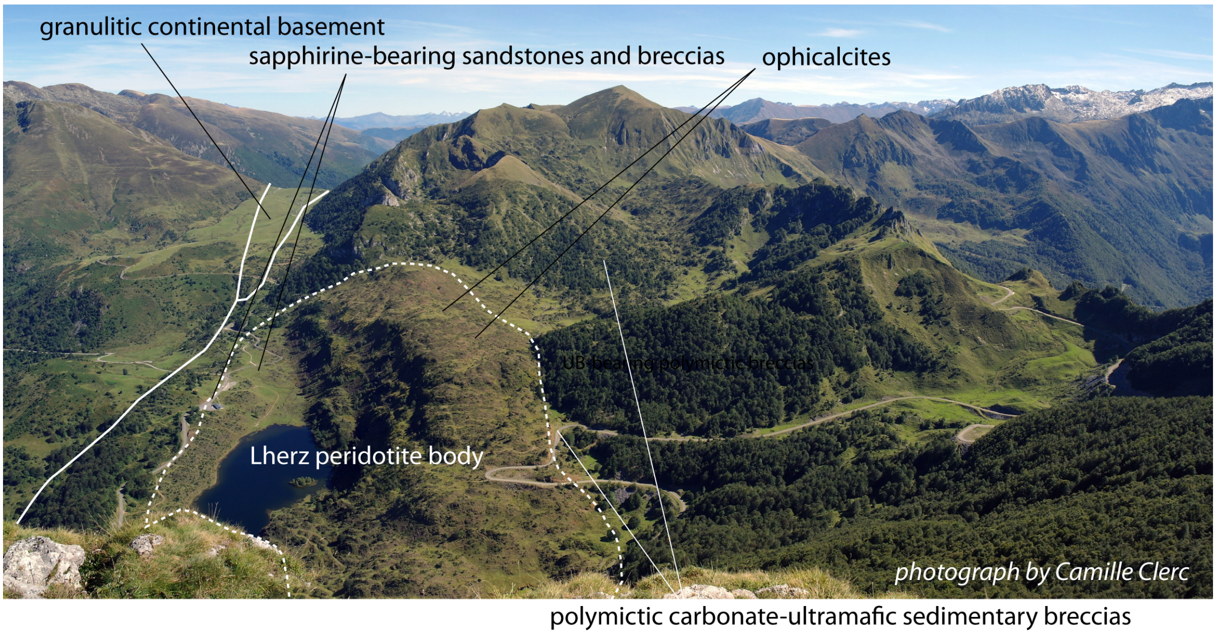
4th Serpentine days 2016
25-29 September
Sète, France

Processes of mantle exhumation during the Cretaceous rifting event in the North Pyrenean Zone : tectonic and sedimentary records.



Field-trip guide book to the subcontinental peridotites of Lherz and Bestiac,

French Pyrenees,

sept 30th – Oct 01st 2016

Yves Lagabrielle[1] and Michel de Saint Blanquat[2]

1 : CNRS-Géosciences Rennes UMR 6118 Université de Rennes1
Campus de Beaulieu 35042 Rennes Cedex, France

2 : CNRS-Géosciences Environnement Toulouse / Observatoire Midi-Pyrénées
14 avenue Edouard-Belin 31400 Toulouse France

PART A : INTRODUCTION TO THE FIELD TRIP

THE PYRENEAN PERIDOTITES : SOME BASIC DATA AND MORE RECENT CONCEPTS

The Pyrenean peridotites consist of about 40 fragments of generally well-preserved subcontinental mantle, a few hundred meters to 3 km across (Lacroix, 1883; Monchoux, 1970; Fabriès et al., 1991, 1998; and many others). Most of these peridotites occur within a narrow belt of Mesozoic sediments running over ~ 400 km, parallel to the North Pyrenean Fault (NPF) that marks the limit between the Iberia and Eurasia plates (Fig. 1, 2 and 3). The significance of these small mantle fragments scattered along a major tectonic boundary has long been a matter of debate. Various scenari have been proposed for their emplacement, ranging from purely tectonic mechanisms, such as solid intrusion of hot or cold mantle rocks into sediments (Minnigh et al., 1980; Vielzeuf and Kornprobst, 1984), to tectono-sedimentary processes involving disintegration and transport of mantle rocks previously exhumed on the seafloor (Choukroune, 1973; Fortané et al., 1984 ; Lagabrielle and Bodinier, 2008 ; Jammes et al., 2009 ; Lagabrielle et al., 2010).

1. Composition

All the massifs are composed of layered spinel lherzolites. Layering is defined by ubiquitous centimetre to decimetre thick parallel beds of spinel websterite. Locally, concentrations of clinopyroxene and spinel in very thin, numerous, and diffuse layers are observed, leading to clinopyroxene-rich lherzolites. In the Lherz, Freychinede, and Moncaup bodies, there are thicker layers (up to 1 m) of garnet-rich pyroxenites (after Fabriès et al., 1991). Continuous, thick bands of harzburgites or clinopyroxene-poor lherzolites lie parallel to the spinel websterite layering, especially in the Lherz and Fontete Rouge bodies (Ave Lallemant, 1967; Conquere, 1978). These bands attain thicknesses up to some 20 m, and also contain narrow layers of spinel websterite. In Lherz and Freychinede bodies, the layering is cross-cut by a later generation of amphibole-bearing pyroxenite dykes, up to 30 cm thick, and of thin hornblendite veins (Lacroix, 1917; Ave Lallemant, 1967; Conquere, 1971a, 1978). The harzburgites are affected by a foliation, represented by a general flattening of minerals. The elongation of spinel defines a mineral lineation in the foliation plane.
Lherz belongs to the Eastern Lherzolites. By contrast, the Western Lherzolites are characterized by a predominance of clinopyroxene-rich spinel lherzolites, an abundance of coarse-granular textures, the absence of thick harzburgitic bands, lower proportions of pyroxenites, the absence of high-pressure amphibole-pyroxenite dykes, and a greater development of high-stress deformation textures which define 100 m-scale mylonitic shear zones (Turon de la Técouère) (after Fabriès et al., 1998). Similar shear zones also exist in the Lherz body.

2. Petrological Evolution : refertilization processes and late Cretaceous melting

At Etang de Lherz, the peridotites show petrological and geochemical characteristics typical of sub-continental lithosphere, such as low equilibration temperatures (800-900°C), a wide range of isotopic compositions, old osmium ages and vein-related, metasomatic features comparable to those observed in mantle xenoliths (Bodinier et al., 1988, 1990, 2004; Downes et al.,1991; Fabriès et al., 1991; Reisberg and Lorand, 1995).

The most fertile lherzolites (15% clinopyroxene) were generally regarded as pristine mantle, only weakly affected by partial melting. In an important contribution in year 2007, the Montpellier team led by J.L. Bodinier presented new consistent structural and geochemical data from the Lherz massif indicating that the lherzolites do not represent pristine mantle. Detailed structural mapping clearly shows that the lherzolites are secondary rocks formed at the expense of the harzburgites. Variations of major, minor and trace elements through the harzburgite–lherzolite contacts indicate that the lherzolites were formed through a refertilization process involving interaction of refractory, lithospheric mantle with upwelling asthenospheric partial melts (Le Roux et al., 2007).

Thus, the lherzolites are formed at the expense of old, ~ 2.5 Ga (Reisberg and Lorand, 1995), harzburgitic lithosphere by igneous refertilization indicating significant mantle uplift. This process probably occurred during the post-Variscan, post-collisional thermal event responsible for granulitic metamorphism in the western Pyrenees (Pin and Vielzeuf, 1983). After this event, the peridotites underwent cooling in the mantle lithosphere before being cross-cut by a late generation of amphibole-pyroxenite dykes (Conquéré, 1971; Bodinier et al., 1987; Vétil et al., 1988). These dykes are considered to represent melt conduits for mid-Cretaceous (Albian) alkaline magmatism in the Pyrenees (Golberg et al., 1986; Montigny et al., 1986; Bodinier et al., 1987).

Henry et al. (1998) focused on these anhydrous and amphibole-bearing pyroxenites that represent the high-pressure segregates of successive tholeiitic and alkaline magmas under mantle conditions, respectively. In two localities (Caussou and Montaut) the peridotites themselves contain several percent of modal amphibole. ^{40}Ar–^{39}Ar ages on amphiboles from Lherz and Caussou samples cluster in the 103–108 Ma range and Sm–Nd internal isochrons on garnet amphibole pyroxenites from Lherz yield ages of 104 +-5 Ma with initial εNd values between +5 and +7. Middle Cretaceous ages recorded by both dating methods argue for a rapid uplift of ultramafic slices into the crust. In agreement with previous studies, the ages and the range of initial εNd values confirm the genetic link, in this area, between the crystallization of amphibole under mantle conditions and the Cretaceous alkaline magmatism known in the North Pyrenean Zone (NPZ) since ca. 105 Ma (text after Henry et al., 1998)

3. Serpentinization

Most of the eastern bodies (Ariège Department) are weakly serpentinized. This alteration is much more pronounced at the periphery of the massifs and along faults, thus preserving large internal areas nearly free of serpentine. The protogranular and coarse-textured peridotites are generally <5% serpentinized. The porphyroclastic peridotites are slightly more serpentinized, the average degree of this alteration ranging from 5-15% in the lherzolites to 20-30% in the harzburgites. The average degree of pseudomorphic serpentinization considerably increases in the Western Pyrenean massifs. Actinolitic amphiboles may also replace pyroxenes (e.g., Urdach massif). Moreover, a rodingitic alteration giving rise to grossular + diopside + chlorite + vesuvianite assemblages has partially affected spinel pyroxenite parageneses in the Sarraille and Urdach massifs (Western Pyrenees) (Gaudichet, 1974).

4. Geological setting and processes of emplacement at crustal levels

Two types of geological settings have to be distinguished among the Pyrenean ultramafic bodies. In the first type (Sedimented type = 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 (figure 1). In the second type (Tectonic type = T type), the mantle rocks form hectometric to kilometric 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 that the Aptian-Early Albian. They are unconformably overlain by the Albian-Cenomanian flysch formations and have experienced HT-LP mid-Cretaceous metamorphism at variable grades. Such a tectonic setting characterises most of the lherzolite bodies exposed in the western Pyrenees (Lagabrielle et al., 2010, de Saint Blanquat et al., 2016).

The processes of emplacement of the Pyrenean lherzolite bodies have long been a matter of debate and led to highly differing interpretations with two contrasting end-members as follows (Lagabrielle and Bodinier, 2008):

1. The lherzolites have been emplaced tectonically within the Mesozoic sedimentary sequences. Brecciation is regarded as the result of the intrusion of solid mantle rocks into upper crustal levels during rifting processes preceeding the Pyrenean orogeny (Vielzeuf and Kornprobst, 1984, and references herein). Minnigh et al. (1980) proposed that the breccias derive from in-situ disaggregation of carbonate sediments as the result of quenching due to endothermic decomposition reactions of the carbonates. This would imply heat transfer, fluid circulation and brecciation by hydraulic fracturing of both the peridotites and the sedimentary host-rocks at a very large scale. This interpretation is in conflict with the results of later investigations showing that the Pyrenean metamorphism is not related to direct contact between hot mantle rocks and sedimentary formations (Golberg, 1987 ; Dauteuil and Ricou, 1989 ; Golberg and Leyreloup, 1990). Gravity modelling also confirms that the size of the Lherz body was

not sufficient to allow heat transfer leading to the HT-LP metamorphism of the entire Lherz region (Anderson, 1984).

2. The lherzolites are not intrusive bodies but are clasts within sedimentary formations and have been exhumed as portions of the Mesozoic basement of the Pyrenean basins before or during the Cretaceous. Indeed, some authors report primary sedimentary contacts between the lherzolites and surrounding sedimentary formations (Choukroune, 1974; Duée et al., 1984 ; Fortané et al., 1986). Choukroune (1973, 1980) proposed a sedimentary origin for the breccias around Etang de Lherz, arguing that: (1) lherzolite clasts and monogenic lherzolitic breccias layers are abundant in a wide area, some km away from the main body of Lherz, (2) the breccias are associated with fine-grained ultramafic clastic rocks showing graded bedding and flute-casts typical of sediment transport in an subaqueous environment and, (3) the breccias systematically contain pebbles of deformed marbles exhibiting Pyrenean metamorphic mineralogical assemblages in a matrix that experienced weaker metamorphic overprint.

In their 2008 Terra Nova paper, Lagabrielle and Bodinier proposed for the first time that exposure of the Pyrenean subcontinental mantle to the Albian basin floor occurred following exhumation along a mantle/crustal detachment. This hypothesis was based on field observations in various sites that will be visited during this field trip. Since 2008, numerous articles have been published confirming or assuming such an hypothesis. However, it must be noticed that some authors do not agree with the observations conducted in these places. In a comment to Clerc et al. (2013) paper describing the ultramafic bearing sediments, Debroas et al. (2013) argue on the occurrence of cataclastic breccias invided by deposits of recent karstic origin. These points will be observed and discussed.

5. Emplacement of the lherzolite slices and major synchronous events in the NPZ

The pre-rift Mesozoic sequences of the fossil Cretaceous passive margins forming the Northern Pyrenean belt are characterized by high temperature deformations in relation with thinning of the continental basement (figure 4). This was outlined by Vielzeuf and Kornprobst (1984) and clearly established by Golberg and Leyreloup (1990). The compilation of chronological and geological data from the North Pyrenean Zone confirms the clear correlation between the distribution of the highest paleotemperatures in the pre-rift sedimentary cover and the loci of extreme crustal stretching (Clerc et al., 2014). Geological evidence such as the occurrence of peridotite bodies directly underlying metamorphic pre-rift sediments indicate an early attenuation of the rifted continental crust in the most internal regions of the Cretaceous basins. This led Clerc and Lagabrielle (2014) to propose a mechanism of crustal thinning involving lateral extraction of the continental crust. The boudinage of the continental crust occurred under thermal conditions allowing coeval ductile deformation of the Paleozoic basement and of the pre-rift sediments leading to the widening basins devoid of large faulted blocks and lacking scarps exposing the Paleozoic crustal rocks.

In the North Pyrenean Zone, Albian-Cenomanian flysch sequences were deposited synchronously with the syn-metamorphic ductile deformation of the pre-rift sequences. (Clerc et al., 2016). Since the base of the flysch deposits also recorded locally the high-temperature tectonic event, the evolution of the basins involves continuous basal extraction of the pre-rift metamorphic sediments. This early high-temperature deformation event which is now clearly linked to extensional tectonics under high geothermal gradient, relates to the “phase anté-Cénomanienne” as described by Pyrenean geologists from observations in the Mesozoic cover all along the North Pyrenean Zone since 1930.

An updated map of HT-LP metamorphism based on a dataset of more than hundred peak temperature estimated using thermometric approach of Raman spectroscopy of the carbonaceous material (RSCM) collected during the past 5 years has been published by Clerc et al. (2014). This dataset is completed by previous PT estimates based on mineralogical assemblages (mainly Golberg and Leyreloup, 1990) and by the chronological constraints obtained so far. Ages are ranging mainly from 110 to 90 Ma and no westward or eastward propagation of the metamorphism and magmatism can be clearly identified. In contrast, it seems possible to emphasize progressive propagation of the thermal anomaly from the base to the surface of the continental crust. The highest grades of metamorphism are always associated to the regions where subcontinental mantle rocks have been unroofed or exhumed.

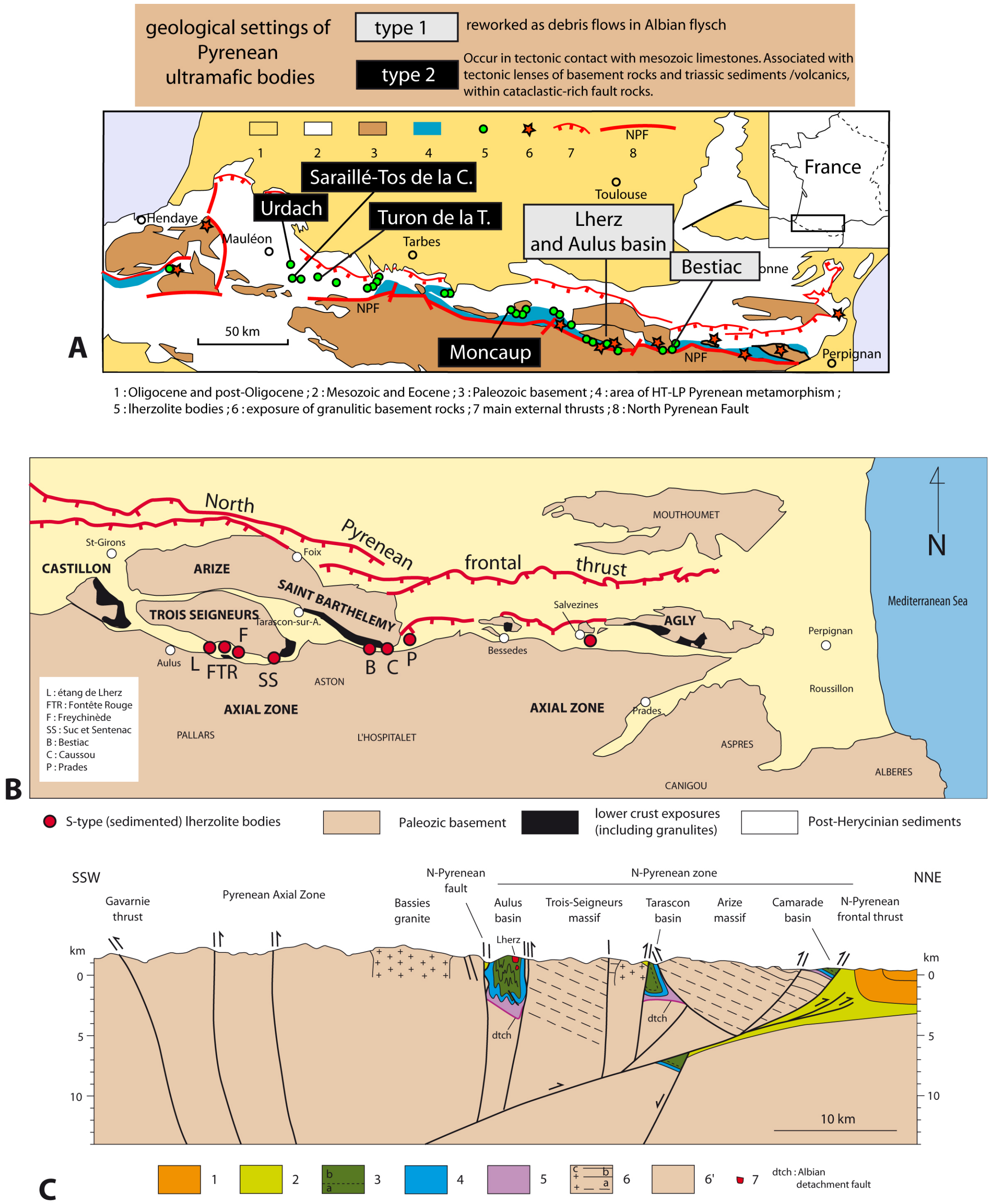
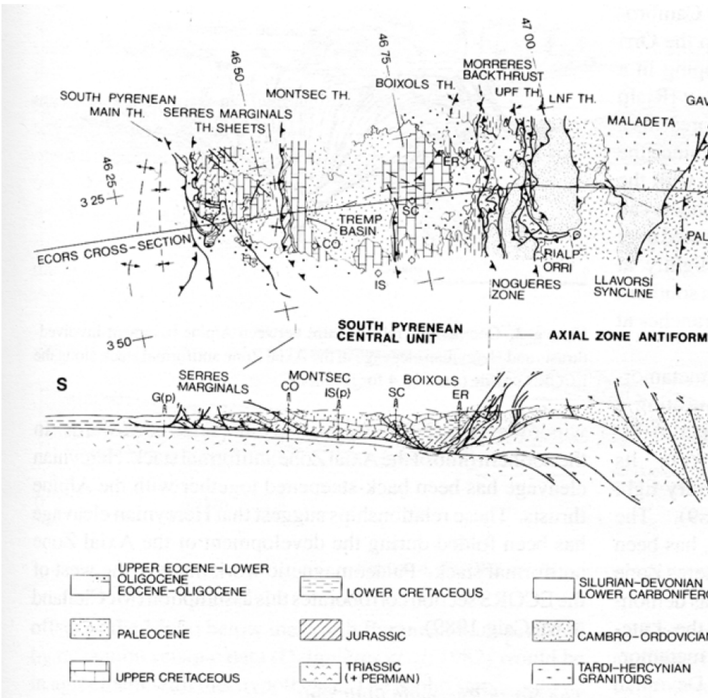
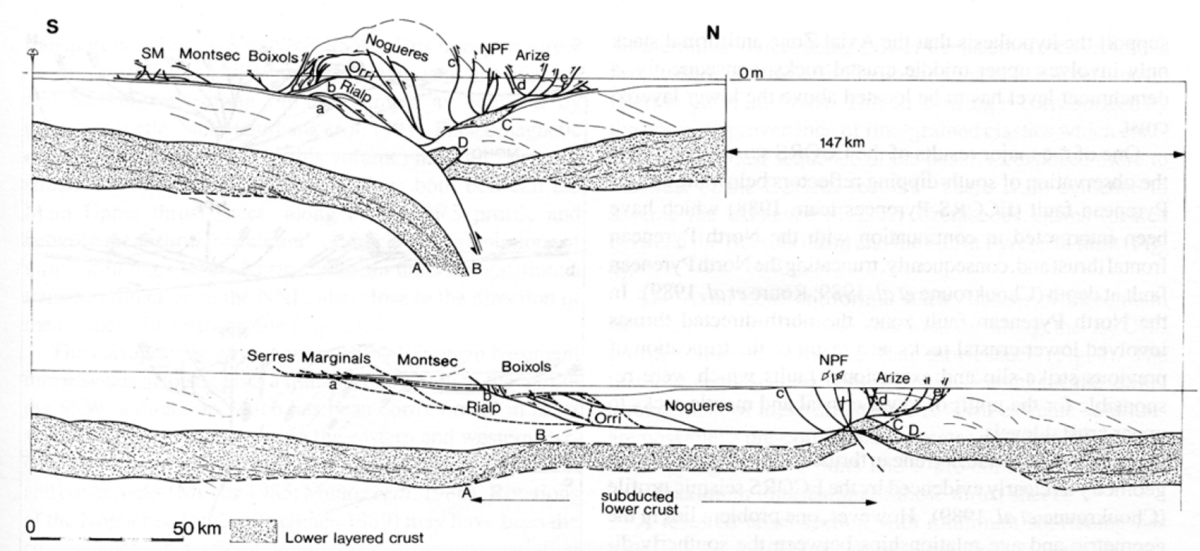


Figure 1. Localization of the Lherz and Bestiac bodies in the frame of the North Pyrenean Zone (A, B) and cross section showing the geological setting of the Aulus basin and Lherz peridotites (modified after Lagabrielle et al., 2010)





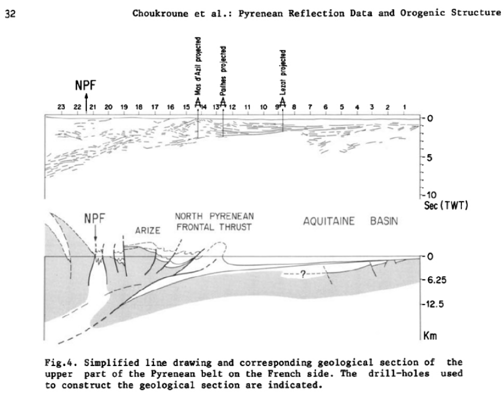


Figure 2.
Tectonic setting of the Aulus basin
in the frame of the structure of the Pyrenean belt
(after Munoz, 1992, top
and Choukroune et al. 1989, right)

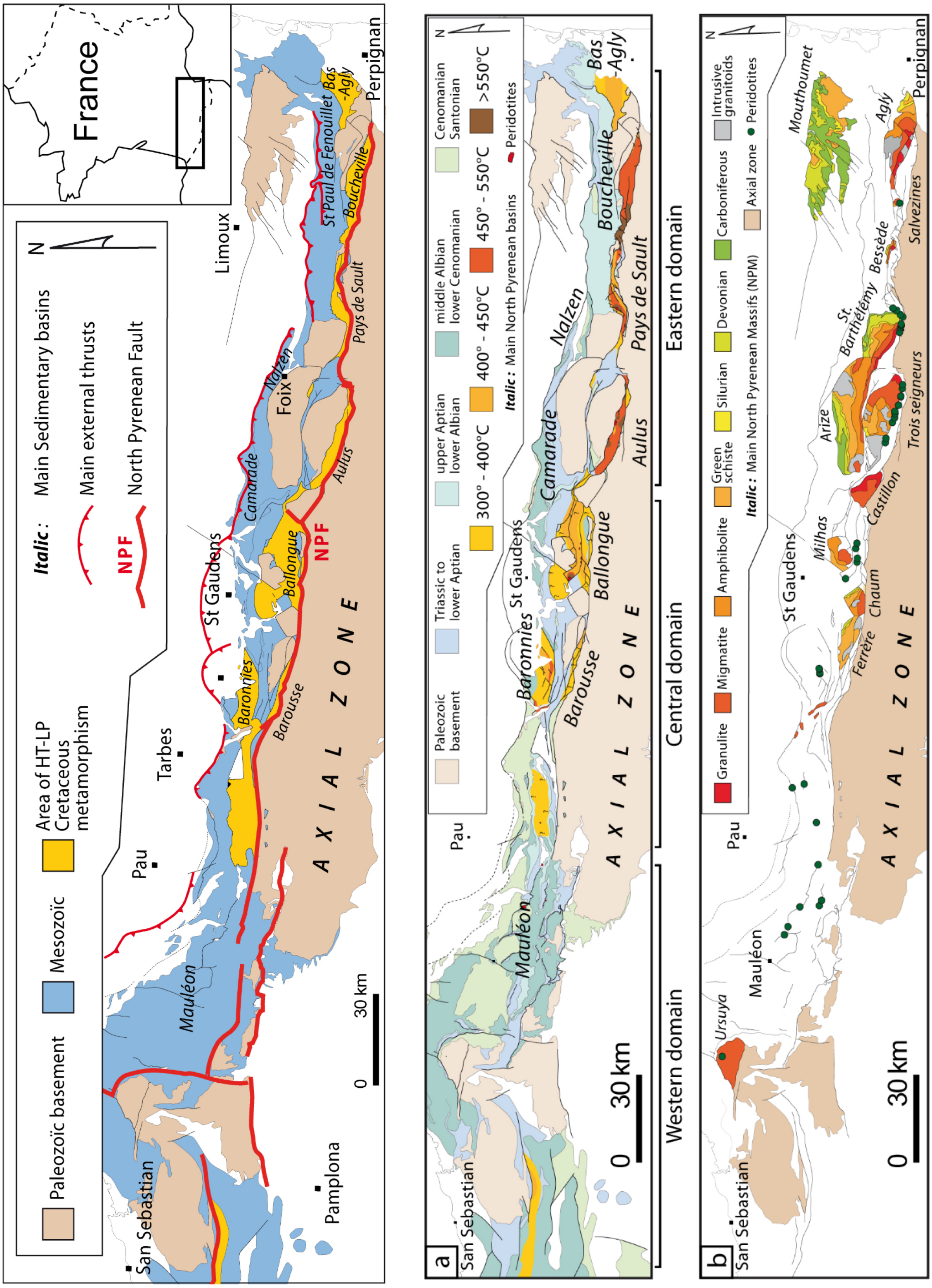


Figure 3.
Three maps showing the main geological characteristics of the North Pyrenean Zone (NPZ) after Clerc and Lagabrielle (2014) and Clerc et al., (2015).

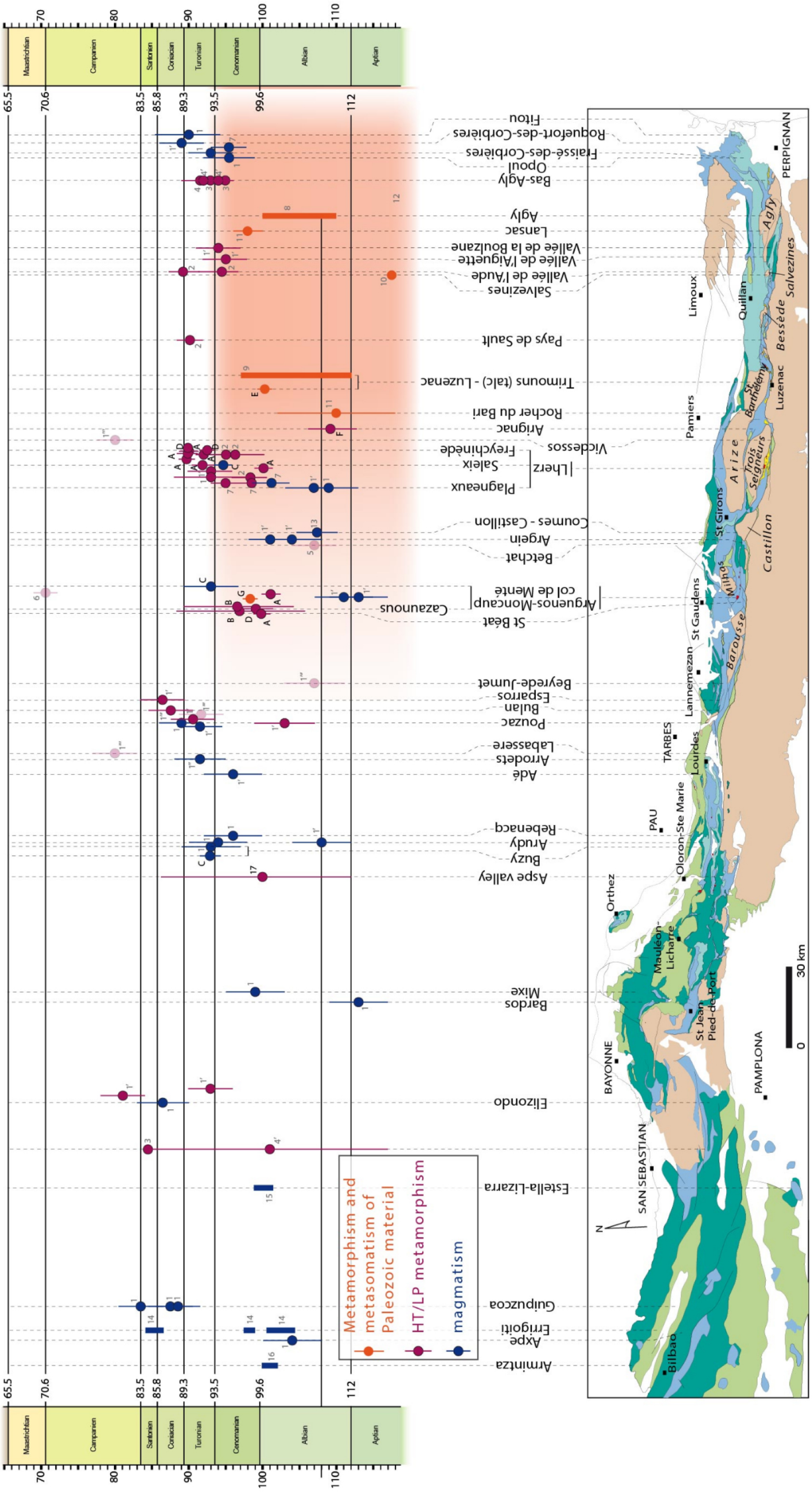


Figure 4.
Chronological data for the North Pyrenean metamorphism and magmatic event after Clerc et al. (2014).

PART B : FIELD TRIP
Day One : Yves Lagabrielle

Field evidence of mantle denudation with special attention to serpentinization imprint in the Lherz lherzolite body

A. Introduction

We will start in the Etang de Lherz area with an overview of the geological setting of the mantle bodies in the North Pyrenean Zone : Axial Zone basement, granulite lenses, HT-LP metamorphic Mesozoic marbles, polymictic sedimentary breccias.
Geological and chronological constraints obtained so far in the region and proposed geodynamical evolution according to recent models. Discussion about some implications on mantle/crust coupling in relation with the processes of crustal thinning.
Several stops along the Etang de Lherz mantle body will allow the following observations :

- harzburgites/lherzolites relationships and evidence of refertilization,
- the late melting stage of the mantle rocks during the Cretaceous event (emplacement of alkaline melt products : « lherzites »,
- development of shear bands with tectonite-type foliation related to the exhumation,
- serpentinization along the tectonite corridors,
- development of fracturation, initiation of carbonation and related ophicalcites.

We will then focus on the relationships between the mantle rocks and their sedimentary cover :

- observation of various types of ophicalcites, ultramafic sandstones, microbreccias and polymictic breccias deposited on the ultramafic basement, including the saphirine-kornerupine sandstones.
- field evidence for various sources of the clastic sediments : fresh or serpentinized mantle rocks, gabbros, meta-ophites, meta-evaporitic sediments, meta-dolomites, marbles, etc…

At the end of the trip, all the geological observations will be compiled, and additionnal informations will be provided including geochronological and geochemical data and isotope mineralogical compositions of the observed rocks. A model for the emplacement of the NPZ mantle bodies will be proposed.

B. Geological setting of the Lherz body

The Lherz body, in the central Pyrenees, is a S-type body that appears on the 1/50.000 map of the French BRGM, Aulus sheet, by Ternet et al., (1997). The Lherz massif is the type-locality of lherzolites and one of the most studied occurrence of mantle rocks worldwide. It is only 1.5 km long and belongs to a series of ultramafic bodies of restricted size (a few m to some hundred of m), occurring within sedimentary formations of the Mesozoic platform, mostly limestones and dolomites (i.e. Fontête Rouge body).

The clastic formations also include numerous layers of polymictic breccias reworking lherzolitic clasts. These layers are found far from any lherzolitic body, implying that lherzolitic clasts cannot derive from the in situ fragmentation of an ultramafic body alone, but might also have been transported far away from their sources by sedimentary processes.

A detailed analysis of the contacts between the Lherz ultramafic body and the surrounding limestones confirms that there is no fault contact there and that sediments composed of ultramafic material have been emplaced into fissures within the brecciated carapace of the peridotites. These observations bear important constraints for the mode of emplacement of the lherzolite bodies. We infer that mantle exhumation may have occurred during Albian strike-slip deformation linked to the rotation of Iberia along the proto-North Pyrenean Fault.

Lagabrielle et al. (2016) show that the massive marbles of the Aulus basin, in the vicinity of the Lherz body, display an evolution from hot and ductile to cold and brittle deformation, indicative of an exhumation process ending with the sedimentary reworking of both the deformed Mesozoic metasediments and the exhumed ultramafic rocks. Crystal Preferred Orientations (CPO) measured in the marbles support deformation mechanism by dislocation creep of calcite which are dominant between 400°C and 600°C ; these deformation temperatures are within the range determined earlier by Clerc et al (2015), using RSCM (Raman Spectroscopy of Carbonaceous Material) geothermometry. As a consequence, the transition from ductile to brittle deformation in the prerift marbles and the origin of the syn-rift breccias are clarified.

Due to continuous exhumation along detachments faults, the brecciated metamorphic carbonates of the pre-rift NPZ sedimentary cover were passively uplifted towards shallower levels and progressively unroofed while transported passively on the back of the exhumed ultramafic footwall. This is consistent with the interpretation of the North Pyrenean peridotites as remnants of subcontinental mantle rocks exhumed within the pre-Pyrenean rift system. The tectonic decoupling between the Mesozoic sedimentary cover and the Paleozoic basement plays a major role and leads to the juxtaposition of metamorphosed and deformed Mesozoic sediments (ductilely deformed and cataclastic) directly on top of the exhumed mantle rocks. It finally appears that the Lherz area exposes evidence of tectonic denudation of the peridotites below pre-rift sediments metamorphosed during the extension of the basin floor in a thermal regime characterized by a very high gradient.

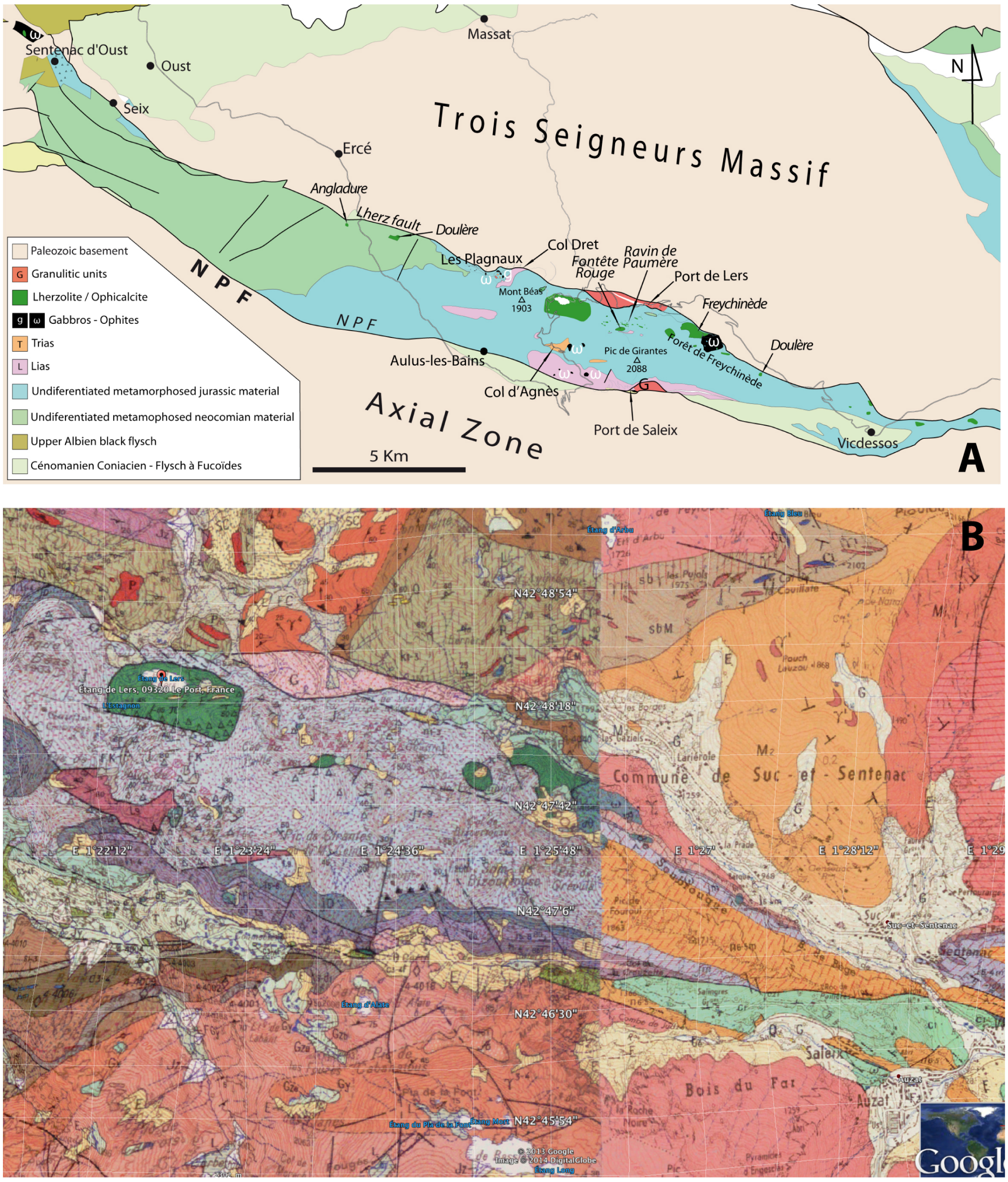


Figure 5.
The Aulus basin and the exposures of mantle rocks in the Central NPZ.
A. Simplified map, B. a compilation of the Aulus and Vicdessos, 1/50000 BRGM sheets.

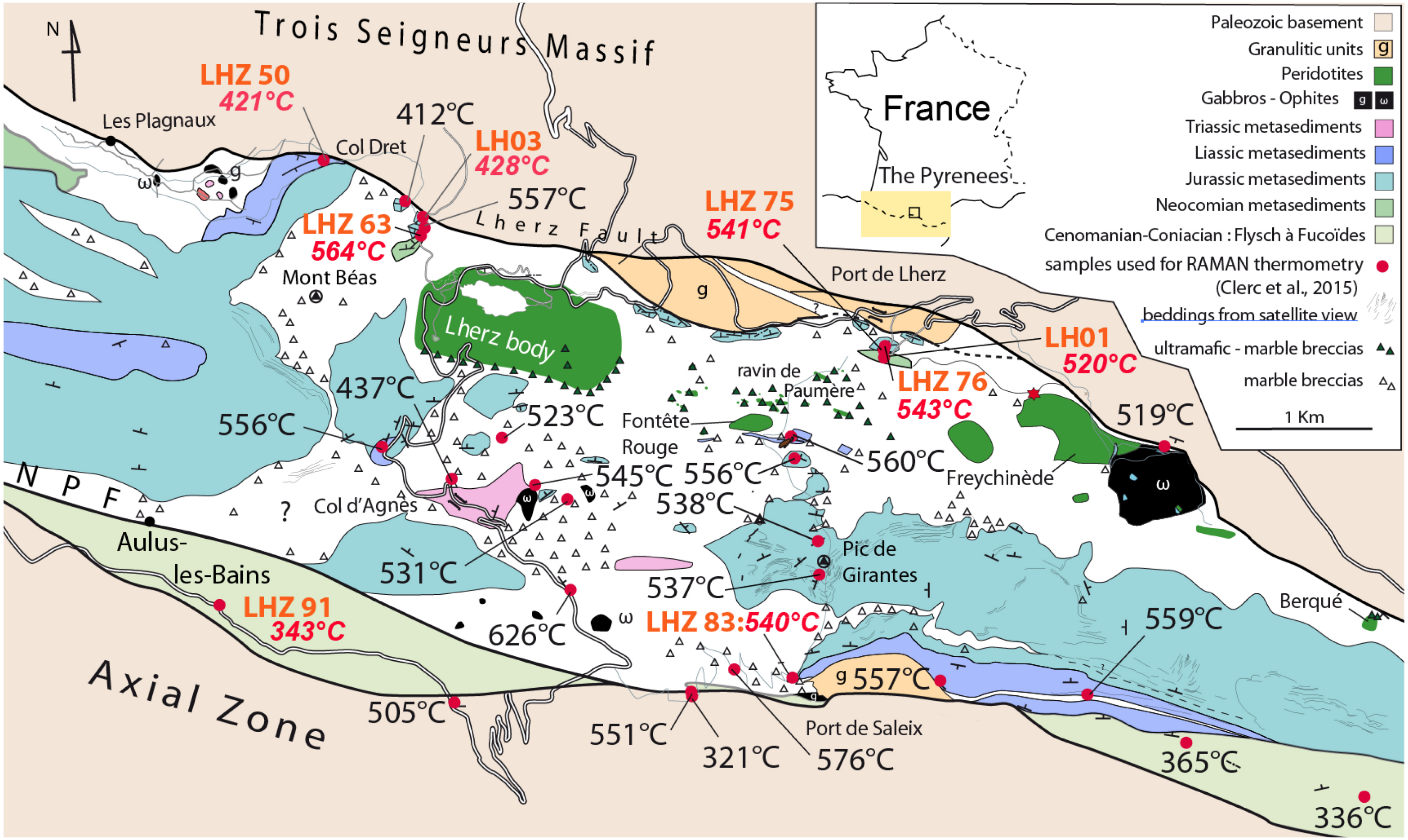
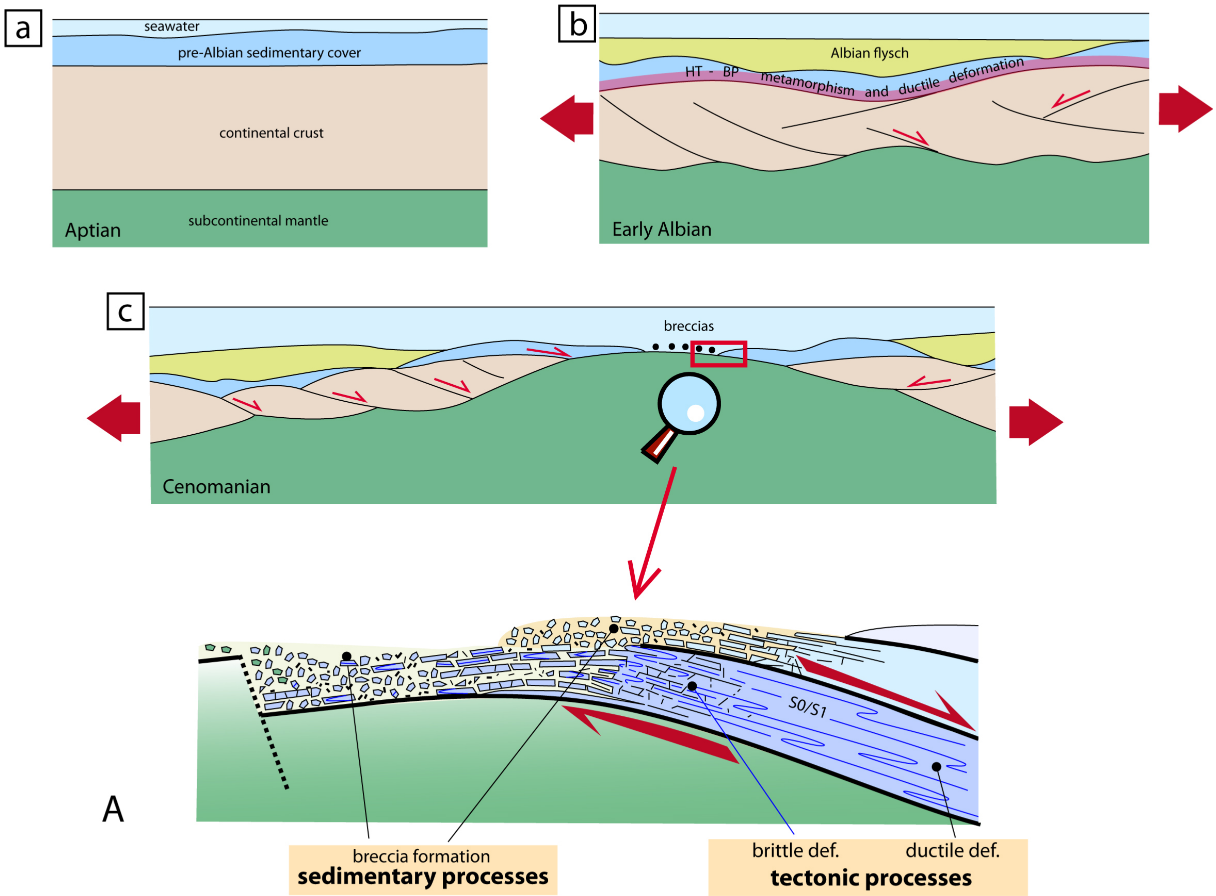
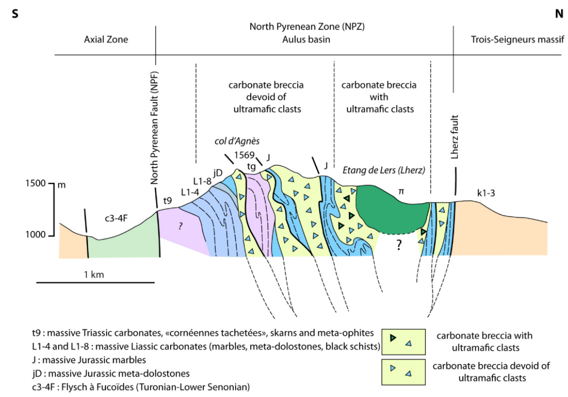


Figure 6. Geological map of the central Aulus basin and RSCM Temperatures obtianed from the carbonate formations (Lagabrielle et al., 2016).





Lagabrielle et al., fig.2

C

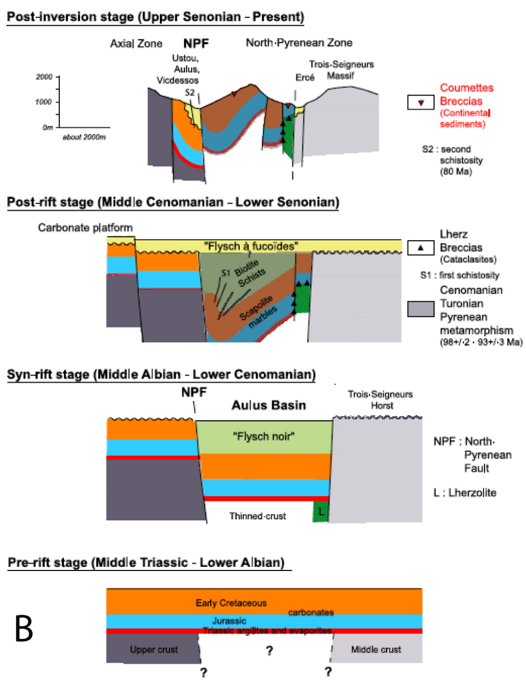


Figure 7.
Models for the Emplacement of the Lherz breccias and mantle body after Lagabrielle et al., (2016) (A) and after Debroas et al., (2013) (B), and cross section of the Aulus basin (C).

FIG. 7. – The four main evolution stages of the Aulus basin [Debroas *in* Ternet *et al.*, 1997].

Bull. Soc. géol. Fr., 2013, n° 6

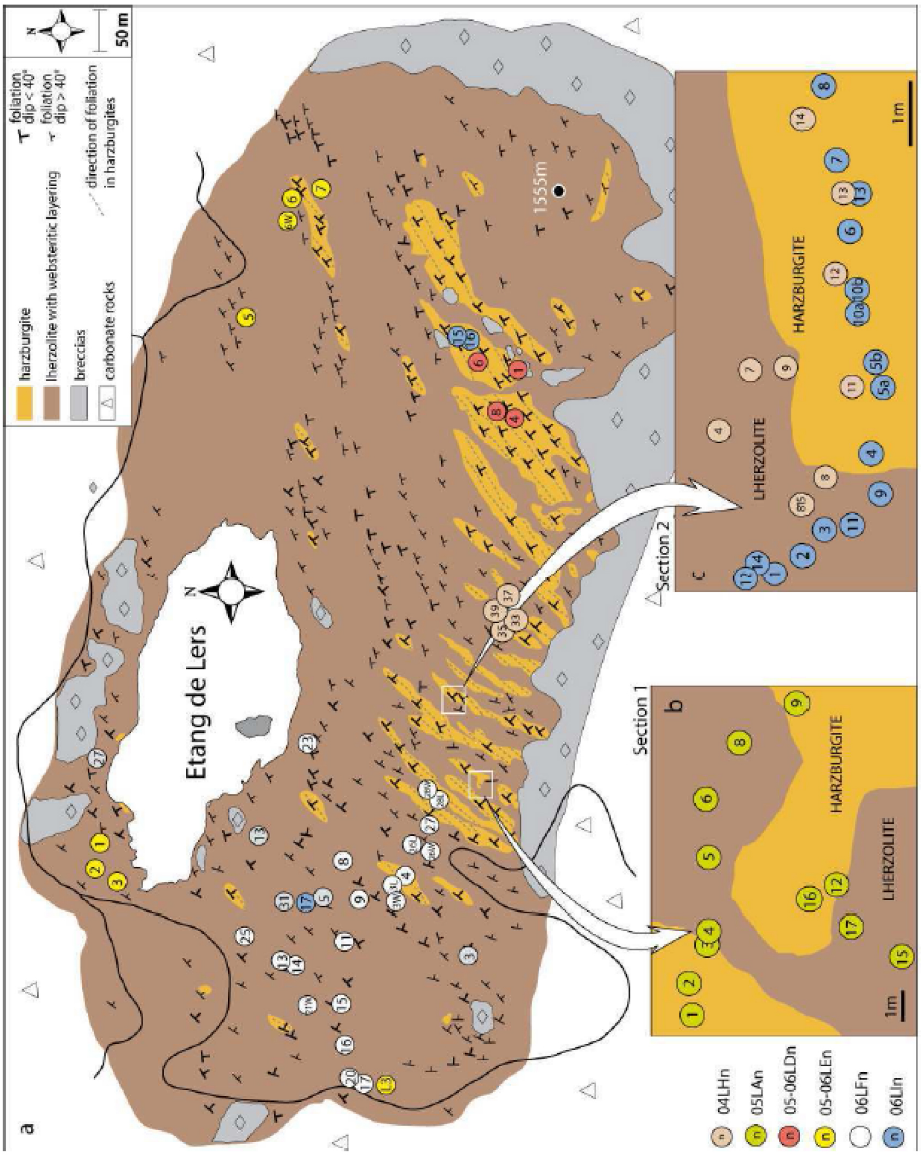


Fig. 6: (a) Map of the Lherz massif realized during this study (Le Roux et al., 2007) presenting the location of the harzburgites, lherzolites and websterites sampled during this study, and used for microstructural, petrophysical, geochemical and isotopic analyses; (b) detail of the section 1. The samples are part of the 05LA sampling series; (c) detail of the section 2. The grey samples are part of the 04LH sampling series; the white samples are part of the 06LI sampling series.

Figure 8.
Map and photograph after the work of Le Roux (Thesis 2008) and Le Roux et al. (2007) showing the relationships between the ancient harzburgitic spinel foliation and the websteritic layering resulting from the impregnation by MORB-like melts.

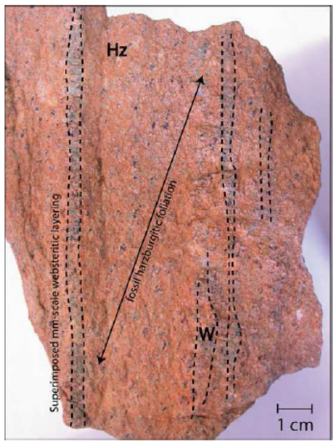


Fig. 2: Print of the fossil harzburgitic foliation in harzburgites (Hz) close to the contact, cross-cut by a latter mm-scale websteritic layering (W) related to the refertilization. The thin layering superimposed to the harzburgitic foliation initiates the development of cm-scale websteritic veins.

C. Breccias in the Etang de Lherz region and contact between lherzolite and limestones (text after Lagabrielle and Bodinier, 2008) (figures 5 to 11).

1. Various types of breccias (figure 9)

The lherzolites of the Etang de Lherz region are exposed within the Aulus basin, a Mesozoic basin inverted during the Pyrenean orogeny. The former basin now corresponds to a narrow belt of Jurassic and Lower Cretaceous limestones, marbles and dolomites which have been deformed and brought into a vertical position between the Paleozoic units of the Trois Seigneurs to the North and of the Axial Zone to the South. The meta-sediments are characterized by a wide variety of breccias, as shown on the BRGM geological map (Colchen et al., 1997; Ternet et al., 1997) (Fig. 5). The lherzolites appear as numerous small bodies, ranging in size from a few meters to several hundreds of meters, some of them exhibiting a brecciated fabric. Massive ultramafic bodies frequently appear in close association with layers of breccias having a mixed ultramafic-carbonate composition. Ultramafic breccias may also form mappable lenses, up to 300 m long, aligned within the limestones. The largest peridotite exposure, with a rectangular shape and 1.5 km long, forms the Lherz body. Beside the lherzolitic bodies, minor ophitic and gabbroic bodies are also observed (Fig. 5).

We studied breccias located at various distances from the lherzolite body, as well as within the massif itself. Detailed observations along the trail from Port de Lherz to Pic de Girantes (ravin de Paumères, north of the Fontête-Rouge summit), reveal that the entire peridotite-bearing section consists of clastic rocks with an overall vertical bedding (Fig. 5 and 8). There is no massive carbonate formation exposed here. Therefore the Jurassic age of the host-marbles of the peridotite bodies cannot be proven. The largest volume of clastic rocks consists of breccias and minor conglomerates mainly composed of fragments of white to pink marble and dolomite, with additional ultramafic fragments. Carbonate clasts are angular to subangular, rarely rounded, with sizes ranging from one mm to a few dm. The breccias are generally poorly sorted, but locally, ultramafic sandstones sequences show graded and cross bedding, and slumps. Some large marble clasts are foliated and exhibit mm-sized retromorphosed scapolites, confirming post-metamorphic brecciation, as earlier reported by Choukroune (1973; 1980). Dark-grey clasts of metapelitic rocks (Liassic, Aptian?) are abundant in some layers, and in such cases, graded bedding is observed. Locally, the ultramafic breccias form m-thick, vertical, monomictic layers and lenses interbedded within the carbonate clastic formations. The breccias contain various proportions of matrix, and in matrix-supported breccias, the composition of the matrix varies from pure carbonate to pure ultramafic material. Isolated blocks of breccias made up of marble clasts floating within a monomictic graded, ultramafic sandstone matrix are abundant close to the Port de Lherz.
Various breccia-types are observed close to, and within the main body of Lherz.

- Type 1 is found along the southern and eastern borders of the ultramafic outcrops, where it forms a 50 to 200 m thick, continuous carapace of monomictic breccias (Le Roux et al., 2007) (Fig. 8). These breccias never include carbonate clasts and often appear as layers sandwiched between panels of massive peridotite. The continuity of mantle structures is generally preserved throughout these breccias, at least at the outcrop scale. Websterite layers and hornblendite ("lherzite") dikelets, for instance, can be followed over several meters within the breccias, being only slightly offset along brittle faults, which indicates little displacement between clasts. This type of in-situ formed breccias bear characteristics of cataclastic breccias.

- Type 2 breccias are observed close to the contact with the carbonate sediments (Site LHZ 6). Their aspect resembles that of the cataclastic breccias but they typically include isolated clasts of limestones and look more heterogenous. The transition between type 1 and 2 is not sharp, suggesting that the source of the ultramafic debris can be found within internal cataclatic fault zones cross-cutting the lherzolitic body.

- Type 3 breccias are observed in restricted places within the massif (for instance at Sites LHZ 4 and LHZ 5, where they appear to fill large fissures opened within the peridotites They are composed of thin layers of graded ultramafic sandstones with cross-lamination, including cm-sized blocks of fresh lherzolite and isolated serpentine clasts. These deposits closely resemble the graded ultramafic sandstones overlying and inserted within the ultramafic basement of some Apenninic and Alpine ophiolites (Decandia and Elter, 1972; Cortesogno et al., 1981; Bernoulli and Weissert, 1985). Fragments of ultramafic minerals such as pyroxene, olivine and spinels, less than 1 mm across, form most of the fine-grained matrix and are associated with grains of serpentinite and millimetric fragments of deformed marbles. Type 3 further differs from the other types of breccias in Lherz in showing an extreme variety of ultramafic clasts in term of mineralogical composition (peridotites, websterites, honblendites etc.), mantle textures (coarse-granular to mylonitic) and degree of serpentinization (fully serpentinized clasts and fresh lherzolite debris). The majority of the

peridotite clasts are composed of fresh, pyroxene-rich, coarse-granular lherzolites different from the Lherz peridotites. These rocks are more reminiscent of peridotites from other bodies, such as Fontête Rouge (Fabriès et al., 1991). This points to a mixed and relatively far provenance of the ultramafic clasts in Type 3 breccia. Besides the ultramafic clasts, the breccias generally contain debris of carbonate rocks. These include clasts of deformed marbles showing here also metamorphic minerals typical of the Pyrenean metamorphism. Clasts of former monomictic carbonate breccias, or of polymictic ultramafic-carbonate breccias are often observed.

- Type 4 breccias are clastic rocks closely resembling the so-called ophicalcites of the Apenninic and Alpine ophiolites (Lemoine et al., 1987) that developed on seafloor exposures of exhumed mantle. They typically include dominant, poorly sorted, angular clasts of serpentinite and minor poorly serpentinized lherzolites. As frequently observed in Alpine ophicalcites (e.g. Früh-Green et al., 1990), late carbonate veins cross-cut the breccias, a consequence of circulation of fluids after deposition. Such ophicalcite breccias infill fissures opened within the massive peridotites as observed along the road at Site LHZ 8.

We closely studied the contacts between carbonates and ultramafics. These are well exposed along the road at Sites LHZ 2a and LHZ2b and show a highly contorted outline. Two main observations have to be emphasized. 1) Where observed, the carbonates are always welded onto the irregular surface of the ultramafics. 2) The contact is not rectilinear at a meter scale; rather, the surface of the lherzolites is fractured and fissures are filled with carbonate breccias mixed with ultramafic debris as illustrated in Fig. 6C. These observations preclude a fault contact at this location. Late carbonate veins cross cut both the lherzolites and the marble breccias suggesting post-depositional metamorphic evolution and fluid circulation. Detailed field observation and thin-section analysis show that the sedimentary layer in direct contact with the lherzolites is a carbonate micro-breccia reworking mm-sized lherzolitic clasts and isolated mineral grains originating from the disaggregation of the lherzolite (pyroxene, olivine, serpentinite and amphiboles from lherzite dikelets). This is well observed at Site LHZ 2b. At Site LHZ 2a, the lherzolites show a mylonitic fabric, cut and offset by later small faults and fissures, which is clearly cut by the contact with the sediments. Two meters to the south of the carbonate-ultramafic contact at Site LHZ 2a, the carbonate breccias form vertical strata made up of fragments of pink to white-grey marbles and dolomites. Some of these beds, up to 1 m thick, include up to 30-40 % of lherzolitic clasts outlining the vertical bedding. Such clear bedding of the breccias precludes an origin through quenching and hydraulic fracturing due to hot rock intrusion.

We observed new exposures of middle- to high-grade metamorphic rocks between peridotites and carbonates along the northern boundary of the Etang de Lherz area (Site LHZ 7). Lacroix (1895) and Monchoux (1970, 1972) have described three predominant types within similar rocks: (1) biotite- and scapolite-rich rocks, (2) spinel amphibolites, (3) anthophyllite- and phlogopite-rich rocks, also containing variable proportions of magnesian hornblende, sapphirine, kornerupine, Al-spinel, altered cordierite, scapolite, calcite, tourmaline, and subordinate amounts of rutile and apatite. Monchoux (1972) interpreted the sapphirine-bearing assemblages as mafic crustal rocks modified by the combined effects of metasomatism and metamorphism (800-900°C and 0.6-0.9 GPa) in contact aureoles of peridotites during the early stages of their exhumation. The deep-seated metamorphic rocks would have been dragged towards the surface during later stages of the exhumation of the peridotites. Our observations indicate the existence of two distinct rock facies within this suite. One (Type a) is made of generally broken, idiomorphic minerals (except for phlogopite) that have lost all of their primary textural relationships. This highly friable rock type is carbonate-free and probably derives from a metamorphic protolith through intense cataclasis (Monchoux, 1972). The other rock facies (Type b) is distinguished by the presence of a carbonate matrix and the presence of small clasts (< 1 cm) of ultramafic rocks (Fig. 7). It is identical to Type a in terms of mineralogical composition, except that the minerals are broken to smaller pieces. In the field, the Type b facies contains clasts of Type a rocks, of ultramafic and of additional undetermined rocks (work in progress). It occurs in direct contact with the Lherz peridotite; it is associated with ultramafic sediments, and obviously results from sedimentary reworking of the Type a.

2. Interpretation: Sedimentary origin of some of the Lherz breccias

The observations reported above demonstrate that the lherzolites and some associated deep-seated roks, have been submitted to sedimentary reworking. However, apart from Type 1 breccias regarded as cataclastic breccias, tectonic fragmentation alone cannot explain a number of highly distinctive features such as : (1) the occurrence of numerous polymictic ultramafic–carbonate breccia layers interbedded within the clastic sedimentary sequence of the Aulus basin, some km away from the main Lherz body; (2) the presence of *graded ultramafic sandstones within fissures of the Lherz body, and (3) the mixing of serpentinized clasts with unweathered mantle debris in ophicalcite-type breccias. These features imply : (1) reworking and transport of a two-component clastic material by gravitational processes, including rock falls, debris flows and grain flows, (2) reworking of ultramafic fine-grained material and deposition in an sub-aqueous environment within fissures opened within an ultramafic basement and (3) mixing of debris from various sources including regions of highly serpentinized mantle. Since serpentinization of mantle rocks is thought to develop generally at temperatures lower than 300-350°C (Andréani et al., 2007)*, *the association of poorly serpentinized lherzolites and serpentinites suggests that brecciation processes did not occur under temperature conditions calculated for the Pyrenean metamorphism.*

These observations demonstrate that ultramafic rocks have been exhumed and exposed on the seafloor together with Mesozoic sediments, and have been incorporated as exotic debris within a clastic sequence as synthetized in Fig. 8. Due to the progressive contact between Type 1 cataclastic breccias and Type 2 sedimentary breccias, we may propose that tectonic brecciation at depth preceded sedimentary reworking. Brecciation occurred possibly during shearing leading to exhumation, but further investigations are requested to better constrain the P,T conditions and the kinematic of this cataclastic event.

Finally, taking into account the clastic origin of the ultramafic material around the Etang de Lherz, we have to address the question of the significance of the Lherz body itself. The clastic formations are almost continuous around the ultramafic body, with a remaining doubt along its northwest side where exposures are scarce. Under such conditions, the Lherz body might represent either a small remnant of the ultramafic basement of the sedimentary basin, a tectonic slice along a major detachment fault, or a large olistolith embedded within a clastic sedimentary sequence. These interpretations are in line with gravity modelling showing that the Lherz body is of small size and is not rooted within the Pyrenean basement (Anderson, 1984). In the two first cases, the Lherz body would exhibit a tectonic contact on its northwestern side against the tectonized corridor along the NFP. In the third case, the polymictic clastic formation reworking the mantle debris would be completely disconnected from its original basement of unknown composition.

3. Geodynamical implications and conclusions

Our new field observations in the region of Etang de Lherz bear important constraints for the mode of emplacement of the Pyrenean lherzolites. Following Choukroune (1973, 1974, 1980), we confirm that the lherzolite bodies around Etang de Lherz are enclosed within a sedimentary clastic sequence resulting from the accumulation of debris reworked from exposures of platform carbonates and ultramafic rocks. This interpretation is consistent with field data in the Béarn region where lherzolitic bodies also form restricted exposures regarded as olistholiths emplaced within flysch formations of Cretaceous age (Duée et al., 1984 ; Fortané et al., 1986). In that sense, the sedimentary sequence of the Aulus basin can be compared to the Cretaceous-Eocene successions of the Northern Apennines where gravity deposits including ophiolitic debris flows (olistostromes) and olistoliths crop out extensively (Abbate et al., 1970; Marroni and Pandolfi, 2001). The largest ophiolitic olistoliths of the Apennines are 1-2 km long and 200-300 m thick, a size similar to that of the Lherz body. Gravity emplaced ultramafic-rich bodies showing characteristics similar to the Lherz polymictic clastic sequences have been also reported from various orogenic belts such as the Californian Coast Ranges (e.g. Lockwood, 1971), or the internal Alps (Deville et al., 1992).

From these observations, it is clear that subcontinental mantle has been exposed on the floor and/or along the flanks of a deep, tectonically active basin that now forms the Aulus region. At present, exhumation of mantle rocks is known to occur at the foot of non-volcanic continental margins such as the Galicia-Iberia Atlantic margin (Boillot et al., 1980, 1985; Abe, 2001 ; Whitmarsh et al., 2001, Manatschal, 2004), along the axial reliefs of slow-spreading ridges (Lagabrielle et al., 1998; Karson et al., 2006), within small oceanic basins (Seyler and Bonatti, 1988), or along the walls of oceanic fracture zones (Bonatti et al., 1971 ; Auzende et al., 1989). In these different geodynamic settings, mantle exhumation is always accompanied by sediments yielding large volumes of debris of dominantly ultramafic composition, ranging from fine-grained turbidites to debris-flows and rock slides, as first reported on the flanks of the Gorringe Bank (Lagabrielle and Auzende, 1982). In the Pyrenean case, mantle exhumation cannot be viewed as a process linked to the opening of a wide ocean, since no relicts of oceanic lithosphere are present within the mountain belt. By contrast to the Tethyan ophiolites, the low degree of pervasive serpentinization of most of the Pyrenean lherzolites suggests very rapid exhumation followed by instantaneous sedimentary reworking and burial within detrital sequences. This is consistent with transtensive conditions at the foot of a rapidly stretched continental crust. This scenario is illustrated in Fig. 9. It may have occurred during the opening of a series of pull-apart basins *along the Iberia/Europe plate boundary due to oceanic spreading in the Bay of Biscaye during the Albian (Le Pichon et al., 1970 ; Choukroune and Mattauer, 1978 ; Olivet, 1996).*

Thinning of the continental lithosphere in the region where lherzolites are now exposed is confirmed by additional evidence, as follows.
(1) Radiometric ages (Ar-Ar and Sm-Nd) obtained on amphiboles from Lherz and Caussou. These ages indicate crustal emplacement of the ultramafic rocks around 110-105 Ma (Henry et al., 1998).
(2) Pyrenean HT metamorphism. This involves heat transfer through fluid circulation and occurred inresponse to continental thinning during the Late Cretaceous.
(3) Alkaline magmatism of Cretaceous age (105 Ma), that indicates partial melting of upwelling mantle.
(4) A major mylonitic event dated at 110-100 Ma which occurred along normal faults cross-cutting Paleozoic basement close to the NPF (Costa and Maluski, 1988; Saint Blanquat, 1993). One of these faults testifies to fluid circulation and Mg enrichment linked to continuous shearing between 112 and 97 Ma (Schärer et al., 1999). The occurrence of several basement units exhibiting granulitic metamorphic assemblages located along the NPF (Fig. 1) indicates that the lower continental crust has been also exhumed, possibly along these faults, a fact already noticed by Vissers et al. (1997).

An important point must be added to this discussion. Numerous clasts of carbonate included in the polymictic breccias exhibit HT-LP Pyrenean metamorphic parageneses and internal deformation. This would imply a post-Albian age for the clastic sedimentation. On the other hand, the clastic sequence itself has experienced a metamorphic evolution, which would in turn indicate pre-Late Albian sedimentation. Although this point needs further investigations, most of the geological data suggest that mantle exhumation occurred during the Albian. The ultramafic rocks may have been emplaced at shallow lithospheric levels earlier than the Cretaceous, during Variscan post-orogenic crustal thinning or during Triassic or Liassic rifting episodes. According to some kinematic reconstructions (Sibuet et al. 2004), a realm of thinned crust and/or oceanic crust was present before the Cretaceous between the Iberian and European plates.

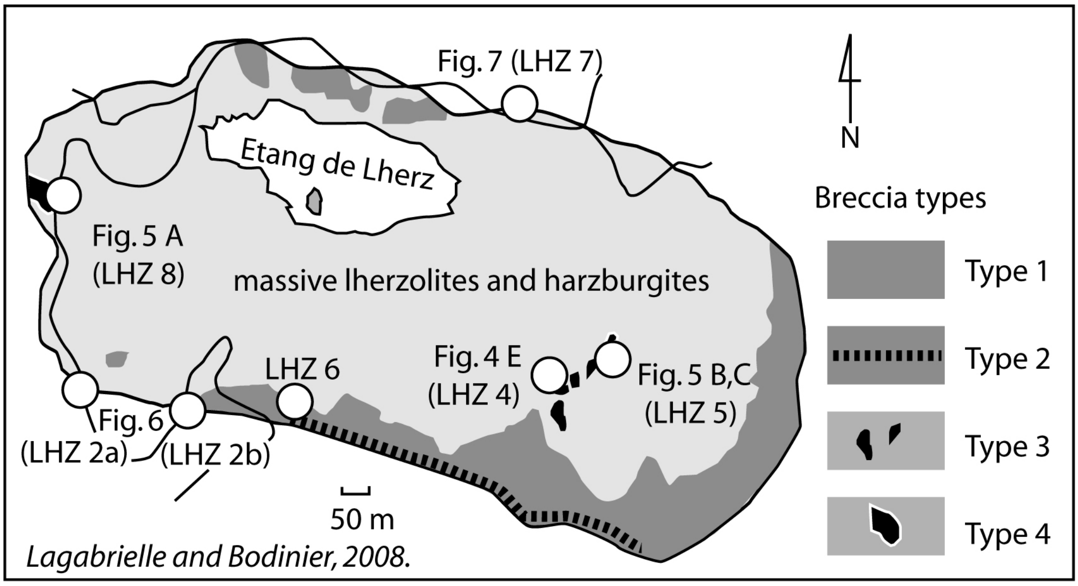
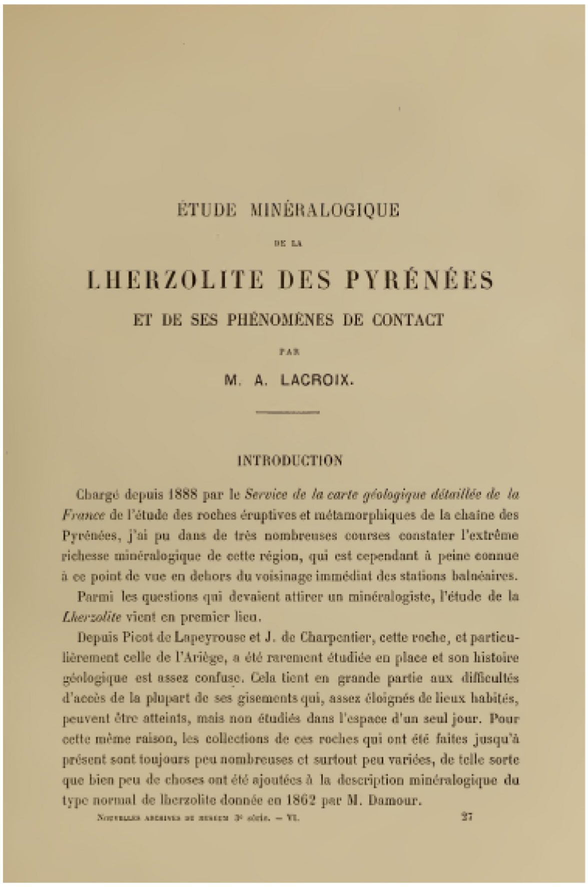


Figure 9 : types of breccias exposed around the Lherz body (see text for explanation)

Figure 10. Graded-bedded ultramafic sandstone showing evidence of tectonic deformation



ÉTUDE MINÉRALOGIQUE

DE LA

LHERZOLITE DES PYRÉNÉES

ET DE SES PHÉNOMÈNES DE CONTACT

PAR

M. A. LACROIX.

INTRODUCTION

Chargé depuis 1888 par le *Service de la carte géologique détaillée de la France* de l'étude des roches éruptives et métamorphiques de la chaine des Pyrénées, j'ai pu dans de très nombreuses courses constater l'extrême richesse minéralogique de cette région, qui est cependant à peine connue à ce point de vue en dehors du voisinage immédiat des stations balnéaires.

Parmi les questions qui devaient attirer un minéralogiste, l'étude de la *Lherzolite* vient en premier lieu.

Depuis Picot de Lapeyrouse et J. de Charpentier, cette roche, et particulièrement celle de l'Ariège, a été rarement étudiée en place et son histoire géologique est assez confuse. Cela tient en grande partie aux difficultés d'accès de la plupart de ses gisements qui, assez éloignés de lieux habités, peuvent être atteints, mais non étudiés dans l'espace d'un seul jour. Pour cette même raison, les collections de ces roches qui ont été faites jusqu'à présent sont toujours peu nombreuses et surtout peu variées, de telle sorte que bien peu de choses ont été ajoutées à la description minéralogique du type normal de lherzolite donnée en 1862 par M. Damour.

Nouvelles archives du Muséum 3e série. — VI. 27

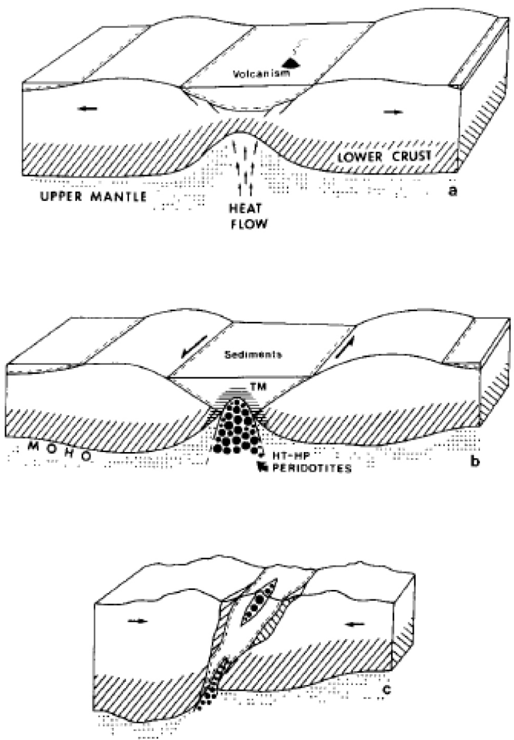
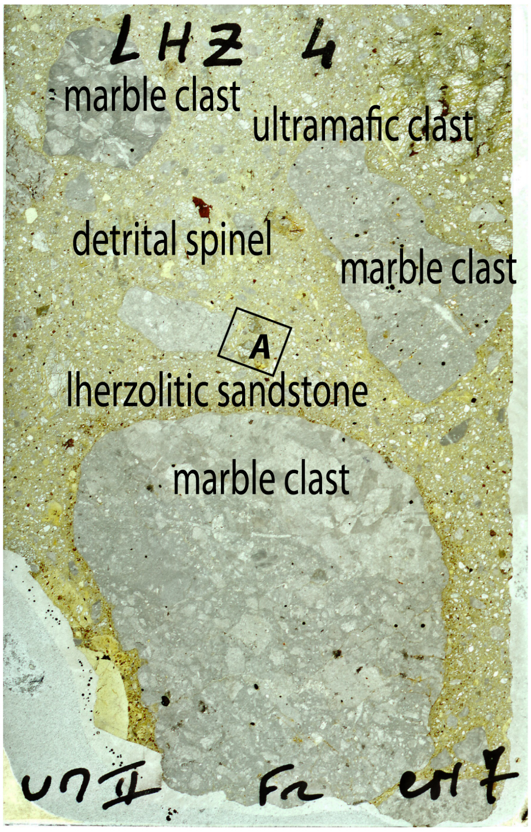


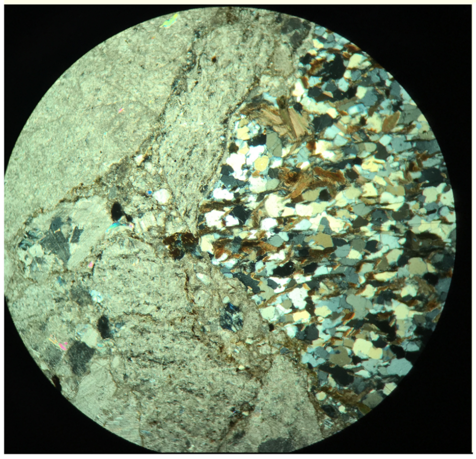
Fig. 3. A model for the emplacement of lherzolites and granulites in the North Pyrenean Zone at Lherz. (a) lower Cretaceous; (b) Albian; (c) upper Cretaceous, upper Eocene. *TM* – thermal metamorphism.

Figure 11.
Almost 100 years between these 2 contributions but same questions about the emplacement of the Pyrenean mantle bodies after Lacroix (1894) and Vielzeuf and Kornprobst (1984).

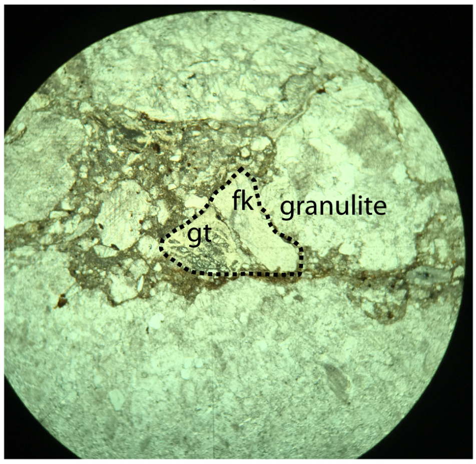
D. Supplementary material : photograph, thin section, geochemical data from some visited sites along the Lherz peridotite body.

A wide variety of lithologies as sources of the Lherz breccias

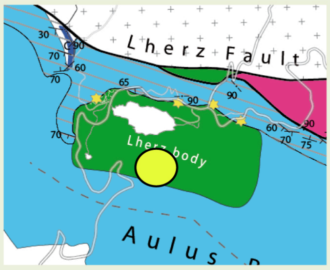




Biotite bearing-quartzite



1. Tectonic breccias on top of the lherzolite body



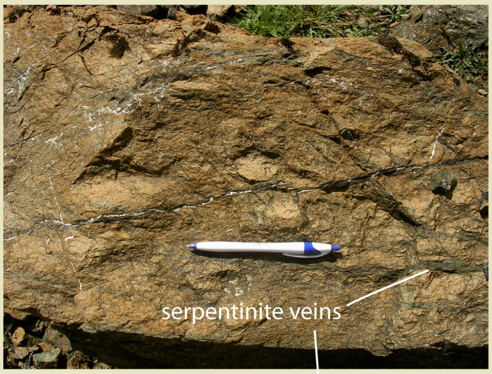
The lherzolite is not a pristine lherzolite,
but a harzburgite infiltrated by melting products
which crystallized as pyroxenite layers
(websterite banding).
Here a websterite layer is cross cut by a normal fault

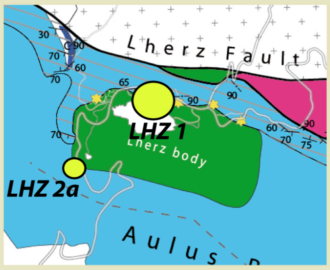
By place, on the top of the lherzolite body, coarse 100% ultramafic breccias are observed.
These breccias are extremely cohesive and do not provide any character of sedimentary breccias.

Moreover, a lherzite dikelet cutting through the ultramafic rocks is only slightly displaced among the breccia elements by faults having minor displacements. This clearly indicates that this brecciation is of tectonic origin. Locally the lherzite is not cut by the fault but only ductily deformed. This indicates that brecciation occurred during of immediately after lherzite emplacement, in relation with the exhumation of the mantle during the Mid-Cretaceous.

These breccias correspond to the Type 1 as defined by Lagabrielle and Bodinier, 2008. It is found in direct contact with or within the ultramafic body, and consists of a carapace of monomictic breccias resulting from the cataclastic deformation of the peridotites during exhumation. These breccias typically lack carbonate clasts and contain little to no carbonate veins and cement.

2. Late, moderate T foliation, serpentinization and carbonation





Generally, the lherzolite is not serpentinized.
However, by place a pervasive serpentinization is observed.
Note also that some clasts of the sedimentary breccias are 100% serpentinized (next plates).

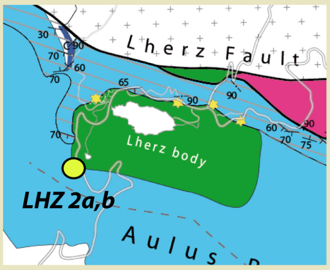
There is a clear link in the area of sample LHZ 1 between local serpentinization and the presence of a foliation within the lherzolites. This foliation is «mylonitic» and is marked by the reduction of the size of the Ol and Px grains (See Vauchez, Vissers,...). This foliation may have developed under T conditions of 800°C-600°C, that is during the late stage of the exhumation of the mantle in the upper crustal environment.
Early serpentinization clearly develops along the mylonitic bands.

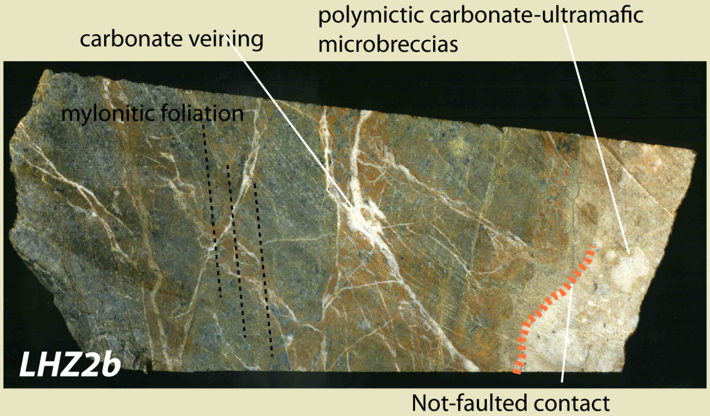
Calcite veins infill fractures opened within the foliated lherzolites

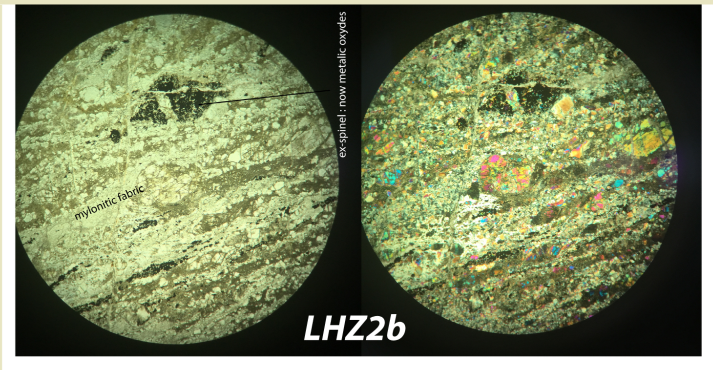
Thin sections of samples LHZ1a and LHZ 1b. Note that calcite veining occurs parallel to the 800°C-600°C foliation is itself locally replaced by serpentine minerals. Carbonation also occurs perpendicular to the cataclastic foliation

Samples LHZ 2a and LHZ 2b are at the contact between the lherzolite and the microbreccia.
Here, the mantle rocks show a pervasive mylonitic foliation. Note that calcite veining cross-cuts the foliation.

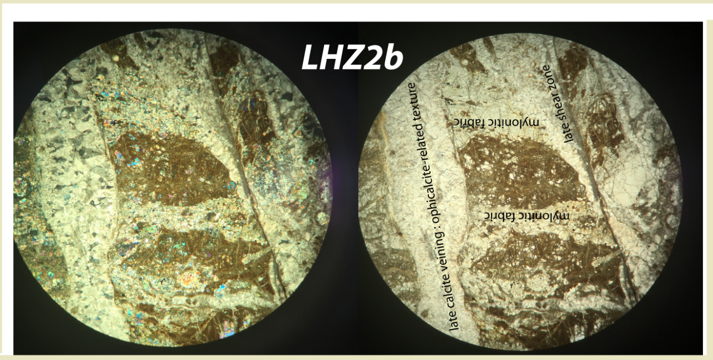
3. Late, moderate T foliation, serpentinization and carbonation (2)

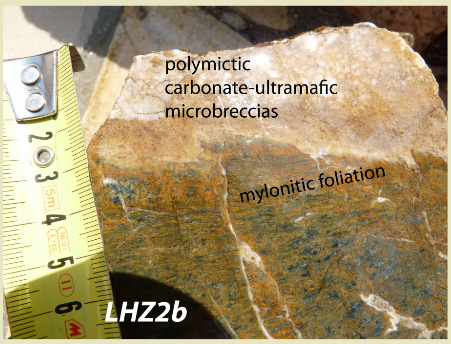




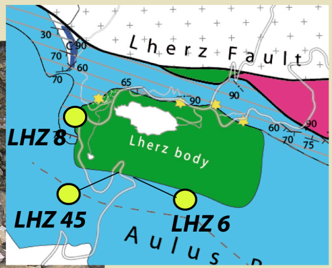


Sample LHZ2b shows how the fracturing linked to the late carbonation intersects the mylonitic foliation



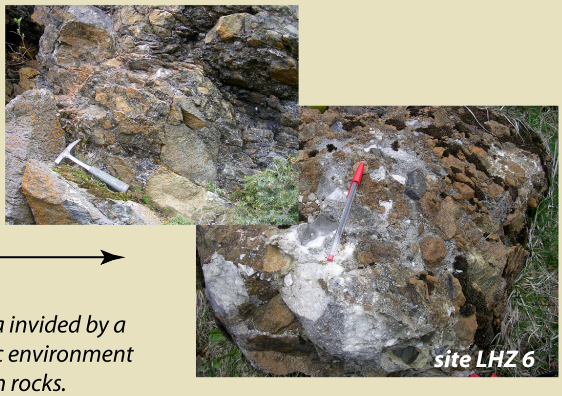


4. Sediments on top of the ultramafic body. Fissuring and ophicalcites

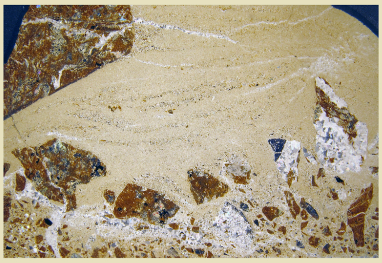


The lherzolites are intensively fissured at the boundary of the Lherz body. Ultramafic-bearing carbonate microbreccias infill the fissures.

Type 2 breccias are observed close to the contact with the carbonate sediments (Site LHZ 6). Their aspect resembles that of the cataclastic breccias but they typically include isolated clasts of limestones and look more heterogenous. The transition between type 1 and 2 is not sharp, suggesting that the source of the ultramafic debris can be found within internal cataclastic fault zones cross- cutting the lherzolitic body.



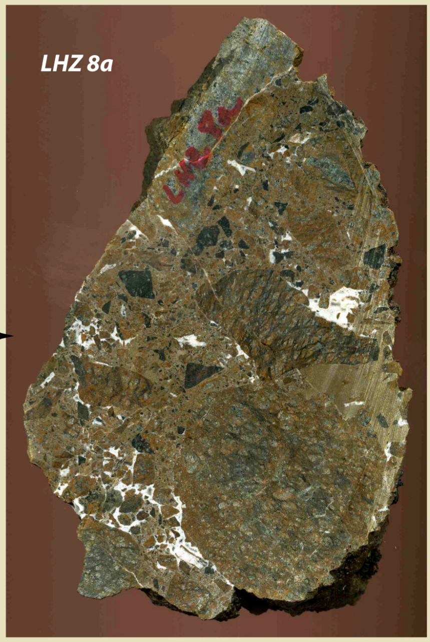
When the network of open fissures is dense, the rock is a breccia invided by a carbonate cement and resembles the ophicalcites from oceanic environment and from ophiolites. Serpentinization is more important in such rocks.

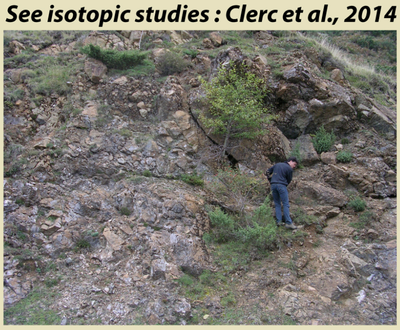


Ultramafic sandstone (LHZ 8)

See isotopic studies : Clerc et al., 2014

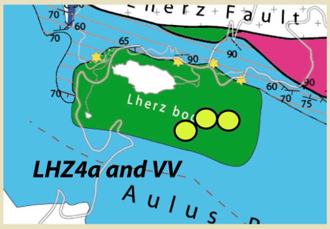
Sample LHZ 8a Note the carbonate matrix between some clasts (white patches) and the mixing of serpentine-free and serpentinized lherzolite fragments





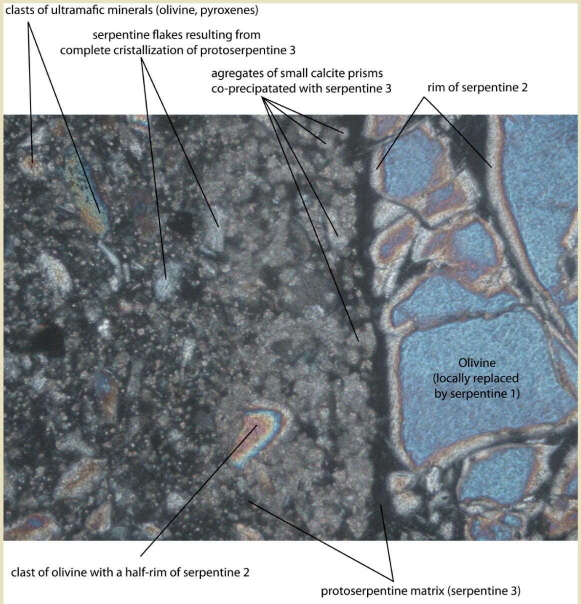
Exposures of ophicalcite at location where sample LHZ 8 was collected.

5. The sedimentary ophicalcites

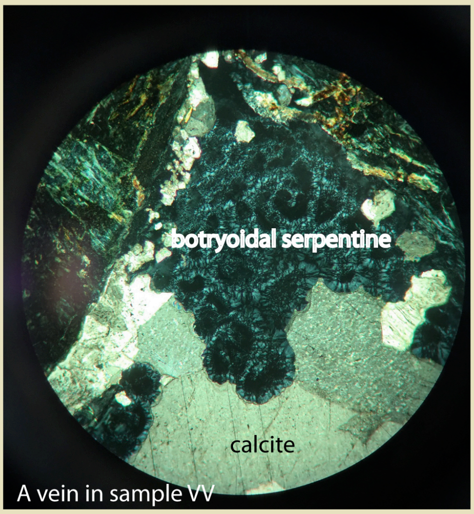


Size of clasts range from less than one mm to some cm. Ultramafic sandstones show clear graded bedding.

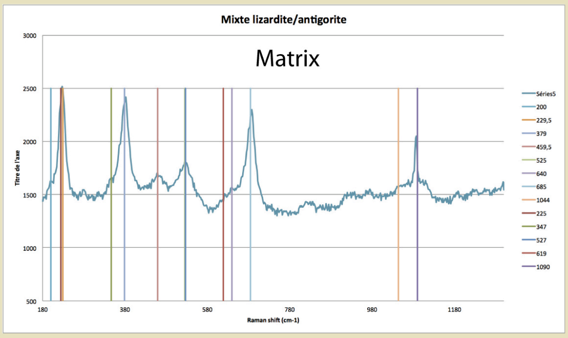
Samples VV and LHZ4 are ophicalcites showing clear evidence of sedimentary reworking. Various clasts of serpentinized ultramafic rocks (mainly clinopyroxenites unknown at Etang de Lherz) are mixed with marbles debris.

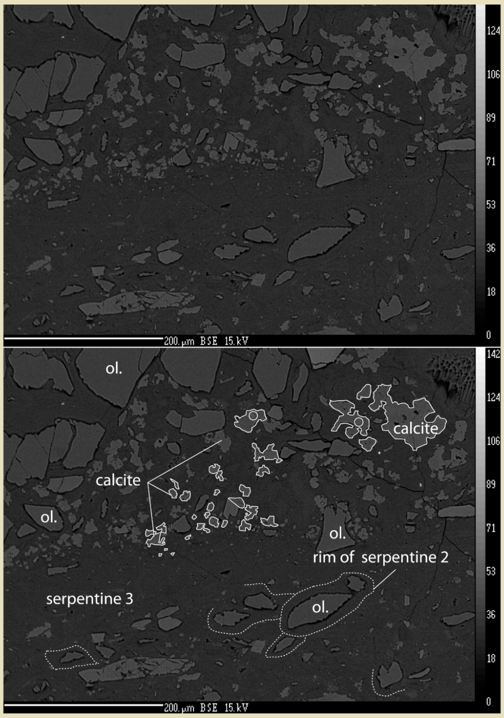


Thin section : VV A4 (2)



The matrix consists of a homogeneous greenish material. Under the microscope, a serpentine-like mineral is dotted of numerous very small calcite crystals.





Microprobe and MEB analyses still under progress demonstrate that both calcite and serpentine precipitated simultaneously. Similar co-precipitation is reported form the ophicalcites of Chenaillet massif (Lafay et al., in progress).

Lizardite is recognized in the clasts, whereas antigorite and a mix antigorite/lizardite forms the matrix in association with calcite

Microprobe image of thin section VVA4 (2)

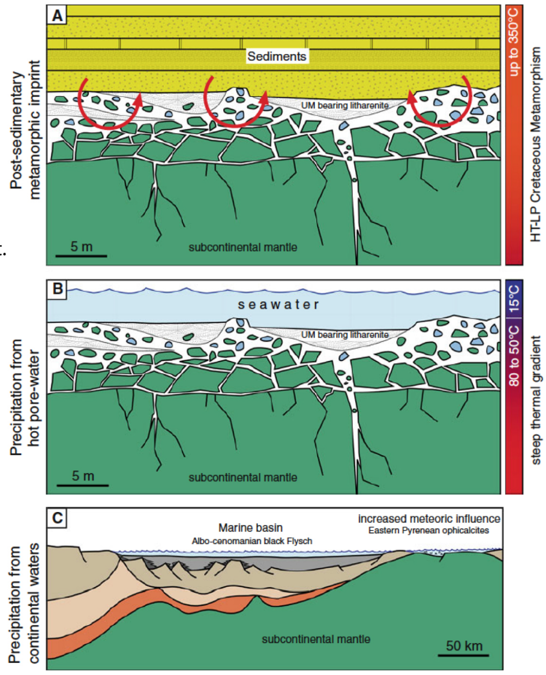
6. The ophicalcites : stable isotope study

Int J Earth Sci (Geol Rundsch)
DOI 10.1007/s00531-013-0927-z

ORIGINAL PAPER

Ophicalcites from the northern Pyrenean belt: a field, petrographic and stable isotope study

Camille Clerc · Philippe Boulvais · Yves Lagabrielle · Michel de Saint Blanquat



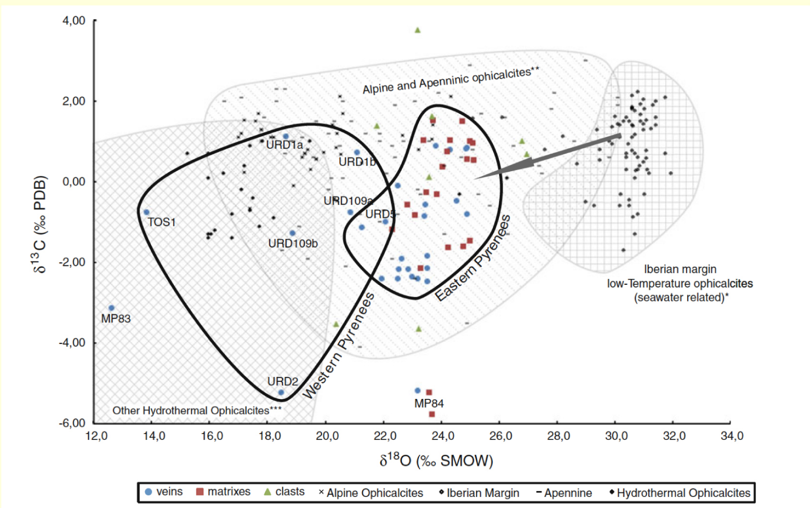
Brecciated and fractured peridotites with a carbonate matrix, referred to as ophicalcites, are common features of mantle rocks exhumed in passive margins and mid-oceanic ridges. Ophicalcites have been found in close association with massive peridotites, which form the numerous ultramafic bodies scattered along the North Pyrenean Zone (NPZ), on the northern flank of the Pyrenean belt. We present the first field, textural and stable isotope characterization of these rocks. Our observations show that Pyrenean ophicalcites belong to three main types: (1) a wide variety of breccias composed of sorted or unsorted millimeter-to meter-sized clasts of fresh or oxidized ultramafic material, in a fine-grained calcitic matrix; (2) calcitic veins penetrating into fractured serpentinite; and (3) pervasive substitution of serpentine minerals by calcite. Stable isotope analyses (O, C) have been conducted on the carbonate matrix, veins and clasts of samples from 12 Pyrenean ultramafic bodies. We show that the Pyrenean ophicalcites are the product of three distinct genetic processes:

i) pervasive ophicalcite resulting from relatively deep and hot hydrothermal activity;

ii) ophicalcites in veins resulting from tectonic fracturing and cooler hydrothermal activity; and

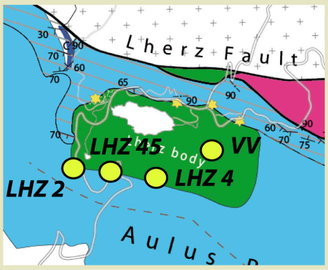
iii) polymictic breccias resulting from sedimentary processes occurring after the exposure of subcontinental mantle as portions of the floor of basins which opened during the mid-Cretaceous.

We highlight a major difference between the Eastern and Western Pyrenean ophicalcites belonging respectively to the sedimentary and to the hydrothermal types. Our data set points to a possible origin of the sedimentary ophicalcites in continental endorheic basins, but a post-depositional evolution by circulation of metamorphic fluids or an origin from relatively warm marine waters cannot be ruled out. Finally, we discuss the significance of such discrepancy in the characterics of the NPZ ophicalcites in the frame of the variable exhumation history of the peridotites all along the Pyrenean realm.

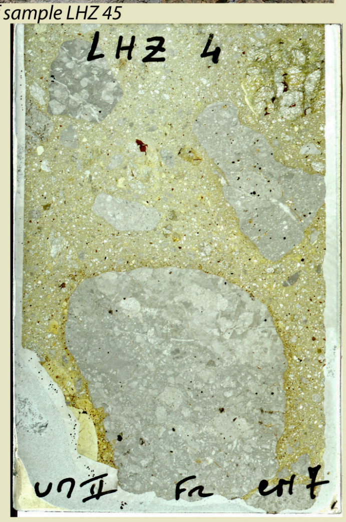


7. Sediments on top of the ultramafic body. Polymictic sedimentary microbreccias

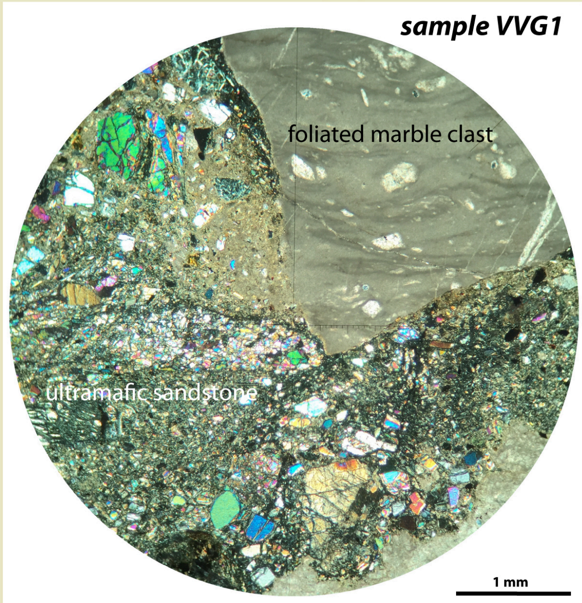
Exposure at the location of sample LHZ 45



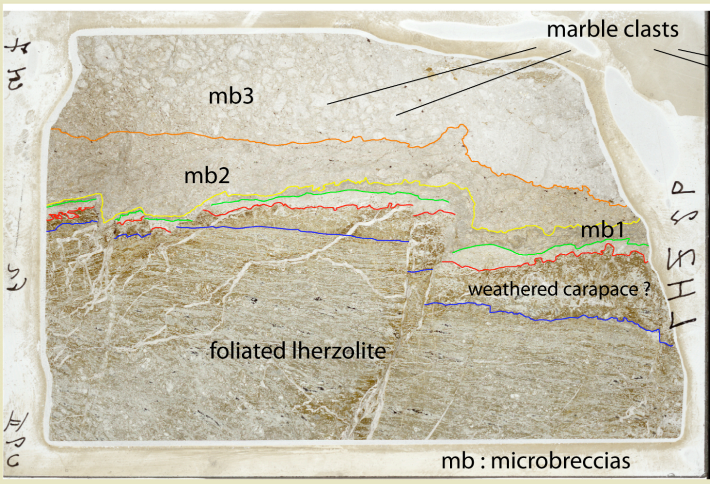
Along the Col d'Agnès raod, the lherzolite is in direct contact with a microbreccia made up of small fragments of metamorphic limestones (marbles) mixed with ultramafic-derived clasts in various proportions.

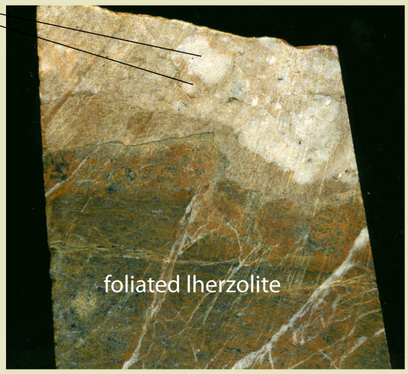


Typical aspect of the LHZ 4 and VV samples : polycristalline marble debris (rounded or not) in a 50-50% carbonate/ ultramafic sand-sized matrix.



Many clasts exhibit a ductile deformation with mineralogical assemblages typical of the HT Pyrenean metamorphism (large calcite crystals and scapolites). Other debris derive from the ultramafic rocks.





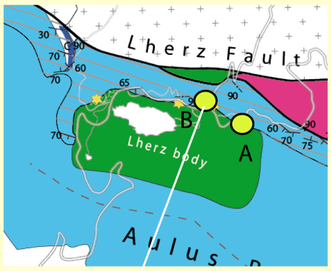
Thin section and hand specimen of sample LHZ 2a2b showing the contact between the lherzolite and the metasediments.

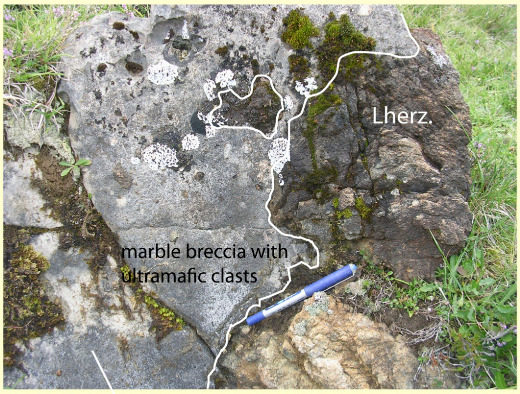
These observations preclude a fault contact at these locations. In addition, the tectonic fabric shown by the lherzolite (800°-600°C T mylonitic foliation) is not consistent with a brittle behaviour of the carbonates. A fault contact consistent with the fabric of the mantle rocks would have required ductily deformed marbles here.

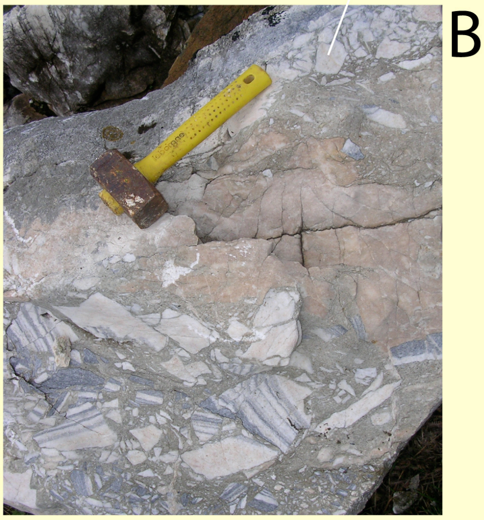
8. A depositional contact at the NE corner of the lherzolite body

Breccias on top of the lherzolites can be observed at site A, at a very close distance (10-20 m) from the sapphirine-bearing sandstones and breccias (see plate 11).

The lherzolite body is not fully exposed here. However, this in one proof more that the contact between metasediments and ultramafic basement is depositional







Marble breccia : only carbonate clasts are observed. These clasts are polycristalline, ductily deformed marble. The matrix is a pale-green, metamorphic assemblage of phyllitic minerals and calcite

A careful examination of the metasediment is required. This allows to detect the brecciated texture and, by place the presence of ultramafic clasts

Dominant carbonate breccias are exposed around site A, but loose blocks with different lithologies are frequent. Examples are shown on photograph above with different amount of marble clasts and lherzolite debris floating within a sandy ultramafic-carbonate matrix.

9. Lithology of the ultramafic-marble breccias : a summary

Breccias on top of the lherzolites include : 1. ophicalcite of type I and II (according to M. Lemoine criterias)
2. ultramafic-carbonate breccias in a sandy ultramafic-carbonate matrix. Two end-members are defined among these breccias as shown here
3. Sapphirine (+associated minerals)-bearing sandstones and breccias

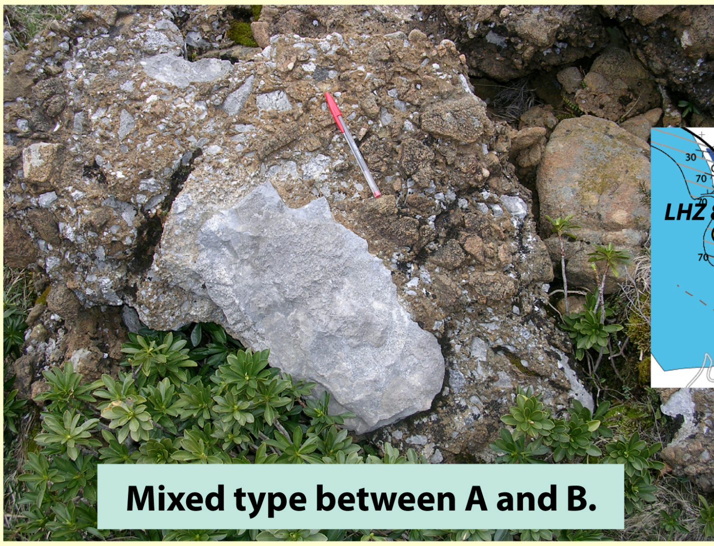
Marble clasts in a sandy, 80% ultramafic matrix

End-member A

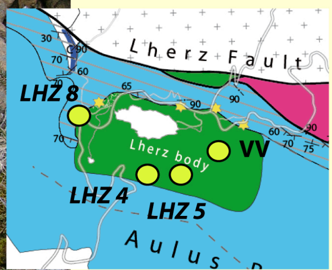
Ultramafic clasts in a sandy, 80% carbonate matrix

End-member B

Proportion of ultramafic and marble components may vary both in the matrix and in the clasts



Mixed type between A and B.



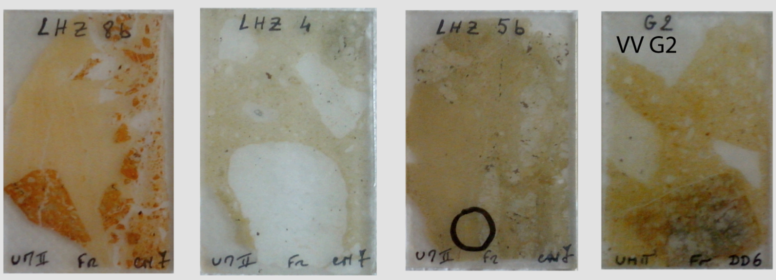
Description of thin sections.

LHZ 8b : ultramafic sandstone matrix , graded-bedded, ultramafic clasts. Oxydized, in association with the ophicalcites at site LHZ 8. Calcite veining well-developed with veins cutting through clasts and matrix.

LHZ 4 : light colored polycristalline marble clasts, green colored ultramafic-carbonate sandstone matrix, no graded-bedding visible, calcite recrystallisation in matrix.

LHZ 5b : ultramafic clasts in an ultramafic sandstone matrix (OL, CPX, OPX, Sp, serp. infra-mm debris). The matrix is graded-bedded. Phyllite tablets are observed in some beds. The biggest tablets are aligned parallel to the bedding. But the smallest ones do not show prefered orientattion. ***We infer that this is evidence for a metamorphic texture.*** This is confirmed by the recrystallisation of calcite in the matrix and by the presence of numerous small fissures filled with secondary calcite.

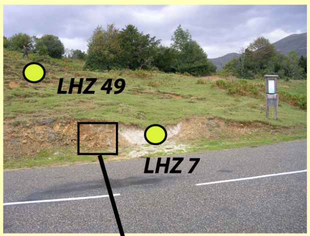
VV G2 : ultramafic and marble clasts. The matrix is welded by a protoserpentine, very small prisms of calcite are widespread in the matrix. Small phyllites and calcite veining are frequent



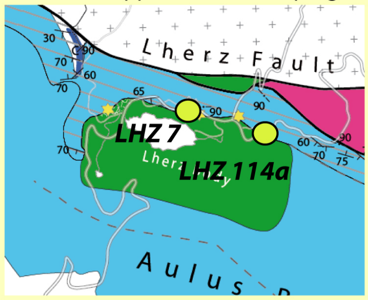
The ultramafic-derived clasts display many different lithologies (lherzolite, harzburgite, websterite, pyroxenite etc.), variable mantle textures (equant coarse-granular to mylonitic) and variable degrees of serpentinization (totally fresh to fully serpentinized).

10. The sapphirine-bearing sandstones and breccias

Anthophyllite- and phlogopite-rich rocks, also containing variable proportions of magnesian hornblende, sapphirine, kornerupine, Al-spinel, altered cordierite, scapolite, calcite, tourmaline, enstatite with anhydrite inclusions (Foucard) and subordinate amounts of rutile and apatite. We identified Cl-apatite as inclusions in sapphirine (work in progress).

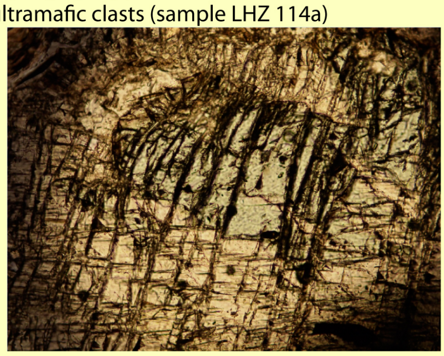


Brownish ultramafic sandstones (sample LHZ 49)

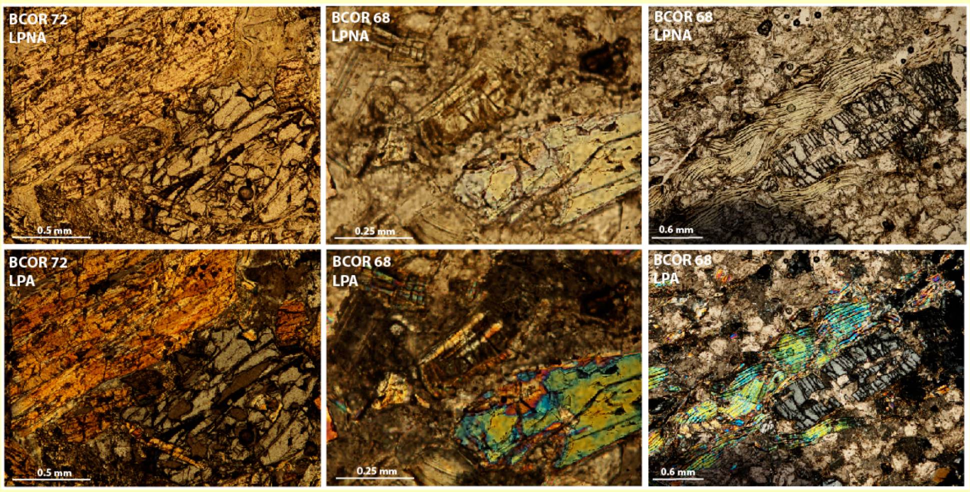


Breccia with sapphirine rich clasts (light grey), meta-ophite and meta-evaporitic clasts (site Momo). Note the presence of pockets of graded bedded ultramafic brownish sandstones.

Light grey sapphirine sandstones with ultramafic clasts (sample LHZ 114a)

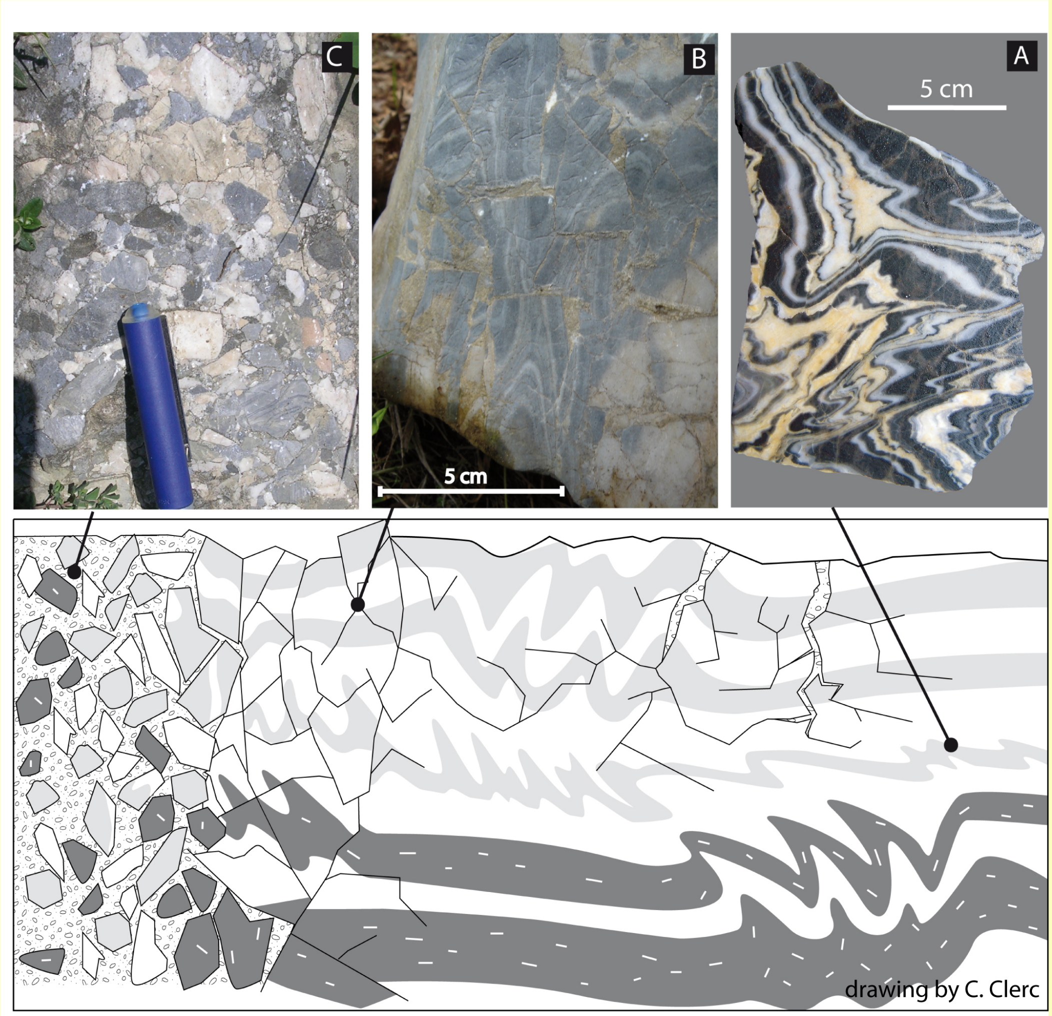


sapphirine BCOR68



association of sapphirine, phlogopite and anthophyllite

11. From ductilely deformed marbles to carbonate breccias



The transition from ductile deformation to cataclastic brecciation followed by sedimentary reworking occurred during the exhumation of the deeper mantle and crustal levels as described in Lagabrielle et al., (2016), CRG paper

The ductilely deformed Jurassic marbles

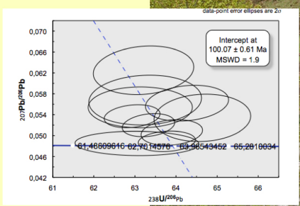
Polymictic sedimentary carbonate breccia

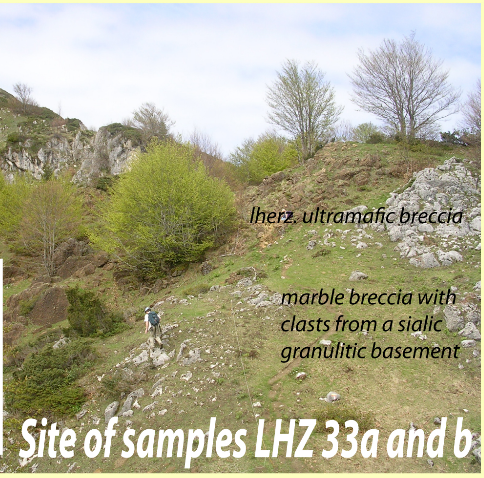
12. Geodiversity of sources in the Lherz breccias : from granulitic basement to isolated sapphirine clasts

MOSTLY OUT of the VISITED SITES, but of IMPORTANCE

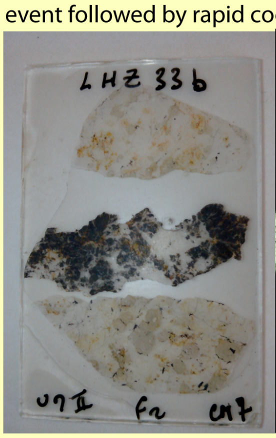
The Lherz breccias show evidence of mixing of debris originating from the disaggregation of various sources :
- the metamorphic prerift cover of the NPZ including Liassic «cornéennes», white marbles, grey marbles , meta dolomites (L-M Jurassic) with scapolites, micaceous Triassic metasediments,
- the mantle rocks, including CPx rich rocks that do not exist in the Lherz massif itself,
- the Paleozoic basement including newly discovered clasts of granulitic composition (qz, Fk, gt, sill).

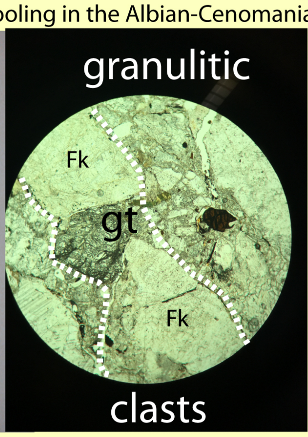
Sample LHZ0 : Polymictic, ultramafic-rich microbreccia including a sapphirine crystal debris !

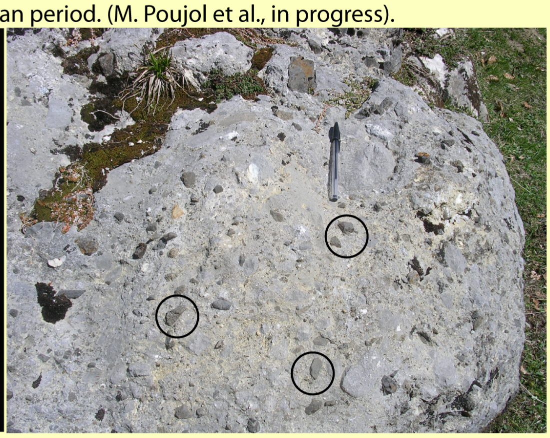




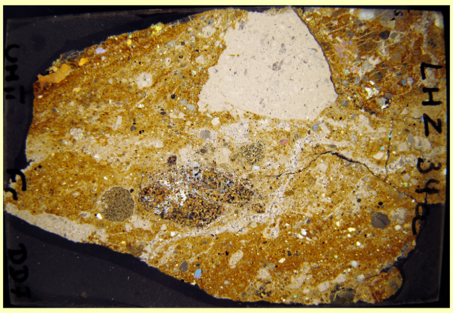
The site where clasts of granulitic basement have been collected within the polymictic, ultramafic-rich breccias (in situ Laser U/Pb dating of zircons and rutiles from the granulite clasts confirm an early Permian metamorphic event followed by rapid cooling in the Albian-Cenomanian period. (M. Poujol et al., in progress).







Sample LHZ 33 b, contains 3 pieces from clasts collected from the polymictic breccias. 2 of them are quartz-feldspaths rocks with garnets. The piece of rock in the center is a black marble with very large scapolites



Sample LHZ 34 a includes a variety of small fragments deriving from metaophites and amphibole-bearing rocks (lherzite) with numerous debris of ultramafic composition.

A dm-sized clast of orange-coloured Triassic deformed marble in the area of samples LHZ 34

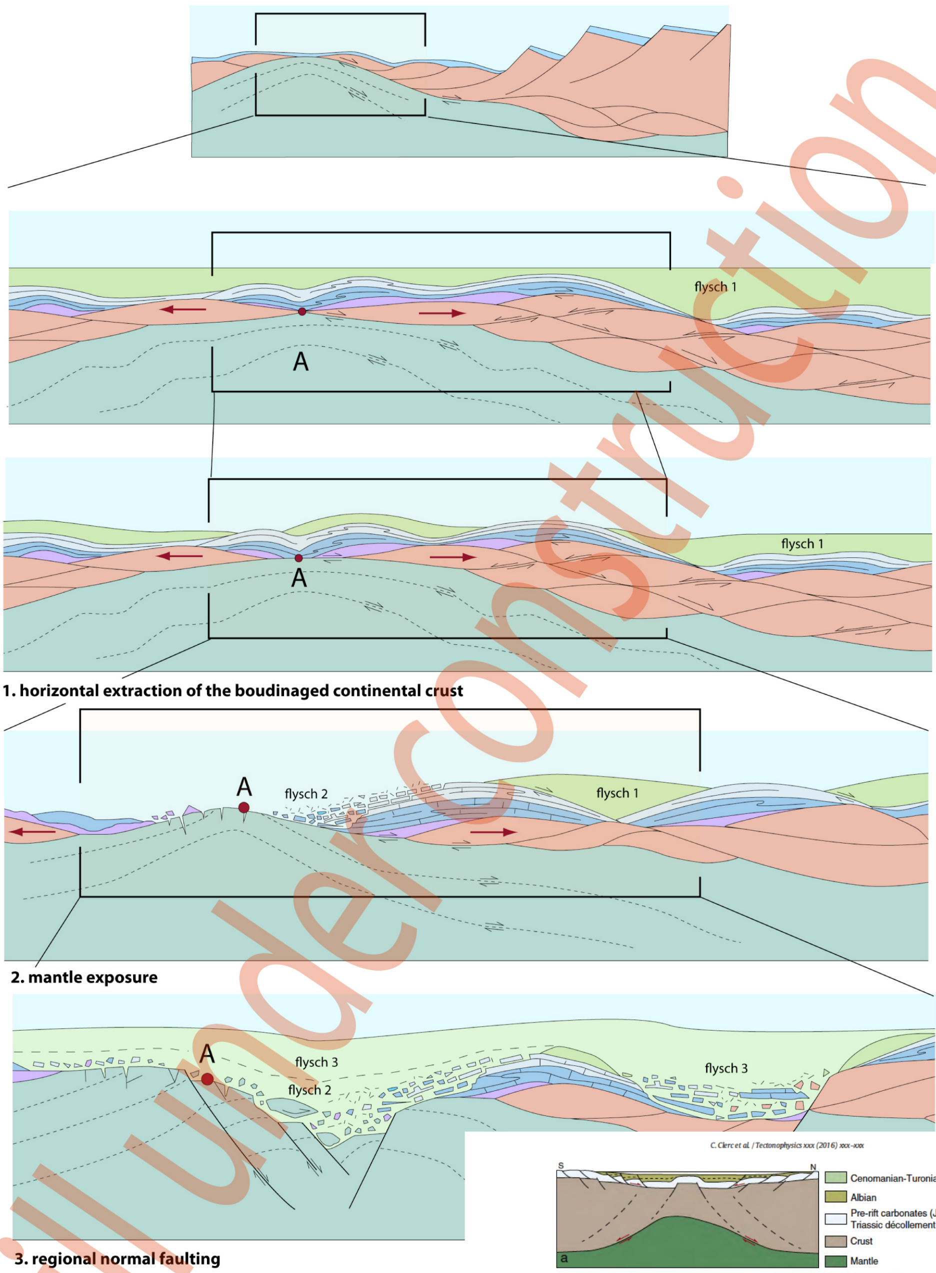
The Lherz breccia enigma : A possible model

Hot margin domain

boudinaged
upper and lower crust

Cold margin domain

boudinaged
lower crust only



C. Clerc et al. / Tectonophysics xxx (2016) xxx–xxx 13

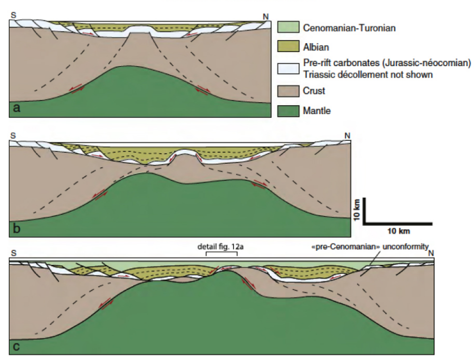


Fig. 11. a, b and c) Three steps conceptual model of margin evolution and related exhumation of metamorphic pre-rift Mesozoic sediments, based on features characteristic of the North-Eastern Pyrenean domain (step by step description in the text).

Clerc et al., Tectonophysics, 2016

Day Two (half day) : Michel de Saint Blanquat

On the way back to Perpignan, we will stop at the Bestiac area starting with an overview of the geological setting of the mantle bodies here : field evidence of sedimentary reworking of mantle rocks and synthetic geological cross-section of the NPZ. Special attention will be payed to the presence of the North Pyrenean massifs showing major metasomatic extensional shear zones of Mid-Cretaceous age (Luzenac talc deposits).

An olistolith of highly serpentized ultramafic rock allows the observation of the phacoidal fabric related to the exhumation processes. Finally a link will be proposed (and discussed !) between the evolution of the continental basement and the coeval exhumation of the mantle rocks. All our observations are consistent with a model of extreme continental thinning implying lateral extraction of the crust and ductile deformation of the pre-rift cover under a Cretaceous blanket of flysch deposits.

The following text is after :

de Saint Blanquat M, Bajolet F., Grand'Homme A., Proietti A., Zanti M., Boutin A., Clerc C., Lagabrielle Y., Labaume P., (2016). Cretaceous mantle exhumation in the central Pyrenees: New constraints from the peridotites in eastern Ariège (North Pyrenean zone, France). C. R. Geoscience (2016), http:// dx.doi.org/10.1016/j.crte.2015.12.003.

The Bestiac area represents the most spectacular examples of S-type peridotites in the Pyrenees thanks to its exceptional outcropping conditions and easy accessibility. The main bodies are located on the slope north of Bestiac village.

The Bestiac body. The general map of the Bestiac area is given in figure 1 and a detailed map of the eastern part is given in figure 2. The Bestiac massif is composed of about twenty sub-vertical lenses of brecciated peridotite, mainly spinel-lherzolite. The peridotite exhibits a clear magmatic layering in a few places. One unique feature of Bestiac massif is its serpentinisation: with the Bois du Fajou massifs, it is the only Pyrenean peridotitic massif known to date showing a mixture between peridotite blocks that have undergone different serpentinisation histories. Most of the lenses are constituted by fresh lherzolite (Fig. 3). Others are made of fresh lherzolites cut by at least two generations of serpentines veins (Fig. 4, 5, and 6). Finally, three lenses are constituted by totally serpentinized peridotite (Fig. 7). All the visible contacts are progressive and in a few places the breccia exhibits clear sedimentary bedding (Fig. 8, 9 and 10). In some places, non-serpentinized peridotitic fragments are located close to the edges of totally serpentinized large lenses. The breccia is polymictic and mainly composed of lherzolite fragments cemented in a cristallized calcite matrix (Fig. 11), but often evolves to marble fragments cemented in an ultramafic matrix (Fig. 12). The marble clasts are mainly constituted by white-grey marbles of probably Jurassic age, but also by blocs of various color (black, beige, brown...) of unknown age (Palaeozoic ? Lower Cretaceous ?). Rare clasts of pelite were observed. The matrix of the breccia is slightly recrystallized and contain metamorphic minerals, mainly white micas. All the lenses of peridotite are cut by carbonate-filled fractures forming ophicalcites, especially near their contact with host rock. The orientation of structural elements is given in figure 13, and clearly shows the relative chronology between pre-, syn- and post-brecciation events: the spatial coherence increases from intra-peridotite or intra-marbles structural elements, like magmatic and tectonic foliations and serpentinite veins, to the bedding of the breccia, and finally to the late fracture cleavage and faults which affect the whole breccia and show a N-S shortening.

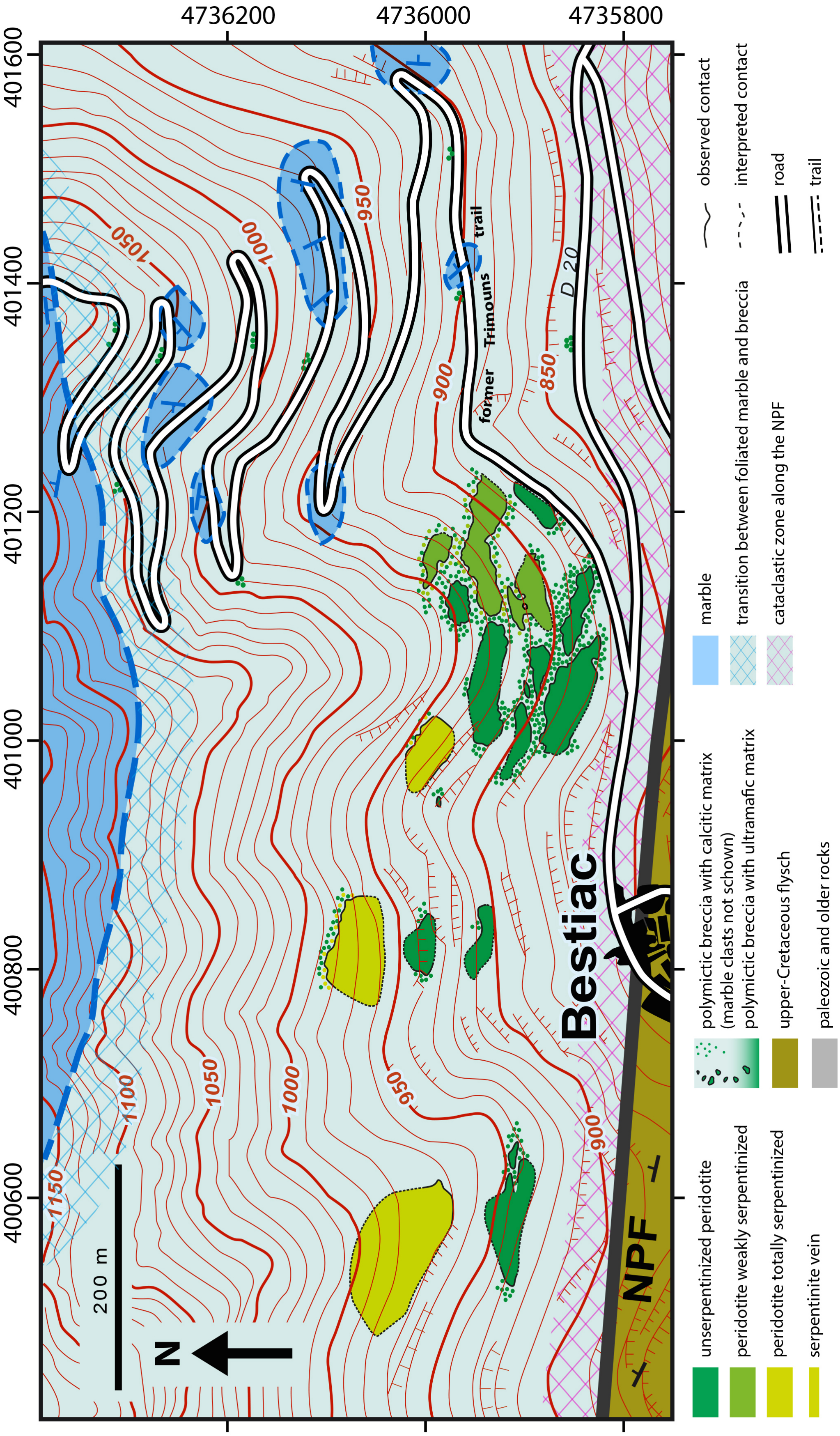


Figure 1 : general map of the Bestiac area. UTM 31T grid (meter).

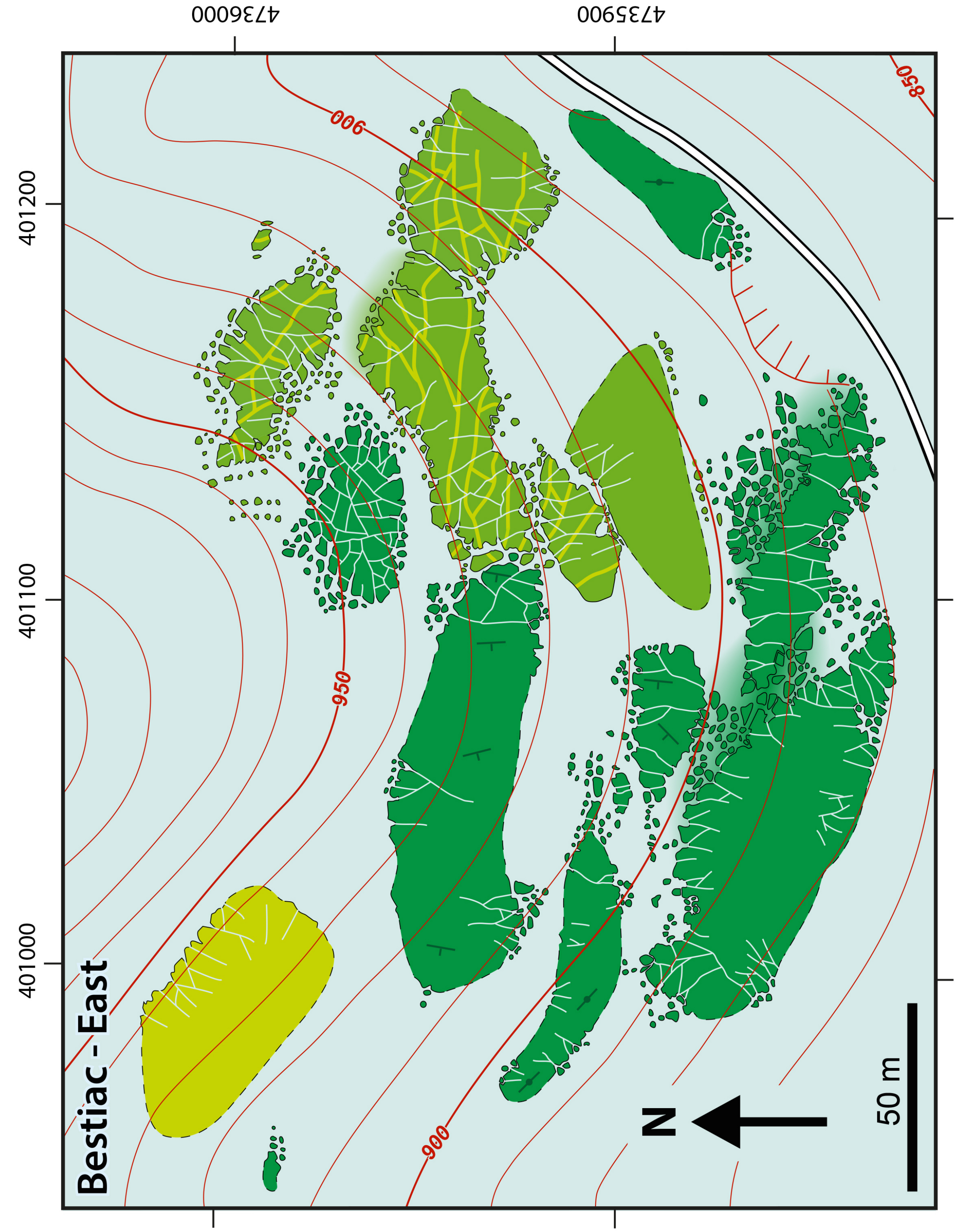


Figure 2 : detailed map of the eastern part of the Bestiac massif. UTM 31T grid (meter).
See figure 1 for caption.


Figure 3 : fresh peridotite with websteritic layering.


Figure 4 : partly serpentinized peridotite cut by two networks of serpentinite veins black V1 and green V2

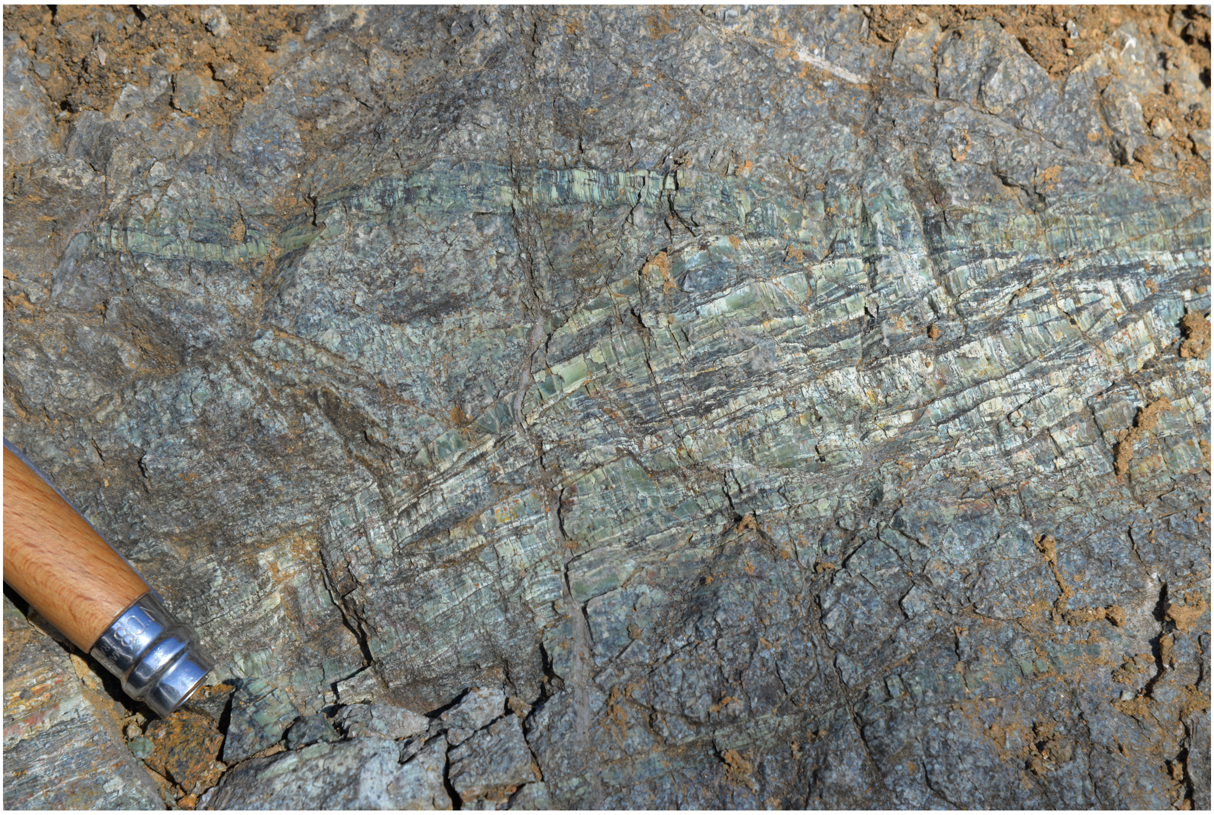


Figure 5 : detail of a V2 vein.

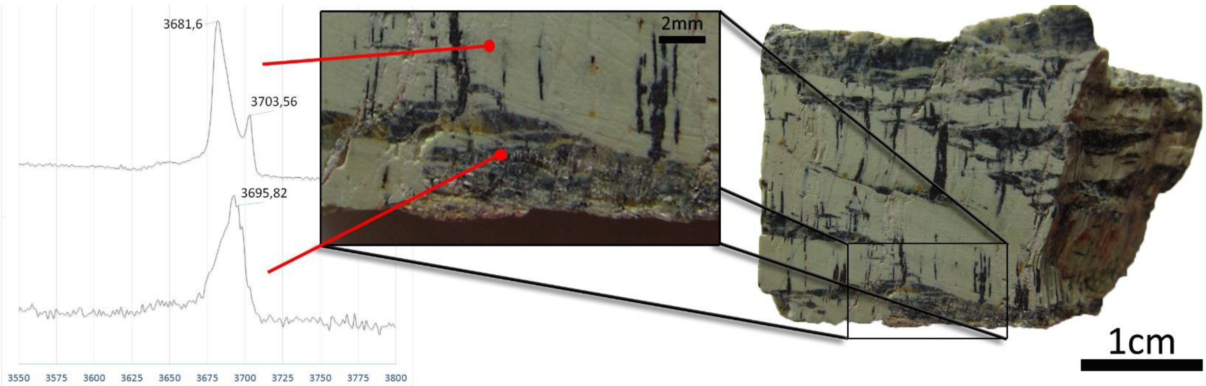


Figure 6 : Raman spectra of a composite V2 vein with centimetric lizardite and millimetric chrysotile veins. Top : lizardite spectra. Bottom : fibrous chrysotile spectra.


Figure 7 : totally serpentinized peridotite.


Figure 8 : sedimentary layering in a deformed peridotite-bearing breccia.

Figure 9 : sedimentary layering in fine-grained peridotite-bearing breccia.

Figure 10 : polished slab from outcrop of figure 9.

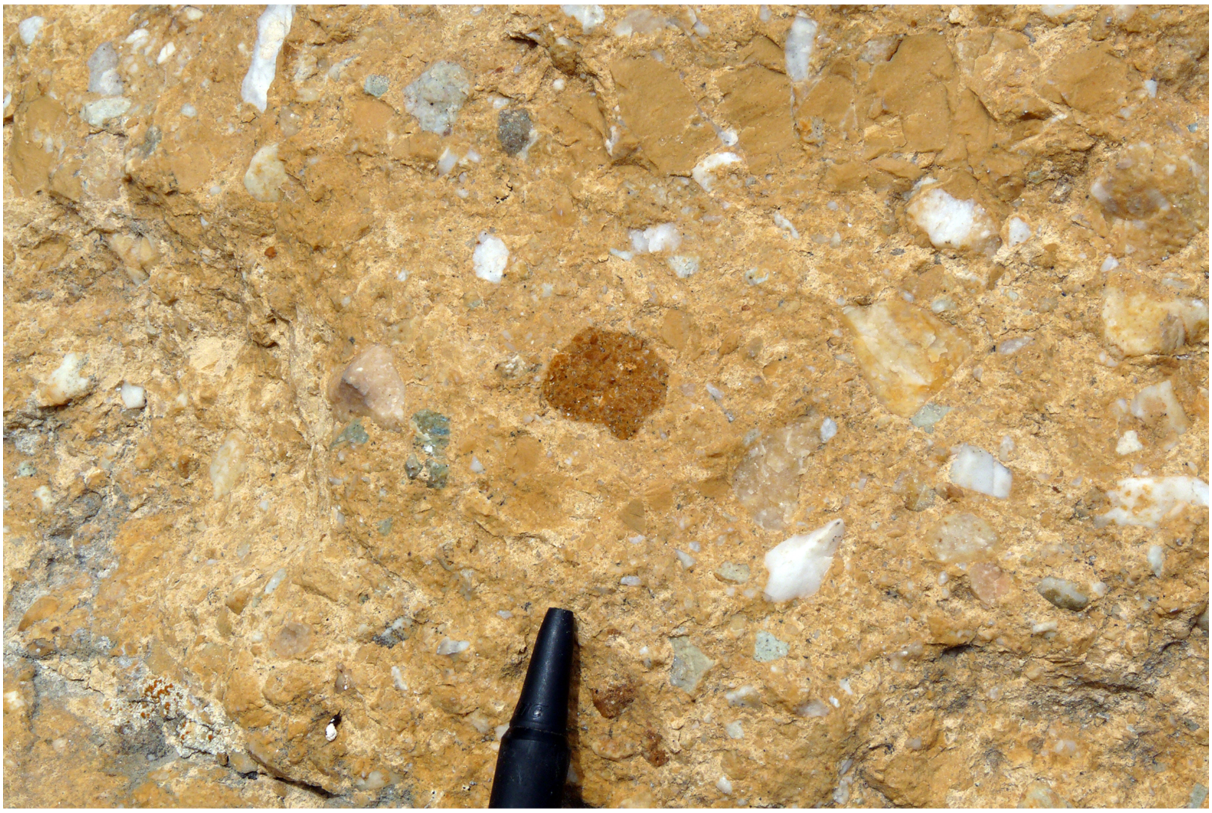


Figure 11 : polymictic peridotite-bearing breccia with calcitic matrix.

Figure 12 : polymictic breccia with ultramafic matrix and marble clasts.

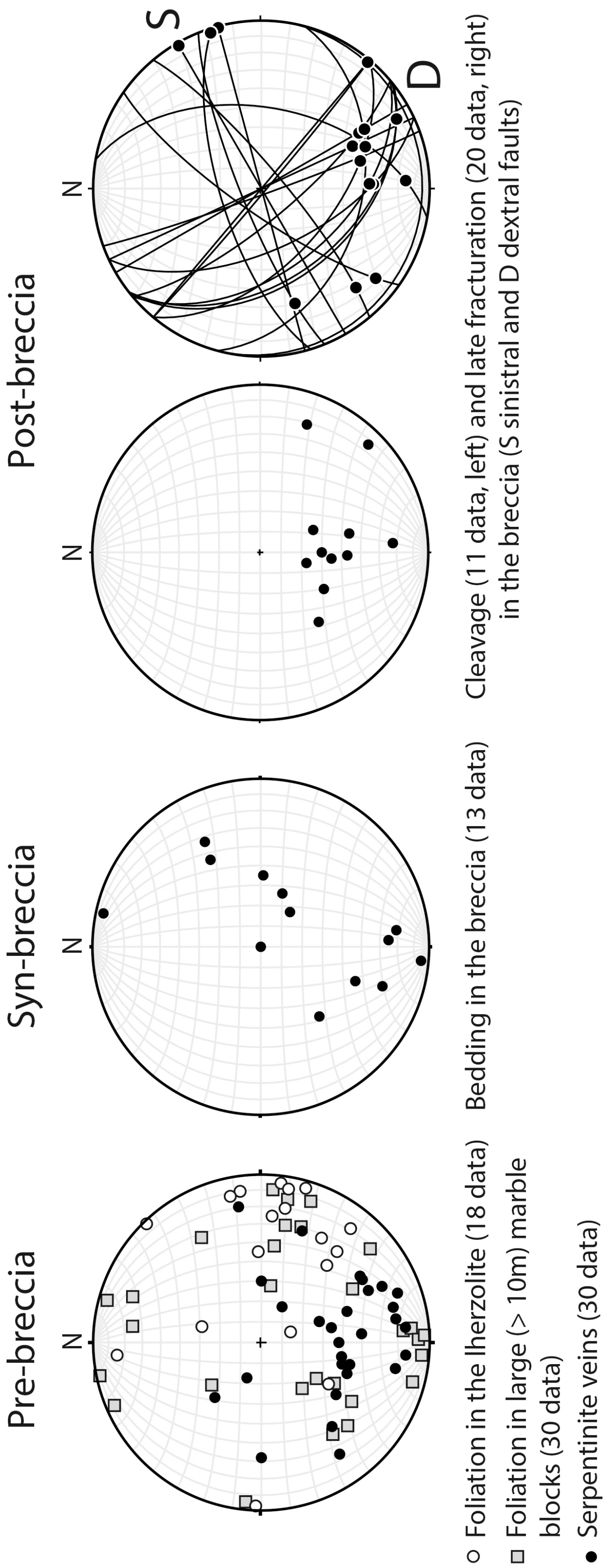


Figure 13 : structural data from the Bestiac area organized chronologically with respect to the field relationships (equal area, lower hemisphere).

References

Abbate, E., Bortolotti, V. and Passerini, P., 1970. Olistostromes and olistoliths, Sedimentary Geology, **4**, 521-557.

Abe, N., 2001. Petrochemistry of serpentinized peridotite from the Iberia Abyssal Plain (ODP Leg 173): its character intermediate between sub-oceanic to sub-continental upper mantle. In: *Non-volcanic Rifting of Continental Margins: Evidence From Land and Sea* (R.C.L. Wilson, R.B. Whitmarsh, H.P.J. Taylor and N Froitzheim, eds). *Geol. Soc. London, Spec. Publ,* **187**, 143-159..

Albarède F. and Michard-Vitrac A (1978) Age and significance of the North Pyrenean metamorphism. *Earth Planet. Sci. Lett.* **40**, 327-332.

Anderson, H.J., 1984. Gravity modelling of the lherzolite body at Lers (French Pyrennes) ; some regional implications. Geol. Mag., **122**, 51-56.

Andreani, M., Mével., C., Boullier, A.-M. and Escartin, J., 2007. Dynamic control on serpentine crystallization in veins : constraints on hydration processes in oceanic peridotites. Geochem., Geophys., Geosystems. 8, 2. Q02012/2006GC001373.

Aslanian, D., Moulin, M., Olivet, J.-L., Unternehr, P., Matias, L., Bache, F., Rabineau, M., Nouzé, H., Klingelheofer, F., Contrucci, I. and Labails, C., 2009. Brazilian and African passive margins of the Central Segment of the South Atlantic Ocean: Kinematic constraints: *Tectonophysics*, **468**, p. 98–112, doi: 10.1016/j.tecto.2008.12.016.

Auzende, J.M., Bideau, D., Bonatti, E., Cannat, M., Honnorez, J., Lagabrielle, Y., Malavieille, J., Mamaloukas-Frangoulis, V. and Mével, C., 1989. Direct observation of a section through slow-spreading oceanic crust. *Nature*, 337, 6209,-726-729.

Barruol, G., Souriau, A., Vauchez, A., Diaz, J., Gallart, J., Tubia, J. and Cuevas, J., 1998. Lithospheric anisotropy beneath the Pyrenees from shear wave splitting: *Journal of Geophysical Research*, **103**, p. 053.

Berger, G.M., Bessière, G., Bilotte, M. and Viallard, P., 1997. Carte géol. France (1/50 000), feuille Tuchan (1078):.

Berger, G.M., Fonteilles, M., Leblanc, D., Clauzon, G., Marshal, J.P. and Vautrelle, C., 1993. Notice explicative, carte géol.. France (1/50 000), feuille Rivesaltes (1090). Orléans : BRGM, 117 p. Carte géologique par Fonteilles M., Leblanc D., Clauzon G., Vaudin J.-L., Berger G.-M. (1993).:.

Bernoulli, D. and Weissert, H. 1985, Sedimentary fabrics in Alpine ophicalcites, South Pennine Arosa zone, Switzerland. Geology, **13**, 755-758.

Bernus-Maury, C., 1984. Etude des paragéneses caractéristiques du métamorphisme mésozoïque dans la partie orientale des Pyrénées [Thèse]: 253p. p.

Bertrand, L., 1940. Sur la structure géologique du versant nord des Pyrénées: **204**, p. 205–283.

Bessière, G., 1987. Modèle d'évolution polyorogénique d'un massif hercynien: le Massif de Mouthoumet (Pyrénées audoises) [Thèse]: 314 p.

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

Bodinier, J.-L., Dupuy, C. and Dostal J.,1988. Geochemistry and petrogenesis of Eastern Pyrenean peridotites. *Geochim. Cosmochim. Acta* **52**, 2893-2907.

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

Bodinier, J.-L., Menzies, M.A., Shimizu, N., Frey, F.A., and McPherson, E., 2004. Silicate, hydrous and carbonate metasomatism at Lherz, France: contemporaneous derivatives of silicate melt-harzburgite reaction. *J. Petrol.* **45**, 299-320.

Bodinier, J.-L., Vasseur, G., Vernières, J., Dupuy, C., and Fabriès, J., 1990. Mechanisms of mantle metasomatism : Geochemical evidence from the Lherz Orogenic peridotite. *J. Petrol.* **31**, 597-628.

Boillot G, Grimaud S, Mauffret A, Mougenot D, Kornprobst J, Mergoil-Daniel J, Torrent G (1980) Ocean-continent boundary of the Iberian margin : a serpentinite diapir west of the Galicia Bank. *Earth Planet. Sci. Lett.* **48**, 23-34.

Boillot, G., Winterer E.L.*, et al.* (1985) Résultats préliminaires de la campagne 103 du Joides Resolution (Ocean Drilling Program) au large de la Galice (Espagne) : sédimentation et distension pendant le "rifting" d'une marge stable : hypothèse d'une dénudation tectonique du manteau supérieur. *C. R. Acad. Sci. Paris* **301**, 627-632.

Bonatti, E., Honnorez, J. and Ferrara, G., 1971. Peridotite-gabbro-basalt complex from the equatorail Mid-Atlantic Ridge. Phil. Trans. Roy. Soc. London., 268, 385-402.

Boulvais, P., de Parseval, P., D'Hulst, A. and Paris, P., 2006. Carbonate alteration associated with talc-chlorite mineralization in the eastern Pyrenees, with emphasis on the St. Barthelemy Massif: *Mineralogy and Petrology*, **88**, p. 499–526, doi: 10.1007/s00710-006-0124-x.
Boulvais, P., in press. Fluid generation in the Boucheville Basin as a consequence of the North Pyrenean metamorphism: *Comptes Rendus Geosciences*, **in press**.
Boulvais, P., Ruffet, G., Cornichet, J. and Mermet, M., 2007. Cretaceous albitization and dequartzification of Hercynian peraluminous granite in the Salvezines Massif (French Pyrénées): *Lithos*, **93**, p. 89–106, doi: 10.1016/j.lithos.2006.05.001.
Chelalou, R., Nalpas T., Bousquet R., Prevost M., Lahfid A., Poujol M., Ringenbach J.-C. and Ballard J.-F., 2015. New sedimentological, structural and paleo-thermicity data on the Boucheville basin (eastern North Pyrenean Zone, France).: Comptes Rendus Géosciences, *in press.*
Choukroune P., 1973. La brèche de Lherz dite "d'explosion liée à la mise en place des lherzolites" est une brèche sédimentaire d'âge cénozoïque. C.R. Acad. Sc., 277, p. 2621-2624. Paris.
Choukroune P., 1974. Structure et évolution tectonique de la zone Nord-Pyrénéenne. Analyse de la déformation dans une portion de chaîne a schistosité subverticale. Thèse d'Etat, USTL, Montpellier, 330 p.
Choukroune, P. and ECORS Team, 1989. The Ecors Pyrenean deep seismic profile reflection data and the overall structure of an orogenic belt: *Tectonics*, **8**, p. PP. 23–39, doi: 198910.1029/TC008i001p00023.
Choukroune, P. and Mattauer, M., 1978. Tectonique des plaques et Pyrénées: Sur le fonctionnement de la faille transformante nord-Pyrénéenne; comparaisons avec les modèles actuels: *Bulletin de la société géologique de France*, **20**, p. 689–700.
Choukroune, P. and Séguret, M., 1973. Carte structurale des Pyrénées: ELF-ERAP.
Choukroune, P., 1973. La brèche de Lherz dite 'd'explosion liée à la mise en place des lherzolites' est une brèche sédimentaire d'âge Cénozoïque.: *C. R. Séances Acad. Sci. Ser. D*, **277**, p. 2621–2624.
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.*,, p. 176 pp.
Choukroune, P., 1980., Comment on « Quenching: an additional model for emplacement of the lherzolite at Lers (French Pyrenees) » Geology, 8, 514-515.
Choukroune, P., Mattauer, M., 1978. Tectonique des plaques et Pyrénées : sur le fonctionnement de la faille transformante nord pyrénéenne; comparaison avec des modèles actuels. *Bull. Soc. Géol. Fr.* **20**, 689-700.
Clerc, C. and Lagabrielle, Y., 2014. Thermal control on the modes of crustal thinning leading to mantle exhumation. Insights from the Cretaceous Pyrenean hot paleomargins.: *Tectonics*,, p. 2013TC003471, doi: 10.1002/2013TC003471.
Clerc, C., Boulvais, P., Lagabrielle, Y. and Blanquat, M., 2013. Ophicalcites from the northern Pyrenean belt: a field, petrographic and stable isotope study: *International Journal of Earth Sciences*,, p. 1–23, doi: 10.1007/s00531-013-0927-z.
Clerc, C., Lagabrielle, Y., Labaume, P., Ringenbach, J. C., Vauchez, A., Nalpas, T., Bousquet, R., Ballard, J.F., Lahfid, A., & Fourcade, S. (2016). Basement–Cover decoupling and progressive exhumation of metamorphic sediments at hot rifted margin. Insights from the Northeastern Pyrenean analog. *Tectonophysics*, *686*, 82-97
Clerc, C., Lagabrielle, Y., Neumaier, M., Reynaud, J.-Y. and Saint-Blanquat, M., 2012. Exhumation of subcontinental mantle rocks: evidence from ultramafic-bearing clastic deposits nearby the Lherz peridotite body, French Pyrenees: *Bulletin de la Societe Geologique de France*, **183**, p. 443–459, doi: 10.2113/gssgfbull.183.5.443.
Clerc, C., Lahfid, A., Monié, P., Lagabrielle, Y., Chopin, C., Poujol, M., Boulvais, P., Ringenbach, J.-C., Masini, E. and de St Blanquat, M., 2015. High-temperature metamorphism during extreme thinning of the continental crust: a reappraisal of the north Pyrenean paleo-passive margin: *Solid Earth*, **6**, p. 643–668, doi: doi:10.5194/se-6-643-2015.
Colchen, M., Ternet, Y., Debroas, E.J. et al., 1997. Carte géologique de la France au 1/50000, feuille 1086, Aulus-les Bains, 1997, éditions BRGM
Combes, P.-J. and Peybernès, B., 1989. Tectonique albienne dans les gisments de bauxites des Pyrénées ariègeoises (France) en relation avec l'évolution géodynamique de la marge passive européenne: *C. R. Acad. Sci. Paris, serie II*, **308**, p. 953–959.
Combes, P.-J., 1969. *Recherches sur la genèse des bauxites dans le Nord-Est de l'Espagne, le Languedoc et l'Ariège (France)*: Montpellier, France.

Conquéré F. and Fabriès J., 1984 - Chemical disequilibrium and its thermal significance in spinel-peridotites from the Lherz and Freychinede ultramafic bodies (Ariège ; French Pyrenees). In : Kornprobst J. (ed) Kimberlites II : The Mantle and Crust-Mantle Relationships ; pp. 319-332.

Conquéré F., 1971. Les pyroxénolites à amphibole et les amphibolites associées aux lherzolites du gisement de Lherz (Ariège, France) : un exemple du rôle de l'eau au cours de la cristallisation fractionnée des liquides issus de la fusion partielle de lherzolites. *Contrib. Mineral. Petrol.* **33**, 32-61.

Contrucci, I., Matias, L., Moulin, M., Géli, L., Klingelhofer, F., Nouzé, H., Aslanian, D., Olivet, J.L., Réhault, J.-P. and Sibuet, J.-C., 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: *Geophysical Journal International*, **158**, p. 529–553, doi: 10.1111/j.1365-246X.2004.02303.x.

Corre, B., Lagabrielle, Y., Labaume, P., Fourcade, S., Clerc, C., and Ballèvre, M. (2016). Deformation associated with mantle exhumation in a distal, hot passive margin setting: Example of the Saraillé Massif (Chaînons Béarnais, North-Pyrenean Zone). *Comptes Rendus Geoscience*, Special Issue, The Pyrénées : M. Godard, Y. Lagabrielle, M. de Saint Blanquat, eds.

Cortesogno, L., Galbiati, B. and Principi, G., 1981. Descrizione dettagliata di alcuni caratteritici affioramenti di brecce serpentiniche de la Liguria orientale ed interpretazioni in chiave geodinamica. Ofioliti, 6, 47-76.

Costa, S. and Maluski, H., 1988. Use of the 40Ar-39Ar stepwise heating method for dating mylonite zones: An example from the St. Barthélémy massif (Northern Pyrenees, France): *Chemical Geology: Isotope Geoscience section*, **72**, p. 127–144, doi: 10.1016/0168-9622(88)90061-9.

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

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

de Saint Blanquat M, Bajolet F., Grand'Homme A., Proietti A., Zanti M., Boutin A., Clerc C., Lagabrielle Y., Labaume P., (2016). Cretaceous mantle exhumation in the central Pyrenees: New constraints from the peridotites in eastern Ariège (North Pyrenean zone, France). C. R. Geoscience (2016), http://dx.doi.org/10.1016/j.crte.2015.12.003.

Debroas, E.-J., 1976. Sédimentogenèse et position structurale des flyschs crétacés du versant nord des Pyrénées centrales: *Bull. Bur. Rech. Géol. Min.*, **I**, p. 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. Géol. Fr.*, **20**, p. 639–648.

Debroas, E.-J., 1987. Le flysch à fucoïdes d'Uchentein témoin d'un escarpement turono-sénonien inférieur de la paléofaille nord pyrénéenne, Pyrénées Centrales, France.: *Strata*,, p. 77–93.

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): *Bulletin de la société Géologique de france*, **8**, p. 273–285.

Decandia, F. A. and Elter, P., 1972. La zona ofiolitifera del Bracco nel settore compreso fra Levanto e la Val Graveglιq (Appennino Ligure). *Mem. Soc. Geol. It.*, **11**, 503-530.

Deville, E., Fudral, S., Lagabrielle, Y., Marthaler, M., and Sartori, M., 1992. From oceanic closure to continental collision : a synthetic view from the HP-LT belt of the Western Alps. *Geol. Soc. Am. Bull.* 104, 127-139.

Downes, H., Bodinier, J.-L., Thirlwall, M.F., Lorand J.-P., and Fabriès, J.,1991. REE and Sr-Nd isotopic geochemistry of the Eastern Pyrenean peridotite massifs: sub-continental lithospheric mantle modified by continental magmatism. *J. Petrol. sp. volume "Orogenic Lherzolites and Mantle Processes"*, 97-115.

Duée, G., Lagabrielle, Y., Coutelle, A., Fortané, A., 1984. Les lherzolites associées aux chaînons béarnais (Pyrénées Occidentales) : mise à l'affleurement anté-dogger et resédimentation albo-cénomanienne. *C.R. Acad. Sci.*, Paris, t. 299, série II, n° 17, p. 1205-1209.

Durand-Delga, M., 1964. Remarques sur la stratigraphie et la structure du Mésozoïque situé entre Estagel et Perpignan (Pyrénées-Orientales): *Comptes Rendus de l'Académie des Sciences, Paris*, **259**, p. 837–840.

Durand-Delga, M., 1965. Au sujet de la phase anté-cénomanienne à l'Est de Quillan: *C. R. somm. Soc. geol. Fr.*, **2**, p. 61–62.

Fabriès, J., Lorand, J.-P., and Bodinier, J.-L., 1998. Petrogenetic evolution of orogenic lherzolite massifs in the central and western Pyrenees. *Tectonophysics* **292**, 145-167.

Fabriès, J., Lorand, J.-P., Bodinier, J.-L., and Dupuy, C.,1991. Evolution of the upper mantle beneath the Pyrenees: Evidence from orogenic spinel lherzolite massifs. *J. Petrol., sp. volume " Orogenic*

lherzolites and mantle processes", 55-76.
Fortané, A., Duée, G., Lagabrielle, Y. et Coutelle, A., 1986. Lherzolites and the Western "Chaînons Béarnais" (French Pyrénées) : structural and paleogeographical pattern. *Tectonophysics,* 129, p. 81-98.
Früh-Green, G.L., Weissert, H. and Bernoulli, D. 1990, A multiple fluid history recorded in Alpine ophiolites. *J. Geol. Soc.London*, **147**.959-970.
Golberg, J-M, Maluski, H., Leyreloup AF., 1986. Petrological and age relationship between emplacement of magmatic breccia, alkaline magmatism, and static metamorphism in the North Pyrenean Zone. *Tectonophysics* **129**, 275-290.
Golberg, J-M., and Maluski, H., 1988. Données nouvelles et mise au point sur l'âge du métamorphisme pyrénéen. *C. R. Acad. Sci. Paris* **306**, 429-435.
Golberg, J.-M. and Leyreloup, A.-F., 1990. High temperature-low pressure Cretaceous metamorphism related to crustal thinning (Eastern North Pyrenean Zone, France): *Contributions to Mineralogy and Petrology*, **104**, p. 194–207.
Golberg, J.-M., 1987. *Le métamorphisme mésozoïque dans la partie orientale des Pyrénées: relation avec l'évolution de la chaîne au Crétacé.*: Université des Sciences et Techniques du Languedoc, Montpellier.
Golberg, J.-M., Maluski, H. and Leyreloup, A.-F., 1986. Petrological and age relationship between emplacement of magmatic breccia, alkaline magmatism, and static metamorphism in the North Pyrenean Zone: *Tectonophysics*, **129**, p. 275–290, doi: 10.1016/0040-1951(86)90256-8.
Goujou, J.C., Golberg, J.-M. and Leyreloup, A.-F., 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, serie II*, **307**, p. 39–44.
Handy, M.R., M. Schmid, S., Bousquet, R., Kissling, E. and Bernoulli, D., 2010. Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps: *Earth-Science Reviews*, **102**, p. 121–158, doi: 10.1016/j.earscirev.2010.06.002.
Harris, L.B., Koyi, H.A. and Fossen, H., 2002. Mechanisms for folding of high-grade rocks in extensional tectonic settings: *Earth-Science Reviews*, **59**, p. 163–210, doi: doi:10.1016/S0012-8252(02)00074-0.
Henry, P., Azambre, B., Montigny, R., Rossy, M., Stevenson, R.K., 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, 103-123.
Jammes, S., Manatschal, G., Lavier, L.L. and Masini, E., 2009. Tectonosedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees: *Tectonics*, **28**, doi: 10.1029/2008TC002406.
Jammes, S., Tiberi, C. and Manatschal, G., 2010. 3D architecture of a complex transcurrent rift system: The example of the Bay of Biscay-Western Pyrenees: *Tectonophysics*, **489**, p. 210–226, doi: 10.1016/j.tecto.2010.04.023.
Karson, J.A., Früh-Green, G.L., Kelley, D.S., Williams, E.A., Yoerger, D.R., and Jakuba, M. 2006. Detachment shear zone of the Atlantis Massif core complex, Mid-Atlantic Ridge, 30°N. Geochem. Geophys. Geosystems. 7, 6, Q06016, doi : 10. 1029/20O5GC001109.
Lacroix, A. 1895. Les phénomènes de contact de la lherzolite et de quelques ophites des Pyrénées. Bull. Carte géol. Fr., 6, 181-186.
Lacroix, A., 1894. Etude minéralogique de la lherzolite des Pyrénées et de ses phénomènes de contact. Nouv. Archives Muséum 6, 209–308.
Lagabrielle Y, Bideau D, Cannat M, Karson JA, Mevel C (1998) Ultramafic-mafic plutonic rock suites exposed along the Mid-Atlantic Ridge (10°N-30°N): Symmetrical-assymetrical distribution and implications for seafloor spreading processes. In: WR Buck, PT Delaney, JA Karson and Y Lagabrielle (eds.)*Faulting and Magmatism at Mid-Ocean Ridges*. pp. 153-176. American Geophysical Union.
Lagabrielle Y. de Saint Blanquat, M. and Godard M. 2016. From rifting to mountain building : The Pyrenees. *Comptes Rendus Geoscience*, Special Issue, The Pyrénées : M. Godard, Y. Lagabrielle, M. de Saint Blanquat, eds.
Lagabrielle Y., Clerc C., Vauchez A., Lahfid A., Labaume P., Azambre B., Fourcade F., Dautria JM. (2016). Very high geothermal gradient during mantle exhumation recorded in mylonitic marbles and carbonate breccias from a Mesozoic Pyrenean paleo-margin (Lherz area, North Pyrenean Zone, France). *Comptes Rendus Geoscience*, Special Issue, The Pyrénées : M. Godard, Y. Lagabrielle, M. de Saint Blanquat, eds.

Lagabrielle Y., Clerc C., Vauchez A., Lahfid A., Labaume P., Azambre B., Fourcade F., Dautria JM. (2016). Very high geothermal gradient during mantle exhumation recorded in mylonitic marbles and carbonate breccias from a Mesozoic Pyrenean paleo-margin (Lherz area, North Pyrenean Zone, France). *Comptes Rendus Geoscience*, Special Issue, The Pyrénées : M. Godard, Y. Lagabrielle, M. de Saint Blanquat, eds.

Lagabrielle, Y. & Auzende, J.M., 1982 .- Active *in situ* disaggregation of oceanic crust and mantle on Gorringe Bank : analogy with ophiolitic massives. *Nature,* 297, 5866, p. 490-493.

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

Lagabrielle, Y., Clerc, C., Vauchez, A., Lahfid, A., Labaume, P., Azambre, B., Fourcade, S. and Dautria, J.-M., 2015. Very high geothermal gradient during mantle exhumation recorded in mylonitic marbles and carbonate breccias from a Mesozoic Pyrenean paleomargin (Lherz, North Pyrenean Zone, France): *Comptes Rendus Géosciences*.

Lagabrielle, Y., Labaume, P. and St Blanquat, M., 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**, p. 1–26, doi: 10.1029/2009TC002588.

Lago, M., Arranz, E., Pocoví, A., Galé, C. and Gil-Imaz, A., 2004. Permian magmatism and basin dynamics in the southern Pyrenees: a record of the transition from late Variscan transtension to early Alpine extension: *Geological Society, London, Special Publications*, **223**, p. 439–464, doi: 10.1144/GSL.SP.2004.223.01.19.

Le Pichon, X., Bonnin, J. and Sibuet, J.C., 1970. La faille nord-pyrénéenne : faille transformante liée à l'ouverture du Golfe de Gascogne. C.R. Acad. Sc. Paris, 271, série D, 1941-1944.

Le Roux, V. 2008. Melt-rock interactions and melt-assisted deformation in the Lherz peridotite, with implications for the structural, chemical and isotopic evolution of the lithospheric mantle. Thesis, PhD Montpellier

Le Roux V., Bodinier J.-L., Tommasi A., Alard O., Dautria J.-M., Vauchez A. and Riches A.J.V., 2007. The Lherz spinel lherzolite: refertilized rather than pristine mantle. Earth Planet. Sci. Lett., in press.

Légier, C., Tempier, C. and Vauchez, A., 1987. Tectoniques tangentielle ductile synmétamorphe d'âge Crétacé supérieur dans la couverture du massif de l'Agly (zone Nord-pyrénéenne orientale).: *Comptes Rendus de l'Académie des Sciences, Paris*, **305**, p. 907–911.

Lemoine M., Boillot G. and Tricart P., 1987. Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Apennines): In search of a genetic model. *Geology*, **15**: 622-625.

Lockwood, J.P., 1971. Sedimentary and gravity slide emplacement of serpentinites. Geol. Soc. Amer. Bull., 82 919-936.

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, 432-466.

Marroni, M., Pandolfi, L., 2001. Debris flow and slide deposits at the top of the Internal Liguride ophiolitic sequence, Northern Appennines, Italy : A record of frontal tectonic erosion in a fossil accretionary wedge. The Island Arc, 10, 9-21.

Masini, E., Manatschal, G., Tugend, J., Mohn, G. and Flament, J.-M., 2014. The tectono-sedimentary evolution of a hyper-extended rift basin: the example of the Arzacq–Mauléon rift system (Western Pyrenees, SW France): *International Journal of Earth Sciences*, **103**, p. 1–28, doi: 10.1007/s00531-014-1023-8.

Mattauer, M. and Henry, J., 1974. Pyrenees: *Geological Society, London, Special Publications*, **4**, p. 3 –21, doi: 10.1144/GSL.SP.2005.004.01.01.

Mattauer, M. and Proust, F., 1964. Sur l'allure de la discordance anté-cénomanienne dans le bassin de Quillan (partie orientale des Pyrénées): *C.R. somm. S.G.F.*,, p. 340–342.

Mattauer, M., 1968. Les traits structuraux essentiels de la chaîne des Pyrénées.: *Revue Géogr. phys. Géol. dyn.*, **10**, p. 3–12.

Minnigh, L.D., Van Calsteren, P.W.C., den Tex, E. 1980. Quenching : an additional model for emplacement of the lherzolite at Lers (French Pyrenees). Geology, 8, 18-21.

Monchoux, P., 1970. Les lherzolites pyrénéennes : contribution à l'étude de leur minéralogie, de leur genèse et de leurs transformations. Thèse d'Etat, thesis, Toulouse.

Monchoux, P., 1972. Roches à sapphirine au contact des lherzolites pyrénéennes. Contrib. Mineral. and Petrol ., 37, 47-64.

Montigny R, Azambre B, Rossy M, Thuizart R (1986) K-Ar study of Cretaceous magmatism and metamorphism from the Pyrenees : age and length of rotation of the Iberian Peninsula. *Tectonophysics* **129**, 257-273 .

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

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

Muñoz, J.A., 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. In: *Thrust Tectonics* K. McClay, London, p. 235–246.

Olivet, J.L., 1996. La cinématique de la plaque Ibérie. *Bulletin des Centres de Recherche Exploration-Production Elf-Aquitaine* **20**, 131-195.

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

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

Paquet, J. and Mansy, J.-L., 1991. La structure de l'Est des Pyrénées (transversales du massif de l'Agly): un exemple d'amincissement crustal.: *Comptes Rendus de l'Académie des Sciences - Serie II*,, p. 913–919.

Passchier, C.W., 1984. Mylonite-Dominated Footwall Geometry in a Shear Zone, Central Pyrenees: *Geological Magazine*, **121**, p. 429–436, doi: 10.1017/S0016756800029964.

Peybernès, B., 1976. Le jurassique et le Crétacé inférieur des Pyrénées franco-espagnoles antre la Garonne et la Méditerranée. [Thèse]: Univ. Toulouse, 459 p.

Pin, C. and Vielzeuf, D.,1983. Granulites and related rocks in Variscan median Europe; a dualistic interpretation. *Tectonophysics* **93**, 47-74.

Poujol, M., Boulvais, P. and Kosler, J., 2010. Regional-scale Cretaceous albitization in the Pyrenees: evidence from in situ U-Th-Pb dating of monazite, titanite and zircon: *Journal of the Geological Society*, **167**, p. 751–767, doi: 10.1144/0016-76492009-144.

Ravier, J., 1959. Le métamorphisme des terrains secondaires des Pyrénées: *Mem. Soc. Geol. Fr.*, **86**, p. 1–250.

Reisberg, L., and Lorand, J.-P.,1995. Longevity of sub-continental mantle lithosphere from osmium isotope systematics in orogenic peridotite massifs. *Nature* **376**, 159-162.

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

Rosenbaum, G., Lister, G.S. and Duboz, C., 2002. Relative motions of Africa, Iberia and Europe during Alpine orogeny: *Tectonophysics*, **359**, p. 117–129, doi: doi:10.1016/S0040-1951(02)00442-0.

Roure, F., Choukroune, P., Berastegui, X., Munoz, J.A., Vilien, A., Matheron, P., Bareyt, M., Seguret, M., Camara, P. and Deramond, J., 1989. Ecors deep seismic data and balanced cross sections: Geometric constraints on the evolution of the Pyrenees: *Tectonics*, **8**, p. 41–50.

Saint Blanquat, M. (de), 1993. La faille normale ductile du massif du Saint Bathélémy. Evolution hercynienne des massifs nord-pyrénéens catazonaux considérés du point de vue de leur histoire thermique. Geodinamica Acta, 1993, 6, 1, 59-77.

Schärer, U., de Parseval, P., Polvé, M. and de Saint Blanquat, M., 1999. Formation of the Trimouns talc-chlorite deposit (Pyrenees) from persistent hydrothermal activity between 112 and 97 Ma. Terra Nova, 11, 30-37.

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

Seyler, M., and Bonatti, E., 1988. Petrology of a gneiss-amphibole lower crust unit from Zabargad island, Red Sea. *Tectonophysics* **150,** 177-208.

Sibuet J.C., Srivastava S.P. & Spakman W. (2004).- Pyrenean orogeny and plate kinematics.- *Journal of Geophysical Research*, Washington, vol. 109, B08104, doi : 10.1029/2003JB002514, 18 p.

Sibuet, J.-C., 2004. Pyrenean orogeny and plate kinematics: *Journal of Geophysical Research*, **109**, doi: 10.1029/2003JB002514.

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

Srivastava, S.P., Sibuet, J.-C., Cande, S., Roest, W.R. and Reid, I.D., 2000. Magnetic evidence for slow seafloor spreading during the formation of the Newfoundland and Iberian margins: *Earth and Planetary Science Letters*, **182**, p. 61–76, doi: doi:10.1016/S0012-821X(00)00231-4.

St Blanquat, M., Bajolet, F., Clerc, C., Grand'Homme, A., Proietti, A., Boutin, A., Lagabrielle, Y. and Labaume, P., 2015. Cretaceous mantle exhumation in the Central Pyrenees: New constraints from the lherzolites in eastern Ariege (North Pyrenean Zone, France): *Comptes Rendus Geosciences*.

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

Stampfli, G.M., Borel, G.D., Marchant, R. and Mosar, J., 2002. Western Alps geological constraints on western Tethyan reconstructions: *Journal of the Virtual Explorer*, **08**, doi: 10.3809/jvirtex.2002.00057.

Teixell, A., 1998. Crustal structure and orogenic material budget in the west central Pyrenees: *Tectonics*, **17**, p. 395–406, doi: 199810.1029/98TC00561.

Teixell, A., Labaume, P., Lagabrielle, Y. The crustal evolution of the west-central Pyrenees revisited: inferences from a new kinematic scenario (2016). *Comptes Rendus Geoscience*, Special Issue, The Pyrénées : M. Godard, Y. Lagabrielle, M. de Saint Blanquat, eds.

Ternet Y., Colchen M., Debroas E.J., Azambre B., Debon F., Bouchez J.L., Gleizes G., Leblanc D., Bakalowicz M., Jauzion G., Mangin A., Soulé J.C., 1997. *Notice explicative, Carte géol. France (1/50 000), feuille Aulus les Bains (1086)*. Orléans: BRGM, 146 p. Carte géologique par M. Colchen *et al*. (1997).

Ternet, Y., Colchen, M., Debroas, E.-J., Azambre, B., Debon, F., Bouchez, J.-L., Gleizes, G., Leblanc, D., Bakalowicz, M., Jauzion, G., Mangin, A. and Soulé, J.-C., 1997. *Notice explicative, Carte géol. France (1/50 000), feuille Aulus les Bains (1086)*: BRGM, Orléans.

Tugend, J., Manatschal, G., Kusznir, N.J., Masini, E., Mohn, G. and Thinon, I., 2014. Formation and deformation of hyperextended rift systems: Insights from rift domain mapping in the Bay of Biscay-Pyrenees: *Tectonics*, **33**, p. 1239–1276, doi: 10.1002/2014TC003529.

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

Vacherat, A., Mouthereau, F., Pik, R., Bernet, M., Gautheron, C., Masini, E., Le Pourhiet, L., Tibari, B. and Lahfid, A., 2014. Thermal imprint of rift-related processes in orogens as recorded in the Pyrenees: *Earth and Planetary Science Letters*, **408**, p. 296–306, doi: 10.1016/j.epsl.2014.10.014.

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

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

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

Vissers, R.L.M. and Meijer, P.T., 2012. Mesozoic rotation of Iberia: Subduction in the Pyrenees? *Earth-Science Reviews*, **110**, p. 93–110, doi: 10.1016/j.earscirev.2011.11.001.

Vissers, R.L.M., Drury, M.R., Newman, J., and Fliervoet, T.F. 1997. Mylonitic deformation in upper mantle peridotites of the North Pyrenean Zone (France) : implications for strength and strain localization in the lithosphere. Tectonophysics, 279, 303-325.

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