Thermal control on the modes of crustal thinning leading to mantle exhumation. Insights from the Cretaceous Pyrenean hot paleomargins.

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Key Points:

- Tectonics mode of crustal thinning depends on rifting-related thermal anomaly
- Hot prerift sediments are systematically observed on top of mantle rocks
- Lateral extraction of the continental crust occurs under high thermal regime

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Thermal control on the modes of crustal thinning leading to mantle exhumation: Insights from the Cretaceous Pyrenean hot paleomargins

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Abstract The prerift Mesozoic sequences of the Cretaceous passive margins fossilized in the North Pyrenean Zone (NPZ) are characterized by high-temperature deformation in relation with thinning of the continental basement. Our compilation of chronological and geological data confirms a clear correlation between the distribution of the highest paleotemperatures in the prerift sedimentary cover and the loci of extreme crustal stretching. Geological evidences such as the occurrence of peridotite bodies directly underlying metamorphic prerift sediments indicate an early attenuation of the rifted continental crust. This leads us to propose a mechanism of rifting involving boudinage of the continental crust. The lateral extraction of the Paleozoic basement occurred under the prerift cover that is decoupled on the Triassic clays and evaporites. The thermal conditions allowing coeval ductile deformation of the crust and of the prerift sediments leaded to the widening of basins devoid of large faulted blocks. We discuss the implications on the origin and significance of the granulites and the relations between flysch deposition and high-temperature metamorphism of the prerift sediments. In the NPZ, Albian-Cenomanian flysch sequences were deposited synchronously with the synmetamorphic ductile deformation of the prerift sequences. Since the base of the flysch deposits also recorded locally the high-temperature tectonic event, we propose an original mechanism for the evolution of the basins involving continuous deformation of the prerift metamorphic sediments. At the scale of the Pyrenean domain, our results suggest a strong lateral variability in the tectonic style of passive margins, in direct link with their thermic pattern.

1. Introduction

The Pyrenean belt is one of the very rare examples worldwide where sediments metamorphosed under high to very high thermal conditions during continental rifting are widely exposed [*Golberg and Leyreloup*, 1990; *Vielzeuf and Kornprobst*, 1984; *Dauteuil and Ricou*, 1989; *Vauchez et al.*, 2013]. The northern edge of the Pyrenean belt is now considered as a relevant analog of distal passive margin and its preorogenic evolution is largely revisited [*Lagabrielle and Bodinier*, 2008; *Jammes et al.*, 2009; *Lagabrielle et al.*, 2010; *Masini et al.*, 2014; *Clerc*, 2012; *Clerc et al.*, 2012, 2014]. The metasediments, which suffered the Cretaceous High Temperature-Low Pressure (HT-LP) metamorphism, belong to the North Pyrenean Zone (NPZ), a domain resulting from the inversion of transtensional basins, which opened north of the Paleozoic Axial Zone of the Pyrenean belt during the Cretaceous (Figure 1). The metamorphic Mesozoic sediments are associated with fragments of subcontinental mantle and with slices of continental basement and sedimentary rocks of undetermined age showing granulitic paragenesis [*Lacroix*, 1900; *Azambre and Ravier*, 1978; *Vielzeuf*, 1980]. The Paleozoic basement of the NPZ is exposed in massifs of limited extension (a few hundred meters to 40 km large) named the North Pyrenean massifs, generally entirely surrounded by Mesozoic material. The occurrence along the NPZ of massifs of Paleozoic rocks and subcontinental mantle bodies closely associated with synrift metamorphic sediments provide a unique chance to reconstruct the architecture and evolution of a distal passive margin.

The ages of the HT-LP metamorphism affecting the Mesozoic cover of the NPZ were consistently estimated between 110 Ma (Albian) and 85 Ma (Santonian) [*Albarède and Michard-Vitrac*, 1978b; *Golberg et al.*, 1986; *Montigny et al.*, 1986]. The intensity of the HT-LP metamorphism is directly related to the magnitude of crustal attenuation, with high-grade rocks systematically associated with peridotites or granulites and lower grade rocks associated with middle to upper crustal units [*Golberg and Leyreloup*, 1990, Figure 2].

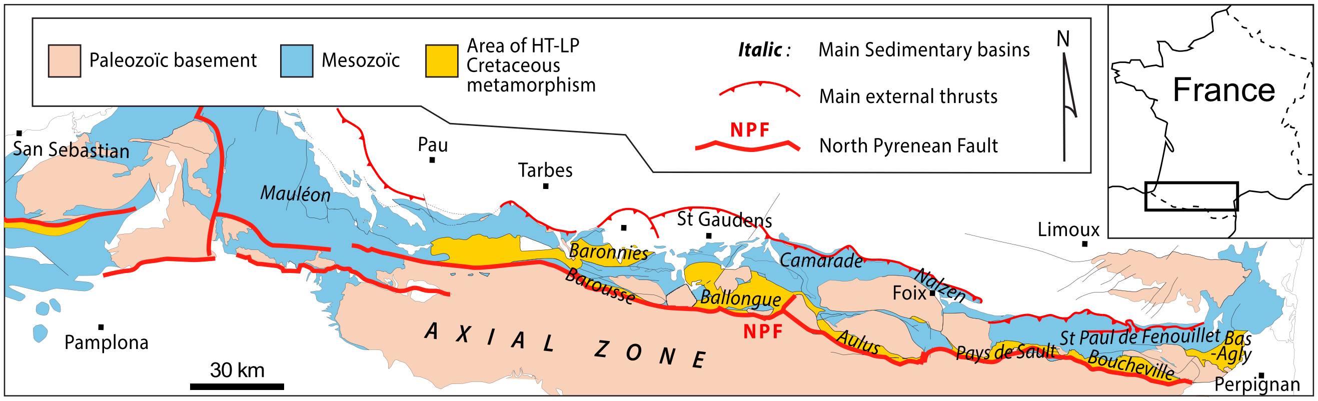

Figure 1. Simplified geological map of the northern Pyrenean belt. The area between the North Pyrenean Fault (NPF) and the main external thrusts is known as the North Pyrenean Zone (NPZ).

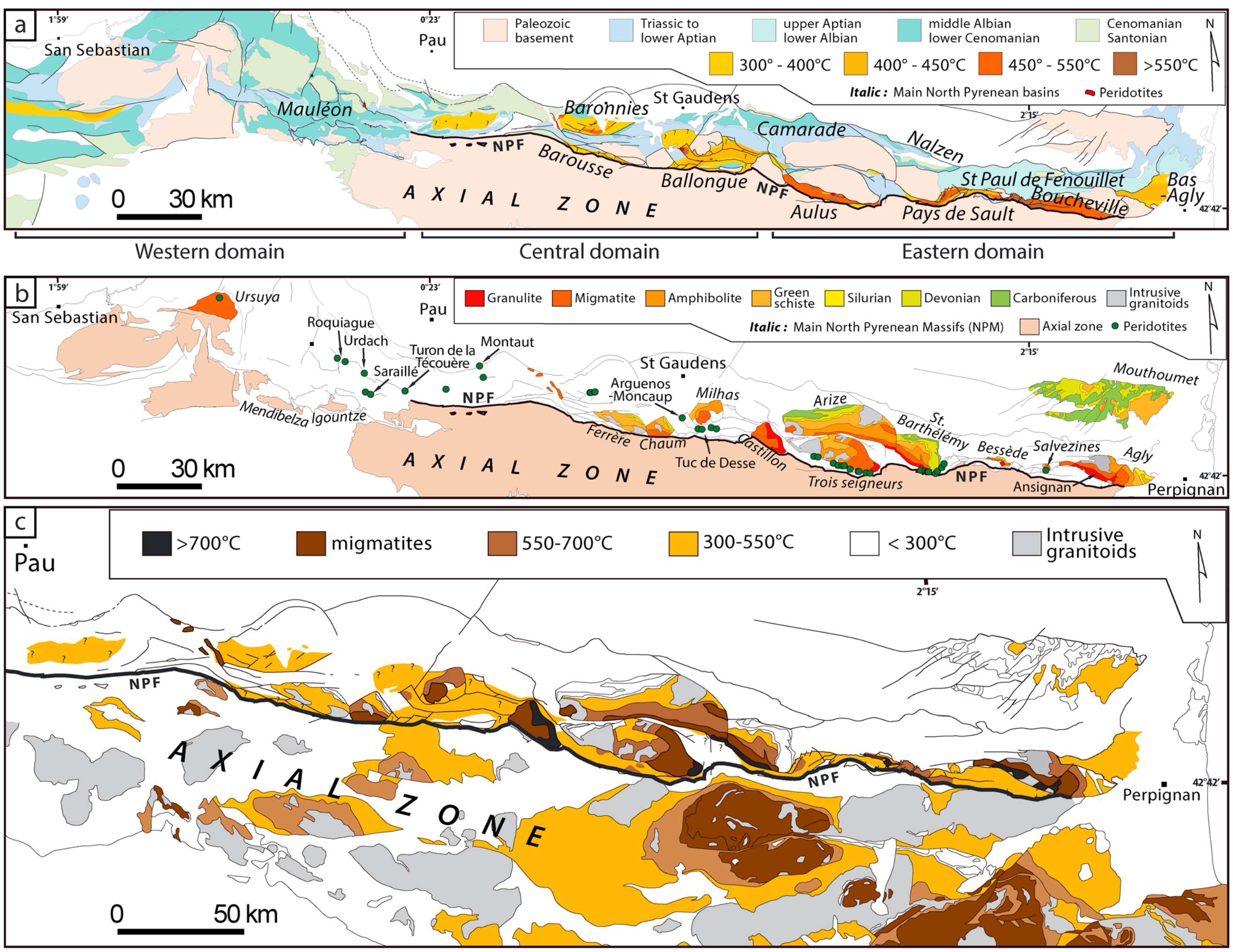

Figure 2. Maps of the Pyrenean belt compiled from various data [*Choukroune and Séguret*, 1973; *Golberg and Leyreloup*, 1990; *BRGM and IGME*, 1998; *Jammes et al.*, 2009] and from the 1/50,000 geological maps of the BRGM. (a) Isometamorphic map of the NPZ [paleotemperatures are compilated from *Golberg and Leyreloup*, 1990; *Clerc*, 2012; *Vauchez et al.*, 2013]. (b) Simplified geological map of the NPZ massifs with location of the outcropping peridotite bodies. (c) Isometamorphic map of both the Paleozoic basement and the Mesozoic cover for the entire northern Pyrenees, including the Axial Zone.

In this article, we consider the deformational and metamorphic history of the prerift (Triassic to Aptian) and synrift (Albian to Coniacian) sediments of the NPZ and examine for the first time the possible relationships between the thermal evolution of the Cretaceous basins and the modes of crustal thinning of the Pyrenean paleomargin. A general model of crustal thinning is based on constraints obtained from both the structure of the Paleozoic basement exposed in the northern Pyrenean massifs and the geological setting of the peridotite bodies. In contrast with most of the passive margins studied onland [*Lemoine et al*., 1987; *Froitzheim and Eberli*, 1990; *Manatschal and Nievergelt*, 1997; *Manatschal*, 2004] and offshore [*Contrucci et al*., 2004; *Moulin et al*., 2005; *Leroy et al*., 2010; *Péron-Pinvidic and Manatschal*, 2008], where no testimonies of extension-related thermal anomaly is identified, our study points to a mechanism of crustal thinning under high thermal regime, by which the crust is progressively attenuated and extracted horizontally. We also discuss the significance of the granulitic rocks in such a model and consider its impact on the development of the Cretaceous flysch basins.

2. Thermal Evolution and Modes of Rifting in the Cretaceous Basins: What the Prerift Cover Tells Us?

After an early rifting episode during the Late Aptian, narrow, nonconnected Albian basins opened north of the basement of the Pyrenean Axial Zone, along a wide domain opened between Iberia and Europe [*Choukroune and Mattauer*, 1978; *Olivet*, 1996; *Jammes et al*., 2009]. They connected together during the Cenomanian when the rift zone became wider and deeper. The main infills of the basins are dark-colored, pelites, sandstone, and breccias deposits, refered to as “Flysch noir” or “Flysch ardoisier” in the literature [*Debroas*, 1976, 1978, 1990; *Souquet et al*., 1985]. They are labeled Black flysch in the following. The Black flysch is organized into three megasequences (I, II, and III), which are the records of three successive steps in the opening of the basins. Megasequence I corresponds to the opening of narrow half grabens, megasequence II registers the opening of en echelon 10 km wide basins, and megasequence III records the coalescence of the basins into a large trough with internal and external parts separated by central highs [*Debroas*, 1990].

Unlike the Alpine analog, the north Pyrenean domain never underwent subduction, and the thermal pattern registered in the prerift and synrift material is not overprinted by major crustal overthrusts or subductions. The pre-Pyrenean inverted margins hence offer a valuable direct access to the thermal imprint of the crustal thinning and subsequent continental breakup. In order to investigate the correlations between the tectonic behavior of the thinned crust and its thermal evolution, we have compiled a new map of the Cretaceous paleotemperatures in the Triassic to Turonian material (Figure 2a). This map is based on new data obtained by RAMAN spectrometry of carbonaceous material [*Clerc*, 2012] and on a compilation of previous data [*Choukroune and Séguret*, 1973; *Bernus-Maury*, 1984; *Golberg*, 1987; *Goujou*, 1987; *Golberg and Leyreloup*, 1990].

Three main thermal domains can be distinguished from west to east along the NPZ.

1. The Western domain corresponds to the Mauléon basin. It presents low grades of HT-LP metamorphism with temperatures lower than 350°C. The highest temperatures are found close to mantle rock exposures (Saraillé, Roquiague).
2. The Central domain includes the Baronnies, Barousse, and Ballongue basins. It presents high grades of HT-LP metamorphism with peak temperatures of 300°–450°C, and locally more than 550°C close to mantle exposures (Argenos-Moncaup body).
3. The Eastern domain includes the Aulus, Pays de Sault, Boucheville, and Agly basins. It presents the highest grades of HT-LP metamorphism with peak temperatures up to 600°C and above. In addition to the west-east thermal zonation, a north-south thermal gradient is well observed in the Eastern domain (i.e., the Camarade and St Paul de Fenouillet basins present no manifestations of the Cretaceous metamorphism). Among the prerift and synrift metasediments, the highest temperatures are found in the southernmost regions (Boucheville and Aulus basins), whereas the northern regions are characterized by a rapid decrease of the HT-LP metamorphic imprint.

In the following, we examine the impact of the rifting episode on the Mesozoic sediments in the three domains defined above. In the cartoons of Figures 3 and 4, we have summarized the main characteristics of these deposits and their settings within the basins.

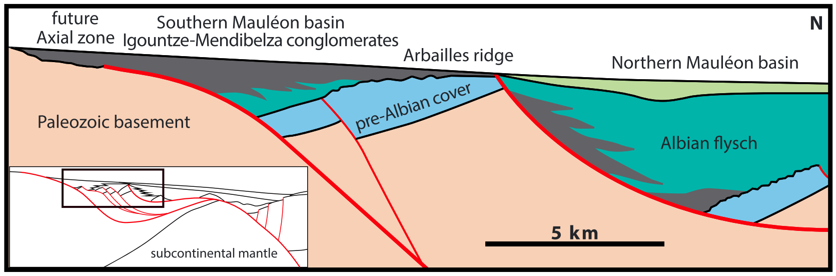

Figure 3. Reconstructed profile across the Mauléon basin and Arbailles ridge (after *Masini et al.* [2014]).

2.1. Western Domain

In the Western domain, coarse clastic formations related to the activity of paleoscarps are well developed along the border of the Cretaceous basins (i.e., the Mauléon basin and sub-basins). The Cretaceous clastic formation are well developed at the western tip of the Axial Zone where they correspond to a conglomeratic formation of Albian-Cenomanian age, the so-called « poudingues de Mendibelza ». The « poudingues de Mendibelza» contain Paleozoic material and stratigraphically onlap the Paleozoic formations of the Igountze and Mendibelza massifs or their Permo-Triassic cover which is locally preserved (Figures 2 and 3) [*Boirie and Souquet*, 1982]. Most of the conglomerates were deposited during the late Albian at the foot of steep slopes of

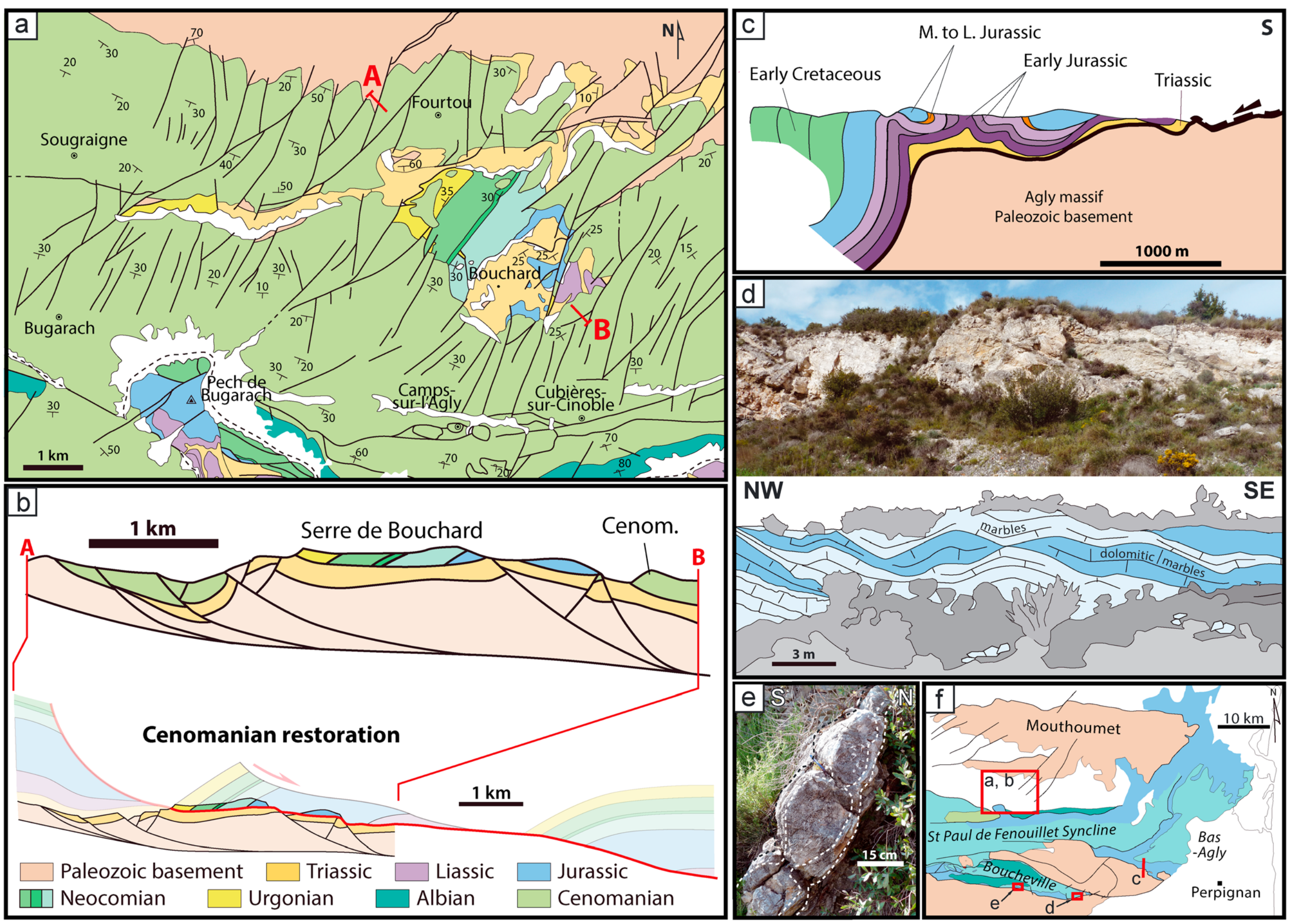

Figure 4. (a) Geological map of the southern border of the Mouthoumet massif in the Bouchard-Fourtou area (after *Crochet et al.* [1989]). (b) A cross section along the A-B profile (after *Bessière* [1987]) and its Cenomanian restoration showing decollement and tilting of the Mesozoic cover are proposed. (c) Decollement, basal truncation, and boudinage of the prerift Mesozoic cover of the Agly massif (after *Vauchez et al.* [2013]). Field illustrations of this boudinage in Mesozoic marbles in the (d) Belesta (coordinates 42°43′19 N–02°35′48E) and (e) Sournia areas (coordinates 42°43′40 N–2°26′49E). Elements a, b, c, d, and e of the figure are localized in f (same legend as Figure 2a).

the North-Iberian paleomargin and represent syntectonic, fan-delta-fed immature turbidite systems a few kilometers wide [*Boirie*, 1981; *Boirie and Souquet*, 1982; *Masini et al*., 2014]. Poorly sorted breccias are abundant and display frequent facies changes and mix between mass transport and rock fall indicating close active scarps. Very large blocks and huge olistoliths have traveled through narrow canyons. The Larrau-Sainte-Engrace unit lies tectonically below the Mendibelza and Igountze massifs. It is composed of a chaotic assemblage of heterometric blocks of Triassic evaporites and dolomites, Paleozoic basement (including granulites), in a matrix of micaceous black marls having affinities with the Albian flysch [*Ducasse et al*., 1986]. This chaotic unit represents scree deposits in response to the exhumation of early tectonized Triassic formations and basement.

2.2. Central Domain

In the Central domain, the clastic formations related to the activity of paleoscarps are also well developed along the border of the Cretaceous basins. They progressively pass into thinner pelitic flysch deposits, which may reach more than 5000 m thick [*Debroas*, 1990]. These basins have smaller dimensions and their shapes are increasingly controlled toward the East by the emergence of the North Pyrenean massifs, whose size globally increases eastward. The basins are frequently triangle or lozenge-shaped, with a maximum of breccias deposits along their northern and southern borders. In the Ballongue and Baronnies basins, the breccias consist of a chaotic assemblage of decametric blocks of sediments belonging to the prerift Mesozoic sedimentary sequence and of basement rocks in a silt matrix [*Debroas*, 1976, 1978, 1990]. The Middle Albian deposits contain only Mesozoic clasts, whereas Paleozoic schists and quartzites together with granite debris generally appear during the latest Albian–early Cenomanian. This indicates early erosion of the sedimentary cover followed by granite exhumation, a typical chronology expected in the frame of denudation processes along steep border faults.

These examples collectively demonstrate that in the western part of the European paleomargin, the upper crust undergoing the Albian-Cenomanian rifting behave in a brittle mode leading to the formation of large fault scarps providing voluminous clastic deposits at the edges of the flysch basins. This is also true in a lesser extent in Central domain, which present smaller basins and higher temperatures of peak metamorphism. As such, the central NPZ appears as a transitional domain sharing structural and thermal characteristics of both the Western and Eastern domain.

The clastic formations described above rework fragments of the continental crust and its prerift cover, but they do not rework ultramafic material. Therefore, in the regions where they are exposed, the mantle has not been exhumed to the surface. However, we have indications that in some parts of the western and central domains, the crust has been removed completely during the Cretaceous rifting. In the areas showing the strongest metamorphic imprint, peridotite bodies associated with thin slices of continental material are found in tectonic contact with the Mesozoic metasediments, thus indicating an early juxtaposition during the HT episode [*Golberg and Leyreloup*, 1990; *Lagabrielle et al*., 2010; *Clerc*, 2012]. The best examples are the Saraillé peridotites in the Mauléon Basin and the Argenos-Moncaup body in the Ballongue basin. This point is discussed in detail in section 3.2.

2.3. The Eastern Domain

In the inverted Albian basins transported along the main external thrusts (Figure 1), the imprint of the Cretaceous metamorphism is extremely low. These basins display characteristics similar to those reported from the Western domain and from the northern region of the Central domain. The breccias of the Camarade basin are composed of heterometric blocks of clast-supported Paleozoic schists and quartzites accumulated over more than thousand meters in relation with syn-sedimentary faulting at the border of a lozenge-shaped basin [*Bilotte et al*., 1987]. In addition, large olistoliths of schists and quartzites are found in the Camarade flysch. In the Saint Paul de Fenouillet Cretaceous basin, the turbiditic marls of the Late Albian flysch include numerous olistoliths of Jurassic dolomites and Albian limestones indicating faulting along the northern border of the NPZ [*Bessière et al*., 1989; *Crochet et al*., 1989].

The deformation mode of the Mesozoic cover changes drastically when moving toward the south of the Saint Paul de Fenouillet basin and in the Boucheville basin, following the increase in metamorphic imprint. On the proximal part of the paleomargin (Mouthoumet massif) and on the top of the North Pyrenean Agly massif, the prerift cover generally appears incomplete. Sedimentary formations of various ages, from the Triassic to the Aptian, are intensely truncated and/or scalped. Tectonic contacts are commonly observed between

Liassic and Paleozoic, Jurassic and Paleozoic, middle or upper Jurassic and Triassic, Aptian and Liassic, or Triassic and Cretaceous and Paleozoic. However, no stratigraphic repetition of any member of the sedimentary series is ever observed, every tectonic contact is subtractive. Such a geometry is hardly consistent with a contractional deformation; rather, it relates better to extensional tectonics involving normal faults connected to various decollement layers. In the proximal part of the paleomargin, it is possible to infer that the decollements were verging toward the most thinned parts of the margin. This is peculiarly well visible in the Bouchard plateau (also known as the "Fourtou window") of the Mouthoumet massif where a tectonic block of the sedimentary cover is tilted toward the NO and is found sealed below the Cenomanian sediments [*Bessière*, 1987; *Crochet et al.*, 1989; *Clerc*, 2012] (Figures 4a and 4b).

In the southern part of the Eastern domain, the metamorphic imprint is strong, with peak temperatures reaching 600°C in the Black flysch. A peculiar feature of these HT domains is that the early phase of deformation of the prerift Mesozoic sediments is particularly well expressed. Folding and ductile shearing of the Triassic-Albian sedimentary pile occurred clearly before the deposition of the Cenomanian Flysch. On the northern flank of the Agly massif, subtractive contacts and general decollement of the prerift Mesozoic cover are observed [*Durand-Delga*, 1964] (Figure 4c). Here, the deformation is extensional and clearly synmetamorphic, with tectonic lineation indicating a top to the north-north-east vergence [*Vauchez et al.*, 2013]. At the border of the Boucheville massif, the Mesozoic sequence is everywhere severely thinned under a ductile regime, with frequent boudinage and tectonic subtractions of comprehensive portions of the original succession (Figures 4d and 4e).

Finally, in the southernmost regions of the Eastern domain, the synmetamorphic extensional event led to partial or entire attenuation of the pre-Albian cover, which is boudinaged and discontinuous. From the historical point of view, it has to be noticed here that this Cretaceous tectonic event relates to the "Pre-Cenomanian phase" of previous authors [*Casteras*, 1933; *Mattauer and Proust*, 1965; *Durand-Delga*, 1965]. The significance of this early event has been a matter of debate since a long time. It has been related to an early extensional deformation in the future NPZ realm (see review in *Choukroune* [1976]) but was not recognized as synmetamorphic with the HT at that time. The link between the ductile deformation in the NPZ metasediments and the HT-LP metamorphism has been proposed after the 1980s [*Vielzeuf and Kornprobst*, 1984; *Golberg and Leyreloup*, 1990]. As reported above, this link has finally been demonstrated by *Vauchez et al*. [2013]. This study was based on temperature estimates of calcite deformation fabric in the cover of the Agly massif.

3. Behavior of the Continental Basement During Crustal Thinning and Mantle Unroofing

3.1. Insights From the Geology of the North Pyrenean Massifs

The North Pyrenean massifs are from west to east the Ferrère, Chaum, Milhas, Castillon, Trois-Seigneurs, Arize, Saint-Barthelemy, Bessèdes, Salvezines, Agly, and other smaller massifs (Figure 2b). These amygdale-shaped massifs align and extend along the belt axis, where they are systematically tilted so that the oldest units and those having the highest metamorphic grade globally croup out to the south, in contact with metasediments displaying the highest grades of the HT/LP Cretaceous metamorphism. In addition, the ultramafic bodies of the ZNP are found along the southern rims of the North Pyrenean massifs. 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.*, 2013]. The occurrence of basement units exhibiting granulitic metamorphic assemblages at various locations along the NPZ (Figures 2b and 2c) indicates that the middle to lower continental crust has been also exhumed along such shear zones, a fact already noticed by [*Vissers et al.*, 1997] and confirmed by [*Jammes et al.*, 2009] in the Ursuya massif of the Mauléon basin. One of these faults, well exposed in the St Barthélémy massif, involved fluid circulations and Mg enrichment linked to continuous shearing between 112 Ma (Albian) and 97 Ma (Cenomanian) [*Schärer et al.*, 1999]. In addition, the crust suffered a generalized hydrothermal alteration as revealed by the albitization and the dequartzification of the North Pyrenean massifs [*Boulvais et al*., 2006, 2007; *Poujol et al*., 2010; *Fallourd et al*., 2014]. The activation of major extensional shear zones in association with HT-LP metamorphism and metasomatism collectively point to a severe crustal thinning during the Cretaceous, which developed during the growing up of the thermal anomaly. The fact that the ages of the Cretaceous metamorphism obtained in the paleozoic basement of the North Pyrenean massifs are slightly older (Aptian to early Cenomanian) [*Boulvais et al*., 2007; *Schärer et al*., 1999; *Poujol et al*., 2010] than those obtained in the Mesozoic cover (Albian to Santonian) [*Albarède and Michard-Vitrac*, 1978b; *Golberg et al*., 1986; *Montigny et al*., 1986] suggests a progressive upward migration of the thermal anomaly through the continental crust.

The NPZ granulitic assemblages are symptomatic of relatively low pressures. For instance for the Ansignan charnockites, temperatures are estimated around 650–800°C for pressures of around 3.5 to 6 kbar [*Andrieux*, 1982a,1982b; *Vielzeuf*, 1984; *Barbosa and Fonteilles*, 1986]. In the Lherz area, PT estimate for the Granulitic complex of the Port de Lherz and Port de Saleix range around 750–800°C for pressures of 7±0.5 kbar, which are the highest pressures recorded in the Pyrenean granulites [*Vielzeuf*, 1980, 1984]. Rb/Sr ages on 2 biotites—whole rocks couples from the Port de Saleix granulites (Lherz area) indicate ages of 93 Ma (Cenomanian) and 81 Ma (Campanian) resulting from possible retromorphosis of former granulites [*Vielzeuf*, 1984]. According to this author, the granulitic assemblages are considered to have grown during the Variscan or post-Variscan period, but an origin by recrystallization during the Cretaceous crustal thinning event cannot be excluded, as discussed in section 5.1.

3.2. Early Juxtaposition of Prerift Sediments Over Mantle Rocks

In Table 1, we present a compilation of the geological settings of the NPZ mantle bodies. This compilation reveals that in most cases, the material directly overlying the mantle rocks consists of metamorphic Mesozoic sediments. The distribution of the peak temperatures of the HT-LP metamorphism concentrated on the mantle bodies strongly suggests an early juxtaposition immediately following continental breakup. Early tectonic contact between mantle basement and metasediments was suggested previously by *Jammes et al*. [2009, 2010] and *Lagabrielle et al*. [2010]. These authors pointed to the occurrence of a layer of tectonic breccias made up of Mesozoic material, mainly Triassic, at the boundary of the mantle bodies. In some localities (Urdach, Saraillé, Montaut, etc; see review in Table 1), the ultramafic bodies are associated with thin slices of continental crust. These slices represent remnants of continental material abandonned over the mantle rocks during the crustal thinning [*Jammes et al*., 2009; *Lagabrielle et al*., 2010].

Thus, one of the most striking features of the NPZ is that the mantle rocks have been directly in tectonic contact with the prerift sediments, with an almost complete removal of the continental crust. The early juxtaposition of prerift sediments and mantle rocks during the Cretaceous was also deduced from the presence of Cretaceous breccias containing dominant marbles and mantle rocks material with extremely rare Paleozoic clasts. These breccias are exposed only in some localities, in an area including the metamorphic basins of Aulus and Pays de Sault (breccias of Lherz, Vicdessos, Bestiac, etc.) [*Lagabrielle and Bodinier*, 2008; *Lagabrielle et al*., 2010; *Clerc et al*., 2014].

3.3. Additional Evidence of Hot Rifting Along the NPZ: Magmatic Activity Coeval With Crustal Thinning and Mantle Uplift

The NPZ is affected by a well-developed magmatic activity responsible for the emplacement of a wide variety of alkaline intrusive and effusive rocks [*Montigny et al*., 1986; *Azambre et al*., 1992; *Rossy et al*., 1992]. The ages of the magmatic rocks are distributed between the lower Albian (113 Ma) and the upper Coniacian–lower Santonian (85 Ma) [*Golberg et al*., 1986; *Montigny et al*., 1986]. Some manifestations of the Cretaceous alkaline magmatism have also been recognized within the peridotite bodies of the NPZ, where they appear as dykes of amphibolite bearing pyroxenites and hornblendites considered to represent transmantellic melt conduits for the Cretaceous alkaline magmatism [*Conquéré*, 1971; *Bodinier et al*., 1987; *Vétil et al*., 1988]. Absolute datations of these rocks indicate Albian ages around 110–105 Ma [*Vershure et al*., 1967; *Golberg et al*., 1986; *Henry et al*., 1998]. The peridotite massifs of Tuc de Desse, Arguenos-Moncaup, Montaut, and Turon de la Técouère also contain gabbroic intrusions that present chilled margins along their contact with the peridotites, indicating that some of the mantle rocks were already cooled during the emplacement of some of the magmatic rocks [*Azambre and Monchoux*, 1998].

Table 1. Inventory of the Terrains Surrounding the Ultramafic Units Along the North Pyrenean Zone[a]

Ultramafic Outcrops	Coordinates	Directly Overlying Material	Basement Material Observable in the Vicinity	References
Salvezines	42°46′02.64″N 2°18′01.14″E	Metamorphosed Mesozoïc sediments	Condensed palozoïc basement (Salvezines)	*Choukroune* [1976] and *Golberg* [1987]
Tarascon Area (Bestiac, Caussou, Urs, etc.)	42°45′44.60″N 1°45′44.55″E	Metamorphosed Mesozoïc sediments (Trias to Aptian)	Granulitic gneisses and metamorphosed Paleozoïc sediments	*St Blanquat et al.* [1990] and *Destombes et al.* [1969]
Vicedessos area (Lercoul, Sem, Sentenac)	42°46′02.64″N 2°18′01.14″E	Metamorphosed Mesozoïc sediments (Liasic to Jurassic)	Migmatitic paleozoïc basement (St Barthelemy)	*Destombes et al.* [1969]
Lherz area (Freychinède, Lherz, Doulère, etc.)	42°48′26.03″N 1°22′44.22″E	Metamorphosed Mesozoïc sediments (Trias to Aptian)	Migmatitic and granulitic paleozoic basement (Trois Seigneurs)	*Colchen et al.* [1997], *Clerc et al.* [2012], and *Clerc et al.* [2014]
Arguenos-Moncaup area	42°58′16.97″N 0°42′43.49″E	Metamorphosed Mesozoïc sediments (Trias to Aptian) +/- hectometric scales of paleozoïc basement	Amphibolitic and migmatitic paleozoic basement (Milhas)	*Hervouët et al.* [1987], *Canérot and Debroas* [1988], *Clerc* [2012]
Baronnies area (Avezac-Espechère)	43°03′43.84″N 0°19′30.76″E	Metamorphosed Mesozoïc sediments (Upper Aptian to Lower Albian)	none	*Azambre et al.* [1989]
Saint-Pé-de-Bigorre (Chapelle St Marc)	43°06′01.76″N 0°09′09.41″O	Metamorphosed Mesozoïc sediments (Liasic to Jurassic)	none	*Casteras et al.* [1970a]
Montaut	43°08′15.77″N 0°09′58.10″O	Devonian sediments and Upper Aptian	Paleozoïc sediments (Silurian, Devonian)	*Casteras et al.* [1970a]
Moncaut	43°04′00.42″N 0°18′54.29″O	Metamorphosed Mesozoïc sediments (Trias to Aptian)	Permian sediments	*Casteras et al.* [1970a]
Turon de la Técouère	43°03′50.99″N 0°29′32.30″O	Metamorphosed Triasic sediments (Keuper)	Silurian	*Casteras et al.* [1971]
Sarance anticline (Saraillé, Tos de la Coustette)	43°03′17.90″N 0°38′37.55″O	Metamorphosed Mesozoïc sediments (Trias to Aptian) thin scales of Paleozoïc basement (100 m thick)	Steatized and hyper condensed paleozoïc basement	*Lagabrielle et al.* [2010] and *Casteras et al.* [1971]
Urdach	43°07′16.44″N 0°40′08.55″O	Hyper-thinned (<1000 m) continental crust and metamorphosed mesozoïc sediments (Triasic to Cenomanian)	Odovician schistes; gneisses and granites reworked in Cenomanian wildflysch	*Debroas et al.* [2010] and *Casteras et al.* [1970b]
Roquiague structure (Chabalgoïty, Cécénéguiet)	43°09′39.17″N 0°44′42.13″O	Metamorphosed Triasic sediments (Keuper) and Albian-Cenomanian flysch	none	*Casteras et al.* [1971]
Ursuya (Sorhano Hartzburgite)	43°21′45.15″N 1°17′34.81″O	Window in Granulitic basement	Granulites, Albian and younger sediments	*Vielzeuf* [1984], *Boissonnas et al.* [1964] and *Masini et al.* [2014]
General observations		Systematic presence of mesozoïc material (except Ursuya window)	When present in the vicinty, paleozoïc basement material is higly thinned and generally metamorphosed toward migmatitic or granulitic facies	

[a]Compiled after *Choukroune* [1976], *Golberg* [1987], *St Blanquat et al.* [1990], *Destombes et al.* [1969], *Colchen et al.* [1997], *Clerc et al.* [2012], *Clerc et al.* [2014], *Hervouët et al.* [1987], *Canérot and Debroas* [1988], *Clerc* [2012], *Azambre et al.* [1989], *Casteras et al.* [1970a, 1970b], *Casteras et al.* [1971], *Lagabrielleet al.* [2010], *Debroas et al.* [2010], *Vielzeuf* [1984], *Boissonnas et al.* [1964], and *Masini et al.* [2014].

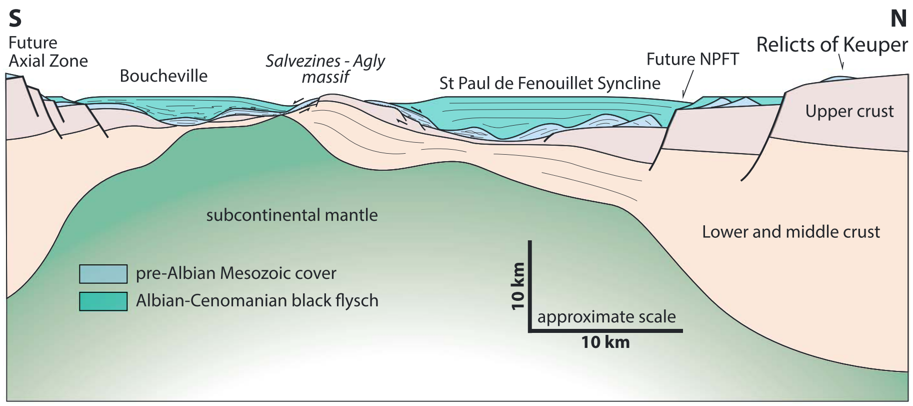

Figure 5. A conceptual reconstructed section across the European paleomargin of the eastern Pyrenees (after a balanced cross section of *Clerc* [2012]). The section includes the Boucheville, Bas-Agly, and Saint Paul de Fenouillet Cretaceous basins. It shows the Salvezines continental boudin. Thick lines represent faulted contacts.

Numerous evidences exist showing that magmas have been traveling across the sediments of the Cretaceous basins. They are mostly known in the western Pyrenees. They are represented by gabbroic intrusions, dikes, and sills of teshenites and by pillow lavas [*Azambre*, 1967; *Azambre and Rossy*, 1976; *Azambre et al*., 1992]. In addition, several cases of injection of magma directly within the ductily deformed Mesozoic marbles have been reported [*Thiébaut et al*., 1979; *Barrère et al*., 1984].

4. Synthesis of Geological and Chronological Data and Proposition of a Model of Crustal Stretching Under Hot Regime in the Pyrenean Realm

4.1. Specific Geological Patterns of the NPZ in Response to the Hot Cretaceous Rifting Event

Based on the geological records listed in the review above, we are now able to outline the specific character linked to the hot Cretaceous rifting event as expressed in the NPZ. These characters can be summarized as follows:

1. First of all, juxtaposition of prerift cover over mantle rocks occurred in the most internal parts of the Cretaceous basins. The metasediments resting over the mantle rocks underwent metamorphic conditions up to more than 600°C and have been ductily deformed during this tectonic juxtaposition.
2. The very hot conditions in which crustal thinning occurred in the internal part of the basins are not only recorded by the metamorphic evolution of the sedimentary cover of the NPZ. Magmatic consequences of crustal thinning and mantle uplift are recorded both in the mantle and in the metasediments of the NPZ between 113 Ma (lower Albian) and 85 Ma (upper Coniacian-lower Santonian).
3. There are clear changes in the expression of crustal thinning across the entire NPZ. From West to East, as well as locally from North to South, the superficial expressions of continental stretching pass from cold-faulted borders, into dominant truncated slided rafts of prerift sediments, and finally into ductily deformed prerift series. These changes are at least largely controlled by the thermal regime of the thinned region. The most dramatic thinning leading to mantle unroofing is always recorded in the regions showing the highest regional metamorphic grades in the Mesozoic metasediments (i.e., up to 600°C in the Central domain; up to 350°C in the Western domain). Opposition has to be made between the Igountze-Mendibelza or Baronnies and Ballongue basins bounded by steep faults and the flysch basins of the Southeastern domain (Boucheville, Agly, Aulus). The regions of high thermal grade generally lack evidence of block faulting, suggesting a ductile mode of thinning of the crust. In the Eastern domain, the north-south succession of the Saint-Paul-de-Fenouillet, Bas-Agly, and Boucheville basins suggests that the structure of the hottest regions of the stretched margin was dominated by topographic undulations in relation with the presence of crustal boudins. This peculiar architecture is simplified in the section of Figure 5. The homogeneous sedimentary infill of the basins indicates that no major scarps have controlled the subsidence [*Berger et al*., 1993; *Bessière et al*., 1989].

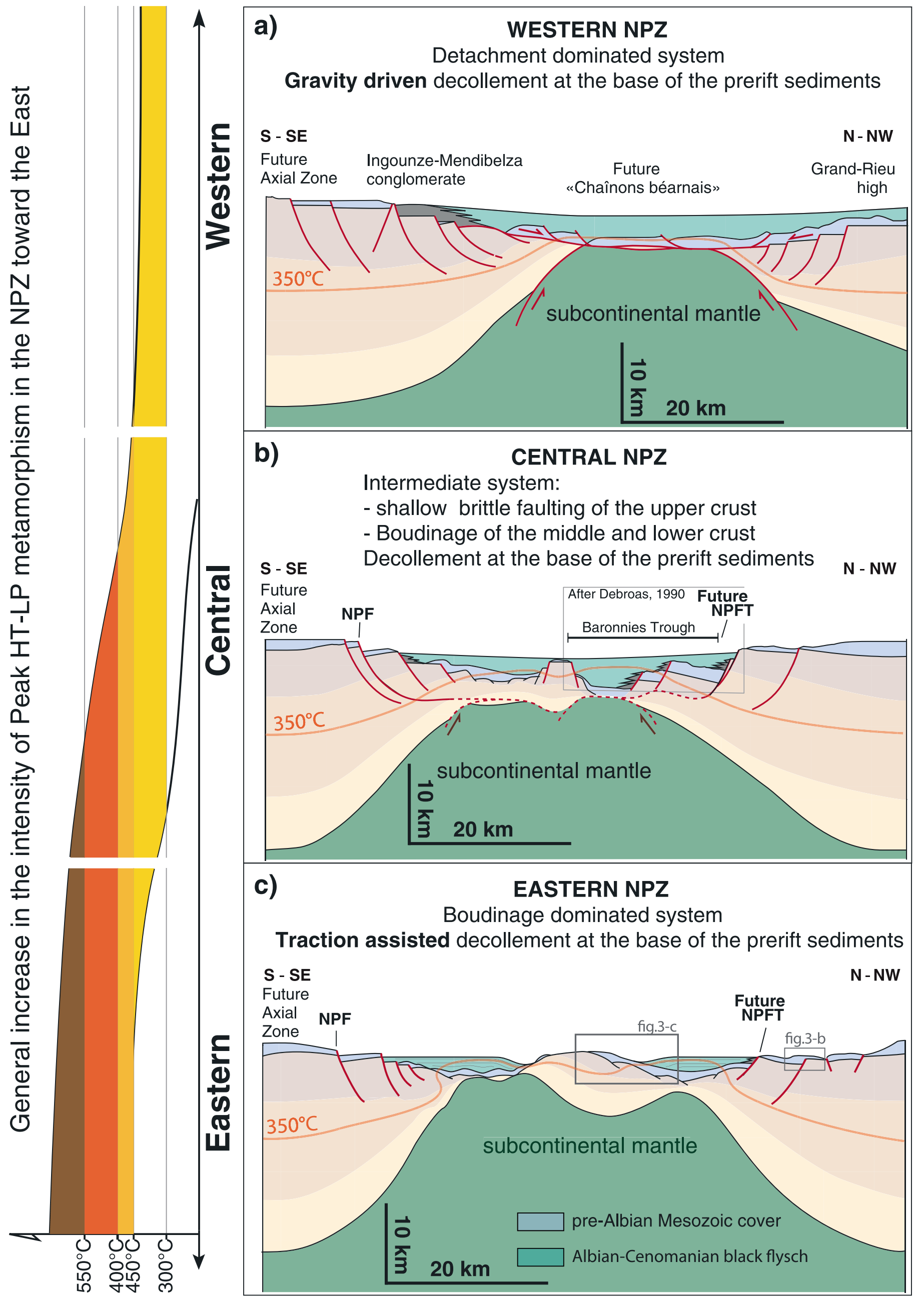

Figure 6. Models for the Cenomanian architecture of the paleomargins of the Pyrenean Cretaceous basins. From West to East, one must note that numerous faults cross-cut the crust in the Western domain and that progressively, toward the east, in the internal part of the basins, the crust is rather boudinaged and form lens-shaped crustal boudins, such as the Agly massif. This evolution in the mode of rifting is clearly related to the thermicity of the paleomargin. The orange curve represents a possible 350°C isotherm extrapolated from Figure 2.

4.2. A model of Continental Breakup Under HT Regime Involving Attenuation and Lateral Extraction of the Crust

We deduce from the geological constraints listed above (section 4.1, points 1, 2, and 3) that under the hottest parts of the Cretaceous basins, the crust has been thinned without major fault blocks (Figures 5 and 6c). The space opening between the two continental domains led to the direct juxtaposition of mantle peridotites and metamorphic sediments. Such model of continental thinning and breakup differs significantly from the

Western domain (Figure 6a) and from most models based on observation from the Western Iberian margin and the Alpine analog involving faulted blocks and detachment faults [*Boillot et al*., 1980; *Boillot and Froitzheim*, 2001; *Froitzheim and Manatschal*, 1996; *Manatschal et al*., 2001; *Whitmarsh et al*., 2001; *Péron-Pinvidic et al*., 2007; *Péron-Pinvidic and Manatschal*, 2008]. It implies that boudins of thinned crust are removed laterally from their original place, between the pre-rift cover and the subcontinental mantle. When thinning is increasing, isotherms move closer to the surface with the result that the brittle-ductile transition propagates upward and may reach sediments deposited at the early stage of the basin opening (i.e., ductilly deformed Albian breccias of Castel-Nerou) [*Goujou et al*., 1988].

5. Discussion: Implications of a Model of Crustal Stretching Under Hot Regime

5.1. Some Limitations in Our Current Understanding of the Modes of Crustal Stretching in the Pyrenean Realm

In the following, we first list some gaps in our current knowledge of the geological evolution of the NPZ and Axial Zone, which lead us to discuss some aspects of the proposed model.

From a single geological reconstruction of the shallow part of the Cretaceous basins, different possible architecture at depth can be reconstructed. In the present state of the investigations, we assume that there is no robust constraints from the geological record in the NPZ and in the Axial Zone to determine the precise mechanisms controlling the crustal thinning. The main questions and uncertainties are as follows.

1. Details about the existence, geometry, and orientation of Variscan structures such as thrusts and strike slip faults that may have been reactivated during the rifting are missing in many places.
2. The existence of mesozoic structures, such as an aborted Triassic rift and possible Jurassic to Aptian strike-slip major faults [*Jammes et al*., 2009; *Cathelineau et al*., 2012], is assumed to have existed in the Pyrenean realm, but they are not clearly identified. These structures would have resulted in a weakening of the lithosphere and an early thinning of the continental crust before the main Cretaceous stretching event.
3. The thickness of the crust and its thermal regime at the initiation of the Cretaceous rifting is unknown. These data are fundamental to construct a rheological profile.
4. Little is known about the rheological response of the crust during the growing up of the Cretaceous thermal anomaly. Therefore, the internal rheological evolution of the model during the thinning phase will be unknown.
5. The exact motion of the Iberian plate during Albian-Cenomanian times is still debated, and current kinematic reconstructions suggest as well transtensional [*Olivet*, 1996; *Sibuet*, 2004] as pure extensional [*Tucholke et al*., 2007; *Jammes et al*., 2009; *Bronner et al*., 2011] movements as a leading mechanisms for the Cretaceous crustal thinning. All these parameters may have had a strong control on the final architecture of the margin and would require further investigations.

5.2. Differences Between the "Eastern Pyrenean" Model of Continental Stretching and Earlier Models From the Literature (Figure 7)

Our reconstruction of Figure 5 allows us to define a new type of hot, Pyrenean paleomargin composed of a proximal region of thick crust crosscut by normal faults and a distal region of ductily thinned crust underlying the distal portions of the black flysch basins. This type of margin is simplified in the lower cartoon of Figure 7a. It can be compared to the two main types of margins defined by *Huismans and Beaumont* [2011] on the basis of the behavior of the lithosphere. In the type I, faulted blocks of the continental crust are lying directly over the lithospheric mantle, which is exposed in the distal part of the margin. This situation, which implies the presence of a large detachment fault at the base of continental extensional allochthons, does not correspond to the reconstructions from the NPZ, where prerift sediments most often tectonically overlie the subcontinental mantle. However, the type I of *Huismans and Beaumont* [2011] shares an important character with the Pyrenean paleomargins since in this model, mantle rocks are exposed in the distal portion of the margin. The type II of *Huismans and Beaumont* [2011] is mainly characterized by a very large distal margin domain in which the crust has been ductily thinned over tens of kilometers. This domain corresponds to the regions of the paleomargin, which have been affected by the HT-LP metamorphism. Hence, we assume that our model cannot compare solely to one of the two types of *Huismans and Beaumont* [2011]. Moreover, it catches one important characteristic from both of them, as synthetized in Figure 7.

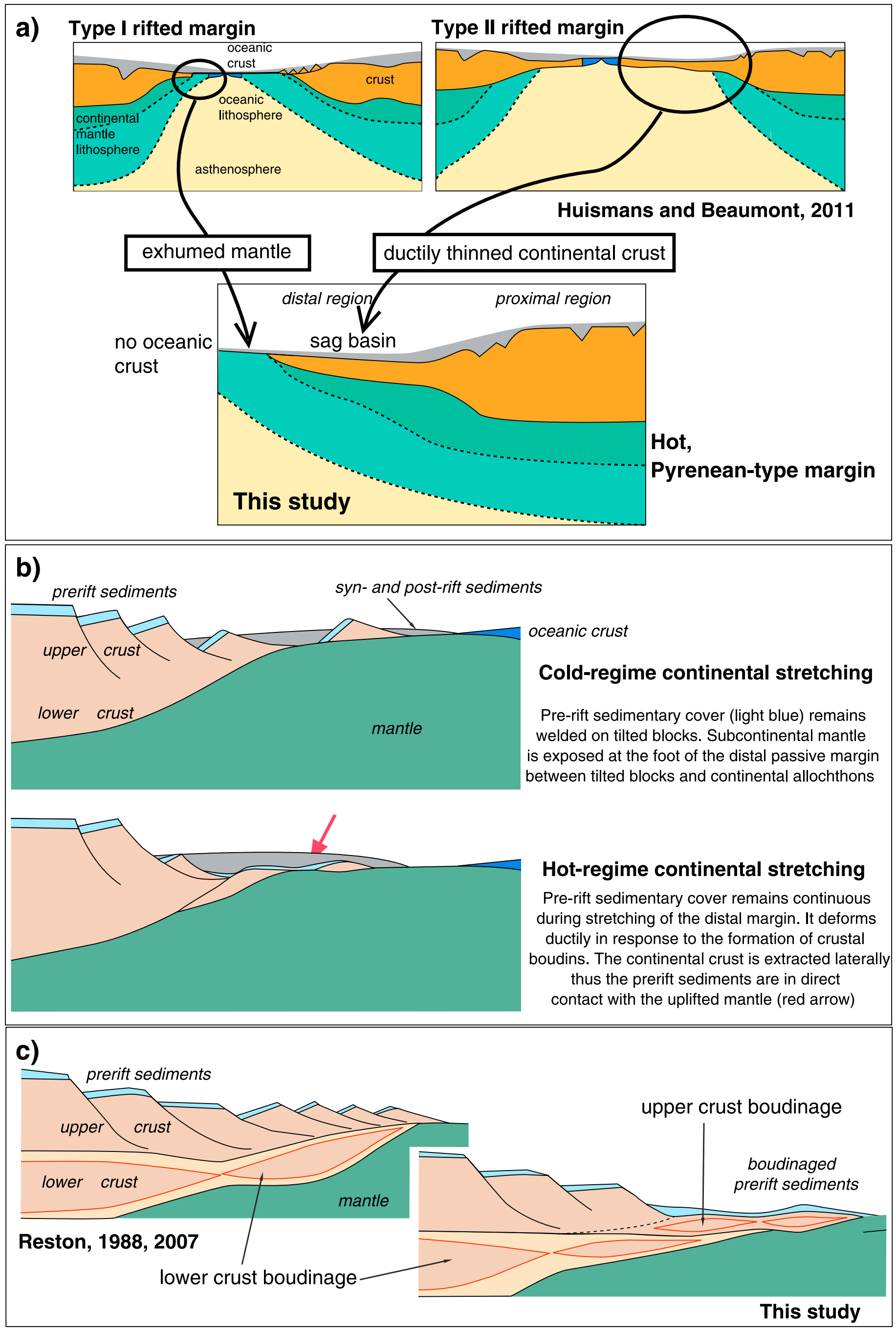

Figure 7. Cartoons illustrating the main differences between the model of hot continental stretching proposed in this article and some models of passive margin formation from the literature. (a) The model of hot passive margin established from the Pyrenean case (lower sketch) includes fundamental characteristics from both margins of type I and II by *Huismans and Beaumont* [2011]. (b) The lower cartoon represents an idealized section of a passive margin, which originated under the conditions of hot-regime stretching. It strongly differs from a cold margin, which is characterized by the formation of continental allochthons. (c) Lower crustal boudinage is proposed in a model by *Reston* [2007]. Our study allows us to propose an alternative model in which the upper crust is also boudinaged.

The tectonic behavior of the prerift sedimentary cover in the metamorphic domain of the NPZ indicates a wide wavelength undulation of the top of the lithosphere in the most distal part of the paleomargin. Here, boudins formed in the ductily thinned crust mark the transition toward the exhumed mantle. Thus, in the regions of the passive margins undergoing a hot thermal gradient, the prerift sediments may remain linked to the mantle during the final stages of the crustal thinning. The crust is therefore laterally extracted from the sediments/mantle interface as shown in Figure 7b. This model differs significantly from the models of “cold” passive margins undergoing mantle exhumation as proposed from the Alpine paleomargins analogs or from the western Iberian margin case [*Boillot et al.*, 1980; *Boillot and Froitzheim*, 2001; *Froitzheim and Manatschal*, 1996; *Manatschal et al.*, 2001; *Whitmarsh et al.*, 2001; *Manatschal*, 2004; *Péron-Pinvidic et al.*, 2007; *Péron-Pinvidic and Manatschal*, 2008]. In such “cold” models, crustal allochthons are formed rather than crustal boudins and the prerift cover remains welded to the crustal allochthons. Thus, it is cut into disconnected pieces and “windows” are open within the crustal blocks (and their welded prerift cover) allowing the mantle to be exosed over wide surfaces. These important differences are explained in Figure 7b.

5.3. Boudinage of Both the Lower and Upper Crusts

Our model implies the boudinage of the continental crust. Investigations in the NPZ with the precise goal to describe the tectonic imprint of the Cretaceous extensional deformation on the Paleozoic basement are rare at present-day [*Passchier*, 1984; *St Blanquat et al.*, 1986; *Costa and Maluski*, 1988; *St Blanquat et al.*, 1990; *Paquet and Mansy*, 1991; *Vauchez et al.*, 2013]. Therefore, very little is known about the crustal layers which are affected by the boudinage. Data from the Agly massif where granulite-facies rocks are exposed tends to indicate that both the lower crust and the upper crust are affected by boudinage (see *Vauchez et al.* [2013] for a discussion). Boudinage of the crust under high thermal conditions has rarely been specifically considered in the numerous models of passive margins evolution (see *Sutra* [2011] for a review). More attention has been payed to the brittle behavior of the upper crust and to the formation of tilted blocks or of extensional allochthons. The question of the behavior of the lower crust has been treated by *Reston* [1988, 2007], *Brun and Beslier* [1996], and *Driscoll and Karner* [1998]. *Brun and Beslier* [1996] consider that the upper mantle has a brittle behavior and that the lower crust flows without forming boudins. Boudinage of the crust is proposed in the interpretation of seismic lines of the Norwegian margin (More Basin) by *Osmundsen and Ebbing* [2008] which shows an appropriate image to what the NPZ domain could be before the later inversion. It is also noteworthy that in the interpretations of the structure of the South Atlantic margins, the distal portion of the margin [*Moulin et al.*, 2005, Zone III] is characterized by a very thin crust, higly deformed over at least 100 km width, which is interpreted as the result of ductile deformation and boudinage [*Unternehr et al.*, 2010]. Analog modeling may also provide valuable analogs involving boudinage of the crust during extension [*Gartrell*, 1997]

The formation of crustal boudins is proposed by *Reston* [1988], who considers that lower crust may have a semibrittle behavior with the formation of low-strain lenses, 10 km long in average, separated by shear zones (Figure 7c). In such a model applied to passive margin formation, the crustal boudins are never exhumed to the surface and remain hidden by the tilted blocks of the upper crust [*Reston*, 2007]. Therefore, this model does not fit with the geological constraints from the Pyrenean system where the crustal boudins are uplifted and tectonically underlie the prerift sediments. In the cartoon of Figure 7c, we propose an alternative model deriving from the *Reston* [2007] model in which the upper crust is also boudinaged. We assume that such a model may apply to the NPZ case.

5.4. Variability in Stretching Modes and Subsidence

The distal part of the Eastern domain is characterized by a sedimentation apparently controlled by subsidence without intervening major high-angle normal faults. As such, it resembles the nonbrittle regional subsidence of the sag basins described in the literature where it is attributed to the extension of the lower crust through continuous ductile deformation [*Driscoll and Karner*, 1998; *Unternehr et al.*, 2010] or through boudinage [*Brun and Beslier*, 1996]. In the eastern part of the Pyrenean paleomargin, the alternation of crustal boudins separated by interboudins of peridotite and prerift metasediments may induce strong side effects diminishing the isostatic subsidence expected for exhumed peridotites (Figures 5 and 6c). This effect, along with the hot thermal regime may lead to shallow mantle exhumation, a scenario already proposed in the Lherz region [*Clerc et al.*, 2014]. The question of mantle exhumation at shallow level also arises from the examination of current distal passive margins. The deposition of thick evaporite formations on the hyperthinned domain of the Angolan and Brazilian conjugate margins [*Evans*, 1978; *Nürnberg and Müller*, 1991; *Jackson et al.*, 2000; *Heine et al.*, 2013] may suggest indeed a shallow marine environment among other possible interpretations.

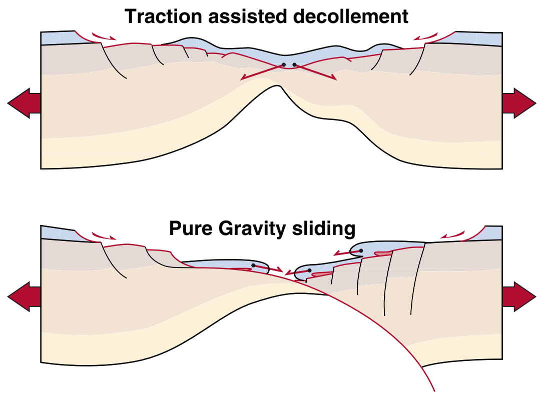

Figure 8. Behavior of the Mesozoic cover (blue) in response to lateral extrusion of the crust (light brown). Two end-member models involving cover decollement followed by gravitational sliding (up) or static behavior of the sediments with no relative movement with respect to the mantle (down).

In the Central domain of the NPZ, there is a sharp transition between the "faulted margin" and the zone of unroofed mantle. This may suggest that the subcontinental mantle has been uplifted and was located very close beneath the faulted crust following the rifting, a situation reported and discussed in Figure 6b. The Central domain appears as a transitional domain between the cooler, fault-dominated Western domain (Figure 6a) and the hotter and smoother Eastern domain (Figure 6c). This reflects an important variability in the modes of crustal thinning along the 400 km of the Pyrenean domain.

5.5. Behavior of the Prerift Sediments: Gravity Sliding Versus Tectonic Coupling

Previous articles have emphasized the importance of tectonic decoupling between the Mesozoic sedimentary cover and the underlying basement leading to the juxtaposition of Mesozoic sediments directly on top of mantle peridotites [*Lagabrielle et al*., 2010; *Jammes et al*., 2010]. This process points to the connection between a deep detachment fault (that favors mantle unroofing) and levels of decollement at the base of the prerift sedimentary cover (that tends to hide the exhumed mantle). The model of slide rafts was mainly based on the examples from the Western domain where evidences of gravity gliding are found. It implies that a large domain is created with slopes allowing the gravity displacement of the sediments. Such processes are observed along the southern Australian margin where seismic profiles reveal relationships between mantle and sediments which involve large gliding of thick sedimentary piles on exhuming mantle [*Espurt et al*., 2009]. This is consistent with the presence of large border faults and the opening of a wide Cretaceous basin such as expected toward the Bay of Biscay oceanic crust. We now question the application of this model to the Eastern domain because of two reasons. (1) Due to the intensity of the ductile shearing, we are not able to individualize here major rafts, as it was possible in the Western Pyrenees. (2) Our reconstruction of the paleotopography points to relative smooth topography contrasting with the steep borders of the Western basin, a situation not in favor of gravity sliding. Therefore, in Figure 8, we propose an alternative model to the gravity sliding of sediment rafts in which the sedimentary cover do not move relatively to the mantle during the extraction of the ductile crust. This model accounts for a deformation mode of the metasediments with dominant flattening and boudinage. This deformation pattern is consistent with the internal structure of the strongly sheared Mesozoic sedimentary remnants underlying the Albian flysch at the edges of the Boucheville and Agly basins [*Vauchez et al*., 2013].

5.6. Lateral Extraction of the Crust and Significance of Granulites

Remnants of granulitized crust exposed within the tilted North Pyrenean massifs and as small slices along the main faults of the NPZ display the highest grade of metamorphism observed nowadays in the Pyrenees, including the Axial Zone (Figure 2b). Considering the intensity of the Cretaceous metamorphism affecting the prerift and synrift Mesozoic sediments (frequently $>$600°C; Figure 2a), one must reconsider the intensity of the metamorphism in the Paleozoic basement and the possible local granulitization of continental crust during the Cretaceous (Figure 9a). For *Vielzeuf and Kornprobst* [1984], the granulites probably represent the lowermost part of the crust during Variscan times, later retrogressed by erosion and crustal thinning, with a possible superposition of the HT-LP Cretaceous metamorphism (Figure 9b). Considering the 3.5 to 7.5 kbar pressures recorded in these rocks, we question this attribution to the lower crust. For us, they may either represent lower crustal units granulitized at midcrustal level (Figure 9a, case 1), middle crust granulitized in situ (Figure 9a, case 2), or thinned lower and middle crust granulitized at midcrustal level (Figure 9a, case 3). In the second case, remnants of the lower crust would be generally lacking in the Pyrenean realm.

In any case, with the granulites representing either the lower or middle crust, we note two pressure gaps between (i) the Mesozoic sedimentary cover ($P \leq 4$ Kb) [*Golberg and Leyreloup*, 1990] and the mantle peridotites (depth = 45–50 km) [*Fabriès et al*., 1991] and between (ii) the granulites and the mantle peridotites.

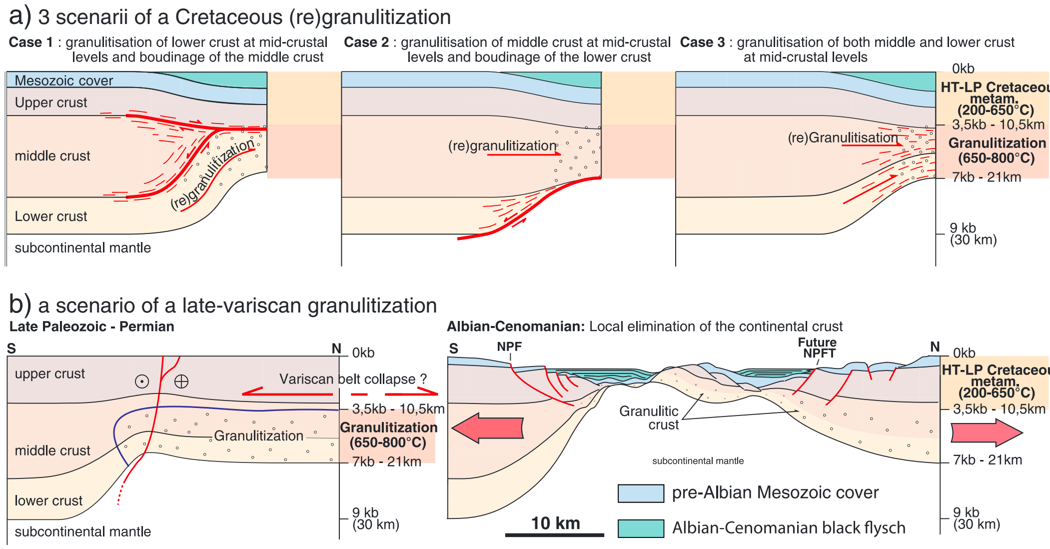

Figure 9. Cartoons showing different hypothesis for the origin and significance of the granulites exposed in the NPZ.

These two pressure gaps imply the existence of at least two efficient extensional structures of lithospherical scale responsible for the juxtaposition of these very different rock types. Our review above points toward a progressive elimination of the continental crust to explain the origin of these gaps.

High-grade Paleozoic material is overrepresented in the NPZ in regards to the Axial Zone (Figures 2b and 2c). If a continuous granulitic layer was present at the base of the post-Variscan crust, it would have been exhumed as well by the thrusts responsible for the uplift of the deep part or the axial zone. We are well aware that this remark does not eliminate a late Variscan age for the granulitization, with these rocks being located along a Paleozoic lineament at the emplacement of the future NPZ. Therefore, the problem is rather complex and we may envision either (i) a Cretaceous high grade metamorphism of these rocks responsible for their (re) granulitization (Figure 9a) or (ii) the strong localizing control of the Paleozoic heritage on the structuration of the Cretaceous Breakup (Figure 9b).

In Figure 9, we illustrate the different possible situations and we show the good superposition of the P, T fields of the HT metamorphic event in the Mesozoic sediments on one hand and of the granulites of the NPZ on the other hand. This superposition is consistent with the hypotheses of a Cretaceous (re)granulitization.

5.7. Underthinning of the Prerift Cover and Exhumation From Beneath the Flysch Pile

The ages of the HT-LP metamorphism obtained on metasediments from the paleomargin give a bracket between 97 and 85 Ma, that is, Cenomanian to upper Coniacian–lower Santonian [*Albarède and Michard-Vitrac*, 1978a; *Golberg et al*., 1986; *Golberg and Maluski*, 1988]. Therefore, a very specific character of the NPZ is that deposition of flysch sediments was occurring as sediments belonging to the same basin were metamorphosed under HT conditions. This implies that the flysch pile served as a cover to account for the pressures recorded by the metamorphic assemblages, which fall in the range 0.5–4 Kb, most often around 0.5 to 1.5 kb, [*Bernus-Maury*, 1984; *Golberg and Leyreloup*, 1990]. This is in accordance with a burial under 3–6 km of sediments which can be reached by combining the entire thickness of the Albian flysch and one part or the entire thickness of the Cenomanian deposits [*Goujou et al*., 1988]. This value is consistent with depth expected at the foot of distal margins. In addition, studies of breccias deposits such as the Lherz breccias report the presence of clasts of the metamorphic metasediments and mantle rocks with the exclusion of any additional clast of nonmetamorphic sedimentary material [*Clerc et al*., 2012]. The origin of these breccias has been a matter of debate, but one interpretation implies an exhumation of the metamorphosed prerift cover coeval with the exposure of the mantle rocks on the basin floor following the deposition of a large part of the Albian flysch [*Lagabrielle and Bodinier*, 2008; *Clerc et al*., 2012, 2014]. In order to take into account these constraints, we assume that in the ultimate stage of the margin evolution, that is, during mantle rocks exhumation, the continuous extension of the basin floor triggered the exhumation of the prerift Mesozoic cover from beneath the flysch pile (tectonic underthinning). This cover has been ductily deformed in response to the syn-metamorphic extensional deformation in the most distal part of the margin.

One of the important consequences of this interpretation is that during the basal synsedimentary extraction, the prerift sediments underwent an important deformation responsible for the unconformity observed at the base of the Cenomanian deposits. The field and cartographic pattern of this unconformity suggests that the precenomanian tectonics was dominated by extensional movements responsible for subtractive accidents, decollements and raft tectonics affecting mainly the prerift sediments and the base of the Albian Flysch (Figure 4b). After the Pyrenean tectonic inversion, this process may lead to a geological pattern in the field consistent with what is related to the so-called "Phase Pré-Cénomanienne," including the unconformity of the Cenomanian deposits over various terms of the metamorphic prerift sequence. Such basal tectonic underthinning leading to unconformities between clastic deposits is reported from the regions of present-day continental margin consisting of hyperextended continental crust and zones of exposed subcontinental mantle [*Unternehr et al*., 2010; *Masini et al*., 2012].

At present, very few examples of hot and mobile basins over distal margin exhuming subcontinental mantle or deep crust are reported from the mountain belts worldwide. In the Zagros mountains, mapping reveals that prerift cover and mantle have been early superposed in the Kermanshah ophiolite [*Wrobel-Daveau et al*., 2010], where high temperature are recorded in the Mesozoic sediments along their contact with the peridotites [*Hall*, 1980]. In the Zagros of Iraq, *Jassim et al*. [1982] described similar metamorphism affecting sediments close to exhumed ultramafic rocks with temperatures up to 750°C over 2.5 km thickness.

6. Conclusions

In this article, we have shown that the major character of the NPZ evolution is that prerift sediments have been intensively deformed and metamorphosed during crustal thinning leading to continental breakup and to mantle unroofing. The tectonic and metamorphic evolution of the eastern NPZ Basins is consistent with extensional tectonics under an abnormally high geothermal gradient in relation with crustal thinning during the mid-Cretaceous.

The "boudinage" of the continental crust occurred under thermal conditions allowing coeval ductile deformation of the acidic basement and of the prerift sediments leading to the widening of an internal basin devoid of large faulted blocks and lacking scarps exposing the Paleozoic crustal rocks.

We have highlighted the original architecture of a continental margin revealing different features poorly recognized at present in other mountain belts or along current passive margin. These features point to a type of continental margin showing the following characters:

1. There are rapid changes in the modes of crustal thinning in response to the thermal evolution and to the migration of the rifting-related thermal anomaly. Cold continental crust of the proximal margin is thinned through large border faults and passes progressively to hot, strongly thinned, and boudinaged crust devoid of brittle structures.
2. Hot prerift sediments are tectonically resting on top of unroofed mantle as a consequence of the lateral extraction of the ductile crust. The thermal evolution of the metasediments is controlled by the geometry of the regions of exhumed mantle. The crustal boudins of continental crust may act as zones with lower thermal gradient.
3. The distal margin represents a sedimentary basin having a flat floor in which homogeneous thin-grained sediments (flyschs) are deposited. Due to continuous extension, the floor of the basin is mobile and is continuously extracted from below the sedimentary pile, leading to internal unconformities.

These systems are not accessible in present-day distal margins. Therefore, the data obtained from the Pyrenes are important to investigate the architecture and geological evolution of some present-day margins whose distal regions are still hardly reachable for in situ study. In particular, the high variability of structural and thermal modes which characterize the paleomargins at the scale of the sole Pyrenean domain has to be kept in mind when considering other margins worldwide.

Acknowledgments

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References

Albarède, F., and A. Michard-Vitrac (1978a), Datation du métamorphisme des terrains secondaires des Pyrénées par des méthodes Ar-Ar et Rb-Sr. Ses relations avec les péridotites associées, *Bull. Soc. Geol. Fr.*, *20*(7), 681–688, doi:10.1016/0012-821X(78)90157-7.

Albarède, F., and A. Michard-Vitrac (1978b), Age and significance of the North Pyrenean metamorphism, *Earth Planet. Sci. Lett.*, *40*(3), 327–332, doi:10.1016/0012-821X(78)90157-7.

Andrieux, P. (1982a), La charnockite d'Ansignan: Mise en place et évolution paragénétique. Introduction à l'étude des équilibres grenat-orthopyroxène. Thèse, Clermont-Ferrand.

Andrieux, P. (1982b), Conditions de cristallisation et évolution paragénétique d'une charnockite hercynienne: Le complexe granulitique d'Ansignan (massif de l'Agly, Pyrénées-Orentales), *Bull. Mineral.*, *105*, 253–266.

Azambre, B. (1967), Sur les roches intrusives sous-saturées du Crétacé des Pyrénées, Thèse, Paris: Université Paris 6.

Azambre, B., and P. Monchoux (1998), Métagabbros amphiboliques et mise en place crustale des lherzolites des Pyrénées (France), *C. R. Acad. Sci. Ser. IIA Earth Planet. Sci.*, *327*(1), 9–15, doi:10.1016/S1251-8050(98)80012-8.

Azambre, B., and J. Ravier (1978), Les écailles de gneiss du faciès granulite du port de Saleix et de la région de Lherz (Ariège), nouveaux témoins du socle profond des Pyrénées, *Bull. Soc. Geol. Fr.*, *20*(3), 221–228.

Azambre, B., and M. Rossy (1976), Le magmatisme alcalin d'âge crétacé dans les Pyrénées occidentales; ses relations avec le métamorphisme et la tectonique, *Bull. Soc. Geol. Fr.*, *7*(18), 1725–1728.

Azambre, B., F. Crouzel, E.-J. Debroas, J.-C. Soulé, and Y. Ternet (1989), Carte géol. France (1/50 000), feuille Bagnères-de-Bigorre (1053), Orléans.

Azambre, B., M. Rossy, and F. Albarède (1992), Petrology of the alkaline magmatism from the Cretaceous North-Pyrenean rift zone (France and Spain), *Eur. J. Mineral.*, *4*(4), 813–834.

Barbosa, J., and M. Fonteilles (1986), Examen critique des résultats fournis pas certains baromètres couramment utilisés en terrains granulitiques: Exemples des granulits de Bahia (Brésil) et du massif de l'Agly (France), *Bull. Mineral.*, *109*, 359–376.

Barrère, P., C. Bouquet, E.-J. Debroas, H. Pélissonier, B. Peybernès, J.-C. Soulé, P. Souquet, and Y. Ternet (1984), Notice explicative, Carte géol. France (1/50 000), feuille Arreau (1072), BRGM éditions, Orléans: BRGM.

Berger, G. M., M. Fonteilles, D. Leblanc, G. Clauzon, J. P. Marshal, and C. Vautrelle (1993), Notice explicative, in *Carte Géologique de la France á 1/50 000. 1090, Rivesaltes*, edited by M. Fonteilles et al., 117 pp., BRGM, Orléans.

Bernus-Maury, C. (1984), Etude des paragéneses caractéristiques du métamorphisme mésozoïque dans la partie orientale des Pyrénées, Thèse, Paris.

Bessière, G. (1987), Modèle d'évolution polyorogénique d'un massif hercynien: Le Massif de Mouthoumet (Pyrénées audoises), Thèse, Toulouse.

Bessière, G., M. Bilotte, B. Crochet, B. Peybernès, Y. Tambareau, and J. Villatte (1989), Notice explicative, Carte géol. France (1/50 000), feuille Quillan (1077), BRGM éditions, Orléans: BRGM.

Bilotte, M., E.-J. Debroas, P. Baby, G. Crouzet, J. Deramond, M. Bonnemaison, and D. Giot (1987), Rôle des chevauchements nord-pyrénéens et des massifs de l'Arize et du Saint-Bathélémy dans l'évolution tecto-sédimentaire et la structure des bassins flyschs du Crétacé. Programme National Géologie Profonde de la France (GPF3) 143. Thème 6: Allochtonie des massifs paléozoïques nords-pyrénéens, Orléans: BRGM.

Bodinier, J.-L., J. Fabriès, J.-P. Lorand, and C. Dupuy (1987), Geochemistry of amphibole pyroxenite veins from the Lherz and Freychinède ultramafic bodies (Ariège, French Pyrenees), *Bull. Mineral.*, *110*, 345–358.

Boillot, G., and N. Froitzheim (2001), Non-volcanic rifted margins, continental break-up and the onset of sea-floor spreading: Some outstanding questions, *Geol. Soc. London Spec. Publ.*, *187*(1), 9–30, doi:10.1144/GSL.SP.2001.187.01.02.

Boillot, G., S. Grimaud, A. Mauffret, D. Mougenot, J. Kornprobst, J. Mergoil-Daniel, and G. Torrent (1980), Ocean-continent boundary off the Iberian margin: A serpentinite diapir west of the Galicia Bank, *Earth Planet. Sci. Lett.*, *48*(1), 23–34, doi:10.1016/0012-821X(80)90166-1.

Boirie, J.-M. (1981), Etude sédimentologique des Poudingues de Mendibelza (P.A.), PhD thesis, Toulouse, France: Univ. de Toulouse.

Boirie, J.-M., and P. Souquet (1982), Les poudingues de Mendibelza: Dépôts de cônes sous-marins du rift albien des Pyrénées, *Bull. Cent. Rech. Explor.-Prod. Elf-Aquitaine*, *6*(2), 405–435.

Boissonnas, J., J. P. Destombes, C. Heddebaut, G. Le Pochat, S. Lorsignol, P. Roger, and Y. Ternet (1964), *Carte Géologique France (1/50 000), Feuille Iholdy (1027)*, edited by J. Boissonnas et al., 36 pp., BRGM, Orléans.

Bouhallier, H., P. Choukroune, and M. Ballèvre (1991), Evolution structurale de la croute profonde hercynienne; exemple du massif de l'Agly (Pyrénées orientales, France), *C. R. Acad. Sci. Paris Ser. II*, *312*, 647–654.

Boulvais, P., P. de Parseval, A. D'Hulst, and P. Paris (2006), Carbonate alteration associated with talc-chlorite mineralization in the eastern Pyrenees, with emphasis on the St. Barthelemy Massif, *Mineral. Petrol.*, *88*(3), 499–526, doi:10.1007/s00710-006-0124-x.

Boulvais, P., G. Ruffet, J. Cornichet, and M. Mermet (2007), Cretaceous albitization and dequartzification of Hercynian peraluminous granite in the Salvezines Massif (French Pyrénées), *Lithos*, *93*(1-2), 89–106, doi:10.1016/j.lithos.2006.05.001.

BRGM and IGME (1998), Synthèse géologique et géophysique des Pyrénées. Tectonique Hercynienne. Carte Struturale, vol. 1, Géologie Régionale.

Bronner, A., D. Sauter, G. Manatschal, G. Peron-Pinvidic, and M. Munschy (2011), Magmatic breakup as an explanation for magnetic anomalies at magma-poor rifted margins, *Nat. Geosci.*, *4*(8), 549–553, doi:10.1038/ngeo1201.

Brun, J. P., and M. O. Beslier (1996), Mantle exhumation at passive margins, *Earth Planet. Sci. Lett.*, *142*(1-2), 161–173, doi:10.1016/0012-821X(96)00080-5.

Canérot, J., and E.-J. Debroas (1988), Remise en question du "Comlexe de resédimentation albo-cénomanien de la zone nord-Pyrénéenne, *C. R. Acad. Sci. Paris Ser. II*, *307*, 1711–1716.

Casteras, M. (1933), Recherches sur la structure du versant nord des Pyrénées centrales et orientales, *Serv. Carte Géol. Fr.*, *37*(189), 515.

Casteras, M., M Villanova, Y. Godechot, J.-J. Blanc, A. Labourguigne, B. Azambre, and H. Alimen (1970a), Carte géol. France (1/50 000), feuille Lourdes (1052), Orléans.

Casteras, M., J. Canérot, J.-P. Paris, D. Tisin, B. Azambre, and H. Alimen (1970b), Carte géol. France (1/50 000), feuille Oloron-Sainte-Marie (1051), Orléans.

Casteras, M., M. Gottis, M. Clin, J. Guignard, and J.-P. Paris (1971), Carte géol. France (1/50 000), feuille Tardets-Sorholus (1050), Orléans.

Cathelineau, M., M.-C. Boiron, S. Fourcade, G. Ruffet, N. Clauer, O. Belcourt, Y. Coulibaly, D. A. Banks, and F. Guillocheau (2012), A major Late Jurassic fluid event at the basin/basement unconformity in western France: 40Ar/39Ar and K–Ar dating, fluid chemistry, and related geodynamic context, *Chem. Geol.*, *322–323*, 99–120, doi:10.1016/j.chemgeo.2012.06.008.

Choukroune, P. (1976), Structure et Evolution Tectonique de la Zone Nord Pyrénéenne: Analyse de la déformation dans une Portion de Chaîne à Schistosité Subverticale, *Mem. Soc. Geol. Fr. Ser.*, (127), 176.

Choukroune, P., and M. Mattauer (1978), Tectonique des plaques et Pyrénées: Sur le fonctionnement de la faille transformante nord-Pyrénéenne; comparaisons avec les modèles actuels, *Bull. Soc. Geol. Fr.*, *20*, 689–700.

Choukroune, P., and M. Séguret (1973), Carte structurale des Pyrénées. ELF-ERAP.

Clerc, C. (2012), Evolution du domaine Nord-Pyrénéen au Crétacé. Amincissement crustal extreme et thermicité élevée: Un analogue pour les marges passives, PhD thesis, Paris, France: Université Paris 6. [Available at http://tel.archives-ouvertes.fr/tel-00787952.]

Clerc, C., Y. Lagabrielle, M. Neumaier, J.-Y. Reynaud, and M. Saint-Blanquat (2012), Exhumation of subcontinental mantle rocks: Evidence from ultramafic-bearing clastic deposits nearby the Lherz Peridotite Body, French Pyrenees, *Bull. Soc. Geol. Fr.*, *183*(5), 443–459, doi:10.2113/gssgfbull.183.5.443.

Clerc, C., P. Boulvais, Y. Lagabrielle, and M. de Saint Blanquat (2014), Ophicalcites from the Northern Pyrenean Belt: A field, petrographic and stable isotope study, *Int. J. Earth Sci.*, *103*, 141–163, doi:10.1007/s00531-013-0927-z.

Colchen, M., Y. Ternet, and E.-J. Debroas (1997), Carte géol. France (1/50 000), feuille 1086, Aulus-les-Bains, Orléans.

Conquéré, F. (1971), La lherzolite à amphibole du gisement de Caussou (Ariège, France), *Contrib. Mineral. Petrol.*, *30*(4), 296–313, doi:10.1007/BF00404725.

Contrucci, I., L. Matias, M. Moulin, L. Géli, F. Klingelhofer, H. Nouzé, D. Aslanian, J.-L. Olivet, J.-P. Réhault, and J.-C. Sibuet (2004), Deep structure of the West African Continental Margin (Congo, Zaïre, Angola), between 5°S and 8°S, from reflection/refraction seismics and gravity data, *Geophys. J. Int.*, *158*(2), 529–553, doi:10.1111/j.1365-246X.2004.02303.x.

Costa, S., and H. Maluski (1988), Use of the 40Ar-39Ar stepwise heating method for dating mylonite zones: An example from the St. Barthélémy massif (Northern Pyrenees, France), *Chem. Geol. Isot. Geosci. Sect.*, *72*(2), 127–144, doi:10.1016/0168-9622(88)90061-9.

Crochet, B., J. Villatte, Y. Tambareau, M. Bilotte, J.-P. Bousquet, A. Kuhfuss, J. P. Bouillin, J.-P. Gelard, G. Bessière, and J.-P. Paris (1989), Carte géol. France (1/50 000), feuille Quillan (1077), Orléans.

Dauteuil, O., and L. E. Ricou (1989), Une circulation de fluides de haute température à l'origine du métamorphisme crétacé nord-Pyrénéen, *Geodin. Acta*, *3*(3), 237–250.

Debroas, E.-J. (1976), Sédimentogenèse et position structurale des flyschs crétacés du versant nord des Pyrénées centrales, *Bull. Bur. Rech. Géol. Min.*, *1*(4), 305–320.

Debroas, E.-J. (1978), Evolution de la fosse du flysch ardoisier de l'albien supérieur au Sénonien inférieur (zone interne métamorphique des Pyrénées navarro-langudociennes), *Bull. Soc. Geol. Fr.*, *20*, 639–648.

Debroas, E.-J. (1990), Le flysch noir albo-cenomanien témoin de la structuration albienne à sénonienne de la Zone nord-pyrénéenne en Bigorre (Hautes-Pyrénées, France), *Bull. Soc. Geol. Fr.*, *8*(2), 273–285.

Debroas, E.-J., J. Canérot, and M. Billotte (2010), Les brèches d'Urdach, témoins de l'exhumation du manteau pyrénéen dans un escarpement de faille vraconnien-cénomanien inférieur (zone nord-pyrénéenne, Pyrénées-Atlantiques, France), *Géol. Fr.*, *2*, 53–63.

Destombes, J. P., E. Raguin, and M. Casteras (1969), Carte géol. France (1/50 000), feuille Vicdessos (1087), Orléans.

Driscoll, N. W., and G. D. Karner (1998), Lower crustal extension across the Northern Carnarvon Basin, Australia: Evidence for an eastward dipping detachment, *J. Geophys. Res.*, *103*(B3), 4975–4991, doi:10.1029/97JB03295.

Ducasse, L., P. C. Vélasque, and J. Muller (1986), Glissement de couverture et panneaux basculés dans la région des Arbailles (Pyrénées Occidentales): Un modèle évolutif crétacé de la marge nord-Ibérique à l'Est de la transformante de Pamplona, *C. R. Acad. Sci. Paris Ser. II*, *303*, 1477–1482.

Durand-Delga, M. (1964), Remarques sur la stratigraphie et la structure du Mésozoïque situé entre Estagel et Perpignan (Pyrénées-Orientales), *C. R. Acad. Sci. Paris*, *259*, 837–840.

Durand-Delga, M. (1965), Au sujet de la phase anté-cénomanienne à l'Est de Quillan, *C. R. Somm. Soc. Geol. Fr.*, 61–62.

Espurt, N., J.-P. Callot, J. Totterdell, H. Struckmeyer, and R. Vially (2009), Interactions between continental breakup dynamics and large-scale delta system evolution: Insights from the Cretaceous Ceduna delta system, Bight Basin, Southern Australian margin, *Tectonics*, *28*, TC6002, doi:10.1029/2009TC002447.

Evans, R. (1978), Origin and significance of evaporites in basins around Atlantic margin, *Am. Assoc. Petrol. Geol. Bull.*, *62*, 223–234.

Fabriès, J., J.-P. Lorand, J.-L. Bodinier, and C. Dupuy (1991), Evolution of the upper mantle beneath the Pyrenees: Evidence from orogenic spinel lherzolite massifs, in *Journal Petrology, Special Lherzolites Issue*, edited by M. A. Menzies, C. Dupuy, and A. J. Nicolas, pp. 55–76, Oxford, doi:10.1093/petrology/Special_Volume.2.55.

Fallourd, S., M. Poujol, P. Boulvais, J. L. Paquette, M. Saint Blanquat, and P. Rémy (2014), In situ LA-ICP-MS U–Pb titanite dating of Na–Ca metasomatism in orogenic belts: The North Pyrenean example, *Int. J. Earth Sci.*, 1–16, doi:10.1007/s00531-013-0978-1.

Froitzheim, N., and G. P. Eberli (1990), Extensional detachment faulting in the evolution of a Tethys passive continental margin, Eastern Alps, Switzerland, *Geol. Soc. Am. Bull.*, *102*(9), 1297–1308, doi:10.1130/0016-7606(1990)102<1297:EDFITE>2.3.CO;2.

Froitzheim, N., and G. Manatschal (1996), Kinematics of Jurassic rifting, mantle exhumation, and passive-margin formation in the Austroalpine and Penninic nappes (eastern Switzerland), *Geol. Soc. Am. Bull.*, *108*(9), 1120–1133, doi:10.1130/0016-7606(1996)108<1120:KOJRME>2.3.CO;2.

Gartrell, A. P. (1997), Evolution of rift basins and low-angle detachments in multilayer analog models, *Geology*, *25*(7), 615–618, doi:10.1130/0091-7613(1997)025<0615:EORBAL>2.3.CO;2.

Golberg, J.-M. (1987), *Le Métamorphisme Mésozoïque Dans La Partie Orientale Des Pyrénées: Relation Avec l'évolution De La Chaîne Au Crétacé*, *Doc. Trav. Centre Geol. Geophys. Montpellier*, vol. 14, Université des Sciences et Techniques du Languedoc, Montpellier.

Golberg, J.-M., and A.-F. Leyreloup (1990), High temperature-low pressure Cretaceous metamorphism related to crustal thinning (Eastern North Pyrenean Zone, France), *Contrib. Mineral. Petrol.*, *104*(2), 194–207, doi:10.1007/BF00306443.

Golberg, J.-M., and H. Maluski (1988), Données nouvelles et mise au point sur l'âge du métamorphisme pyrénéen, *C. R. Acad. Sci. Paris*, *306*, 429–435.

Golberg, J.-M., H. Maluski, and A.-F. Leyreloup (1986), Petrological and age relationship between emplacement of magmatic breccia, alkaline magmatism, and static metamorphism in the North Pyrenean Zone, *Tectonophysics*, *129*(1–4), 275–290, doi:10.1016/0040-1951(86)90256-8.

Goujou, J. C. (1987), *Le métamorphisme mésozoïque dans les Pyrénées centrales. Exemple du bassin de la Ballongue (Ariège, Haute-Garonne)*, edited by D. E. A. de Mémoire, Universite de Montpellier II, Montpellier, France.

Goujou, J. C., J.-M. Golberg, and A.-F. Leyreloup (1988), Réactions de décarbonation dans les roches calcaréo-pélitiques de la Ballongue (zone nord pyrénéenne. 1. Formation de biotite et de plagioclase, *C. R. Acad. Sci. Paris Ser. II*, *307*, 39–44.

Hall, R. (1980), Contact metamorphism by an ophiolite peridotite from Neyriz, Iran, *Science*, *208*(4449), 1259–1262, doi:10.1126/science.208.4449.1259.

Heine, C., J. Zoethout, and R. D. Müller (2013), Kinematic of the South Atlantic rift, *Solid Earth*, *4*, 215–253, doi:10.5194/se-4-215-2013.

Henry, P., B. Azambre, R. Montigny, M. Rossy, and R. K. Stevenson (1998), Late mantle evolution of the Pyrenean sub-continental lithospheric mantle in the light of new 40Ar-39Ar and Sm-Nd ages on pyroxenites and peridotites (Pyrenees, France), *Tectonophysics*, *296*(1-2), 103–123, doi:10.1016/S0040-1951(98)00139-5.

Hervouët, Y., X. Torné, A. Fortané, G. Duée, and J. Delfaud (1987), Resédimentation chaotique de méta-ophites et de marbres mésozoïques de la vallée du Job (Pyrénées commingeoises): Relations détritisme/métamorphisme en zone nord-Pyrénéenne, *C. R. Acad. Sci.*, *305*(8), 721–726.

Huismans, R., and C. Beaumont (2011), Depth-dependent extension, two-stage breakup and cratonic underplating at rifted margins, *Nature*, *473*(7345), 74–78, doi:10.1038/nature09988.

Jackson, M. P. A., C. Cramez, and J.-M. Fonck (2000), Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins, implications for salt tectonics and source rocks, *Mar. Pet. Geol.*, *17*, 477–498.

Jammes, S., G. Manatschal, L. Lavier, and E. Masini (2009), Tectonosedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees, *Tectonics*, *28*, TC4012, doi:10.1029/2008TC002406.

Jammes, S., G. Manatschal, and L. Lavier (2010), Interaction between prerift salt and detachment faulting in hyperextended rift systems: The example of the Parentis and Mauléon basins (Bay of Biscay and western Pyrenees), *AAPG Bull.*, *94*(7), 957–975, doi:10.1306/12090909116.

Jassim, S. Z., G. Buda, M. Neuzilova, and M. Suk (1982), Metamorphic development of the Iraqui Zagros ophiolite zone, *Krystalinikum*, *16*, 21–40.

Lacroix, A. (1900), Sur l'origine des brèches calcaires secondaires de l'Ariège: Conséquences à en tirer au point de vue de l'âge de la lherzolite, *C. R. Acad. Sci. Paris*, *131*, 96–98.

Lagabrielle, Y., and J.-L. Bodinier (2008), Submarine reworking of exhumed subcontinental mantle rocks: Field evidence from the Lherz peridotites, French Pyrenees, *Terra Nova*, *20*(1), 11–21, doi:10.1111/j.1365-3121.2007.00781.x.

Lagabrielle, Y., P. Labaume, and M. St Blanquat (2010), Mantle exhumation, crustal denudation, and gravity tectonics during Cretaceous rifting in the Pyrenean realm (SW Europe): Insights from the geological setting of the lherzolite bodies, *Tectonics*, *29*, TC4012, doi:10.1029/2009TC002588.

Lemoine, M., P. Tricart, and G. Boillot (1987), Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Apennines): In search of a genetic model, *Geology*, *15*(7), 622–625, doi:10.1130/0091-7613(1987)15<622:UAGOFO>2.0.CO;2.

Leroy, S., etal. (2010), Contrasted styles of rifting in the Eastern Gulf of Aden: A combined wide-angle, multichannel seismic, and heat flow survey, *Geochem. Geophys. Geosyst.*, *11*, Q07004, doi:10.1029/2009GC002963.

Manatschal, G. (2004), New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps, *Int. J. Earth Sci.*, *93*(3), 432–466, doi:10.1007/s00531-004-0394-7.

Manatschal, G., and P. Nievergelt (1997), A continent-ocean transition recorded in the Err and Platta nappes (eastern Switzerland), *Eclogae Geol. Helv.*, *90*, 3–27.

Manatschal, G., N. Froitzheim, M. Rubenach, and B. D. Turrin (2001), The role of detachment faulting in the formation of an ocean-continent transition: Insights from the Iberia Abyssal Plain, *Geol. Soc. London Spec. Publ.*, *187*(1), 405–428, doi:10.1144/GSL.SP.2001.187.01.20.

Masini, E., G. Manatschal, G. Mohn, and P. Unternehr (2012), Anatomy and tectono-sedimentary evolution of a rift-related detachment system: The example of the err detachment (central Alps, SE Switzerland), *Geol. Soc. of Am. Bull.*, *124*(9–10), 1535–1551, doi:10.1130/B30557.1.

Masini, E., G. Manatschal, J. Tugend, G. Mohn, and J. M. Flament (2014), The tectono-sedimentary evolution of a hyper-extended rift basin: The example of the Arzacq–Mauléon rift system (Western Pyrenees, SW France), *Int. J. Earth Sci.*, 1–28, doi:10.1007/s00531-014-1023-8.

Mattauer, M., and F. Proust (1965), Sur la présence et la nature de deux importantes phases tectoniques dans les terrains secondaires des Pyrénées orientales, *C. R. Somm. Soc. Geol. Fr.*, *4*, 132–133.

Montigny, R., B. Azambre, M. Rossy, and R. Thuizat (1986), K-Ar study of cretaceous magmatism and metamorphism in the pyrenees: Age and length of rotation of the liberian Peninsula, *Tectonophysics*, *129*(1-4), 257–273, doi:10.1016/0040-1951(86)90255-6.

Moulin, M., D. Aslanian, J.-L. Olivet, I. Contrucci, L. Matias, L. Géli, F. Klingelhoefer, H. Nouzé, J.-P. Réhault, and P. Unternehr (2005), Geological constraints on the evolution of the Angolan margin based on reflection and refraction seismic data (Zaïngo Project), *Geophys. J. Int.*, *162*(3), 793–810, doi:10.1111/j.1365-246X.2005.02668.x.

Nürnberg, D., and R. D. Müller (1991), The tectonic evolution of the South Atlantic from Late Jurassic to present, *Tectonophysics*, *191*, 27–53.

Olivet, J. L. (1996), La cinématique de la plaque ibérique, *Bull. Cent. Rech. Explor. Prod. Elf-Aquitaine*, *20*(1), 131–195.

Osmundsen, P. T., and J. Ebbing (2008), Styles of extension offshore mid-Norway and implications for mechanisms of crustal thinning at passive margins, *Tectonics*, *27*, TC6016, doi:10.1029/2007TC002242.

Paquet, J., and J.-L. Mansy (1991), La structure de l'Est des Pyrénées (transversales du massif de l'Agly): Un exemple d'amincissement crustal, *C. R. Acad. Sci. Ser. II*, *312*, 913–919.

Passchier, C. W. (1984), Mylonite-dominated footwall geometry in a shear zone, central Pyrenees, *Geol. Mag.*, *121*(05), 429–436, doi:10.1017/S0016756800029964.

Péron-Pinvidic, G., and G. Manatschal (2008), The final rifting evolution at deep magma-poor passive margins from Iberia-Newfoundland: A new point of view, *Int. J. Earth Sci.*, *98*(7), 1581–1597, doi:10.1007/s00531-008-0337-9.

Péron-Pinvidic, G., G. Manatschal, T. A. Minshull, and D. S. Sawyer (2007), Tectonosedimentary evolution of the deep Iberia-Newfoundland margins: Evidence for a complex breakup history, *Tectonics*, *26*, TC2011, doi:10.1029/2006TC001970.

Poujol, M., P. Boulvais, and J. Kosler (2010), Regional-scale Cretaceous albitization in the Pyrenees: Evidence from in situ U-Th-Pb dating of monazite, titanite and zircon, *J. Geol. Soc.*, *167*(4), 751–767, doi:10.1144/0016-76492009-144.

Reston, T. J. (1988), Evidence for shear zones in the lower crust offshore Britain, *Tectonics*, *7*(5), 929–945, doi:10.1029/TC007i005p00929.

Reston, T. J. (2007), The formation of non-volcanic rifted margins by the progressive extension of the lithosphere: The example of the west Iberian margin, *Geol. Soc. London Spec. Publ.*, *282*(1), 77–110, doi:10.1144/SP282.5.

Rossy, M., B. Azambre, and F. Albarède (1992), REE and Sr/1bNd isotope geochemistry of the alkaline magmatism from the Cretaceous North Pyrenean Rift Zone (France-Spain), *Chem. Geol.*, *97*(1–2), 33–46, doi:10.1016/0009-2541(92)90134-Q.

Schärer, U., P. de Parseval, M. Polvé, and M. St Blanquat (1999), Formation of the Trimouns talc-chlorite deposit (Pyrenees) from persistent hydrothermal activity between 112 and 97 Ma, *Terra Nova*, *11*(1), 30–37, doi:10.1046/j.1365-3121.1999.00224.x.

Sibuet, J.-C. (2004), Pyrenean orogeny and plate kinematics, *J. Geophys. Res.*, *109*, B08104, doi:10.1029/2003JB002514. [Available at http://archimer.ifremer.fr/doc/00000/10837/.]

Souquet, P., E.-J. Debroas, J.-M. Boirie, P. Pons, G. Fixari, J. Dol, J.-P. Thieuloy, M. Bonnemaison, H. Manivit, and B. Peybernès (1985), Le groupe du Flysch noir (albo-cénomanien) dans les Pyrénées, *Bull. Cent. Rech. Exlpo. Prod. Elf-Aquitaine Pau*, *9*(1), 183–252.

St Blanquat, M. (1993), La faille normale ductile du massif du Saint Barthélémy: Evolution hercynienne des massifs nord-pyrénéens catazonaux considérée du point de vue de leur histoire thermique, *Geodin. Acta*, *6*(1), 59–77.

St Blanquat, M., M. Brunel, and M. Mattauer (1986), Les zones de cisaillements du massif nord Pyrénéen du Saint-Bartelemy, témoins probables del'extension crustale d'âge crétacé, *C. R. Acad. Sci.*, *303*, 1339–1344.

St Blanquat, M., J. M. Lardeaux, and M. Brunel (1990), Petrological arguments for high-temperature extensional deformation in the Pyrenean Variscan crust (Saint Barthélémy Massif, Ariège, France), *Tectonophysics*, *177*(1-3), 245–262, doi:10.1016/0040-1951(90)90284-F.

Sutra, E. M. (2011), *Caractérisation et Quantification de la Déformation Extensive des Marges Passives Peu Magmatiques Profondes: Exemples des Marges Ibérie-Terre Neuve et Sud-Atlantiques*, Université de Strasbourg, Strasbourg. [Availabe at http://www.theses.fr/2011STRA6232.]

Thiébaut, J., M. Debeaux, E.-J. Debroas, and P. Souquet (1979), Découverte de roches d'affinités teschenitiques dans les marbres mésozoïques de Saint-Béat (Haute-Garonne), *C. R. Acad. Sci. Paris*, *288*(23), 1695–1697.

Tucholke, B. E., D. S. Sawyer, and J.-C. Sibuet (2007), Breakup of the Newfoundland Iberia rift, *Geol. Soc. London Spec. Publ.*, *282*(1), 9–46, doi:10.1144/SP282.2.

Unternehr, P., G. Péron-Pinvidic, G. Manatschal, and E. Sutra (2010), Hyper-extended crust in the South Atlantic: In search of a model, *Petrol. Geosc.*, *16*(3), 207–215, doi:10.1144/1354-079309-904.

Vauchez, A., C. Clerc, L. Bestani, Y. Lagabrielle, A. Chauvet, A. Lahfid, and D. Mainprice (2013), Preorogenic exhumation of the North Pyrenean Agly Massif (Eastern Pyrenees-France), *Tectonics*, *32*(2), 95–106, doi:10.1002/tect.20015.

Vershure, R. H., E. H. Hebeda, N. A. Boelrigh, H. N. A. Priem, and H. G. Avé Lallemant (1967), K/Ar age of hornblende from hornblendite vein in the alpine ultramafic mass of the Etang de Lers (Ariège), French Pyrénées, *Leidse Geol. Meded.*, *42*, 59–60.

Vétil, J.-Y., J.-P. Lorand, and J. Fabriès (1988), Conditions de mise en place des filons des pyroxénites à amphibole du massif ultramafique de Lherz (Ar!ège, France), *C. R. Acad. Sci. Paris*, *307*, 587–593.

Vielzeuf, D. (1980), Pétrologie des écailles granulitiques de la région de Lherz (Ariège). Thèse de 3ème cycle, Clermont-Ferrand.

Vielzeuf, D. (1984), Relations de phases dans le faciès granulite et implications géodynamiques. L'exemple des granulites des pyrénées. Thèse, Clermont-Ferrand.

Vielzeuf, D., and J. Kornprobst (1984), Crustal splitting and the emplacement of Pyrenean lherzolites and granulites, *Earth Planet. Sci. Lett.*, *67*(1), 87–96, doi:10.1016/0012-821X(84)90041-4.

Vissers, R. L. M., M. R. Drury, J. Newman, and T. F. Fliervoet (1997), Mylonitic deformation in upper mantle peridotites of the North Pyrenean Zone (France): Implications for strength and strain localization in the lithosphere, *Tectonophysics*, *279*(1-4), 303–325, doi:10.1016/S0040-1951(97)00128-5.

Whitmarsh, R. B., G. Manatschal, and T. A. Minshull (2001), Evolution of magma-poor continental margins from rifting to seafloor spreading, *Nature*, *413*(6852), 150–154.

Wrobel-Daveau, J.-C., J.-C. Ringenbach, S. Tavakoli, G. Ruiz, P. Masse, and D. Frizon de Lamotte (2010), Evidence for mantle exhumation along the Arabian margin in the Zagros (Kermanshah area, Iran), *Arabian J. Geosci.*, *3*(4), 499–513, doi:10.1007/s12517-010-0209-z.