IEC-14

July 10-13, 2022

Lyon - FRANCE

14th International Eclogite Conference (IEC-14)

Pre-conference field trip

July 7-9

High-pressure metamorphism in the Armorican Massif (Hercynian belt)

Field guidebook

by

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At the western edge of the European Variscides, the South Armorican Domain (Fig. 1; Armorican Massif, NW France) is part of the Ibero-Armorican arc, which extends further west into the Iberian Peninsula (Galicia and northern Portugal) and has been interpreted as resulting from a collision between the Laurasia and Gondwana continents during the Upper Palaeozoic (*e.g.*, Brun & Burg, 1982; Matte, 1991). In this context, blueschists-facies and eclogite-facies rocks may belong to a palaeo-subduction zone, highlighting the suture(s) zone(s). However, there are actually at least two concentric belts of high-pressure metamorphism in the Ibero-Armorican arc (Fig. 1):

(a) Towards the interior of the arc, a blueschist-facies belt (or Groix Unit) consists of glaucophanite, glaucophane eclogite and serpentinite boudinaged within garnet-chloritoid-phengite micaschists. From west to east, the main occurrences of this belt are: Tras-os-Montes (Portugal), Groix Island, Dumet Island, and Bois-de-Céné region (Armorican Massif).

(b) Arranged parallel to this belt but outward from the arc, other units consist of eclogites, serpentinite and eclogite-facies paragneiss and orthogneiss. From west to east, the main occurrences of are: Cabo Ortegal (Galicia), Audierne Bay, Champtoceaux Complex and Les Essarts Unit (Armorican Massif).

During the 3 days of field trip, we shall visit one occurrence of the blueschist-facies belt (Groix Island, visited on July 7; part 1 of this guide), and two examples of the outer eclogite-facies belt (Les Essarts Unit, visited on July 8, part 2; and the Champtoceaux Complex, visited on July 9, part 3).

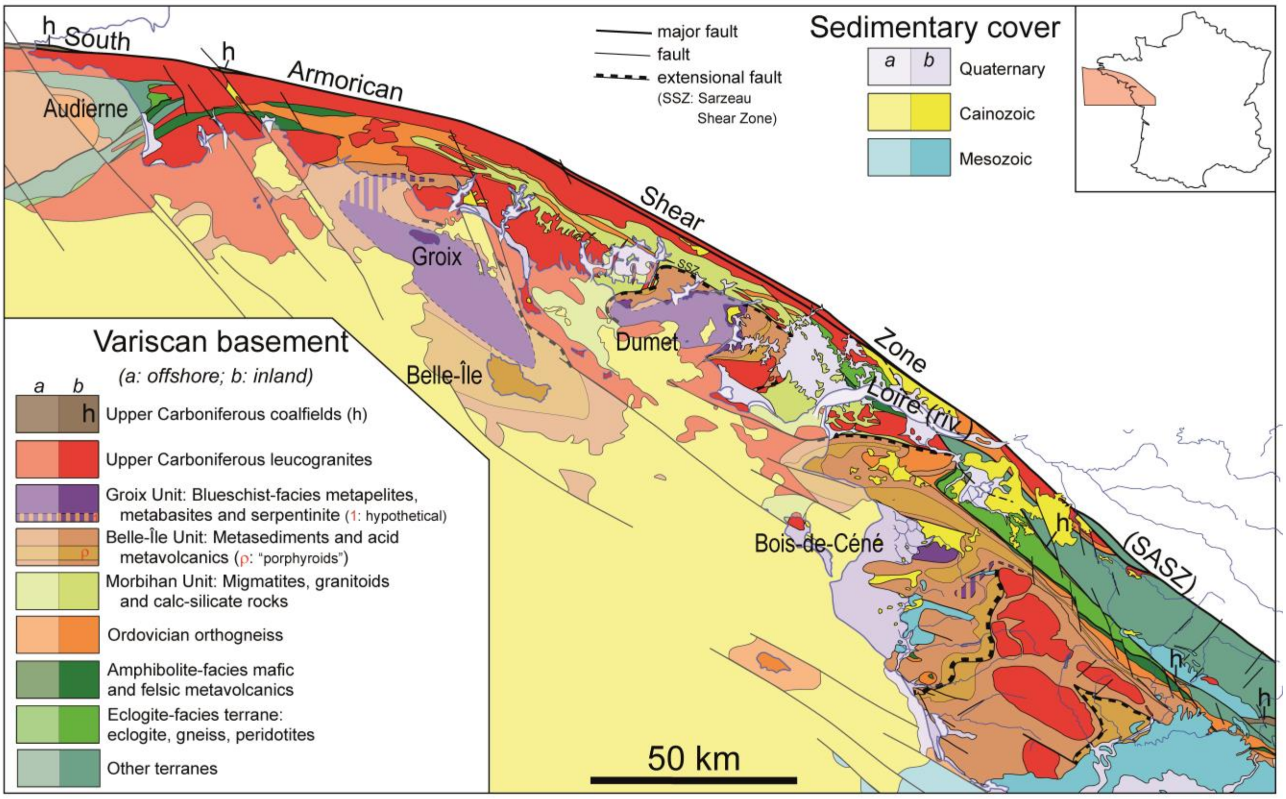


Figure 1- Geological sketch map of the South Armorican Domain

Schedule of the field trip

Thursday July 7th: Groix Island		
08h45	Meeting at the port of Lorient (pier for Groix Island)	
09h15-10h30	boarding; crossing from Lorient to Groix (*Port Tudy*)	(by boat)
10h45-11h	From *Port Tudy* to *Pointe des chats*	(by minibus)
11h-16h	Geological route along the coast from *Pointe des chats* to *Kersauce* (*Locmaria*), with lunch break	(by foot)
16h15-16h45	From *Kersauce (Locmaria)* to *Port Tudy* Beer/coffee	(by minibus)
16h45-18h	boarding: crossing from Groix to Lorient	(by boat)
18h15-20h45	Lorient – Nantes	(by bus)

Friday July 8th: Les Essarts Unit (Vendée)		(by bus)
8h-9h	Nantes – La Piltière	
9h-9h30	La Piltière (Stop 1)	
9h30-10h30	La Compointrie (Stop 2)	
10h30-11h15	Moulin des Pouzinières (Stop 3)	
11h15-12h45	La Gerbaudière (Stop 4)	
12h45-13h15	La Ruffelière (Stop 5)	
13h15-14h30	Lunch break at La Roche-aux-Lutins (Stop 6)	
14h30-15h	La Roche-aux-Lutins - La Chabotterie	
15h-15h30	La Chabotterie (Stop 7)	
15h30-16h	La Chabotterie – Grezay	
16h-17h15	Grezay (Stop 8)	
17h15-18h30	Grezay-Nantes	

Saturday July 9th: Champtoceaux Unit		(by bus)
8h30-9h30	Nantes – La Picheraie	
9h30-10h30	La Picheraie (Stop 1: metagranitoid)	
10h30-11h	La Picheraie (Stop 2: eclogite)	
11h-12h	La Picheraie – Champtoceaux	
12h-13h15	Lunch break	
13h15-17h30 (?)	Champtoceaux – Paris	

Acknowledgments

The first part of the field guide devoted to the island of Groix is largely inspired by a previous guidebook written by Michel Ballèvre. We deeply thank him for accepting us to use this previous work and his description of some outcrops.

We would particularly like to thank Mr. and Mrs. d'Audeville from La Piltière, Mr. Nicolas Pucelle from *Carrière et Matériaux du Grand-Ouest* (La Gerbaudière quarry), Mr. and Mrs. Thomassin from La Ruffelière and Mrs. Rémy from Grezay, for their help, their kindness and their always cordial welcome.

Farah Daoulet and Tessa Adrian-Roux, of *Ecole Nationale Supérieure de Lyon* are thanked for the material organization of the field trip.

1
Blueschist-facies rocks from Groix Island (Brittany)

Île de Groix, also called « l'île aux grenats », is a ~ 6 × 2.5 km^2 island off the coast of Lorient (Morbihan). It exposes beautiful metamorphic rocks, especially famous blueschist-facies rocks, of Palaeozoic age and abundant high-pressure rocks and minerals that you will discover throughout the day.

We are in a natural reserve. It is therefore not allowed to use the hammer and to collect samples. Thank you in advance for respecting this!

1.1– <u>Geological overview</u>

1.1.1- History of geological and petrological studies

In 1883 and 1884, the geologist Charles Barrois described the first glaucophanites ever reported in France, on the island of Groix, near the west coast of Brittany. However, unpublished notes by François de Limur, an amateur mineralogist from Vannes in Brittany, designate him as the real discoverer of these rocks, in which he recognized glaucophane. De Limur sent samples to Ferdinand Zirkel in Leipzig, Arnold von Lasaulx in Bonn and Ferdinand Fouqué in Paris. The latter entrusted their study to his student Charles Barrois, who inadvertently forgot to mention Limur's contribution in his articles (see Godard, 2021). In 1887, Barrois demonstrated that certain amphiboles from Andalusia, later called *barroisite* in his honour, were intermediate in composition and optical properties between actinolite and glaucophane.

During the 20th century, the mineralogical inventory of the island was carried out (*e.g.*, Le Bail, 1961, 1970; Chauris, 2014), and led to the discovery of uncommon and numerous mineral species (piedmontite, pseudomorphs after lawsonite, fuchsite, deerite...), making the island of Groix an open-air mineralogy museum.

After the emergence of plate tectonics in the 1960s, the Groix glaucophanites experienced a revival of interest (see historical overview *in* Audren, 1999), and the geology of the island was studied in all its aspects (*e.g.*, Ballèvre, 2009). The blueschist-facies rocks were considered as resulting from a Palaeozoic subduction in an oceanic accretionary prism. Their occurrence became protected within the National Reserve François Le Bail, in December 1982.

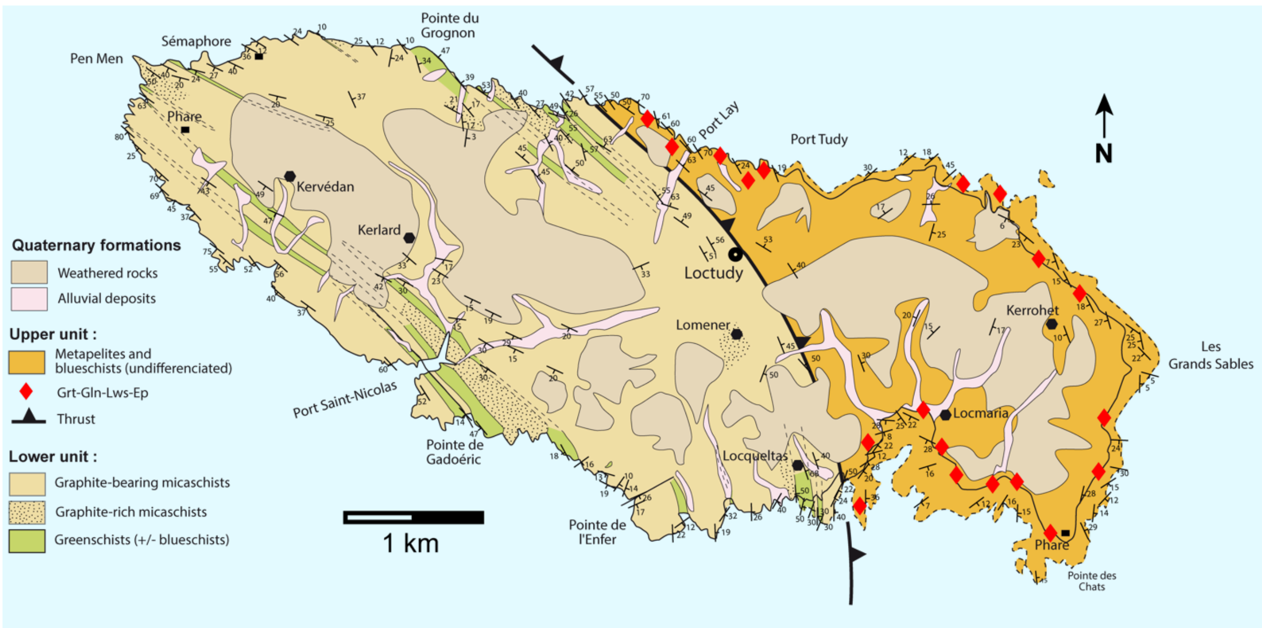


***Figure 1.1- Simplified geological map of Ile de Groix** (after S. Centrella, Msc. thesis)*

1.1.2- Geological framework

Île de Groix consists mainly of phengite+garnet±chloritoid micaschists, in which are stretched mafic bodies with abundant relics of glaucophanite and glaucophane eclogite. A lens of serpentinite, nodules of Mn-rich quartzite and a few levels of orthogneiss add further variety to the petrological richness of the island.

The structural position of the island with respect to the other units of the South-Armorican domain cannot be establish by field data. Geological and geophysical data (Lefort & Segoufin, 1978; Audrain & Lefort, 1986; Audrain & Vigneresse, 1990; Lefort & Vigneresse, 1992) suggest that the Île de Groix blueschists and micaschists are allochthonous over the acid metavolcanics ("porphyroïds") and metasediments of the Belle-Île Unit (Fig. 1) outcropping at Belle-Île, in the Rhuys and Guérande peninsulas, and on the Vendée coast (Le Hébel *et al.*, 2000, 2002). Several equivalents of the Île de Groix formation are known elsewhere in the South Armorican Domain (Fig. 1), *e.g.*, at Dumet Island and *Baie de la Vilaine* (Godard *et al.*, in prep.) and in the Bois-de-Céné region (Vendée). They all consist of micaschists, blueschists and serpentinite, which occupy the core of synforms in the middle of the Belle-Île Unit.

The islandof Groix consists of two domains (Fig. 1.1). The eastern domain is characterized by flat-lying or gently dipping foliations, with variable strike and dips. In the western domain, the foliation is steeply-dipping, with a nearly-constant NW-SE strike (Fig. 1.1). Because no stratigraphy can be established in the Île de Groix rocks, preventing the use of mapping methods for deciphering the large-scale structures, tentative correlations of the thickest metabasite levels have been made by Cogné (1953, 1960). It followed that the western domain presents a major antiformal fold, whose axis is oriented NW-SE, then NNW-SSE (Fig. 1.1). Recent modelling of magnetic data supports this interpretation (Audrain & Lefort, 1986; Lefort & Vigneresse, 1992).

1.2– Description of the sites visited

The southern coast from ***Pointe des Chats*** to ***Locmaria*** (Reserve F. Le Bail) provides excellent exposures of the different kinds of blueschist-facies rocks that can be found on the island. This is why we selected this section for the field trip. The path and the different stops of the day are presented in Figure 1.2.

Figure 1.2- Aerial view of the south-east part of Ile de Groix with the route of the day *(after Google Maps). Red numbers correspond to the stops described below. P: bus drop-off/pick-up.*

<u>Stop 1</u>: Glaucophanites in micaschists

At ***Pointe des chats*** micaschists outcrop with numerous glaucophanite lenses (Fig. 1.3), with flat-lying or slightly dipping foliation. Some of the lenses are fine examples of epidote-glaucophane banded blueschists, the metamorphic layering of which is locally isoclinally folded. Inside the same lens, glaucophane crystals occur either as fine needles a few millimeters long, in which case they show a well-defined shape orientation, or as large crystals up to a few centimeters long dispersed in an epidote matrix, in which case they are poorly oriented in the foliation plane.

Blueschist lenses are sometimes crosscut by veins (Fig. 1.3) which contain large crystals of albite (whitish or greenish), aggregates of dark green lamellae of chlorite, as well as quartz and magnetite. The glaucophanite adjacent to the veins is retrogressed revealing local infiltration of an H_2O rich fluid from the vein into the blueschist (Brière, 1920).

The blueschist lenses are embedded in a matrix of micaschists, with abundant layers of pinkinsh (*i.e.*, garnet-rich) microquartzite deriving from manganiferous metacherts (see Stop 6). Some micaschists show garnet+chloritoid assemblages, while others contain garnet and/or glaucophane.

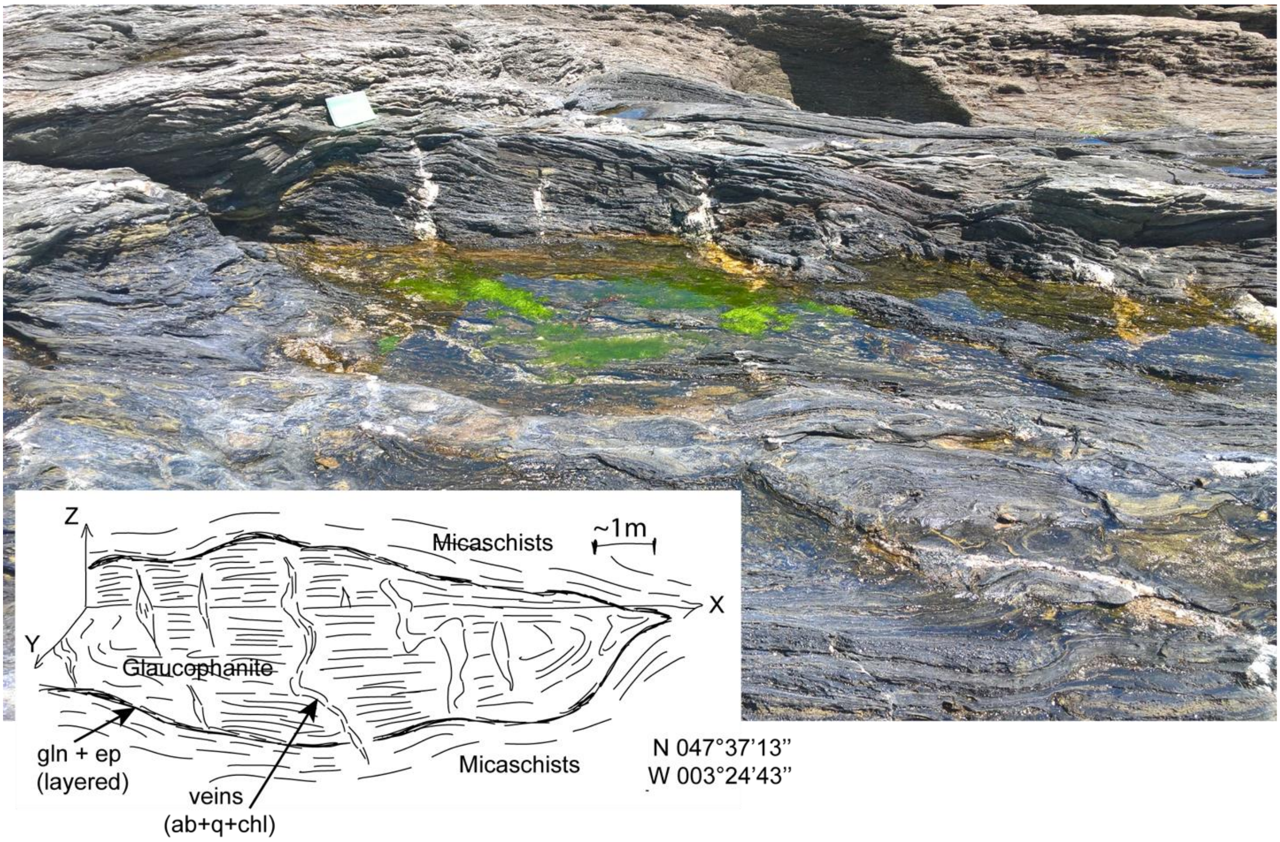


Figure 1.3- Blueschist lens in micaschists. *Dark glaucophanite-bearing lens is crosscut by veins containing albite, chlorite and quartz.*

<u>Stop 2</u>: Greenschist-facies rocks coexisting with blueschist-facies rocks

A large outcrop of mafic rocks can be examined at the southern end part of the shore. This outcrop, studied in detail by Barrientos (1992), shows closely-associated blueschist and greenschist. The blueschist is a banded garnet-bearing epidote-glaucophane rock, with a well-developed foliation and stretching lineation. The greenschist is a more massive rock with an albite-chlorite assemblage. Layering is easily identified in the greenschist, where foliation is less prominent than in the blueschist. We can discuss here the relationships between blueschists and greenschists.

<u>Stop 3:</u> Garnet-bearing blueschists

The following step, located on the eastern side of ***Porh Morvil*** bay, mainly shows a thick sequence of garnet-bearing blueschists (Fig. 1.4). In these rocks, garnet porphyroblasts are embedded in a matrix mainly composed of an assemblage of glaucophane and epidote. Garnet porphyroblasts are surrounded by chlorite pressure-shadows. The elongation of the pressure shadows seems the parallel to the orientation of the glaucophane needles, indicating that the direction of stretching did not change from the blueschist-facies episode to at least the early stage of the greenschist facies.

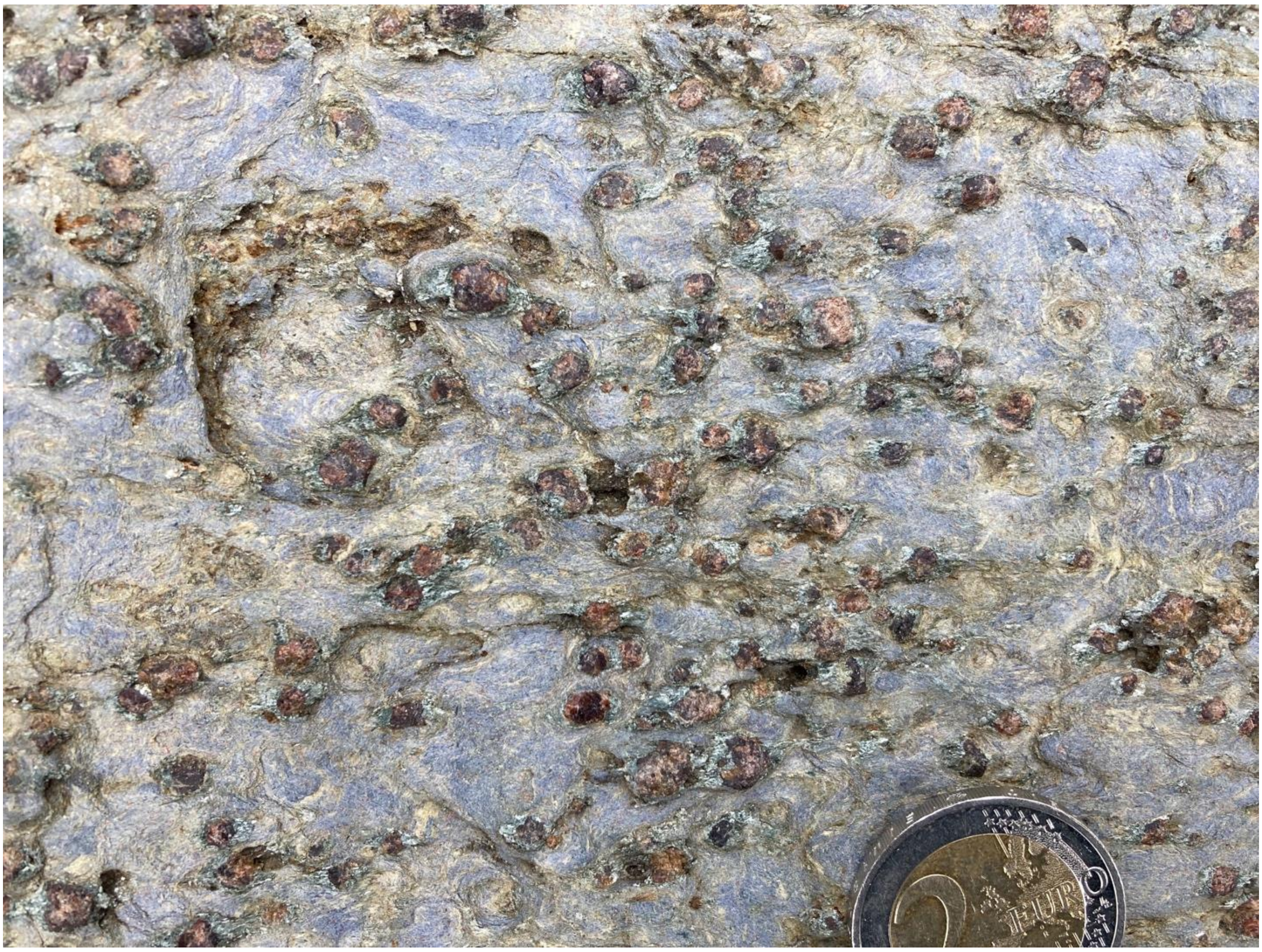


Figure 1.4- Garnet-bearing blueschist. *The matrix is composed of a glaucophane and epidote assemblage. Note the beautiful chlorite-bearing pressure-shadows around garnet porphyroblasts.*

Chloritoid crystals (sometimes up to 2 cm long) in a fine-grained dark blue matrix of glaucophane can be seen in garnet-bearing blueschists. These rocks present spectacular examples of reactional textures (Kiénast & Triboulet, 1972). Chloritoid is surrounded by a whitish-greenish corona, essentially consisting of paragonite and chlorite. In some places, paragonite appears in at the contacts with the chloritoid while chlorite is close to the matrix, emphasizing the differences in mobility of the various ions involved (*i.e.*, Al less mobile than Fe and Mg). The continuous slidding reaction Gln + Ctd + H_2O = Par + Chl being a hydration reaction, the local availability of H_2O during decompression controls the extent of the retrogression.

<u>Stop 4</u>: Clinopyroxene-bearing rocks

A long halt is now recommended at the foot of the cliff, immediately north of the remains of the Sanaga, a Greek ship wrecked during a voyage from Plymouth to Saint-Nazaire (28/03/1971). The main lithologies of the island can be examined here in a restricted area, namely *eclogites*, *garnet-bearing blueschists* similar to those already examined, an *aegyrine-jadeite-bearing rock*, *garnet-bearing micaschists,* in which glaucophane, present in most samples, is difficult to identify with the naked eye or a magnifying lens, and a few levels of *garnet-chloritoid micaschists*.

Two types of Cpx-bearing rocks can be identified here:

(1) Eclogites are foliated, massive rocks, which contain equal proportions of garnet, glaucophane, epidote and a bright green sodic clinopyroxene (Fig. 1.5). White mica is also a common phase in these eclogites. Some eclogites present small veins (about 1 cm thick, 10 cm long) filled with a dark green amphibole (a sodic, barroisitic, variety). Note that the veins are perpendicular to both the foliation and the lineation of the host eclogite, and that the amphibole fibers in the veins have a similar orientation to the glaucophane needles in the host rock. Again, this suggests that the stretching direction was stable during the blueschist-greenschist transition.

(2) Large flattened lenses of a massive greenish rock are seen in the micaschists. This rock essentially consists of garnet (up to 1 cm in diameter) in a greenish matrix made up of a sodic clinopyroxene (aegyrine-jadeite) frequently replaced by minute albite-hematite aggregates (Fig. 1.6). Additional phases of this rock are phengite (concentrated in a few layers), epidote and rare glaucophane. Rutile crystals up to 5 cm long have been found. Note also the presence of veins filled by quartz, phengite and glaucophane. This rock has been analysed by Bernard-Griffiths *et al.* (1986, sample 2444), who misidentified the sodic pyroxene.

Figure 1.5- « Eclogite » from Ile de Groix. *Garnet crystals are embedded in a glaucophane + epidote + omphacite matrix. Quartz veins like the one displayed in the centre of the photograph are not uncommon in these rocks.*

Figure 1.6- « Eclogite » from Ile de Groix. *The rock is composed of garnet crystals in a greenish matrix of sodic clinopyroxene and crosscut by veins filled with quartz, phengite and glaucophane.*

Stop 4: Blocks with cm-sized rutile

As mentioned earlier, rutile is not uncommon in outcrops and/or blocks in the area. They are mostly found in garnet-bearing glaucophanites (Fig. 1.7). Unfortunately, their uranium content is too low to be used for dating.

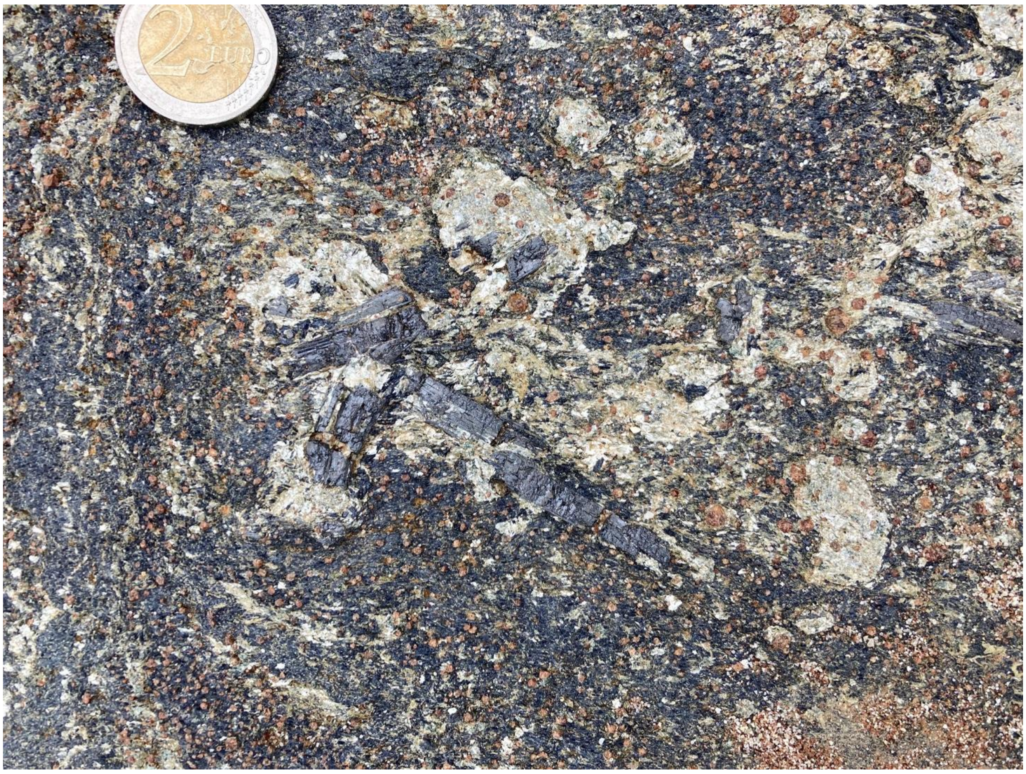


Figure 1.7- Rutile crystals in garnet-bearing glaucophanite. *Photograph of a loose block on the shore (N 47°37'26''; W 3°25'51'').*

<u>Stop 5:</u> Lawsonite pseudomorphs in Garnet-bearing blueschists

Let us now continue to the "amer" (a sea-mark, *i.e.,* a monumental wall painted in white and used by sailors for orientation). The amer is built on a ruined dolmen chamber (*i.e.*, a Neolithic tomb). The cliffs west of the amer display excellent exposures of garnet-bearing blueschists, with numerous diamond- or rectangle-shaped pseudomorphs standing in relief due to differential weathering (Fig. 1.8). It is in this locality that Felix & Fransolet (1972) have sampled pseudomorphs in order to measure their interfacial angles, and thus demonstrated that they derive from lawsonite, whereas they have long been taken for altered andalusite (*e.g.*, Bonnet, 1887). Examined with a magnifying lens, the pseudomorphs show their internal structure, with the epidote-rich inner part and the mica-rich outer part, as well as numerous inclusions of fine-grained garnet. The pseudomorphs are undeformed, and their host rocks are largely unretrogressed, with a dominant colour due to glaucophane. Examination under the microscope reveals that glaucophane is frequently rimmed by a thin overgrowth of a dark green amphibole of barroisitic composition.

Figure 1.8- Lawsonite pseudomorphs in a glaucophane-bearing matrix. *Pseudomorphosed prismatic porphyroblasts after lawsonite, showing rectangular and rhombic sections, are now replaced by epidote (mainly in the inner part) and by albite+white mica (outer part).*

This is the right place for debating the origin of the pseudomorphs and their timing of growth with respect to the deformation. It has been argued that (i) the pseudomorphosed mineral is lawsonite, (ii) the rocks here exposed underwent ductile deformation during lawsonite growth, and (iii) these volumes escaped any significant ductile deformation during and after the lawsonite breakdown.

<u>Stop 6:</u> Manganiferous mineralizations at Les Saisies

The occurrence of manganiferous minerals in the Ile de Groix is known since the identification of piedmontite (Lacroix, 1888; Lacroix, 1893, p. 155) and rhodonite (Lacroix, 1893, p. 632) in samples collected by de Limur. Their location was unfortunately not reported. Kiénast & Triboulet (1973) described piedmontite-bearing schists and nodules in the eastern part of the island (between *Plage des Grands Sables* and *Plage des Sables Rouges*). A nodule from this latter occurrence has been investigated by Cornen (1999). Other occurrences of manganiferous nodules were discovered by mineral collectors (M. Moisan and F. Le Bail) in Les Saisies (***stop 6***), a peninsula on the southern coast of the island (Pierrot *et al.*, 1980, p. 107-108; Chauris *in* Audren *et al.*, 1993, p. 90). In this locality (Fig. 1.9), the nodules have a variable mineralogy, the manganiferous species being tephroite (Mn_2SiO_4), pyroxmangite ($MnSiO_3$), piedmontite, spessartine-rich garnet and jacobsite ($MnFe_2O_4$).

According to field and microprobe work done by Ballèvre and co-workers, the manganiferous occurrences at Ile de Groix are of three different types:

(1) Pinkish quartzites (that can be found on ***stop 6***) contain manganese-rich garnets. The quartzites are found in numerous places, as layers of variable thickness (*e.g.*, about 1 mm at Gadoéric to 0.30 m close to Locmaria), which are found within micaschists or in contact with blueschists. In this latter case, they are observed either interlayered between thick sequences of blueschists or along the interface between the two lithologies.

(2) Associated (or not) to the pinkish quartzites are nodules up to 1 meter in diameter, whose black colour result from the weathering of manganiferous minerals (Fig. 1.9; ***stop 6***). The core of some nodules are more or less weathered, as a result of the preferential dissolution of the carbonates, when present. Different types of manganiferous parageneses are found in the nodules, which are surrounded by piedmontite-bearing micaschists.

(3) In rare instances (*Stang er Marc'h* and *Port Saint Nicolas*), small (less than 0.1 m), black nodules are observed in the micaschists. They contain a minor amount of quartz and abundant spessartine-rich garnet, the dark colour of garnet being due to a large amount of graphite inclusions.

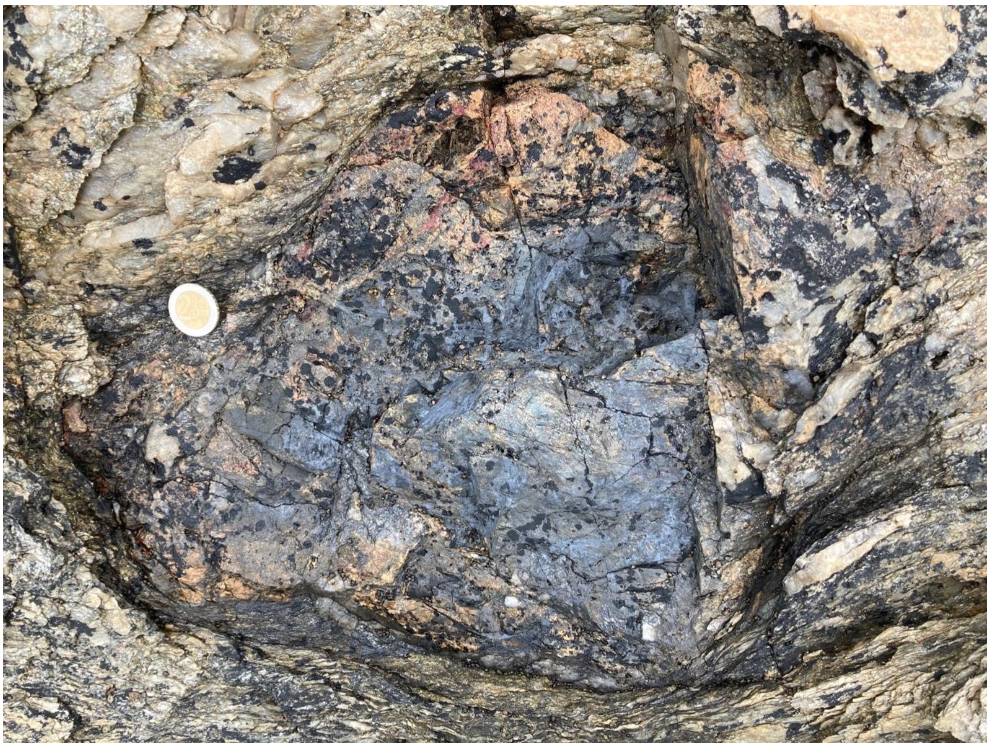


Figure 1.9 - Manganiferous nodule. *The nodule consists mainly of manganiferous quartzites which, from the rim to the core, are successively rich in spessartine (pinkish), in piedmontite (reddish, due to* Mn^{3+}*) and probably in braunite (black). This could denote an increase in manganese valency from rim (*Mn^{2+}*) to core (*Mn^{3+}*).*

The origin of the manganiferous concentrations has not been explored in detail, but is most probably pre-metamorphic rather than syn-metamorphic as proposed by Chauris (1991). The pinkish quartzites and the piedmontite-bearing schists are reminiscent of the manganiferous quartzites so frequently observed on top of the ophiolitic sequences, for example in the western

Alps (*e.g.*, Chopin, 1978; Dal Piaz *et al.*, 1979; Martin & Kiénast, 1987; Tumiati *et al.*, 2010, 2015) and the Apennines (*e.g.*, Bonatti *et al.*, 1976; Cortesogno *et al.*, 1979), an analogy already stressed by Kiénast & Triboulet (1973). In the Alps and the Apennines, the quartzites derive from radiolarites, but such fossils are not observed in the Ile de Groix, certainly due to too intense metamorphism. Other possible equivalents would be the microbanded cherts from the Franciscan Complex (Huebner & Flohr, 1990), which are thought to result from the hydrothermal activity in the ocean floor.

The manganese-rich nodules of Groix (Fig. 1.9) bring to mind, by their mineralogy and their geological environment, the famous and much wider deposit of Praborna (Aosta Valley, Italian Alps), the type locality of the piedmontite which will be visited during the post-conference excursion. At Praborna, the initial chemical features, related to an oceanic hydrothermal environment, have been preserved despite the subsequent high-pressure metamorphism (Tumiati *et al.*, 2010, 2015). Such an oceanic hydrothermal origin can be envisaged, by analogy, for the nodules of the island of Groix, although the origin of the graphite-bearing manganiferous nodules remains more enigmatic.

1.3– Discussion

The metamorphic history of the two units of the island was studied in details by Bosse et al. (2002) and Bosse et al. (2005). It is characterized by an early episode in blueschists facies. The abundance and composition of garnet, as well as other indicators such as the presence of glaucophane-garnet-lawsonite-epidote associations or glaucophane-chloritoid association suggest that the upper unit was buried at higher pressure than the lower unit (Fig. 1.10). Assuming pressure as lithostastic only, peak pressure of 1.6–1.8 GPa for the upper unit and 1.4–1.6 GPa for the lower unit can be interpreted as maximum depth of ~60 km and ~40 km, respectively. The temperatures reached at such depths are relatively low (~ 450-500°C in the upper unit and ~400-450°C for the lower one). The corresponding geothermal gradient was therefore relatively low (about 5-10°C/km), at the time of the peak pressure. Such a cold gradient is characteristic of subduction zones. Blueschist of the Ile de Groix are the remnants rocks buried at depth in a subduction zone now exhumed at the surface.

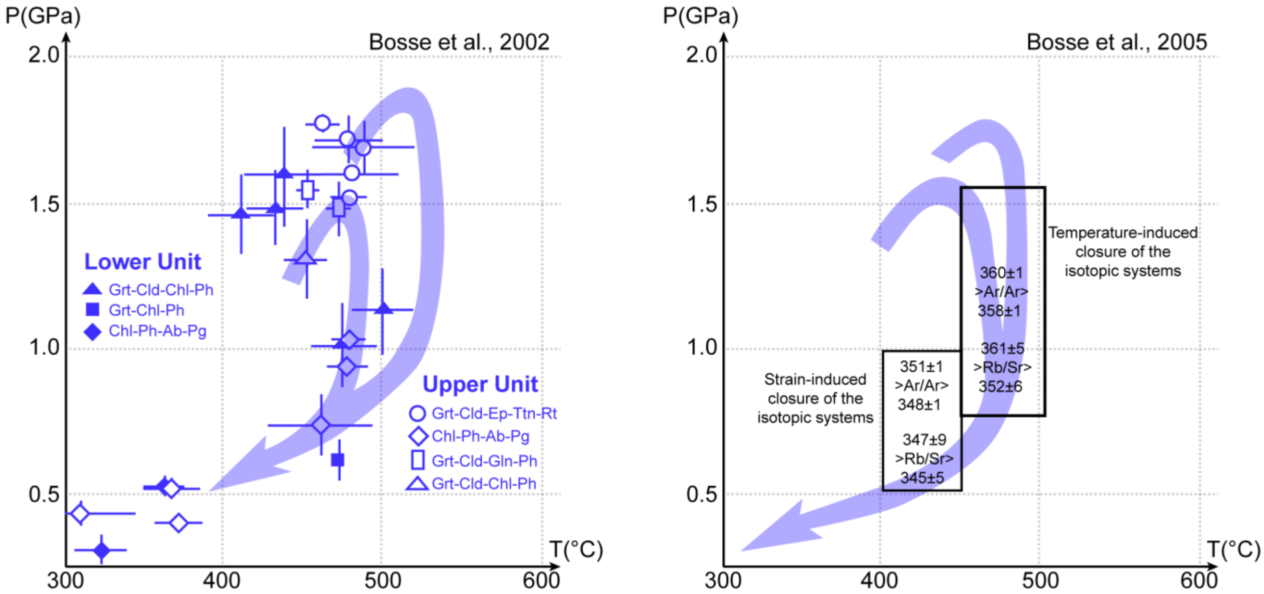


Fig. 1.10 - P-T-t data for the Ile de Groix units *(from Bosse et al., 2002 and Bosse et al., 2005).*

The age of metamorphic peak was established using isotopes in metamorphic minerals (Fig. 1.10). Sm-Nd isochrones could not be obtained, probably because the minerals were not isotopically in equilibrium for this system. The oldest ages obtained by Rb-Sr and Ar-Ar methods suggest that the high-pressure episode occurred at 358–366 Ma (Bosse et al., 2005), i.e. during the late Devonian.

It is also interesting to note that Ile de Groix blueschists have preserved the kinematic record of both subduction and exhumation as a function of lithology (Philippon *et al.,* 2009). Shear criteria synchronous with prograde HP and retrograde greenschist metamorphism are directed to the southeast and northwest, respectively (stretching lineations oriented in a N150°E±30° direction). The top-to-southeast shear is coeval with prograde HP metamorphism and precedes a top-to-northwest shear that coeval with a retrograde metamorphic path. This is a beautiful example of the switch in the state of stress that can occur between burial-related compression (*i.e.*, thrusting related to a northward dipping subduction) and extension at the onset of exhumation (controlled by a northward dipping extensional detachment). For the record, Ile de Groix is the first place where the concept developed later in Yamato and Brun (2017) was discussed during a fieldtrip with students. Jean-Pierre Brun passed away in October 2019. We would like to spare a thought for him here.

The P-T evolution of Ile de Groix blueschists can be considered as indicating the subduction of an oceanic lithosphere (Matte and Mattauer, 1978; Quinquis, 1980). However, no ophiolitic sequence can be identified in the Ile de Groix blueschists, and some of the rocks that should be observed in ophiolitic sequences, like gabbros for instance, are lacking or very rare (e.g. peridotites). Only few isolated outcrops of serpentinites are known along the northern coast (e.g. Le Bail, 1970; Makanjuola and Howie, 1972; Quinquis, 1980).

For this reason, Ile de Groix blueschists have rather been considered either as a mélange between oceanic volcanic material and continentally-derived sedimentary material (Bernard-Griffiths et al., 1986; Audren & Triboulet, 1986), as deposited in a continental rift (Thiéblemont and Triboulet, in Audren et al., 1993, p. 64), or representing an accretionary prism (Ballèvre et al., 1998).

Several arguments (e.g., huge volume of detrital sediments, presence of pinkish quartzites interlayered within the micaschists, no evidence of tectonic contact between mafic and sedimentary materials) lead to the conclusion that Groix would actually represent a large oceanic accretionary prism (Ballèvre et al., 2007, 2009), with many oceanic metasediments including pre-metamorphic manganiferous and ferrous mineralizations, metabasites and serpentinites.

Concerning the age of the protoliths, three arguments support the idea that they are all Paleozoic (Ballèvre et al., 2013): (1) the metacherts, if they are metaradiolarites, necessarily indicate a Paleozoic age because the Radiolarians appear in the Cambrian, and highly diversify during the Ordovician; (2) no evidence of poly-metamorphism is known in the rocks of Ile de Groix (or Dumet or Bois-de-Cené). This indicates the absence of any previous metamorphic event, either because the sedimentation and volcanism are Paleozoic, or because the sedimentation and volcanism, if Proterozoic, were located in a domain south of the Proterozoic active margin, where the Cadomian chain was developed.(3) rare levels of albitic orthogneisses, possibly derived from acidic tuffs or aplitic veins, have provided an age of ~480 Ma (U-Pb on-zircon), indicating that sedimentation is either contemporaneous with the tuffs, or predates the veins injection (El Korh et al., 2012).

To open the discussion, we can note that this age of ~480 Ma for an orthogneiss that does not seem to have recorded high pressure raises question. In the following of the excursion, we will see several examples of gneisses (e.g. Grezay in Les Essarts, La Picherais in Champtoceaux) older than the high pressure event affecting them. In these two cases, we will see that beautiful reaction coronas developed, which has not been described here. Why?

2
Eclogites and eclogite-facies gneisses from Les Essarts Unit (Vendée)

The eclogite-bearing metamorphic complex of Vendée (Southern Armorican Massif, Western France) is a typical example of eclogite-facies metamorphism in the Hercynian belt of Europe. It is well known for the abundance and variety of its eclogites, but is difficult to study because of very poor exposure conditions. In the last four decades, these eclogites have been interpreted in terms of plate tectonics, and considered as being remnants of an old oceanic crust, eclogitized during an eo-Hercynian subduction stage and subsequently incorporated into the Hercynian orogenic belt during a continental collision. The oceanic origin of the Vendée eclogites has been widely accepted, but investigations have pointed out some difficult questions: In particular, the surrounding ortho- and para-gneisses, some of which record two orogenic cycles, are typical of a continental crust, so we need to explain how oceanic eclogites came to be intimately interleaved within such continental gneisses.

The field trip in this region lasts one day (July 8^{th}, 2022) and includes 8 stops that will allow to observe the eclogites and their surrounding gneisses. Here, we first present an overview of the geological framework and studies, before describing the rocks observed at each stop. The origin and geological history of this metamorphic complex are shortly discussed in the last section.

2.1 – Geological overview

2.1.1- *History of geological and petrological studies*

Auguste Rivière discovered the Vendée eclogites in the 1830s and described them together with amphibolites and gneisses of the same region (Rivière, 1835, 1844a, 1844b, 1851). This finding was one of the very first discoveries of eclogite, a few years after René-Just Haüy (1822) had coined the term "eclogite". François Dubuisson (1830) also knew of some eclogites in "Loire-Inférieure" (now Loire-Atlantique), but he did not identify them with Haüy's "eclogite". All these studies were rather rudimentary because they were performed without the polarizing microscope. In 1880, Charles Whitman Cross, a young American student who would later become known for the invention of the CIPW norm, visited the region where he sampled some "eklogit" and amphibolites described in his dissertation thesis, defended at Leipzig University (Cross, 1881).

Indeed, it was Alfred Lacroix (1891) and Charles Baret (1898, 1900) who made the first real petrographic descriptions of the Armorican eclogites. Lacroix entrusted Yvonne Brière, one of his students, with the task of making a detailed study of these rocks. Brière's doctoral thesis (1920) was dedicated to the study of all the eclogites in France and the colonies, but was mainly concerned with the Armorican eclogites. In addition to describing the main occurrences of these rocks, she also made a detailed mineralogical study of them. By highlighting a trend typical of gabbros in their chemical composition (*i.e.*, the tholeiitic trend), she concluded that these rocks had resulted from the metamorphism of gabbroic rocks, in opposition to Eskola's ideas about the magmatic origin of the Norvegian eclogites. Such a metamorphic origin is widely accepted nowadays, but the members of Brière's doctoral dissertation jury at La Sorbonne University harshly criticised this conclusion at the time (Brière, pers. comm.). After Brière's classical work, few studies on these eclogites were undertaken for a long time (Christophe-Michel-Lévy, 1962; Velde & Sabatier, 1972).

Meanwhile, several researchers carried out fieldwork and geological mapping. They provided evidence that the Vendée eclogites, amphibolites and associated gneisses belong to a NW-SE-directed terrain that is bounded by micaschists to the SW and Carboniferous sediments to the NE. Thus, they considered the eclogite-bearing terrain as the core of an anticline.

In the 1970s, plate tectonics produced a revival of interest in eclogites because of their geotectonic implications. Thus, on the basis of rare-earth element patterns, Montigny & Allègre (1974) proposed that the Vendée eclogites were remnants of an old oceanic crust metamorphosed in a palaeo-subduction zone. Javoy & Allègre (1967) and Javoy (1971), studying O isotopic compositions, reached a similar conclusion. Petrological (Godard, 1988) and geochemical studies (Bernard-Griffiths & Cornichet, 1985) also strengthened this hypothesis. Concomitant geochronological work (Peucat *et al.*, 1982) provided a date of 436 ± 15 Ma (U-Pb method on zircon; lower intercept age) that was doubtfully interpreted as the age of the high-pressure (HP) metamorphism, ascribed to an eo-Hercynian subduction.

Further mineralogical and structural studies (*e.g.*, Godard & Smith, 1999; Godard & Van Roermund, 1995; Mauler *et al.*, 2001) were performed on the eclogites, which came to be considered as fragments of an oceanic palaeocrust metamorphosed during subduction and subsequently involved into a Hercynian continental collision. The study of the surrounding para- and ortho-gneisses (Godard, 2001, 2009) revealed that these underwent two orogenic cycles, the first being characterized by a high-temperature evolution typical of a continental crust, with migmatization of metapelites and intrusion of granitoids, and the second causing a HP eclogite-facies metamorphism comparable to that observed in the neighbouring eclogites.

2.1.2- *Geological framework*

Les Essarts HP Unit is made of eclogites and amphibolites derived from eclogites, as well as ortho- and para-gneisses with HP relics (Fig. 2.1). Foliation in Les Essarts Unit is almost subvertical, while stretching lineation is slightly dipping towards NW. Foliations in eclogite and gneiss are similar, suggesting that these rocks deformed simultaneously. Strong unconformity between the two rocks seldom occurs, however (*e.g.*, NW end of La Gerbaudière quarry: Fig. 2.1), due to a difference in rheology between eclogite and gneiss, which produced a boudinage effect.

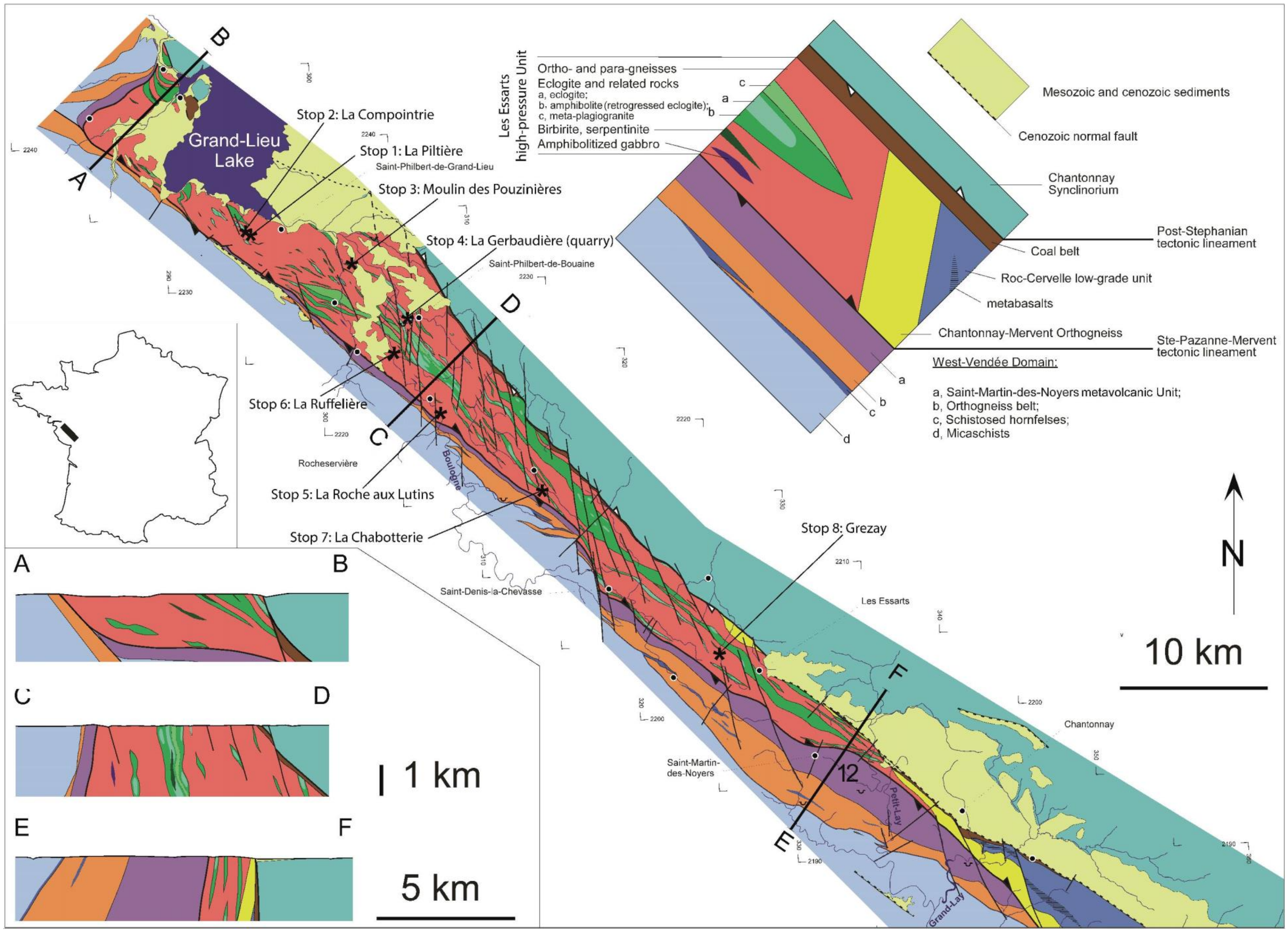
Les Essarts Unit extends in a narrow zone about 150 km long and a few km wide showing a NW-SE trend (Figs. 1 and 2), bounded by two late-Hercynian tectonic lineaments, the Vendée coal belt, to the NE, and the Sainte-Pazanne-Mervent tectonic lineament, to the SW.

The Vendée coal belt extends over 120 km on the NE side of the HP unit, from Port-Saint-Père near Grand-Lieu Lake (NW) to Saint-Laurs (SE), where it disappears under the Jurassic cover of the Aquitaine Basin. Coarse clastic unmetamorphosed deposits (conglomerates, sandstones, schists) constitute the main part of the succession, which also includes intercalations metre-thick coal layers. The continental fossil flora preserved in sediments indicates two episodes of sedimentation, namely Namurian and Westphalo-Stephanian (Upper Carboniferous). The pebbles of the conglomerates are primarily quartz, schists and gneiss, but pebbles of weathered amphibolite and eclogite have also been observed, indicating that some of the eclogites had reached the surface by the Stephanian (around 300 Ma). Although rarely exposed, the contact between the Carboniferous and the Les Essarts HP unit seems to be a sedimentary unconformity that has been reworked and tilted by tectonics, bringing the carboniferous strata into a sub-vertical position.

The NE contact of the Carboniferous coal belt is clearly tectonic, being marked out by a 100-m-wide zone of cataclased schists, greywackes and gneisses. This late-Hercynian tectonic lineament separates the coal belt and the eclogite-bearing Les Essarts Unit (SW) from the Chantonnay Synclinorium (NE). The sequence of the latter includes, from bottom to top, a metaophiolite sequence of serpentinized peridotites overlain by a km-thick amphibolite-bearing zone, Cambrian (?) greywackes and metapelites, ignimbrites, Ordovician (?) quartzites, Siluro-Devonian phtanites and shales. The core of the syncline is composed of Devonian (?) metabasalts with back-arc affinity, in which pillow-lavas have been observed. Metamorphism is late-Hercynian and ranges from low to medium grade (chlorite to biotite-bearing micaschists), in strong contrast with the eclogite-facies metamorphism of the neighbouring HP Les Essarts Unit.

On its SW side, Les Essarts HP Unit is bounded by the Sainte-Pazanne-Mervent tectonic line (Fig. 2), marked by mylonites and ultra-mylonites, approximately 100 meters thick, over a length of more than 150 km. To the SW, beyond this tectonic line, the Saint-Martin-des-Noyers metavolcanic unit (amphibolite, amphibole-bearing gneiss, metapelites), an orthogneiss belt (Ordovician metagranitoid), and the Saint-Gilles micaschist Unit belong to a synform whose core contains the blueschists-facies unit of Bois-de-Céné, equivalent to that of Groix island.

Figure 2.1.- Geological map of Les Essarts Units. **: visited sites (next page).*


Grand-Lieu Lake
Stop 1: La Piltière
Stop 2: La Compointrie
Stop 3: Moulin des Pouzinières
Stop 4: La Gerbaudière (quarry)
Stop 5: La Roche aux Lutins
Stop 6: La Ruffelière
Stop 7: La Chabotterie
Stop 8: Grezay
Saint-Philbert-de-Grand-Lieu
Saint-Philbert-de-Bouaine
Rocheservière
Boulogne
Saint-Denis-la-Chevasse
Les Essarts
Chantonnay
Saint-Martin-des-Noyers
Petit-Lay
Grand-Lay
12
Les Essarts high-pressure Unit
Ortho- and para-gneisses
Eclogite and related rocks
a, eclogite;
b, amphibolite (retrogressed eclogite);
c, meta-plagiogranite
Birbirite, serpentinite
Amphibolitized gabbro
Mesozoic and cenozoic sediments
Cenozoic normal fault
Chantonnay Synclinorium
Post-Stephanian tectonic lineament
Coal belt
Roc-Cervelle low-grade unit
metabasalts
Chantonnay-Mervent Orthogneiss
Ste-Pazanne-Mervent tectonic lineament
West-Vendée Domain:
a, Saint-Martin-des-Noyers metavolcanic Unit;
b, Orthogneiss belt;
c, Schistosed hornfelses;
d, Micaschists
A B
C D
E F
1 km
5 km
10 km
N

2.2 – Description of the sites visited

The field trip begins at Saint-Philbert-de-Grand-Lieu and ends at Grezay, near Les Essarts, following a NW-SE route (see Fig. 2.1 for the position of the stops), which makes it possible to observe the different types of eclogites and their surrounding gneisses.

Stop 1: La Piltière, Saint-Philbert-de-Grand-Lieu (47°02'06" N – 1°39'44" W).

It was near La Piltière that the spectacular rock known as La Compointrie eclogite was discovered and first described by Charles Baret (Baret, 1900). In the garden and on the walls of the house (please, do not sample!), we observe blocks of a beautiful rock, which could compete for the title of "Miss Eclogite" (Fig. 2.2). It is made up of crystals of a pyrope-rich pink garnet, several centimeters in diameter, emerald green omphacite, bluish kyanite, clear amphibole with a pearly luster (magnesiohornblende), zoisite, rutile and accessory pentlandite.

This eclogite, which has the composition of an Mg-rich olivine leucogabbro, corresponds to the cumulative and magnesian pole of a tholeiitic magmatic series (Fig. 2.3; Godard, 1988). Norm calculations showed that the pre-eclogitic gabbroic rock consisted of calcic plagioclase ($\sim An_{62}$), diopside and olivine. The cumulative origin is evidenced by the richness in Cr and Ni (up to 1180 and 200 ppm, respectively), the low content in rare earth elements, and a strong positive anomaly in Eu (Eu/Eu* = 1.76: Fig. 2.3; Bernard-Griffiths & Cornichet, 1985; Godard, 1988).

Some metamorphic reactions can be seen with the naked eye (Fig. 2.2). The garnet crystals are surrounded by a dark mm-thick corona, rich in amphibole. The translucent crystals of omphacite, of a beautiful emerald green colour, are surrounded by a matte greenish to whitish border, appearing to consist, under the microscope, of a diopside+plagioclase symplectite. Kyanite is partially or totally replaced by a pink to whitish cryptocrystalline symplectite, mainly formed of anorthite + corundum ± spinel. Finally, at the contact between magnesio-hornblende and kyanite, a fine corona of margarite and preiswerkite, a rare trioctahedral sodic mica, is sometimes visible under the microscope (Godard & Smith, 1999). All these transformations, subsequent to the eclogite-facies paragenesis, are linked to rehydration and decompression of the rock, and therefore to its retrograde exhumation.

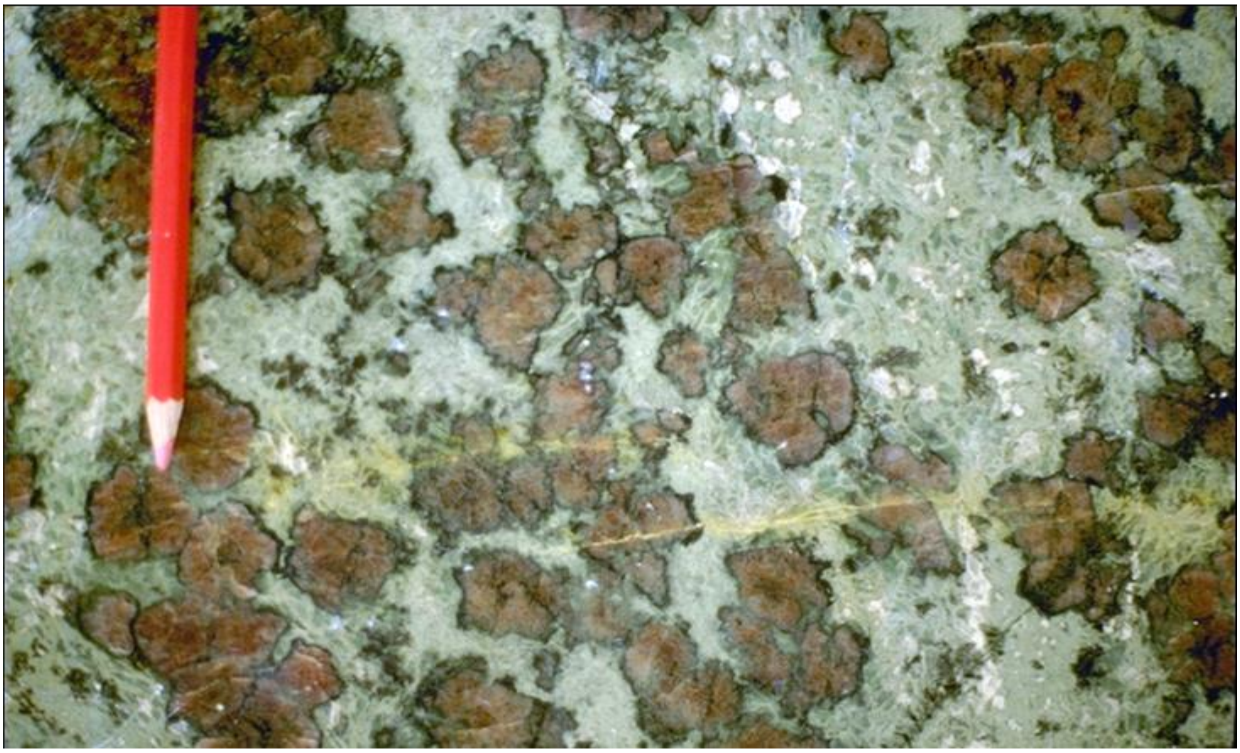


Figure 2.2- La Piltière Mg-rich eclogite. *The whitish spots are pseudomorphs after kyanite; each omphacite crystal is surrounded by a matte greenish border (Cpx+Albite symplectite), and a dark amphibole-rich corona appeared at the garnet-omphacite interface (see text).*

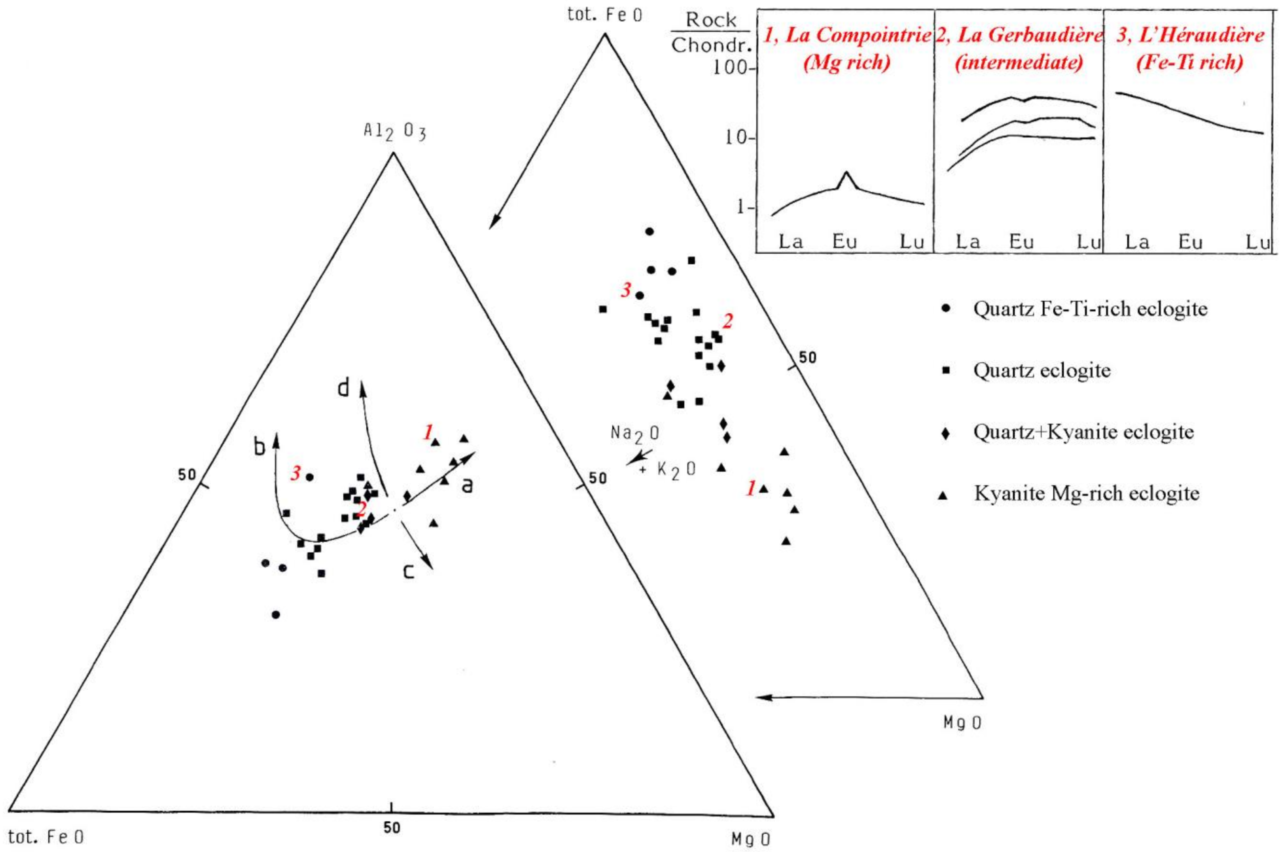


Figure 2.3- Chemical composition of the eclogites, showing the tholeiitic differentiation of their protolith. *a+b: tholeiitic series (a: cumulative trend; b: fractionation trend); c+d: calc-alkaline series (c: cumulative trend; d: fractionation trend); 1, 2, 3 refer to the same samples as the REE patterns; after Godard (1988). By highlighting this differentiation, typical of gabbroic and basaltic rocks, Yvonne Brière (1920) sustained the thesis of a metamorphic origin for these eclogites.*

<u>Stop 2</u>: La Compointrie, Saint-Philbert-de-Grand-Lieu.

At La Compointrie, leave on the right the street called *Chemin de l'éclogite* to walk to the vineyards located to the northwest of the village. These vines cover a small hill resulting from the resistance to erosion of a km-long lens of eclogite, in which numerous blocks of eclogite can be sampled.

In two places (47°02'12" N – 1°40'30" W; 47°02'18" N – 1°40'35" W), one can observe the same Mg-rich type of kyanite eclogite of La Piltière (Stop 1). In the rest of the lens, a more ordinary omphacite-garnet-quartz-bearing eclogite abounds, similar in composition to oceanic rocks (N-MORB composition; intermediate terms in Fig. 2.3).

At one location (47°02'12" N – 1°40'37" W), one can observe skeletal cm-sized "hollow" garnet crystals that have encompassed part of the omphacite-rich matrix, which was thus preserved from subsequent syn-eclogite-facies deformation thanks to the rigidity of garnet (Fig. 2.4; Godard & van Roermund, 1995; Mauler *et al.*, 2001). One of these hollow garnets was broken during deformation (G *in* Fig. 2.4), resulting in ductile deformation of part of the originally protected omphacite. This resulted in a transition between undeformed omphacite (A *in* Fig. 2.4: fine-grained omphacite without significant crystallographic preferred orientation [CPO]) and deformed omphacite from the matrix (B *in* Fig. 2.4: coarse-grained omphacite with a strong CPO, wrapping around the broken end of the garnet G). The increase in grain size correlated with the deformation intensity (*i.e.*, transition from A to B *in* Fig. 2.4) strongly suggests that diffusion creep occurred during the deformation of omphacite.

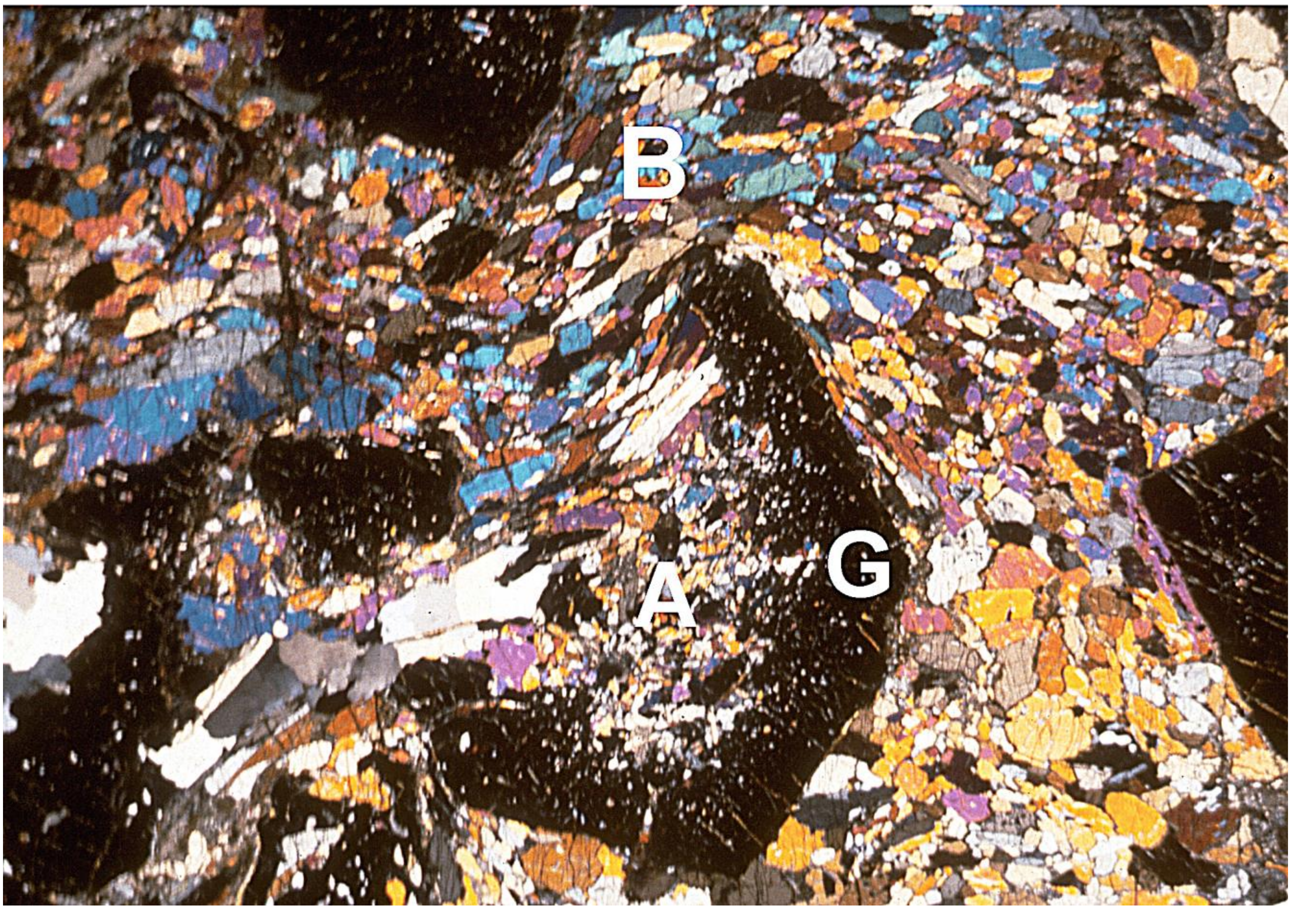


Figure 2.4- Microstructure of omphacite enclosed in a skeletal hollow garnet that has been broken during deformation. *G, broken hollow garnet; A, fine-grained omphacite (+ quartz + rutile) protected from deformation by garnet G, without significant crystallographic preferred orientation [CPO]; B, coarse-grained omphacite (+ quartz + rutile) strongly deformed, showing a clear CPO ("L-type") and wrapping around garnet G. The microphotograph is 1.8 cm large; cross-polarized light; sample C22 from Godard (1988), Godard & van Roermund (1995), Mauler et al. (2001).*

<u>Stop 3</u>: Moulin des Pouzinières, Saint-Colomban (47°01' N – 1°35' W).

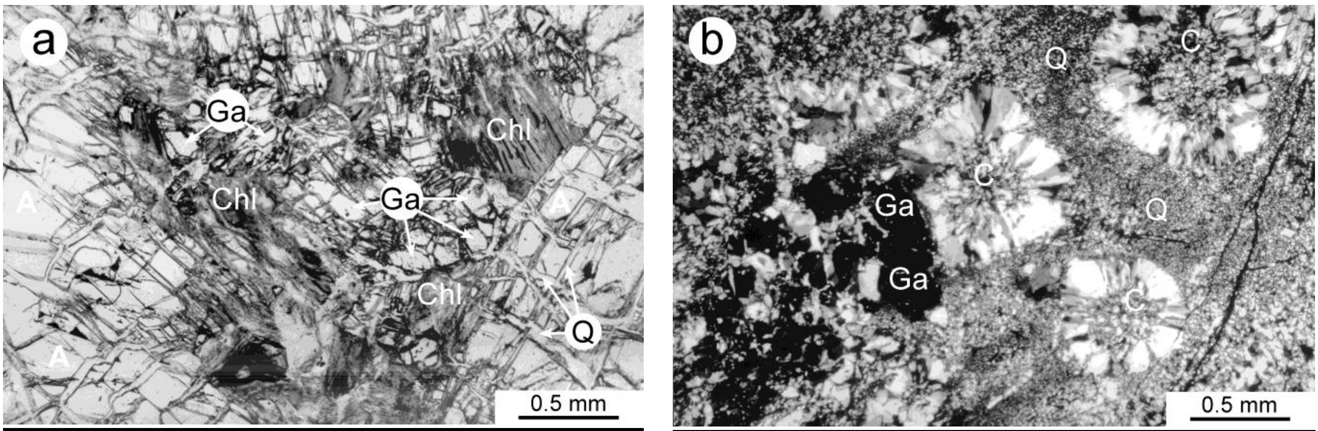


Figure 2.5- Relict ultramafic rock (a) within silicified "birbirite" (b). *Ga: pyrope-rich garnet; Chl: chlorite; A: anthophyllite; Q: quartz (as veinlets in a; cryptocrystalline in b); C: spherical structures of radiated and fibrous chalcedony. Plane-polarized (a) and cross-polarized (b) light. Moulin des Pouzinières.*

Some altered, silicified peridotites, also called "birbirites", are commonly associated with the eclogites. Birbirite is a brownish, iron-bearing, quartzitic rock named by Duparc *et al.* (1927). It is characterised by colloform textures, in which chalcedony and fine-grained quartz occur alongside colloform masses of limonite (Fig. 2.5b). It results from the superficial alteration, hydration and Mg-leaching of peridotite or serpentinite during tropical weathering (*e.g.*, Augustithis, 1965, 1967; Plyusnina *et al.*, 1983). Here, this transformation likely occurred during Palaeogene, a period of tropical weathering in the Armorican Massif. The ultramafic protolith can be recognized in the form of a few rare mineral relics (serpentine, anthophyllite, fuschite, talc) and, occasionally, the "snakeskin" structure that results from the pseudomorphosis of former olive grains.

Near Moulin des Pouzinières, some loose blocks of an ultramafic rock essentially made up of anthophyllite (X_{Mg} = 0.85) occurs among such birbirite (Fig. 2.5a). They also contain relics of garnet (Pyr_{54} Alm_{33} $Gross_{7}$ $Spess_{2}$ $Uvar_{2}$ $Andr_{2}$) that is partly replaced by a kelyphitic corona of chlorite (penninite; Fig. 2.5a). Although suitable *P-T* estimates are not possible due to the high degree of retrogression and alteration, we can infer that the rock likely derived from an eclogite-facies garnet-bearing pyroxenite or peridotite.

Although "petrologically dead", these rocks indicate that there may have existed even more magnesian terms (*i.e.*, garnet peridotites) than the Mg-rich kyanite eclogites (see stops 1, 2), in the cumulative trend of Figure 2.3.

Stop 4: La Gerbaudière quarry, Saint-Philbert-de-Bouaine (46°59' N – 1°32' W).

The largest outcrop of eclogite in Vendée is unquestionably La Gerbaudière quarry, in Saint-Philbert-de-Bouaine, which is dug in an eclogite lens of several km in length (Figs. 2.1 & 2.6). The quarry is operated by the compagny *Carrière et Matériaux du Grand-Ouest*, which kindly welcomes us to the site, and produces aggregates for concretes and road construction. Eclogite is also appreciated for rock filling and ripraps (seawalls, piers) along the Atlantic coast, because its high density makes it resistant to the action of the waves. It is also rarely used as an ornamental stone; for example, the stela dedicated to René-Just Haüy, the inventor of the word eclogite, at Saint-Just-en-Chaussée (northeast France), is an eclogite block from La Gerbaudière.

General overview

We can have a general view of the quarry from a belvedere overlooking the quarry from the SE (46°58'59" N – 1°31'42" W), or from a platform (46°59'03" N – 1°32'00" W) facing the entrance gate, near the SW front of the quarry. The quarry appears oriented NW-SE, parallel to the eclogite lens (Fig. 2.6). The average foliation of the rocks is oriented in the same direction, with a dip that gradually evolves from sub-vertical on the southwest side of the quarry to NE 60 on the northeast side, suggesting downward rooting of the lens.

10 m thick bands of gneiss are present within the eclogite lens, but are difficult to distinguish by their purplish-gray colour. These gneissic bands show a symmetrical arrangement which could reflect their isoclinal folding within the eclogites. The comparison of two geological maps of the quarry drawn 8 years apart (Fig. 2.6A versus 2.6B) indeed shows that the downward progression of the exploitation resulted in the partial junction of the two main bands of gneiss, suggesting the closure of an isoclinal fold downwards.

The eastern end of the quarry is affected by a very intense cataclasis, linked to a late-Hercynian north-south fault which, under the Issoire river, shifts the lens with an apparent dextral offset. A set of late fractures, oriented N 60 and dipping SE, results in regular planes that are easily followed from one level of the quarry to another.

In the northwest end of the quarry, the foliations internal to the eclogite lens draw a large open fold, which does not seem to affect the gneisses outside the lens (Fig. 2.6). This strong disharmony between the internal and external structures of the eclogite lens could result from a boudinage effect.

Finally, the upper levels of the quarry, on the northwest side, appear coloured in beige over a thickness of ten meters. This altered zone is topped by a layer of sands and gravels deposited by a palaeo-river whose delta covered the region during the Ypresian (lower Eocene) (Godard *et al.*, 1994), an epoch known for its tropical weathering in the region. In this upper part, the gneisses are weathered and crumbly, while the eclogites, being devoid of feldspar, have resisted weathering better.

Figure 2.6- Geological maps of La Gerbaudière quarry. *A, in April 1999; B, in June 2007*

Outcrops

The access path to the quarry, on the left, makes it possible to observe the gneisses hosting the eclogite lens. These are very deformed gneisses, which seem partly derived from some granitoid since in places small *augen* of potassium feldspar are observed. The contact between these gneisses and the eclogite is visible at the northwest entrance to the quarry, on either side of the path (46°59'05" N – 1°32'03" W; 46°59'06" N – 1°32'04" W). Amphibolites, about 2 metres thick, mark the contact; mineral foliation and lineation in gneiss, amphibolite and eclogite have similar orientations here (Fig. 2.7a). The presence of at least 30 cm of amphibolite at the gneiss-eclogite interfaces is a general observation in the quarry, which reflects the hydrated retromorphosis of the eclogite at contact with the gneiss.

Beyond this contact, the working faces of the quarry show various eclogite facies, often well preserved but sometimes more or less retrograded. The most common facies is an eclogite with garnet, omphacite, hornblende, quartz and rutile, banded and foliated, whose garnet crystals reach 3 to 5 mm in diameter (Fig. 2.8). Epidote and kyanite are visible in a few zones (Ky *in* Fig. 2.6A). A particular eclogite, with cm-sized garnets, shows pseudomorphs after kyanite, but is quite retrograded.

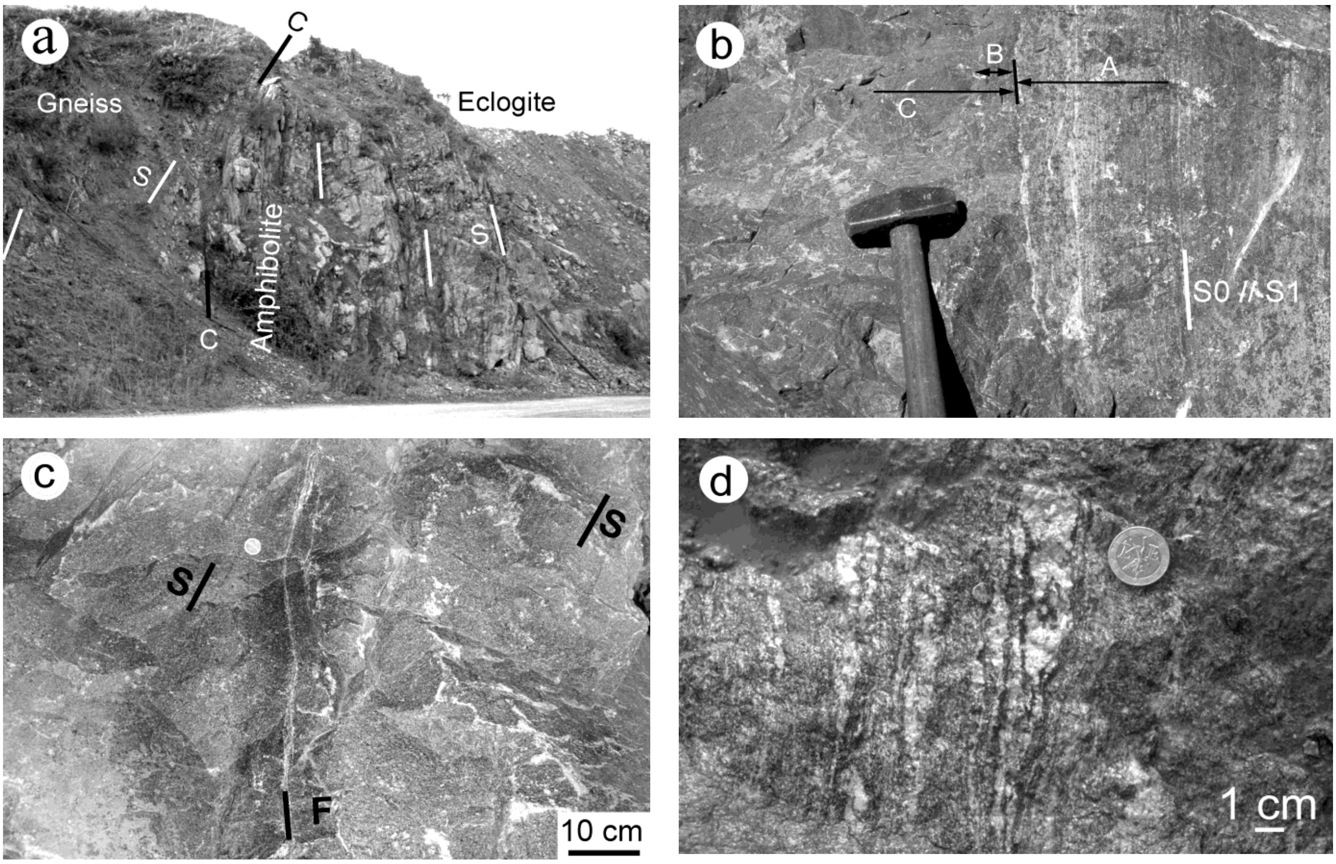


Figure 2.7- Outcrops in La Gerbaudière quarry (Saint-Philbert-de-Bouaine)

(a)- Contact (C) between gneiss and eclogite, at the NW corner of the quarry. S: foliation in the gneiss and eclogite.

(b)- Compositional layering (S0) in the eclogite. A: coarse-grained banded eclogite; B: fine-grained garnet-rich eclogite; C: fine-grained massive eclogite; B resembles a "chilled margin" structure that could be inherited from the pre-eclogite rock; the layering (S0) was transposed parallel to the syn-eclogite-facies foliation (S1).

(c)- Amphibolitisation (dark zone) occurring along a late fracture (F) cutting across the syn-eclogite-facies foliation (S).

(d)- Paragneiss interleaved within the eclogite. A few leucosomes are parallel to the foliation in the gneiss and surrounding eclogite. Incipient migmatisation seems to have occurred after the eclogite-facies metamorphism.

Going towards the NE side of the quarry, one can reach the gneiss bands visible within the lens of eclogite (Fig. 2.6). Purplish brown in colour due to the abundance of biotite, these paragneisses are formed of quartz, biotite, plagioclase, garnet, without K-feldspar. A beginning of melting results in a few leucosomes, which have been observed in them (Fig. 2.7d). Their foliation parallels that of the host eclogites, but no relics of HP metamorphism have been observed in these rocks. It is likely that these gneisses were reequilibrated under amphibolite-facies *P-T* conditions, as suggested by the abundance of plagioclase and the systematic amphibolitisation of eclogites in contact with them.

The progression of the exploitation sometimes makes it possible to observe very rare quartz veins, a few cm in thickness. In addition to quartz, these contain large flakes of phengite, sometimes dm-sized kyanite crystals and more rarely rutile or zoisite. These veins, always parallel to the syn-eclogitic foliation and containing minerals stable in eclogite-facies conditions, could have formed from early fluids.

Petrological evolution

La Gerbaudière eclogite is formed of subhedral crystals of garnet, with an average size of 0.4 cm, arranged in a foliated matrix consisting mainly of green omphacite and quartz. Some dark hornblende crystals are often aligned parallel to the syn-eclogitic foliation (Fig. 2.8). Zoisite, clinozoisite, rutile, ilmenite, pyrite, chalcopyrite and calcite are accessory minerals, and some bands also contain kyanite (Ky in Fig. 2.6A). The rock shows compositional banding, likely inherited from the gabbroic protolith, and marked by alternating decimetric bands that differ mainly in the abundance and size of the garnet crystals (Fig. 2.7b). This banding has been transposed parallel to the syn-eclogitic foliation, which results in the elongation of millimetric crystals of omphacite, visible using a magnifying glass.

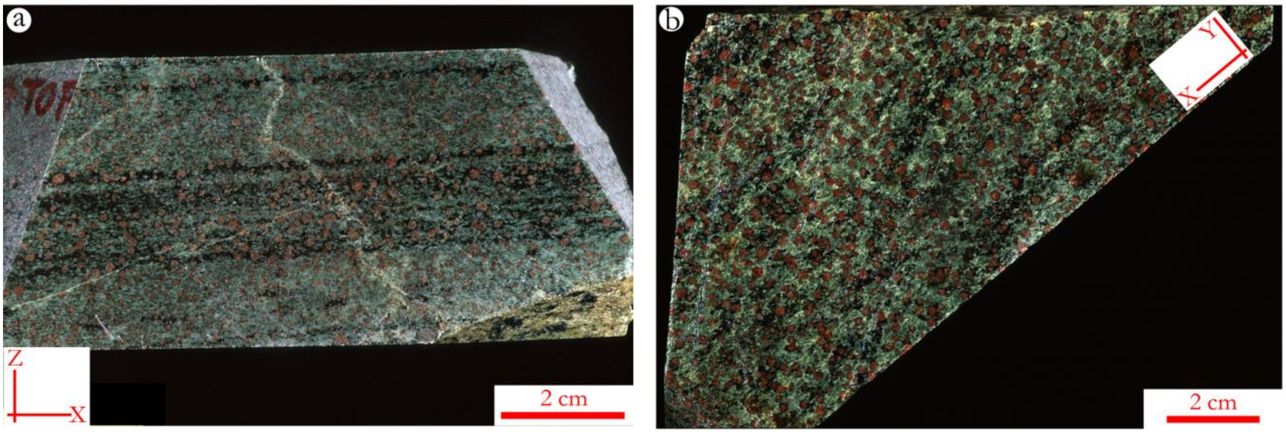


Figure 2.8- Eclogite specimen, showing a strong planar fabric. *La Gerbaudière quarry. Directions X, Y, Z are, respectively, parallel to the stretching lineation, perpendicular to the lineation in the foliation plane, and normal to the foliation.*

La Gerbaudière eclogite is representative of the average eclogite facies of Vendée. Its composition in major elements, traces and rare earths is that of a gabbro and makes it possible to relate its protolith to the tholeiitic series, of which it constituted an intermediate member between the Mg-rich cumulative rocks (Stops 1, 2) and the Fe-Ti-rich differentiated rocks (Stop 8) (Fig. 2.3; Godard, 1988). The REE contents are identical to that of N-type MORBs, and show a slight negative Eu anomaly (1>Eu/Eu*>0.9) (Fig. 2.3; Bernard-Griffiths & Cornichet, 1985).

The pre-eclogite evolution has sometimes been “fossilized” in the garnet crystals, in the form of microinclusions (Figs. 2.9 & 2.10). In some garnet crystals, these inclusions are arranged in distinct zoisite+quartz and rutile+amphibole+quartz zones (Fig. 2.9), which are interpreted as pseudomorphs after plagioclase and amphibole, respectively, and reveal the ophitic structure of the gabbroic protolith. This microstructure suggests that the latter had undergone amphibolitisation and saussuritisation, probably linked to oceanic metamorphism, before eclogitisation (Godard, 2001; see legend of Fig. 2.9). In other rocks, strongly-zoned euhedral garnet crystals (Grt_2 *in* Fig. 2.10), belonging to the eclogite paragenesis, have embedded oriented inclusions of amphibole, pyroxene, quartz, together with early anhedral garnet crystals (Grt_1 *in* Fig. 2.10). We interpret this structure as an early foliated paragenesis (with garnet Grt_1, amphibole, pyroxene…) belonging to an early stage of the prograde evolution.

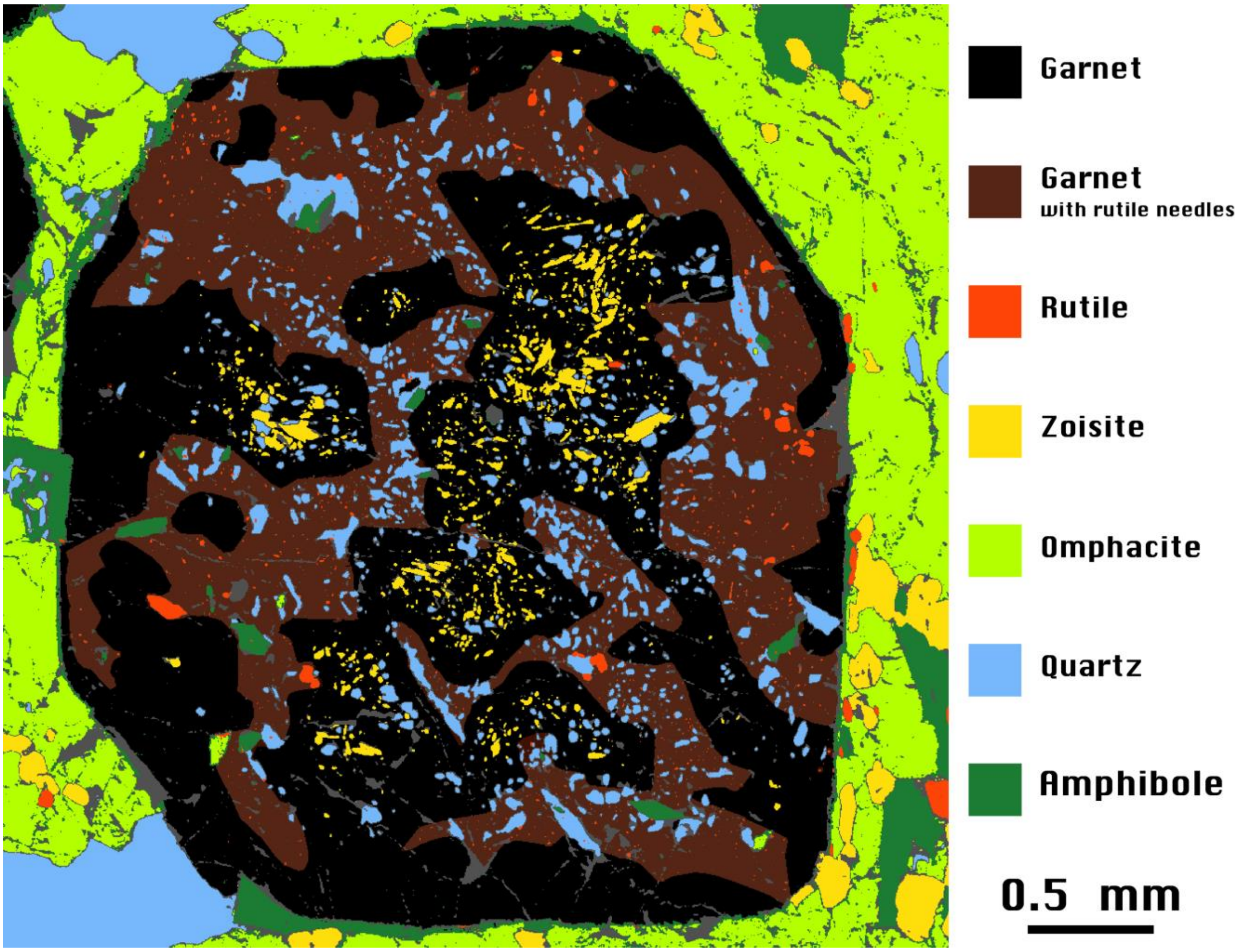


Figure 2.9- Microstructural relics of the pre-eclogite rock (1). *In some garnet crystals, the inclusions are arranged in zoisite+quartz zones and rutile+amphibole+quartz zones. These zoisite-rich and rutile-rich zones show sharp and regular boundaries that resemble the ophitic texture of a gabbroic rock, and are likely pseudomorphs after, respectively, the felsic and mafic parts of the protolith. Zoisite-rich zones could be relics of zoisite+albite pseudomorphs after magmatic plagioclase (i.e., "saussurite"); the preferred concentration of zoisite in the core of these zones could reflect a zoning of the former magmatic plagioclase, with an An-rich core. The rutile-rich zones are pseudomorphs after some Ti-bearing pre-eclogite mafic mineral, most likely amphibole, some of which was enclosed during garnet growth. These structures show that the pre-eclogite rock was here an amphibolitised and saussuritised microgabbro.*

The metamorphic peak conditions have been roughly estimated at T≈700°C and P>16 kbar (*e.g.*, Godard, 1988) but are better defined for the surrounding gneiss (Stop 8). Peucat *et al.* (1982) proposed an age of 436 ± 15 million years (Ordovician) for this metamorphism, using the U-Pb method on zircon. The eclogites then underwent a phase of ductile deformation under the conditions of the eclogite facies, which imprinted a strong mineral foliation and a more discreet lineation in the rock, resulting in a strong “SL-type” crystallographic preferred orientation of the omphacite (Godard & van Roermund, 1995; Mauler *et al.*, 2001).

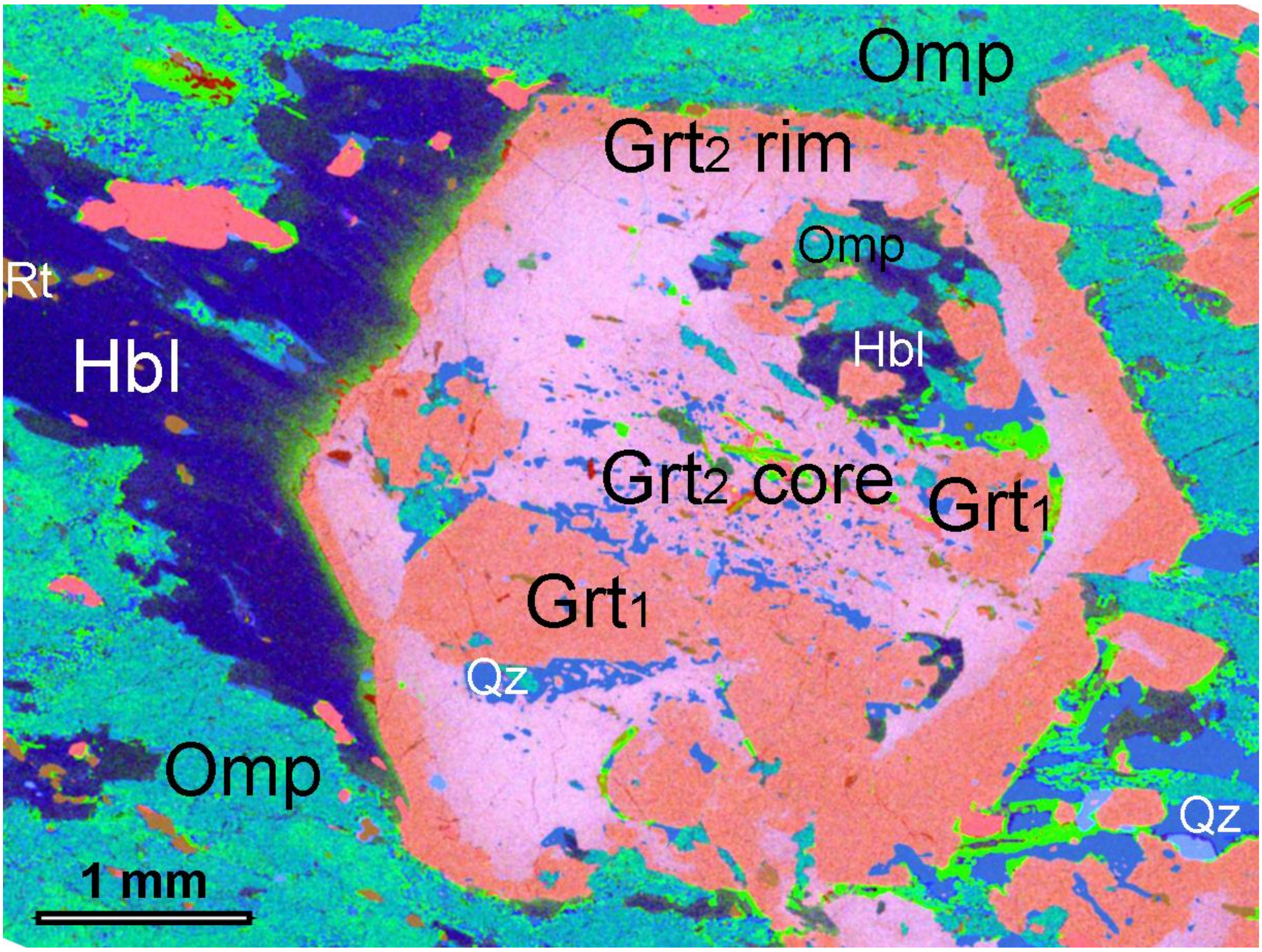


Figure 2.10- Microstructural relics of the pre-eclogite rock (2). *In some eclogite samples, subhedral garnet crystals are strongly zoned (Grt$_2$, with increasing X_{Mg} from core towards rim) and enclose numerous oriented inclusions of amphibole (Hbl), pyroxene (Omp), quartz (Qz) and a first generation of anhedral garnet (Grt$_1$). These inclusions are interpreted as belonging to a foliated garnet-bearing amphibolite that preceded the eclogite paragenesis.*

The rock underwent several transformations related to its exhumation. This retrograde metamorphism is manifested in particular by the destabilization of omphacite, whose grass-green translucent crystals are corroded by a greenish border, visible under a magnifying glass and which appears under the microscope as a symplectite of diopsidic clinopyroxene and albitic plagioclase, formed during the following decompression reaction:

1 Omphacite (Jd_xDi_{1-x}) + *x* Quartz → *x* Albite + *1-x* Diopside (with $x \approx 0.3$ to 0.4).

In some levels, this transformation of the omphacite is almost total ("retrograded eclogite" in Fig. 5). The rock is then lighter and has lost density (approximately 2.9 instead of 3.3).

Another retrograde reaction consists in the growth of amphibole (hornblende) as coronas around garnet crystals, in contact with omphacite:

Garnet + Omphacite + H_2O → Hornblende + Albitic plagioclase.

Amphibole and associated plagioclase may have more or less invaded the rock, which then takes on a dark colour, so that all the intermediates exist between eclogite and garnet amphibolite. Amphibolitization generally progresses from the contacts with gneiss, but also along fractures intersecting the syn-eclogitic foliation (Fig. 2.7c) and allowing the infiltration of water which acted as a reactant.

<u>Stop 5</u>: La Ruffelière, Saint-Philbert-de-Bouaine (46°57'43" N – 1°32'28" W).

The vast majority of the rocks that host the eclogite lenses consist of highly-deformed para- and ortho-gneisses (i.e., metapelites and metagranitoid), with micaschist appearance. These highly-foliated gneisses are particularly visible in the descent of La Gerbaudière quarry (Stop 4). However, at a few points, they are not or only slightly deformed, and the early structures and parageneses which are then preserved there reveal a complex poly-orogenic history (Godard, 2009). We will observe these exceptional rocks at La Ruffelière (Stop 5) and at Grezay (Stop 8).

The Ruffelière manor was destroyed in 1417, during the Hundred Years' War, rebuilt in the 1420s by Aliette de Polhay and Jehan de Goulaine, then burned down again in 1794 during the Vendée civil war (Aillery, 1914). The walls were built with a paragneiss showing dark pseudomorphs of cordierite several centimetres in size. We shall focus in particular on the slab forming the door sill of the postern, to the right of the main cart door, where a metapelitic rock shows dark cm-sized pseudomorphs after cordierite crystals, from which they have sometimes retained the pseudo-hexagonal shape (Fig. 2.11). The rock is known to be in place at some distance, on the other bank of the Boulogne River (46°58'04" N – 1°32'50" W). In the courtyard, one can observe an outcrop of migmatitic gneiss, showing alternations of leucosomes and melanosomes.

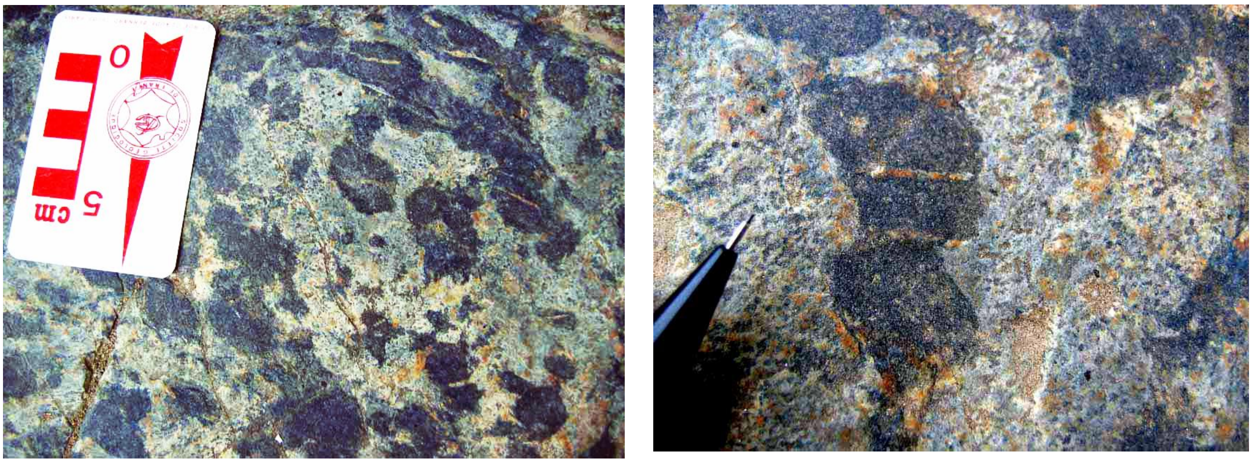


Figure 2.11- Pseudomorphs after cordierite in paragneiss (La Ruffelière). *A few pseudomorphs display the pseudohexagonal shapes of former cordierite.*

Under the SEM, cordierite appears totally replaced by a crypto-crystalline assemblage with kyanite + garnet + quartz ± micas. Microscopic garnet + phengite coronas formed at the contact between plagioclase and biotite crystals. If the formation of cordierite porphyroblasts and migmatisation are clearly the traces of a high temperature metamorphism, kyanite, garnet and phengite, appearing as pseudomorphs after cordierite and as coronas between biotite and plagioclase, are on the other hand due to the subsequent HP metamorphism. This complex metamorphic history will be presented in detail in Grezay (Stop 8), where similar rocks occur.

<u>Stop 6</u>: Roche-aux-Lutins, Rocheservière (46°55'57" N – 1°30'27" W).

The right bank of the Boulogne River, south-east of Rocheservière, offers remarkable outcrops of gneiss. There can be observed the gradual transition between a strongly-foliated gneiss (Lourdes grotto) and a less-deformed ortho-gneiss (after the bridge: Fig. 2.12). The metagranitic origin of this last rock is attested by the presence of large crystals of orthoclase, transformed into microcline but presenting perthitic lamellae and Carlsbad twins. Under the microscope, the ortho-gneiss does not show any of the HP reaction structures observed at La Ruffelière or Grezay (Stops 5 and 8). The age of the granitic protolith, determined by the U-Pb method on zircon (483 ± 4 Ma: C. Guerrot *in* Godard, 2001), dates back to the Cambrian-Ordovician boundary.

Two undeformed metabasite veins crosscut this ortho-gneiss almost parallel to its foliation (Fig. 2.12). This metabasite, mainly composed of schillerised clinopyroxene, plagioclase and brown amphibole, has preserved its magmatic microgranular texture. It underwent a very incomplete eclogitisation, which resulted in the growth of some metamorphic garnet and an enrichment of the magmatic clinopyroxene in jadeite (9 mol %) where it is in contact with the still-preserved magmatic plagioclase (Godard, 2001).

This outcrop illustrates a fact that is still poorly explained: the preservation within Les Essarts Unit of rocks almost free of eclogite-facies metamorphism among other totally eclogitized rocks.

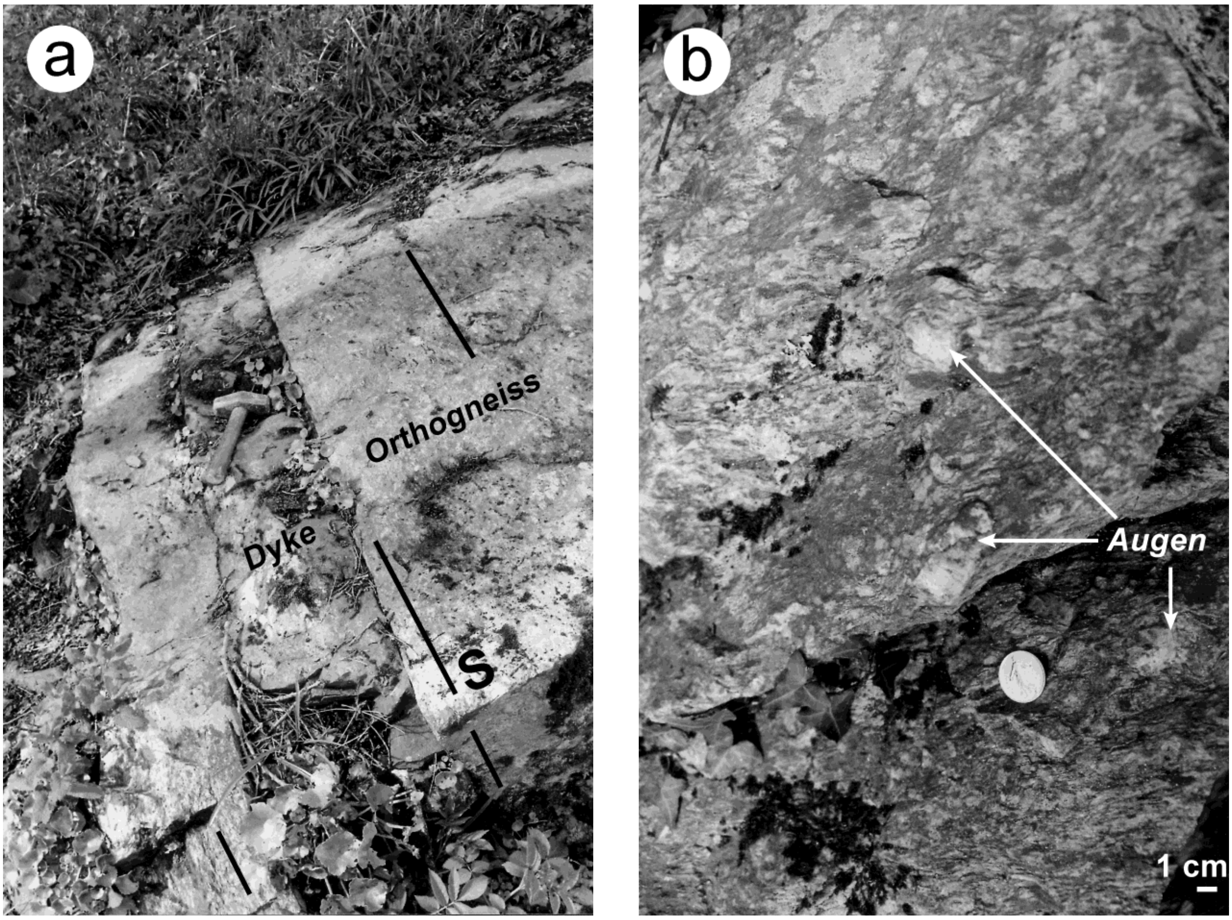


Figure 2.12- Orthogneiss and mafic dykes having escaped most of the eclogite metamorphism.
(a) Undeformed mafic dyke crosscutting slightly obliquely the foliation (S) of the host orthogneiss; (b) Orthogneiss (metagranitoid) with large K-feldspar "augen". Roche-aux-Lutins, Rocheservière.

Stop 7: La Chabotterie, Saint-Sulpice-le-Verdon (46°52'48" N – 1°24'21" W).

The walls of the starred restaurant near the manor of La Chabotterie contain fine specimens of a dark eclogite rich in Fe and Ti, which also exists as loose blocks in the fields to the south. The omphacite in these eclogites has a dark green colour and its garnet is bright red, these colours reflecting the iron richness of these minerals. In addition, there is a relative abundance of rutile (TiO_2), up to 4% of the volume of the rock, and the common presence of clinozoisite. This type of Fe-Ti-rich eclogite corresponds to the evolved term of the tholeiitic differentiation of the gabbroic protolith (full circles in Fig. 2.3). It could represent a few % of the volume of all Vendée eclogites.

In certain blocks visible on the walls, a leucocratic rock occurs in bands a few cm thick that alternate with Fe-rich eclogites (Fig. 2.13). This rock consists of mm-sized crystals of garnet and amphibole, embedded in a matrix rich in quartz and albitic plagioclase, but without potassium feldspar. The banding, due to variations in proportion and size of the minerals, was transposed parallel to the foliation, itself parallel to the foliation of the associated eclogites. This banded rock, always associated with eclogites or amphibolites, is quite common in the Essarts Unit ("meta-plagiogranite *in* Fig. 2.1), where it has been described under the name of "keratophyre" (Ters, 1979) or "banded leptynites" (Godard, 2001). It has a plagiogranite composition and may derive from the ultimate term of the tholeiitic series that also produced the gabbroic protolith of the eclogites. However, no clear evidence of eclogite-facies metamorphism has been detected in this rock, in which plagioclase (possibly retrograde) is quite abundant.

Figure 2.13- La Chabotterie Fe-Ti eclogite (dark) and associated leucocratic rock (clear). *The layering has been transposed parallel to the foliation in both rocks.*

<u>Stop 8</u>: Grezay, Les Essarts (46°46'55.4" N – 1°15'36.2" W).

Grezay is, together with La Ruffelière (Stop 5), one of the few gneiss occurrences with evidence of eclogite-facies metamorphic overprint (Godard, 2001). The best outcrop is located in a small abandoned quarry (46°46'55.4" N – 1°15'36.2" W), but the same rocks are also visible in a few places along the valley (*e.g.*, 46°46'58.2" N – 1°15'39.0" W; 46°46'57.0" N – 1°15'37.2" W), and were observed in the trench of the nearby A87 motorway. Finally, the walls of Grezay manor (46°47'0.5" N – 1°15'37.2" W), rebuilt in the "Clisson style" in the 19th century, show a remarkable sampling of various metagranitoids, orthogneiss, paragneiss and migmatites with evidence of superimposed eclogite-facies metamorphism.

The most common rock in the quarry is a nebulitic migmatite. A few dark cm-sized spots testify to the presence, as at La Ruffelière (Stop 5), of pseudomorphs after cordierite porphyroblasts. Garnet and phengite coronas, which developed during eclogite-facies metamorphism at the interfaces between feldspars and biotite, are sometimes visible with the help of a magnifying glass.

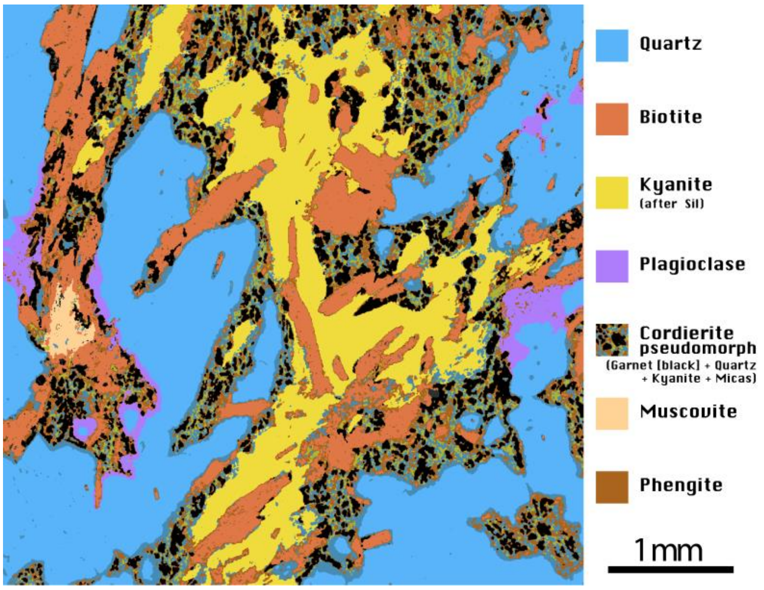


Figure 2.14- Migmatisation reaction in Grezay paragneiss. *Pseudomorphed cordierite occurs at the triple points Bt–Qz–Sil [now Ky], whereas Bt–Qz and Bt–Sil contacts remained stable. This structure indicates that cordierite has grown through the well-known migmatisation reaction: Bt + Qtz + Sil (± Pl) → Crd + melt (± Grt ± K-feldspar).*

These ortho- and para-gneisses show evidence of two distinct high-grade episodes (Godard, 2009):

(a) The first episode was characterised by intrusion of granitoids, migmatisation and high-temperature metamorphism of cordierite-bearing metapelites (T ≈ 650 °C, P ≈ 0.4 GPa). At this stage, cordierite grew in metapelites at the expense of pre-existing sillimanite, biotite and quartz (Fig. 2.14).

(b) The second episode is an eclogite-facies overprint (T ≈ 700 °C, P ≈ 2.0 GPa), which gave rise to many pseudomorphic and coronitic reactions and caused HP minerals to grow (garnet, phengite, kyanite, rutile, and probably jadeite) at the expense of the previous high-temperature parageneses (Figs. 2.15 to 2.19). The primary plagioclase appears replaced, under the microscope, by a crypto-crystalline mosaic with albite and kyanite microliths, interpreted as a pseudomorphosis of jadeite (Fig. 2.16).

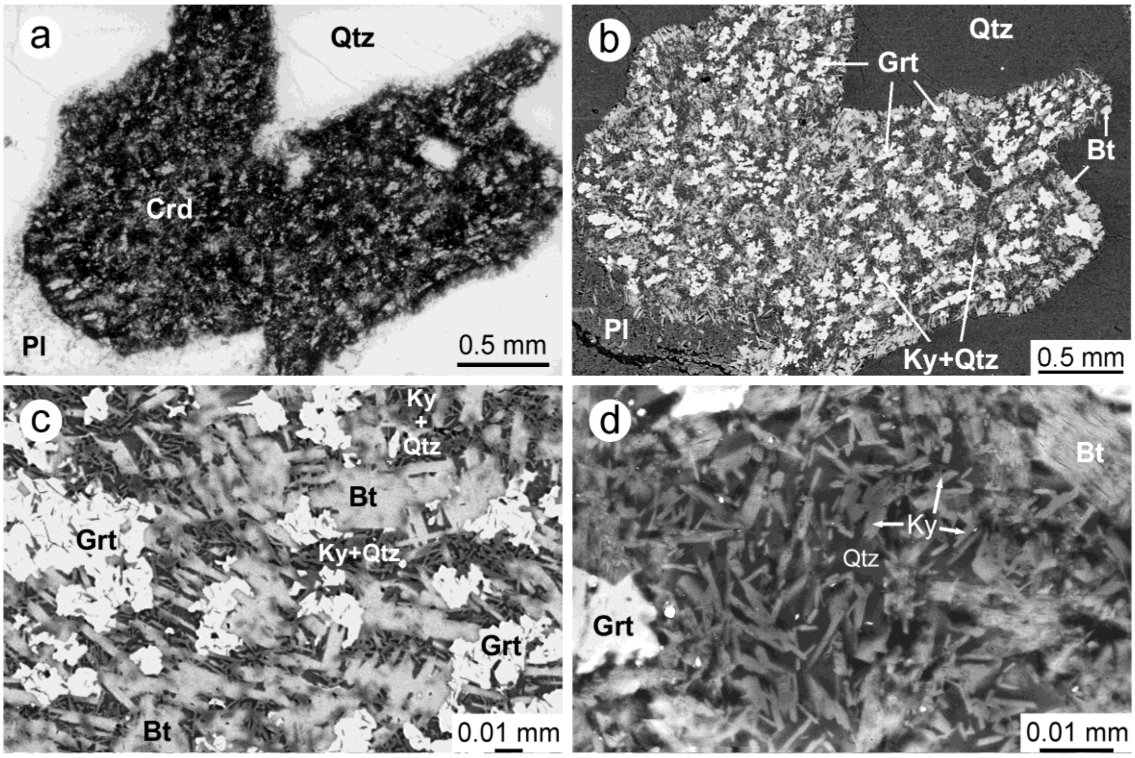


Figure 2.15- HP pseudomorph after cordierite in Grezay paragneiss. *The pseudomorph (Crd) is made up of Ca-free garnet, quartz and kyanite rodlets with some mica flakes (mainly biotite, Bt). (a) Plane-polarised light and (b, c, d) BSE images.*

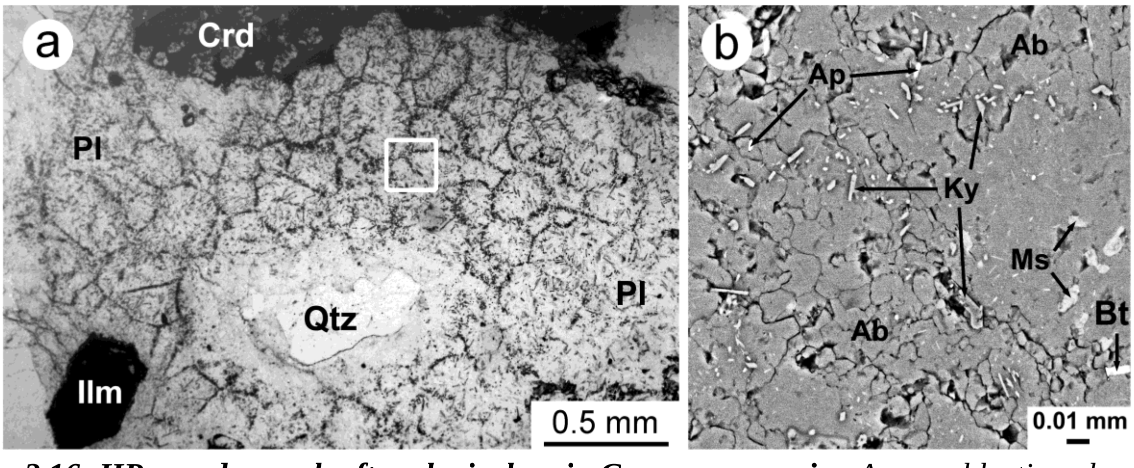


Figure 2.16- HP pseudomorph after plagioclase in Grezay paragneiss. *A granoblastic polygonal aggregate of plagioclase (Pl: $Ab_{89–91}$) is picked out by minute kyanite rods that delineate a honeycomb-like structure. The cells could represent former plagioclase single crystals before the albite-to-jadeite transition. (a) Plane-polarised light and (b) BSE images.*

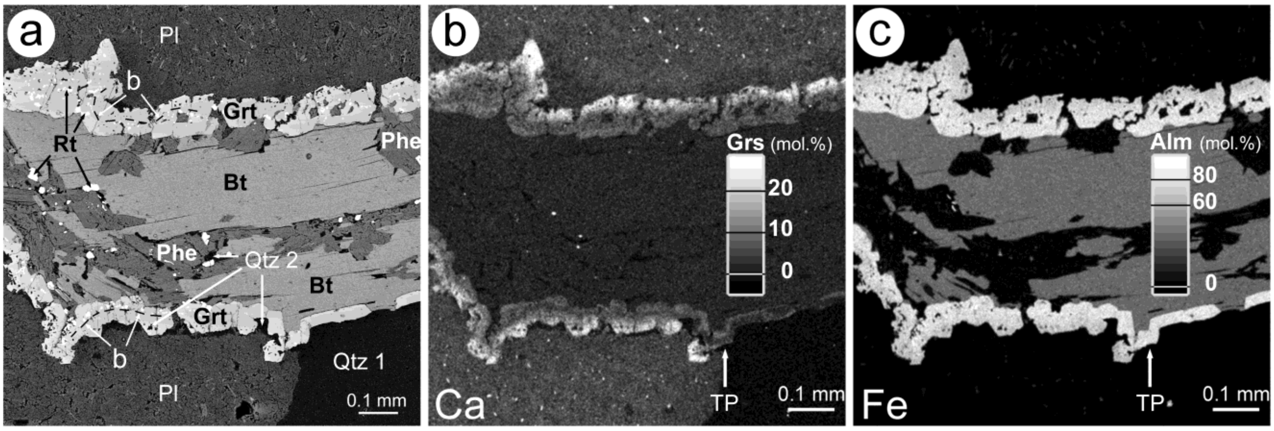


Figure 2.17- HP corona between plagioclase and biotite in Grezay paragneiss*. The corona is made of garnet, phengite, quartz and minor rutile. (a) BSE image; (b and c) calibrated maps of Ca and Fe, showing the zoning of garnet.*

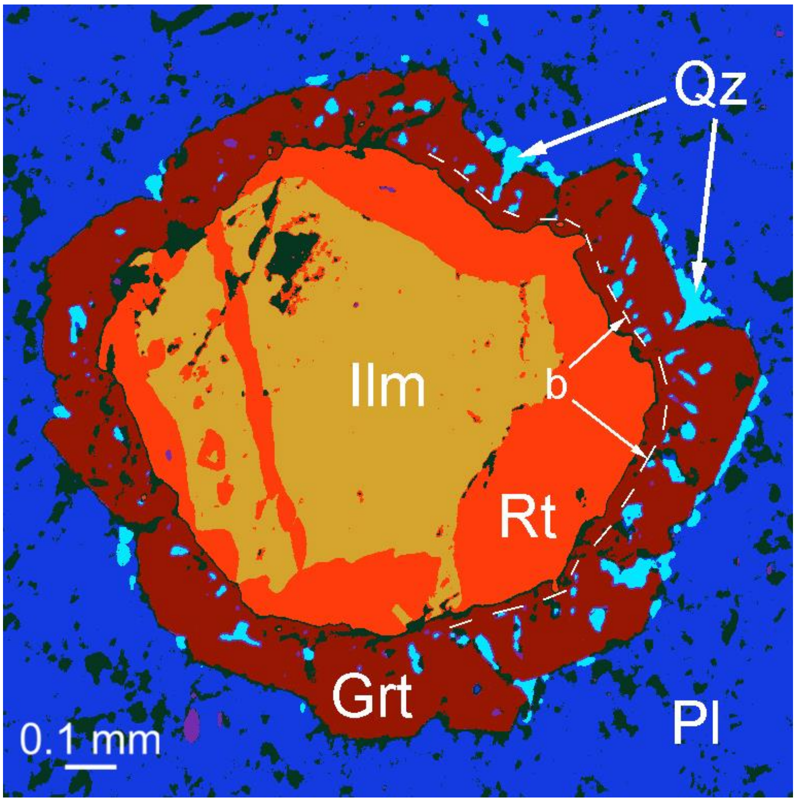


Figure 2.18- HP corona between plagioclase and ilmenite in Grezay paragneiss*. The corona is made of garnet, rutile and minor quartz; line b: boundary in the garnet corona between an inner rutile-bearing zone and an outer quartz-bearing one, interpreted as the original interface between ilmenite and plagioclase.*

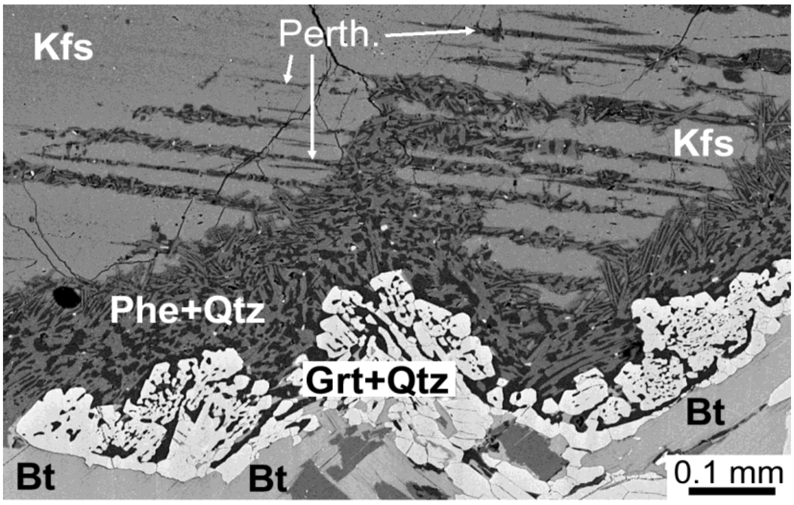


Figure 2.19- HP corona between K-feldspar and biotite in a Grezay migmatitic paragneiss*. The corona is made of garnet+quartz on the biotite side, and phengite+quartz on the feldspar side. This Phe+Qtz symplectites has grown preferentially along the perthitic exsolution lamellae, indicating that the albite exsolution in K-feldspar (i.e., a first retrogression) occurred before the eclogite-facies meta-morphism. BSE image.*

These two high-grade stages were separated by a first retrogression (T < 350 °C), attested to by the following pieces of evidence: (1) The eclogite-facies phengite+quartz symplectites that partly replaced the high-temperature K-feldspar (Fig. 2.19) grew preferentially parallel to perthitic lamellae, indicating that the latter had already been exsolved when the HP metamorphism occurred. (2) The eclogite-facies pseudomorphs after cordierite, composed of Grt + Ky + Qz + micas (Fig. 2.15), are rich in K and deficient in Mg + Fe relative to a true cordierite (Fig. 2.20); their composition is similar to that of an altered cordierite (so-called "pinite"), indicating that cordierite had been altered to chlorite + muscovite before being replaced by the HP pseudomorphs.

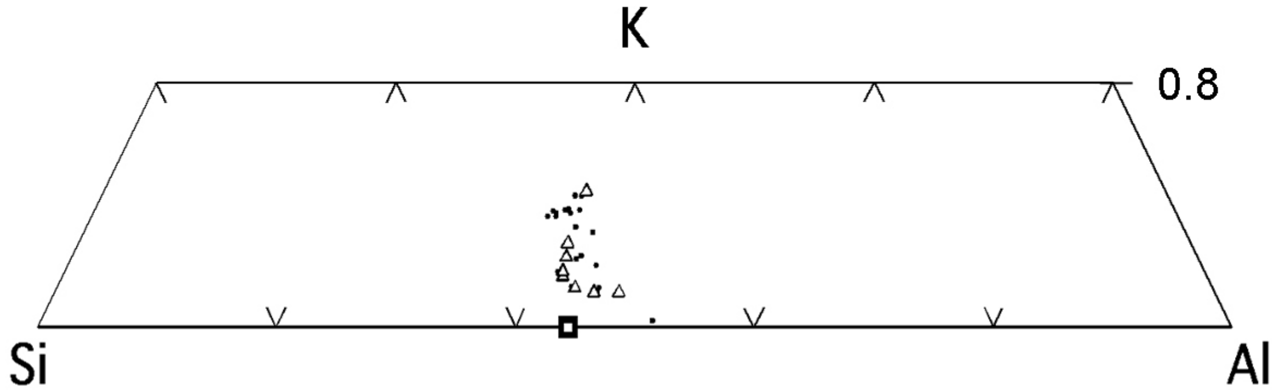


Figure 2.20- Composition of pseudomorphs after cordierite: evidence for cordierite alteration. *Square: theoretical cordierite composition; triangles: composition of pseudomorphs after cordierite (Grezay), obtained by scanning at the electron microprobe; dots: "pinite" compositions from the literature.*

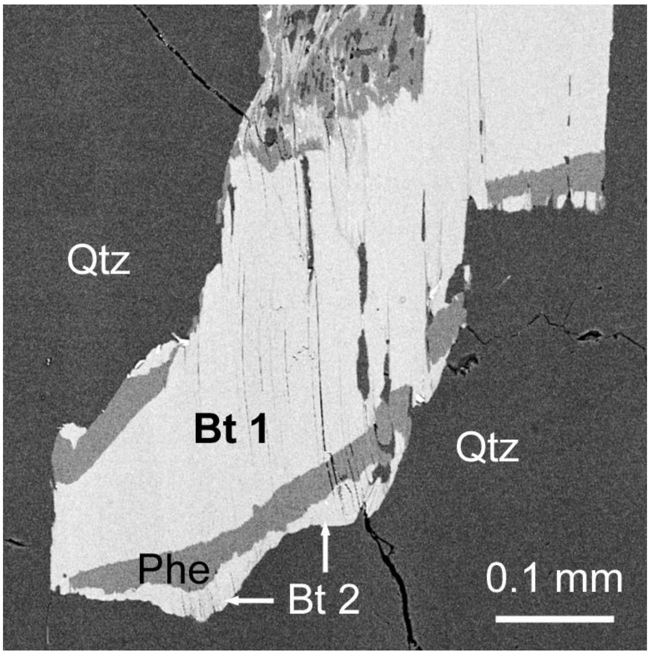


Figure 2.21- Biotite reappearance during the last retrogression of in Grezay paragneiss. *During prograde HP metamorphism, biotite (Bt_1) was partly replaced by phengite; during retrogression, phengite is in turn replaced by some secondary biotite (Bt_2).*

Finally, some microstructures account for the ultimate retrogression, after the HP metamorphism (Fig. 2.21).

The compositions of various reaction microdomains, estimated by mass-balance studies, have been used to model *P–T* pseudosections, which, when taken together, reveal a complex *P–T* path with the two distinct cycles (Fig. 2.22; Godard, 2009). Therefore, the ortho- and para-gneisses probably belong to a pre-Hercynian continental crust (first cycle) that was involved in the same eo-Hercynian subduction (second cycle) as the neighbouring eclogitized oceanic mafic rocks. The dating of two generations of monazite from Grezay by the U-Pb method (Fig. 2.23; Mnz1: 458±3 Ma; Mnz2: 373±13 Ma) suggests that the high-temperature and high-pressure cycles would be Ordovician and Upper Devonian, respectively.

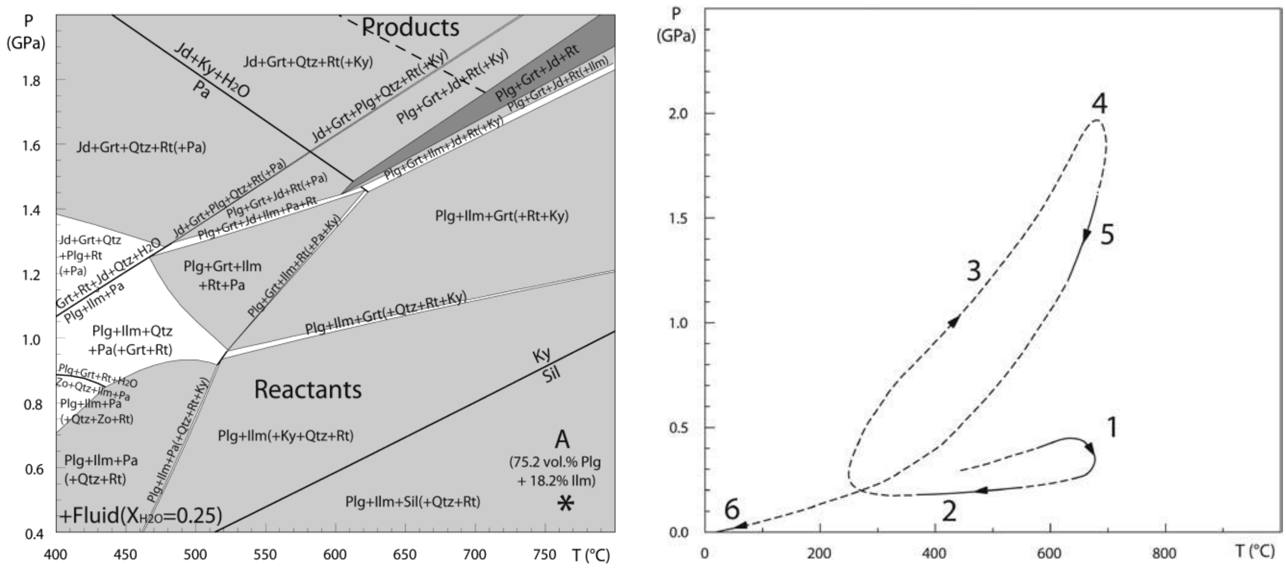


Figure 2.22- P-T evolution of the Grezay paragneiss*. Various P–T pseudosections valid for one specific reaction microdomain have been modelled (left: P–T pseudosection for the coronitic reaction at the plagioclase-ilmenite interface: Fig. 2.18). All together, they provide a complex P–T path with two metamorphic cycles (right) (see Godard, 2009, for the details).*

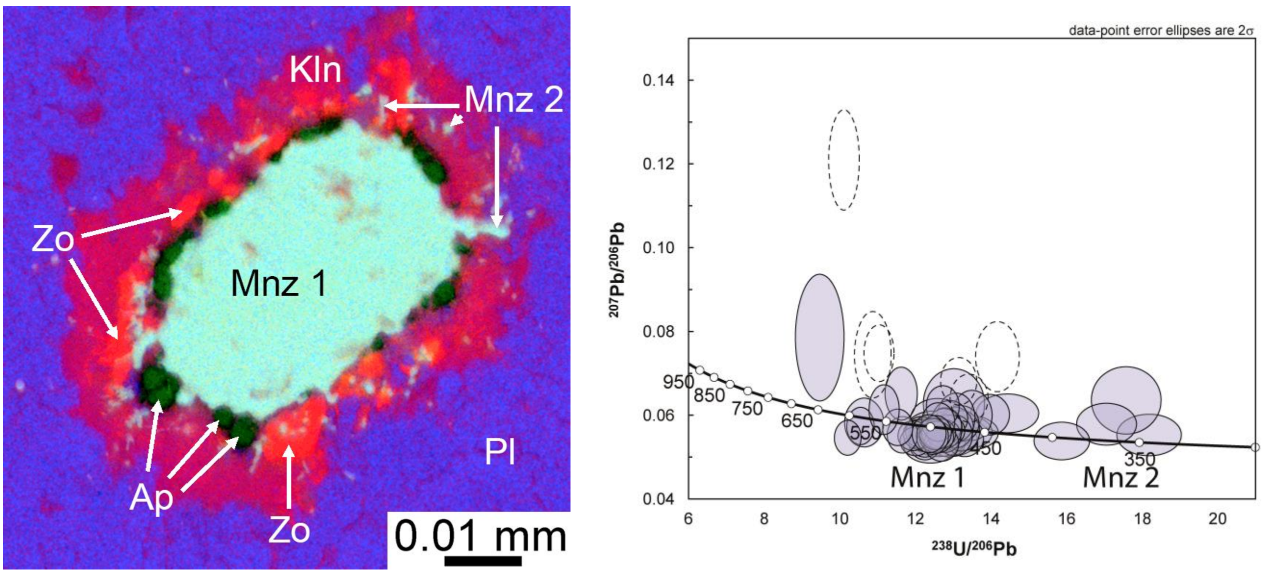


Figure 2.23- Dating of monazite from Grezay paragneiss*. Upon contact with plagioclase (left), monazite 1 reacted with plagioclase during the HP event, producing apatite, zoisite, and REE-enriched monazite 2. The dating of the two monazites by the U-Pb method (right) provides ages for the high-T metamorphic cycle (i.e., Mnz 1) and the HP cycle (i.e., Mnz 2) (V. Bosse, unpub. data).*

2.3 – Discussion

The Vendée eclogites and associated rocks (amphibolite, birbirite) have the geochemical characteristics of rocks typical of an oceanic crust, and therefore seem to derive from a "lost ocean" involved in the complex play of plate tectonics. The pre-eclogitic rocks belonged to a tholeiitic series, including serpentinite (birbirite: Stop 3), ancient noritic cumula rich in plagioclase and olivine (Stops 1, 2), abundant N-MORB gabbro (Stop 4), Fe-Ti-rich gabbro and some plagiogranite (Stop 7). The gabbroic protolith was amphibolitised and saussuritised before eclogite-facies metamorphism (Fig. 2.9), which could be attributed to oceanic hydrothermal metamorphism, as well as to the very strong dispersion of the oxygen isotopic composition (Javoy, 1971; Agrinier *in* Godard, 2001). The eclogite-facies parageneses, with a metamorphism peak at T≈700°C and P>16 kbar, indicates a subduction at a depth of more than 50 km. An intense ductile deformation episode took place under eclogite-facies conditions (Stop 4), and could be linked to the incorporation of eclogites into the surrounding gneiss during a continental collision. It was followed by the exhumation of the eclogites towards the surface, evidenced by a more or less static retrograde metamorphism (Stops 1, 2 and 4), which made them transform into amphibolite.

The host rocks of the eclogites (migmatites and cordierite-bearing paragneiss; metagranitoid and ortho-gneiss) are typical of a continental crust, contrary to the eclogites. Some of these rocks have preserved the trace of two distinct metamorphic stages (Stops 5 and 8), the first of high temperature (cordierite-bearing migmatites) and the second of HP eclogite-facies conditions (Godard, 2009). These two stages, being separated by a first retrograde metamorphism, probably correspond to two distinct orogenic cycles (Fig. 2.22). These rocks would therefore belong to a pre-Hercynian continental crust, entrained in the same Eo-hercynian subduction as the eclogites of oceanic origin, and intensely deformed with them under eclogite-facies conditions (*e.g.*, Godard, 1983, 2009).

The late Hercynian evolution of this formation was marked by its exhumation before the end of the Carboniferous, as evidenced by the presence of eclogite pebbles in Late-Carboniferous ("Stephanian") sediments. This formation has only been preserved within a narrow tectonic sliver, delimited by two Late-Hercynian major faults, the Vendée coal belt to the northeast and the Sainte-Pazanne-Mervent tectonic line to the southwest (Fig. 2.1).

Whatever the details of its evolution, the Les Essarts Unit appears very different from the blueschist-facies Groix Unit, visited during the first day, and of which there is an equivalent at Bois-de-Céné, just 10 km SW of Saint-Philbert-de-Grand-Lieu (Fig. 1). This contrast underlines the presence of at least two distinct concentric high-pressure metamorphic belts in the Ibero-Armorican arc.

3
Eclogites and eclogite-facies metagranitoid from Champtoceaux Complex (Brittany and Anjou)

The last day of the field trip, Saturday June 9th, is dedicated to the Champtoceaux Complex, located north of Nantes. It will allow us to observe the eclogite-facies metagranitoid of La Picherais and some nearby eclogites, unfortunately visible only as loose blocks.

3.1– Geological overview

3.1.1- History of geological and petrological studies

The eclogites of the Champtoceaux Complex were first described scientifically as "eurites grenatiques" by François Dubuisson (1830). They were however known and valued long before for their very fine grain, their hardness and their density, by the Neolithic populations of the Center-West of France who used them to make Neolithic axes. They were studied by Lacroix (1891) and Brière (1920) at the same time as the eclogites from Les Essarts Unit (see Section 2.1.1). Lacroix noted that, unlike these, the eclogites were generally very fine grained, and formed small lenses from one to a few meters, stretched in very deformed gneisses (Fig. 3.1).

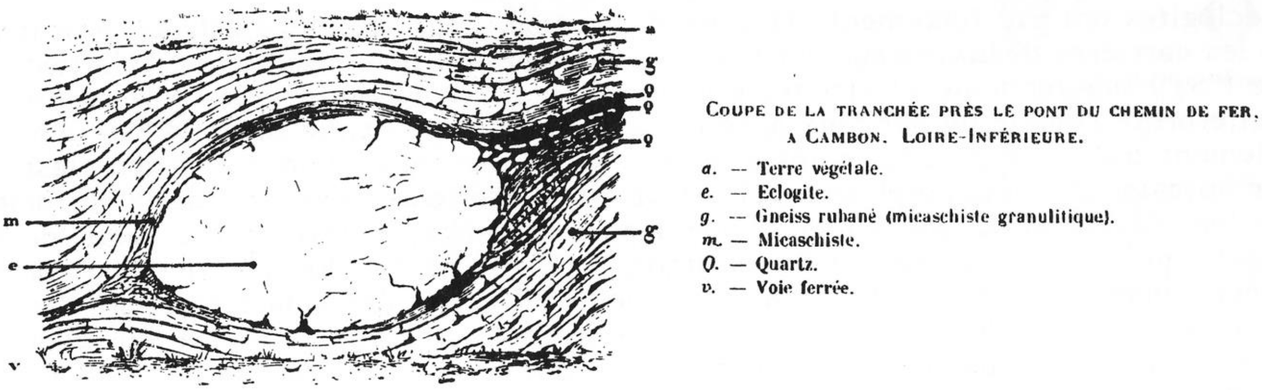


Figure 3.1- Metre-sized eclogite lens stretched in gneiss, in the railway trench near Campbon *(Lacroix, 1891). e: eclogite; m: micaschists; g: gneiss; q: quartz veins.*

After the regional geological works of the 19th and 20th centuries, Jean Cogné reinterpreted in 1966 the Champtoceaux Complex as being a deep-rooted “nappe”, made essentially of high-grade metamorphic rocks. Petrological, microstructural and geochronological studies were then undertaken on the eclogites (Godard *et al.*, 1981; Godard, 1988; Bosse *et al.*, 2000) and the surrounding metagranitoids and orthogneisses (Lasnier *et al.*, 1973; Paquette *et al.*, 1984; Ballèvre *et al.*, 2002).

3.1.2- Geological framework

The Champtoceaux Complex (Fig. 3.2) is located between the South Armorican shear zone and the Nort-sur-Erdre fault, which coincides with a Late-Carboniferous coal belt (*Sillon houiller de la Basse-Loire*), similarly to what occurs further south on the NE border of the Essarts Unit (See section 2.1.2). It lies structurally on top of the Mauves Unit and below the Mauges Unit (Fig. 3.2). The Mauves Unit is constituted by a thick, a priori monotonous, series of metagrauwackes (albitic micaschists) whose protoliths are supposed to be Proterozoic. The Mauges Unit (in the upper allochthonous position) is made up of a Proterozoic basement (micaschists, amphibolites and metavolcanics), on which a Palaeozoic sedimentary succession lies unconformably. The latter begins either in the Cambrian (Cléré-sur-Layon) or in the Lower Ordovician (Châteaupanne).

The Champoceaux Complex comprises a set of superimposed slices (Fig. 3.2). The composite middle allochthonous unit includes the Folies-Siffait Unit (amphibolites and metaperidotites, of oceanic affinity) and the Drain Unit (peridotites and metagabbros, recognised as oceanic). The

Champtoceaux Unit, made up of migmatitic orthogneisses probably derived from cadomian protoliths, migmatic metapelites and rare lenses of eclogite, is structurally situated between the two oceanic units. The lower slices (lower allochthonous), are mainly composed of acid orthogneiss ("leptynites") derived from Ordovician granitoids (Saint-Mars-du-Désert orthogneiss: Paquette *et al.*, 1984; Cellier orthogneiss: Ballèvre *et al.*, 2002) and metapelites (micaschists) of unknown age, but which are probably also Palaeozoic. Among these lower slices, the Cellier Unit contains the most notable and abundant eclogite-facies relics and will be visited at La Picherais (Fig. 3.2); it is mainly made up of an orthogneiss whose transition with an undeformed metagranitoid can be occasionnaly observed and which encloses numerous meter-sized eclogite lenses.

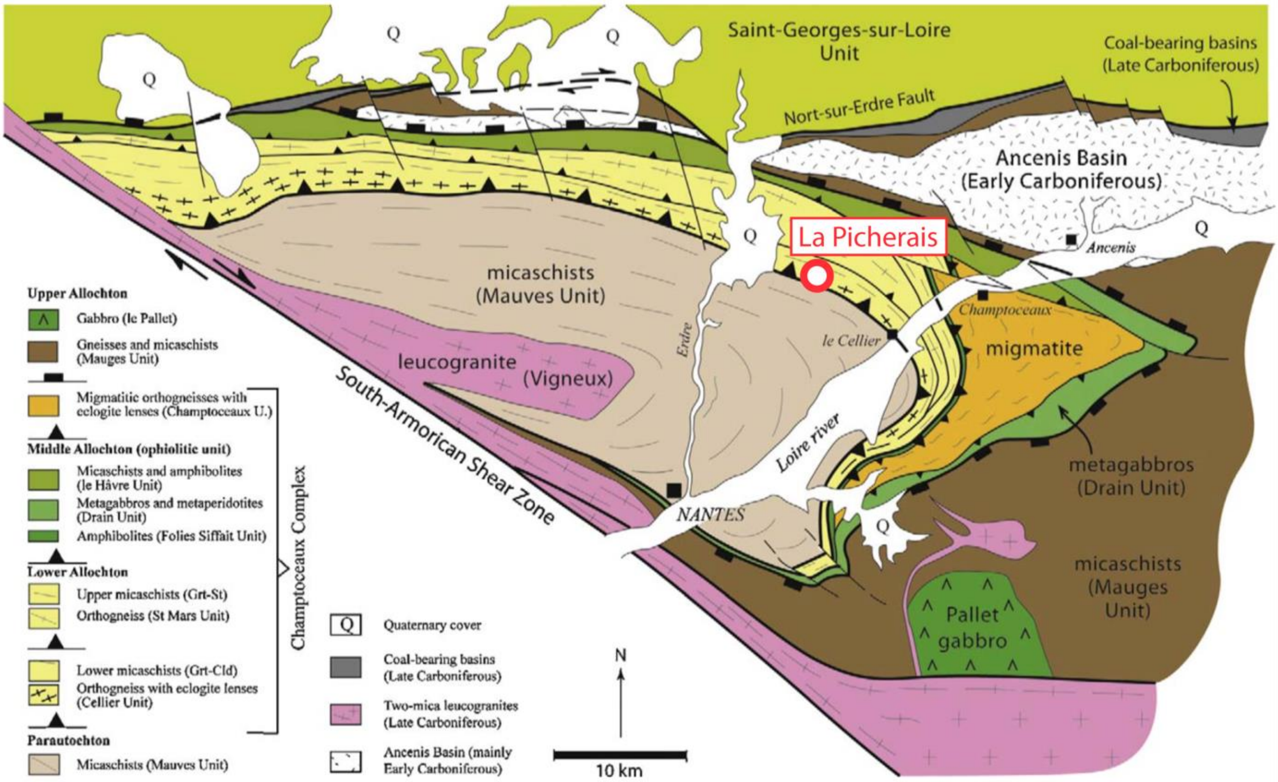


Figure 3.2- Sketch geological map of the Champtoceaux complex *(Ballèvre et al., 2009).*

3.2 – <u>Description of the sites visited</u>

The main stops of the day are at "La Picherais", in the lower allochton unit.

<u>Stop 1</u>: La Picherais metagranite (47°21'1.5" N – 1°25'41.6" W).

At a first glance, this metagranite looks like an ordinary undeformed granite. However, its inspection under the microscope reveals reaction zones between biotite and feldspars (Fig. 3.3).

This granite was first described by Lasnier *et al.* (1973) as an undeformed core of some "charnockitic" granite showing at its rims a gradual transition to the strongly-deformed orthogneiss in which it is embedded. The name charnockite was inappropriate, since this metagranite does not contain pyroxene; on the other hand, the authors clearly described the coronitic reaction between biotite and primary plagioclase and the transformation of the latter into a pseudomorph of neo-plagioclase, white mica and zoisite (see Fig. 3.3). They attributed this reaction to a pre-cadomian granulite-facies process occurring at high temperature. The discovery and studies of the jadeite-bearing metagranite of Monte Mucrone (Italian Alps) and similar rocks metamorphosed under HP conditions (*e.g.*, Compagnoni & Maffeo, 1973) led to the reconsideration of this rock as an HP eclogite-facies metagranite. It indeed presents petrological characteristics very close to those of the Monte Mucrone metagranite as well as the gneisses and metagranite that we saw yesterday at Grezay.

Figure 3.3- "La Picherais" metagranite. *(left) outcrop (right) microphotograph showing biotite, quartz and "dirty" plagioclase. Note the coronitic reaction between plagioclase and biotite.*

Microscope observations and SEM studies recently performed show microstructures very similar to those observed at Grezay yesterday:

(1) Garnet-bearing coronas at biotite–plagioclase interfaces (Figs. 3.4 and 3.5):

Garnet and phengite grew at the biotite-plagioclase interfaces. Garnet shows a clear boundary between an almandine-bearing zone, on the biotite side, and a grossular-rich quartz-bearing zone, on the plagioclase side (Fig. 3.5). This change in garnet composition corresponds to the original interface between biotite and plagioclase. In the polycrystalline plagioclase close to the corona, depletion in the Ca-content confirms that anorthite was consumed to produce grossular in garnet. These microstructures are very similar to those observed at Grezay (compare with Fig. 2.17).

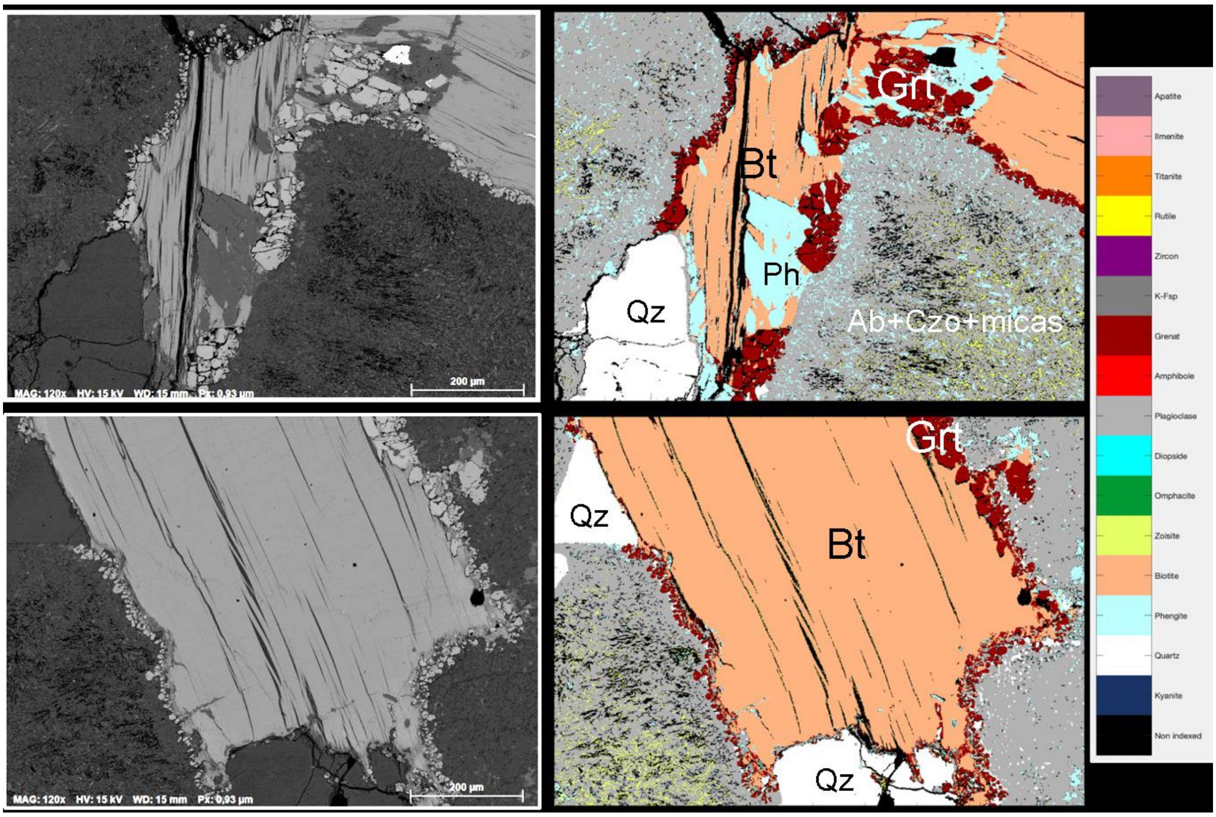


Figure 3.4 – La Picherais metagranite: Grt+Qz+Ph corona between biotite and plagioclase*.* *BSE images (left) and associated phase identification maps (right) highlighting how the Grt+Qz±Ph corona is located at the Pl-Bt boundaries and interrupted at the Bt-Qz interface.*

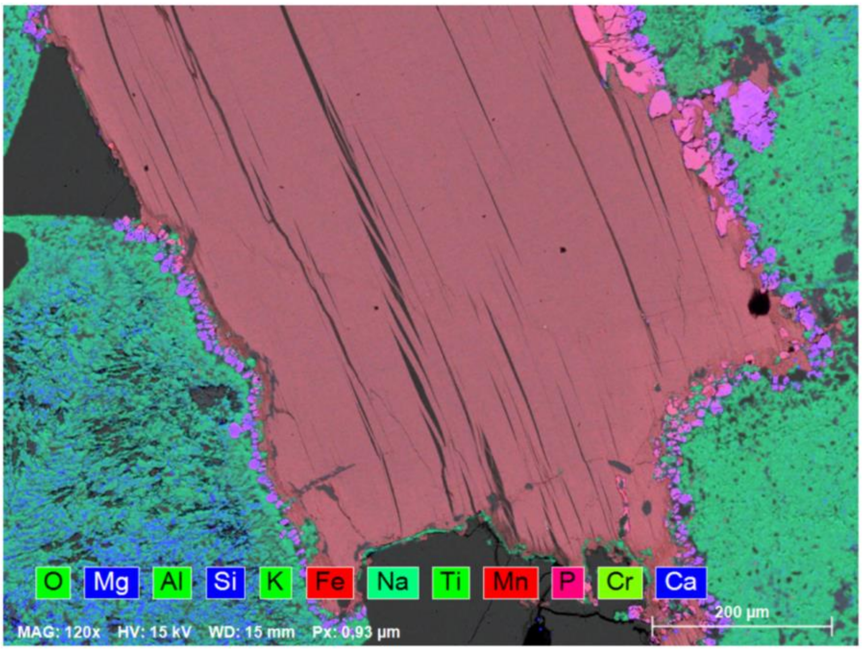


Figure 3.5 – La Picherais metagranite: corona between biotite and plagioclase. *Combination of element maps showing Ca-content variation in garnet. Note also that zoisite in the plagioclase pseudomorph is less abundant near the garnet corona which has absorbed Ca.*

(2) Garnet + rutile coronas at ilmenite–plagioclase interfaces (Fig. 3.6):

Ilmenite–plagioclase interfaces also produced nice coronas as depicted in Figure 3.6. From the ilmenite core to the plagioclase, the following sequence of phases can be found: [Ilm]/Rt/alm-rich Grt + Rt inclusions/grs-rich Grt + Qtz inclusions/[Pl] (Fig. 3.6). Here again, an internal boundary in the garnet corona between two zones (alm-rich vs. ca-rich with quartz inclusions) probably coincides with the former ilmenite–plagioclase interface, and a slight depletion in the Ca-content is again observed in the polycrystalline plagioclase close to the corona. This microstructure is again very similar to that observed at Grezay (compare Figs. 2.18 and 3.6).

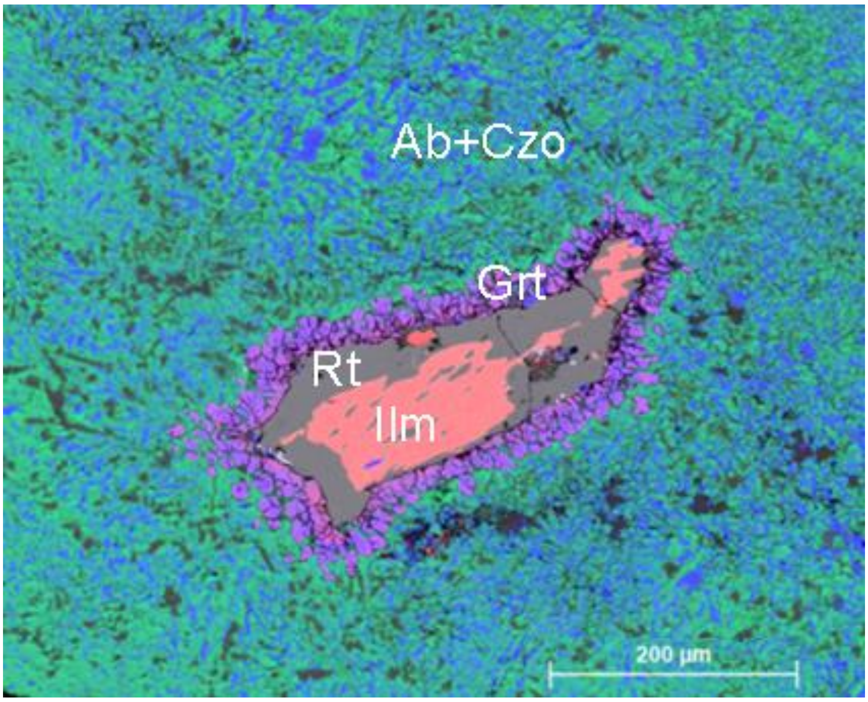


Figure 3.6 – La Picherais metagranite: corona between ilmenite and plagioclase. *Combination of element maps showing Ca-content variation in garnet. Ilmenite destabilizes in rutile. Garnet (+ minor quartz) and rutile developed at the contact between ilmenite and plagioclase. Albite, clinozoisite, white micas and minor kyanite replaced the former plagioclase. To be compared with Figure*

(3) Pseudomorph after plagioclase (Figs. 3.4, 3.6):

Plagioclase forms a microcrystalline mosaic of polycrystalline albite, in which minute rodlets of zoisite, micas and in some cases kyanite can be found. This is very similar to what we saw yesterday at Grezay and could be explained by the transformation of the initial plagioclase into jadeite, now completely retrogressed into albite.

<u>Stop 2</u>: La Picherais eclogite (47°21'6.1" N – 1°25'42.8" W).

In nearby fields, it is easy to collect loose blocks of eclogite like the one shown in Figure 3.6. The samples are quite weathered on their surface but are representative of beautiful well-preserved eclogites.

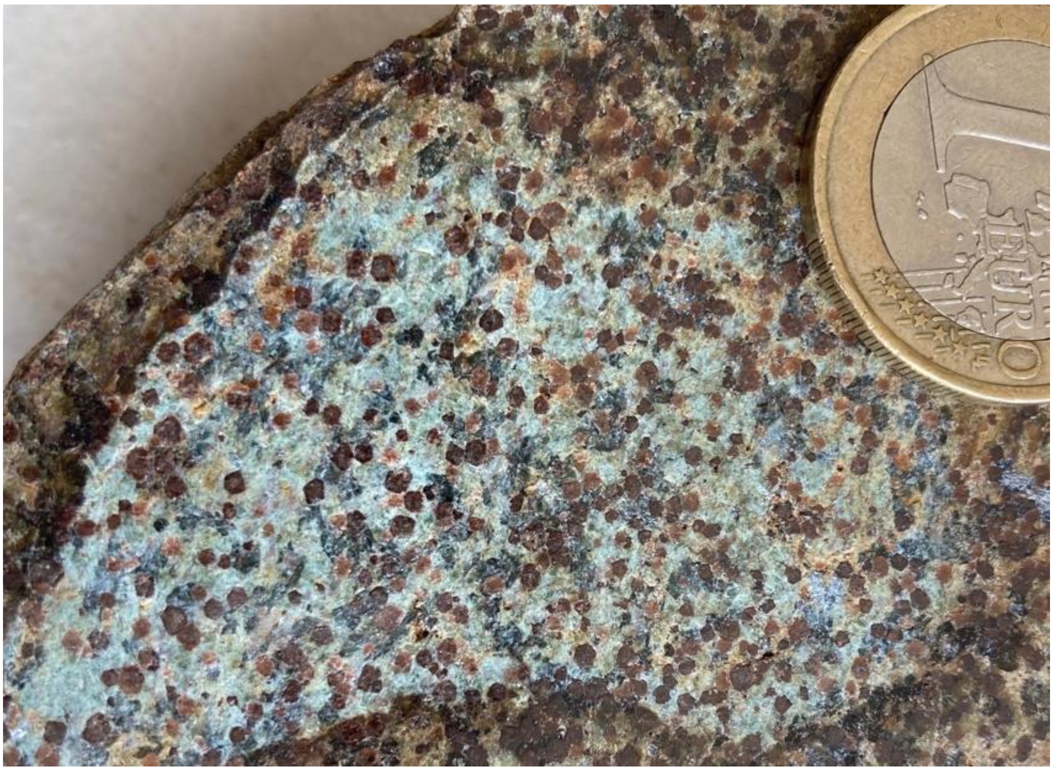


Figure 3.7 – Eclogite loose block near La Picherais metagranite, *(47°21'6.1"N – 1°25'42.8"W).*

Outcrops of eclogitic mafic boudins are rarely observable (and deserve to be preserved!). They measure at most a few meters in length and show an eclogite lens stretched and boudinaged in a strongly-foliated orthogneissic matrix deriving from the metagranite (see Figs. 3.1 & 3.8). The outcrop shown in Figure 3.8 is located at about 600 meters to the east of Stop 1, but is not easily accessible and we will not visit it.

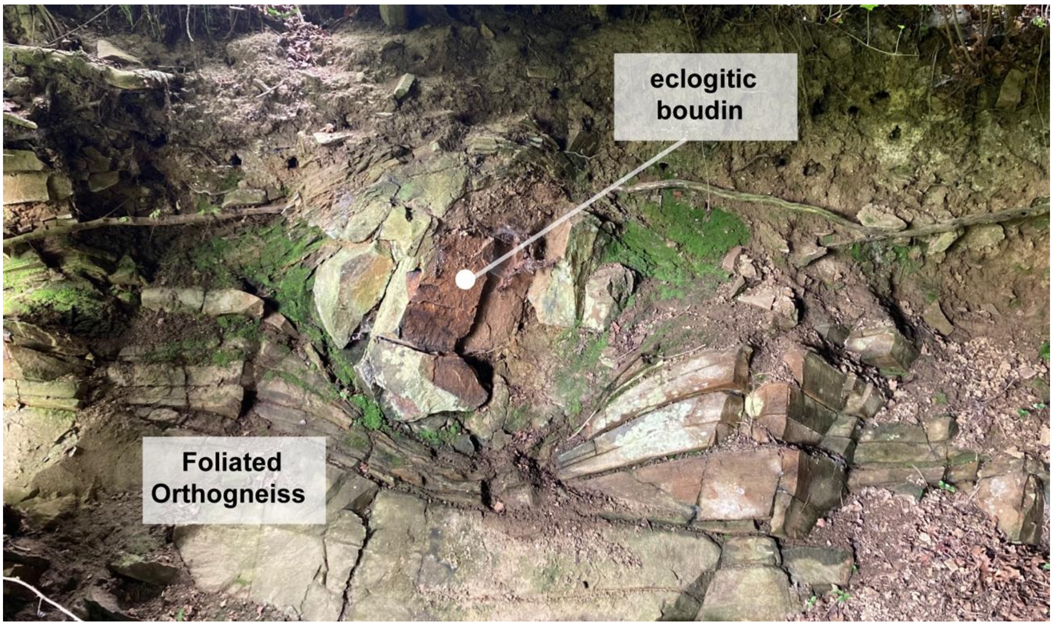


Figure 3.8 – Metre-sized eclogite lens *(by courtesy of Michel Ballèvre). Observe the foliation of the host gneiss that wraps around the eclogite boudin.*

In a few blocks of the fine-grained eclogite observed at La Picherais, amphibole prophyroblasts can be seen. In some other localities, this poeciloblastic amphibole is glaucophane (Fig. 3.9; Brière, 1920; Godard *et al.*, 1981). Glaucophane formed at the expense of the eclogite paragenesis, enclosing numerous garnet micro-crystals (Fig. 3.9), but is not associated with plagioclase, unlike many late amphiboles in eclogites. It resulted from a continuous sliding reaction (glaucophane is zoned) that occurred after the peak but still in HP conditions (Godard *et al.*, 1981).

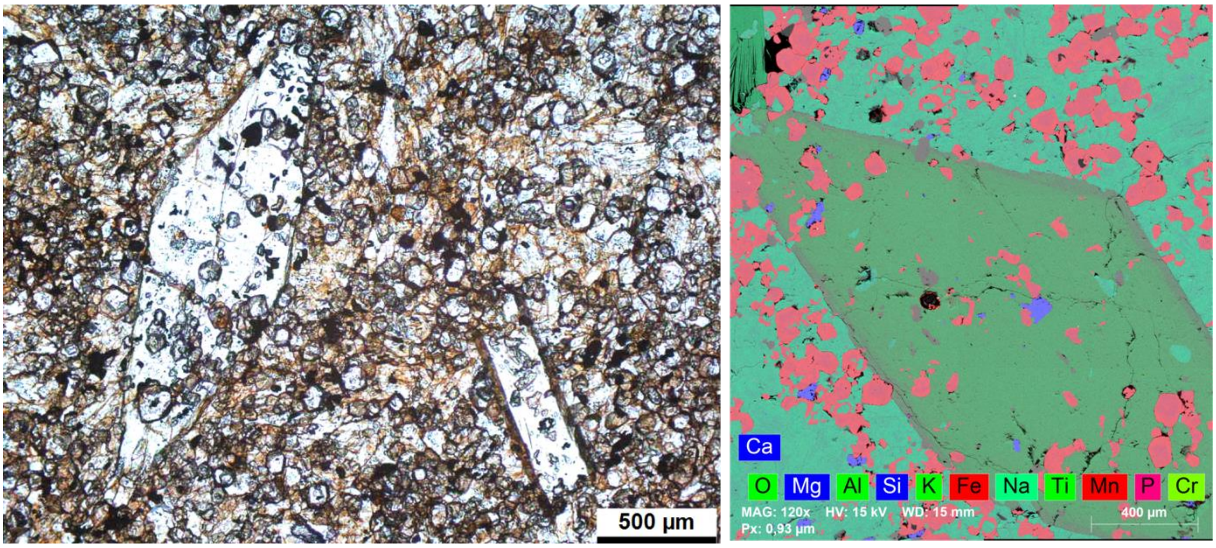


Figure 3.9 – Poeciloblasts of glaucophane in eclogite from La Bréhardière *(Godard et al., 1981). Some of the garnet microcrystals are atoll-shaped, with their "lagoon" mostly made up of quartz and phengite. When embedded in a glaucophane prophyroblast, these atolls went corroded and the quartz they contain disappeared. This indicates that the glaucophane growth consumed mainly omphacite, but also garnet and a little quartz.*

<u>Stop 3</u>: Champtoceaux migmatitic gneiss (47°20'20" N – 1°15'56" W).

We leave La Picherais to reach the town of Champtoceaux, on the south bank of the Loire. The slopes overlooking the Loire, which offer a panoramic view of the river, make it possible to observe numerous outcrops of more-or-less migmatitic orthogneiss. These rocks lie in the middle of the Champtoceaux Complex (Fig. 3.2) and have not yielded evidence of HP metamorphism. Eclogite-facies metamorphism may have been restricted to certain tectonic slices like the Cellier Unit, or its traces may have disappeared due to migmatization during retrogression.

After having lunch, we can engage a scientific discussion on the observations made during the field trip, after which we shall have to travel to Paris by coach.

3.3 – <u>Discussion</u>

The HP units of the Champtoceaux Complex, in particular the Cellier unit, are mainly composed of orthogneisses, in which some relics of undeformed metagranite and very few hornfels have been observed. The granitic protoliths are Ordovician (Paquette *et al.*, 1984; Ballèvre *et al.*, 2002). Small eclogite bodies are boudinaged in these rocks, but their volume is negligible compared to that of the Vendée eclogites. It is customary to say that all the eclogites from the Champtoceaux Complex would not be enough to fill the quarry of La Gerbaudière. Their composition does not show such marked tholeiitic differentiation as in Les Essarts Unit (Godard, 1988). It therefore seems that the protolith of these rocks could have been dykes of mafic rocks in a granite-rich continental crust. Since evidence for eclogite-facies metamorphism has been observed in the metagranite, hornfels.

P-T estimates existing in the literature for the eclogites belonging to the lower allochton unit of the Champtoceaux Complex are presented in Figure 3.10. We can take time here to discuss their retrogression path.

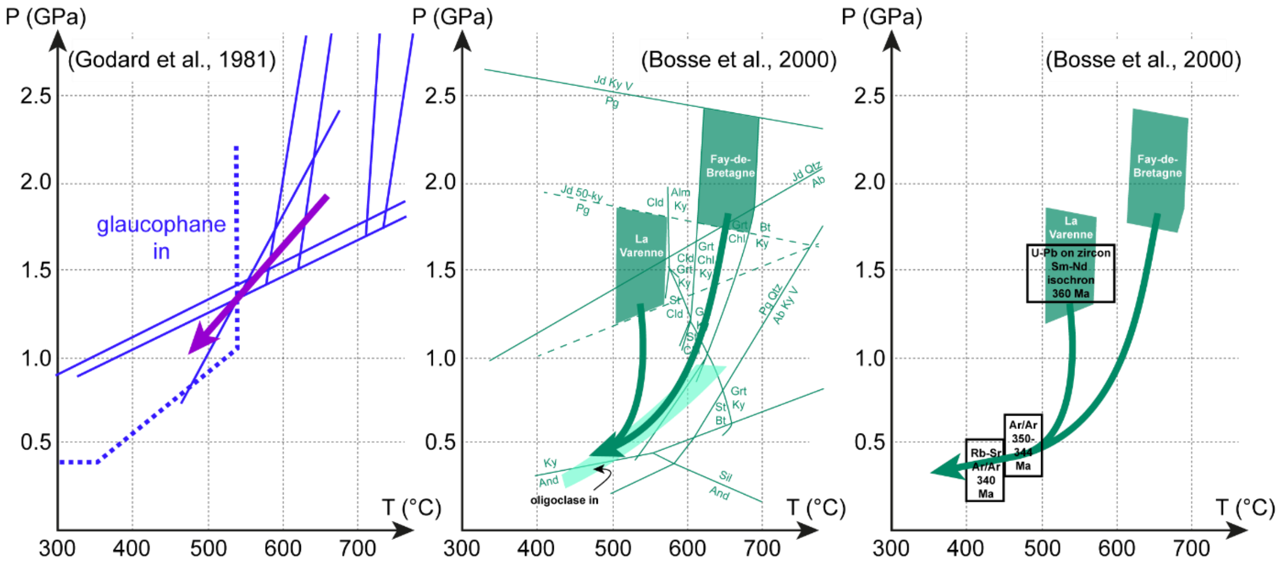


Figure 3.10 – P-T evolution of the Champtoceaux eclogites*, from the littérature.*

References

AILLERY E. L., 1914.- Archives du diocèse de Luçon. Chroniques paroissiales par l'abbé Aillery, revues et augmentées par M. l'abbé J. Huet curé-doyen de Maillezais. Luçon, Bideaux, t. 9, 770 p. [pp. 56-64].

AUDRAIN J. & LEFORT J.-P., 1986.- Le lever magnétique de Groix (Massif armoricain): une aide pour l'interprétation des structures profondes de l'île. Hercynica, II, 65-70.

AUDRAIN J. & VIGNERESSE J.-L., 1990.- Le lever magnétique de l'Ile de Groix (Morbihan). Comptes-Rendus de l'Académie des Sciences de Paris, (II) 311, 319-324.

AUDREN C., TRIBOULET C., CHAURIS L., LEFORT J.-P., VIGNERESSE J.-L., AUDRAIN J., THIÉBLEMONT D., GOYALLON J., JÉGOUZO P., GUENNOC P., AUGRIS C. & CARN A. (1993). Notice explicative de la feuille Ile de Groix à 1/25000 (carte géologique). BRGM, Orléans.

AUGUSTITHIS S.S., 1965.- Mineralogical and geochemical studies of the platiniferous dunite-birbirite-pyroxenite. Chemie der Erde, 24: 159-196.

AUGUSTITHIS S.S., 1967.- On the phenomenology and geochemistry of differential leaching and element agglutination processes. Chemical Geology, 2: 311-329.

BARET C., 1898.- Minéralogie de la Loire-Inférieure. Bulletin de la Société des Sciences naturelles de l'Ouest de la France, VIII: 1-175 + 19 pl. h.t.

BARET C., 1900.- Éclogite à disthène de Saint-Philbert-de-Grand-Lieu (Loire-Inférieure). Bulletin de la Société des Sciences naturelles de l'Ouest de la France, X: 225-227.

BARRIENTOS X., 1992.- Petrology of coexisting blueschists and greenschists, Ile de Groix, France: implications for preservation of blueschists. PhD Thesis, Harvard University, 252 p.

BERNARD-GRIFFITHS J. & CORNICHET J., 1985.- Origin of eclogites from south Brittany, France: A Sm-Nd isotopic and REE study. Chemical Geology, Isotope Geoscience Section, 52: 185-201.

BERNARD-GRIFFITHS J., CARPENTER M.S.N., PEUCAT J.-J., JAHN B.-M., 1986.- Geochemical and isotopic characteristics of blueschist facies rocks from the Ile de Groix, Armorican Massif (northwest France). Lithos, 19, 235- 253.

BONATTI E., ZERBI M., KAY R. & RYDELL H., 1976.- Metalliferous deposits from the Apennine ophiolites : Mesozoic equivalents of modern deposits from oceanic spreading centers. Geological Society of America Bulletin, 87, 83-94.

BONNEY, T.G., 1887. Note on some Specimens of Glaucophane- rock from the lle de Groix. The mineralogical Magazine and Journal of the mineralogical Society, VII: 150-154.

BOSSE V., BALLÈVRE M. & VIDAL O., 2002.- Ductile thrusting recorded by the garnet isograd from blueschist-facies metapelites of the Ile de Groix, Armorican Massif, France. Journal of Petrology, 43, 485-510.

BOSSE V., FÉRAUD G., BALLÈVRE M., PEUCAT J.-J., CORSINI M., 2005.- Rb-Sr and 40Ar/39Ar ages in blueschists from the Ile de Groix (Armorican Massif, France) : Implications for closure mechanisms in isotopic systems. Chemical Geology, 220, 21-45.

BRIÈRE Y., 1920.- Les éclogites françaises. Leur composition minéralogique et chimique. Leur origine. Bulletin de la Société française de Minéralogie, XLIII: 72-222 + pl. i-iv; Thèse ès-Sciences naturelles, Sorbonne, 1920, Giard et brière (éd.), 143 p. + 4 pl.

BRUN J.P. & BURG J.P., 1982.- Combined thrusting and wrenching in the Ibero-Armorican Arc; a corner effect during continental collision. Earth Planet. Sci. Lett., 61: 319-332.

CHAURIS L., 1991.- Contribution à la minéralogie de la France. VII – L'occurrence manganésifère de Garz al Louët en La-Chapelle-Neuve (Côtes d'Armor). Sa place dans les minéralisations en manganèse du Massif armoricain. Bulletin de la Société des Sciences Naturelles de l'Ouest de la France, 13, 81-83.

CHOPIN C., 1978.- Les paragenèses réduites ou oxydées de concentrations manganésifères des "schistes lustrés" de Haute-Maurienne (Alpes françaises). Bulletin de Minéralogie, 101, 514-531.

CHRISTOPHE-MICHEL-LÉVY M., 1962.- Idées actuelles sur l'origine et la formation des éclogites. A propos des éclogites de Loire-Atlantique et de Vendée. Comptes-Rendus du Congrès des Sociétés savantes de Paris et des Départements, Section des Sciences, 87ème Session, Poitiers: 551-556.
COGNÉ J., 1953.- L'île de Groix (Morbihan) (Feuille Ile de Groix au 50.000°). Bulletin du Service de la Carte Géologique de la France, LI (239), 277-286.
COGNÉ J., 1960.- Schistes cristallins et granites en Bretagne méridionale. Le domaine de l'anticlinal de Cornouaille. Mémoires pour servir à l'explication de la carte géologqiue détaillée de la France, Imprimerie Nationale, Paris, 382 pp.
COGNÉ J., JEANNETTE D. & RUHLAND M., 1966.- L'Ile de Groix: étude structurale d'une série métamorphique à glaucophane en Bretagne méridionale. Bulletin du Service de la Carte Géologique d'Alsace-Lorraine, 19, 41-95.
CORNEN G., 1999. Occurrence of HP relics in the manganese-ore of Groix island (South Brittany, France). European Union of Geosciences Meeting, X, Journal of Conference Abstracts, 4, 475.
CORTESOGNO L., LUCHETTI G. & PENCO A.M., 1979.- Le mineralizzazioni a manganese nei diaspri delle ofioliti liguri: mineralogia e genesi. Rendiconti della Societa Italiana di Mineralogia e di Petrologia, 35, 151-197.
CROSS C. W., 1881.- Studien über bretonische gestein. Mineralogische und Petrographische Mittheilungen, (n. f.), III: 374 p.
DAL PIAZ G.V., DI BATTISTINI G., KIÉNAST, J.-R. & VENTURELLI G., 1979. - Manganiferous quartzitic schists of the Piemonte ophiolite nappe in the Valsesia-Valtournanche area (Italian western Alps). Memorie dell Istituto Geologico e Mineralogico di Padova, 32, 1-34.
DUBUISSON F. R. A., 1830.- Catalogue de la collection minéralogique, géognostique et minéralurgique du département de la Loire-Inférieure, appartenant à la mairie de Nantes. Nantes, Mellinet, 319 p.
DUPARC L., MOLLY E. & BORLOZ A., 1927.- Sur la birbirite, une roche nouvelle. C.R. des Séances de la Société de Physique et d'Histoire naturelle de Genève, 44 (3): 137-139.
FÉLIX C., FRANSOLET A.M., 1972.- Pseudomorphes à épidote s.l., paragonite, muscovite s.l., chlorite, albite,... de porphyroblastes de lawsonite (?) dans les glaucophanites de l'île de Groix (Bretagne - France). Annales de la Société Géologique de Belgique, 95, 323-334.
GODARD G., 1983.- Dispersion tectonique des éclogites de Vendée lors d'une collision continent-continent. Bulletin de Minéralogie, 106: 719-722.
GODARD G., 1988.- Petrology of some eclogites in the Hercynides: the eclogites from the southern Armorican massif, France. In: SMITH D. C. (Ed.), "Eclogites and eclogite-facies rocks", Elsevier, Amsterdam: 451-519.
GODARD G., 2001.- The Les Essarts eclogite-bearing metamorphic Complex (Vendée, southern Armorican Massif, France): Pre-Variscan terrains in the Hercynian belt? Géologie de la France, 2001 (1-2): 19-51 + 2 cartes géologiques h.t.
GODARD G., 2009.- Two orogenic cycles recorded in eclogite-facies gneiss of the Southern Armorican Massif (France). European Journal of Mineralogy, 21: 1173-1190.
GODARD G., CHEVALIER M., BOUTON P. & MOUROUX B., 1994.- Un fleuve yprésien du Berry à la Vendée, témoin de l'évolution paléogéographique et tectonique du Centre-Ouest de la France au Cénozoïque. Géologie de la France, 1994 (4): 35-56.
GODARD G. & SMITH D. C., 1999.- Preiswerkite and Na-(Mg,Fe)-margarite in eclogites. Contributions to Mineralogy and Petrology, 136: 20-32.
GODARD G. & VAN ROERMUND H. L. M., 1995.- On clinopyroxene strain-induced microfabrics from eclogites. Journal of structural Geology, 17 (10): 1425-1443.
HAÜY R. J., 1822.- Traité de minéralogie. Seconde édition, revue, corrigée et considérablement augmentée par l'auteur. Paris, Bachelier et Huzard, 4 vol. in-8° + atlas [t. II, p. 456; t. IV, p. 548].
HUEBNER J.S., FLOHR M.J.K., 1990.- Microbanded manganese formations: protoliths in the Franciscan Complex, California. U.S. Geological Survey Professional Paper, 1502.

JAVOY M., 1971.- Composition isotopique de l'oxygène dans les roches éclogitiques. Comptes-Rendus hebdomadaires des Séances de l'Académie des Sciences [Paris], 273: 2414-2417.
JAVOY M. & ALLÈGRE C., 1967.- Étude de la composition 18O/16O de quelques éclogites: conséquences pétrologiques et géophysiques. Bulletin de la Société géologique de France, (7) 9: 800-808.
KIÉNAST J.-R. & TRIBOULET C., 1972.- Le chloritoïde dans les paragenèses à glaucophane, albite ou paragonite. Bulletin de Minéralogie, 95, 565-573.
KIÉNAST, J.-R. & Triboulet C., 1973.- Sur la piémontite de l'île de Groix (Morbihan, France). Comptes-rendus de l'Académie des Sciences de Paris, (D) 276, 1377-1379.
LACROIX A., 1891.- Étude pétrographique des éclogites de la Loire-inférieure. Bulletin de la Société des Sciences naturelles de l'Ouest de la France, I: 81-114 + 2 pl.; 1995, 17 (3): 76-108 + 2 pl. [réédition].
LACROIX A., 1888.- Matériaux pour la minéralogie de la France. IV – Piémontite de l'île de Groix. Bulletin de la Société Francaise de Minéralogie, XI, 148-149.
LACROIX A., 1893. - Minéralogie de la France et de ses colonies. I. Librairie Polytechnique Baudry et Cie, Paris, 273p.
LE BAIL F., 1961.- Compte-rendu de l'excursion de la Société Française de Minéralogie et de Cristallographie en Bretagne. Bulletin de la Société Française de Minéralogie et de Cristallographie, 84, 213-221.
LE BAIL F., 1970.- Observations minéralogiques en Basse-Bretagne. IV- L'île de Groix (Morbihan). Penn ar Bed, 60, 217-238.
LEFORT J.-P. & SEGOUFIN J., 1978.- Etude géologique de quelques structures magnétiques reconnues dans le socle péri-armoricain submergé: implications géodynamiques concernant la fracturation proto-atlantique et l'orogenèse hercynienne. Bulletin de la Société Géologique de France, (7) XX, 185-192.
LEFORT J.-P. & VIGNERESSE J.-L.,1992.- Le lever magnétique et gravimétrique de Groix: une aide pour comprendre les structures profondes de l'île et son mode de mise en place. Bulletin de la Société Géologique de France, 163, 3-11.
LE HÉBEL F., FOURCADE S., GAPAIS D., MARIGNAC C., CAPDEVILA R. & MARTINEAU F., 2000.- Fluid-assisted spreading of thickened continental crust : preliminary data from the Variscan belt of South Brittany (France). Journal of Geochemical Exploration, 69-70, 561-564.
LE HÉBEL F., VIDAL O., KIÉNAST J.-R. & GAPAIS D., 2002.- Les "porphyroïdes" de Bretagne méridionale: une unite de HP-BT dans la chaîne hercynienne. Compte-rendu Geoscience, 334, 205-211.
MARTIN S., KIÉNAST J.-R., 1987.- The HP-LT manganiferous quartzites of Praborna, Piemonte ophiolite nappe, Italian Western Alps. Schweizerische Mineralogische und Petrographische Mitteilungen, 67, 339-360.
MATTE P., 1991.- Accretionary history and crustal evolution of the Variscan belt in Western Europe. Tectonophysics, 196: 309-337.
MAULER A., GODARD G. & KUNZE K., 2001.- Crystallographic fabrics of omphacite, rutile and quartz in Vendée eclogites (Armorican Massif, France). Consequences for deformation mechanisms and regimes. Tectonophysics, 342: 81-112.
MONTIGNY R. & ALLÈGRE C., 1974.- A la recherche des océans perdus: les éclogites de Vendée témoins métamorphisés d'une ancienne croûte océanique. Comptes-Rendus hebdomadaires des Séances de l'Académie des Sciences [Paris], Série D, 279: 543-545.
PEUCAT J.-J., VIDAL P., GODARD G. & POSTAIRE B., 1982a.- Precambrian U-Pb zircon ages in eclogites and garnet pyroxenites from South-Brittany (France): an old oceanic crust in the West European Hercynian belt? Earth and Planetary Science Letters, 60: 70-78.
PHILIPPON M., GUEYDAN F., PITRA P. & BRUN J. P., 2013.- Preservation of subduction-related prograde deformation in lawsonite pseudomorph-bearing rocks. J. Metamorph. Geol. 31, 571–583.
PIERROT R., CHAURIS L., LAFORÊT C. & PILLARD F. (1980). Inventaire minéralogique de la France n°9: Morbihan (56). BRGM, Orléans, 315 p.

PLYUSNINA I.I., VASILYEVA YE.R. & MOROZOVA N.I., 1983.- Phase transformation of silica in weathered crusts of ultrabasic rocks of Central Kazakhstan. Moscow Univ. Geol. Bull., 38: 87-91.
RIVIÈRE A., 1835.- Note sur la carte géognostique de la Vendée. Comptes-Rendus hebdomadaires des Séances de l'Académie des Sciences [Paris], I: 237.
RIVIÈRE A., 1844a.- Mémoire minéralogique et géologique sur les roches dioritiques de la France occidentale. Bulletin de la Société géologique de France, (2), I: 528-569.
RIVIÈRE A., 1844b.- Sur les roches dioritiques de la France occidentale, c'est-à-dire sur les roches d'épanchement qui appartiennent aux terrains du groupe carbonique (terrain de vieux grès rouge et terrains carbonifères) [extraits]. Comptes-Rendus hebdomadaires des Séances de l'Académie des Sciences [Paris], XVIII: 1184-1188.
RIVIÈRE A., 1851.- Mémoire sur le terrain gneissique ou primitif de la Vendée. Mémoires de la Société géologique de France, (2), IV (2): 49-175.
TERS M., 1979.- Carte géologique de la France à 1/50000, feuille Saint-Philbert-de-Grand-Lieu + notice de 79 p. B.R.G.M., Orléans.
TUMIATI S., MARTIN S. & GODARD G., 2010.- Hydrothermal origin of manganese in the high-pressure ophiolite metasediments of Praborna ore deposit (Aosta Valley, Western Alps). European Journal of Mineralogy, 11, 577–594.
TUMIATI S., GODARD G., MARTIN S., MALASPINA N. & POLI S., 2015.- Ultra-oxidized rocks in subduction mélanges? Decoupling between oxygen fugacity and oxygen availability in a Mn-rich metasomatic environment. Lithos, 226, 116-130.
VELDE B. & SABATIER H., 1972.- Eclogite from Northern Vendée, France. Bulletin de la Société française de Minéralogie et de Cristallographie, 95: 397-400.
YAMATO P. & BRUN J.P., 2017.- Metamorphic record of catastrophic pressure drops in subduction zones", Nature Geoscience, 10, 46-50, doi:10.1038/ngeo2852.