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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

Yves Lagabriele,¹ Pierre Labaume,¹ and Michel de Saint Blanquat²

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[1] The Pyrenean peridotites (lherzolites) form numerous small bodies of subcontinental mantle, a few meters to 3 km across, exposed within the narrow north Pyrenean zone (NPZ) of Mesozoic sediments paralleling the north Pyrenean Fault. Recent studies have shown that mantle exhumation occurred along the future NPZ during the formation of the Albian-Cenomanian Pyrenean basins in relation with detachment tectonics. This paper reviews the geological setting of the Pyrenean lherzolite bodies and reports new detailed field data from key outcrops in the Béarn region. Only two types of geological settings have to be distinguished among the Pyrenean ultramafic bodies. In the first type (sedimented type or S type), the lherzolites occur as clasts of various sizes, ranging from millimetric grains to hectometric olistoliths, within monogenic or polymictic debris flow deposits of Cretaceous age, reworking Mesozoic sediments in dominant proportions as observed around the Lherz body. In the second type (tectonic type or T type), the mantle rocks form hectometric to kilometer slices associated with crustal tectonic lenses. Both crustal and mantle tectonic lenses are in turn systematically associated with large volumes of strongly deformed Triassic rocks and have fault contacts with units of deformed Jurassic and Lower Cretaceous sediments belonging to the cover of the NPZ. These deformed Mesozoic formations are not older than the Aptian-early Albian. They are unconformably overlain by the Albian-Cenomanian flysch formations and have experienced high temperature-low pressure mid-Cretaceous metamorphism at variable grades. Such a tectonic setting characterizes most of the lherzolite bodies exposed in the western Pyrenees. These geological data first provide evidence of detachment tectonics leading to mantle exhumation and second emphasize the role of gravity sliding of the Mesozoic cover in the preorogenic evolution of the Pyrenean realm. In the light of such evidence, a simple model of basin

development can be inferred, involving extreme thinning of the crust, and mantle uprising along a major detachment fault. We demonstrate coeval development of a crust-mantle detachment fault and generalized gravitational sliding of the Mesozoic cover along low-angle faults involving Triassic salt deposits as a tectonic sole. This model accounts for the basic characteristics of the precollisional rift evolution in the Pyrenean realm. **Citation:** Lagabriele, Y., P. Labaume, and M. de Saint 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.

1. Introduction

[2] The Pyrenees is a narrow, 400 km long and N110° trending continental fold-and-thrust belt that developed in response to the collision between the northern edge of the Iberia Plate and the southern edge of the European Plate during the Late Cretaceous-Tertiary [Choukroune and ECORS Team, 1989; Muñoz, 1992; Deramond *et al.*, 1993; Roure and Choukroune, 1998; Teixell, 1998]. In the Pyrenean domain, Triassic and Jurassic rifting events preceded the development of Cretaceous rifts which culminated in the crustal separation between the Iberia and European plates [Puigdefabregas and Souquet, 1986; Vergés and Garcia-Senz, 2001]. Continental rifting in the Pyrenean realm occurred coevally with oceanic spreading in the Bay of Biscaye between Chron M0 and A33o (approximately 125–83 Ma), in relation with the counterclockwise rotation of Iberia relative to Europe [Le Pichon *et al.*, 1970; Choukroune and Mattauer, 1978; Olivet, 1996; Sibuet *et al.*, 2004]. Rotation was achieved just before the Albian according to recent paleomagnetic data collected onland [Gong *et al.*, 2008].

[3] The northern flank of the Pyrenees is well known for the occurrence of numerous small-sized exposures of subcontinental mantle rocks, mostly lherzolites, widespread within Mesozoic sedimentary formations forming the north Pyrenean zone (NPZ) (Figure 1). Since their early descriptions by Lacroix [1895], there was a more than 100 years long debate relative to the origin and significance of these ultramafic remnants. Very recent field studies in the surroundings of Etang de Lherz (central Pyrenees), the type locality of the lherzolite, have revealed that a large amount of mantle exposures do in fact represent fragments of subcontinental material reworked through sedimentary pro-

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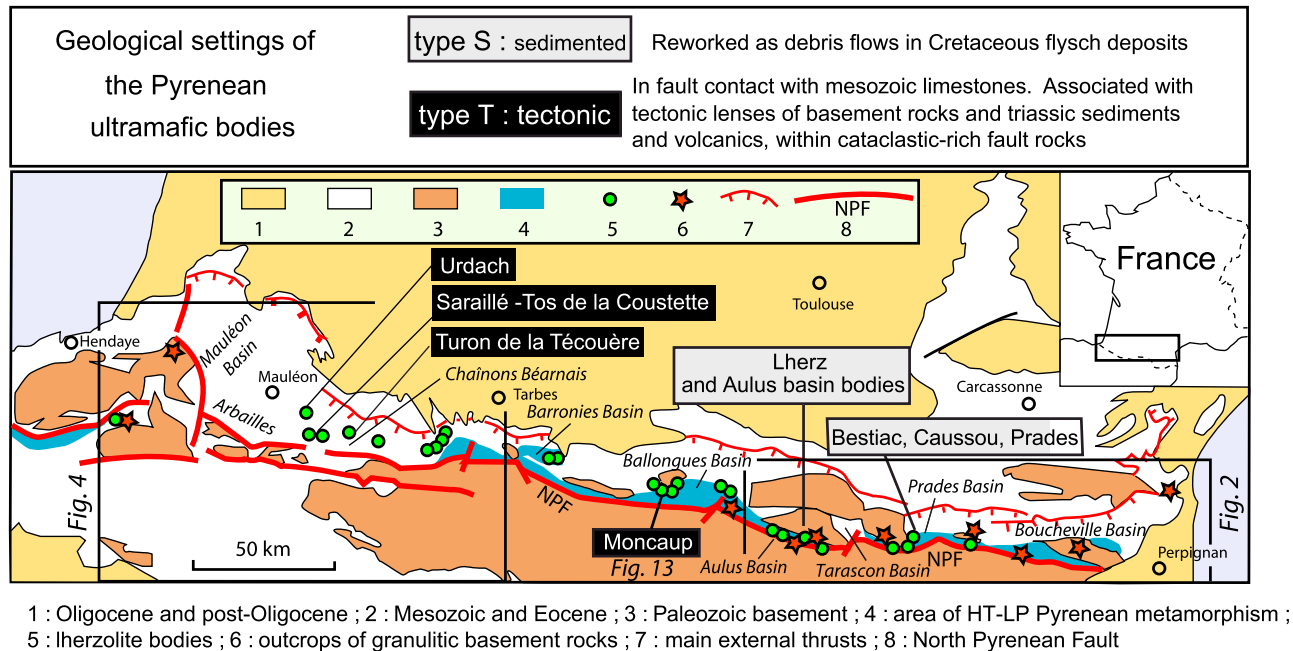


Figure 1. Simplified map of the Pyrenean belt with the location of the main ultramafic bodies and outcrops of lower crust. S type (sedimented) and T type (tectonic) lherzolites are distinguished on the basis of their geological setting as discussed in text. The main mid-Cretaceous basins are shown in italic. Location of Figures 2, 4, and 13 is indicated.

cesses within Cretaceous basins of the NPZ [Lagabrielle and Bodinier, 2008]. This demonstrates that exhumation of subcontinental mantle occurred along the NPZ during transtensional deformation linked to the separation between the Iberia and the European plates. Therefore, exhumation of subcontinental mantle following extreme continental thinning during the mid-Cretaceous Pyrenean rifting event has been proposed as a general mechanism accounting for the presence of ultramafic material within the NPZ [Lagabrielle and Bodinier, 2008]. In addition, interpretation of geophysical profiles in the Aquitaine region by Jammes *et al.* [2009], enriched with field data from the Mauléon basin, also concluded to extreme crustal thinning and finally to tectonic exhumation of both the lower crust and the subcontinental mantle during the Aptian-Albian period in the western Pyrenees. In the light of these recent studies, mantle exhumation appears undoubtedly as an important mechanism accompanying the processes of extreme thinning of the continental crust. Considering these new results should help improving our understanding of the preorogenic evolution not only of the Pyrenees but also of nonvolcanic passive margins in general, where mantle rocks are exhumed during the preorogenic rifting stages.

[4] A recent analysis of the geological setting of the Pyrenean lherzolites [Lagabrielle and Bodinier, 2008] has shown that careful analysis of this setting may yield important information on their exhumation history. Basically, the Pyrenean ultramafic rocks are associated with relatively few lithologic types including: brecciated Triassic metasediments (including metaevaporites) and ophiolites, pre-Albian

Mesozoic sedimentary sequences, small tectonic lenses of Variscan crustal units (including granulites) and, in some localities, clastic ultramafic-bearing sedimentary series of Cretaceous age. An important challenge is now to revisit the most representative exposures of lherzolites across the entire belt, in order to extract a set of critical data constraining the processes of mantle exhumation and crustal thinning. In this article, we first make the point of the various geological settings of the ultramafic bodies. We show that they can be classified into two distinct categories, based on few basic criteria relative to their geological environments. These criteria provide information not only on mantle exhumation processes, but also on the behavior of the Mesozoic sedimentary cover in response to the progressive thinning of the continental crust during the preorogenic Pyrenean evolution.

2. Pyrenean Mantle Bodies: Two Main Types of Geological Settings

[5] The Pyrenean peridotites form numerous small bodies of subcontinental mantle, a few meters to 3 km across, scattered within the North Pyrenean Zone (NPZ) of Mesozoic sediments paralleling the North Pyrenean Fault [Monchoux, 1970; Fabriès *et al.*, 1991, 1998] (Figure 1). Models of emplacement of the Pyrenean lherzolites published in the last 40 years involve purely tectonic mechanisms, such as solid intrusion of mantle rocks into sediments during the Pyrenean orogeny [Lallemand, 1967; Minnigh *et al.*, 1980; Vielzeuf and Kornprobst, 1984] or preorogenic exhumation

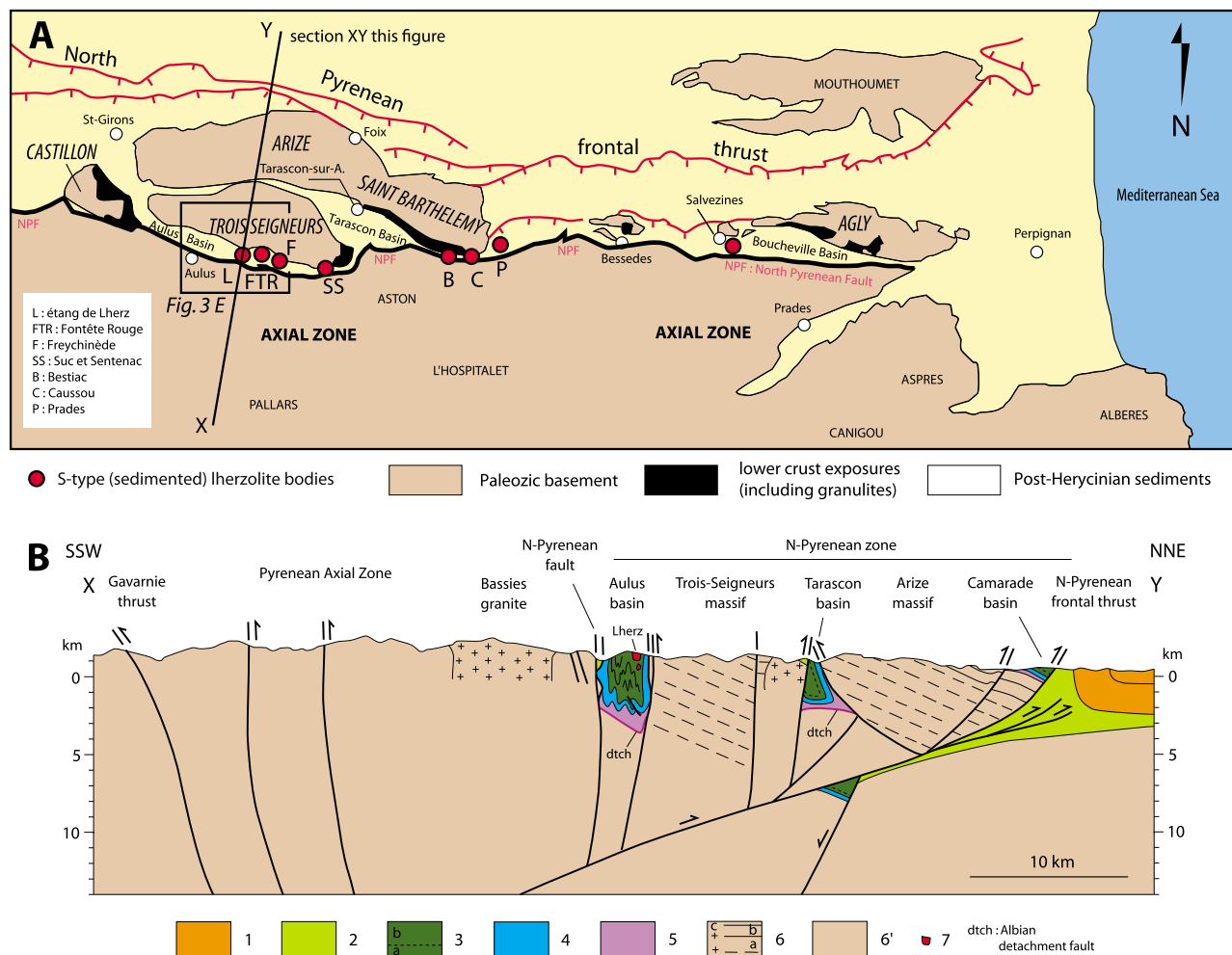


Figure 2. (a) Simplified geological map of the central-eastern Pyrenees showing the Paleozoic north Pyrenean massifs (names in italic). The exposures of lower crust are indicated. Area of Figure 3e is shown. (b) Geological section XY of the north Pyrenean zone in the central-eastern Pyrenees cutting through the Aulus basin (Lherz area) and the western end of the Tarascon basin (location in Figure 2a). 1, Paleogene foredeep; 2, Late Cretaceous foredeep; 3, Aptian-Albian (a, Urgonian facies limestones; b, flysch and breccia); 4, Jurassic to Barremian; 5, Triassic; 6, Palaeozoic (a, infra-Silurian metamorphic rocks; b, Silurian to Carboniferous metasediments; c, granite); 6', undifferentiated Palaeozoic rocks; 7, lherzolite.

of mantle rocks and subsequent sedimentary processes during the Mesozoic or the Cenozoic [Choukroune, 1973; Fortané et al., 1986; Lagabrielle and Bodinier, 2008; Jammes et al., 2009].

[6] Prior to any discussion of the modes of emplacement of the Pyrenean mantle bodies, a point must first be made on their geological environment. In this section, we show that the geological settings of the Pyrenean mantle bodies can be classified within only two distinct types. Such classification is based on a compilation of published data, completed with new field investigations in key areas. In the first type of geological settings, the lherzolite bodies are found within clastic sedimentary formations of Cretaceous age. This is the case of the Cretaceous basin of Aulus, where the Lherz body is exposed [Lagabrielle and Bodinier, 2008] and for the Bestiac-Prades bodies exposed in the SE of the Tarascon

basin [de Saint Blanquat, 1985] (Figures 1 and 2). In the second type of settings, the lherzolite bodies form hectometric to kilometeric units, never more than a few hundred meters thick, tectonically associated with cataclastic Triassic rocks and with small tectonic lenses of crustal material (micaschists, gneisses, granites). They exhibit clear tectonic relationships with the surrounding Mesozoic formations of the NPZ, and rare evidence of sedimentary reworking. This is the case for most of the Béarn ultramafic bodies and for the Moncaup body in the central Pyrenees (Figure 1).

2.1. Sedimented Type (S Type): Lherzolite Bodies Within Cretaceous Clastic Formations

[7] The eastern Pyrenean lherzolite bodies reside within the narrow belt of Mesozoic sediments, representing exten-

sional Cretaceous basins preserved between the Paleozoic units of the Pyrenean axial zone to the south and the Paleozoic massifs of the NPZ to the north (the so-called north Pyrenean massifs). The north Pyrenean massifs formed the upper part of horst systems during the Cretaceous and, together with the extensional Cretaceous basins were thrust toward the north, above the Upper Cretaceous foreland basins during the Cenozoic [Curnelle and Durand-Delga, 1982; Souquet and Peybernès, 1987]. The now inverted basins form narrow discontinuous zones of verticalized Jurassic-Early Cretaceous limestones, marbles, dolomites, rare metapelites and voluminous flysch and polymictic breccias deposits (Boucheville, Prades, Tarascon and Aulus basins, Figure 2) [Choukroune, 1976]. Along the north Pyrenean fault (NPF) that bounds the axial zone to the north, the metasediments are strongly sheared and suffered the Pyrenean high temperature-low pressure (HT-LP) mid-Cretaceous metamorphic event which lasted almost 25 Ma between 110 and 85 Ma (late Aptian-Coniacian), in relation with crustal thinning and hydrothermal circulations [Albarède and Michard-Vitrac, 1978; Montigny et al., 1986; Thiébaud et al., 1988; Golberg and Maluski, 1988; Dauteuil and Ricou, 1989]. The most typical high-grade mineralogical assemblages are found in the ductily deformed marbles and metaevaporites. They include scapolite, phlogopite, diopside and locally dolomite and dravite [Choukroune, 1976; Golberg, 1987; Golberg and Leyreloup, 1990]. The high content in elements such as Cl, Na, Ba, B, Mg, K, P and S within the metamorphic minerals indicate that an important portion of the metamorphic fluids circulated within the Triassic evaporites.

[8] The most famous mantle bodies in the central-eastern Pyrenees are the lherzolites of Etang de Lherz, Freychinède and Prades-Bestiac. At Etang de Lherz, the ultramafic rocks form a large body, 1.5 km long, surrounded by voluminous breccia formations [Choukroune, 1973, 1976; Colchen et al., 1997; Ternet et al., 1997]. The breccias represent monomict and polymict debris flow deposits composed of clasts of ultramafic and carbonate rocks of various sizes (from less than one mm to a few dm), mixed in different proportions [Lagabriele and Bodinier, 2008] (Figure 3). Carbonate material of the breccias is composed of metamorphic Mesozoic sediments, including dominant white to pink marbles (Late Jurassic, Early Cretaceous) and dark dolomites and metapelites (Lias). Besides the lherzolitic debris, minor clasts of ophitic and gabbroic composition are also observed. The breccias most often lack Variscan basement material. The ultramafic-bearing layers are found far from any lherzolitic body, implying that lherzolitic clasts have been transported away from their source by sedimentary processes during the mid-Cretaceous. In some places, sequences of channelized debris flows deposits of purely ultramafic composition are observed (Figure 3). A detailed analysis of the primary contact between the Lherz ultramafics and the surrounding limestones indicates that mixed ultramafic-carbonate clastic sediments have been emplaced into fissures opened within the brecciated carapace of the peridotites (Figure 3). These observations put strong constraints on the mode of emplacement of the lherzolite bodies since they demonstrate that mantle exhumation and disaggregation on the seafloor occurred within the NPZ basins during the mid-Cretaceous,

as stressed by Lagabriele and Bodinier [2008]. The clastic formations south of Etang de Lherz also include large olistoliths of sheared, pre-Albian Mesozoic metasediments indicating that mantle exhumation and subsequent sedimentary reworking was coeval with gravity instabilities of the Mesozoic cover capping the Paleozoic basement of the axial zone and the north Pyrenean massifs.

[9] An important characteristic of the ultramafic-bearing breccias of the entire eastern NPZ is the presence of dominant clasts of Mesozoic metasediments, bearing mineralogical assemblages of the Pyrenean metamorphism and exhibiting a high-temperature foliation [Dauteuil et al., 1987; Golberg and Leyreloup, 1985; Lagabriele and Bodinier, 2008]. This is well observed in the region of Etang de Lherz as well as around the Bestiac bodies [de Saint Blanquat, 1985]. This observation indicates deformation and subsequent reworking of the sedimentary cover of the NPZ during the 110–85 Ma time interval corresponding to the thermal pulse of the Pyrenean event. In some breccia samples, such as those exposed at Col d'Agnès 1 km south of the Lherz body [Golberg, 1987; Golberg and Maluski, 1988], metamorphic minerals have also grown within the matrix, between clasts of metasediment and ultramafic rocks, thus confirming a long period of thermal culmination [Lagabriele and Bodinier, 2008]. Finally, a complete geological cycle including metamorphism, exhumation, disaggregation, sedimentation and further metamorphism developed within the basins of the NPZ during the more than 20 Myrs long thermal culmination of the mid-Cretaceous.

[10] By contrast to the eastern metamorphic NPZ, monomictic and polymictic lherzolite-bearing breccias are extremely rare in the western NPZ. Only one occurrence of polymictic ultramafic-crustal breccia has been reported so far within the Albian-Cenomanian flysch of the Chaînons Béarnais, close to the lherzolite body of Urdach [Duée et al., 1984; Fortané et al., 1986]. This site is described in detail below.

2.2. Tectonic Type (T type): Lherzolites Lenses Associated With Tectonized Middle-Upper Triassic and Crustal Rocks

[11] Several lherzolite bodies reside in the Chaînons Béarnais, within the folded and thrust Mesozoic sequences of the NPZ, north of the western termination of the axial zone (Figures 4–6). The Mesozoic sediments form a succession of three E-W trending, parallel fold structures, the Mail Arrouy, Sarrance and Layens anticlines, bounded by north (Layens) and south (Mail Arrouy and Sarrance) verging, post-Cenomanian thrusts [Castéras et al., 1970] (Figures 5 and 8). The base of the stratigraphic sequence is represented by Upper Triassic evaporites, breccias and ophites and is followed by Mesozoic platform carbonates, both forming the original cover of the northern Iberian margin [Canérot et al., 1978; Canérot and Delavaux, 1986]. The platform carbonates include Lower Jurassic dolomites and Upper Jurassic to Aptian platform limestones (Urgonian facies), which form the current main reliefs. The flysch of Albian to Cenomanian age is preserved within the synclines. Growth structures within the Urgonian limestones and fre-

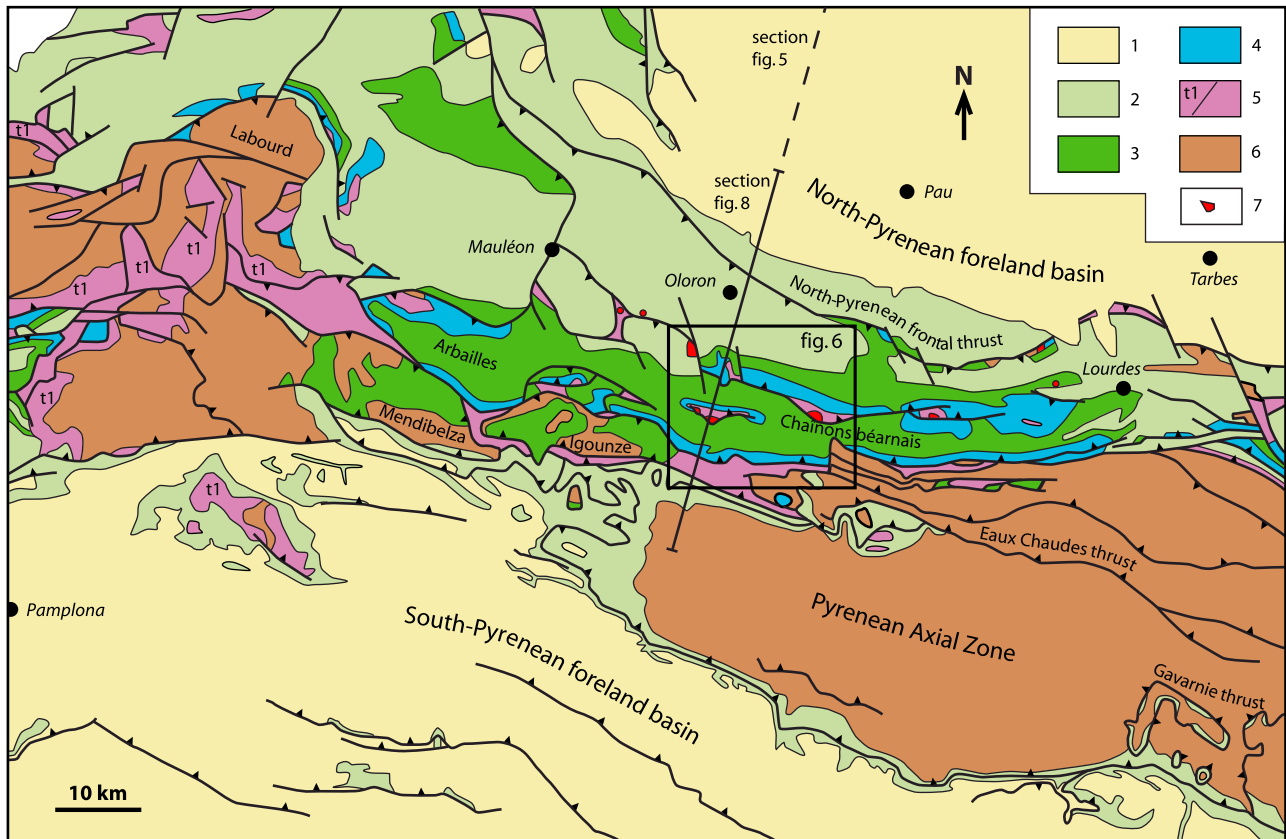


Figure 4. Geological map of the northwestern Pyrenees (location in Figure 1), with the location of sections shown in Figures 5 and 8, and of the geological map of the Chaînons Béarnais in Figure 6 (after the 1:400,000 geological map of the Pyrenees by BRGM-IGME). 1, Tertiary; 2, Upper Cretaceous; 3, Lower Cretaceous; 4, Jurassic; 5, Triassic (t1 refers to Lower Triassic, mainly Buntsandstein); 6, Palaeozoic basement; 7, lherzolite.

quent transition between the platform carbonates and the flysch deposits [Castéras, 1970] document an onset of tectonic instabilities at the Aptian-Albian transition. The three units of the Chaînons Béarnais tectonically overlie a sole of deformed Upper Triassic material mainly exposed in the

hanging wall of the thrust faults bordering to the south the Mail Arrouy and Sarrance anticlines. This platform carbonate sequence is therefore entirely disconnected from its former Paleozoic basement which is known only as very small tectonic slices associated with the lherzolite bodies.

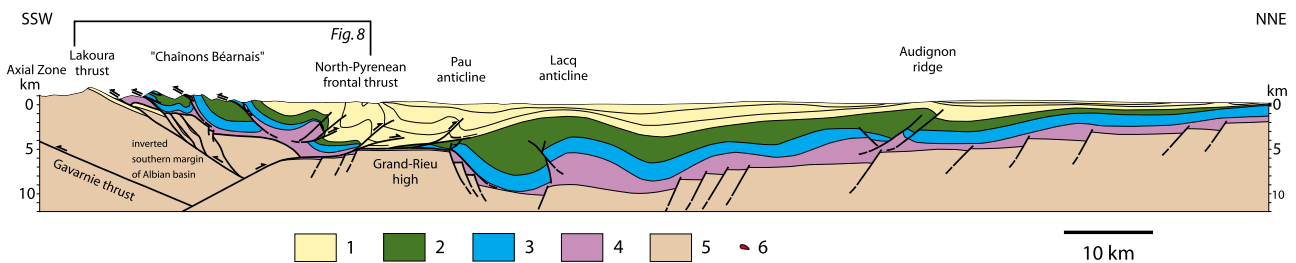


Figure 5. Geological section of the north Pyrenean zone and north Pyrenean foreland basin in the western Pyrenees (location in Figure 4). See detail of the north Pyrenean zone in Figure 8; northern part of section is adapted from Biteau *et al.* [2006]. In order to emphasize the contribution of the mid-Cretaceous basin deposits to the overall structure of this region, the post-Albian to Quaternary deposits are shown using one unique color pattern. 1, Upper Cretaceous-Tertiary (Pyrenean foreland basins); 2, Aptian-Albian; 3, Jurassic to Barremian; 4, Triassic; 5, Palaeozoics basement; 6, lherzolite.

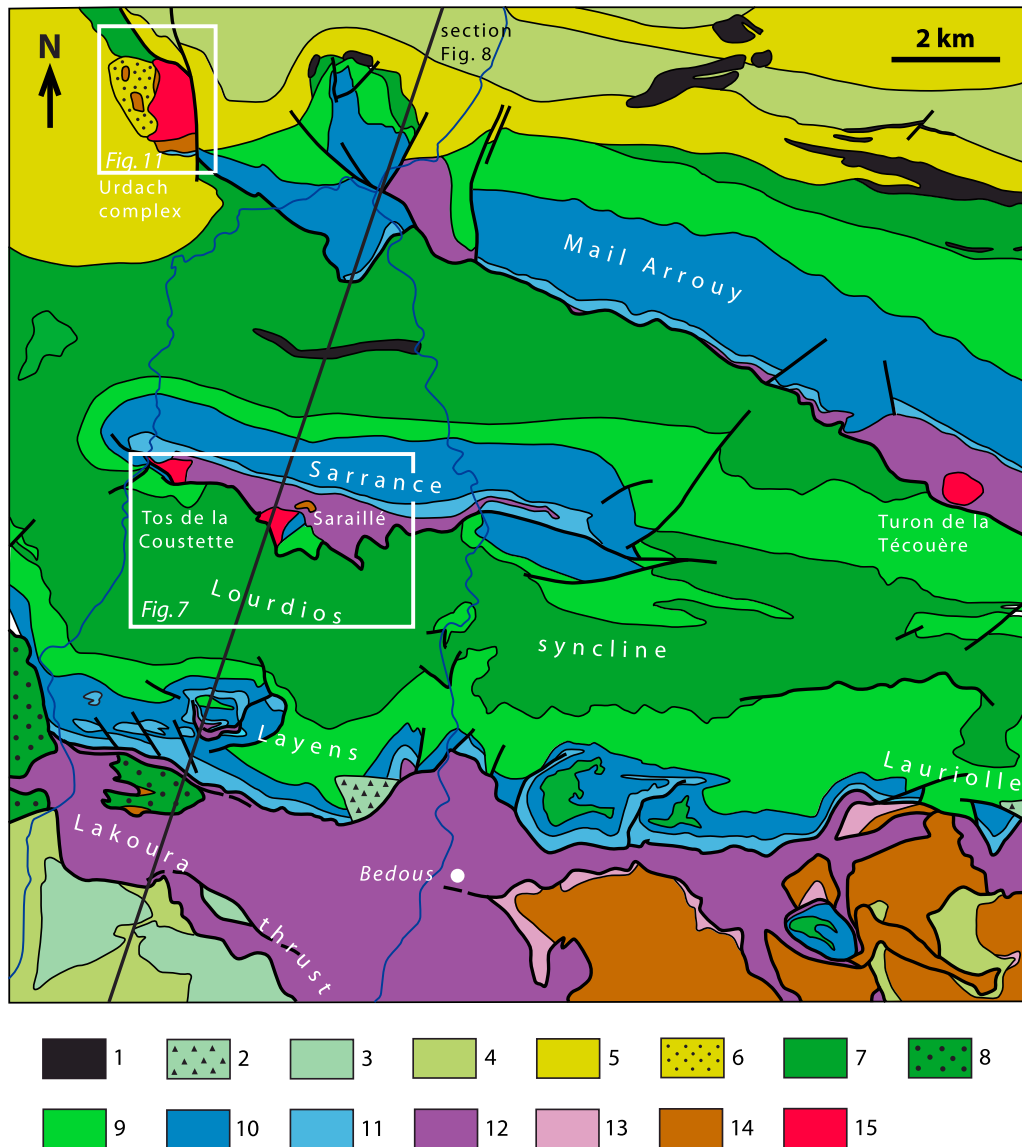


Figure 6. Geological map of the “Chaînon Béarnais” region (location in Figure 4), after 1:50,000 geological maps by BRGM [Castéras, 1970]. Location of maps in Figures 7 and 11, and of section of Figure 8 is shown. 1, Cretaceous volcanics; 2, Late Cretaceous? (Layens and Lauriolle breccia); 3, Campanian-Maastrichtian (flysch); 4, in the south Cenomanian to Santonian (“calcaires des canyons” platform limestones) and in the north Turonian (flysch); 5, Cenomanian (flysch); 6, Cenomanian (flysch and conglomerates associated with the Col d’Urdach lherzolite basement complex); 7, Albian (flysch); 8, Albian (Igounze-Mendibelza conglomerate); 9, Aptian (Urgonian facies limestones and associated marls); 10, Middle-Upper Jurassic and Lower Cretaceous up to Barremian; 11, Lower Jurassic; 12, Middle-Upper Triassic (marls, carbonates, evaporites, ophites; detachment fault rocks); 13, Lower Triassic (sandstones and conglomerates; tegument of the Palaeozoic basement); 14, Palaeozoic basement; 15, lherzolite.

By contrast to the eastern Pyrenees, most of the pre-Albian carbonates here have not suffered the high-grade Pyrenean metamorphism. Ductily deformed Mesozoic sediments bearing HT-LP paragenesis are found only in restricted places, close to fault contacts with Triassic and mantle rocks. This observation which is highly relevant to the

question of the exhumation of the lherzolites was reported in previous studies [Fortané *et al.*, 1986; Thiébaud *et al.*, 1992].

[12] The four main Béarn ultramafic bodies reside: (1) in the southern flank of the Sarrance anticline (Saraille and Tos de la Coustette bodies), (2) at the western tip of the Mailh Arrouy anticline (Urdach body), and (3) in the strongly tectonized zone of Benou, along the southern border of

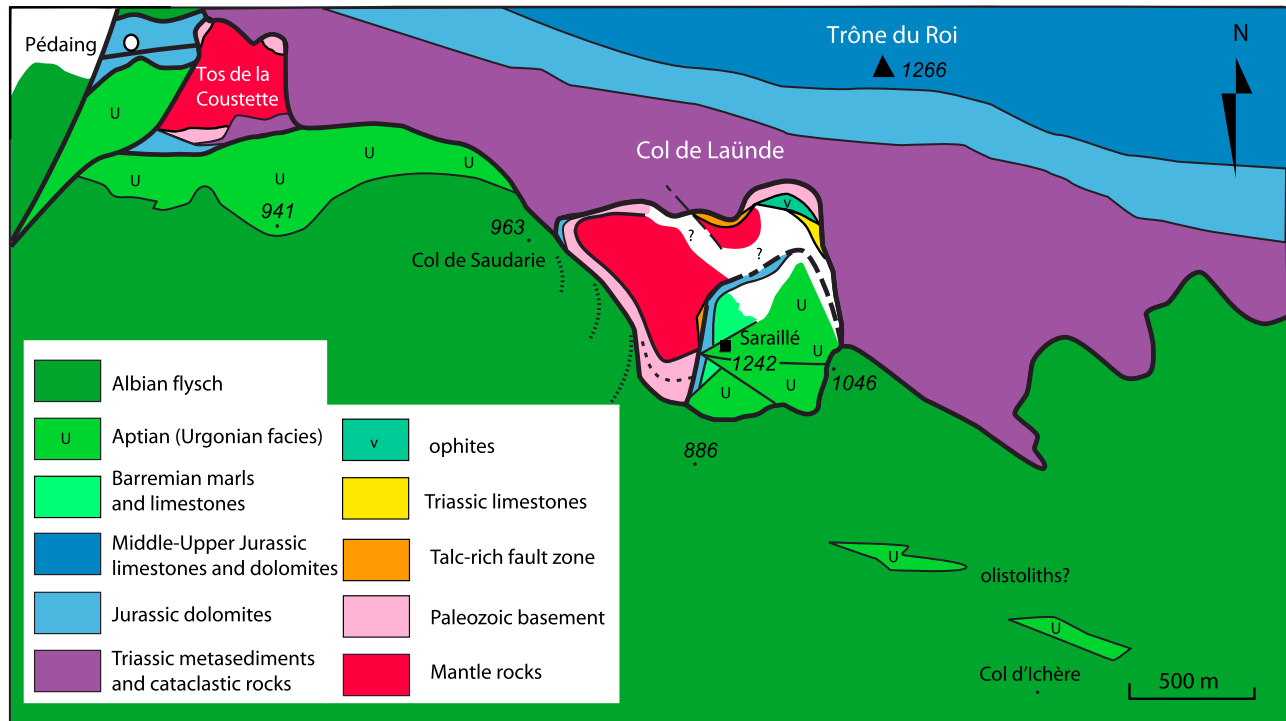


Figure 7. Geological map of the Sarrance structural unit with location of the Sarailié and Tos de la Coustette ultramafic bodies. Contours are based on maps by *Fortané et al.* [1986], *Canérot and Delavaux* [1986], and on our new field observations.

the Mail Arrouy thrust structure (Turon de la Tècouère) (Figure 4).

2.3. Sarailié and Tos de la Coustette Bodies

[13] The Sarailié summit exposes a tectonic complex of Mesozoic sediments and crustal rocks together with serpentinized mantle rocks, resting tectonically over the verticalized Albian flysch of the Lourdios syncline [*Castéras, 1970*] (Figure 7). The Sarailié complex can be divided into two main subunits (Figure 8). The basal subunit comprises a series of tectonic lenses of lherzolites, Paleozoic crustal rocks and ophiolites associated with cataclastic Upper Triassic sediments. The upper subunit, forming the Sarailié summit itself, consists of verticalized Mesozoic carbonates, locally strongly deformed and metamorphosed, which tectonically overlie the basal subunit. Thickness of the sedimentary section of this upper subunit is reduced with respect to sequences exposed in the surroundings. It includes dark metadolomites (Callovo-Oxfordian), black schists of probable Barremian age, only exposed in restricted places, and

white fossiliferous marbles showing the typical regional Urgonian fossiliferous facies (Aptian-Albian) [*Canérot and Delavaux, 1986*]. The lherzolites form a 500 m long and 30 m thick lens-shaped, almost horizontal body. The mantle rocks overlie a thin tectonic slice of continental crust material including hectometric lenses of granite and mylonitic granite, gneisses, micaschists and rare amphibolites. This composite tectonic slice is no more than 20 m thick here. It extends continuously beneath the lherzolites as observed along both the northern and southern flanks of the Sarailié massif. Immediately beneath the Sarailié summit, this crustal layer is folded and becomes vertical (Figure 9). To the east, the Mesozoic sediments are in direct contact with the verticalized Albian flysch, but remnants of deformed Triassic and sheared Aptian carbonates are observed within the contact zone. By contrast to a previous interpretation by *Fortané et al.* [1986] and in accordance with the conclusions of *Canérot and Delavaux* [1986], we confirm that the mantle rocks and the Mesozoic cover are in fault contact. A lenticular, strongly sheared, talc-rich layer up to 15 m thick is

Figure 8. Geological environment of the Sarailié-Tos de la Coustette massifs. (a) Panorama and (b) geological section of the Sarrance structure viewed from the west. (c) Geological section of the north Pyrenean zone across the “Chaîmons Béarnais” (detail from section in Figure 5). 1, Miocene molasse; 2, Paleogene foredeeps; 3, Campanian-Maastrichtian foredeeps; 4, Cenomanian to Santonian; 5, Aptian-Albian (a, Urgonian facies limestones; b, flysch; c, Igouze-Mendibelza conglomerate); 6, Jurassic to Barremian; 7, Triassic; 8, Palaeozoic basement; 9, lherzolite (bodies labeled 1–3 illustrate the geological setting of the main lherzolite massifs as follows: 1, Sarailié; 2, Tos de la Coustette; 3, Turon de la Tècouère).

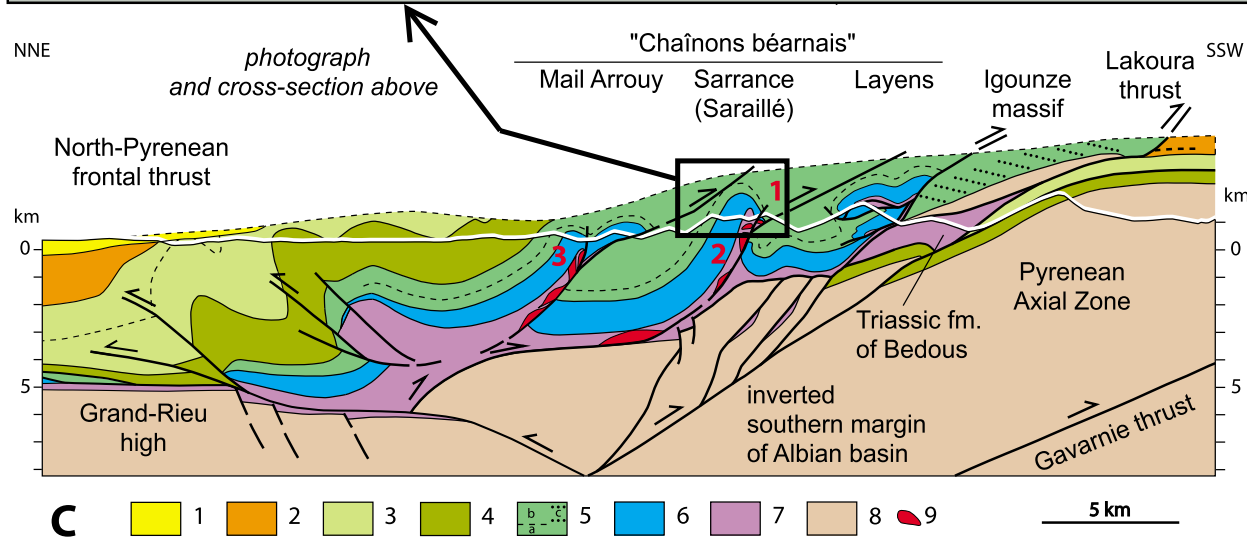
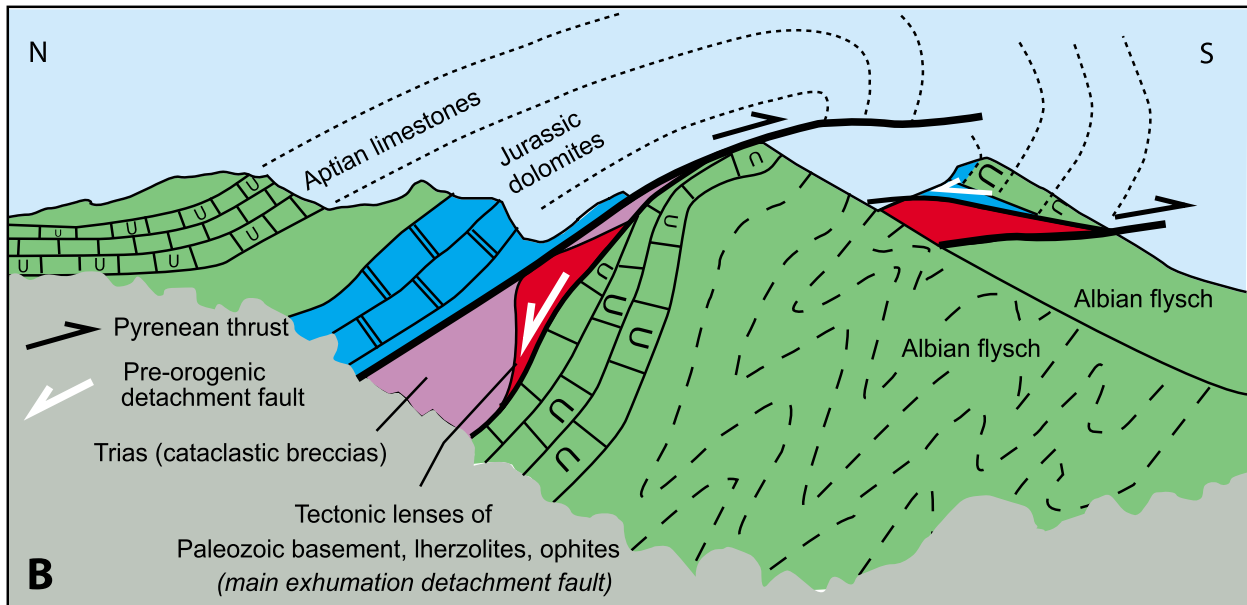


Figure 8

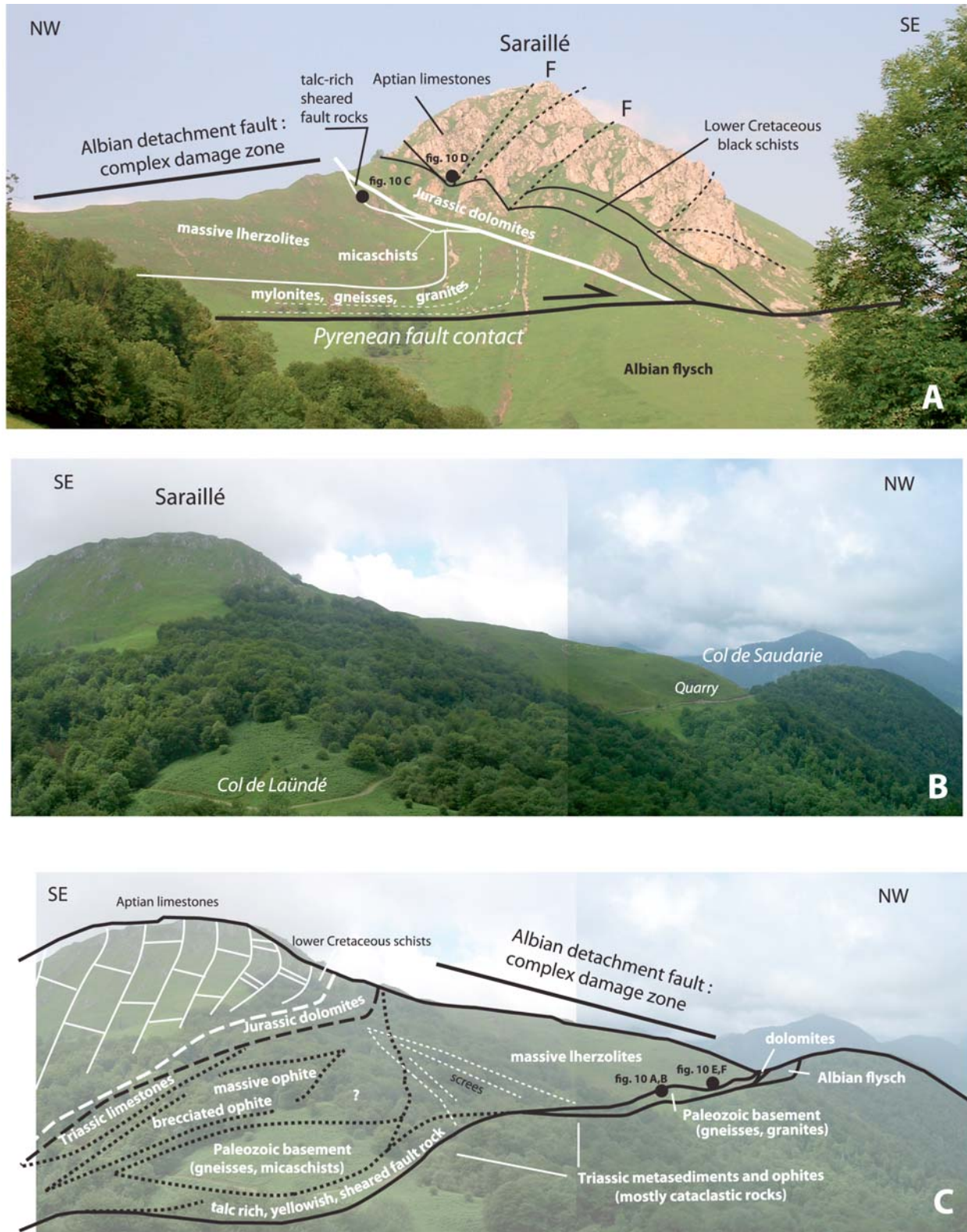


Figure 9. The two opposite flanks of the Saraille complex illustrating some basic aspects of the structure of a Pyrenean detachment fault zone. The damage zone is a complex assemblage of various tectonic lenses of deep and shallow crustal levels. Note location of photographs shown in Figure 10. (a) Geological interpretation of the southwestern flank of the Saraille massif. (b and c) Geological interpretation of the northern flank of the Saraille massif between Col de Laüundé and Col de Saudarie.

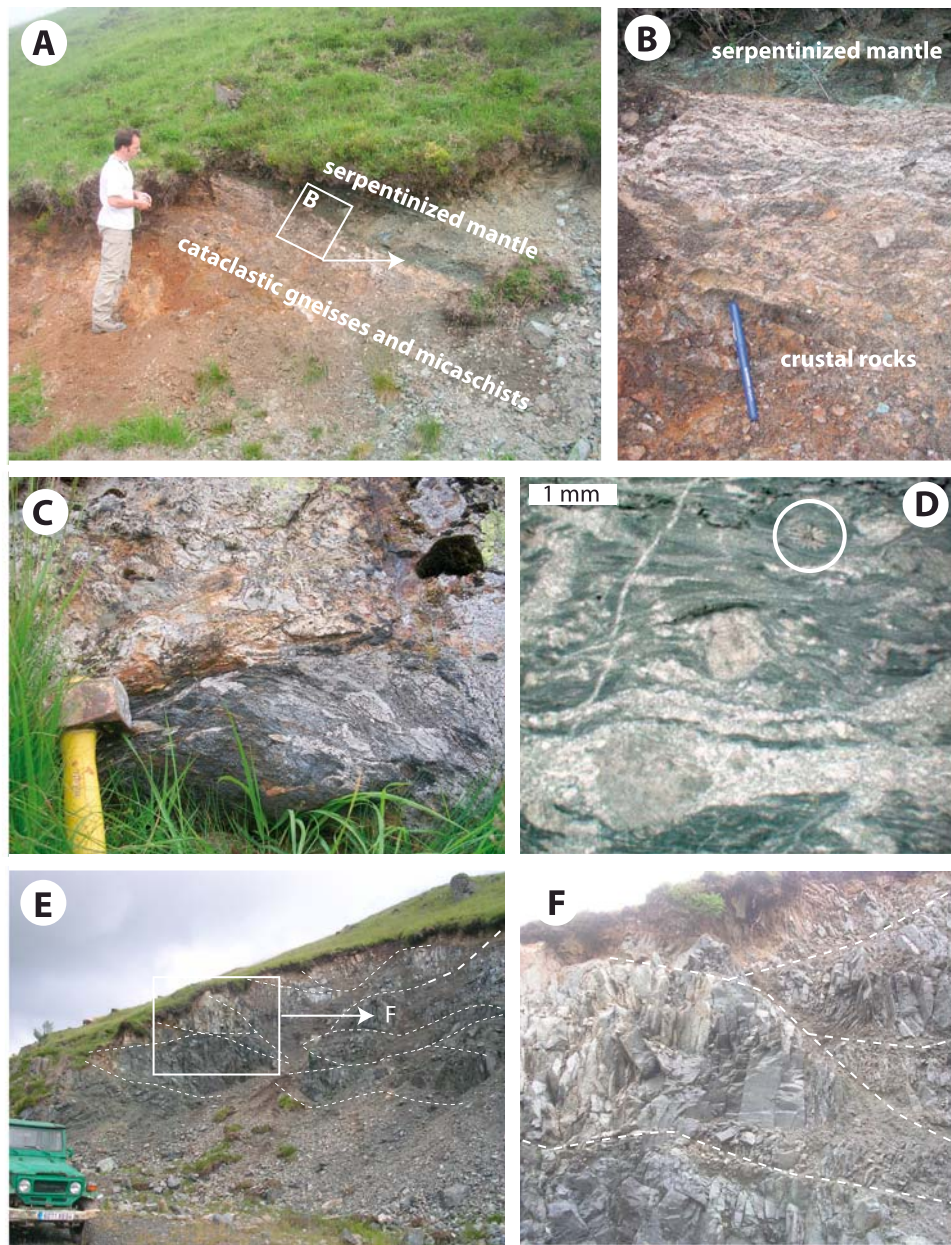


Figure 10. Photographs of significant geological features from the Saraillé detachment complex (location of photographs in Figure 9). (a and b) Fault contact between the Paleozoic basement and the Saraillé lherzolites; (c) an aspect of the sheared, talc-rich fault rocks from the tectonic fault zone separating the Saraillé lherzolites from the Jurassic dolomites; (d) sheared Mesozoic marble close to the fault contact, with deformed microfossils (circle); and (e and f) late tectonic fabric within the Saraillé lherzolite body characterized by multiple tectonic lenses at various scales separated by low-temperature, serpentized shear zones.

observed between the ultramafic rocks and the sediments (Figures 9 and 10). Where massive and not altered, the talc exhibits a pink color and contains numerous pyrite grains. In this section, the mineralogical assemblage includes talc, chromium chlorite and dolomite [Fortané *et al.*, 1986]. It is locally friable and desilicified, then reaching a yellow-gray color. It passes into a thin shear zone rich in iron oxides, separating the gneisses and micaschists from the carbonates.

Both this talc-rich lens and the oxidized layer suffered important shearing as shown by a strong tectonic fabric marked by undulating foliation planes delineating tectonic lenses at all scales (phacoids). Our new observations indicate that the Mesozoic sediments located up to few meters above this major shear zone also experienced strong shearing, cataclastic deformation and associated metamorphism. Typical deformed rocks are cataclastic carbonate breccias developed at

the expense of dolomitic sediments as well as ductily sheared Aptian marbles containing deformed fossils (Figure 10). Intensity of the deformation and mineralogical paragenesis indicate fault contact under the conditions of the mid-Cretaceous Pyrenean thermal event. Our observations are consistent with the early description of narrow regions in the Chaînons Béarnais which experienced HT-LP metamorphism, as reported by *Fortané et al.* [1986] and *Thiébaud et al.* [1992].

[14] A road opened recently along the northern flank of the Sarailié massif allows new observations better constraining the tectonic setting of this complex. The fault contact between the mantle and the crustal rocks can be studied in detail in two places along this road (Figure 9). At both exposures, this contact is extremely sharp and shows shallow opposite dips, suggesting an undulating attitude at the hectometric scale (Figure 10). Where observed, the gneisses are affected by a pervasive shallow-dipping foliation, and by the development of S-C structures associated with a N-S stretching lineation showing a top to the north sense of shear. This fabric is typical of deformation taking place in the greenschist facies metamorphic domain. All continental rocks suffered important hydrothermal alteration coeval with this deformation as revealed by the presence of quartz veins and by the local development of abundant oxydization products within the foliation planes. Pervasive foliation also developed within the mantle rocks, here entirely serpentized (Figure 10). Foliation planes within both the crustal and mantle rocks are remarkably parallel, which indicates a common evolution at least during the last stages of deformation under greenschist facies, upper crustal conditions. These observations clearly indicate that a late event of deformation under shallow crustal conditions affected both the mantle and the crustal rocks. This deformation is consistent with conditions accompanying the late stages of mantle exhumation as shown by studies of oceanic rocks drilled at ODP Sites on the Iberia margin or collected in Alpine analogs [e.g., *Manatschal*, 2004].

[15] A new quarry opened within the western edge of the Iherzolites body allows observation of the internal deformation affecting the mantle rocks overlying immediately the crust/mantle contact. The Iherzolites are almost completely serpentized and are crosscut by shallow-dipping undulating shear planes defining a series of plurimetric tectonic lenses (Figure 10). Vertical tight fracture planes develop within the lenses, defining decimetric microlithons. Such tectonic fabric, characterized by the association of metric to hectometric lenses provides a suitable image of the overall geometry of the detachment fault damage zone at a regional scale. There is no ophicarbonated breccia here, which confirms that the Sarailié mantle rocks have never been exposed on the floor of the Albian basin.

[16] Remnants of an older HT deformation event are observed in crustal mylonites exposed along the southern flank of the Sarailié massif. This deformation is more consistent with temperature conditions that developed during the Variscan orogeny [*de Saint Blanquat*, 1993]. The mylonites bear a stretching lineation with a top to the south sense of shear.

[17] New exposures of mantle rocks have been observed along the northern flank of the Sarailié massif, a few hundred meters west of Col de Launde, in an area where poorly exposed Paleozoic micaschists were already reported [*Castéras*, 1970; *Fortané et al.*, 1986]. Here, mantle rocks overly a tectonic sole composed of talc-rich, ultramafic-brecciated rocks and polymictic cataclastic breccias (Figure 9). These rocks are poorly exposed in the forest extending down to the Launde valley, at the foot of the Trône du Roi summit. The cataclastic breccias are yellowish to orange-colored, indurated rocks composed of an assemblage of angular clasts of Triassic sediments and centimetric mafic fragments. The very frequent occurrence of loose blocks of carnageules, characterized by dissolved fragments of former evaporites, set within a solid silicified and carbonated matrix, has to be noticed. Immediately south of Col de Launde, these breccias lie close to ophites and brecciated mafic rocks with ophitic affinity forming scarce exposures (Figure 9). These mafic remnants define a lens-shaped area, a few hundred of meters long, associated with rare exposures of recrystallized brownish Triassic carbonates (Muschelkalk?).

[18] The Tos de la Coustette Iherzolite body, close to the Pédaing village, resides 3 km west of the Sarailié summit, at the western termination of the Sarrance anticline (Figure 7). This ultramafic body, 400 m long, has been studied in detail by *Fortané et al.* [1986]. It is in fault contact with small tectonic lenses of Paleozoic basement and Triassic metaevaporites (Keuper) outcropping above and beneath the mantle rocks. This complex unit of Triassic, crustal and mantle rocks lies in turn in tectonic contact against verticalized Jurassic dolomites and Aptian limestones forming the southern, reverse flank of the Sarrance anticline. The Aptian carbonates correlate with the verticalized Aptian carbonates of the Sarailié summit.

2.4. Urdach and Turon de la Tècouère Bodies

[19] Other Iherzolite bodies in the Béarn region show geological settings having strong affinities with that of the Sarailié-Tos de la Coustette complex [*Castéras*, 1970; *Fortané et al.*, 1986].

[20] 1. The Urdach body (Figure 11) consists of a 1.5 km long Iherzolite slice, exposed at the limit between the Albian and the Cenomanian flysches at the western termination of the Mail Arrouy thrust sheet, between Col d'Urdach and Col d'Etche. In the southern part of the Urdach body, despite of the poor conditions of exposure, it can be shown that mantle rocks are tectonically associated with crustal rocks including one unit of Paleozoic micaschists, 500 m long, one small slice of granitic rock and basement breccias (Figure 11). In the southeast corner of the massif, lenses of strongly deformed Triassic and Jurassic sediments lie close to the Iherzolites and a fault contact between dark dolomites and the ultramafics can be observed in an old quarry close to Col d'Urdach. Poor exposures do not allow to better assess a complete geological setting, but a geometry similar to that of the Sarailié and Tos de la Coustette bodies, involving a fault contact with the metasediments is locally demonstrated. To the northwest of the Urdach body, the Soum d'Ombret hill

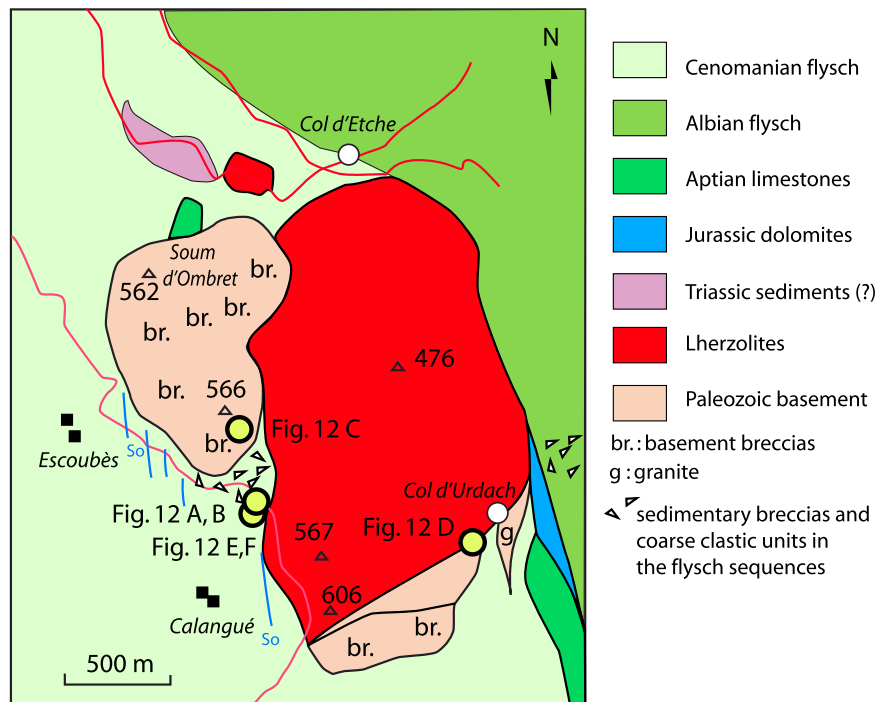


Figure 11. Geological map of the Urdach tectonosedimentary complex (location in Figure 6) with location of photographs shown in Figure 12. Contours are based on a previous map by *Duée et al.* [1984] and on our new field observations.

exposes sedimentary breccias composed of a variety of crustal rocks including clasts of granite, gneisses, micaschists, mylonites, mafic rocks and rare ultramafics (Figure 12). A chaotic assemblage of large blocks of continental material, one to a few meters across each, belonging to this breccia unit is exposed along the road, south of Soum d'Ombret. Unsorted breccias, with angular basement clasts including crustal mylonites, form meter thick layers interbedded within the graded bedded sandstones and pelites forming the dominant material of the Cenomanian flysch as observed in a trench along the road bounding the western side of the Urdach complex. These breccias represent thinner, lateral equivalent of the Soum d'Ombret breccias. In addition, the flysch comprises graded bedded turbidite layers of ultramafic clastic material ranging in size from gravels to thin sand (Figure 12). Finally, as deduced from the geology of the Sarailé complex, the very close association of crustal and mantle rocks in the Urdach complex also suggests an early tectonic juxtaposition during faulting along a major detachment fault. In addition, differing from the Sarailé-Tos de la Coustette bodies, the Urdach composite body is closely associated with coarse clastic deposits interbedded within the Cretaceous flyschs, indicating sedimentary reworking of crustal and mantle material from a proximal source during the Albian-Cenomanian. Due to the abundance of such clastic material, *Duée et al.* [1984] proposed that the Urdach body might represent a large olistolith included within the Cenomanian flysch, but in a recent study, *Jammes et al.* [2009] rather suggested that the lherzolite body lies in tectonic contact over the verticalized flysch. Whatever the

geological setting of the Urdach body is, sedimentary reworking of crustal and ultramafic material indicates that lherzolites and juxtaposed slices of continental crust have been exposed on the seafloor during the Late Cretaceous. This is confirmed by the occurrence of ophi-carbonate breccias and the presence of limestones infilling fissures within the Urdach ultramafics as observed in a quarry on the western side of the lherzolite body [*Jammes et al.*, 2009]. The map view geometry of the Cenomanian flysch surrounding the Urdach complex suggests unconformable relationships with the underlying rocks [*Castéras*, 1970] (Figure 6). This indicates that erosion of the pre-Cenomanian sedimentary sequence occurred during the Albian tectonic phase also responsible for the faulting of strongly deformed Triassic and Jurassic sediments against the tectonic assemblage of lherzolites and associated crustal rocks.

[21] 2. The Turon de la Tècouère is a conical lherzolite body 600 m across and 200 m high [*Visser et al.*, 1997] lying in the flat plain of Bedou, south of the Mail Arrouy ridge, where exposures are extremely poor (Figures 4 and 5). It is associated with scattered outcrops of strongly sheared Aptian marbles, Jurassic dolomites, Paleozoic schists and ophiolites. There is a contrast between the strong tectonic fabric and the metamorphic evolution of the Mesozoic carbonates lying close to the mantle body and the overall low-grade deformation of the Mesozoic sediments exposed in the Mail-Arrouy structure to the north. This strongly suggests that the Turon de la Tècouère-Benou complex represents scarce exposures of a tectonic assemblage of slices of crustal basement, mantle rocks and sheared pre-Albian sediments

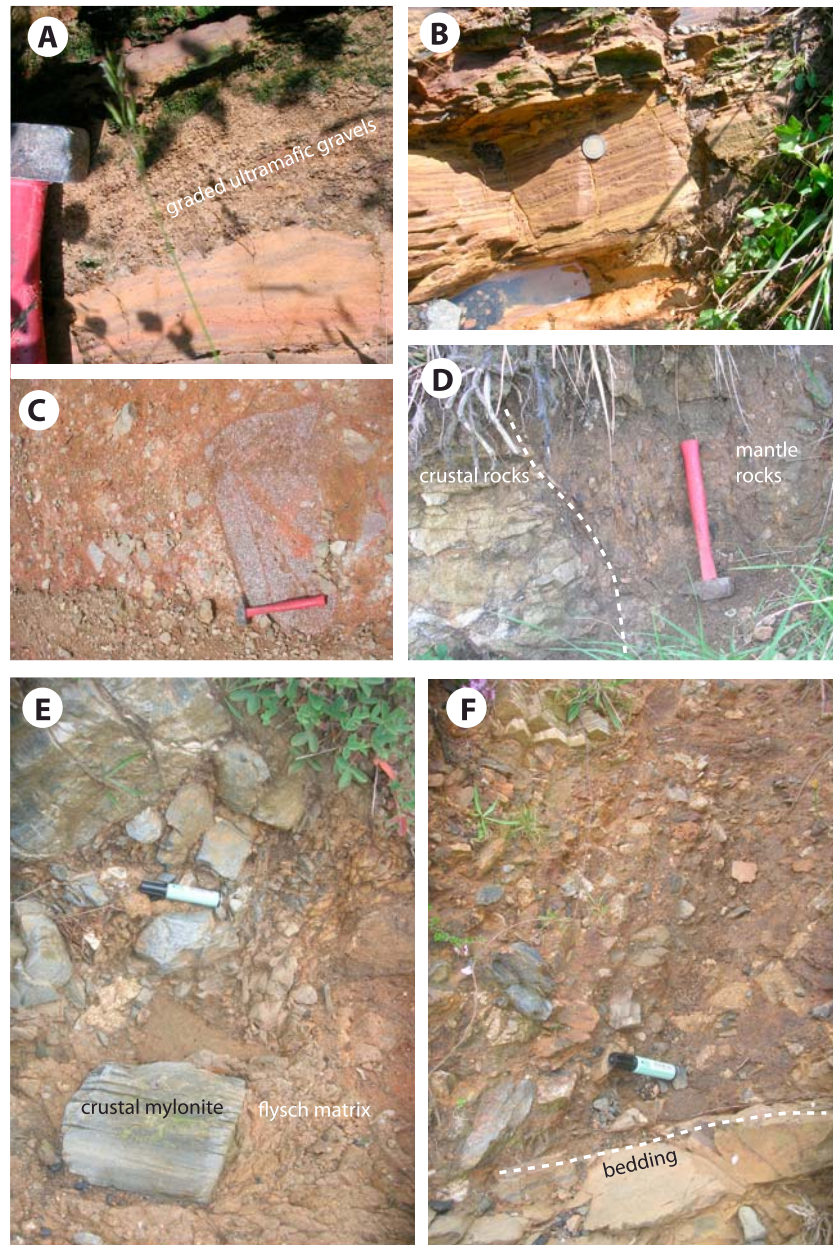


Figure 12. Photographs of significant geological features from the Urdach tectonosedimentary detachment complex (location in Figure 11). (a and b) Gravel- to silt-sized bedded ultramafic debris in the Cenomanian flysch; (c) breccia of Soum d’Ombret composed of fragments of Paleozoic basement rocks and rare clasts of ultramafic material; (d) the fault contact between the Urdach lherzolites and Paleozoic crustal rocks; and (e and f) Paleozoic basement breccia forming separate chaotic levels within the Cenomanian flysch, as observed in the trench bordering the road northwest of the Urdach body.

similar to the other ultramafic-bearing complexes of the western NPZ.

2.5. Moncaup Body

[22] Exposures of ultramafic rocks are frequent in the central NPZ, east of the Chaînons Béarnais, along a belt extending from the Turon de la Tècouère to a series of

bodies lying around the Milhas Paleozoic massif (Figure 4). These mantle remnants are systematically associated with basement and Triassic rocks, often in diapiric structures (e.g., the Montcaut body, 15 km east of the Turon de la Tècouère). The Moncaup lherzolite body, north of the Milhas Paleozoic massif, has a triangular shape with 3 km long sides, making it the largest ultramafic body of the Pyrenees. Its geological setting has been studied in detail by

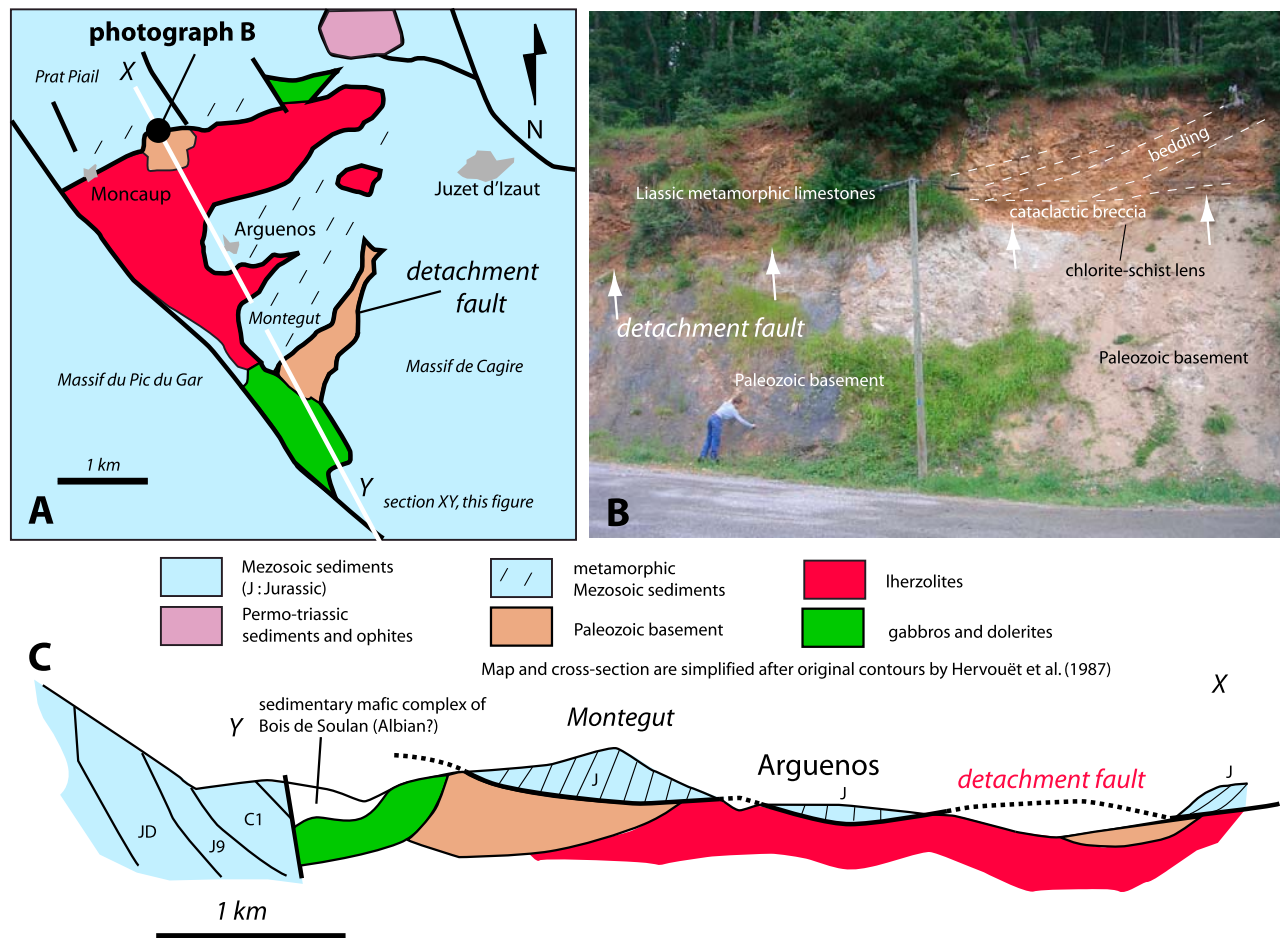


Figure 13. Simplified (a) geological map and (c) cross section of the region of Juzet d'Izaut-Moncaup after *Hervouët et al.* [1987]. (b) Photograph shows the detachment fault exposed along a recent scarp at the junction between roads D618 and D39.

Torné [1986]. On the geological section of Figure 13 [*Hervouët et al.*, 1987], the Moncaup body appears in the heart of a complex consisting of various lithologies including crystalline basement rocks, mafic rocks (gabbros, dolerites, ophites) associated with Keuper breccias and verticalized Mesozoic sediments. All lithologies are in fault contact and the overall geometry of this complex consists of an assemblage of flat-lying tectonic lenses of mantle and crustal rocks typical of the structure around T-type lherzolite bodies.

[23] Good exposures along a recent scarp located at the junction between roads D618 and D39, 3 km east of the Moncaup village, allow to observe the contact between a tectonic lens of basement rocks overlying the main mantle unit, and the lower part of the Mesozoic sedimentary sequence consisting of yellowish to brownish Liassic carbonates. The contact is a shallow dipping fault, locally subhorizontal. It is marked by the development of a dm thick layer of cataclastic breccia composed of crushed Liassic marbles, and includes tectonic lenses of light gray chlorite-rich schists, in a position comparable to that of the

Sarailé talc-rich lenses. This suggests long-lived interactions between mantle and crustal rocks before faulting against the Mesozoic cover. Mineral lineation and tectonic striation on the foliation surfaces of the chlorite schist lenses trend E-W, which precludes the hypothesis of a development during the N-S compression of the Pyrenean orogeny. The beds of Liassic sediments are truncated along their basal contact with the Variscan basement, with a geometry consistent with extensional detachment tectonics (Figure 13).

3. Pyrenean Mid-Cretaceous Chaotic and Breccia Units: Significance With Respect to Detachment Tectonics

[24] The above compilation of both literature and new data on the setting of the lherzolite bodies confirms that during the Albo-Cenomanian subcontinental mantle reached very shallow crustal levels in the bottom of rift basins distributed along the future NPZ. Moreover, we have reported above clear evidence from the central-eastern Pyrenees, that

extreme crustal thinning along the future NPZ also led to local exposure and sedimentary reworking of subcontinental mantle mixed with previously deformed and metamorphosed clastic elements deriving from the original sedimentary cover of the NPZ. Similar conclusions were reached from investigations in the Western Pyrenean domain [Jammes *et al.*, 2009]. An important step is now to check whether such a major process of crustal thinning involving disaggregation of the platform cover sequence has been recorded all along the NPZ, even in areas where mantle rocks are not exposed. In this section, we present a review of the main mid-Cretaceous coarse clastic sedimentary formations which develop laterally or at the base of the thick flysch sequences of Albian-Cenomanian age along the NPZ.

3.1. Eastern Pyrenean Basins: Marble-Bearing Sedimentary Breccias and Ductily Deformed Marbles

[25] Narrow, nonconnected Albian basins opened north of the basement of the Pyrenean axial zone along the boundary between Iberia and Europe, between various crustal blocks now forming the Agly, Saint Barthélémy, Trois-Seigneurs, Arize and Castillon north Pyrenean massifs [Debroas, 1987, 1990] (Figure 2). In response to the tectonic inversion of the Late Cretaceous-Tertiary orogeny, these basins now represent narrow discontinuous zones of verticalized Mesozoic sediments such as the Boucheville, Prades, Tarascon and Aulus basins (Figure 1), which locally involve voluminous polymict breccias [Choukroune, 1976]. The striking feature of the deformation history of the metamorphic part of these eastern NPZ basins is the presence of a ductile deformation phase, expressed as a strong foliation (the S1 of Choukroune [1976]), shear zones and isoclinal folds. Radiochronological dating of metamorphic minerals has shown that this deformation event is Albian-Cenomanian in age and synchronous with the HT-LP metamorphism [Golberg and Maluski, 1988].

[26] Exhaustive study has never been devoted to the mid-Cretaceous breccias of the eastern NPZ. Based on the example of the Aulus basin described in section 2, we have shown that the polymict breccias most often include dominant clasts of the metamorphosed Mesozoic cover. However, the breccias may locally be formed of up to 100% of ultramafic clasts as observed at Etang de Lherz, Bestiac, Caussou and Prades.

[27] All workers who studied the transition from the ductily deformed marbles to the sedimentary breccias along the eastern NPZ noticed that (1) ductily deformed metasediments progressively pass into hydrofractured tectonic breccias [Choukroune, 1976; Dauteuil, 1988] and (2) there is a progressive transition from these monomict hydrofractured breccias to the polymict sedimentary breccias. This suggests a progressive transition from ductile stretching to cataclastic deformation and then to sedimentary reworking during extension, in relation to basin development under HT conditions. This evolution is consistent with detachment tectonics involving intense hydrothermal circulations.

[28] First attempts to explain the mid-Cretaceous ductile event of the NPZ in the frame of exhumation processes were published in the years 1980–1990. In the regions of the Bessèdes and Salvezines Paleozoic massifs, Dauteuil [1988]

suggested that ductile foliation of Mesozoic marbles was acquired before the Eocene, as the consequence of an extensional event accompanying the tectonic unroofing of the basement of the eastern NPZ. For Légier *et al.* [1987] the very first deformational event affecting the sedimentary cover of the northern flank of the Agly massif was a ductile phase of kilometer- to meter-sized isoclinal folds, synchronous with the HT-LP Pyrenean metamorphic event with a N-S stretching lineation. Three subunits separated by north verging thrust are recognized within the Mesozoic cover of the Agly massif, which suffered different metamorphic evolution from scapolite muscovite to the south to sericite assemblages to the north. Mylonites developed in the lower limb of the folds, with a top to the north sense of shear. These features are now interpreted as the effect of ductile extension in relation to the exhumation of the Agly continental block during the mid-Cretaceous (A. Vauchez, personal communication, 2009). A similar hypothesis has been proposed for the deformed sedimentary sequence associated with the Saint Barthélémy massif [de Saint Blanquat, 1985; de Saint Blanquat *et al.*, 1986].

[29] Hence, the tectonic and metamorphic evolution of the eastern NPZ massifs is consistent with extensional tectonics under an abnormally high geothermal gradient in relation to crustal thinning during the mid-Cretaceous. This early ductile phase is better developed in the central-eastern NPZ basins, and is restricted to the southern edges of these basins along contacts with the Paleozoic basement including granulitic slices.

3.2. Ballongue and Barronies Basins

[30] Both basins belong to the central NPZ (Figure 1). The main infill of the Ballongue basin corresponds to the late Albian-Cenomanian “Flysch ardoisier.” Coarse clastic formations linked to paleoscarps are observed along the northern and southern border of the basin [Debroas, 1987]. Along the northern border, the Castel-Nerou breccias consist of a chaotic assemblage of decametric blocks of Aptian limestones and sedimentary breccias lenses in a silt matrix. No granite clasts are observed in the lowermost breccias. To the south, the Alos breccias are Cenomanian in age and are linked to the paleoscarps exposing Paleozoic basement. They include granite clasts and blocks of late Albian sediments. All these observations indicate that the granite material appeared 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. Exhumation did not reach mantle rocks, however.

[31] The Barronies basin infill corresponds to the “Flysch Noir” of middle Albian to early Cenomanian age [Debroas, 1990]. As the Ballongue basin, the Barronies basin is marked by various types of peripheral coarse breccias. The middle Albian deposits contain only Mesozoic clasts whereas Paleozoic clasts are found in late Albian and early Cenomanian deposits. The basin is marked by an evolution during a divergent sinistral strike-slip movement from isolated kilometric half-grabens toward an unique, more than 100 km long, E-W trending trough.

3.3. Chaotic Mid-Cretaceous Formations and Conglomerates in the Western Pyrenees

[32] The various flysch sequences of Albian and Cenomanian age of the western NPZ locally contain large volumes of chaotic breccias reflecting major instabilities of the basin margins. We already reported the presence of crustal and mantle detritus in the flysch sequences of the Urdach complex in the Chaînons Béarnais. Some kilometres south of Urdach, olistoliths of various material, including Triassic rocks scattered within the Albian flysch of the Sarrance structure are reported on maps and cross sections by *Fortané et al.* [1986] and reported on map by *Canérot and Delavaux* [1986] (Figure 7). In the Layens thrust structure, the Layens and Lauriolle Breccias (Figure 6) are described in detail by *Canérot and Delavaux* [1986] and *James and Canérot* [1999]. The Lauriolle breccia is composed of dominant clasts of sedimentary material and consists of two members. Paleozoic, Trias, and Jurassic blocks are reworked within the lower member and Aptian limestones are reworked within the upper member. The lower breccia member passes laterally to Gargasian limestones and the upper breccia unit passes laterally to the Albian flysch (marnes à spicules). This indicates that the entire Mesozoic succession, including the Triassic formations, as well as the Paleozoic basement, has been exposed along scarps of the former Albian basin. In addition, occurrence of the Lauriolle breccias shows inception of tectonics in Aptian times, consistent with other estimates. Such clastic formations in the mid-Cretaceous sequences have been linked to salt tectonics [*James and Canérot*, 1999; *Canérot et al.*, 2005]. As discussed below, such detrital sedimentation might be related to gravity sliding of the sedimentary cover and progressive denudation of its basement as well.

[33] The Cretaceous north Pyrenean margin clastic sediments 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” (Figure 4). During the Pyrenean compressional phases, these clastic sediments and their basement have been thrust of about 20 km to the south [*Teixell*, 1993, 1996]. The Poudingues de Mendibelza stratigraphically onlap the Paleozoic formations of the Igounze and Mendibelza massifs or their Permo-Triassic cover which is locally preserved. Most of the conglomerates were deposited during the late Albian at the foot of steep slopes of the north Iberia margin and represent syntectonic, fan-delta-fed immature turbidite systems a few kilometres wide [*Boirie*, 1981]. Poorly sorted breccias are abundant and display frequent facies changes and mix between mass transport and rockfall indicating nearby active scarps. Very large blocks and huge olistoliths have traveled through narrow canyons. The Poudingues de Mendibelza underlie the Errozaté Cenomanian to Santonian breccia [*Durand-Wackenheim et al.*, 1981]. This chaotic formation, well developed in the southern Mendibelza area, is composed of large blocks of basement and Cretaceous carbonates in a carbonate matrix. This indicates activity of the basin margin up to the Santonian.

[34] The Mesozoic sedimentary formations which originally capped the Igounze and Mendibelza basement and its

Permian-Lower Triassic cover are now missing. The conglomerates onlap the Variscan basement and its tegument, but also locally chaotic Triassic formations (Keuper breccias and olistoliths) and fault breccias [*Ducasse and Vélasque*, 1988]. *Johnson and Hall* [1989] indicate that the basement is commonly brecciated near the contact with the clastic cover and that the uppermost conglomerate beds dip less steeply than the lowermost ones. Thus they propose that the Cretaceous clastic deposition occurred above the denudated (and locally eroded) footwall of an active low-angle normal fault. This is consistent with tectonic denudation of the Paleozoic basement due to sliding of its Mesozoic cover along a low-angle detachment. The allochthonous units now form the Arbailles massif as proposed by *Le Pochat* [1980] and *Ducasse et al.* [1986]. A similar scenario was proposed by *Jammes et al.* [2009] for the Chaînons Béarnais.

3.4. Tectonized and Resedimented Triassic Formations Along the Pyrenean Belt

[35] The Larrau-Sainte-Engrâce unit (Figure 14) lies tectonically below the Mendibelza and Igounze massifs. It is composed of a chaotic assemblage of heterometric blocks of Triassic evaporites (Keuper) and dolomites, Paleozoic basement (including granulites at Négumendi), in a matrix of micaceous black marls having affinities with the Albian flysch [*Ducasse et al.*, 1986]. For this reason, the Larrau-Sainte-Engrâce unit can be interpreted as a chaotic unit of Albian age, representing scree deposits in response to the exhumation of tectonized Triassic formations. The Larrau-Sainte-Engrâce unit probably differs from the Bedous formations exposed more to the east in the the Aspe Valley [*Canérot et al.*, 2005] and which comprises different south verging thrust sheets mainly composed of Triassic materials but devoid of Albian flysch remnants (e.g., the Bedous ophite, associated with Muschelkalk and Keuper sediments). An important feature regarding the Triassic formations of Larrau-Sainte-Engrâce and Bedous is the overall development of mineralogical assemblages typical of the thermal Pyrenean metamorphism [*Thiébaud et al.*, 1988, 1992]. During the Pyrenean compression, both the Larrau-Sainte-Engrâce and Bedous Triassic complexes were thrust southward above the Upper Cretaceous cover of the axial zone by the Lakoura thrust [*Teixell*, 1993, 1996].

[36] Other exposures of Triassic evaporite complexes, in close association with chaotic formations including metasediments and crustal mantle material, occur along the north Pyrenean frontal thrust and within the NPZ. They are described by *Henry and Zolnai* [1971], *Thiébaud et al.* [1988, 1992], *Canérot and Lenoble* [1993], *James and Canérot* [1999], and *Canérot et al.* [2005]. Metaevaporites from these complexes are characterized by the development of HT-LP metamorphic assemblages. Surprisingly, HT metaevaporites are also exposed in areas where the remaining Mesozoic sediments are devoid of strong Pyrenean metamorphic imprint. The typical sites of HT metaevaporites are Arignac in the Tarascon basin, Betchat and Bonrepaux near Salies du Salat, Caresse-Salies du Béarn and Gotein in the western Pyrenees (Figure 14). The evaporite complexes consist of polymict breccias with a gypsum cement including

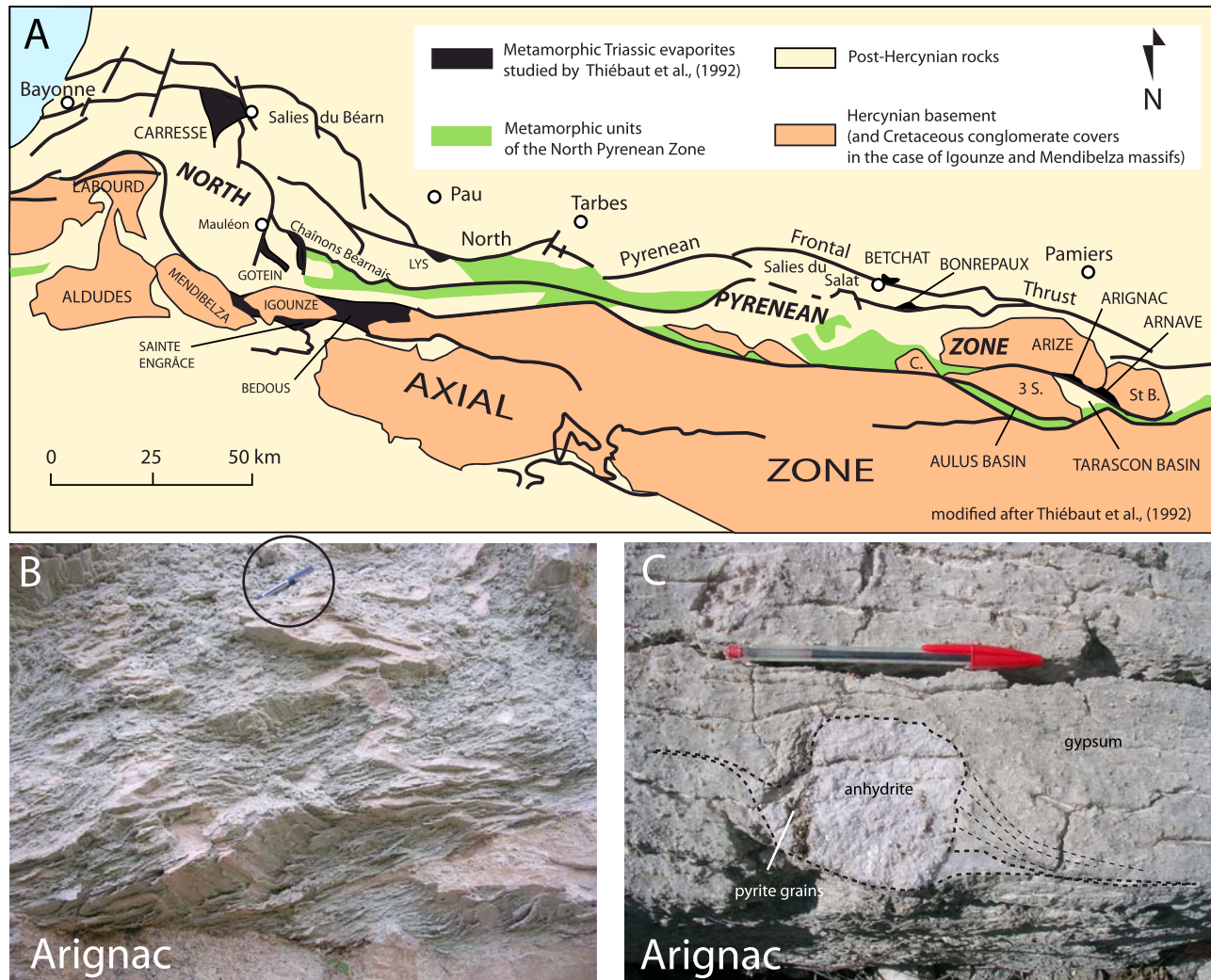


Figure 14. Some significant aspects of the metamorphic and tectonized Triassic rocks from the Pyrenean belt. (a) Geological map of the Pyrenees after *Thiébaud et al.* [1992] showing the distribution and the names of the main outcrops of metamorphic Triassic evaporites complexes. Note the presence of metamorphosed Triassic evaporites far northward from the metamorphic units of the north Pyrenean zone. (b and c) Strongly sheared metaevaporites from the Arignac quarries showing well-developed foliation, lineation, a axis folds, and asymmetric deformed clasts.

blocks of marbles, ophites, dolomites and anhydrite (Figure 14). The mineralogical assemblages include phlogopite, talc, sheridanite, dravite, albite, dolomite quartz. In the marbles, frequent paragenesis of actinote-phlogopite-albite or dipyre-pargasite are observed [*Thiébaud et al.*, 1988, 1992]. The Betchat complex includes various chaotic breccias associated with the large mass of metamorphic halite exploited at Salies-du-Salat. Chaotic breccias of evaporitic material with large clasts of crystalline material (granite, gneisses, amphibolites, micaschists) are stratigraphically overlain by a nonmetamorphic Albian flysch. These breccias tectonically overly a gypsum-rich complex including hectometric to centimetric blocks of ophites and dolomites, and a level of Hercynian basement breccias, interbedded within a Santonian flysch (85 Ma). K/Ar dating of phlogopites in the

rim of dipyres from dolomitic clasts yielded ages around 107 ± 3 Ma [*Thiébaud et al.*, 1988, 1992]. At Bonrepaux, the metamorphic Triassic rocks also conformably underlie nonmetamorphic Albian flysch deposits. At Arignac, the Triassic gypsum includes a rich assemblage of Pyrenean metamorphic minerals. New structural analysis in ancient gypsum quarries reveals a strong shear fabric of the salt formations with numerous tectonic lenses limited by shear bands, a well-defined lineation trending E-W and a axis folds paralleling the lineation (Figure 14). These features are consistent with a large amount of displacement of the metaevaporitic formations during the mid-Cretaceous thermal culmination.

[37] Reworking of Triassic clastic sediments including evaporites, dolomites and ophites within Albo-Cenomanian

flysch sequences has long been demonstrated by a combined geological analysis of outcrops and well data in the Mauléon and Arzacq basins [Henry and Zolnai, 1971]. These authors conclude that during the Albian and Cenomanian, brecciated Triassic evaporites and related sedimentary and volcanic rocks have been exposed and reworked as debris flow deposits and olistostromes within the subsiding basin. This is well observed at Meharin, close to the northern edge of the Labourd massif. Similar processes continued during the Late Cretaceous. As envisioned by Henry and Zolnai [1971], these informations, from combined field and well data are consistent with diapiric tectonics and gravity sliding of the evaporites, leading to the exhumation of brecciated Triassic rocks.

3.5. Summary: Significance of the Albo-Cenomanian Chaotic Formations With Respect to Extensional and Gravity Tectonics

[38] The above compilation of geological data from basins located all along the NPZ shows that during the Albian-Cenomanian times a wide variety of clastic products were provided by actively deforming zones having various lithologies. Some basins show a classical behavior for rifted continental areas with clast sources shifting from platform sediments to continental basement during progressive erosion of the basin margins (Ballongues, Barronies). Other types of basins are characterized by coeval sedimentation of dominant clasts of ductily deformed sediments and ultramafic rocks with rare crystalline components (Aulus, Bestiac). The central-eastern NPZ breccias overlie deformed and metamorphosed Mesozoic, pre-Albian sediments which reveals an important shearing event prior to the clastic sedimentation. The presence of Triassic cataclastic elements in numerous breccias indicates that source rocks for the detritus were deformed zones developed within and above a tectonic sole of metaevaporitic formations affected by intense hydrothermal circulations. The existence of a tectonic sole allowing gravity sliding of large portions of the initial cover of the NPZ basement rocks has been first envisioned thanks to the geological study of the Mendibelza-Igounze and Arbailles regions. Finally, the high variety of clastic products deposited in the former NPZ basins reveals different types of geological environments. This indicates that various types of tectonic processes are recorded by the sedimentary processes, including high-angle basement faults, low-angle cover detachment over a tectonic sole of tectonized evaporites and deep detachments allowing exhumation of granulitic and mantle rocks. These tectonic mechanisms are discussed in section 4.

4. Discussion—Detachment Tectonic and Gravity Sliding: The Missing Links?

[39] In sections 2 and 3, we have listed and synthesized a number of geological features which are highly relevant to the question of the processes of mantle exhumation coeval with the formation of the Albo-Cenomanian basins of the NPZ. In order to decipher the mechanisms that drove mantle exhumation, we now discuss the significance of the tecto-

nostratigraphical record at a broad scale and we attempt to propose an integrated model for the preorogenic evolution of the NPZ.

4.1. Kinematic and Paleogeographic Constraints

[40] The paleogeographic and kinematic reconstructions of the Iberia-Europe plate system remain a subject of major debate. In his reconstruction based on oceanic magnetic anomalies, Olivet [1996] assumed that the break up between the Newfoundland and Iberian margins occurred at the anomaly J (126–118.5 Ma) and that a period of extension occurred between the Barremian and the middle Albian. This period was followed by the transcurrent motion of Iberia of the order of 300 to 500 Km, from the middle Albian to the early Senonian (107–90 Ma). By contrast, for Jammes *et al.* [2009], most of the E-W directed movement between Iberia and Europe had to occur between latest Jurassic to late Aptian times. Sibuet *et al.* [2004] proposed a different reconstruction with important stretching in the eastern Pyrenean domain before 118 Ma. Paleomagnetic investigations on the Iberia plate [Gong *et al.*, 2009] confirm that a major strike slip displacement occurred along the future NPZ during the late Aptian, that is prior to the main period of extensional deformation and crustal stretching in the Pyrenean realm. This might suggest a two-step evolution for the Pyrenean realm implying pre-Albian strike-slip motion followed by pure tensional deformation leading to mantle exhumation during the Albian-Cenomanian. Thus, in these conditions, extreme crustal stretching and mantle exhumation between Iberia and Europe occurred after transcurrent tectonics. Geological records from the Cretaceous basins located along the NPZ indicate that the onset of the Pyrenean flysch sedimentation started during the middle Albian by the development of half grabens, some kilometres wide only, in a context of sinistral transtensional deformation. These basins enlarged during the late Albian and finally merged into a wider and unique trough during the Cenomanian [e.g., Debvoas, 1987, 1990]. Increase in tectonic activity related to the deepening of the Pyrenean Cretaceous basins occurred as soon as the late Aptian as shown by numerous evidence of reworking of continental bauxites in the NPZ sedimentary sections [Combes and Peybernès, 1996]. Therefore, our knowledge of the timing and kinematic context of mantle exhumation still needs to be precised. The geological data presented in this paper do not provide constraints that may help deciphering yet between a pure tensional and a transtensional regime for mantle exhumation in the Pyrenean realm.

4.2. Types of Fault Contacts in Lherzolite-Bearing Units

[41] Analysis of the geological setting of the Chaînons Béarnais lherzolite bodies, with emphasis on the Saraillé summit, has revealed remarkable jumps in the intensity and P-T conditions of deformation between different fault contacts. Contacts separating mantle rocks from the deformed pre-Albian sediments occurred under the conditions of the HT mid-Cretaceous event with important fluid circulations leading to talc development. By contrast, the contact sepa-

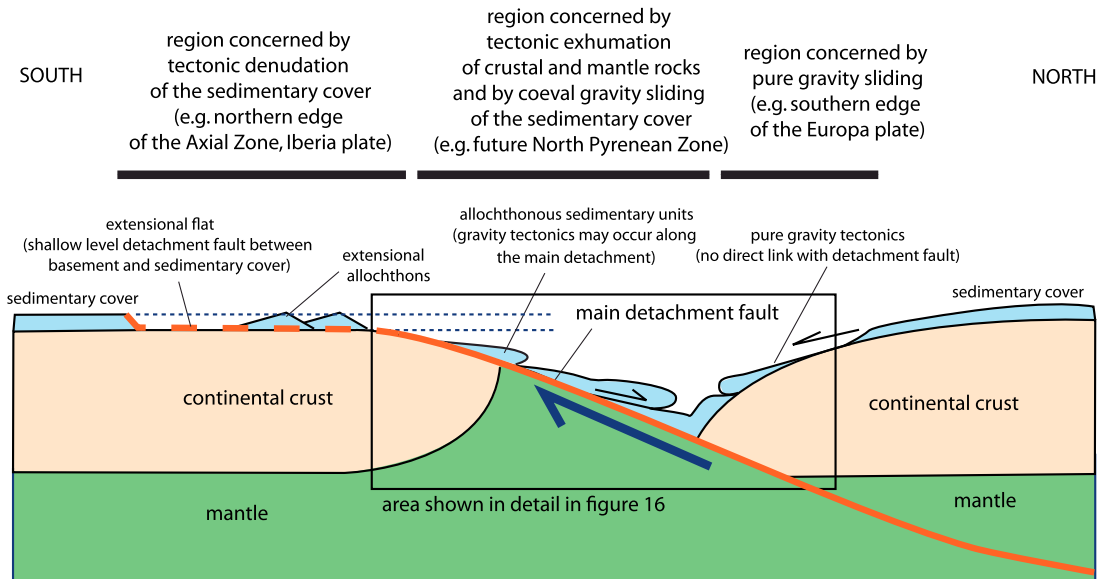


Figure 15. A conceptual model of detachment tectonics and gravity sliding which applies to the precol-lisional evolution of the Pyrenees.

rating the Sarail  unit from the Albian flysch is colder and do not show evidence of significant fluid circulation. This is a major indication that the following two types of contacts are observed in the NPZ (Figure 16): (1) An early tectonic juxtaposition of pre-Albian Mesozoic sediments and an assemblage of tectonic slices of crustal and mantle rocks representing the damage zone of a major detachment fault; this juxtaposition involves a tectonic sole of various Triassic cataclastic rocks. (2) Younger and colder contacts which developed during the Latest Cretaceous and the Tertiary, in relation to the Pyrenean compressional tectonics. In many places, field evidence of pre-Albian tectonics in relation to the “hot” contacts can be found. This is the case for the ductile deformation of the metamorphic NPZ in the central-eastern Pyrenees and it coincides with the “ant -Cenomanian” tectonic phase described by ancient authors in the NPZ [Cast ras, 1974].

4.3. Evidence for Large-Scale Crustal Denudation and Gravity Sliding of the NPZ Mesozoic Cover

[42] The eastern NPZ breccias which surround the S-type lherzolites are characterized by coexisting debris deriving from the following two distinct sources: (1) ultramafic rocks and (2) ductily deformed and metamorphosed sediments from the NPZ cover. Clasts of Paleozoic micaschists, granites, gneisses and amphibolites are extremely rare compared to the bulk volume of the basin infills. In a geodynamical context of continental rifting with active crustal stretching and mantle exhumation, one would expect a higher content of crust-derived components into the sedimentary fluxes. This implies that (1) during sedimentary reworking of mantle rocks exposed on the seafloor, the Paleozoic crustal basement was rarely exposed in the source areas and (2) that during mantle unroofing, the continental crust remained

hidden beneath a continuous sedimentary cover. This is only possible if during crustal thinning, generalized sliding of the sedimentary cover occurred over its former crustal basement, along a shallow detachment fault. As summarized in Figure 15, this allowed the tectonic juxtaposition, at the foot of the extended margin, of a deep detachment (that favors mantle unroofing) and a shallow detachment (that tends to hide exhumed mantle). The field evidence collected so far near the lherzolites of the Cha nons Bearnais and Etang de Lherz is consistent with such a hypothesis. Therefore, we assume that this model may apply to the entire length of the Pyrenean realm during the late Aptian to Cenomanian extensional phase.

[43] This hypothesis has never been proposed yet at the scale of the entire Pyrenean belt, but sliding of portions of the NPZ cover has been envisioned previously for local situations. As reported above, authors stressed more than 20 years ago the importance of gravity tectonics in the preorogenic evolution of the Pyrenees on the basis of tectonostratigraphic studies in the western NPZ. Based on field analysis in the Arbailles region, in the Mendibelza and Igounze massifs and in the Lakhoura unit, *Le Pochat* [1980], *Ducasse et al.* [1986], *V lasque and Ducasse* [1987], and *Ducasse and V lasque* [1988] shed light on the importance of synsedimentary gravity tectonics and large-scale gliding of the NPZ cover. The fan geometry associated with the onlap of the “poudingues de Mendibelza,” the frequent occurrence of debris flow deposits and slumps and the rapid subsidence recorded by the migration of Aptian reefs, led these authors to propose that the entire Arbailles massif glided to the north in response to the subsidence and northward tilting of the Mendibelza crustal block. *Ducasse et al.* [1986] proposed that generalized sliding of the pre-Albian Mesozoic cover occurred along a system of tilted blocks, leading in some places to gravity-driven compres-

sional deformation with folding and stacking of slided sedimentary units separated by synsedimentary thrusts. Gravity-driven compression is shown by well data from the Arbailles region (Ainhice well [Ducasse *et al.*, 1986]). A preorogenic geometry implying gravity sliding of the sedimentary cover of the NPZ with extensional rollovers, together with clastic sedimentation on top of denudated blocks was used in the restored crustal section of the Mauléon and Arzacq basins by Daignières *et al.* [1994].

[44] Based on the example of the Arbailles case, we can infer that gravity gliding was responsible for the preorogenic evolution of the nearby Chaînons Béarnais. In their whole, the Mail Arrouy, Sarrance and Layens thrust structures likely represent a group of three slided units, initially deposited above the northern edge of the north Iberia continental margin (the future Pyrenean axial zone) which glided toward the bottom of the actively opening basin where mantle rocks were being exhumed. A comparable hypothesis, implying detachment tectonics of discontinuous allochthons units in the frame of mantle exhumation was proposed by Jammes *et al.* [2009]. In their model, Jammes and coauthor hypothesize relatively small and totally disconnected rafts. In our model, based on the structures exposed in the eastern part of the Chaînons Béarnais, we assume larger rafts which have not been disconnected (see discussion below).

4.4. Gravity Sliding Over a Fluid-Injected Tectonic Sole of Triassic Evaporites and the Significance of the Pyrenean Metamorphism

[45] Studies in the western NPZ brought ample evidence for tectonic allochthony of the Triassic deposits in response to pure salt tectonics in diapirs or to extensional tectonics due to gravity sliding along slopes of the actively opening Albian basins. As clarified by our compilation in section 3 above, sedimentological analysis of the chaotic Larrau-Sainte-Engrâce unit, the Lauriolle breccias, the Betchat complex, and well data in the Aquitaine region, collectively demonstrate that the evaporitic chaotic formations were exposed by place on the seafloor during Albian and Cenomanian times. Such situations have been explained by pure diapiric tectonics, without horizontal mobility and by local sliding in response to diapiric extrusion [e.g., Mediavilla and Mauriaud, 1987; James and Canérot, 1999; Canérot *et al.*, 2004]. But evidence of generalized sliding of large portions of the margin favors the hypothesis of diapiric tectonics during generalized horizontal transport as confirmed by the tectonic fabric of the eastern NPZ metaevaporites (Figure 14). Diapirs are indeed well explained as a consequence of raft tectonics as shown by numerous examples collected along margins experiencing generalized salt tectonics such as the Angola margin [Mauduit *et al.*, 1997] and the Mexican margin [Rangin *et al.*, 2008]. As shown by numerous examples provided by various deep passive margins, salt diapirs are extruded in extensional region, between sliding rafts having differential velocities [Fort *et al.*, 2004]. We have applied this process to our reconstruction of NPZ basin margins development shown in Figure 15.

[46] As stressed by Thiébaud *et al.* [1992], a striking feature regarding the evaporitic complexes of the entire NPZ is that they are everywhere brecciated and metamorphosed, even in areas devoid of any metamorphic imprint in the rest of the Mesozoic cover. HT-LP assemblages from evaporites are known all along the belt, from the Mendibelza region to the eastern Pyrenees. This points to the link between hydrothermal activity and Pyrenean metamorphism and consequently implies that the contribution of salt-derived products in the upper part of the sedimentary sequence is a key feature. This implies indeed that gliding of the NPZ cover over the Triassic sole everywhere occurred under high-temperature conditions and with active fluid circulations, even in regions supposed to have escaped the Pyrenean thermal event. We may conclude that in regions such as the Chaînons Béarnais, anomalous heat has not been transferred to the entire volume of the overlying sedimentary sequences. This is consistent with a highly heterogeneous distribution of the metamorphic field, in relation to discontinuous and variable fluid fluxes.

[47] Discontinuous fluid fluxes are also demonstrated by the heterogeneous distribution of the metamorphic imprint in the nonbrecciated, deformed pre-Cenomanian Mesozoic sediments of the central-eastern NPZ. Hot fluids as main medium of heat transfer leading to dynamothermal metamorphism are indicated by the vertical geometry and the heterogeneity of the distribution of isograds [Golberg and Leyreloup, 1990]. Models of conductive heat transfer applied to these regions are not able to account for the distribution of the metamorphic assemblages in a narrow corridor along the NPZ, as well as for the rapid lateral changes of temperature conditions at a kilometer scale [Dauteuil and Ricou, 1989]. Therefore, we assume that the metamorphism of the NPZ sedimentary cover is the result of intense convective fluid circulations during gravity sliding in an abnormal thermal environment linked to mid-Cretaceous rapid crustal thinning accompanying a sinistral drift of Iberia.

4.5. Tectonic Inversion of the Extensional Mid-Cretaceous Structures

[48] Reconstructing the geometry of the extensional system at the end of the mid-Cretaceous period has a major impact on our knowledge of the tectonic processes that led to the early phases of the construction of the Pyrenean collisional wedge. First of all, we demonstrate that the rifted continental crust of the Iberia and European plates have been separated by a domain of exhumed material that spread during almost 20 Myr. We are well aware that important part of the tectonic history occurred during transcurrent displacement, as discussed in section 4.1. We point to the fact that all estimates of the initial width of the mid-Cretaceous basins have to be revisited since a significant portion of these basins derive from the exhumation of mantle material. Our models favor a geometry implying exhumation of the subcontinental mantle beneath Europe, in a similar kinematics as that proposed by Jammes *et al.* [2009]. This indeed allows most of the gravity instabilities to develop at the Iberian margin, as deduced from the current geological record. As a consequence for the development of the Pyrenean

belt, this model favors the hypothesis that the exhumed subcontinental European mantle will be buried by subduction beneath the European crust during the tectonic inversion. We confirm therefore that the mid-Cretaceous detachment faults zones will be used as thrust systems during the contractional phases [Jammes *et al.*, 2009]. At the scale of the entire system, one may ask whether the axial zone in its whole represents a “block H” as defined from numerical modeling of crustal extension [Lavie and Manatschal, 2006]. Whatever the case, the thrusts that develop on the southern flank of the Pyrenees are likely linked to the northern ones through a common history during the stretching phase.

5. Conclusion: Mantle Exhumation, Salt Tectonics, and Major Thermal Anomaly Along the NPZ

[49] We have shown that only two types of geological settings have to be distinguished among the Pyrenean ultramafic bodies. In the sedimented type (S type), the lherzolites occur as clasts of various sizes, ranging from millimetric grain to hectometric olistolith, within monogenic or poly-mictic debris flow deposits of Cretaceous age. This is the case for the Lherz body. In the tectonic type (T type), the mantle rocks form hectometric to kilometric lenses and are associated with crustal tectonic slices. Both crustal and mantle tectonic lenses are in turn in fault contact with large volumes of strongly deformed Triassic formations and with Jurassic and Lower Cretaceous sediments belonging to the cover of the NPZ, not older than the Aptian-early Albian. From this simple classification, we derive a number of important constraints for the emplacement of the mantle rocks and the overall evolution of the NPZ domain. The very close association of crustal and mantle lenses in T-type lherzolites suggests juxtaposition during faulting along a major detachment linked to the unroofing of the subcontinental Pyrenean mantle during the mid-Cretaceous. Analysis of the geological environment of the S-type lherzolites indicates transition from ductile stretching to cataclastic deformation and then to sedimentary reworking of the NPZ sedimentary cover under HT conditions during Albian extension. This evolution is consistent with detachment tectonics involving allochthony of a salt layer and intense hydrothermal circulations.

[50] As summarized in our model shown in Figures 15 and 16, a two-step evolution for the Albian NPZ basins can be reconstructed. First, as a consequence of rifting followed by extreme thinning of the crust, the mantle rocks progressively rose up to the surface along a detachment which developed at the foot of the stretched European continental margin. The damage zone of this detachment is composed of tectonic lenses of crust and mantle rocks whose thickness might be of the order of a few hundred meters based on the size of the lenses preserved in the Urdach, Sarailé-Tos de la Coustette and Moncaup complexes. Such size corresponds to the description of damage zones of major continental and oceanic detachments [John and Cheadle, 2009]. Second, as the detachment reached the surface, gravity sliding of the Mesozoic cover of the

Iberian margin occurred over a tectonic sole of Triassic material. Gliding was accompanied by the ductile deformation of the Mesozoic cover and led to the emplacement of rafted portions of the margin sediments over the lherzolite-bearing damage zone (Figures 15 and 16). The major syntectonic thermal event associated with this detachment tectonics activated the circulation of salt-enriched fluids in relation to the thermal dissolution of the Triassic evaporites.

[51] In the western Pyrenees, the HT-LP assemblages of highest grade are found only in the Triassic metasediments. This indicates that maximum temperatures at the base of the sedimentary cover reached similar values to that of the eastern domain. However, the total amount of heat or the ability of the fluids to distribute such heat were different from west to east. This can be explained by the size of the former Albian basins. In Figure 17, we propose two reconstructions of the Albian basins based on available crustal scale-balanced sections [Muñoz, 1992; Teixell, 1998], and in which the mantle has been exhumed in the deepest portions of the central basins according to our model. It must be noticed that in these reconstructions, tectonic displacements during mantle exhumation are imposed to occur within the plane of the section. Thus, these are rather 2-D than 3-D reconstructions which do not strictly account for transtensional stretching, a mechanism that might have been of importance in the Pyrenean realm. As already stated above, the geological data set compiled in this article does not provide constraints allowing it to decipher between a fully tensional and a transtensional context for the exhumation of the Pyrenean mantle.

[52] In the eastern part of the future NPZ, at the site of Etang de Lherz, the region of exhumed mantle is narrow. Heat transfer from the tectonically uprising mantle is restricted to a narrow zone between crustal blocks, and sediments that accumulate in the bottom of the deep basins cannot travel far away and are metamorphosed in situ. In the western reconstructed section, at the emplacement of the future Chaînons Béarnais, closer to the oceanic spreading center of the Bay of Biscaye, the Albian basins are wider. The continental walls of the basins are far from each other and we may assume that the thermal anomaly was widely distributed. Metamorphic fluids circulated mostly within the Triassic tectonic sole. This sole was in contact with the main detachment fault over large surfaces, due to large-scale sliding, distributing thermal anomalies over a wider volume and avoiding upwelling of convective fluids high within the sliding sedimentary pile.

[53] As highlighted in Figures 16 and 17, our model accounts for a great number of basic characteristics of the pre-orogenic evolution of the Pyrenean belt including: the systematic occurrence of deformed and metamorphic Triassic rocks in the NPZ, the pre-Cenomanian deformation of the NPZ Mesozoic sequences, the presence of abundant mantle-bearing clastic formations of Albian-Cenomanian age, and the denudation of the northern edge of the axial zone prior to the Cenomanian transgression. The thermal anomaly which accompanied this exhumation event is also recorded within the continental formations of the Pyrenean basement suggesting a huge, long-lived hydrothermal pulse not only restricted to the exhumed domain. Active circula-

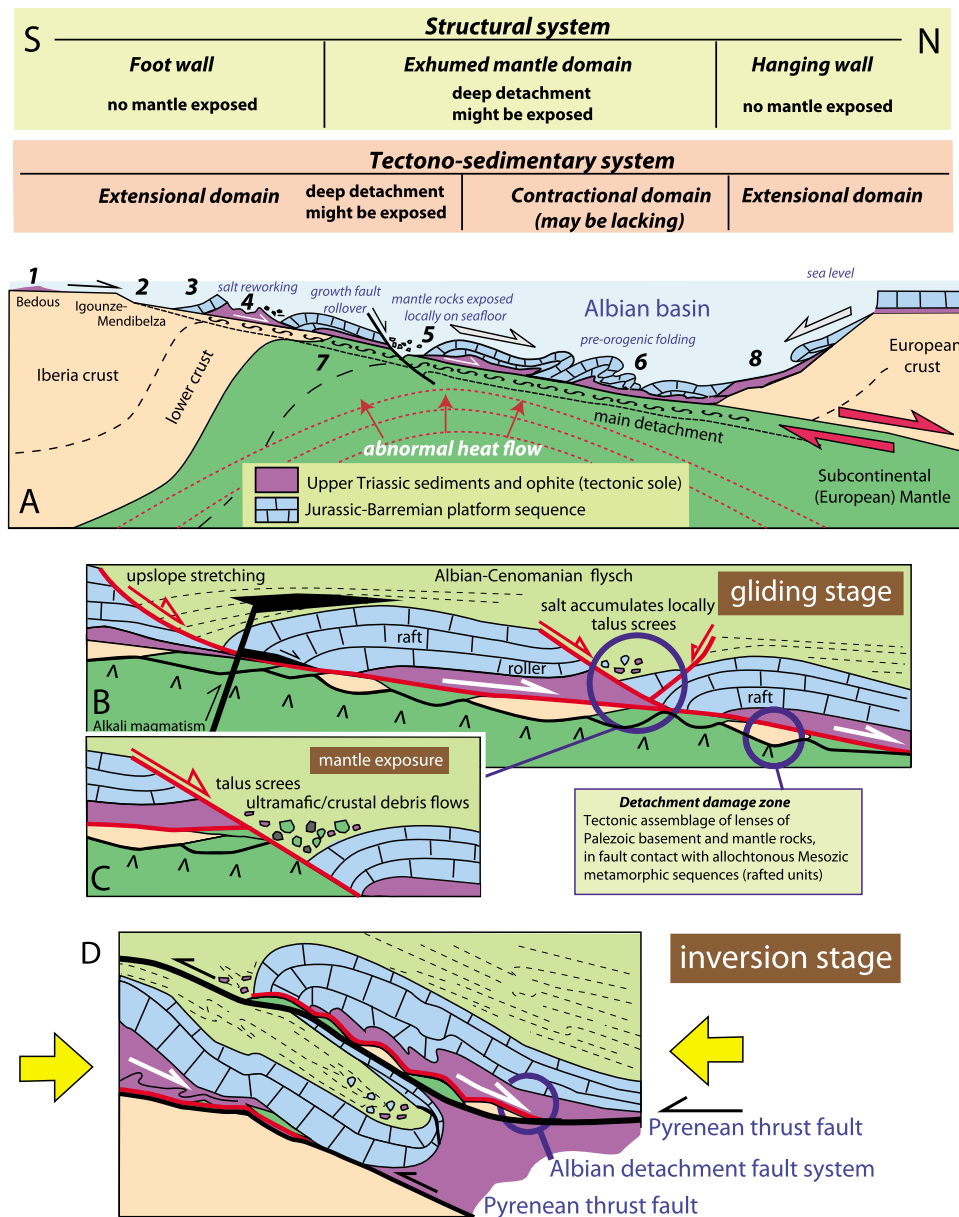


Figure 16. Conceptual models of mantle exhumation, detachment tectonics, and raft tectonics which applies to the precollisional evolution of the western Pyrenees. Note that the area shown corresponds to the central portion of Figure 15. (a) Generalized 2-D view of the overall extensional system including the most significant tectonic and sedimentological aspects of the proposed model. Labels 1–6 refer to specific current features of the Pyrenean belt as follows: 1, abandoned chaotic Triassic sole of Bedous; 2, denudated crust of the Igounze and Mendibelza massifs; 3, isolated Mesozoic allochthonous units lying over Upper Triassic deposits at the northern margin of the axial zone; 4, extensional salt diapir [e.g., *James and Canérot, 1999*]; 5, polymictic breccia deposits of the Urdach complex; 6, preorogenic folding and thrusting (Arbailles area); 7, tectonic contact between detachment damage zone and allochthonous Mesozoic rafts (Sarailé); 8, large exposures of the Triassic sole [e.g., *Henry and Zolnai, 1971*]. (b) Detailed model of the tectonic relationships between the rafted Mesozoic units and the damage zone of the detachment fault system. Continuous gliding of the allochthonous units over the exhumed units tends to hide the damage zone of the detachment. Only late normal faulting might allow the detachment fault rocks to be exposed. (c) This leads to the submarine reworking of mantle and deep crustal material (e.g., Urdach complex and most of the S-type lherzolites exposed in the central-eastern Pyrenees). (d) Tectonic inversion of the extensional system described in Figures 16a and 16b, leading to the incorporation of detachment fault rocks into the Pyrenean orogenic wedge during the contractional phase.

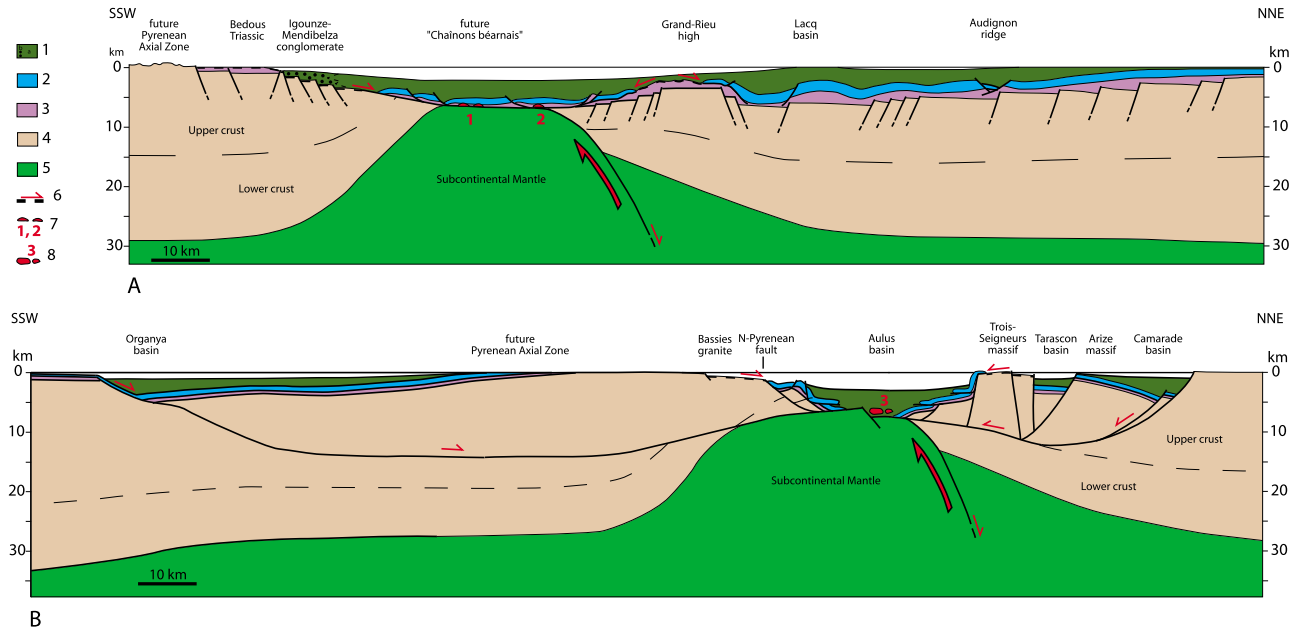


Figure 17. Models of Albian extensional structure in the Pyrenean domain. (a) Western Pyrenees section, corresponding to the present-day section in Figure 5. Only the domains with mantle denudation and the southern basin margin were inverted during the Pyrenean orogeny, now forming the north Pyrenean zone and the northern part of the axial zone. The northern part of the basin became the north Pyrenean foreland basin and was not inverted, except for local cover structures. (b) Central-eastern Pyrenees section, corresponding for its northern part to the present-day section in Figure 2. The model is adapted from *Muñoz* [1992], modified to insert a domain with mantle denudation below the Aulus basin. The whole basin was inverted during the Pyrenean orogeny, the northern part becoming the north Pyrenean zone, thrust northward above the former northern basin margin. To the south, southward inversion of the Organya basin resulted in the formation of the Noguères and Orri basement thrust sheets in the axial zone and related decolled units in the cover [Muñoz, 1992]. 1, Aptian-Albian (a, flysch; b, Igounze-Mendibelza conglomerate; Urgonian limestones facies not differentiated); 2, Jurassic to Barremian; 3, Triassic; 4, Palaeozoics (continental crust); 5, subcontinental mantle; 6, tectonic denudation; 7, tectonic lenses of crustal and mantle rocks along the extensional detachment (1, Sarailé and Tos de la Coustette; 2, Turon de la Tècouère (Figure 17a)); 8, olistoliths of mantle rocks (3, Lherz (Figure 17b)).

tion of hot fluids is known to have occurred within the north Pyrenean massifs, as shown by overall albitization in the Agly massif [Demange *et al.*, 1999], and in the Salvezine massif, where the fluid circulation is dated at 117 Ma [Boulvais *et al.*, 2007]. Moreover, the formation of the Trimouns talc at the expense of dolomitic Paleozoic formation in the Saint Barthélémy massif lasted at least 10–15 Ma during the Albian [Schärer *et al.*, 1999]. Since the talc is strongly deformed and located in a décollement zone which cuts the whole Saint Barthélémy massif, an important deformation event affecting the internal structure of basement blocks took place necessarily during the mid-Cretaceous [Passchier, 1984; de Saint Blanquat *et al.*, 1986, 1990; Costa and Maluski, 1988; de Saint Blanquat, 1993]. This deformation, with a low-angle geometry, and a north-south-directed kinematic is associated with an important vertical thinning of the lithological series, strongly suggesting an extensional context [de Saint Blanquat *et al.*, 1986]. In addition, the metasomatic formation of talc from silicic and dolomitic rocks is known to necessitate a large amount of

fluids [Moine *et al.*, 1989; Schärer *et al.*, 1999; Boulvais *et al.*, 2006]. Finally, there is no doubt that the thermal Albian event had an important impact on the entire future NPZ domain and was able to deeply modify the composition of the continental crust itself with possible geochemical influences from exhumed mantle rocks, Triassic evaporites and Albian seawater. We may wonder whether similar processes are able to develop during mantle exhumation at the foot of most of the passive margins worldwide. If this was the case, a lot could be understood from the Pyrenean belt concerning the tectonic behavior, the fluid evolution and the thermal history of the still poorly known regions of the continent-ocean transition experiencing mantle exhumation.

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