Classic localities explained:
The Eastern French Pyrenees –
from Mountain Belt to Foreland Basin

Dorothy Satterfield,
Hugh Rollinson
and Roger Suthren

Environmental Science, University of Derby,
Kedleston Road, Derby, UK. DE22 1GB
d.satterfield@derby.ac.uk

Abstract

The Pyrenees are a young mountain belt formed as part of the larger Alpine collision zone. This excursion explores the development of the Pyrenean Mountain Belt in southern France, from its early extensional phase in the mid-Cretaceous and subsequent collisional phase, through its uplift and erosion in the Late Cretaceous and again in the Eocene, which led to the development of the Aquitaine-Languedoc foreland basin. One of the complexities of the Pyrenean Belt is that thrusting, uplift and erosion during the Pyrenean orogeny exposed older Variscan basement rocks in the central core of the mountains, rocks which were metamorphosed during an earlier event in the late Carboniferous. Thus, this orogenic belt also tells the story of an earlier collision between Laurussia in the north and Gondwana in the south at ca 300 Ma, prior to the onset of the Pyrenean events at ca. 100 Ma. Here we seek to unravel these two separate orogenic stories.

Introduction - the geological evolution of the Pyrenees

The Pyrenees are a mountain range within the larger Alpine continental collision zone. They form an almost linear geographical feature, more than 400 km long, stretching from the Atlantic Ocean in the west to the Mediterranean in the east and make a natural topographic border (Figure 1) between Spain and France. The Pyrenees formed as a result of the anticlockwise rotation of the southern Iberian plate into the southwest portion of the European plate. Northward subduction of oceanic lithosphere was followed by partial subduction of Iberian continental lithosphere. This rotation occurred during the opening of the Bay of Biscay during the Cretaceous and continued until the early Miocene. The suture between the two plates is now represented by the North Pyrenean Fault (Figure 2).

Figure 1. View north across the Palaeozoic metamorphic basement of the Agly Massif to the prominent folded east-west Mesozoic limestone ridges in the North Pyrenean Zone.

For many years the geometry of the Pyrenean collision was poorly understood, and this was only clarified in the late 1980's with the results of the ECORS deep seismic profile which shows northward dipping reflectors beneath the central Pyrenees, indicating that the southern Iberian plate was thrust beneath the over-riding European plate. After this problem had been solved, research into the major structure of the Pyrenees contracted for several decades. Now, however, new models of convergence have been developed which show that prior to the Pyrenean collision there was a period of extension and extreme crustal attenuation. This extension ultimately led to the exhumation of mantle peridotites during the late Cretaceous, and it is a recent understanding of these processes which has helped to clarify the early tectonic setting of the Pyrenean mountain belt.

The geological evolution of the Pyrenees is complex. Although the main geological activity took place during the Pyrenean-Alpine mountain building event (starting in the Cretaceous), many of the rocks involved are much older and were themselves deformed in an earlier mountain building event: the Variscan or Hercynian orogeny. Thus, in places it is possible to see two superimposed orogenic events. The Variscan events relate to closure of the Rheic Ocean and the convergence of the continents Laurussia in the north and Gondwana in the south. This major event throughout Europe also included the most southerly part of Britain (Cornwall, South Wales). These events occurred in the late Carboniferous (320-300 Ma). In contrast, the Pyrenean events took place from the Late Cretaceous to the Oligocene (83 to 28 Ma).

The region makes an excellent venue for a final-year undergraduate ‘capstone’ field trip, integrating studies of the evolution of the mountain belt and its associated foreland basin. This field trip is shared by modules in Crustal Evolution and Basin Analysis at the University of Derby. The soils of the basin and the lower altitude parts of the mountain belt are the basis of the Languedoc-Roussillon wine region, one of the world’s largest contiguous vineyards.

The Major Geological Structure of the Pyrenees

Structurally, the Pyrenees may be subdivided into five zones (Table 1 and Figure 2). The two foreland basins, the Aquitaine-Languedoc basin in France and the Ebro basin in Spain comprise a basement of older Variscan rocks overlain by a late Mesozoic to Paleogene sedimentary fill. In France the Variscan basement rocks are exposed north of the foreland basin in the Montagne Noire, the southernmost extension of the Massif Central.

In the sections below we briefly describe each of the major zones of the Pyrenean Mountain Belt as seen in southern France. Then we describe localities where the major features of each zone can be examined.

NORTH	*Unconformity with Variscan basement* (Montagne Noire)
European plate	Aquitaine Foreland basin and its eastward extension the Languedoc basin (France); includes fold-thrust *Sub-Pyrenean Zone* in south
	North Pyrenean frontal thrust
	North Pyrenean zone (France)
	North Pyrenean Fault – suture?
	Axial Zone (France, Spain and Andorra)
	Major thrust
Iberian Plate	South Pyrenean Thrust Zone (Spain)
	South Pyrenean frontal thrust
	Ebro foreland basin (Spain).
SOUTH	*Unconformity with Variscan basement*

Table 1. The major structural zones of the Eastern Pyrenees

The Axial Zone is structurally part of the southern Iberian plate. It is almost exclusively made up of older rocks of the Variscan basement. These include Upper Proterozoic to Carboniferous sediments deformed by south-verging thrusts and folds and a series of E-W elongate metamorphic gneiss domes (known locally as massifs) which expose high grade rocks in their cores. The northern boundary of the axial zone is the North Pyrenean Fault, which can be traced for 300 km and which is interpreted by some authors as the suture between the Iberian and European plates.

Many of the massifs are highly metamorphosed. For example sillimanite-bearing pelites from the Canigou Massif record metamorphic conditions of 725 +/- 25 ^{o}C and 4.5 +/- 0.5 kbar, implying an average peak geothermal gradient of 45-50^{o}C km^{-1}, indicative of high temperature-low pressure Variscan metamorphism. Under these conditions, pelite melting led to the formation of migmatites in the middle crust and anatectic granites in the upper crust, where they are associated with metamorphosed lower Palaeozoic sediments. The deeper crustal levels are exposed towards the east. U-Pb zircon geochronology indicates that metamorphism and partial melting took place between ca. 320-300 Ma.

A major high-elevation Miocene erosion surface identified in many localities in the Axial Zone indicates that uplift of this region stabilized in the Miocene. Thermochronology in the western Pyrenees indicates that this took place between 30-20 Ma (Oligocene to early Miocene). This was followed by a period of quiescence and then another period of post-orogenic uplift between 9-8 Ma (late Miocene).

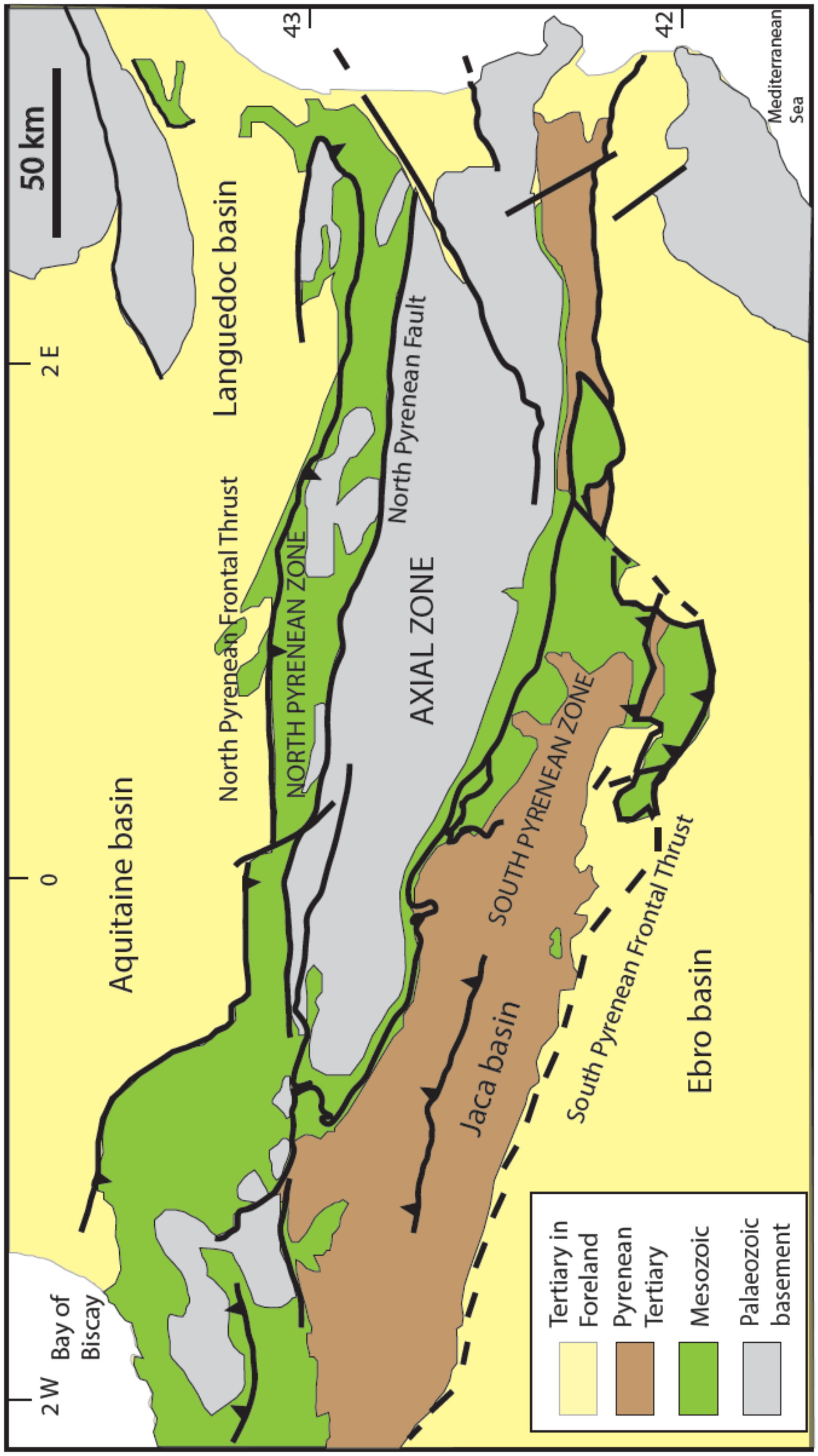

Figure 2. Structural map of the Pyrenees showing the principal zones of the mountain belt.

The North Pyrenean Zone is a narrow zone, located between the North Pyrenean Fault and the North Pyrenean Frontal Thrust (Figure 2), made up of a series of northward verging thrust slices. These include gneisses and migmatites and both Palaeozoic sedimentary rocks (some metamorphosed) and Mesozoic sedimentary rocks. Typically, crystalline rocks form gneiss domes or massifs between which are synclinal structures containing Triassic to Cretaceous sediments, locally metamorphosed. Thus, this part of the mountain belt contains a record of both Variscan events and Pyrenean events.

Major up-thrust blocks include the Trois-Seigneurs Massif, the Arize Massif, the Saint-Barthélémy Massif and in the east the Agly and Mouthoumet Massifs, discussed further below (see Figure 4). Most are cored with gneisses and flanked with metasediments, and record Variscan metamorphism. Typically the crystalline core and sedimentary rocks are interpreted as a basement-cover relationship. Mesozoic sedimentary rocks are preserved in major detached synclinal structures, the detachment facilitated by the presence of ductile gypsum-bearing Upper Triassic (Keuper) marls.

At its southern boundary is a small area of extreme metamorphism, known as the North Pyrenean Metamorphic Zone. This records the earliest stages of extension and continent separation at the commencement of the Pyrenean event in the mid-Cretaceous, through the exposure of mantle peridotites. These are associated with marbles, derived from Mesozoic limestones, which record very high metamorphic temperatures thought to be related to high mantle heat flow during extension. Evidence of submarine exhumation of the mantle peridotites comes from the presence of sedimentary peridotite breccias, limestone breccias (now marble) and polymict limestone-peridotite breccias and conglomerates. The juxtaposition of mantle peridotites and shallow marine limestones is thought to be due to extreme crustal attenuation in which the lower crust was thinned and in places removed.

Structural studies indicate that by the mid-Cretaceous this area had developed pull-apart basins indicating trans-tensional movement in the North Pyrenean Zone. However, the main shortening occurred in Eocene-Oligocene times (50-30 Ma). Fission track ages from zircons suggest that the North Pyrenean Zone was uplifted in the Cretaceous.

The foreland may be divided into two parts - the Variscan basement and the overlying Cretaceous to Paleogene sedimentary basins.

The underlying basement is exposed to the north in the Montagne Noire and its eastward continuation, the Cévennes. This is a range of hills >1200 m high, cored by granites and high-grade metamorphic rocks. To the north and south there are large-scale thrust nappe structures of sedimentary rocks of late Precambrian to Carboniferous age. These include Cambrian shallow-marine carbonates and clastics, Ordovician deep-marine mudstones and sandstones, Devonian pelagic and shelf carbonates, and detrital and pelagic deep marine Carboniferous sediments. The main Variscan metamorphism and deformation occurred in Carboniferous times 320-300 Ma ago. Post-tectonic, late Carboniferous (Stephanian) to Permian sediments lie unconformably on earlier, deformed sedimentary rocks. These sediments were deposited in extensional fault basins formed during post-orogenic collapse.

The Aquitaine-Languedoc Basin lies between the front of a fold-thrust mountain chain, the Pyrenees and the adjacent foreland, and can be termed a foreland basin. There is generally a sharp contact, either an angular unconformity or a steep fault, between the Montagne Noire rocks and the much younger (Late Cretaceous to Paleogene) Languedoc Basin sediments to the south. The history of basin development is intimately linked to the formation of the Pyrenees. The basin has a complex Campanian to Paleocene fill of both marine and continental origin. Deposition was controlled by palaeogeographic changes associated with the converging Western European and Iberian plates. The Languedoc basin has an asymmetrical fill, thickest in the centre and south, and a thinning, onlapping pattern against the Montagne Noire to the north. Late Cretaceous basin filling started with offshore to shallow marine sedimentation. The basin then preserves a range of continental foreland basin environments including fluvial channels and floodplains, carbonate-rich lakes, and a variety of paleosols. A rich fauna of dinosaur bones and eggs have been recovered from these sediments. Continental deposition continued into the Paleocene, with occasional marine incursions. The succession passes upwards into early Eocene marine sediments when high sea-level allowed connections to the Atlantic Ocean, reverting to fluvial and lacustrine formations in the mid-Eocene. All these rocks were involved, to a greater or lesser extent, in compressive deformation associated with the formation of the Pyrenees. The stratigraphic framework for the late Cretaceous to early Paleogene sedimentary sequences is based upon fossiliferous marine units in the Upper Cretaceous, the Upper Paleocene and the Lower Eocene. Within continental successions, dating is more difficult, though the sparse fauna and flora can be used at certain horizons, as can palaeomagnetism. Elsewhere, laterally continuous paleosols and lacustrine limestones may be used as lithostratigraphic markers.

Models of Convergence

Current thinking on the nature of convergence between the Iberian and European plates is illustrated in Figure 3. After an early extensional phase, progressive closure of the Cretaceous basin led to the restoration of the normal crustal thickness. By the mid-Eocene the southern, Iberian, plate ramped up over the European plate. With continued shortening the Iberian crust decoupled either at the middle-crust lower-crust boundary (west-central Pyrenees) or within the middle crust (east-central Pyrenees), such that the lower crust (+/- some middle crust) was subducted beneath the European plate. In this model there is a total crustal shortening of 114 km.

Post-Pyrenean tectonic activity. In the late Oligocene, the region was affected by extensional tectonics responsible for the formation of the Narbonne-Sigean basin and related basins, due to sea-floor spreading along the west Mediterranean margin. In addition, there was Paleogene to Recent extensional faulting, such as the major Cévennes fault system. This fault system is still active and is responsible for occasional earthquakes of moderate magnitude.

Volcanic rocks formed in the Pliocene and Pleistocene are mainly alkali basalt lavas and pyroclastics and are also related to young extensional tectonics. These define a N-S trend, and are a southward continuation of the much more extensive Neogene to Recent volcanism of the Massif Central.

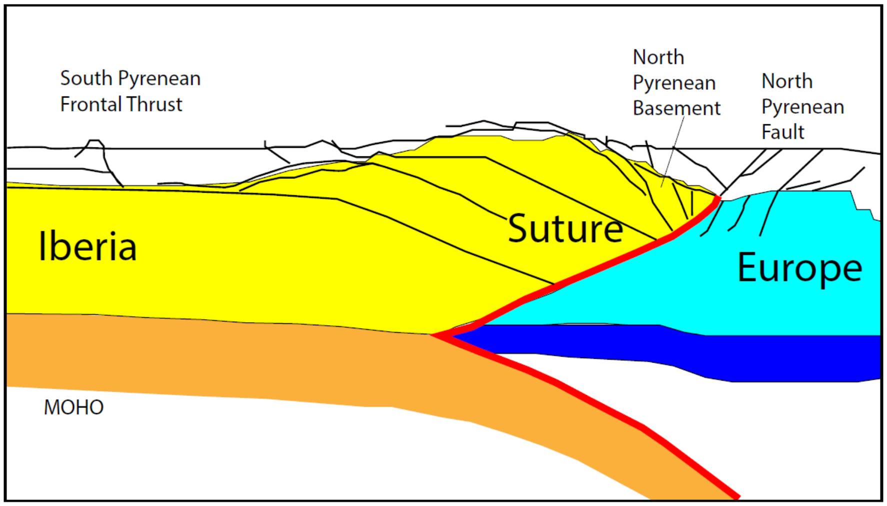

Figure 3. Structural cross section through the Pyrenean Belt.

Excursion details

The localities described below are shown on the tectonic map in Figure 4. They are ordered roughly from south to north, from the core of the mountain belt to the foreland basin and then to the Variscan foreland, although this may not be the most convenient order in which to visit them. The GPS locations are based upon WGS 84. More detail about the localities is provided at virtual-geology.info/regional-geol/pyrenees.htm .

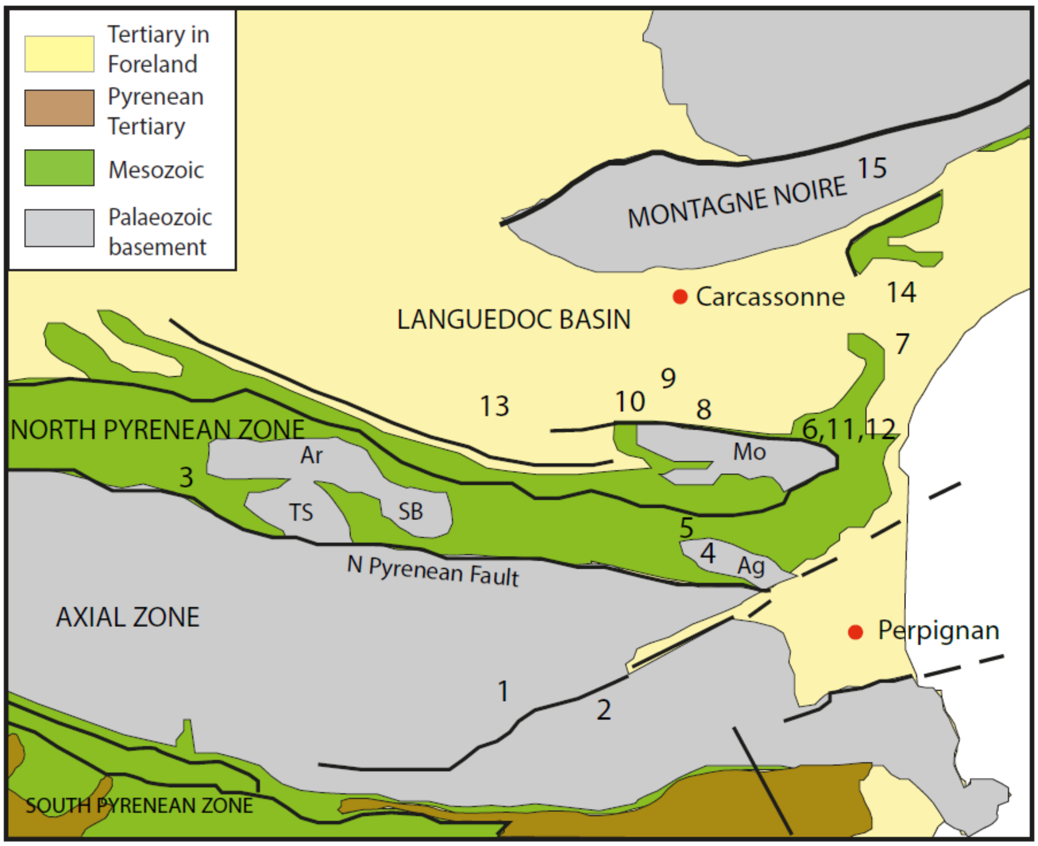

*Figure 4. Locality map for the outcrops visited in this excursion***.** *Massifs: Ag – Agly, Ar - Arize, Mo – Mouthoumet, SB – St Barthélémy, TS – Trois Seigneurs.*

The Axial Zone

In these localities the rocks of the older Variscan basement of the former Iberian plate are exposed, reactivated during the Pyrenean collision.

Locality 1. The Mont-Louis Granite (D29 road cutting at 31T 0422283 4704130)

The Axial Zone contains a number of high-level, late Variscan granites and the Mont-Louis Granite is one of these - a huge, sheet like body which extends for over 600 km^2 along the French-Spanish-Andorran border. It is intruded into unmetamorphosed lower Palaeozoic sediments to the east and Carboniferous formations to the west. It comprises several facies, from leucogranite to tonalite and its intrusion has been dated by U-Pb zircon geochronology at 305 +/-5 Ma.

Here it is tonalitic and contains abundant stretched and aligned mafic xenoliths (Figure 5), which show varying degrees of assimilation. There are two types. Some contain hornblende and so may have originally been basaltic. Others are more biotite-rich and may have pelitic precursors. The xenoliths may give some clues to the original material which melted in the deeper crust to produce this granite. Alignment of the xenoliths may have taken place during a late magmatic event related to the emplacement of the pluton, synchronous with Variscan thrusting.

Figure 5. A xenolith-rich area of the Mont-Louis granite.

Locality 2. Gorges de la Carança (car park at 31T 0436042 4708184)

The gorges are located at the village of Thuès-entre-Valls, in the Carança-Canigou Massif of the Axial Zone, to the east of the Mont-Louis granite. The rocks of the Massif comprise metamorphosed lower Palaeozoic sediments interlayered with pre-Variscan orthogneisses. They represent a deeper level of the Axial Zone in which the peak metamorphic conditions reached sillimanite grade: 725 +/- 25 ^{o}C and 4.5 +/- 0.5 kb.

A walk of about half a km along the narrow track from the entrance of the gorge shows a range of mylonitic lithologies. Careful observation of lithologies along the track shows a story of grain size reduction from rocks which were originally granitic augen gneisses, with large, cm-scale feldspar augen (Figure 6a), through rocks with a fine grained mylonitic matrix containing broken feldspar fragments a few mm across, to very fine grained and banded mylonites (Figure 6b). Look out for banded gneisses containing both components - coarse-grained augen gneiss and mylonitic bands.

The mylonites seen here formed during the Variscan deformation, but fault movement was reactivated along the same WSW-ENE trend during the Neogene. The north-dipping Têt fault is a brittle normal fault, which in part defines the margin of the Roussillon Basin, an extensional and still active fault-bounded basin. The narrowness of the gorge suggests rapid recent uplift and downcutting.

Figure 6. Gorges de Carança mylonites showing (a) the likely protolith of augen gneiss (b) the effects of grain size reduction in the mylonites.

The North Pyrenean Zone

The North Pyrenean Zone comprises Variscan crystalline massifs and Jurassic and Cretaceous sediments forming detached and repeating synclinal structures, locally metamorphosed during the Pyrenean event. The Col de Port viewpoint *(31T 0373681 4750762)* provides views of two of the large crystalline massifs: Trois Seigneurs to the south, and Arize to the north. Further east, the peaks of the St Barthélémy Massif can be viewed on a clear day.

Locality 3. The Lers peridotites at Étang de Lers (31T 0367534 4740883)

This is the classic area in which to examine the Lers (formerly Lherz) peridotites, the type locality for lherzolites. They are exposed in the North Pyrenean Metamorphic Zone, a narrow zone just north of the North Pyrenean Fault, and here are squeezed between the Axial zone to the south and the Trois Seigneurs Massif to the north. For many years these rocks were thought of as the classical fertile mantle, containing clinopyroxene as well as olivine, orthopyroxene and spinel. However recent studies show that they are not pristine, unmelted mantle; rather they are depleted mantle harzburgites, refertilised during later melt percolation and impregnation. This finding has major implications for the way in which we estimate the composition of the Earth’s primitive mantle.

The rocks are beautifully exposed in the hillsides around Étang de Lers and in road cuttings to the west and south of the lake. Walk from the café along the D8F road uphill for about 2 km, to *31T 0367229 4740229*. In the peridotites, note the presence of green clinopyroxene, often present in cm-wide veins (Figure 7b). They also show mantle flow banding (Figure 7a) indicated by deformed orthopyroxenite veins a few cm wide standing proud of the peridotite host. In places there are black very fine-grained veins of serpentinite.

Associated with the peridotites are marbles; some are brecciated. The road zig-zags across the peridotite-marble contact several times, displaying monomict marble breccias, monomict peridotite breccias and polymict peridotite-marble breccias (Figure 7c, d). Close examination shows that some of these breccias are tectonic in origin and related to stretching, whereas others are sedimentary and probably represent submarine debris flows. It is a new understanding of these exposures and the origin of the breccias which has led to the most recent ideas about basin extension, prior to collision, which is transforming our thinking about the early (pre-collisional) evolution of the Pyrenees. The peridotites are thought to be ancient, sub-continental lithospheric mantle refertilised in the Proterozoic, but exhumed on the sea-floor in the early Cretaceous through extreme crustal attenuation, and subjected to submarine weathering. The marbles, which show evidence of extreme geothermal gradients, were bought into contact with the peridotites during this period of crustal thinning and were metamorphosed as a result of their proximity to the mantle rocks.

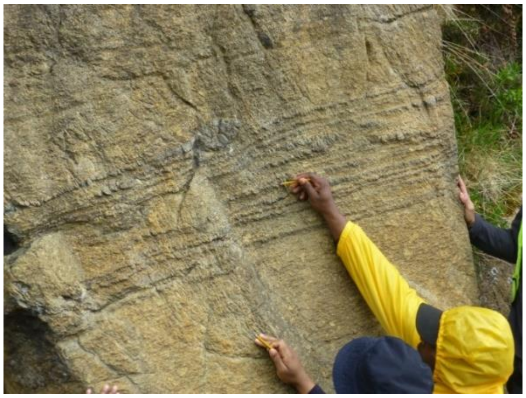

Figure 7. Lers peridotites showing (a) banded peridotite with orthopyroxenite bands *(b) harzburgite with clinopyroxene-rich vein*

(c) peridotite breccia with marble matrix *(d) marble breccia with detrital peridotite matrix.*

Locality 4. The metamorphic zones of the Agly Massif

The Agly Massif, at the easternmost end of the north Pyrenean Zone, is about 35 km in length and comprises metamorphosed Variscan basement. The main lithologies are pelitic metasediments, higher grade gneisses and granites. The sediments are lower Ordovician to middle Devonian in age and record a sequence of metamorphic zones, akin to Barrow's Zones of the Scottish Highlands although with a different sequence of index minerals. The metamorphic grade increases westwards. The core is made up of gneisses and granites and U-Pb zircon ages on deformed granitoids give Variscan ages in the range 317-307 Ma. The main deformation appears to have taken place in a Variscan transpressional regime. The massif is bounded by major E-W Pyrenean faults that separate it from synclines cored by Cretaceous strata.

This locality starts at Coll del Bou *(31T 0474040 4730628)* where views to north and south help to place the Agly Massif into a regional context. To the south is the extensional Roussillon basin, and beyond it Canigou, a 2785m high mountain in the Axial Zone of the high Pyrenees. To the north are the repeating Cretaceous limestone ridges of the detached synclines in the North Pyrenean Zone.

In this part of the massif there is an increase in grade from chlorite and biotite zone slates, through cordierite and andalusite schists to migmatites. Low grade Ordovician slates can be seen eastwards along the botanic trail towards Força Real (*31T 0475208 4730575*), where they are weakly deformed and still preserve bedding parallel to the cleavage. These rocks are in the chlorite zone. Return to Coll del Bou: along the track to the west, it is possible to see with a hand lens small biotite porphyroblasts in the slates, indicating the biotite zone.

From here travel the short distance to Col de la Bataille *(31T 0472900 4730536)* and walk through the vineyards to Caladroy. Turn off the road onto a vineyard track (*31T 0472591 4730449*), taking a left turn at *31T 0471638 4730745.* Along this track note the increase in metamorphic grade. The slates become schists and are strongly micaceous (muscovite-bearing) although there is no field evidence for the cordierite and andalusite zones. Walk past the Caladroy chateau to the D38 road cuts *(31T 0470633 4729962)* which show migmatites and evidence of the partial melting of pelites. These rocks are made up of alternating bands a few cm wide of dark biotite-rich schist and white quartzo-felspathic granite (Figure 8) and quartzo-feldspathic augen. In places the quartzo-feldspathic units are up to 1m wide and are discordant. This outcrop is interpreted as *in situ* partial melting of pelites with the biotite schist forming the restite (pelite from which a granitic melt has been removed) and the quartzo-feldspathic unit representing the melt, which in places contains small (mm) pink garnets, indicative of an S-type granite.

One regional feature of the Variscan metamorphism, from the Axial Zone to the Montagne Noire, is its high temperature, low pressure character. Such conditions could imply high mantle heat flow, although mafic rocks which might be associated with high mantle heat flow are absent. The extreme change in metamorphic grade from the chlorite zone at Força Real to partial melting at the Caladroy road cutting suggests a probable temperature increase of the order of 400°C over a distance of little more than 4 km. It is possible that there is a fault along this traverse although none has been mapped.

Figure 8. Caladroy migmatites showing dark, biotite-rich, restite bands and light coloured melt bands and melt patches.

Locality 5. Gorge south of St-Paul-de-Fenouillet - thrusts and synclines in Jurassic-Cretaceous limestones (31T 0458918 4738679)

Deformed Jurassic and Lower Cretaceous limestones form thrust synclinal structures and prominent topographic ridges in the north Pyrenean zone, north of the Agly Massif (Figure 1). At St- Paul-de-Fenouillet, east-west limestone ridges can clearly be seen, defining the northern and southern limbs of the Fenouillèdes Syncline. The limestone ridges provided excellent defensive positions: note the mediaeval Chateau de Quéribus on the ridge to the north.

Follow the D619 south from St Paul de Fenouillet, through the inverted southern limb of the syncline. Roadside outcrops are in dark mudstones and limestones of Lower Cretaceous (Aptian-Albian). The inverted contact with the older ‘Urgonian’ limestones forming the spectacular east-west ridge is crossed at the northern end of the gorge cut by the Agly river. A warm water spring (24°C) emerges in the gorge. At the south end of the gorge – Clue de la Fou - near the D619/D19 junction, the limestones in the old quarries are massive and bioclastic. Follow the D19 road cuts to the southeast. Immediately south of the limestone is massive quartz, then a fault breccia of large granite fragments in quartz. Several hundred metres up the road, you will encounter weathered massive granite. This Variscan granite on the north edge of the Agly Massif was thrust northwards over the much younger limestone ridge during the Pyrenean mountain building. Below the south-dipping reverse fault, the limestones were folded into a footwall syncline with an inverted southern limb. Upper Triassic gypsum provided a lubricating horizon during this deformation. Gypsum is exposed in the old quarries (*31T 0461530 4738464*) near Lesquerde, the next village east on the D19. In the entrance to the active gypsum mine here, granite can be seen thrust northwards over gypsum.

Locality 6. Upper Triassic sediments at Durban-Corbières (31T 0485857 4760038)

Triassic (Keuper) marls (red siltstones) with beds of gypsum are hugely important in providing a detachment surface for the large synclinal and thrust structures made up of Mesozoic limestone in the north Pyrenean Zone. These rocks can be viewed in road cuttings along the D27 east of Durban-Corbières. Here there are alternating thin beds of red marl and grey-white gypsum, cut by veins of clear gypsum (selenite). The cutting shows a huge variety of ductile and brittle structures (Figure 9) indicating the tectonically disrupted nature of this horizon. The sediments were originally deposited in desert lakes in a hot, arid environment. They contain quartz crystals which grew diagenetically. The outcrop is very fragile: please do not hammer.

Figure 9. Deformed Triassic red marls and gypsum east of Durban-Corbières.

The Foreland Basin

The sedimentary fill of the foreland basin (Table 2) from the Late Cretaceous to the Middle Eocene represents the progressive erosion and unroofing of the North Pyrenees. This group of localities (7- 14) follows the stratigraphy in order from Late Cretaceous to Miocene.

Series	*Stage*	*Start Age (Ma)*	*Sedimentation*
Eocene	Bartonian	41.2	Fluvial sandstones & conglomerate, floodplain siltstones, lacustrine limestones
	Lutetian	47.8	
	Ypresian	56.0	Marine sandstone, marl and limestone
Paleocene	Thanetian	59.2	Lacustrine limestones and paleosols with rare marine sandstone/limestone interbeds
	Selandian		
	Danian	61.6	Calcareous siltstones with thin, narrow conglomerate-filled channels
Upper Cretaceous	Maastrichtian	66.0	Lacustrine limestones, siltstones, local fluvial conglomerates
	Campanian	72.1	Fluvial sandstones & calcareous floodplain siltstones
	Santonian	83.6	Marine sandstone, mudstones & conglomerates
	Coniacian	86.3	

Table 2. A summary of the foreland basin stratigraphy in the field area.

Locality 7. Abbaye de Fontfroide, Eastern Corbières – Late Cretaceous (31T 0491585 4775211) in parking area below a prominent rocky ridge

The sandstone and rudist limestone beds indicate relatively shallow, distinctly marine conditions during the Coniacian – Santonian (86 – 83.6 Ma). Thick sandstone beds alternate with 1-2 m thick beds of *Hippurites* rudists, unusually shaped bivalves which built reef-like structures (Lespinasse et al., 1982). Six rudist reef beds have been identified at Fontfroide.

Rudist reefs extend NE and SW on both sides of the car park, but are more easily accessible on the raised side to the SW (Figure 10a). Prominent limestone beds are found about 65 m from the end of the car park nearest to the abbey entrance, and the one closest to the abbey contains the best examples of rudists (Figure 10b).

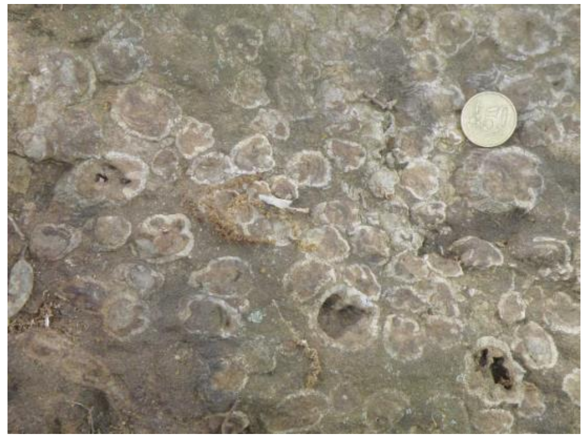

Figure 10 (a) Overturned limestone ridge NW of the Abbey entrance View is to the north; *(b) rudists in growth position; coin 23mm diameter*

Locality 8. Rennes-les-Bains – Late Cretaceous marine sediments (river section near swimming pool, 31T 0444528 4752384)

Upper Cretaceous Coniacian and Santonian deposits (86 – 83.6 Ma) in the Upper Aude Valley record a gradually shallowing marine setting. This change of environment may also record the early stage of the collision of Iberia and Europe.

In the river section, bedding surfaces show well-preserved body and trace fossils (Figure 11a). These include bivalves, occasional echinoids and rare ammonites and belemnites. Laterally continuous, bedded, well-consolidated bioclastic limestones with thinner marl interbeds (Figure 11b) form the river cliff and border the parking area. In places there is a hint of lamination but most beds are highly bioturbated.

Figure 11 Upper Cretaceous, Rennes-les-Bains (a). Bioclastic limestone with bivalves. *(b) interbeds of bioturbated limestone and siltstone.*

Locality 9. Alet-les-Bains (31T 0439150 4761152)

Terrestrial siliciclastic deposits of Campanian age are known as the Alet Sandstone. The basal contact with older sediments is not seen here but further south the Alet Sandstone lies on the marine Montagne des Cornes Formation or the Sougraigne Blue Marl, both Santonian in age.

The Alet Sandstone represents the change from marine to continental (fluvial) environments in the foreland basin. Along the road north of the town, examine deposits of coarse sandstone, pebbly sandstone and conglomerate (Figure 12) up to 3.5 m thick in places, some showing cross bedding. Sand is primarily quartz. Conglomerates and pebbles include vein quartz, quartzite, black chert and sandstone of various colours, derived by erosion from Palaeozoic rocks of the nearby Mouthoumet Massif. The coarse sediment and structures are consistent with deposition in high energy, possibly braided, rivers.

Figure 12. Alet Sandstone with conglomerate fining up to coarse sandstone. Pole is 1.3 m long.

Locality 10. Espéraza (car park closest to the museum 31T 0436219 4753950)

The museum, *Le Musée des Dinosaures*, presents palaeontology through time, but with a special focus on dinosaurs, notably those found in the Upper Cretaceous of the Upper Aude Valley. Groups and individuals can book tours of the museum and of an excavation site through the website http://www.dinosauria.org/fr/.

Three formations in the Upper Aude Valley record continuing continental sedimentation from the Campanian into the Maastrichtian (Figure 13). The lowest, just above the Alet Sandstone, is the Campagne Marl, on average 25-30 m thick. The primarily silty mudstone with occasional thin, narrow, sandy channels and paleosols is interpreted as a flood plain deposit. The overlying Estous Sandstone is cross-bedded, with conglomerate lenses and channel structures. It is up to 12 m thick and is interpreted to be a fluvial deposit. Finally, the overlying Maurine Red Marl is a poorly consolidated siltstone, again with occasional thin sandy channels, roughly 20-30 m thick, and represents a return to a flood plain setting with soil development.

The Campanian-Maastrichtian can be visited at the Bellevue site near Campagne-sur-Aude. The steep road past the Salazar winery climbs to a small sandstone cliff on a left-hand bend (*31T 0435009 4752128*). The walk up the hill is through the soft Campagne Marl. On the climb, look southeast across the valley, where the same sequence is exposed (Figure 13). The Estous Sandstone forms a bench. Above the Maurine Red Marl is a prominent white cliff of limestone up to 20m thick (Vignevieille Limestone). In this area, there are two distinct beds of the limestone with a thin marl (visible notch) separating them. Recent palaeomagnetic research combined with dinosaur egg-shell and charophyte dates indicates that the Cretaceous-Tertiary boundary is roughly in the middle of the limestone. To the south, the higher hills around Quillan are of Lower Cretaceous limestones in the North Pyrenean Zone, thrust northwards over the late Cretaceous-Paleocene basin fill.

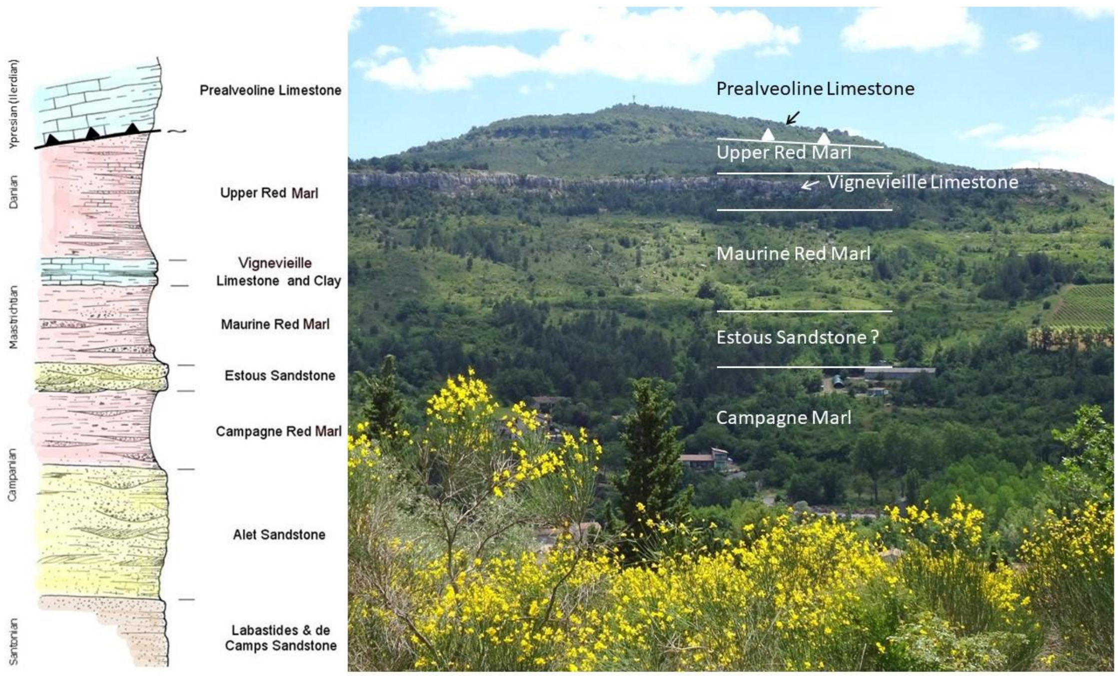

Figure 13. Upper Cretaceous-Eocene stratigraphy of the Upper Aude Valley. The hill top is an erosional remnant of overthrust L Cretaceous of the North Pyrenean Zone

The sandstone cliff is a very good exposure, about 4m thick, of the medium to coarse quartz-rich Estous Sandstone (Figure 14a). At its base, colour-mottled siltstones represent a paleosol (fossil soil). Cross-bed sets up to a metre thick with thin mudstone interbeds are well-exposed. Dinosaur egg shell fragments (Figure 14b) and even small bone fragments can be found, but this is a site of special scientific significance, so please do not hammer the outcrops.

Figure 14 (a) Estous Sandstone channel above Cave Salazar

(b) Estous Sandstone with gently curved dinosaur egg shell fragments. Scale bar 10 mm.

Above the Estous sandstone is the rather poorly exposed Maurine Red Marl, about 90 m thick. The lower part of this unit has been excavated for dinosaur remains. One site can be toured by arrangement with the dinosaur museum in Espéraza. The museum displays numerous bones and a reconstructed titanosaur from the site.

Locality 11. Albas Ridge (31T 0478528 4761210), Eastern Corbières

Continental sediments can be examined in a laterally continuous, well-exposed section (Figure 15). At the layby on the D106 south of the ridge, and elsewhere, the geology is explained on interpretative signs: "Le Rando du Géologue" The walk up the south side of the ridge will take about two hours. The sediments are loose, and it is easy to slide on them, although the outcrops on the west side of the D106 are less steep and it is possible to climb more easily through the stratigraphy (Figure 15).

Sediments exposed in the valley vineyards are bright orange, poorly consolidated silty sandstones (or sandy siltstones) of the uppermost Maastrichtian (68 – 66 Ma). Lenses of consolidated sandstone several metres wide and 1 m thick occasionally contain broken dinosaur egg shell fragments. Rare nests of whole eggs have been found. Mottled purple, orange and grey sediments suggest ancient root action and soil formation. The lenses of sandstone bordered by root traces and broken egg shells support a terrestrial environment of small rivers and flood plains which persists up much of the slope.

Proceeding up the slope, rocks are Paleocene in age and an increasing abundance of tiny calcite crystals (*Microcodium*) can be found in red mottled deposits interpreted as calcrete or calcareous paleosols. In three dimensions they appear to surround rootlet traces which taper and split. Their origin is disputed but they have been interpreted as biologically-aided precipitation of calcium carbonate forming within root cells.

Figure 15. Aerial view of the Albas Ridge. Section dips and youngs north (left). Poorly consolidated red floodplain sediments in vineyards in the valley (right) are Maastrichtian. They contain fluvial channels filled with well-cemented pebble conglomerate, which become more frequent upwards. Prominent white units are laterally extensive Paleocene lake limestones. Broad valley on the left is underlain by Paleocene floodplain sediments with paleosols; ridge at back left is early Eocene marine limestones.

The Cretaceous-Paleogene boundary occurs in the lower slopes, but its exact position cannot be determined. Sharp-based conglomerate lenses 1-3 m high and 5-10 m across occur are interpreted as stream channel deposits. Farther up the slope these disappear and are replaced by a laterally continuous limestone bed about 3-10 m thick with a carbonate conglomeratic base. This limestone can be traced laterally for 5 km or more and is interpreted to be a shallow but widespread lake since no marine fossils have been found. Further up the sequence, near the crest of the hill just south of the village a marl with marine fossils, 3.5 m thick and of Thanetian age, represents a short-lived marine incursion.

From the top of the Lower Thanetian limestone to the base of an identifiable Ypresian (Lower Eocene) marine limestone (ca. 56 Ma), there is an estimated thickness of 230 m of siltstones and sandstones, interpreted to be fluvial and floodplain deposits with occasional lacustrine/palustrine limestone beds 3.5 to 4.3 m thick. These occur on the south-facing slope to the north of Albas village. The slope is capped by Lower Eocene marine limestones and marls, but these are more easily accessed at the next location.

Locality 12. Coustouge to Jonquières road section (from 31T 0478803 4766023 to 31T 0477893 4765866)

The earliest Eocene sediments are early Ypresian, and limestone and marl beds with numerous fossils, locally abundant gastropods, bivalves and large benthic foraminifera, prove the rocks are marine. Fossiliferous beds alternate with sandy units which may be laminated, wave-rippled or cross-bedded, suggesting shallow seas. These rocks may record the start of a new phase of compression between the Iberian and European plates: The weight of the rocks being thrust to the north loaded and depressed the older rocks allowing seawater to invade eastwards from the Atlantic. Meanwhile uplifted rocks in the south were eroded to renew sediment supply.

Exposed along the road section are limestones, sandstones and marls formed ca. 56 – 48 Ma. Starting just west of Coustouge, the road towards Jonquières ascends the section, which is highly fossiliferous (Figure 16 a, b). Most beds are highly bioturbated, but some show sedimentary structures including wave ripples (Figure 16c), cross-bedding and soft-sediment deformation. Overlying this section on the hillside west of the 2.0 km marker, fluvial sediments of Lutetian age outcrop – the ‘Molasse de Carcassonne’.

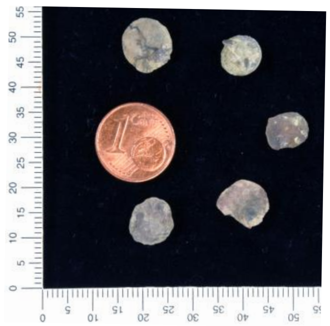

Figure 16 (a). Large benthic foraminifera at 0.5 m on road section. Coin = 15 mm diameter.

(b) Turritella gastropods approximately 1.32 m along road.

(c) wave ripples at 1.28 km along road

Locality 13. Aigues-Vives (31T 0462034 4786146) and around St Jean (31T 0461781 4787298)

Early to Middle Eocene sediments in the basin, thought to be Lutetian, 47.8 to 41.3 Ma are exposed as raised ridges of sandstone and pebble conglomerate (Figure 17a) above vineyard soils north of the D610 east of Carcassonne, especially around Aigues-Vives. They are several metres wide but can be traced for tens to hundreds of metres. They are interpreted as fluvial channels transporting significant amounts of coarse sandy and pebbly sediment. The red soils in the vineyards represent the finer flood-plain deposits between the channels, and some show paleosol features. At the margins of some channels, clear erosive contacts can be seen with the underlying flood-plain sediments. Numerous small quarries exploited the sandstones to build the mediaeval city of Carcassonne.

The area is now agricultural (vines and fruit trees) but there are abundant outcrops. It is possible in some areas to measure directions of transport from cross-beds and pebble orientation. A complex network of channels can be followed through the vineyards around St-Jean, north of Aigues-Vives (Figure 17b).

Figure 17. (a) long narrow conglomerate ridge S of Aigues-Vives; ridge represents an exhumed fluvial channel; scale bar is 1.5 m high

(b) Long, narrow, conglomerate and sandstone ridges (shaded) stand out above floodplain siltstone in vineyards, 1.25 km NW of Aigues-Vives village. (Google Earth Aug 2018).

Locality 14. Malpas (*Malpas Tunnel 31T 0510318 4794993) near Nissan-les-Ensérune*

Major compression of the Iberian and European plates ceased in Late Eocene to Oligocene time. However, there is evidence of Miocene and later fault movements, and minor earthquakes are still recorded in the region.

Near the Maison du Malpas Tourist Office, a path and stairs descend to the north portal of the Canal du Midi tunnel. Before entering the tunnel there are marine Miocene sediments on the opposite side of the canal (Figure 18). They are convoluted indicating soft sediment deformation shortly after deposition, perhaps as result of earthquake activity. On the drive or walk west along the road to the archaeological site at Oppidum d'Ensérune, good exposures of Miocene bioclastic marine limestones are seen, some of them in grain silos from ca. 600BC, carved into the rock and later bisected by the road.

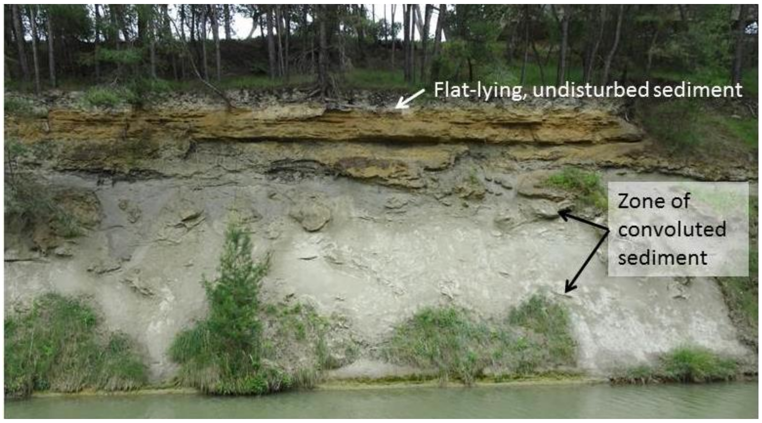

Figure 18. Canal du Midi cutting several metres high just outside the Malpas Tunnel showing convolute sediment below undisturbed, thin beds of shallow-marine sandstone

Montagne Noire – the foreland basement

The Variscan basement is exposed north of the Aquitaine-Languedoc Basin in the Montagne Noire. This range of hills is the southernmost expression of the Massif Central. The Gorges d'Héric are at the eastern end of the Montagne Noire Axial Zone, which is in fault contact to the south with a suite of southerly verging recumbent folds made up of rocks of Palaeozoic age. Locally, the Gorges d'Héric outcrops are part of the Caroux gneiss dome, which is a gneiss antiform overturned to the north. The emplacement of the recumbent folds took place in the late Carboniferous. It was followed by the formation of the migmatites of the gneiss dome, followed finally by the emplacement of anatectic granites at 322-333 Ma. However, there is also a suite of older Ordovician granitoids in this area which were emplaced between 450-470 Ma into older sediments. They are not well dated and there are conflicting results.

Locality 15. Gorges d'Héric (Car park 31T 0497372 4824527)

Walk from the car park a few hundred metres north along the track into the gorge. At the concrete 'Bridge of Sighs' (Pont des Espirs) over the river (*31T 0497285 4824732)*. The geology here is very complex, but beautifully exposed in river-washed outcrops. Note the cross-cutting muscovite pegmatites with large black tourmaline crystals, often concentrated at the margins of the pegmatites, and some huge white feldspar crystals up 20 cm or more across. These pegmatites cut a complex suite of intensely foliated augen gneisses (Figure 19) and more massive units. The augen may be up to 3 cm long. Some are single grains whereas others may be pockets of granitic melt. Both have a strong sigmoidal form and record intense shear strain. The grain size of the matrix varies giving rise to darker and lighter varieties. In addition, there are more massive, quartz-rich, equigranular units as concordant bands 10-20 wide, within the gneisses. The gneisses have been interpreted as orthogneisses - deformed granitoids and the concordant massive quartz-rich bands as paragneisses - former sediments; both are cut by the later pegmatites. Similar relationships are seen by continuing the walk along the road up the gorges. The steep-sided gorge suggests rapid recent uplift and downcutting.

Figure 19. Gorges d'Heric. Augen gneiss

Figure 20. Climbing dunes in pyroclastic surge deposits, Cap d'Agde tuff ring. Flow was uphill, towards the right.

Pleistocene volcanoes

Locality 16. Cap d'Agde

Numerous young alkali-basalt volcanoes, in north-south alignment, occur in the region north and east of Béziers. One of the best exposed is on the coast at Cap d'Agde, at the beaches south and east of the aquarium (La Plagette *31T 0541503 4791413* to La Grande Conque, *31T 0541920 4791705*). The breakwater at the south end of the section is composed of fresh blocks of alkali basalt containing sparse mantle peridotite inclusions. The cliffs behind both beaches show sections through a tuff ring, with cross-bedded pyroclastic surge deposits and bombs (Figure 20). This indicates interaction of basaltic magma with water, probably seawater, causing violent explosions like those seen at Surtsey in 1963.

Further Reading

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