Earth Mantle Workshop

September 12-15th
Toulouse, France

Field excursion guide

The Lherz orogenic peridotite massif
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Abstract

The Pyrénées result from the convergence between Iberia and Europe between the end of the Cretaceous and the Cenozoic (~80-20 Ma). Bodies of mantle peridotites (serpentinized to various degrees) are present exclusively in the North Pyrenean Zone, and are generally associated with carbonate and ultramafic breccias. The various studies carried out on these objects have demonstrated that the exhumation of the mantle is caused by the formation of a hyper-extended rift between Iberia and Western Europe, inducing high temperature/low pressure metamorphism between 115 and 80 Ma (Late Aptian to Campanian) and accompanied by small occurrences of contemporary alkaline igneous rocks. The mantle was exhumed along large lithospheric-scale detachments, disaggregated along normal fault scarps and transported-sedimented with carbonate breccias in the subaquatic floor of an intra-continental rift separating Iberia to the rest of Western Europe.

1 The Pyrenean belt - focus on the North Pyrenean Zone

The Pyrenees are a mountain range separating Spain from France and surrounded by two foreland basins, namely the Ebro basin in Spain and the Aquitaine basin in France. The Paleozoic basement of the Pyrenees was strongly affected by the Variscan (Carboniferous) orogeny, but its present day structural and geomorphologic organization is mostly the result of a Cretaceous rifting event followed by orogenic growth related to oblique convergence between the Iberian and Europe from Upper Cretaceous (Santonian) to Late Paleogene/Early Neogene. The northern part of the belt is classically subdivided into (Figures 1 and 2), from south to north:

1. the **Axial Zone**, formed of Late Precambrian to Paleozoic low grade metasediments, Cambrian-Ordovician and Carboniferous plutons and Late variscan HT/LP metamorphic domes.
2. The **North Pyrenean Zone (NPZ),** located between the North Pyrenean Fault (NPF) to the South and the North Pyrenean Frontal Thrust (NPFT) to the North. It exposes basements massifs (called North Pyrenean massifs) made of Late Precambrian and Paleozoic metamorphic and igneous rocks separated by Mesozoic sedimentary basins containing small ultramafic massifs (Figures 1 and 2). Cretaceous metamorphism under HT-LP conditions (peaking at 600°C) between 110 and 85 Ma transformed carbonates into marbles within the so-called "internal metamorphic zone" (IMZ).
3. The Northern **Sub-Pyrenean Zone**, north of the NPFT, where Cretaceous to Cenozoic sediments belonging to the Aquitaine basin are affected by folding and thrusting with deformation generally increasing towards the North Pyrenean Zone.

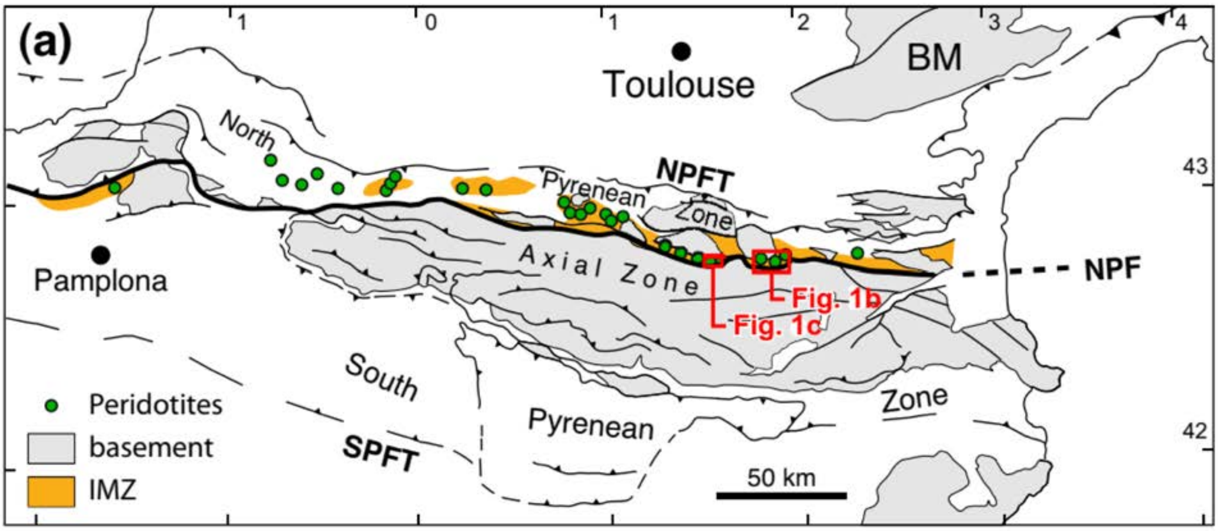


Figure 1. Map showing the main zones of the Pyrenean belt and their bordering faults (St Blanquat et al., 2016). Occurrences of ultramafic rocks are grossly aligned in the North Pyrenean Zone. The yellow domains highlight areas that recorded Cretaceous HT-LP metamorphism (IMZ: internal metamorphic zone; NPF: North Pyrenean Fault; NPFT: North Pyrenean Frontal Thrust; BM: Black Mountain).

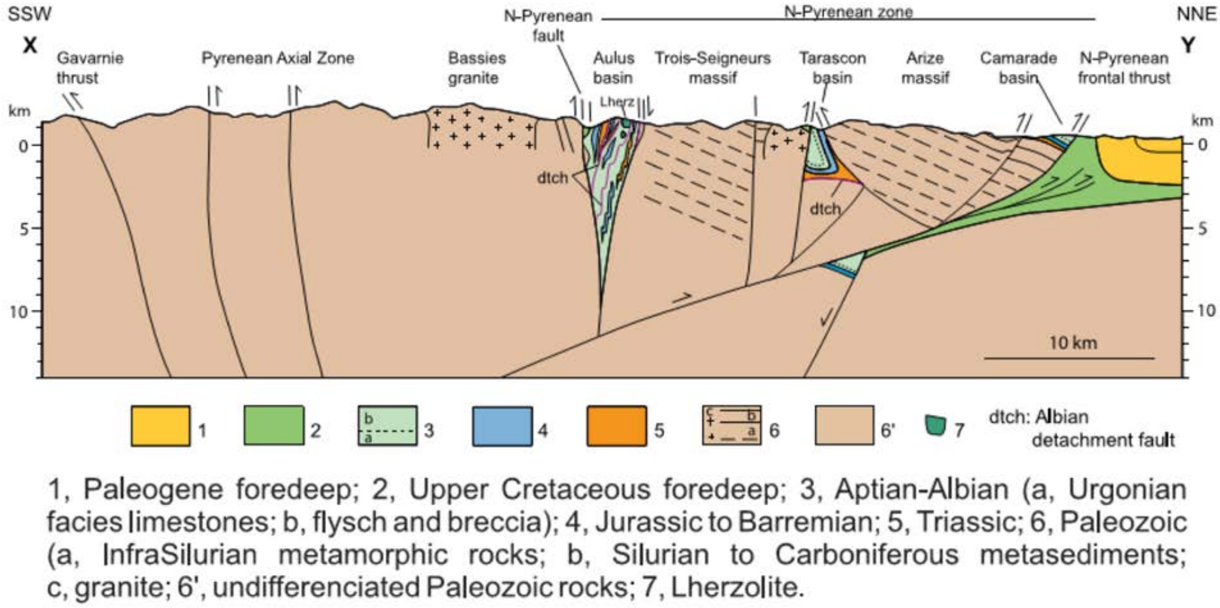


Figure 2. S-N cross section from the axial to the Sub-Pyrenean zone (Clerc et al., 2012). Note the squeezed inverted Mesozoic basins sandwiched between crystalline Paleozoic massifs. The Lherz orogenic peridotite massif belongs to the Aulus basin, just north of the North Pyrenean fault.

2 The place of ultramafic massifs in the evolution of the Pyrenean belt

The peridotite/serpentinite bodies are cropping out all along the North Pyrenean Zone (Figure 1) but are more abundant in the central-eastern segment of the belt. They occur either as large sedimentary clasts mixed with metasedimentary (often carbonated) breccias or form tectonic slices also involving deep crustal granulitic rocks (Lagabrielle et al., 2010). Early works on the Cretaceous evolution of the North Pyrenean Zone, considered these massifs as tectonic slices and explained their emplacement by a Cretaceous compressive event. Since the 80's, most authors converged toward a mid-Cretaceous (~110-85 Ma) extensional/transtensional event as the driver of exhumation of peridotites and granulites (Vielzeuf and Kornprobst, 1984; Clerc et al., 2015; Lagabrielle et al., 2016). A hyperextended Pyrenean rift formed between Iberia and France during the opening of Bay of Biscay (also known as "Golfe de Gascogne", separating Brittany and Iberia) related to the opening of the Atlantic ocean (Figure 3).

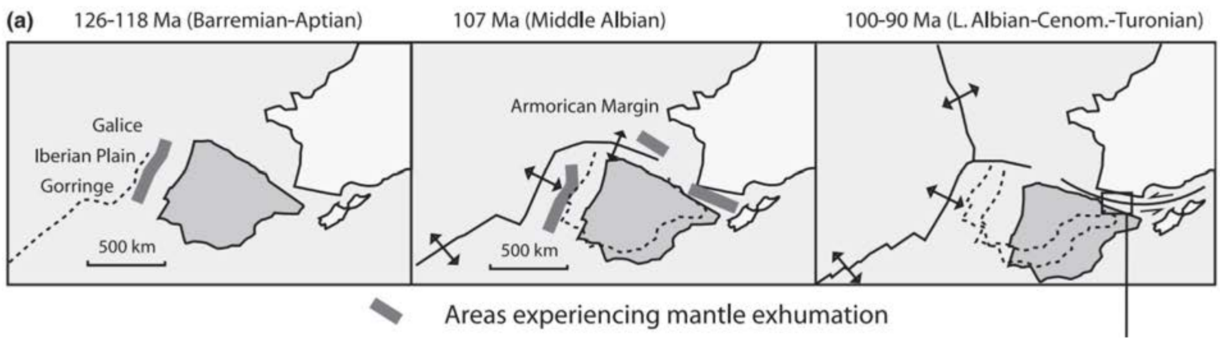


Figure 3: Areas of mantle exhumation related to the opening of the Bay of Biscay during the Lower Cretaceous (Lagabrielle and Bodinier, 2008).

This hypothesis was born from multi-disciplinary works combining: (i) the studies of Cretaceous breccia (and more generally reconstruction of Aptian to Senonian sedimentary paleo-environments); (ii) kinematics of Cretaceous deformation; (iii) geochronology and P-T estimation of Cretaceous (Albian to Cenomanian) metamorphism

2.1 The origin of breccias - examples from the Lherz peridotite massif

The Lherz massif belongs to the inverted Mesozoic Aulus basin made of metamorphosed Triassic to Cretaceous sedimentary units (Figures 4 and 5). One of the most striking features is the presence of breccias around and within the ultramafic massif with a matrix grading from purely ultramafic to purely carbonated. The specificity of Lherz breccias is the presence of ultramafic breccias and sandstones showing graded and cross bedding as well as slump structures. Several types of breccias can be identified in and around Lers (Lagabrielle and Bodinier, 2008): Type 1 breccias are monomictic and exclusively made of ultramafic clasts. They are found within the massif but close to the borders; Type 2 breccias located along the border of the massif are polymictic with contain isolated carbonate clasts; Type 3 breccias are isolated within the Lherz massif, probably filling fissures and contains ultramafic clasts cemented by an ultramafic sandstone matrix; Type 4 resembles famous ophicalcite, they are ultramafic breccias cut across by late carbonate veins. Finally, pure carbonate breccias containing marble clasts are found several tens to hundreds of metres outside the massif within the formation hosting the ultramafic body.

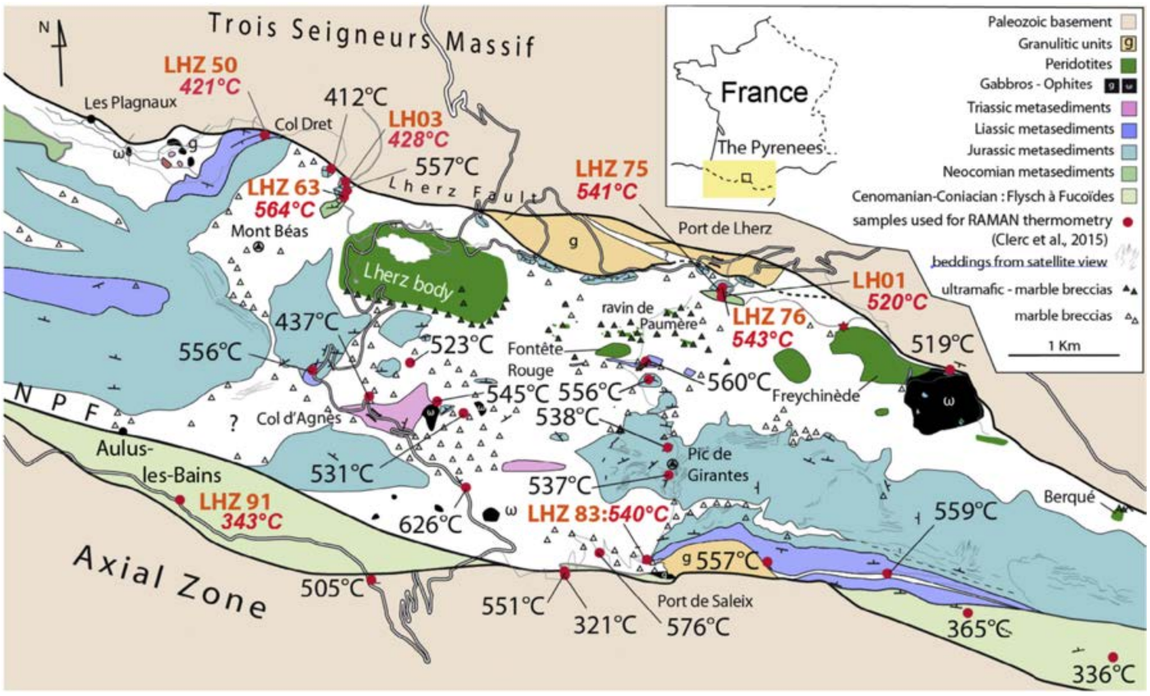


Figure 4. Geological map of the Aulus basin after Lagabrielle et al. (2016). Temperatures of metamorphism were estimated by Raman spectroscopy on carbonaceous material (see Clerc et al., 2015).

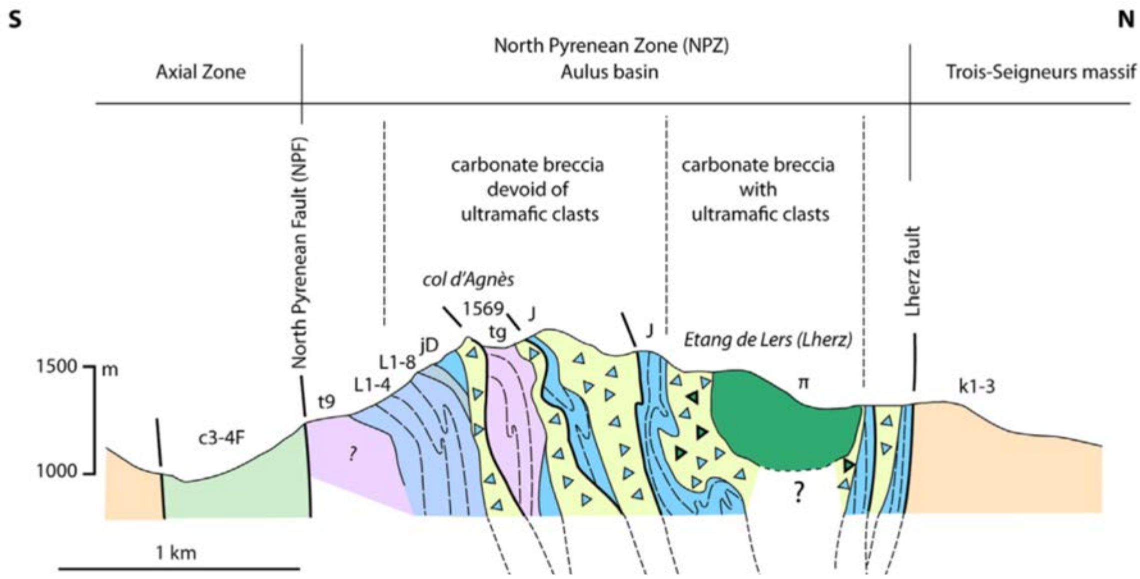


Figure 5. S-N cross section into the Aulus basin hosting the Lherz massif (Lagabrielle et al., 2016). Note that the ultramafic body is not rooted and surrounded by breccias.

The cataclasic aspect of some of these breccias have led some authors to propose that lherzolites were tectonically emplaced within Mesozoic series (see Debroas et al., 2013) while the hornfels texture of some surrounding metamorphic rocks has been interpreted as reflecting hot diapiric emplacement of mantle lherzolite into carbonates (see Vielzeuf and Kornprobst, 1984 for a discussion of different mechanisms and detailed references). However, the Lherz massif seems to form a large, unrooted clast within the Mesozoic units of the Aulus basins and the contact with surrounding breccias is often sedimentary and more rarely tectonic (Figures 4 and 5). That is mainly why a lot of authors now converge toward the fact that breccias (including lherzolitic clasts and olistoliths) were formed by (tectono-)sedimentary processes before the Late Cretaceous to Cenzoic inversion. In the most recent models (see Clerc et al., 2012 and Lagabrielle et al., 2016 for the Lherz example), it is proposed that cretaceous hyper-extension led to extreme thinning of the crust and tectonic/gravity sliding of the carbonated Mesozoic cover onto the uplifted mantle (the Mesozoic carbonates are underlain by soft Triassic-Liassic evaporites facilitating both gravity- and tectonic-driven sliding of the cover). Fragments of mylonitic lherzolite and plastically deformed marbles clasts support the major role of the lithospheric-scale detachment in the formation of breccias. Mixing of lherzolitic, mantle-derived material with upper crustal carbonated material, probably occurred along normal brittle fault scarps (Figures 6 and 7). Hydro-fractured breccias formed by circulation of hydrothermal fluids are also recognized in many places and are in agreement with the Cretaceous metamorphic evolution of the Pyrénées (see below).

While many progresses have been made recently on the understanding of the mantle-derived rocks and breccias in the North Pyrenean Zone, the debate on their origin is still active within the geological community. It is sure that several processes have led to the great diversity of breccias in the NPZ, especially when taking into account the effects of the Upper Cretaceous to Cenozoic inversion and the formation of salt diapirs.

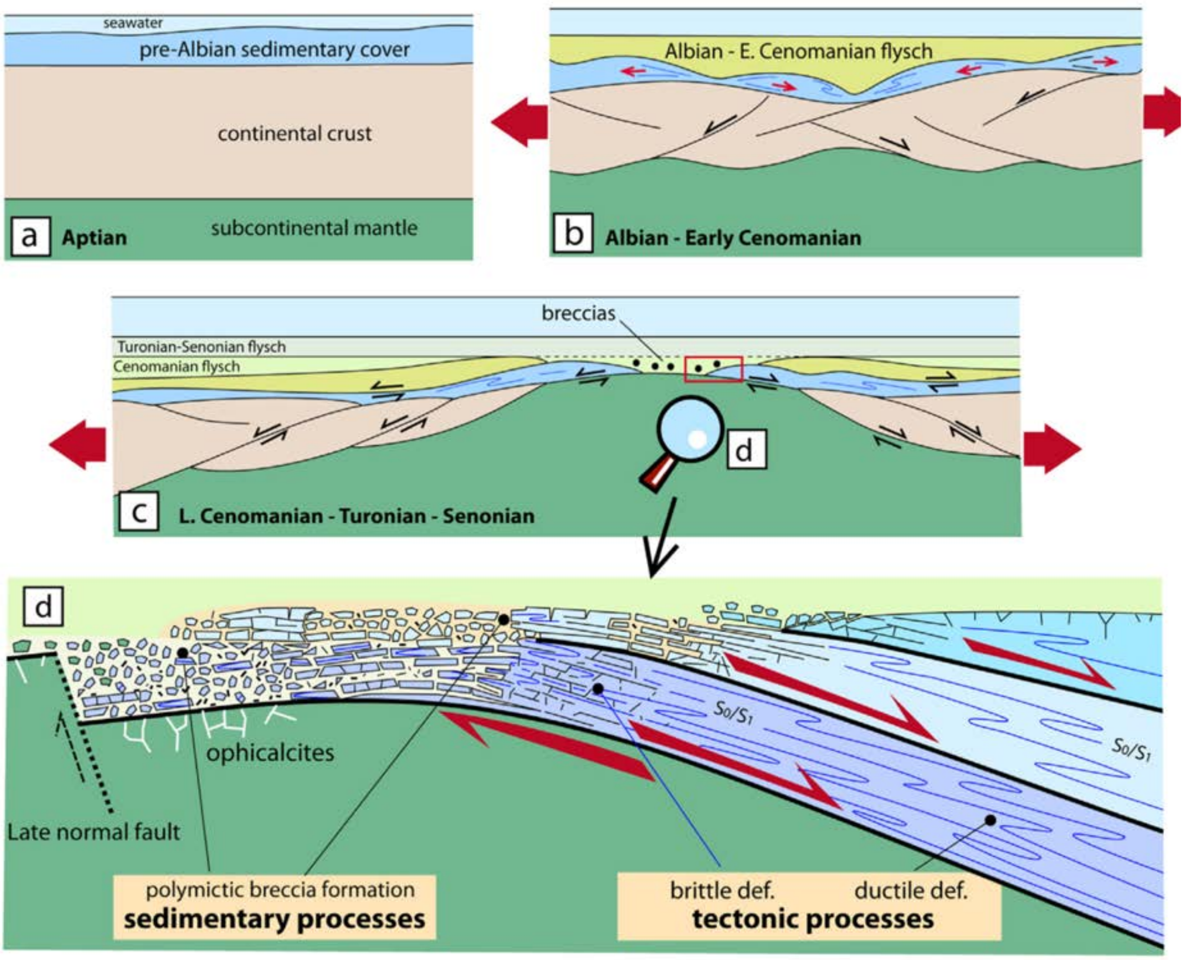


Figure 6. Conceptual geological model (Lagabrielle et al., 2016) showing the evolution of the North Pyrenean Zone during the Cretaceous rifting event. Note the submarine exhumation of mantle and the disaggregation of carbonate and mantle rocks to form polymictic breccias.

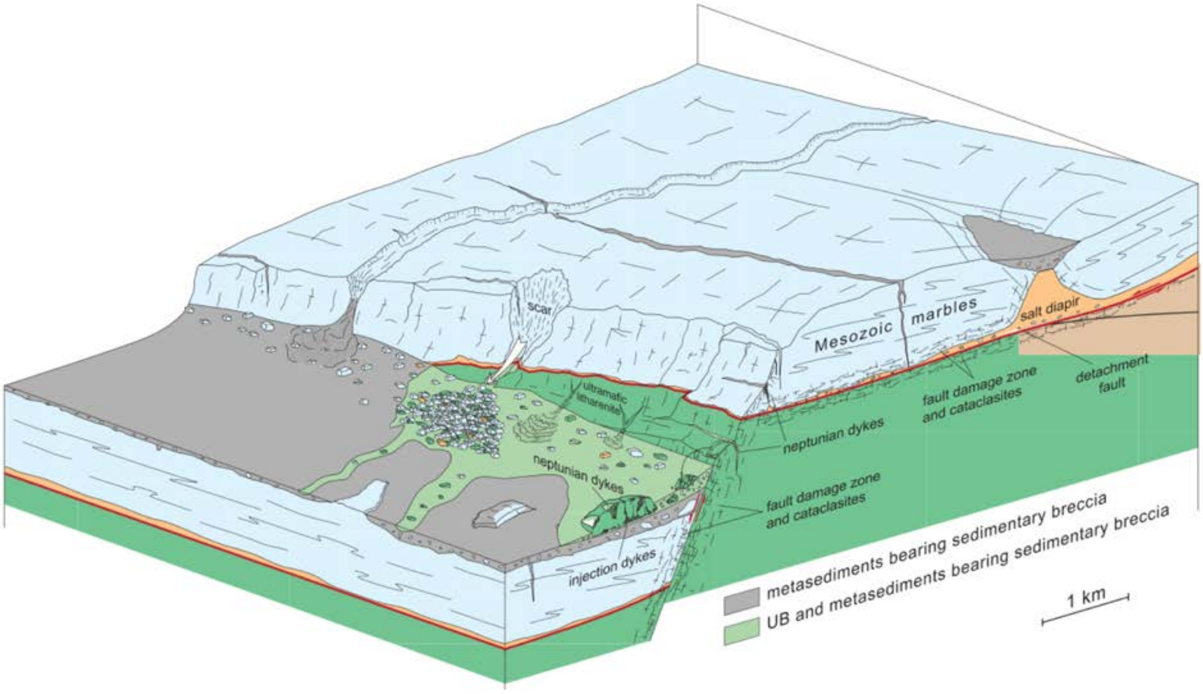


Figure 7. Reconstitution of the depositional environment for the Lherz breccias. Note that the Mesozoic carbonate cover (blue) is sliding on a detachment level (red) made of Triassic-Liassic evaporites (orange). Mantle is green, lower crust is light orange.

2.2 Cretaceous deformation and metamorphism

It is of course complicated to study Cretaceous kinematics in a belt whose finite deformation state is strongly influenced by post-cretaceous orogenic events and also by a late Variscan Carboniferous to Permian extension affecting Precambrian and Paleozoic rocks. Despite the challenge of determining the age of a deformation phase, an extensional origin of at least some of the Cretaceous structures in the North Pyrenean zone was proposed early in the 1960s (Mattauer, 1968) and confirmed later (Choukroune, 1972; de Saint Blanquat et al., 1986; Clerc et al., 2015). The recent research program on the Pyrenees led by BRGM (French geological survey) and conducted by several French Earth Sciences laboratories in a context where the understanding of continental margins has progressed rapidly has made it possible to associate the Cretaceous event in the Pyrénées with a process of hyper-extension. In the Lherz region and surrounding basement massifs, extensional shear zones observed in the lower to middle crustal levels of the Paleozoic North Pyrenean massifs share locally the same kinematics that the deformation recorded in metamorphosed Jurassic carbonates, meaning that at least a part of the extensive deformation is post-Jurassic. Ar-Ar and U-Pb dating of minerals within extensional shear zones or metasomatized areas in Paleozoic blocks or within stretched Mesozoic marbles yielded ages around 125-90 Ma (Boulvais et al., 2007; Clerc et al., 2015; Boutin et al., 2016; Aumar et al., 2022; Figure 8).

The North Pyrenean Zone includes an area called the Internal Metamorphic zone (close to the North Pyrenean Fault in the Lers region; Figure 1) where pre-Campanian rocks (pre- and syn-rift units) were affected by a HT-LP metamorphism dated between 110 and 85 Ma (see Clerc et al., 2015 for a review of ages). Temperature estimated by Raman spectroscopy on organic material preserved in Mesozoic sedimentary rocks yielded temperatures reaching 580°C in the Aulus basin around the Lherz massif (Figure 4). This HT-LP metamorphism results from uplift of isotherms during Cretaceous extension in the rift, a blanket effect of the Mesozoic sedimentary cover (acting as a thermal insulator) and probably advective heat transfers by hydrothermal fluids (Figure 9).

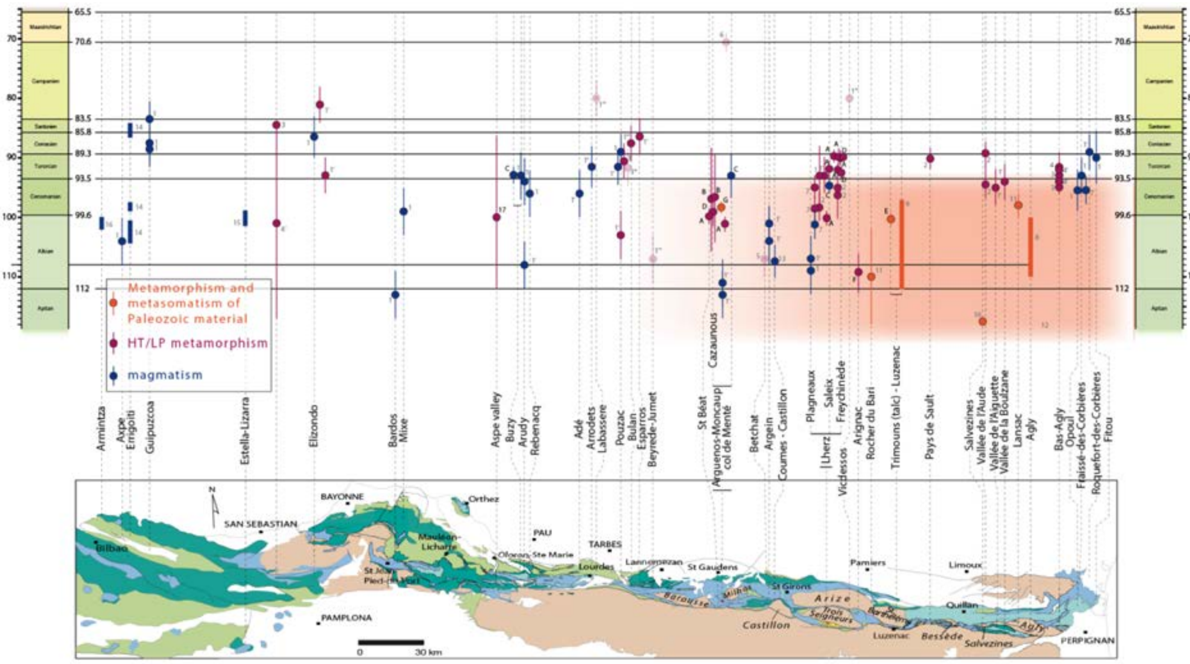


Figure 8. Compilation of radiometric ages dating Cretaceous magmatism (blue dots), metamorphism (red dots) and metasomatism (orange dots) (Clerc et al., 2015).

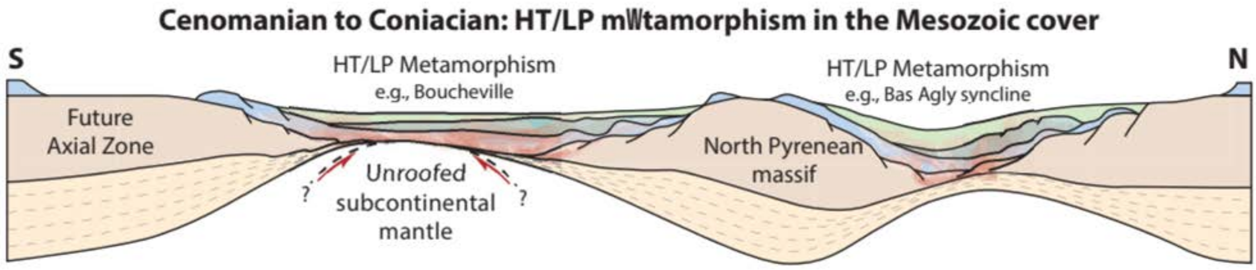


Figure 9. Conceptual model showing the cause of HT-LP metamorphism within Mesozoic rift basins in relation with the exhumation of the mantle (Clerc et al., 2015).

2.3 Cretaceous alkaline magmatism and crustal metasomatism

Mesozoic igneous rocks are scarce in the Pyrénées; this can be explained by the intra-continental nature of the belt characterized by the absence of oceanic crust and hence, ocean-continent subduction. Triassic and Jurassic mafic rocks (basalts and gabbros, often deeply altered) crop out locally and can be linked to the Central Atlantic Magmatic Province (CAMP). The formation of the Cretaceous Pyrenean rift is also marked by the presence of rare and small occurrences of alkaline magmatic rocks, located all along the North Pyrenean Zone with few occurrences in the Sub-Pyrenean domain (Montigny et al., 1986; Azambre et al., 1992). The suite includes alkali basalts, gabbros, olivine cumulates, lamprophyres, teschenites-theralites (undersaturated plagioclase-alkali feldspar-amphibole-clinopyroxene-analcime plutonic rocks), trachytes and nepheline syenites. Ages of emplacement for these magmatic rocks range from 110 to 85 Ma, they are therefore contemporary with the HT-LP metamorphism (see Clerc et al., 2015; Figure 9)..

Geochemical and isotopic signatures (Rossy et al., 1992) show that primitive magma originated by low-degree partial melting of a LREE-enriched mantle while evolved intermediate to felsic rocks were formed after fractional crystallization of mantle-derived magmas.

Albitites were also recognized in the Pyrénées but their origin is twofold. The first type is hydrothermal and formed after metasomatic replacement of Paleozoic granites, gneiss or micaschists. Some have been dated between 117 and 92 Ma (Boulvais et al., 2007; Poujol et al., 2010; Fallourd et al., 2013). Note that this metasomatic event is also responsible for the formation of the giant world-class Trimous Talc deposit hosted in carbonates and aluminous schists at Luzenac (about 35 km east of Lers)(Boutin et al., 2016). The second type is an igneous corundum-bearing albitite (with mega zircons) forming dykes in ultramafic bodies of the Western Pyrénées and emplaced around 100 Ma (Monchoux et al., 2006; Pin et al., 2006). The parental magma was formed by partial melting at very low degrees (<1%) of a hydrous and carbonated mantle peridotite (Pin et al., 2006).

3 The Lherz ultramafic body at “Étang de Lers”

The Lherz body belongs to numerous occurrences of ultramafic massifs grossly aligned in the North Pyrenean Zone (Figure 1) and forming kilometric to decametric scaled outcrops (see de Saint-Blanquat et al., 2016). It lies within the metamorphosed Mesozoic Aulus basin sandwiched between the Trois Seigneurs Paleozoic North Pyrenean massif to the North and North Pyrenean Fault to the South (Figure 4). The Lherz massif is the largest exposure of ultramafic rocks in the Pyrénées and is probably a very large (1.3x0.6 km) olistolith (Lagabrielle and Bodinier, 2008). Discovery and first descriptions of Pyrenean ultramafic rocks were made in the 18th century by De La Méthérie (who invented the term “Lherzolite”), it was then investigated by Alfred Lacroix, a famous French mineralogist and petrograph (see Lacroix, 1901, 1917) but the scientific interest exploded in the 60-90’s (Avé-Lallemant 1967; Monchoux et al., 1970; Conquéré and Fabriès, 1984; Bodinier et al., 1988, 1990; Downes et al., 1991). It was one of the key sites to study the petrological diversity of the mantle as preserved in orogenic peridotite massifs and to discuss the coexistence of fertile and depleted mantle rocks (see Le Roux et al., 2007 and references therein). It has also inspired the numerous lively debates about processes leading to lithological diversity of the mantle between partial melting, convective mingling and melt-rock reactions endmember models (see Le Roux 2008 and Le Roux et al., 2007 for further references).

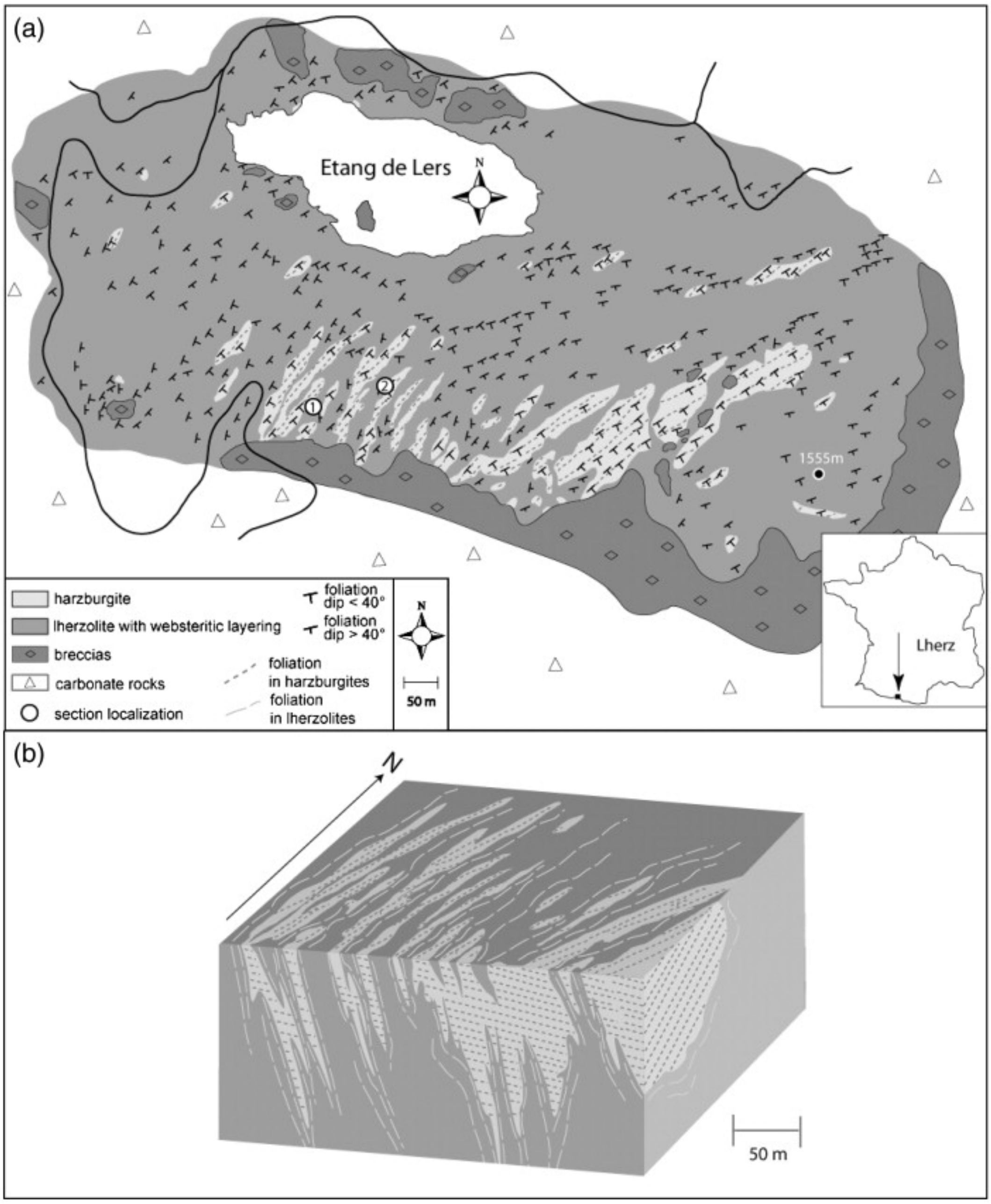


Figure 10. Detailed maps of the Lherz body (a) and bloc diagram (b) showing the structural relationships between harzburgites (white or light grey) and lherzolites (medium grey) published by Le Roux et al. (2007).

The Lherz body is dominated by lherzolites but detailed mapping of structures and lithologies (Conquéré 1978; Le Roux et al., 2007; Figure 10) revealed that lherzolites alternate with metric to decametric harburgitic stripes in the south and eastern portions of the massifs (Avé Lallemant 1967). The foliation within lherzolites is oblique to the foliation in harzburgites and seems to cut across the latter (Le Roux et al., 2008). Both lherzolites and harburgites are cut across by numerous small scale dykes of spinel (and more rarely garnet) websterite but also amphibole-pyroxenites that are generally parallel to planar contacts between harzburgites and lherzolites. Rare occurrences of hornblendites are also mapped in the southern part of the massif. The websterite dykes seems to have been equilibrated with tholeiitic basaltic magmas (Bodinier et al., 1987a) around 1.5 Ga ago (determined with Nd model ages; Le Roux et al., 2016) while amphibole pyroxenites and hornblendites formed during percolation of Cretaceous alkaline magmas (Bodinier et al., 1987b). Reisberg and Lorand (1995) obtained old Os model ages for the differentiation of the Pyrenean sub-continental lithospheric mantle, around 2.0-2.5 Ga. Ar-Ar dating on amphibole at Lers and Sm-Nd mineral isochrons on garnet and amphibole-bearing pyroxenites yielded Cretaceous ages (100-115 Ma and 105 Ma respectively; Henry et al., 1998). The Ar-Ar dates are most probably cooling ages as the closure of Ar diffusion in the amphibole is low (500-600°C) compared to temperature of igneous and mantle processes. But if the percolation of alkaline magmas occurred just before or during the uplift of mantle, the 100-115 Ma dates are probably close to igneous ages (this is also probably true for ages obtained with Sm-Nd mineral isochrons).

4 Program of the day: practical information and geological stops

The aims of this fieldtrip to the "Etang de Lers" are to observe and discuss the petrological diversity of a portion (1.3x0.6 km) of sub-continental lithospheric mantle and to discuss the mechanisms of its exhumation and emplacement into upper crustal levels.

Departure is scheduled at 8:30 am from Toulouse (meeting point: metro station "Université Paul Sabatier"). It takes about 2 hours to travel to Etang de Lers. The geological visit will start around 10.30 am and we will have a lunch break around 12.30 am (lunch box provided). From 1.30 pm we will resume the excursion and stop at 4 pm. We will arrive back in Toulouse around 6-6.30 pm, depending on traffic conditions. It will probably be possible to have a coffee after lunch at the Pub/restaurant located just above the Etang de Lers.

We will start on the road toward Aulus les Bains near the southern edge of the massif, south of the "Etang de Lers" (Figure 11). We will go down towards the pond and make observations all along the road at some suggested stops until the end of the outcrops near the pond. These suggested stops are indicated below (located on Figure 11) and you will be guided there. Note that observation of harzburgite is optional because they are cropping out off the road and one needs to follow a small hiking track going up to 1450m to reach them. However, their location is indicated on the maps and if you want to go and see/sample them, you can go there on your own without the guides.

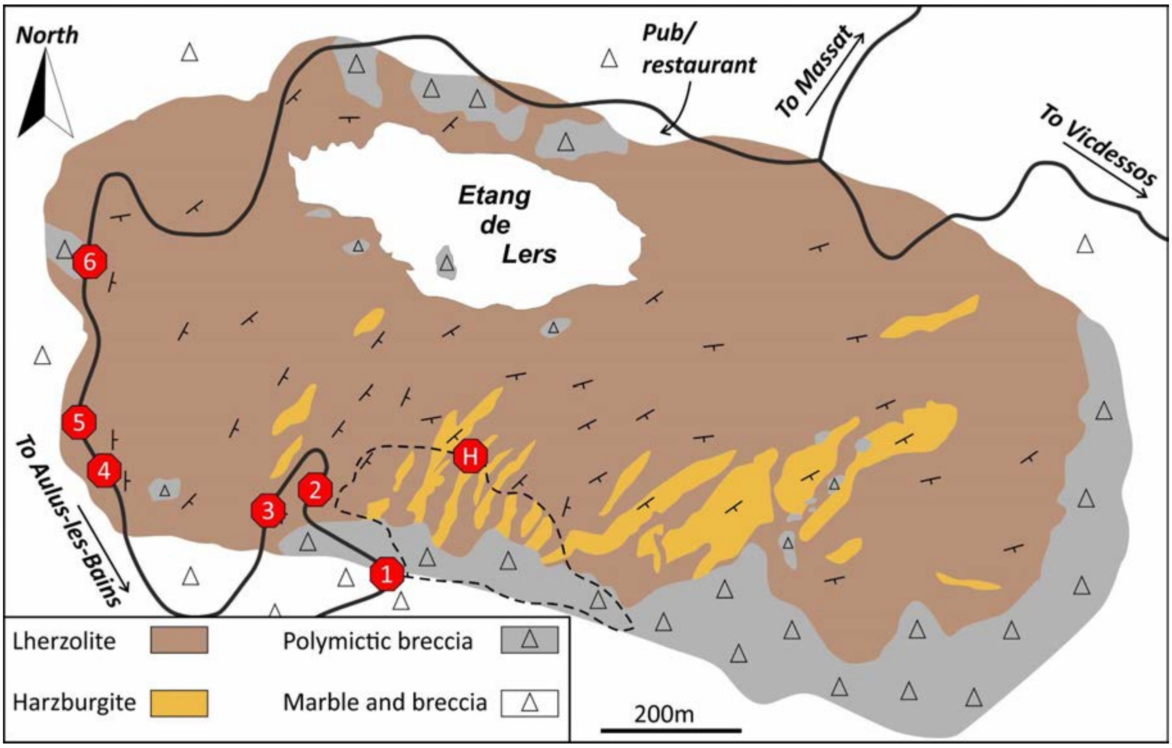


Figure 11. Geological map of the Lherz body (modified after Le Roux et al., 2007) showing the location of proposed stops.

Stop 1 ultramafic and carbonate breccias
Carbonate breccias - UTM X-Y (Zone 31 N): 367172 E - 4740164 N. Alt:1384m
Polymictic breccias - UTM X-Y (Zone 31 N): 367214 E - 4740236 N. Alt 1384m

The Lherz massif is surrounded and hosted by breccias. We will see the transition from monomictic marble breccias outside the massif, polymictic carbonate-ultramafic breccia at the contact and monomictic ultramafic breccia within the southern edge of the massif. The gradual transition between different types of breccias and the geometry of the contact are taken as evidenced for a sedimentary contact between the Lherz massif and its carbonate host. The coarse clastic masses formed by disaggregation of carbonates and peridotites-serpentines along subaquatic fault scarps and deposited within large debris flows on the footwall of normal faults (Fig XX, Lagabrielle and Bodinier, 2008: Clerc et al., 2012). Note that the origin and significance of these breccias is debated (see Debroas et al., 2013). Temperatures measured by Raman spectroscopy on organic matter in marbles were estimated around 450-560°C near Lers and Ar-Ar ages on muscovite and amphibole yielded 90-100 Ma (Cenomian-Turonian) in the Aulus basin.

Stop H (optional) - Harzburgite-lherzolite relationships
UTM X-Y (Zone 31 N): 367337 E - 4740380 N. Alt:1425m

This outcrop is not accessible to everyone as one has to follow a small footpath up to about 1450m (70m positive ascent); this is why it is optional. It exposes the relationships between small (several metres wide) lenses of harburgites (often greyish, with no or rare greenish diopside) and lherzolite (orange with abundant green diopside) as investigated by Veronique Le Roux (Le Roux et al., 2007; Le Roux, 2008).

Stop 2 - Massive lherzolite + serpentine-carbonate filled fractures
UTM X-Y (Zone 31 N): 367123 E - 4740310 N. Alt:1384m

The roadside outcrop shows the typical lherzolite, with discrete diopside and spinel enrichments but also faults, fractures or veins containing serpentine and carbonates.

Stop 3: Garnet websterite dyke ("Ariégite")
UTM X-Y (Zone 31 N): 367067 E - 4740302 N. Alt:1380m

The so-called Ariégite forms a sub-horizontal, about 20 cm-thick dyke of dark pyroxenites containing pinkish garnets (more easily observed with a hand lens). Subsolidus growth of garnet occurred around 910°C and 1.1 GPa (Conquéré and Fabriès, 1984). According to the distribution of trace-elements in pyroxenes, the amphibole-free pyroxenites are segregate formed during the percolation of a tholeiitic basaltic melt similar those those having crystallised Triassic dolerites (Bodinier et al., 1987a).

Stop 4: Hornblendite veins
UTM X-Y (Zone 31 N): 367833 E - 4740349 N. Alt:1377m

Hornblendites and amphibole-pyroxenites occur as thin dykes (up to 3 cm thick) in the lherzolite and more rarely as lenses within pyroxenites. Their distinctive feature is the presence of coarse black kaersutite, sometimes associated with clinopyroxene or phlogopite. Bodinier et al. (1987b and 1990) suggest they formed during percolation of an alkaline basaltic melt, probably during Cretaceous. Ar-Ar dating on amphibole and Sm-Nd mineral isochron on pyroxenites yielded ages around 100-115 Ma (Henry et al., 1998).

Stop 5: Websterite veins

UTM X-Y (Zone 31 N): 367799 E - 4740422 N. Alt:1373m

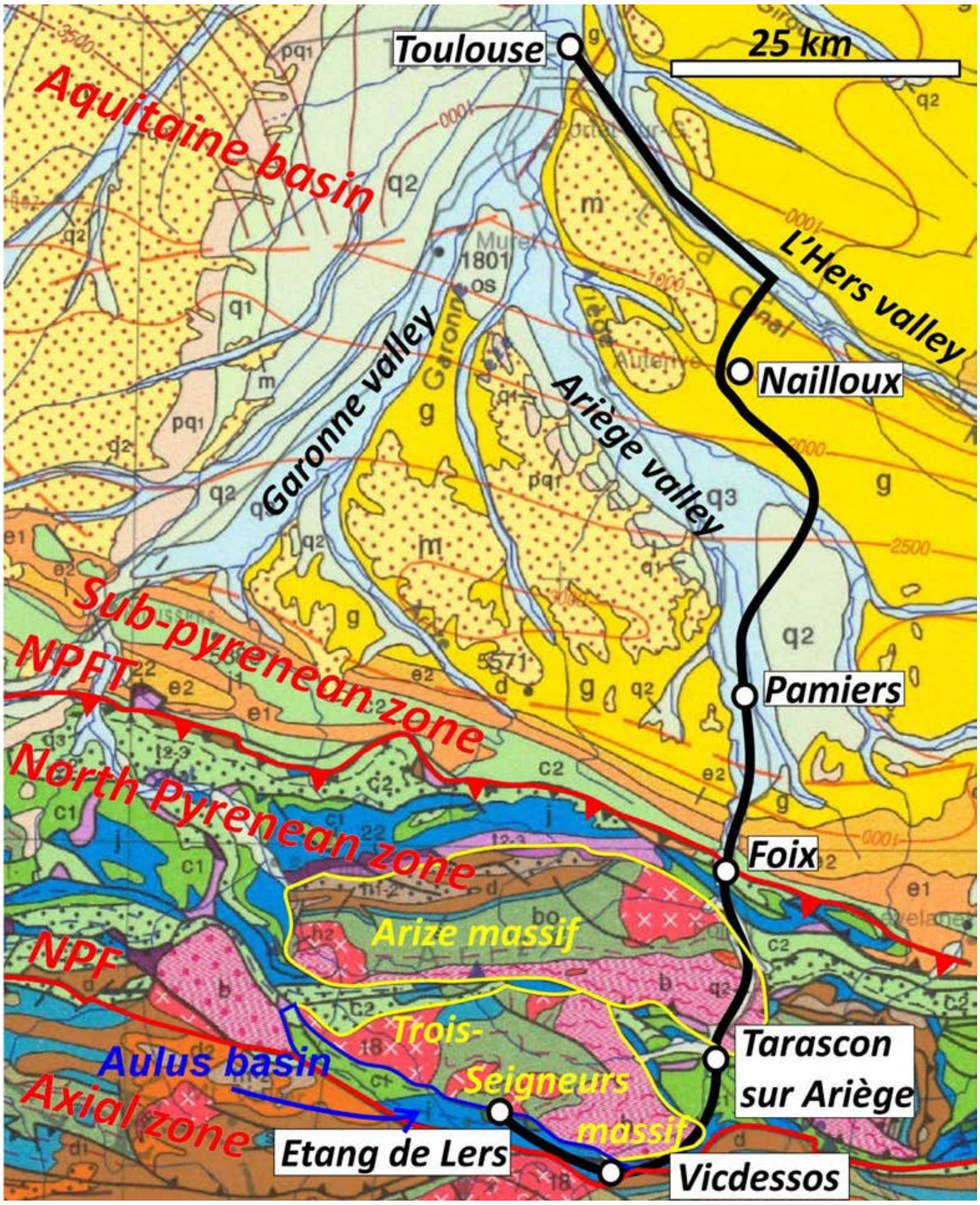
One of the most spectacular features of the Lherz massif is the segregation of pyroxenes forming thin (generally < 5 cm) websterite veins. They represent reactive percolation of tholeiitic basaltic melt at high melt/rock ratios (Bodinier et al., 1987a). Some of the veins are tightly folded and attest to strong deformation of the mantle, probably during Cretaceous exhumation.

Stop 6: Ophicalcite-like breccias
UTM X-Y (Zone 31 N): 366816 E - 4740655 N. Alt:1367m

This outcrop shows a breccia made of angular lherzolite clasts cemented by carbonate veins resembling alpine ophicalcites. The jigsaw fit between the clasts seems to suggested that the lherzolite was brecciated by a hydrothermal fluid that precipitated carbonates but Lagabrielle and Bodinier (2008) propose that this is a former monomictic lherzolite breccia cut across by numerous carbonate veins. Note that hydraulic breccias are described near Lherz (at the "Col d'Agnes"), combination of metamorphism, high heat flow, high sedimentation rates but also migration of Triassic salt diapirs creates a favorable context for hydrothermal circulations.

Geology along the road from Toulouse to Etang de Lers

From Toulouse to Foix (about 1h of travel), we will stay in the Aquitaine basin. The first 25 km will follow the l'Hers river, then we will climb small hills made of Oligocene (g) molassic deposits before reaching the Ariège valley around Pamiers. Just north of Foix, about 10 km south of Pamiers, you will cross the first reliefs of the Pyrénées. At this point we are in the Sub-Pyrenean zone (also called locally the "Petites Pyrénées" or "Plantaurel") where Late Cretaceous to Eocene sedimentary sequences were folded above blind thrusts propagating into the Southern edge of the Aquitaine basin. At Foix, (have a look at the Castles of the Counts of Foix, on your right just after the 2 km long tunnel) we will cross the North Pyrenean Frontal Thrust (NPFT) and enter into the North Pyrenean zone. The latter consists of Paleozoic basement massifs (the so-called North Pyrenean massifs: Arize, Trois-Seigneurs…) surrounded by Triassic to Lower Cretaceous inverted and squeezed sedimentary basins (Aulus basin, Tarascon basin…). In Tarascon you can observe the high cliffs made of Aptian (Lower Cretaceous) limestone. After Vicdessos, near "Port-de-Lers" looking north, you will see the "Pic des Trois Seigneurs" (made of Lower Paleozoic sediments, and carboniferous granites), culminating at 2200m. To the south, you look towards the Axial zone which holds the highest peaks of the belt, culminating around 3000m. The road from Vicdessos to the Etang de Lers follows the contact between the Aulus basin (made of metamorphosed Mesozoic limestones and various types of breccias associated with ultrabasic massifs) and the Paleozoic Trois Seigneurs massifs (Paleozoic metasediments, granites and migmatites).



1:1,000,000 geological map of France cropped around the road from Toulouse to Lers.

(b-pink) Paleozoic migmatites and orthogneiss;
(bo-pale green) Neoproterozoic to Ordovician (meta-) sediments,
(s-green-blue) Silurian (meta-) sediments,
(d-brown) Devonian (meta-) sediments;
(18-red with white crosses) carboniferous granites;
(h) Carboniferous sediments;
(t-violet) Triassic sediments;
(j-blue) Jurassic sediments;
(c1-green) Lower Cretaceous sediments;
(c2-light green) Upper Cretaceous sediments;
(e1 and 2 - orange) Paleocene-Eocene sediments;
(g) Oligocene sediments;
(m) Miocene sediments;
(p) Pliocene sediments;
(q) Quaternary deposits.
NPF: North Pyrenean Fault;
NPFT: North Pyrenean Frontal Thrust.

Suggested and cited references

Avé Lallemant, H.G., 1967. Structural and petrographic analysis of an "alpine-type" peridotite. The lherzolite of French Pyrenees. Leidse Geologische Mededelingen. 42, 1-57.

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

Beaumont, C., Muñoz, J.A., Hamilton, J., Fullsack, P., 2000. Factors controlling the Alpine evolution of the central Pyrenees inferred from a comparison of observations and geodynamical models. J. Geophys. Res. Solid Earth 105, 8121–8145.

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

Bodinier, J.-L., Guiraud, M., Fabriès, J., Dostal, J., Dupuy, C., 1987b. Petrogenesis of layered pyroxenites from the Lherz, Freychinède and Prades ultramafic bodies (Ariège, French Pyrenees). Geochimica et Cosmochimica Acta. 51, 279-290.

Bodinier, J.-L., Dupuy, C., Dostal, J., 1988. Geochemistry and petrogenesis of Eastern Pyrenean peridotites. Geochimica et Cosmochimica Acta. 52, 2893-2907.

Bodinier, J.-L., Vasseur, G., Vernières, J., Dupuy,C., Fabriès, J., 1990. Mechanism of mantle metasomatism: Geochemical evidence from the Lherz orogenic peridotite. Journal of Petrology. 31, 597-628.

Boulvais, P., Ruffet, G., Cornichet, J., Mermet, M., 2007. Cretaceous albitization and dequartzification of Hercynian peraluminous granite in the Salvezines Massif (French Pyrénées). Lithos 93, 89-106.

Boutin, A., de Saint Blanquat, M., Poujol, M., Boulvais, P., de Parseval, P., Rouleau, C., Robert, J.-F., 2016. Succession of Permian and Mesozoic metasomatic events in the eastern Pyrenees with emphasis on the Trimouns talc–chlorite deposit. Int. J. Earth Sci. 105, 747–770.

Choukroune, P., 1972. Relations entre tectonique et métamorphisme dans les terrains secondaires de la zone nord-pyrénéenne centrale et orientale. Bulletin de la Société Géologique de France 1972; S7-XIV (1-5), 3-11.

Clerc, C., Lagabrielle, Y., Neumaier, M., Reynaud, J.-Y., de Saint Blanquat, M., 2012. Exhumation of subcontinental mantle rocks: evidence from ultramafic-bearing clastic deposits nearby the Lherz peridotite body, French Pyrenees. Bull. Soc. Geol. Fr. 183, 443–459.

Clerc, C., Lahfid, A., Monie, P., Lagabrielle, Y., Chopin, C., Poujol, M., Boulvais, P., Ringenbach, J.-C., Masini, E., de St Blanquat, M., 2015. High-temperature metamorphism during extreme thinning of the continental crust: a reappraisal of the North Pyrenean passive paleomargin. Solid Earth 6, 643–668. doi:10.5194/se-6-643- 2015

Conquéré, F., 1978. Pétrologie des complexes ultramafiques de lherzolite à spinelle de l'Ariège (France). Ph.D. thesis, Univ. Paris.

Conquéré, F., Fabriès, J., 1984. Chemical disequilibrium and its thermal significance in spinel peridotites from the Lherz and Freychinède ultramafic bodies (Ariège, French Pyrenees). in: J. Kornprobst (Eds), Kimberlites II. The mantle and Crust-Mantle Relationships. Elsevier, Amsterdam, 319-331.

de Saint-Blanquat, M., Brunel, M., Mattauer, M. 1986. Les zones de cisaillement du massif Nord-pyrénéen du Saint-Berthélémy témoins probables de l'extension crustale d'âge crétacé. Comptes rendus de l'Académie des sciences. Série 2, Mécanique, Physique, Chimie, Sciences de l'univers, Sciences de la Terre, 303(14), 1339-1344.

de Saint Blanquat, M., Bajolet, F., Grand'Homme, A., Proietti, A., Zanti, M., Boutin, A., ... & Labaume, P. 2016. Cretaceous mantle exhumation in the central Pyrenees: new constraints from the peridotites in eastern Ariège (North Pyrenean zone, France). Comptes Rendus Géoscience, 348(3-4), 268-278.

Debroas, E. J., Canérot, J., Bilotte, M. 2013. Comment on:"Exhumation of subcontinental mantle rocks: evidence from ultramafic-bearing clastic deposits nearby the Lherz peridotite body, French Pyrenees" by C. Clerc et al.(Bull. Soc. géol. Fr., 2012, 183, 5, 443–459). Bulletin de la Société géologique de France, 184(6), 621-629.

Downes, H., Bodinier, J.-L., Thirlwall, M.F., Lorand, J.-P., Fabriès, J., 1991. REE and Sr-Nd isotopic geochemistry of Eastern Pyrenean peridotite massifs: Sub-continental lithospheric mantle modified by continental magmatism. Journal of Petrology. 97-115.

Fallourd, S., Poujol, M., Boulvais, P., Paquette, J.-L., de St Blanquat, M., Remy, P., 2014. In situ LA-ICP-MS U-Pb titanite dating of Na-Ca metasomatism in orogenic belts: the North Pyrenean example. Int. J. Earth Sci. 103, 667–682.

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.

Lagabrielle, Y., Bodinier, J.-L., 2008. Submarine reworking of exhumed subcontinental mantle rocks; field evidence from the Lherz peridotites, French Pyrenees. Terra Nova 20, 11– 21.

Lagabrielle, Y., Labaume, P., de Saint 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, TC4012.

Lagabrielle, Y., Clerc, C., Vauchez, A., Lahfid, A., Labaume, P., Azambre, B., Fourcade, S., Dautria, J.-M., 2016. Very high geothermal gradient during mantle exhumation recorded in mylonitic marbles and carbonate breccias from a Mesozoic Pyrenean palaeomargin (Lherz area, North Pyrenean Zone, France). Comptes Rendus Geosci., From rifting to mountain building: the Pyrenean Belt 348, 290–300.

Lacroix, A. 1901. Sur un nouveau groupe de roches très basiques. CR Acad. Sci., Paris, 82, 358-361.

Lacroix, A., Les péridotites des Pyrénées et les autres roches intrusives non feldspathiques qui les accompagnent, C.R. Académie des Sciences, Paris, 1917.

Le Roux, V., Bodinier, J.-L., Tommasi, A., Alard, O., Dautria, J.-M., Vauchez, A., Riches, A.J.V., 2007. The Lherz spinel lherzolite: refertilized rather than pristine mantle. Earth and Planetary Science Letters. 259, 599-612.

Le Roux, V., Tommasi, A., Vauchez, A., 2008. Feedback between melt percolation and deformation in an exhumed lithosphere-asthenosphereboundary. Earth and Planetary Science Letters. 274, 401-413.

Le Roux, V., Nielsen, S. G., Sun, C., Yao, L. 2016. Dating layered websterite formation in the lithospheric mantle. Earth and Planetary Science Letters, 454, 103-112.

Mattauer, M., 1968. Les traits structuraux essentiels de la Chaîne des Pyrenées. Rev. géogr. Phys. Géol. dyn., t. X, n° 1, p. 3 11

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

Monchoux, P., Fontan, F., De Parseval, P., Martin, R. F., Wang, R. C. 2006. Igneous albitite dikes in orogenic lherzolites, western Pyrénées, France: a possible source for corundum and alkali feldspar xenocrysts in basaltic terranes. I. Mineralogical associations. The Canadian Mineralogist, 44(4), 817-842.

Montigny, R., Azambre, B., Rossy, M., Thuizat, R., 1986. K-Ar study of Cretaceaous magmatism and metamorphism of the Pyrenees: age and length of rotation of the Iberian Peninsula. Tectonophysics. 129, 257-273.

Mouthereau, F., Filleaudeau, P.-Y., Vacherat, A., Pik, R., Lacombe, O., Fellin, M.G., Castelltort, S., Christophoul, F., Masini, E., 2014. Placing limits to shortening evolution in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe convergence. Tectonics 33, 2014TC003663.

Pin, C., Monchoux, P., Paquette, J. L., Azambre, B., Wang, R. C., Martin, R. F. 2006. Igneous albitite dikes in orogenic lherzolites, western Pyrénées, France: a possible source for corundum and alkali feldspar xenocrysts in basaltic terranes. II. Geochemical and petrogenetic considerations. The Canadian Mineralogist, 44(4), 843-856.

Poujol, M., Boulvais, P., Kosler, J., 2010. Regional-scale Cretaceous albitization in the Pyrenees: evidence from in situ U–Th–Pb dating of monazite, titanite and zircon. J. Geol. Soc. 167, 751–767.

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

Rossy, M., Azambre, B., Albarède, F., 1992. REE and Sr/1bNd isotope geochemistry of the alkaline magmatism from the Cretaceous North Pyrenean Rift Zone (France-Spain). Chem. Geol. 97, 33–46.

Vielzeuf, D., Kornprobst, J., 1984. Crustal splitting and the emplacement of Pyrenean lherzolites and granulites. Earth and Planetary Science Letters. 67, 87-96.