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Submarine reworking of exhumed subcontinental mantle rocks: field evidence from the Lherz peridotites, French Pyrenees

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ABSTRACT

In the Pyrenees, the lherzolites nowhere occur as continuous units. Rather, they always outcrop as restricted bodies, never more than 3 km wide, scattered across Mesozoic sedimentary units along the North Pyrenean Fault. We report the results of a detailed analysis of the geological setting of the Lherz massif (central Pyrenees), the type-locality of lherzolites and one of the most studied occurrences of mantle rocks worldwide. The Lherz body is only 1.5 km long and belongs to a series of ultramafic bodies of restricted size (a few metres to some hundreds of metres), occurring within sedimentary formations composed mostly of carbonate breccias originating from the reworking of Mesozoic platform limestones and dolomites. 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 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.

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Introduction

The Pyrenean peridotites consist of about 40 fragments of generally well-preserved subcontinental mantle, a few hundred meters to 3 km across (Fabriès *et al.*, 1991, 1998). Most of them 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). The significance of these small mantle fragments scattered along a major tectonic boundary has long been a matter of debate. Various scenarios 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.*, 1986). However, most attempts to solve the question of Pyrenean peridotite emplacement were published more than 20 years ago. Since that time, considerable progress has been made in our understanding of mantle exhumation at passive margins and mid-ocean-ridges. In particular, an important result of recent studies of ocean-continent transitions (OCT) is that subcontinental lithospheric mantle is exposed on the ocean floor at the foot of most non-volcanic passive margins. Mantle rocks exhumed in such settings experienced reworking and transport leading to local accumulation of typical ultramafic-rich clastic sedimentary sequences (Whitmarsh *et al.*, 2001; Manatschal, 2004).

Here, we re-examine the geological setting of the Pyrenean peridotites in the area of Etang de Lherz, the type-locality of lherzolite, and we focus on the relationships between the peridotite bodies and the surrounding sediments. The aim of this study was to identify further the emplacement mechanisms of the Pyrenean peridotites in the light of the scenarios recently suggested for mantle exhumation in extensional and oceanic environments.

Emplacement of the Pyrenean lherzolites: geological constraints and former models

Five constraints based on significant geological, petrological and geochemical data must be considered when addressing the mode of emplacement of the Pyrenean peridotites.

1 Fresh to moderately serpentinized lherzolite is the predominant rock type in all peridotite bodies. 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 lherzolites were recently interpreted as formed at the expense of old, ~2.5 Ga (Reisberg and Lorand, 1995), harzburgitic lithosphere by igneous refertilization (Le Roux *et al.*, 2007). This process probably occurred during the post-Variscan, post-collisional thermal event responsible for granulitic metamorphism in the western Pyrenees (Pin and Vielzeuf, 1983).

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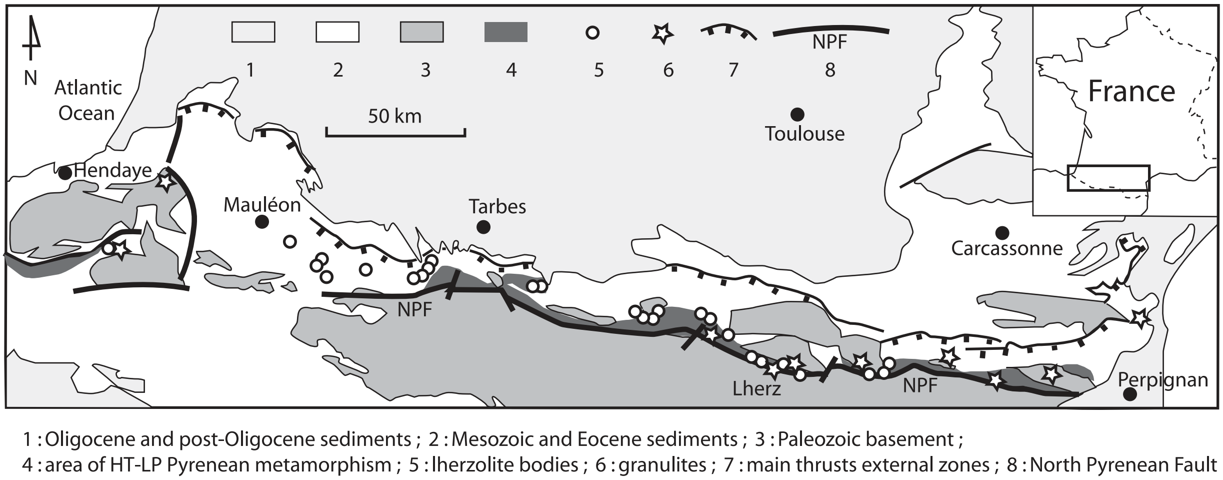

Fig. 1 Location map of the lherzolitic bodies in the eastern Pyrenean belt (modified from Choukroune, 1974).

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).

2 The lherzolites never constitute continuous units, but always appear as restricted bodies never more than 3 km long. They are never associated with larger gabbro or pillow-lava formations of MORB affinity. Therefore, they cannot be considered as parts of an ophiolitic suite representing typical oceanic lithosphere. Their mode of emplacement necessarily differs from the obduction of coherent thrust sheets as typical in Tethyan ophiolites.

3 The lherzolite bodies are always closely associated with sedimentary formations representing inverted Mesozoic basins. They occur within a geological environment often characterized by voluminous detrital formations (flyschs) including turbidites and debris flows linked to tectonic instabilities and sedimentary transport and deposition in basins of Cretaceous age, generally Albian to Cenomanian.

4 The eastern Pyrenean lherzolites are located in a belt of HT-LP Cretaceous metamorphism linked to the NPF that has been dated between 110 and 85 Ma (Albarède and Michard-Vitrac, 1978; Montigny *et al*., 1986; Golberg and Maluski, 1988). Mesozoic limestones now occur as highly deformed marbles bearing typical Pyrenean mineralogical assemblages including scapolite, phlogopite, diopside, etc. This led many authors to suggest a causal relationship between ultramafic intrusions and heat transfer from lower lithopheric levels (see Golberg *et al*., 1986; Golberg and Maluski, 1988; for references). The involvement of hot fluids as mechanism of heat transfer leading to dynamothermal metamorphism was inferred from the heterogeneity in the distribution of the isograds. The thermal anomaly was linked to important crustal thinning and fluid circulation along the NPF area during the sinistral drift of Iberia (Dauteuil and Ricou, 1989).

5 At Etang de Lherz, the ultramafic rocks are surrounded by a variety of voluminous breccia formations composed of clasts of ultramafic and carbonate rocks of various sizes (from less than one mm to a few dm), mixed in different proportions.

Finally, because of the wide range of observations listed above, 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, namely:

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 preceding the Pyrenean orogeny (Vielzeuf and Kornprobst, 1984; and references therein). Minnigh *et al*. (1980) proposed that the breccias derive from in-situ disaggregation of carbonate sediments as the result of quenching caused by 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). 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: (a) lherzolite clasts and monogenic lherzolitic breccias layers are abundant in a wide area, some km away from the main body of Lherz, (b) 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, (c) the breccias systematically contain pebbles of deformed marbles exhibiting Pyrenean metamorphic mineralogical assemblages in a matrix that experienced weaker metamorphic overprint.

Breccias in the Etang de Lherz region and contact between lherzolite and limestones

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 metasediments are characterized by a wide variety of breccias, as shown on the BRGM geological map (Colchen *et al*., 1997; Ternet *et al*., 1997) (Fig. 2). 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 (Fig. 3), forms the Lherz body. Besides the lherzolitic bodies, minor ophitic and gabbroic bodies are observed (Fig. 2).

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. 2). 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 (Fig. 4). Carbonate clasts are angular to subangular, rarely rounded, with sizes ranging from one mm to a few dm. The breccias are generally poorly sorted,

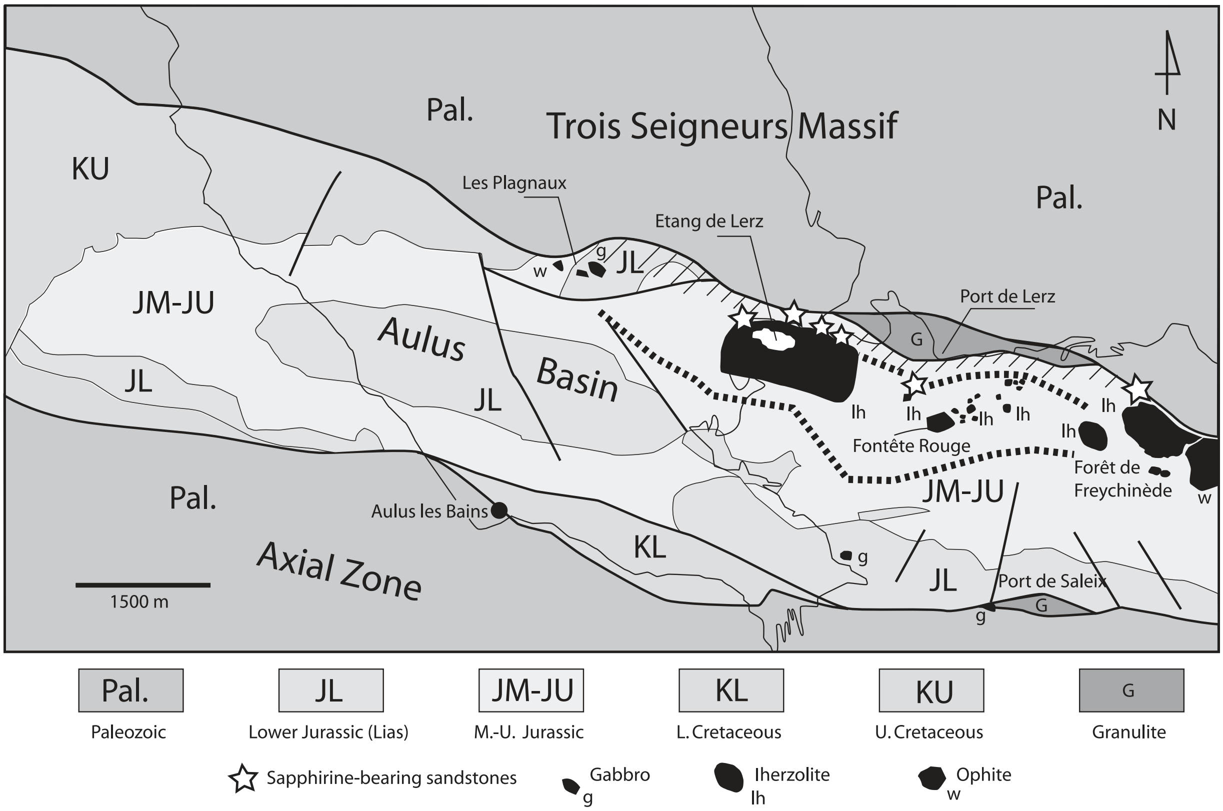

Fig. 2 Simplified geological map of the Aulus-Lherz region showing the distribution of the lherzolite bodies and associated lithologies (redrawn after the BRGM Aulus les Bains 1 : 50 000 geological map by Colchen *et al.* (1997), after Vielzeuf and Kornprobst (1984), and according to our own observations). Note that small lherzolite bodies from 1 dm to 100 m across are scattered around the body of Lherz. Thick dotted line delineates the region where polymictic debris-flow deposits have been recognized during our study. Hatched area represents the region north of the main ultramafic bodies, where strongly deformed Mesozoic sediments are exposed, and where rare sedimentary clastic deposits have been observed.

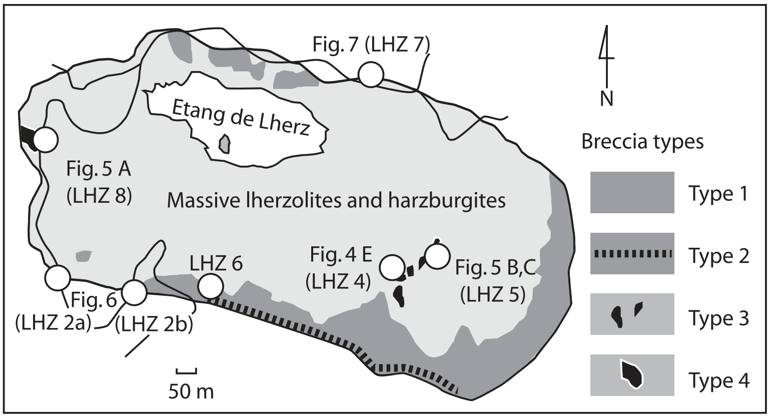

Fig. 3 Detailed map of the Lherz body and location of sample sites and of main types of breccia formations as discussed in the text. Black stars refer to ultramafic breccia locations, white star represents light-coloured sandstone site. Map after Le Roux *et al.* (2007) and Conquéré and Fabriès (1984).

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. 3). 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 indicate 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 (Fig. 3, 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, Fig. 3) where they appear to fill large fissures opened within the peridotites. They are composed of thin layers of graded ultramafic sandstones (Fig. 5) 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 (Fig. 4). 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 (Figs 3 and 5). 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 (Fig. 3).

We closely studied the contacts between carbonates and ultramafics. These are well exposed along the road at Sites LHZ 2a and LHZ2b (Figs. 3 and 6) 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 loca-

Fig. 4 The polymictic breccias. Numerous examples of sedimentary breccias are well exposed in the region between the Lherz and Fontete Rouge bodies, an area delineated by a thick dotted line in the map of Fig. 2. Evidence of sedimentary origin and subaqueous transport of clasts includes graded bedding, frequent erosional channels and cross-bedding, mixing from different sources, round shape of some clasts, etc. (a) Graded polymictic carbonate-lherzolite breccias with interlayered polymictic sandstone beds. (b) Lens of bedded, pure ultramafic sandstone (white arrows) within polymictic carbonate-ultramafic breccia. (c) Matrix-supported breccia. Angular clasts are deformed marbles, the orange-coloured matrix is made up of lherzolitic sandstone. (d) Monomictic ultramafic breccia. (e) Thin section of a fine-grained ultramafic sandstone (grains of serpentinite and millimetric fragments of deformed marbles), breccia of Type 3, location Fig. 3.

tion. 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 lherzolite dikelets). This is well observed at Site LHZ 2b (Fig. 6). 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

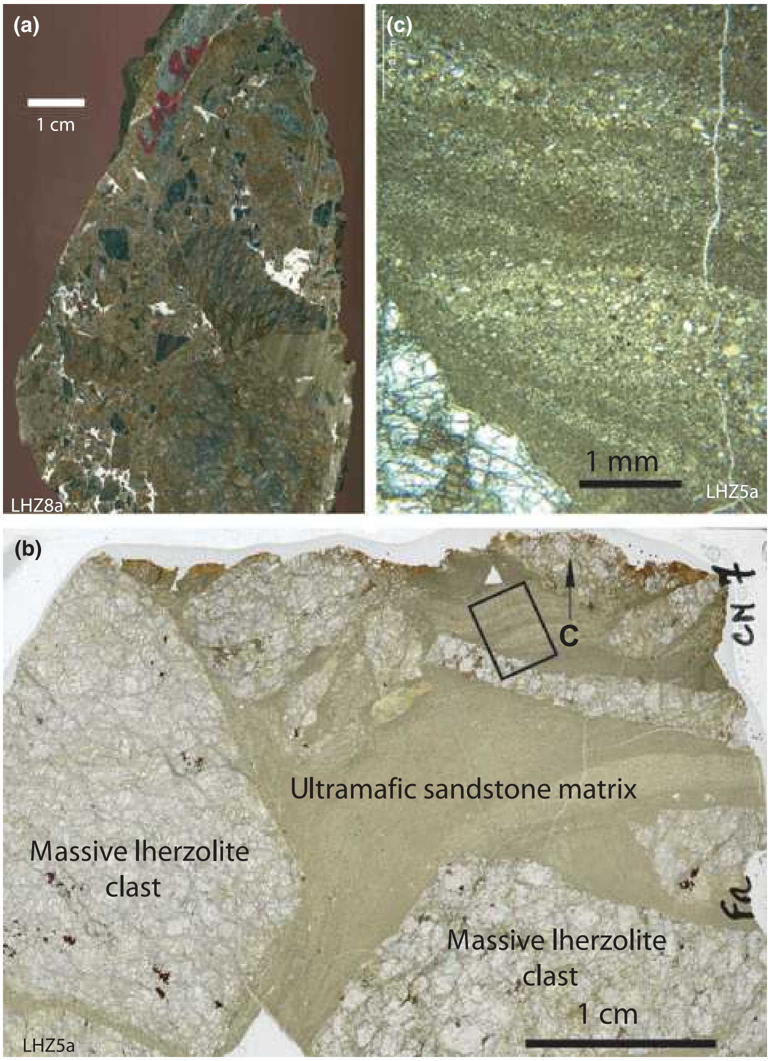

Fig. 5 (a) Ophicarbonate and (b) lherzolitic pebbly sandstones containing angular clasts of coarse-grained lherzolite, (c, enlargement of b). (a) is a Type 4 breccia, (b) belongs to the Type 3 breccias (see text for descriptions and Fig. 3 for location of samples).

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 because of 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, Figs. 2, 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 into 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.

Interpretation: sedimentary origin of some of the Lherz breccias

The observations reported above demonstrate that the lherzolites and some associated deep-seated rocks 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 a subaqueous 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

Fig. 6 Detailed views of the contact between the main body of Lherz and the carbonates of the Aulus basin at Sites LHZ 2a and LHZ 2b, along the southern edge of the massif (see Fig. 3 for location). Here, there is no tectonic contact between the mantle rocks and the sediments. Rather, as frequently observed in Alpine-Apenninic ophiolites, the sediments infill open fissures within the peridotites. Note that the limestones are carbonate micro-breccias, most probably emplaced as debris flows above the exhumed mantle basement. Photographs (a), (b) and (c) are taken from Site LHZ 2b (Fig. 3) exposing the contact on the eastern side of the road. Photograph (d) is from a block recently fallen down from the exposure at Site LHZ 2a, on the western side of the road.

lower than 300–350 °C (Andreani *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 synthesized in Fig. 8. Because of 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 first two cases, the Lherz body would exhibit a tectonic contact on its northwestern side against the tectonized

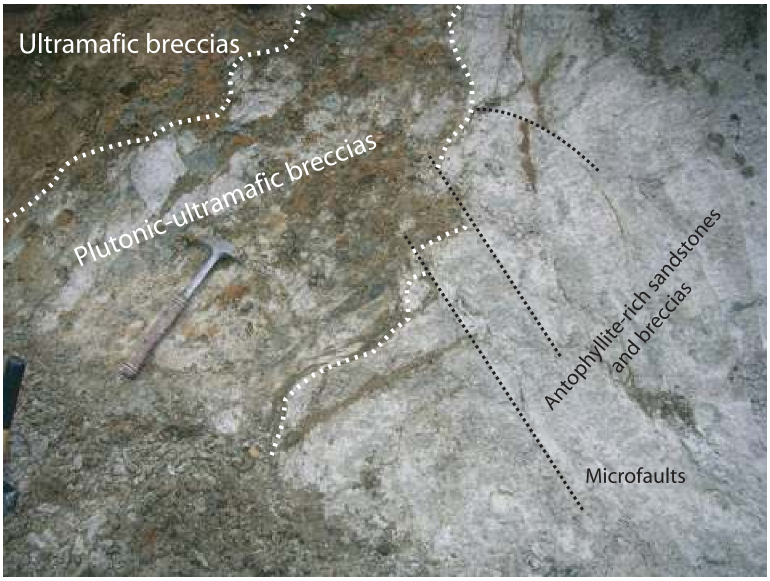

Fig. 7 Antophyliite- and vermiculite-rich sandstones, polymictic and ultramafic breccias exposed along the northern limit of the Lherz body at Site LHZ 7 (see Fig. 3 for location).

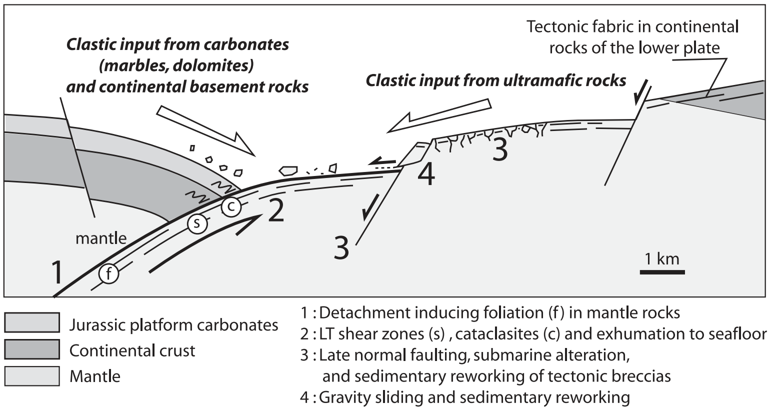

Fig. 8 Cartoon depicting possible geological setting and mode of emplacement of the ultramafic bodies and associated clastic rocks.

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.

Geodynamic 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, as no relicts of oceanic lithosphere are present within the mountain belt. In 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 in response 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; de 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 (Fig. 9). 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

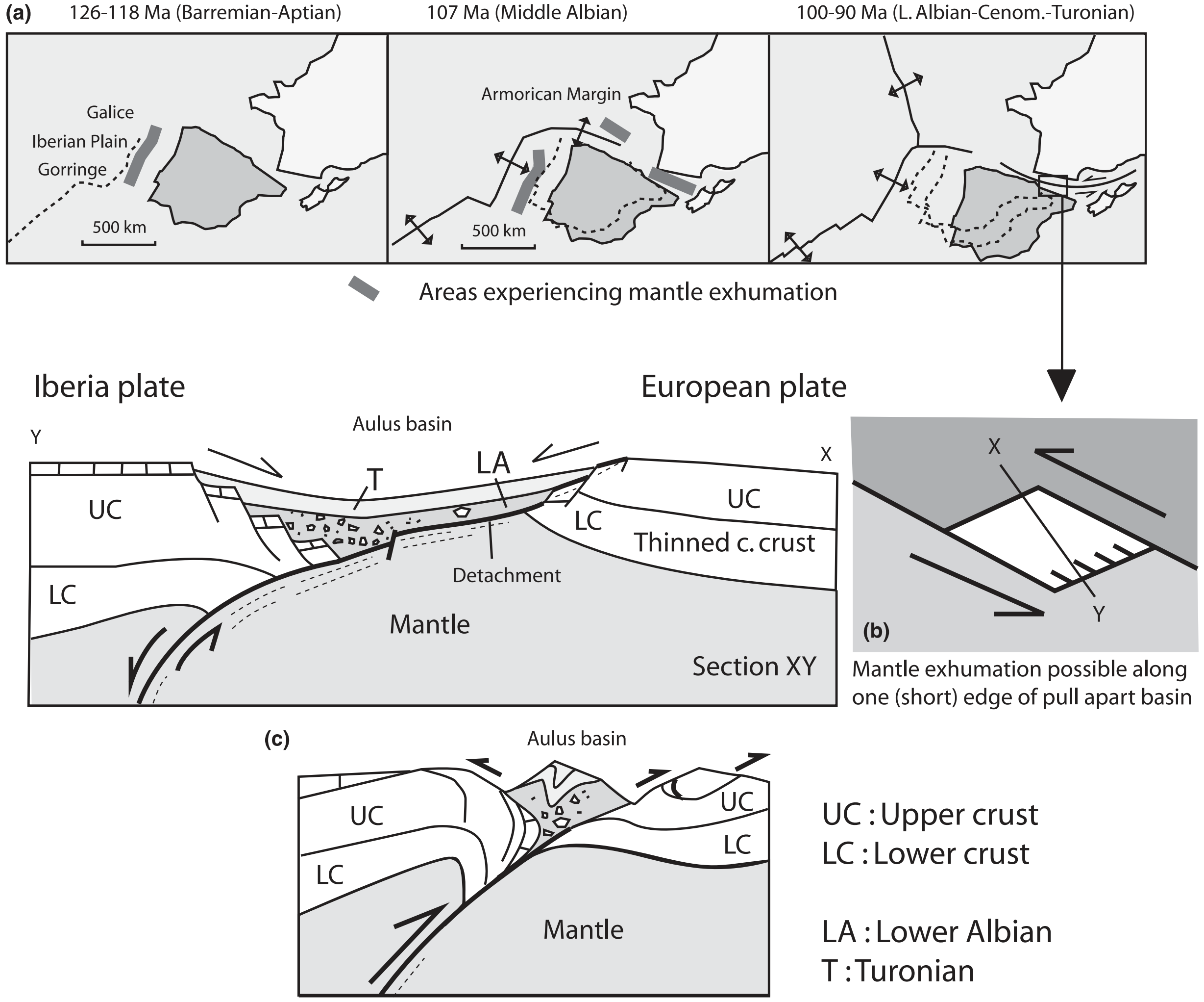

Fig. 9 Geodynamic model of mantle exhumation in the particular context of the Pyrenean belt. (a) Timing of rotation of Iberia (after Olivet, 1996), thick green lines indicate zones of active mantle exhumation. (b) Scenario of mantle exhumation in a pull-apart basin. (c) Evolution of the zone of exhumed mantle during basin inversion due to the Pyrenean orogeny.

between the Iberian and European plates.

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References

Abbate, E., Bortolotti, V. and Passerini, P., 1970. Olistostromes and olistoliths. *Sed. Geol.*, **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.

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.

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

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. Minér.*, **110**, 345–358.

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., 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.

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.

Boillot, G., Grimaud, S., Mauffret, A., Mougenot, D., Kornprobst, J., Mergoil-Daniel, J. and 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, EL., Meyer, A.W., Applegate, J., Baltuck, M., Bergen, J.A., Comas, M.C., Davies, T.A., Dunham, K., Evans, C.A., Girardeau, J., Goldberg, D., Haggerty, J., Jansa, L.F., Johnson, J.A., Kasahara, J., Loreau, J.P., Sierra, E.L., Moullade, M., Ogg, J., Sarti, M., Thurow, J., Williamson, M.W., 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 equatorial Mid-Atlantic Ridge. *Philos. Trans. Roy Soc. Lond.*, **268**, 385–402.

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. Sci. Paris*, **277**, 2621–2624.

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.

Choukroune, P., 1980. Comment on "Quenching: an additional model for emplacement of the lherzolite at Lers (French Pyrenees)" *Geology*, **8**, 514–515.

Choukroune, P. and 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.

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, Orléans, France.

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.

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: *Kimberlites II: The Mantle and Crust-Mantle Relationships* (J. Kornprobst, ed), pp. 319–332. Elsevier, Amsterdam.

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 mylonitic zones: an example from the St. Barthélémy Massif (Northern Pyrenees, France). *Chem. Geol.*, **72**, 127–144.

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

Decandia, F.A. and Elter, P., 1972. La zona ofiolitifera del Bracco nel settore compreso fra Levanto e la Val Graveglia (Appennino Ligure). *Mem. Soc. Geol. Ital.*, **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. **Orogenic Lherzolites and Mantle Processes**, (M.A. Menzies *et al*, eds) *J. Petrol.*, 97–115.

Duée, G., Lagabrielle, Y., Coutelle, A. and Fortané, A., 1984. Les lherzolites associées aux chaînons béarnais (Pyrénées Occidentales): mise à l'affleurement antédogger et resédimentation albo-cénomanienne. *C. R. Acad. Sci. Paris*, **17**, 1205–1209.

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. **Orogenic Lherzolites and Mantle Processes**, (M.A. Menzies *et al*, eds) *J. Petrol.*, 55–76.

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.

Fortané, A., Duée, G., Lagabrielle, Y. and et Coutelle, A., 1986. Lherzolites and the Western "Chaînons Béarnais" (French Pyrénées): structural and paleogeographical pattern. *Tectonophysics*, **129**, 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., 1987. *Le métamorphisme mésozoïque dans la partie orientale des Pyrénées: relation avec l'*évolution de la chaîne au Crétacé. Doctorat thesis, Montpellier II.

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., 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**, 275–290.

Henry, P., Azambre, B., Montigny, R., Rossy, M. and 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.

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**, 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.

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

Lagabrielle, Y., Bideau, D., Cannat, M., Karson, J.A. and Mevel, C. 1998 Ultramafic-mafic plutonic rock suites exposed along the Mid-Atlantic Ridge (10°N–30°N): symmetrical–asymmetrical distribution and implications for seafloor spreading processes. In: *Faulting and Magmatism at Mid-Ocean Ridges* (W.R. Buck, P.T. Delaney, J.A. Karson and Y. Lagabrielle, eds), pp. 153–176. American Geophysical Union, Washington, DC.

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. Sci. Paris*, **271**, 1941–1944.

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.*, **259**, 599–612.

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. Am. 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. and 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. *Island Arc*, **10**, 9–21.

Minnigh, L.D., Van Calsteren, P.W.C. and 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. Petrol.*, **37**, 47–64.

Montigny, R., Azambre, B., Rossy, M. and 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.

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

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

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.

de Saint Blanquat, M, 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. *Geodin. Acta*, **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.

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. and Spakman, W., 2004. Pyrenean orogeny and plate kinematics. *J. Geophys. Res.*, **109**, doi: 10.1029/2003JB002514.

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)*, Orléans: BRGM, 146 p.

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 Planet. Sci. Lett.*, **67**, 87–96.

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.

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