a consequence of the Albian-Cenomanian rifting episode, the subcontinental mantle is now in direct tectonic contact with the prerift sedimentary sequence. (ii) This prerift sedimentary sequence has experienced syn-extension ductile deformation during the rifting along a major detachment. Features (i) and (ii) are both the result of the lateral extraction of the continental crust, the upper crust showing a ductile behaviour. (iii) The detachment faults separating the mantle rocks from the prerift sediments and from the hyperthinned continental crust were the loci of intense hot fluid circulations producing talc and chlorite mineralizations.

5. Conclusion

The recumbent fold of the Saraillé massif shows several features that can be associated with the development of the Pyrenean paleomargin during Albian-Cenomanian extreme crustal thinning. Ductile deformation in Palaeozoic crustal lenses, as well as in the Mesozoic sedimentary cover, is shown to have developed in relation to the detachments responsible for the mantle exhumation during Albian–Cenomanian times. We bring new evidence that extreme crustal thinning of this distal passive margin occurred in a hot thermal environment in relation with the rise of the mantle along a detachment fault. We stress the fact that, in such conditions, an anastomosed pattern of numerous crustal lenses built up, allowing tectonic contact of the prerift sedimentary cover with mantle rocks in the intervals between the crustal lenses. Zones of intense deformation were likely the preferential pathways for the hot fluids responsible for the talc/chlorite layer mineralization.

This contribution brings important constraints to any model of evolution of distal passive margins. In the Saraillé massif, the lower crust is surprisingly lacking and only lenses of upper crust are recognized. This suggests that the lower crust was decoupled from the upper crust during the Albian–Cenomanian rifting and remained at depth in the detachment between the mantle and the crust (Teixell et al., 2016). The lower crust likely underwent a boudinage in the early stages of continental rifting, possibly driven by hydration along the main crustal extensional shear zones, allowing tectonic softening. This provides constraints in reconstructing the rheological profile of the crust before and during the Albian–Cenomanian rifting. Addressing this issue will require further investigations in similar Pyrenean massifs where subcontinental mantle outcrops are in contact with continental rocks.

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