FIELD TRIP GUIDE

07 – 12 September

Paleozoic orogenies in the French Massif Central
A cross section from Béziers to Lyon

1. Introduction

The formation of the continental substratum of Medio-Europa occurred in Paleozoic times. The names of "Hercynian" or "Variscan" are used to deal with the geodynamic processes that took place from Cambrian to Carboniferous. It is now widely accepted that this Paleozoic Belt that crops out from Iberia to Bohemia (Fig. 1) results of a complex interplay of rifting, convergence and collision between three large continents, namely Laurentia, Baltica and Gondwana and several microcontinental stripes such as Avalonia or Armorica (Matte, 2001). Continental drifting and welding resulted in the opening and closure of several oceans such as Iapetus, Rheic and Medio-European. There is however a wide range of opinions concerning the location and width of these oceanic domains and the number, kinematics and timing of collisional processes (e.g. Autran and Cogné, 1980; Franke, 1989, 2000; Ledru *et al.*, 1989; Matte, 1991; 2001; Faure *et al.*, 1997).

The French Massif Central is one of the largest pieces of the Variscan Belt. The whole Massif Central provides a reference cross section throughout the north Gondwana margin deformed and metamorphozed during the Paleozoic. During the last two decades, and recently through the GéoFrance 3D program, advances in geochronology, structural geology, metamorphic and magmatic petrology, allow us to settle a comprehensive structural map of the Massif Central and to discuss a possible scenario accounting for the Paleozoic tectono-thermal evolution.

This field trip presents representative lithological, structural, magmatic, metamorphic and geochronological data of the French Massif Central from unmetamorphozed kilometer-scale recumbent folds to UHP metamorphic rocks. Most of the controversial aspects of collisional orogens such as continental subduction and exhumation of ultrametamorphic rocks, nappe kinematics, inverted metamorphism, syn- to post-orogenic extensional tectonics, crustal melting and tectonic setting of pluton emplacement will be addressed.

Field References

Topographic maps IGN 1/100,000: n° 65 Béziers-Montpellier; n° 58 Rodez-Mende; n° 59 Privas-Alès; n° 50 Saint-Étienne-Le Puy; n° 51 Lyon-Grenoble.

Geologic maps BRGM 1/50,000: n° 1014 Saint-Chinian; n° 988 Bédarieux; n° 862 Mende; n° 863 Le Bleymard; n° 839 Langogne; n° 840 Burzet; n° 792 Yssingeaux; n° 745 Saint-Étienne; n° 721 Saint-Symphorien-sur-Coise; n° 697 Tarare.

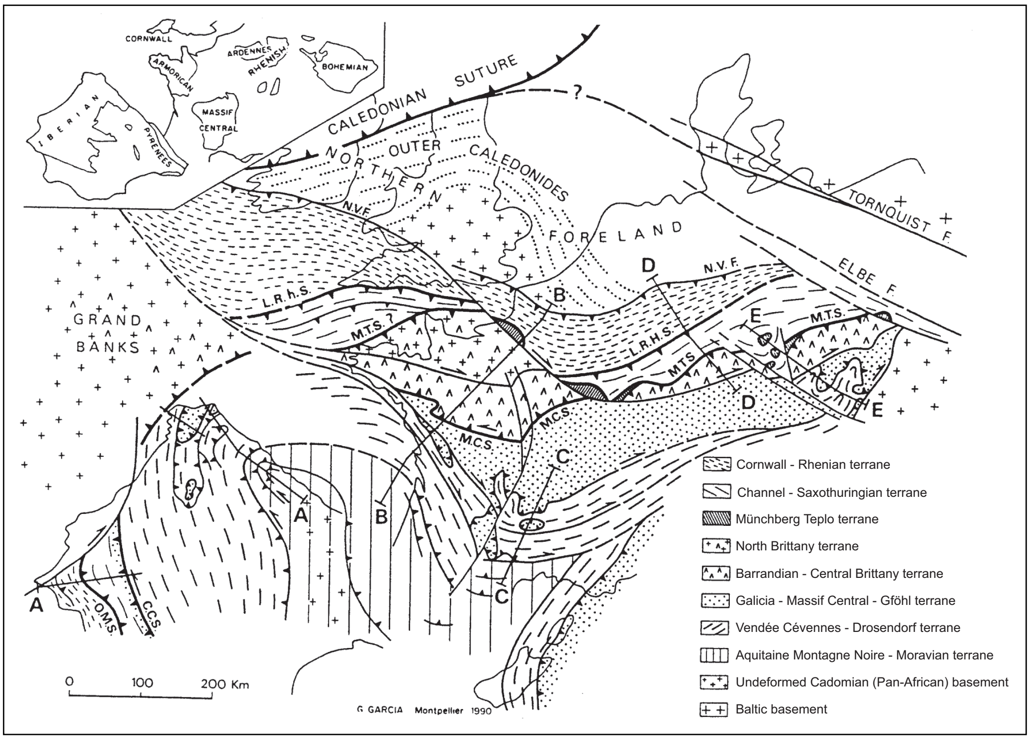
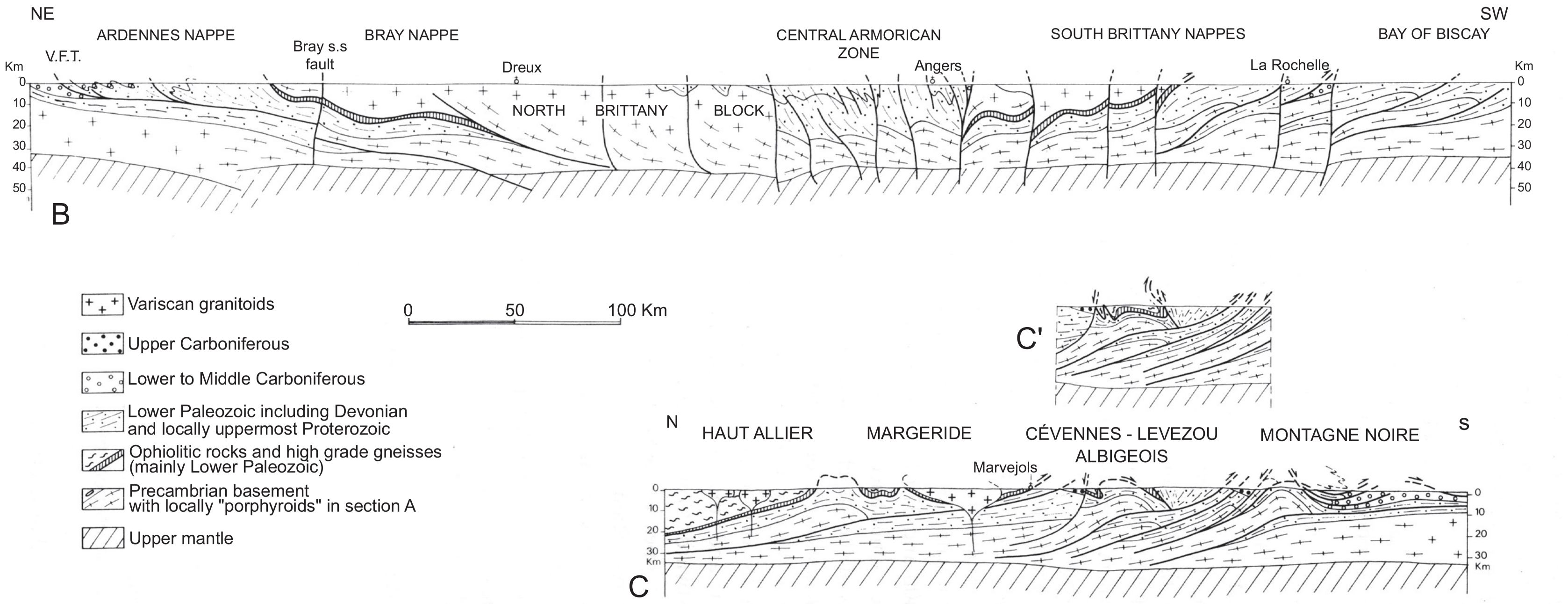


Fig. 1.- Location of the French Massif Central in the frame of the Paleozoic belt of Medio-Europa (Matte, 1991).



Sections through the Iberian and French Variscan massifs. (A) Iberian section. (B) Armorica–Ardennes section. (C) Massif Central section (C') Alternative hypothesis for the Levezou dome.

Fig. 2.- Cross-sections from the Massif Armoricain to Ardenne (B) and through Massif Central (C). C' is an alternative section through the Lévezou klippe (Matte, 1991).

2. Regional geological setting

2.1. A structural map of the French Massif Central

It is now widely accepted that the structure of the French Massif Central is a stack of nappes (Ledru *et al.*, 1989, 1994; Fig. 3). From top to bottom and also from south to north, six main tectonic units are distinguished.

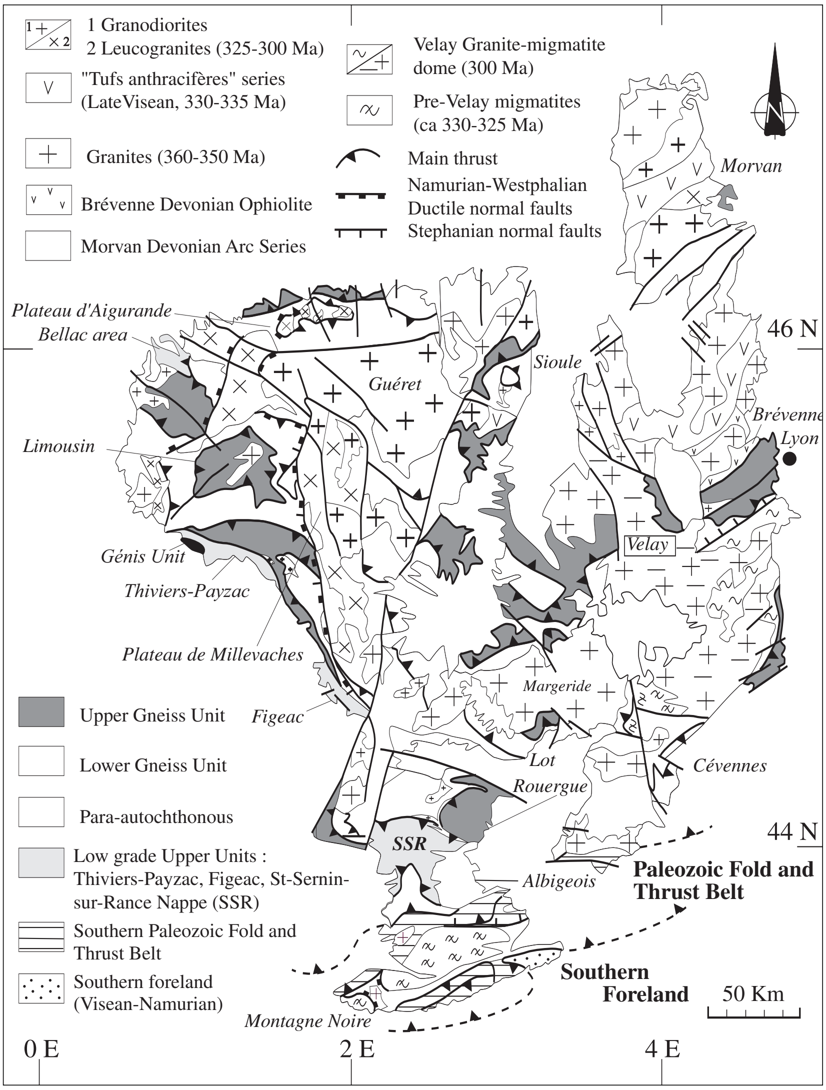


Fig. 3.- Structural map of the Massif Central (adapted from Ledru et al.*, 1989).*

i) The Southern Palaeozoic Fold and Thrust Belt involves a set of continental margin/platform series recording a more or less continuous sedimentation spanning from Early Cambrian to Early Carboniferous. The series are deformed within kilometer-scale recumbent folds well observed in the Montagne Noire area (Arthaud, 1970).

ii) The Para-autochthonous Unit that overthrusts the previous unit consists of a thick metapelite-metagrauwacke series (also called “Cévennes micaschists”) with some quartzite beds and volcanic rocks. Although stratigraphic ages are lacking, a Neoproterozoic to Ordovician age is generally accepted.

iii) The Lower Gneiss Unit (LGU) is lithologically quite similar to the Para-autochthonous Unit. Early Cambrian and Early Ordovician alkaline granitoids, now transformed in augen orthogneiss, are also widespread. Both the Para-autochthonous Unit and Lower Gneiss Unit are interpreted as Proterozoic-Early Paleozoic remnants of the northern Gondwana margin that experienced crustal thinning and rifting in Ordovician times.

iv) The Upper Gneiss Unit (UGU) is made up of a bi-modal association called “leptynite-amphibolite” sequence which is a peculiar assemblage of mafic and felsic rocks. This unit experienced the higher metamorphic pressure under eclogite and HP granulite facies (ca. 20Kb). Locally near Lyon, coesite-eclogite facies ultra high-pressure metamorphism is reached (Lardeaux *et al.*, 2001). The protoliths of the UGU also include metasediments and granitoids. The upper part of the UGU consists of migmatites formed by the partial melting of pelitic and quartzo-feldspathic rocks within which amphibolite block are preserved as restites. Radiometric dates show that the magmatism occurred in Early Ordovician times (ca. 480 Ma) and the high-pressure metamorphism in Late Silurian (ca. 420-410 Ma, Pin and Lancelot, 1982; Ducrot *et al.*, 1983). Due to the occurrence of rare metagabbros and serpentinized ultramafics, the UGU is considered by some authors as a remnant of an oceanic domain, the Medio-European Ocean, that opened in Early Paleozoic times during the rifting that led to the separation of Armorica from North Gondwana (e.g. Dubuisson *et al.*, 1989; Matte, 1991). However, it is worth noting that the Upper Gneiss Unit is not a true ophiolitic sequence since oceanic sedimentary rocks such as radiolarites or siliceous shales are lacking and ultramafics or serpentinites are rare. A likely interpretation is to consider that the UGU is a transitional crust between true continental and oceanic ones.

v) The Thiviers-Payzac Unit that crops out in the south Limousin, is the highest tectonic unit of the allochthonous stack in the French Massif Central. It is formed by Cambrian metagraywackes, rhyolites and quartzites intruded by Ordovician granite. Conversely to the underlying UGU, the Thiviers-Payzac Unit never experienced the high-pressure metamorphism. As revealed by seismic reflection line (Bitri *et al.*, 1999), these relatively low grade rocks tectonically overly the UGU.

vi) In the NE Massif Central, near Lyon, the Brevenne Unit consists of mafic magmatic rocks (pyroclastites, pillow basalts, diabases, gabbros), serpentinized ultramafics, acidic volcanic rocks, and siliceous sediments (radiolarites, siltites). The acidic rocks are dated of 366±5 Ma (U/Pb method on zircon, Pin and Paquette, 1998). Petrology and geochemistry show that the Brevenne Unit and its extension in the Beaujolais area is a Middle Devonian oceanic sequence formed within an oceanic or a back-arc basin opened within the UGU (Sider and Ohnenstetter, 1986; Pin, 1990; Pin and Paquette, 1998). The Brevenne Unit records an early thrusting to the NW over the UGU followed by a NE-SW dextral strike-slip (Feybesse *et al.*, 1988; Leloix *et al.*, 1999). The precise age of the thrusting is unknown but since the metamorphic rocks are concealed below the Early Visean calcareous sandstone of the famous unconformity of Le Goujet (east of Lyon) an Early Carboniferous age is likely (cf. below).

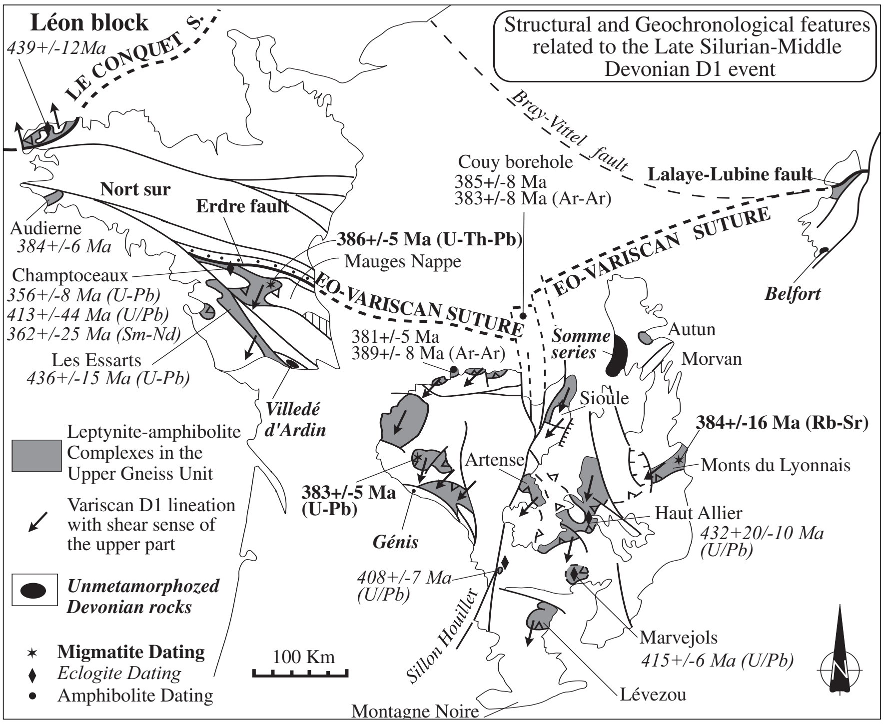


Fig. 4.- Structural and geochronologic features related to the Late Silurian-Middle Devonian D1 event.

2.2. The tectono-metamorphic evolution

Structural information related to the high-pressure metamorphism and the prograde metamorphic evolution is poorly documented since these rocks are known only as relics. It is therefore quite difficult to draw a general view of this event. Moreover, three main synmetamorphic ductile events are recognized.

The earliest deformation found in the UGU, D1, is characterized by a NE-SW trending lineation with a top-to-the-SW shearing developed coevally with an intermediate pressure/intermediate temperature metamorphism and anatexis dated around 385-380 Ma (e.g. Floc'h, 1983; Quenardel and Rolin, 1984; Costa, 1992; Boutin and Montigny, 1993; Duthou *et al.*, 1994; Roig and Faure, 2000; Figs. 4, 5). Since the D1 event is found in the migmatites that form the upper part of the UGU, it occurred during or at the end of the exhumation of the high-pressure metamorphic rocks. The radiometric dates comply with the Devonian stratigraphic age of the unmetamorphozed rocks (e.g. Villedé d'Ardin, Génis, Somme, Belfort areas, Fig. 4). Although a direct unconformity is never observed, field relationships suggest that D1 is older than Middle Devonian.

The second event, D2, is characterized by a NW-SE trending lineation coeval with a barrovian type metamorphism (Figs. 5, 6). $^{40}Ar/^{39}Ar$ dates on biotite, muscovite and amphibole range around 360-350 Ma. Most of the shear criteria developed along the

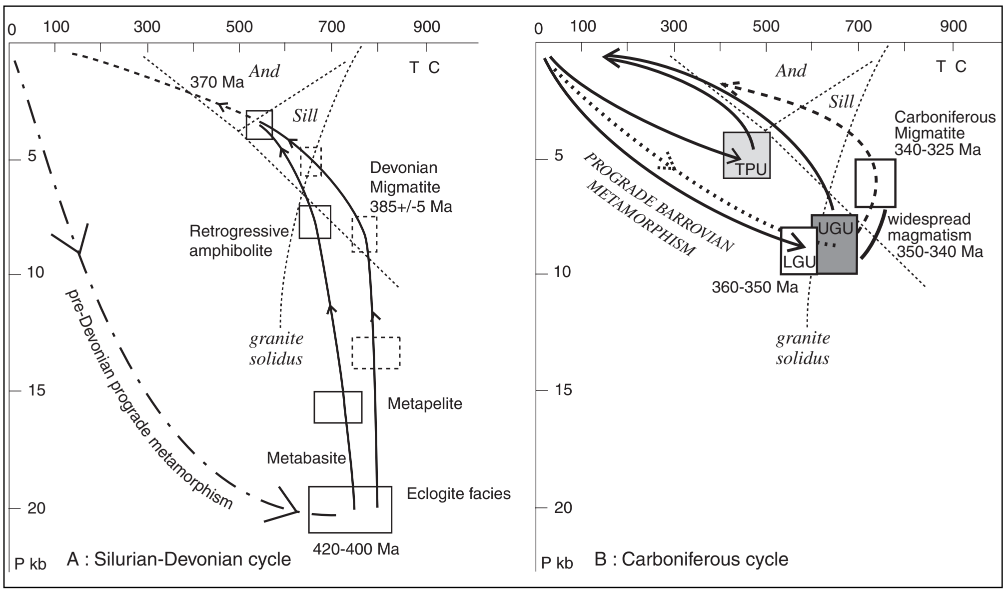


Fig. 5.- P-T paths of the Silurian-Devonian and Carboniferous events for the different units.

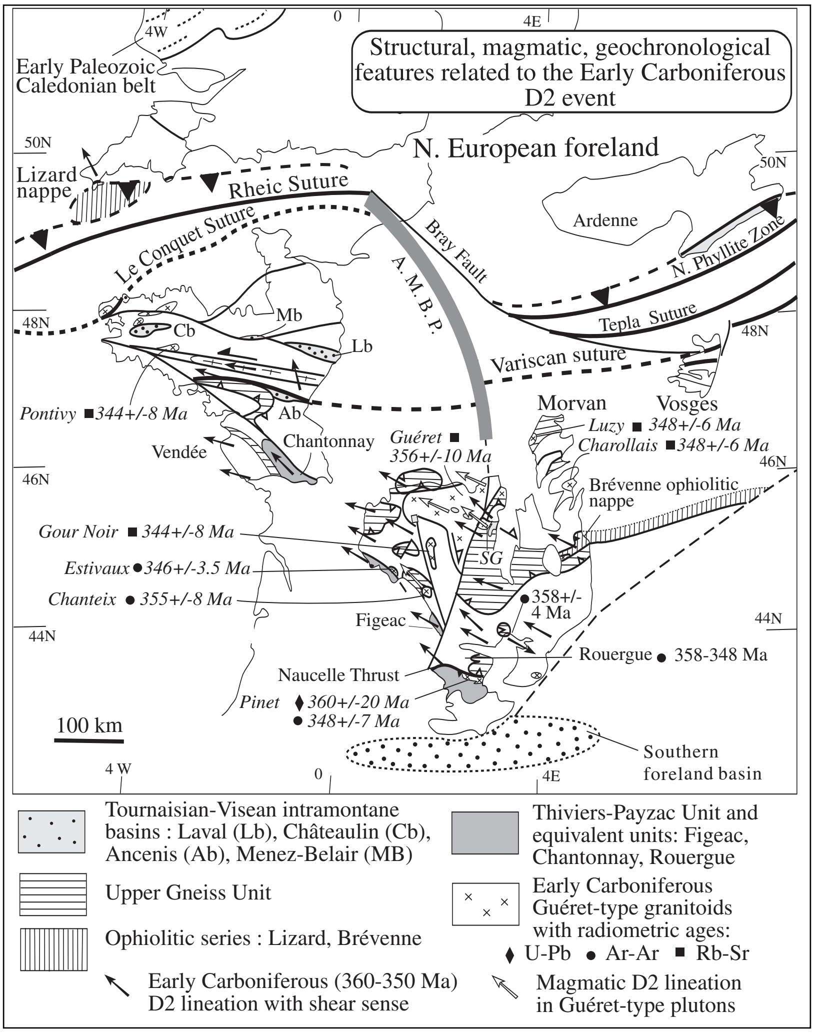


Fig. 6.- Structural, magmatic and geochronologic features related to the Late Devonian-Early Carboniferous D2 event (AMBP: Magnetic Anomaly of Paris Basin).

NW-SE lineation indicate a top-to-the-NW shearing. In the Rouergue area, the Naucelle thrust is related to this event (Duguet and Faure, in press). The last increment of the ductile deformation in the metamorphic series is associated with the emplacement of peraluminous cordierite bearing granitoids such as the Guéret pluton that is the largest massif of this type. These granitoids exhibit magmatic to sub-solidus fabrics that comply with the synkinematic character of these plutons (e.g. Roig *et al.*, 1998). A similar tectonic-metamorphic-magmatic pattern is also recognized in the south part of the Massif Armoricain. The closure of the Brevenne oceanic basins is chronologically and kinematically in agreement with the D2 event (Leloix *et al.*, 1999). The geodynamic significance of the NW-SE lineation parallel to the belt is not clearly understood yet. Several hypotheses have been proposed (e.g. Burg *et al.*, 1987; Bouchez and Jover, 1986; Mattauer *et al.*, 1988) but none of them appears fully convincing. As discussed in section 2.4, this Early Carboniferous deformation is coeval with the closure of the Rheic Ocean and collision between Gondwana and Laurussia.

The third event, D3, is restricted to the southern part of the Massif Central. In the Para-autochthonous Unit of Cévennes-Albigeois, upper greenschist to amphibolite facies rocks are deformed by top-to-the-south ductile shearing along a submeridian lineation (Fig. 7). Available $^{40}Ar/^{39}Ar$ dates on the metamorphic minerals yield Visean ages around 340 Ma (Monié *et al.*, 2000; Faure *et al.*, 2001). This thrusting propagates southward in the Fold and Thrust Belt where kilometer-scale recumbent folds develop from Visean to Namurian. Although in the South Massif Central south-directed compressional regime lasts from Visean to Namurian (345 to 325 Ma), conversely, in the northern part of the massif, the Late Visean (ca. 340 Ma) is a turning point in the tectonic evolution.

From Morvan to Limousin, the Late Visean time corresponds to the onset of syn-orogenic extension caracterized by a huge crustal melting. Structural studies indicate that the syn-orogenic extension is controled by a NW-SE maximum stretching direction (Fig. 7). The NW-SE spreading of the inner part of the Massif Central is also partly accommodated by ductile wrench faults well developed in Limousin (e.g. La Courtine or S. Limousin faults, Fig. 7) and in the Massif Armoricain. At the scale of the whole belt, the Late Visean to Namurian compression is also responsible for the development of north-directed thrusts in Ardenne and SE England.

The last ductile deformation events (ca. 320 Ma and younger ones) took place during the collapse of the belt. Since they are closely associated to magmatism, they will be considered in the next section.

2.3. A magmatic outline

Alike all the Variscan massifs, the Massif Central is also characterized by a voluminous magmatism mainly derived from crustal melting. Several generations of migmatites and granitoids are recognized (e.g. Duthou *et al.*, 1984).

2.3.1. The pre-orogenic magmatism is not presented in detail here. The Early Ordovician bimodal magmatism, responsible for the formation of the leptynite-amphibolite complex in the UGU, and the Cambrian or Ordovician magmatic rocks are ductilely deformed, metamorphozed and included in the stack of nappes.

2.3.2. The Middle to Late Devonian calc-alkaline volcanic and volcanic-clastic rocks that crop out in the Morvan area (called the Somme series) belong to a magmatic arc (Fig. 8; Pin *et al.*, 1982; Delfour, 1989). In the south part of the Massif Armoricain, Eifelian-Givetian basaltic pillow lavas form the Meilleraie series. These

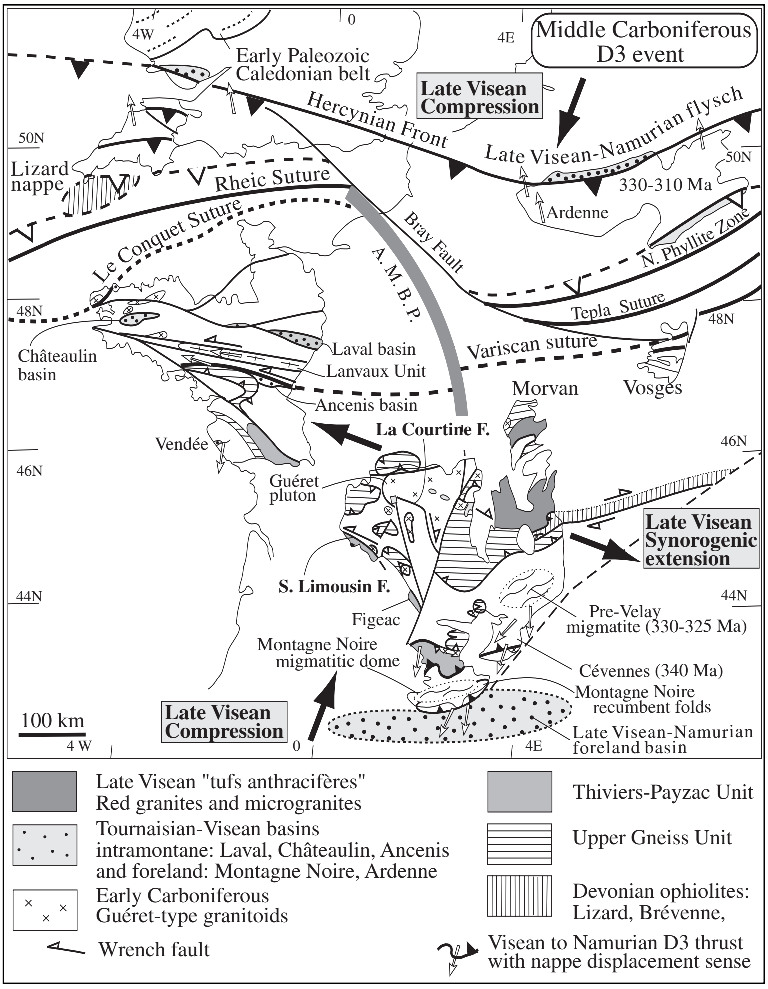
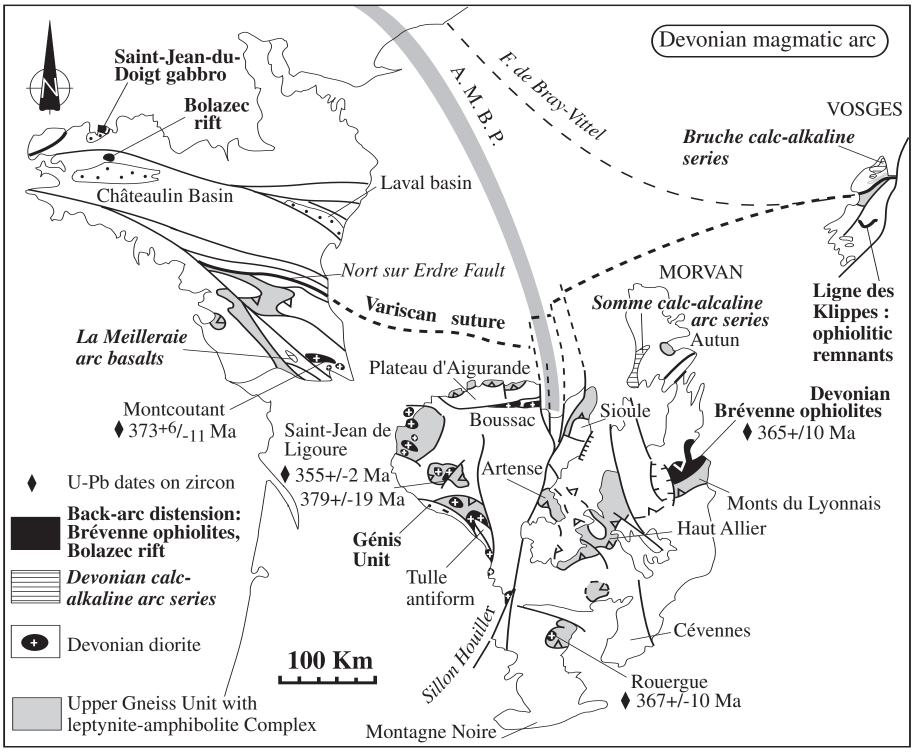


Fig. 7.- Structural and geochronologic features related to the Visean-Namurian D3 tectonics and Late Visean magmatism (AMBP: Magnetic Anomaly of Paris Basin).

rocks are interpreted as the aerial part of a magmatic arc. Moreover, mafic calk-alcaline rocks well known for a long time in the Limousin (Didier and Lameyre, 1971), are interpreted as the deep part of the same Devonian arc. Its geodynamic significance will be discussed in section 2.4.

2.3.3. The Tournaisian late-collisional magmatism is represented by the Guéret-type granites per-aluminous plutons. Their magmatic fabric suggests that the same strain field than the D2 deformation (Fig. 6) controls their emplacement.

2.3.4. The Visean magmatism is well developed in the north and west part of the Massif Central (Fig. 7). It consists in aerial products with lava flows, ignimbrites, pyroclastic deposits, called "Tufs anthracifères series", rhyolitic to dacitic dykes and hypovolcanic microgranites. Geochemistry indicates that crustal melting was triggered by heat imput from the mantle. Moreover, a mantle contribution as the source of magma is also likely (Pin and Duthou, 1990). The structural control of dyke intrusion complies with a NW-SE stretching related to the early stage of orogenic collapse. In the northern Cévennes, the Para-autochthonous Unit is underlain by migmatitic ortho- and paragneiss called "the Masméjean Unit" or pre-Velay migmatites (Faure *et al.,* 2001). The anatexis is dated between 333 and 324 Ma by the Chemical U/Th/Pb method on monazite (Be Mezème, 2002). The migmatites and cordierite granites of the Montagne Noire Axial Zone (cf. D2 field itinerary in section 3) yield similar ages. In the present state of knowledge, this Late Visean event is still poorly studied. It is likely that other pre-Velay migmatites are not yet recognized also within the Velay dome.



2.3.5. The Namurian-Westphalian plutonism corresponds to the main period of magma production in the French Massif Central. It is well acknowledged (Didier and Lameyre, 1971) that this magmatism is represented by two types of granitoids, namely porphyritic monzogranites, such as the Margeride or Pont-de-Montvert-Borne plutons, and biotite-muscovite leucogranites such as the Brame or Millevache massifs (Fig. 9). Although both granite types crop out throughout the Massif Central, the former type is best rep-

Fig. 8.- Map showing the distribution of the Devonian plutons and volcanic rocks related to the magmatic arc and ophiolites (Brévenne, Ligne Klippes) interpreted as back arc basins (adapted from Faure et al.*, 1997).*

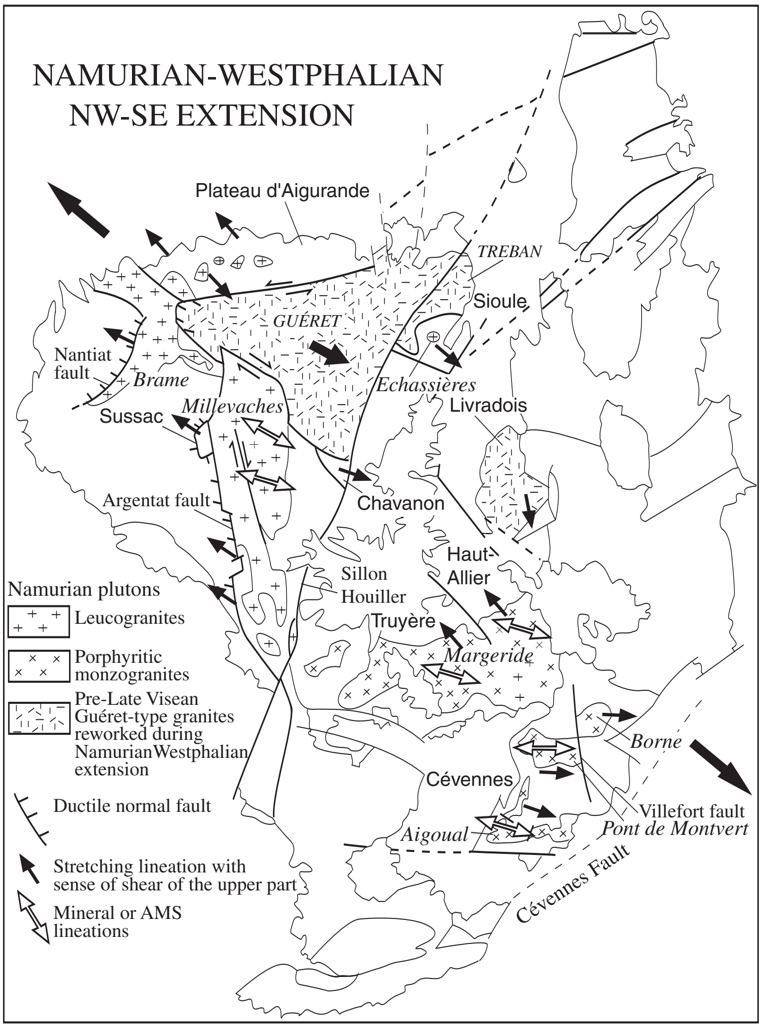


Fig. 9.- Distribution of the main granitic plutons coeval with the stretching lineation and kinematics related to the Namurian-Westphalian extensional tectonics. During this event, the pre-Visean Guéret pluton behaves as a rigid body.

resented in the central and southern parts of the massif and the later type is more abundant in the north and west parts. The two types were derived from different magmas, but field relationships and geochronology show that these two magmatic types emplaced coevally. Petro-structural and AMS studies of the Namuri-Westphalian plutons show that these bodies are characterized by a conspicuous NW-SE trending mineral, stretching and magnetic lineation. The same trend is also observed in biotite and andalusite contact minerals in the pluton host rocks (Fig. 9). In the north Limousin, the Brame pluton is bounded to the west by the Nantiat ductile normal fault that also exhibits a NW-SE trending hot slickenline. A similar kinematics is also found along the Argentat ductile normal fault. This structural pattern is interpreted as the consequence of the syn-orogenic extensional tectonics of the Massif Central (Faure, 1995).

2.3.6. The Stephanian magmatism is represented by cordierite granite and migmatites of the Velay dome, and also by acidic tuf, ash layers and more rarely alkaline basalts interlayers with terrigeneous formations in the coal basins. The Velay dome is bounded to the north by a detachment fault, the Pilat ductile normal fault (Malavieille *et al.*, 1990). Gneiss and micaschists belonging to the LGU that crop out north of the Pilat fault form the substratum of the Late Carboniferous Saint-Étienne basin.

2.4. A possible geodynamic scenario

The above-presented data allow us to discuss a geodynamic evolution model. Presently, two scenari for the evolution of the French Massif Central are proposed. The first one emphasizes a continuous convergence between Gondwana and Laurussia from Silurian to Early Carboniferous (e.g. Matte, 1991; Lardeaux *et al.*, 2001). The second one points out a polycyclic evolution (Pin, 1990; Faure *et al.*, 1997). According to this model, an Early Paleozoic cycle, (Cambrian to Early Devonian), is related to the opening and closure of the Medio-European Ocean and correlatively drifting and rewelding of Armorica to Gondwana. A second orogenic cycle ranging from Middle Devonian to Carboniferous accounts for which the closure of the Rheic Ocean and the collision of Gondwana and Laurussia. Whatever the preferred model, the following stages are acknowledged.

2.4.1. The breaking of the north Gondwana margin

From Cambrian to Early Silurian, the Massif Central belongs to the northern passive margin of Gondwana which extends from South America to China. From the study of Montagne Noire, the Cambrian-Ordovician corresponds to a terrigeneous environment, followed in Devonian by a carbonate platform. The lack of Late Ordovician and Silurian deposits is interpreted as the result of erosion on tilted blocks (Robardet *et al.*, 1994). Evidence for an Ordovician rifting is also inferred from magmatism. In the Para-autochthonous Unit, alkaline mafic volcanics (sometimes with pillow lava), diabase dykes, gabbro intrude the grauwacke-pelite series (Pin and Marini, 1993). In LGU, the alkaline Ordovician granitoids also comply with continental rifting. It is worth noting that "pseudo-calc-alkaline" geochemistry of these granitoids is due to crustal contamination (Duthou *et al.*, 1984; Pin and Duthou, 1990). In the UGU, crustal thinning due to continental rifting is coeval with the emplacement of the leptynite-amphibolite complexes. As a matter of fact, the Cambrian-Ordovician period is characterized by the formation of continental stripes, such as the Armorica microcontinent drifted from the north Gondwana margin. The question of the maximum width of the intervening Medio-European Ocean is not settled yet (see discussion in Robardet, 2003). A rough estimate suggests that this oceanic area was of limited extend (i.e. between 500 and 1,000 km).

2.4.2. The closure of the Medio-European Ocean

On the basis of available dates on the high-pressure metamorphism, the closure of the Medio-European Ocean started in Silurian. All authors accept a northward subduction of the Gondwana margin, however, structural constraints (i.e. kinematics coeval with the development of high-pressure assemblages) or geodynamic evidence (i.e. relics of a magmatic arc) are lacking. By Middle Devonian time, the Armorica microcontinent is rewelded to Gondwana. In NE Massif Central, (North of Lyon), undeformed and unmetamorphozed Givetian sedimentary rocks unconformably cover the migmatites and high pressure rocks (Delfour, 1989; Godard, 1990). Subduction of oceanic and continental rocks is followed by their exhumation in Early to Middle Devonian, around 390-385 Ma. The lack of large volumes of Devonian clastic rocks suggests that exhumation was tectonically assisted. Exhumation results in the extensive retrogression of the high-pressure rocks of the UGU and migmatisation of the pelitic parts.

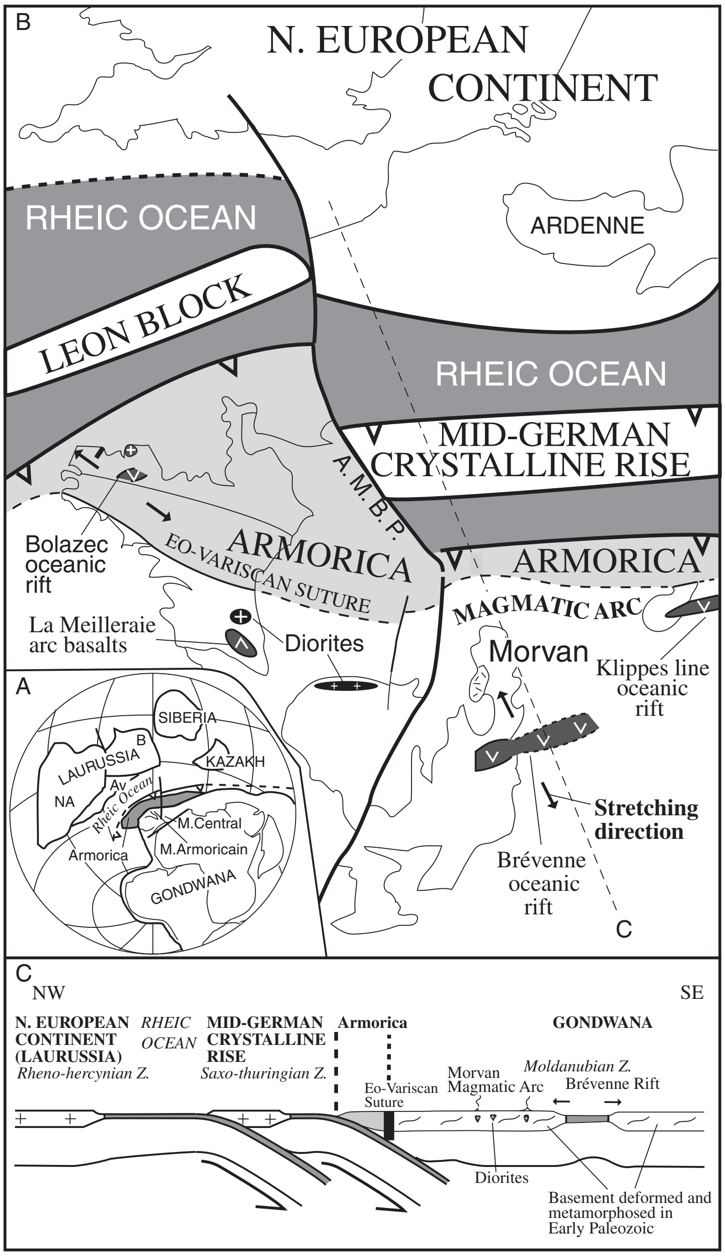


Fig. 10.- Devonian geodynamic reconstruction (map and section) showing the closure of the Rheic Ocean by southward subduction below Gondwana and related microcontinents (from Faure et al.*, 1997).*

2.4.3. Mid-Devonian magmatic arc-back arc system

Frasnian-Fammenian calc-alkaline volcanism in the NE Massif Central and Vosges argue for subduction. In addition, the 380-370 Ma calc-alkaline diorite, tonalite, granodiorite plutons that crop out in NW Massif Central are interpreted as the deep part of this magmatic arc. However, in their present position, these plutons are rootless and tectonically included into the Hercynian nappes. Southward subduction of the Rheic Ocean is viewed as the cause of the calc-alcaline magmatism. At the same time, distension also occurred in the upper plate, giving rise to limited oceanic zones such as the Brévenne in the Massif Central or other areas in the Massif Armoricain and Vosges. Therefore, an arc-back arc pattern appears as the most likely geodynamic setting for Devonian times (Fig. 10). The discussion of the Léon and microcontinents is beyond the scope of this presentation.

2.4.4. The closure of the Rheic Ocean and the Tournaisian collision

Since Late Fammenian, complete closure of the Rheic Ocean led to collision between the North European continent made by the assembly of Laurentia, Baltica and Avalonia during the Caledonian orogeny and Gondwana, including Armorica microcontinent rewelded to it. Intracontinental shortening follows the Lizard ophiolite obduction (which probably extends along the Magnetic Anomaly of Paris Basin). North-directed thrusts develop from South England to Ardennes. In the northern Massif Central, the closure of the Brévenne oceanic area is characterized by top-to-the-NW shearing under upper greenschist-lower amphibolite facies in the mafic rocks. Top-to-the-NW ductile shearing coeval with middle temperature/ middle pressure metamorphism, and dated around 360 Ma is also widespread in western and northern Massif Central. In the southern part of the Massif Central, southward shearing and recumbent folding develops with a progressively younging southward: ca. 345-340 Ma in the Para-autochthonous Unit to 330-325 Ma in the Fold and Thrust Belt.

2.4.5. Late Visean-Namurian syn-convergence extension

As soon as Late Visean (ca 335 Ma), the northern Massif Central experienced crustal melting responsible for the “tufs anthracifères” acidic volcanism and related plutonism. The structural analysis of the Late Visean plutons and dykes emplacement is controlled by a NW-SE maximum stretching direction and argue for an incipient stage of syn-orogenic collapse in the inner part of the belt (Fig. 7). However, the southern and northern external zones of the Hercynian Belt, such as Montagne Noire and Ardenne respectively, are still under compression as shown by the development of kilometer-scale recumbent folds and thrusts.

In Central and southern Massif Central, the thermal overprint is responsible for migmatite and cordierite granite formation. The ca 330 Ma migmatites that crop

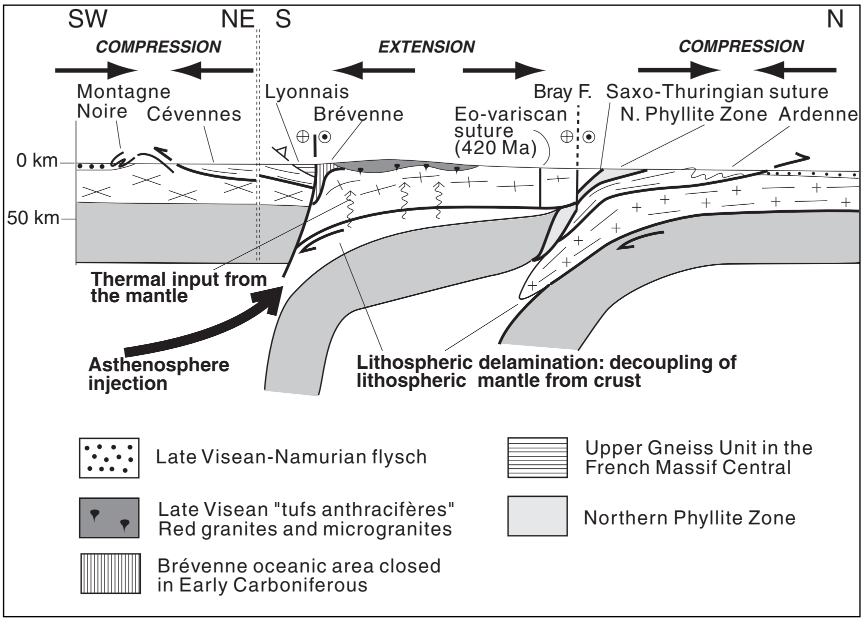


Fig. 11.- Interpretative lithosphere scale cross section through the French Hercynian Belt in Late Visean. Mantle lithosphere delamination may account for the contrasted tectonic regimes (extensional and compressional), magmatism and heat flow in the central part of the belt (modified from Faure et al.*, 2002).*

is characterized by NE-SW stretching, NW-SE and vertical shortening. The amount of extension increases from west to east. NE-SW extension and correlatively coal basins are widespread in eastern Massif Central but are rare in western Massif Central and almost lacking in the Massif Armoricain. Several N-S to NNE-SSW trending wrench faults such as the Sillon Houiller and Argentat fault are interpreted as transfer faults that accommodate different amounts of extension. Magmatism and mid-crustal deformation associated to Late Carboniferous extension are less developed than during syn-convergence extension. The most spectacular structure is the 100km diameter migmatitic-granitic Velay dome (Ledru *et al.*, 2002). Heat imput from the mantle is responsible for high temperature granulitization of the lower crust (Pin and Vielzeuf, 1983).

out in the Montagne Noire Axial Zone and south of the late Carboniferous Velay massif belong to this event. However, in the present state of knowledge, the tectonic setting (namely extensional or compressional tectonic regime) is not settled yet. Decoupling of lithospheric mantle from crust, i.e. lithospheric delamination, might likely play a significant role to account for the magmatism (Fig. 11).

From Namurian to Westphalian (ca 325-310 Ma), orogen parallel extension is well recorded by emplacement fabrics of leucogranites and granodiorites in the Massif Central (Fig. 9). In the Massif Armoricain, leucogranitic are also widespread. There, they are synkinematic plutons coeval with dextral wrenching (e.g. Berthé *et al.*, 1978). However, it is worth noting that both in the Massif Armorican and Massif Central the wrench or extension controlled synkinematic plutons exhibit the same NW-SE maximum stretching direction. This tectonic stage corresponds also to the main metallogenetic epoch for mesothermal gold deposits.

2.4.6. Stephanian post-orogenic NNE-SSW extension

The last stage of the Hercynian orogeny in the French Massif Central corresponds to the collapse of the whole belt. Extensional regime is well recorded by the tectonic setting of intra-mountain Stephanian coal basins. Two structural types of basins are recognized: 1) half-graben bounded by pure normal faults or normal faults with a strike-slip component or 2) pull-apart controlled by wrench faults (Fig. 12). Among these intra-mountain basins, the Saint-Étienne coal basin is one of the most famous since it corresponds to the para-stratotype of the Stephanian stage. Nevertheless the structural control, either as a left-lateral pull apart or a half-graben is not settled yet (Mattauer and Matte, 1998). At the scale of the Massif Central, the deformation pattern of Stephanian extension

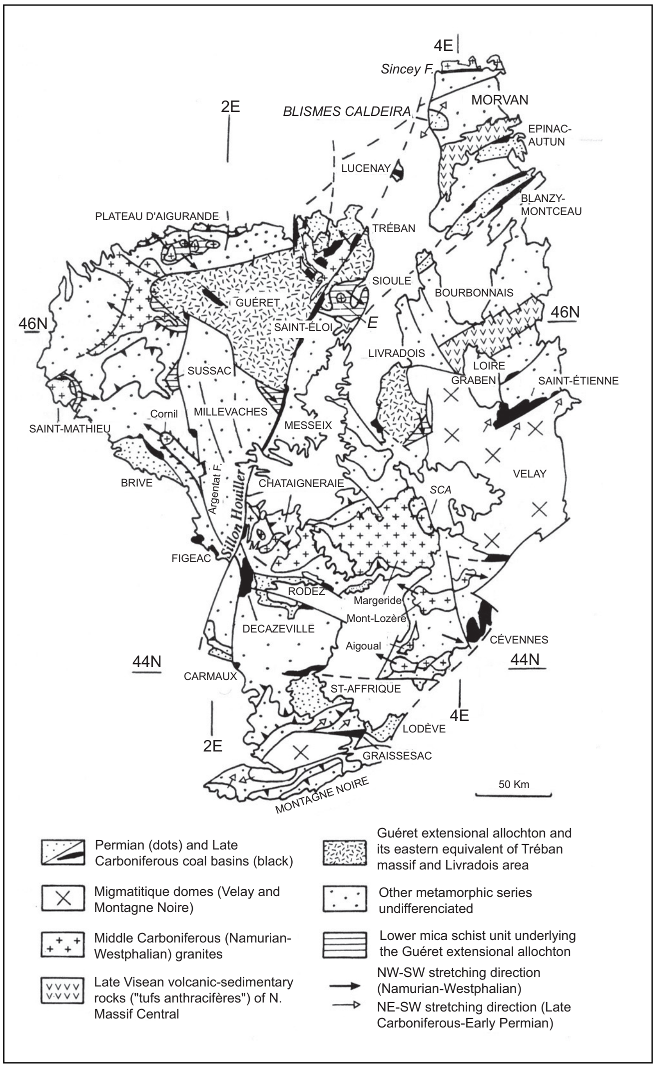


Fig. 12.- Massif Central map showing the Carboniferous extensional structures: coal basins, Velay granite-migmatite dome.

3. Field itinerary

Day 1. Recumbent folding in the Montagne Noire Southern Side

Montpellier—> Béziers —> Cessenon D 136 to Saint-Nazaire de Ladarez

A. Geological setting

Following Gèze (1949) and Arthaud (1970), the Montagne Noire area is classically divided from South to North, into a Southern Side, an Axial Zone and a Northern Side (Fig. 13). This last area is less studied than the previous two. The geology of the Axial Zone will be presented during D2. The Southern Side is worldwide famous for Paleozoic stratigraphy (Lower Cambrian, Lower Ordovician, Devonian, Carboniferous) and the development of kilometer-scale recumbent folds (or nappes). The stratigraphic column is schematically summarized in Fig. 14.

Five tectonic units are recognized in the southern side of the Montagne Noire, namely from top to bottom (Fig. 15):

i) The Pardailhan Nappe (or recumbent fold).

ii) The Mont Peyroux Nappe.

iii) The Monts de Faugères Unit.

iv) The Cabrières Unit.

v) The Para-autochthonous domain.

The Pardailhan Nappe consists of folded and overturned Cambrian to Devonian rocks. The Mont Peyroux Nappe includes Ordovician to Visean rocks. The Monts de Faugères Unit consists of several overturned folds of Devonian to Visean rocks. The Cabrières Unit is an olistostrome, with large-scale olistoliths of Carboniferous and Devonian limestones, Silurian volcanites and Ordovician turbidites are resedimented within a wild-flysch matrix corresponding to the foreland basin of the belt (Engel *et al.*, 1980).

The Pardailhan Nappe exhibits a conspicuous axial planar cleavage, whereas in the Mont Peyroux Nappe, the transition between ductile deformation with axial planar cleavage folds and synsedimentary structures can be observed. On the basis of stratigraphy, those nappes were emplaced in Visean-Namurian times (around 330-325 Ma).

The aim of this first day is to present the polyphase deformation of the Mont Peyroux recumbent fold through a South to North cross section along the Orb river (Fig. 16). There, the stratigraphic succession ranges from Early Ordovician (Tremadoc-Arenig) to Middle Carboniferous (Visean). Along this route, deformation and metamorphism increase from

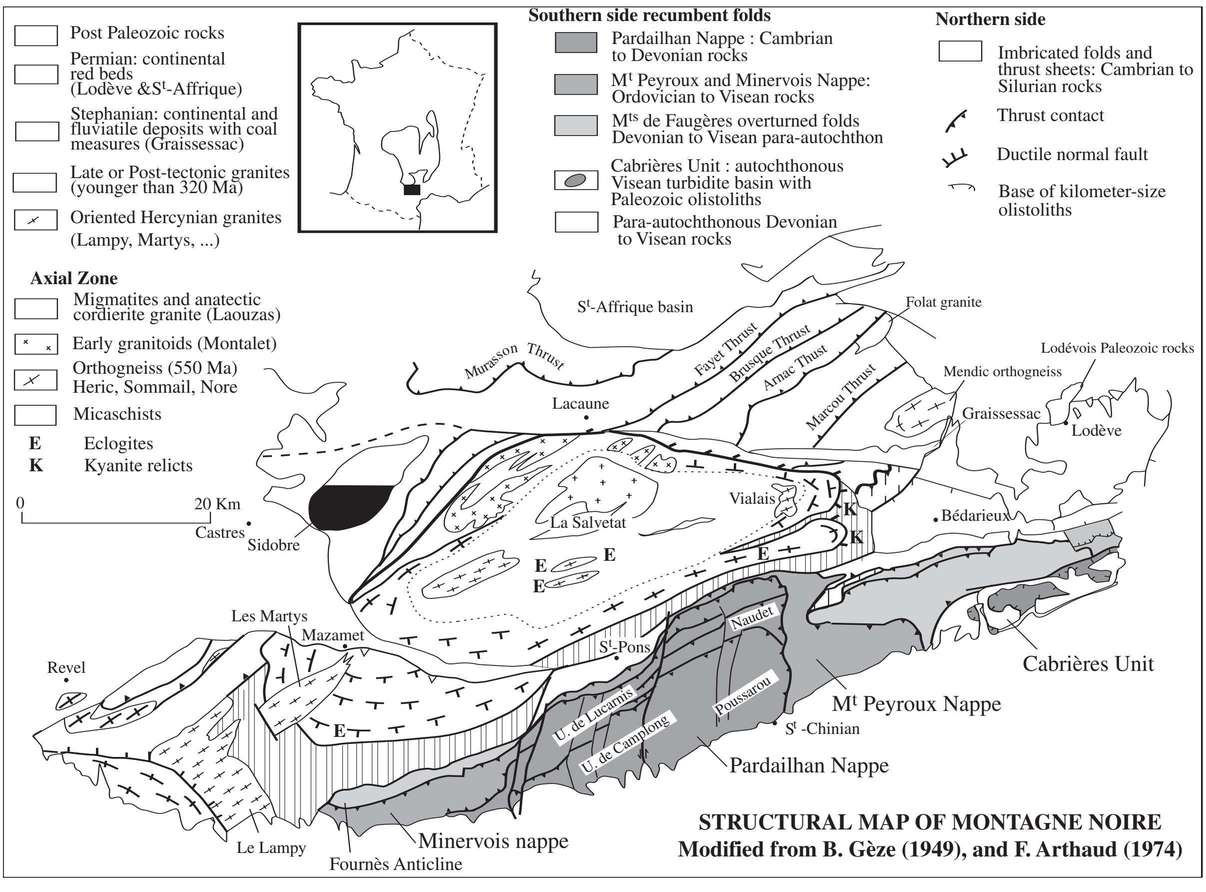


Fig. 13.- Structural map of the Montagne Noire modified from Gèze (1949) and Arthaud (1970).

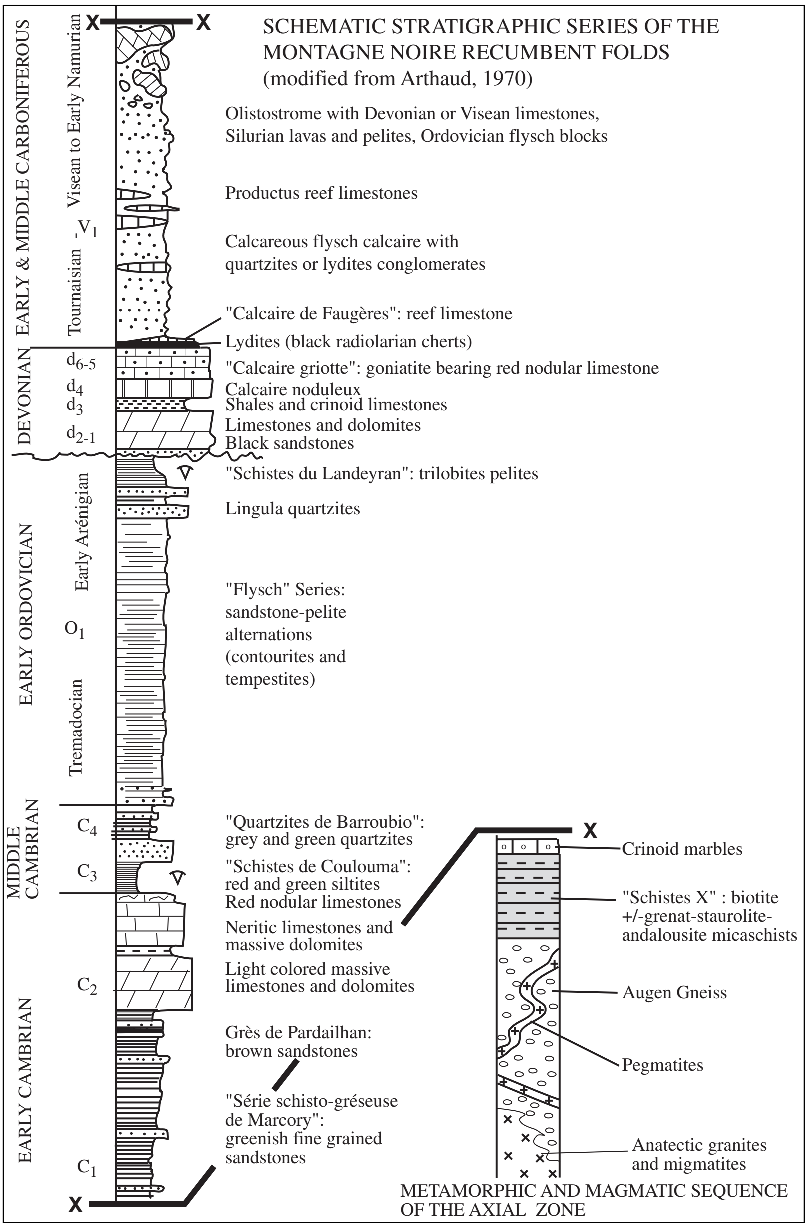


Fig. 14.- Schematic stratigraphic column of the Paleozoic series found in the Montagne Noire southern side recumbent folds (adapted from Arthaud, 1970).

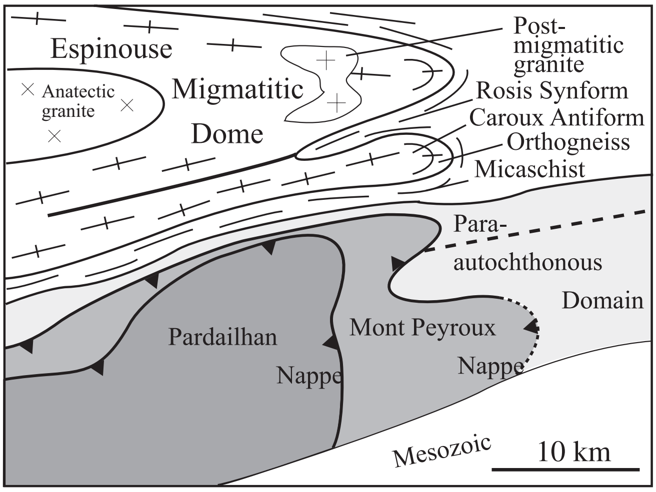


Fig. 15.- Sketch of the main units observed in the eastern part of the Montagne Noire.

South to North, however most of the observed structures develop after recumbent folding during an upright deformation linked with the formation of the Axial Zone dome (cf. D2).

B. Stop description

The stops will show most of the lithological and structural aspects of the Mont Peyroux nappe and Para-autochthonous domain underneath (Figs. 16, 17).

D1.1: Visean flysch with limestone blocks

The landscape shows Eocene limestone unconformably overlying at low angle Paleozoic rocks. The S. part of the section exposes Visean flysch with continuous sandstone beds dipping east (20E 60). The northern part that is folded and sheared exposes disrupted beds with sandstone lenses and limestone blocks. Devonian limestone overlying the Visean turbidite is seen on the other side of the valley and nearly 200 m to the north of this stop.

D1.2: Coumiac quarry (protected area)-Frasnian/Famennian boundary

This old quarry was mined for a red nodular limestone exported all over the world (e.g. the White House in Washington, or the Maison de la France in Rio de Janeiro). The vertical beds (N 30. 90) are Late Devonian (365 Ma) Goniatite limestone called "Griotte marble" (griotte is a kind of cherry). This section has been choosen as the Global Stratotype Section for the Frasnian/Famennian boundary. This series corresponds to the "Famennian Biological Crisis" responsible for one of the most severe mass extinction in the Earth history (Kapper *et al.*, 1993).

D1.3: Early Ordovician turbidite. NE of Lugné

In the landscape, looking to the SE, the vertical cliffs are Early Devonian limestones continuous with those seen in the previous stop (D1-2) in the Coumiac quarry.

Sandstone-mudstone alternations lie subhorizontally, however graded bedding and load cast show that the sequence is upside down. Folds are apparently overturned to the north but correspond in reality to the inverted limb of the Mont Peyroux recumbent fold. This Early Ordovician turbidite is interpreted as deposited along the northern passive margin of Gondwana.

D1.4: Early Ordovician turbidite. Few hundred meters from the previous stop

The subvertical to north dipping upside down beds exhibit numerous load casts, ripple marks and bioturbation

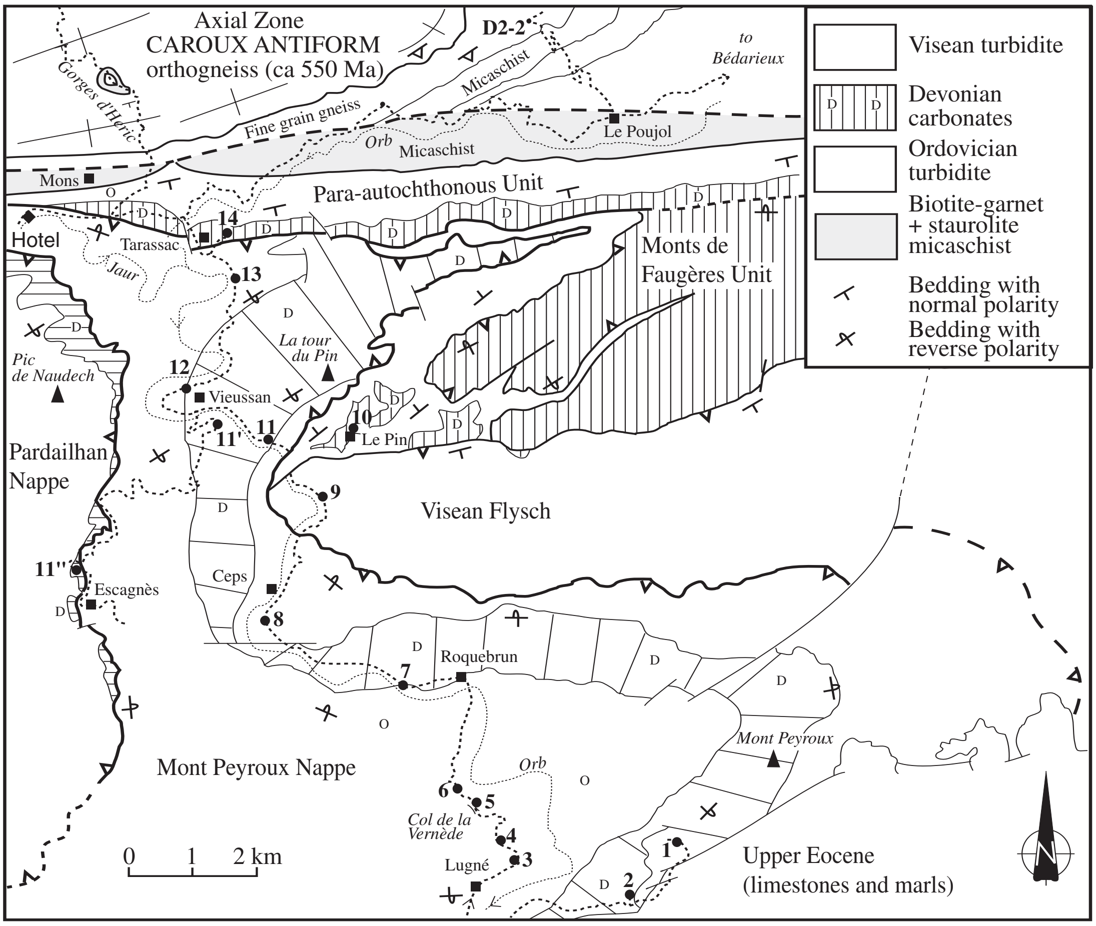


Fig. 16.- D1 route map.

evidences (worm burrows). Locally Lingula shells can be abundant. Sandstones contain abundant floatted muscovite and heavy minerals. In this outcrop, alike in the previous one, cleavage is lacking.

D1.5: Panorama on Roquebrun synform and the Orb River. Col de la Vernède

Below the road, the vineyards and Orb river are located in Ordovician turbidites which form the core of the Roquebrun synform. Looking northward, above Roquebrun village, the white cliffs are Devonian limestones. In the background, the hills with bushes are Visean flysch and in the distance, the last hills are made of Devonian limestone belonging to the Monts de Faugères Unit. To the West (left), the highest mountain is the Pic de Naudech made of inverted Cambrian rocks overlying inverted Ordovician turbidites belonging to the Pardailhan Nappe. Lastly, the farthest mountain to the NW is the Mt Caroux composed of orthogneiss belonging to the Axial Zone.

Along the other side of the road, the Ordovician turbidite is complexly folded. Superimposed folds are observed in the next stop.

D1.6: Superimposed folds in Ordovician turbidite. 200 m down to Roquebrun

The Ordovician turbidite experienced two folding phases. Recumbent isoclinal folds (F1) are deformed by upright open folds (F2) with axes plunging 50°NW. F1 are related to the Mont Peyroux recumbent fold and F2 belong to the kilometer-scale upright folding responsible for the Roquebrun synform, Vieussan synform, and Axial Zone antiform (Fig. 17).

D1.7: Ordovician-Devonian contact. North of Roquebrun

This stop shows the inverted stratigraphic contact between Ordovician detritals and Devonian carbonates in the northern limb of the Roquebrun synform. From south to north: Ordovician turbidite with top-to-the-S base (with load casts) dipping southward is underlain by Devonian calcareous sandstone, followed by limestone and dolomite. At the northern end of the outcrop, undeformed crinoid stems can be observed in the Devonian carbonates.

D1.8: Visean flysch. Chapelle Saint-Poncian, S. of Ceps

Looking to the NW, the white rocks above the village of Ceps are inverted Devonian limestone, and to the W and SW, the vineyards are located in the Ordovician turbidite. The highest white cliff in the background (La Tour du Pin summit) is the northern extension of Devonian formations. Below the cliff and up to Ceps, the lowest parts of the mountains are made of Visean flysch, belonging to several tectonic units.

The outcrop exposes Visean mudstone-sandstone with limestone intercalations dipping southwestwards (S0-1:130 SW 50). Contrasting with the Visean rocks observed at the first stop (point D1-1), here the Visean pelites are slightly metamorphosed (sericite) and exhibit a N70E trending crenulation lineation. Chevron folds and south-directed brittle shear zones with quartz veins deform S0-1. Along the road, Devonian rocks are not observed, a late fault separates Visean and Devonian rocks.

D1.9: Monts de Faugères Unit. Large curve of Orb River below Chapelle Saint-Geminian

Tournaisian(?)-Visean limestone and sericite metapelite present a westward (170W40) dipping foliation and a well marked mineral, stretching and crenulation lineation trending N70E. Pressure-solution is the dominant deformation mechanism. S0-1 is also cut at high angle by west dipping tension gashes filled by fibrous calcite.

D1.10: Para-autochthonous Domain. Le Pin and Le Lau anticlines

Turning right to the road of Le Pin, allows us to observe the underlying Para-autochthonous Domain. North of Le Pin, this outcrop exposes the deepest part of the Orb section. From North to South, the upside down sequence consists of Upper Devonian red nodular limestone (griotte marble) with goniatites (S0: 60NW60) with an inverted limb subhorizontal cleavage; Tournaisian radiolarian black cherts (lydiennes) and nodular limestones (calcaires de Faugères) and Visean flysch. North of this outcrop, the succession becomes normal from Devonian limestone to Visean flysch from bottom to top, respectively. This S-SE verging fold is called "Le Pin" anticline. Bedding-cleavage relationships with cleavage refraction in sandstone beds comply with the anticline geometry. A N70E composite lineation due to elongated nodules and goniatites, crenulation and intersection develops. Regionally, this para-autochthonous series is folded by two anticlines (Le Pin and le Lau folds) overturned to the South.

Back to the main road, the contact between the Para-autochthonous series and the Mont Peyroux nappe is marked by numerous quartz veins (no stop).

D1.11: Recumbent fold in Devonian limestone. Moulin de Graïs

This famous outcrop (Color Plate 1, A) exposes a folded Late Devonian limestone (partly dolomitized). Bedding-cleavage relationships show a southward overturning. The horizontal part of the outcrop is the normal limb. To the south, radiolarian chert (Color Plate 1, B) and limestone are involved in isoclinal folds belonging to the same large-scale structure. It is worth noting that stretching lineation trends close to the fold axis and thus at high angle to the transport direction. In XZ section, pressure shadows indicate top-to-the-NE sense of shear.

D1.11': Optionnal. Landscape on the Vieussan antiform

Turning left on D177, to Berlou, the large curve to the right provides a clear panorama to the northern limb of the Vieussan antiform, well marked in the Devonian limestones.

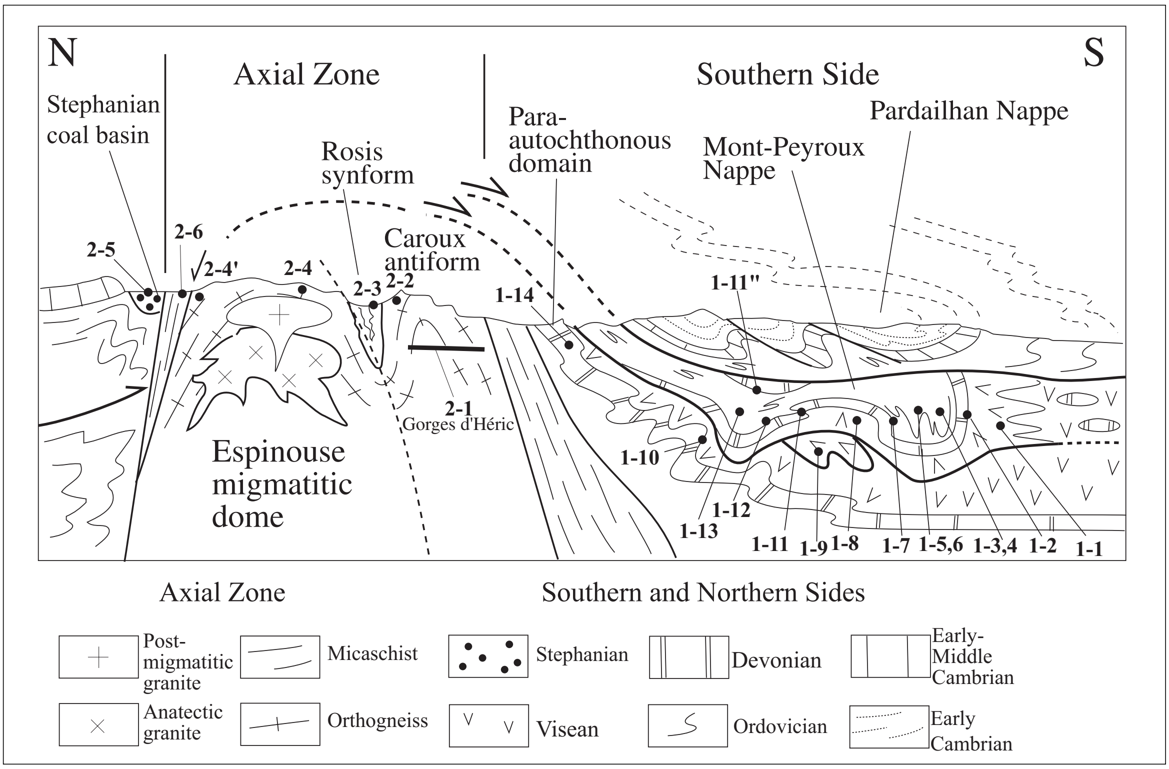


Fig. 17.- Synthetic cross section of the Montagne Noire with location of the D1 and D2 stops.

D1.11": Basal thrust contact of the Pardailhan recumbent fold "Queue de cochon (pig's tail)"

Southward, the road goes through the Ordovician turbidite of the Mont Peyroux recumbent fold deformed both by isoclinal and upright folds. The contact between Ordovician turbidite belonging to the Mont Peyroux recumbent fold and the Devonian limestone boudins marking the basal thrust contact of the Pardailhan recumbent fold can be observed in the tight curve north of Escagnès. In spite of intense shearing, the limestone is weakly or undeformed. Back to Vieussan by the same road.

D1.12: Ordovician/Devonian contact. N. of Vieussan

Looking West, the hill slope shows several white masses corresponding to Devonian limestone boudins along the basal thrust contact of the Pardailhan recumbent fold (Fig. 18). The outrop exposes inverted stratigraphic contact between Ordovician turbidite to the left and Early Devonian sandstone to the right. Isoclinal folds with curved hinges can be observed in the Ordovician sandstone. The angular unconformity between Ordovician and Devonian formations, and the lack of Late Ordovician-Silurian rocks in most of the Montagne Noire southern side can be interpreted as a sedimentary consequence of a remote tectonic-metamorphic event that took place more to the north in the internal zone of the Belt. It is worth noting that sedimentology of eo-Devonian rocks indicates a northern source for the terrigeneous sediments. Detrital volcanic quartz grains, mica, garnet, zircon, rutile, tourmaline support a pre-Devonian metamorphic event occurring in the hinterland.

D1.13: Ordovician turbidite in the north part of the Mont Peyroux recumbent fold. N of Vieussan

Looking to the north, the landscape presents the Axial Zone gneiss and the entrance of Gorges d'Heric visited on D2. The village of Tarassac is built on Devonian marbles (D1-14), the front view is Ordovician turbidite at the western pericline of the Vieussan antiform.

At the outcrop scale, the Ordovician rocks are black pelite and sandstone deformed by upright N80E trending folds (F2) and N50E isoclinal folds (F1). A few biotite grains can be observed in the vertical S2 foliation axial planar to F2.

D1.14: Para-autochthonous Devonian marble. Tarassac, parking of VVP

Muscovite bearing Devonian marble with pink calcite crystals corresponding to deformed crinoid stems exhibit a southward dip (70S60) and well marked subhorizontal mineral and stretching lineation. This marble is separated from the overlying Ordovician turbidite by a major thrust contact corresponding to the basal thrust surface of the Mont Peyroux recumbent fold. The Devonian marble and the under lying metapelites attributed to Ordovician (not seen here) is a normal sequence belonging to the Para-autochthounous Unit. $^{40}Ar/^{39}Ar$ date on muscovite gives 297±3 Ma which is interpreted as the age of a Late Carboniferous gravity sliding event related to the formation of the Axial Zone (Maluski *et al.*, 1991).

End of the 1st day. Overnight in Olargues

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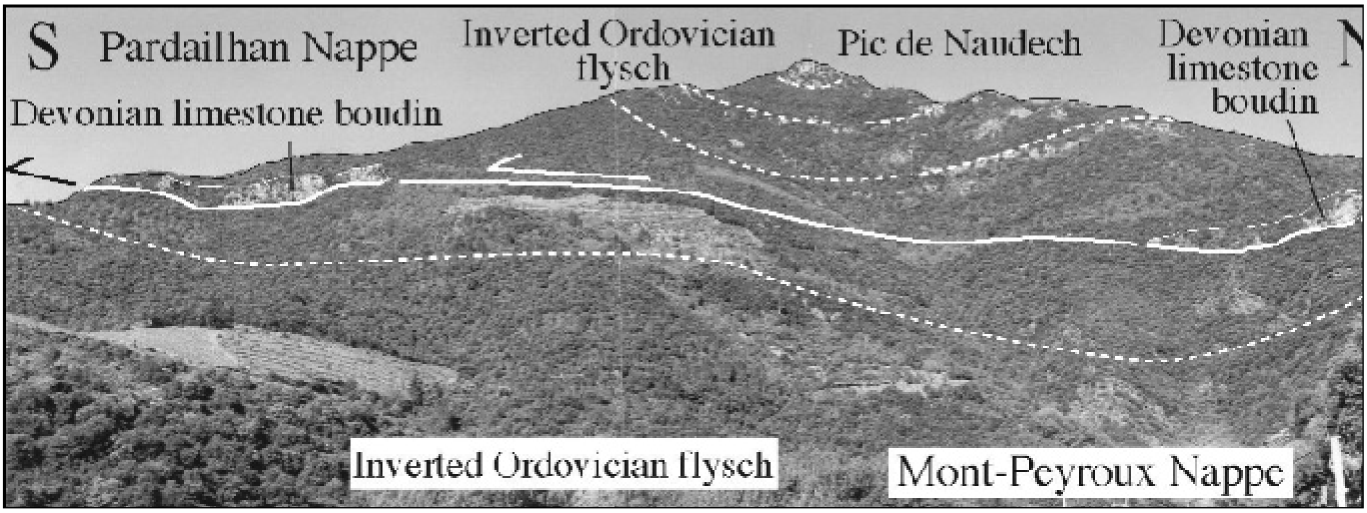

Fig. 18.- Panoramic view of the contact between the Pardailhan (top) and Mont-Peyroux nappe (bottom) marked by Devonian limestone boudins called "pig's tail".

Day 2. Migmatite dome of the Montagne Noire Axial Zone

A. Geological setting

The Montagne Noire Axial Zone remains one of the most controversial area in the geology of Massif Central (cf. extensive references in Soula *et al.*, 2001). The Late Visean-Early Namurian recumbent folds examined during D1 are overprinted by metamorphic and structural features related to a granite-migmatite gneiss dome developed in the Axial Zone (Figs. 13, 17). The foliation of micaschists and gneiss defines a NE-SW long axis elliptical dome which western part is disturbed by the Eocene Mazamet thrust. Some authors argued that the Axial Zone metamorphic rocks correspond to the Precambrian basement of the Paleozoic series observed in the recumbent folds. In the present state of knowledge, there is no argument to support the existence of a Neo-Proterozoic (i.e. Cadomian) orogen in the Massif Central. Therefore, the reality of a Precambrian basement in the Montagne Noire Axial Zone is not supported by the data. The augen orthogneiss seen in the gorges d'Heric, are porphyritic granites intruding a Neo-Proterozoic to Paleozoic metasedimentary series of micaschists and gneiss and transformed into augen gneiss during Hercynian tectonics. Recent U/Pb dating supports an Early Cambrian age for the magmatism. The presence of penninic style recumbent folds overturned to the north has also been assumed (Demange, 1975). Although possible, this interpretation cannot be demonstrated, mainly due to poor outcrop conditions. The Axial Zone gneiss experienced a HT/LP type metamorphism up to partial melting giving rise to migmatites and anatectic cordierite granites (e.g. Laouzas granite). U/Pb dating on single grain zircon and monazite give a ca 330 age. Isograds of this HT/LP metamorphism define the same domal geometry as the foliation. Within the micaschist enveloppe, kyanite relics are locally found (K in Fig. 13). P-T paths for the gneiss core and metamorphic envelope have been proposed (e.g. Soula *et al.*, 2001; Fig. 19). It is worth noting that some amphibolites included in the gneiss are retrogressed eclogites (E in Fig. 13) with estimated pressure and temperature around 9±2 kbar and 750±50°C respectively (Demange, 1985). These high-pressure rocks suggest that the tectonic units situated under the recumbent fold were buried at ca 25-30 km depth. Although no radiometric date is available for the eclogites, a possible interpretation is that the high-pressure metamorphism and a part of the ductile deformation of the gneiss is related to compressional tectonics coeval with recumbent folding of the Paleozoic sedimentary sequence.

The Axial Zone is characterized by a conspicuous NE-SW trending stretching lineation which in the southern and northern sides overprints the recumbent folds (cf. stop D1-14). The kinematic analysis provides contrasted shear criteria. Around the dome northeastern and southwestern terminations, shearing is down dip, i.e. top-to-the-NE and SW respectively. However, along the subvertical dome long limbs, shear criteria are ambiguous, as seen along the famous section of "gorges d'Héric" visited in D2 morning.

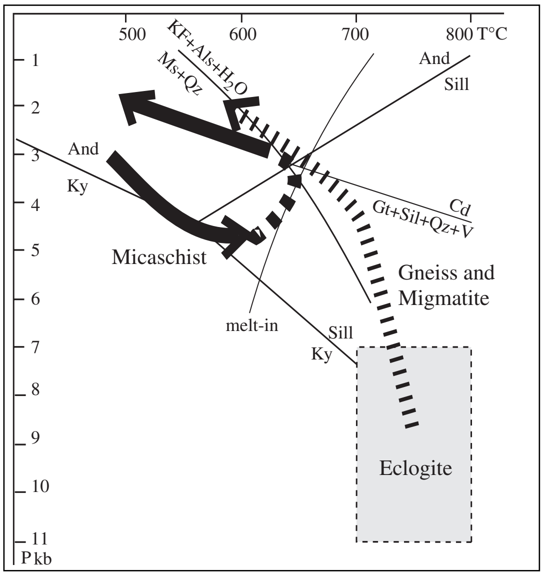

Fig. 19.- P-T paths inferred for the Montagne Noire Axial Zone micaschist and migmatitic gneiss (modified from Soula et al.*, 2001 and Demange, 1985).*

The present shape of the isograds results of the combination of the tectonic and thermal structures due to the uplift of the migmatitic core (Fig. 20). However, the tectonic significance of the Montagne Noire doming remains disputed. Several interpretations are proposed, namely: i) NE-SW ductile wrench zone (Nicolas *et al.*, 1977; Echtler and Malavieille, 1990); ii) NE-SW antiformal stack (Mattauer *et al.*, 1996; Matte *et al.*, 1998; iii) interference between migmatitic diapir and regional NE-SW shortening (Schuilling, 1960; Faure et Cotterau, 1988); iv) "metamorphic core complex" (Van den Driessche and Brun, 1991-1992). A recent discussion of this problem can be found in Soula *et al.* (2001).

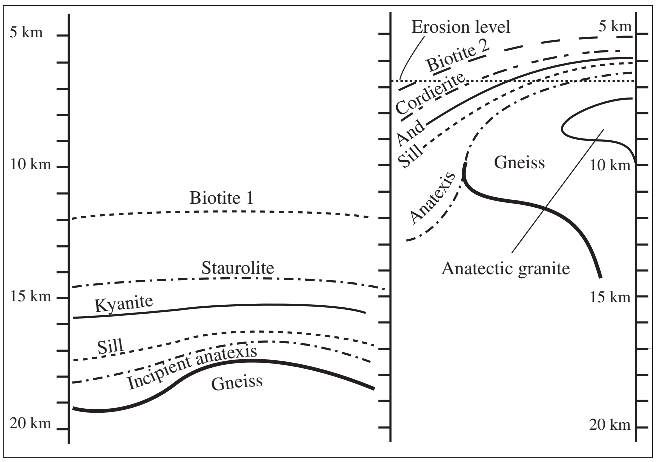

Fig. 20.- Interpretation of the present-day geometry of the Montagne Noire Axial Zone. During upward doming of the migmatitic core, early isograds are deformed and new HT metamorphic minerals crystallize (from Soula et al.*, 2001).*

Although extensional tectonics plays an important role to account for the Late Carboniferous (Stephanian) tectonics (e.g. syntectonic infill of the Graissessac coal basin); the extensional gneiss dome hypothesis cannot account for the bulk structure of the Axial Zone. Indeed, the Vialais granite (Fig. 21) that crosscuts the migmatite foliation is dated by U/Pb on zircon and monazite at 327±5 Ma (Matte *et al.*, 1998).

B. Stop description (Fig. 21)

D2.1: Cross section of the Caroux Massif along the gorges d'Héric track, 1.5 km, easy walk

The morning is dedicated to the observation of the SE part of the Axial Zone, called "Caroux Massif". The Heric augen orthogneiss and paragneiss septa are the most common rock-types. Tourmaline-garnet pegmatitic dykes obliquely cut the foliation. At the entrance of the gorges d'Héric, most of dykes dip southwards whereas near the top of the mountain, the dykes are flat lying.

After the second bridge, the foliation flattens but the lineation keeps the same N60-70E trend. Further north, the development of a NE-SW crenulation, strengthens the gneissic linear fabric. In the paragneiss, meter scale isoclinal folds are refolded by NE-SW trending upright folds.

Pegmatites dykes are also deformed by upright ptygmatitic folds and veins parallel to the fold axes are boudinated. Along the stream, amphibolite boulders (locally containing garnet) including retrogressed eclogites, boulders of migmatites and migmatized augen gneiss, sometimes containing sillimanite nodules are widespread. Outcrop of migmatite will not be visited along this route.

In spite of a clear stretching and mineral lineation, the sigma-type porphyroclast systems exhibit both dextral and sinistral asymmetry at the outcrop scale. The ambiguous sense of shear might be due to superimposed deformation (namely doming overprinted upon low angle shearing) or to strain partitioning with a significant component of pure shear (Color Plate 1, C) during doming.

The bulk structure of the Heric section is a gneiss antiform overturned to the north (Figs. 13, 17). The antiform hinge zone is parallel to upright folds in augen gneiss and meter to millimeter-scale crenulation.

D2.2: Augen gneiss and sheare pegmatite veins at the eastern part of the Caroux dome. Le Vernet

From gorges d'Héric → east to Le Poujol → north (left) to Combes.

Fine grain augen gneiss (Sx 40SE 30) with a N70E trending stretching lineation at the eastern termination of the Caroux antiform. Sigmoidal K-feldspath indicates a down-dip, top-to-the East sense of shear. Pegmatite dykes cross cutting the foliation are also sheared to the

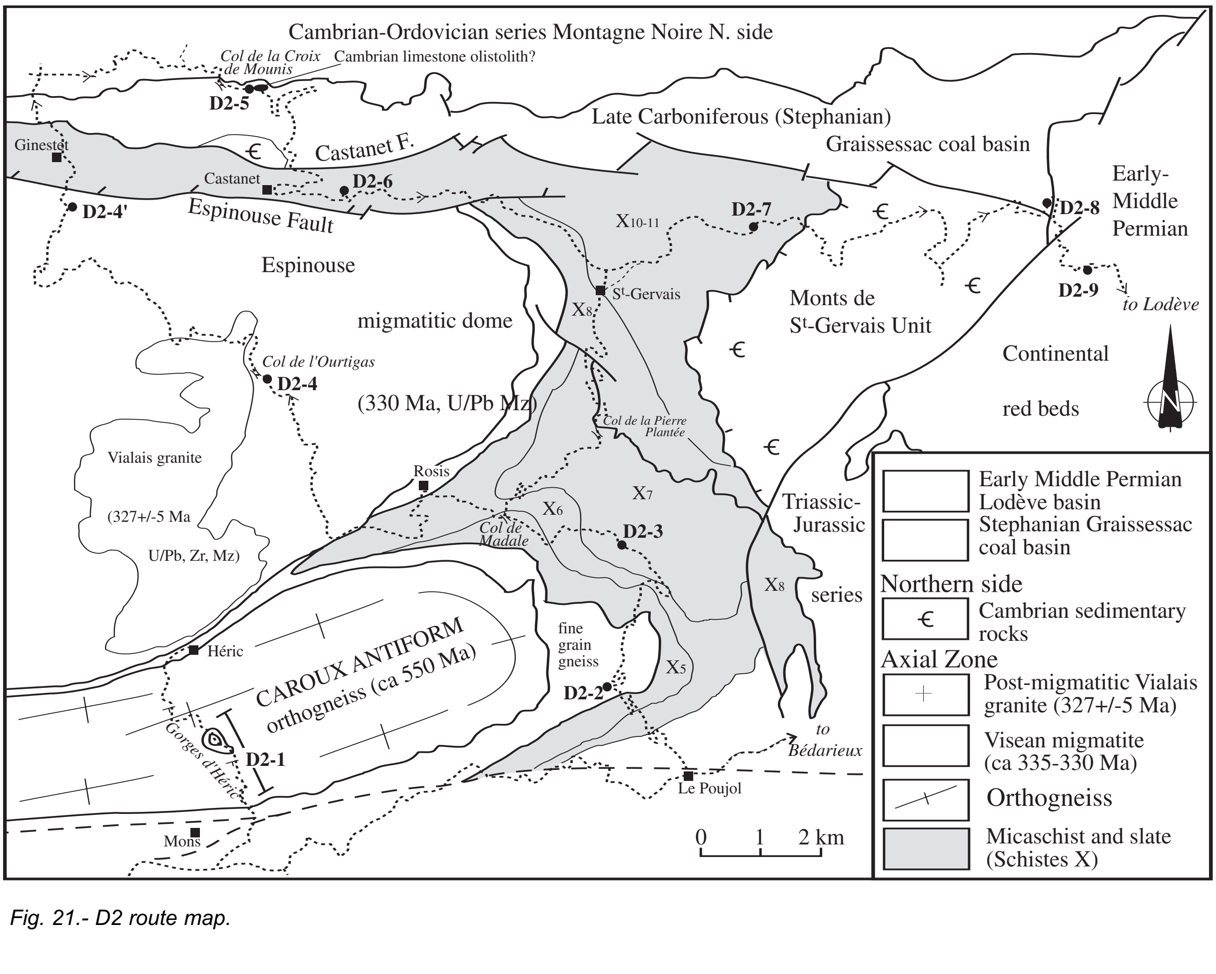

Fig. 21.- D2 route map.

East. Along the road next curves, many asymmetric pegmatite boudins can be observed within weathered gneiss (no stop).

D2.3: Biotite-Garnet-staurolite micaschists. Crossing of the road to Forêt des Ecrivains Combattants

The gneiss-micaschist series experienced a high-temperature and low-pressure metamorphism characterized by biotite, garnet, andalousite, staurolite tight isograds. The eastward dipping foliation (160E15) bears a composite crenulation, mineral and stretching lineation trending N70E along which top-to-the-E shear criteria develops. In thin section, quartz pressure shadows, helicitic garnet and staurolite, and shear bands indicate a top-to-the East shearing (Color Plate 1, D).

After the Col de Madale, the road runs within the Rosis synform which consists of crenulated and folded HT/LP micaschists between the Caroux antiform and the Espinouse dome.

D2.4: Migmatitic orthogneiss. Col de l'Ourtigas

Partial melting develops at the expense of the Heric orthogneiss but MFK and gneissic fabric are still preserved. Migmatisation is dated at 330 Ma. After the pass, the road crosses the northern border of the Vialais granite, however due to poor exposure quality and parking difficulties, the excursion will not stop there.

Optional

D2.4': Sheared augen gneiss and migmatite. S. of Ginestet

The migmatitic orthogneiss experiences a ductile shearing, the NW-SE trending foliation dips 50NE and bears a N60E trending slickenline corresponding to the Espinouse normal fault. ^{40}Ar/^{39}Ar dates on muscovite and biotite indicate 297±3 Ma (Maluski *et al.*, 1991).

North of Ginestet, begins the Montagne Noire Northern Side. In spite of globally poor exposure quality, Early Cambrian carbonates can be observed on top of the mountains.

D2.5: Stephanian conglomerate. Falaise d'Orques

At the pass of Croix de Mounis, the road enters into the Stephanian Graissessac coal basin. In the northern landscape, the Early Cambrian limestone cliffs are exposed.

The Late Carboniferous conglomerate contains cm to m size blocks of Early Cambrian sandstone and limestone. Along the road, a decameter-scale Cambrian limestone block that is probably an olistolith can be observed too. Stephanian beds dipping 110S10 unconformably cover the Paleozoic (Cambrian-Ordovician) sedimentary rocks of the Northern Side. Thus strictly speaking, the southern border fault of the Graissessac basin (Castanet fault) is reactivated after the deposition of the Stephanian rocks.

At the crossing with D22E road to Castanet-le-Haut, the landscape to the east shows the foliation of the Espinouse gneiss dome dipping northeastward. The ductile dextral-normal Espinouse fault separates the Espinouse dome from the Stephanian Graissessac basin.

D2.6: Sheared rocks along the Espinouse fault. N. of Nougayrols

The Graissessac basin substratum (i.e. early Paleozoic rocks of the Northern Side) is sheared by the Espinouse fault. Quartz veins are well developped.

D2.7: Weakly metamorphosed schists. West of Castanet-le-Bas

Weakly deformed and weakly metamorphosed greenish sandstone-pelite series corresponds to the outermost part of the metamorphic rocks surrounding the Axial Zone. Centimeter- to meter-scale folds overturned to the SE can be observed at this outcrop.

East of Verenoux, the road goes through unmetamorphosed and undeformed greenish sandstone and pelite corresponding to the Early Cambrian (grès de Marcory). This Unit (called Monts de Saint-Gervais Unit) belongs to the Northern Side, and forms an extensional allochthon emplaced upon the Axial Zone micaschists. No stop.

D2.8: Stephanian massive sandstone and coal mesures. East of La Mouline

The Late Carboniferous rocks belong to the Graissessac coal basin. They are fluviatile deposits dipping 120NE30 with coal intercalations. Decollement surfaces may develop along coal measures. In the ancient open pit of the Graissessac mine (not visited) synsedimentary folds overturned to the South can be observed. These Late Carboniferous rocks are unconformably covered by Early Permian conglomerates, sandstones and pelites dipping 0E20, but unfortunately the contact cannot be observed there.

D2.9: Permian (Autunian) conglomerate. West of La Tour-sur-Orb

Continental conglomerates with quartz, sandstone pebbles

D2.10: Permian extensional tectonics. Mas d'Alary quarry

In the ancient open pit formerly mined for uranium, continental red beds are cut by north dipping normal faults. Alike other early Permian basins in S. France (e.g. Saint-Affrique, Rodez), the Lodève basin is a half-graben bounded to its southern margin by normal faults.

End of the 2nd day. Drive to Millau (ca 60 km), overnight

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Day 3. The stacking of Upper and Lower Gneiss Units and post-nappe crustal melting

Millau→Highway to La Canourgue Exit No. 39

Leaving Millau to the North, the road crosses the Jurassic limestone plateau called Causse de Sauveterre. Near Séverac-le-Château, Toarcian black shales were mined for oil. The Jurassic sedimentary series observed along the road, is deformed by decameter to kilometer-scale wave-length upright folds and reverse faults. These structures are related to the Eocene compression due to the Pyrenean orogeny.

A. Geological setting

The Marvejols area (Fig. 22) is a famous place in the geology of the French Massif Central since it is one of the first places where Variscan syn-metamorphic nappe thrusting has been documented on the basis of geochronology, metamorphism and tectonics (Pin, 1979). The metamorphic inversion with HP rocks of the Upper Gneiss Unit upon the Lower Gneiss Unit was used as argument for tectonic superposition (Fig. 23). The contact between the two units is a high temperature mylonitic zone (Faure *et al.*, 1979). Moreover, radiometric dates document the tectonic evolution of the area. The Lower Gneiss Unit, called locally the Lot Series, consists of a monotonous succession of metapelite and metagrauwacke intruded by various magmatic bodies:

1. Quartz-diorite orthogneiss is dated at 540±12 Ma by U/Pb isotopic dilution method on zircon populations (Pin and Lancelot, 1978). This rock exhibits a well marked post-solidus planar and linear structure. $^{40}Ar/^{39}Ar$ dating on biotite gives 352±1 Ma (Costa, 1989).
2. Pink K-feldspar orthogneiss of alcaline composition is not well dated due to inherited zircons. By comparison with the Mendic orthogneiss in the Montagne Noire northern side, an Early Cambrian age is generally accepted.
3. An acidic augen orthogneiss with mylonitic zones crops out immediately below the Upper Gneiss-Lower Gneiss Unit contact. An U/Pb age on zircon populations gives a lower intercept age of 346±8 Ma (Pin, 1981). Due to its tectonic setting, and radiometric age this orthogneiss

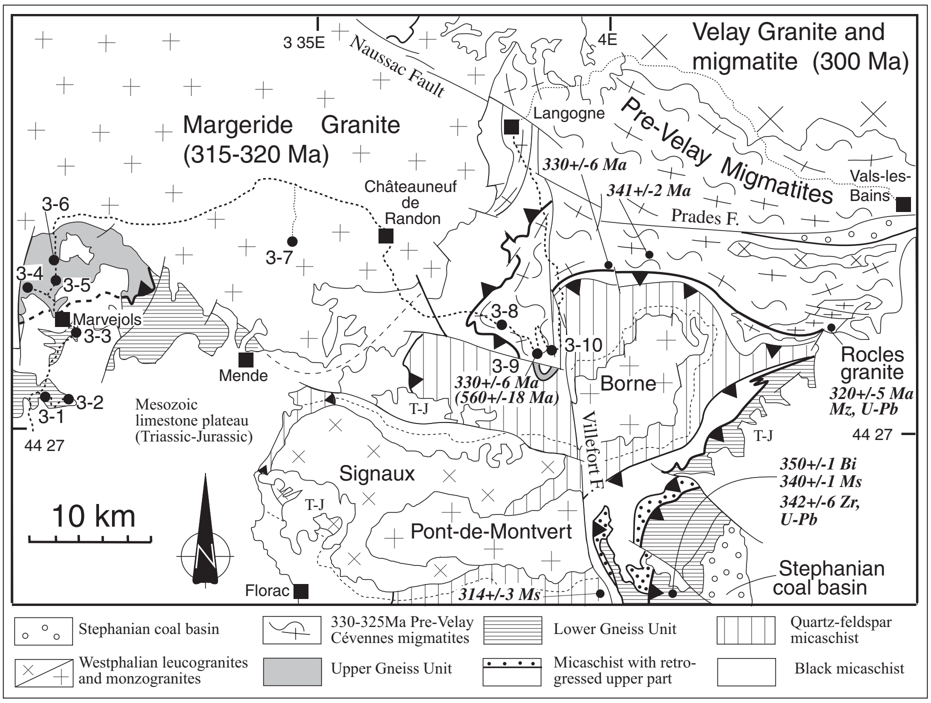


Fig. 22.- D3 route map.

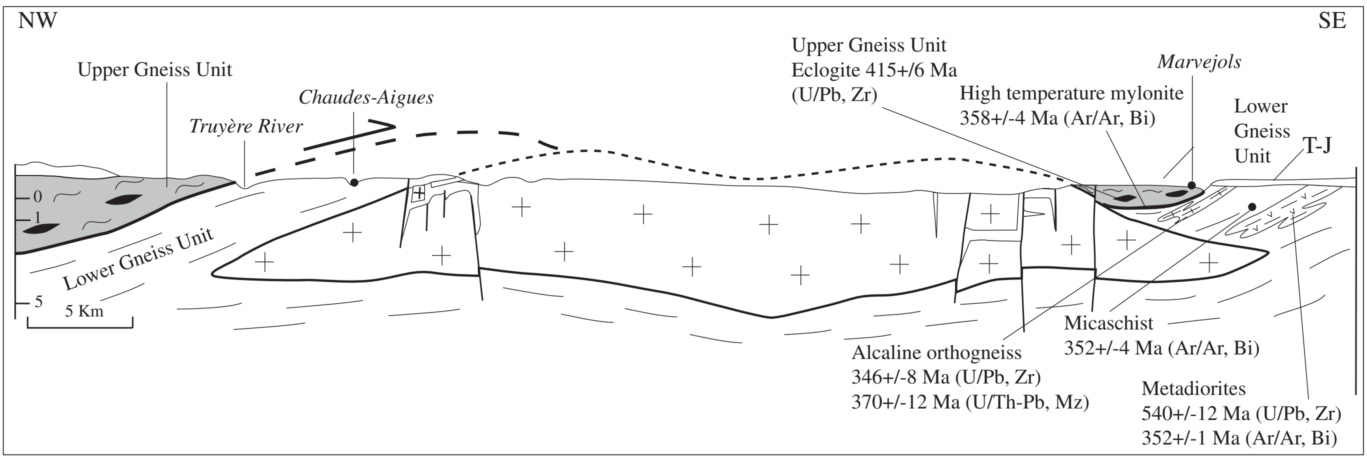


Fig. 23.- General cross section from Marvejols to the Truyère area showing the tectonic superposition of the Upper Gneiss Unit upon the Lower Gneiss Unit and the shape of the Margeride pluton.

is interpreted as a synkinematic pluton coeval with the thrusting of the Upper Gneiss Unit. However, this conclusion does not comply with microstructural data and particularly with the NW-SE stretching lineation developed in the Lower Gneiss Unit (cf. below). A preliminary chemical U/Th/Pb age of 370±12 Ma is obtained on monazite (A. Joly unpublished data).

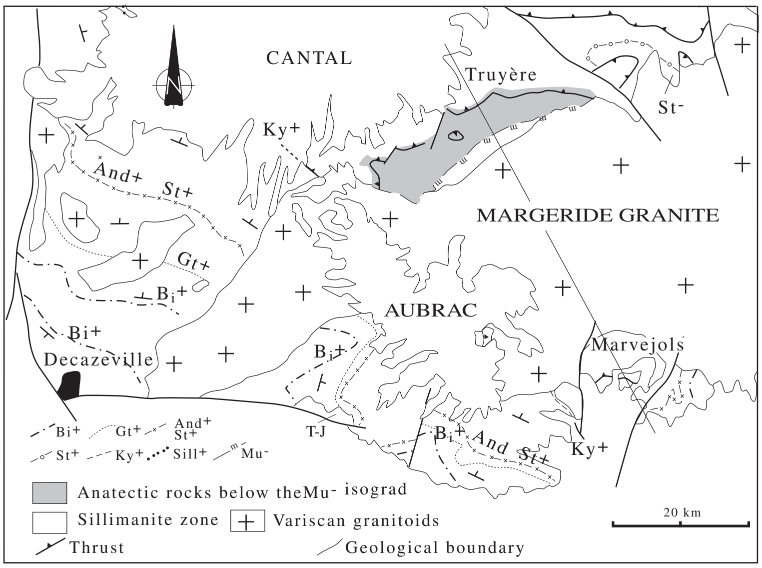


Fig. 24.- Metamorphic map of the Lower Gneiss Unit around the west part of the Margeride pluton (Marvejols, Truyère, Châtaigneraie) showing the inverted metamorphism (adapted from Burg et al.*, 1984).*

4. Other small gneiss masses are recognized in the Lower Gneiss Unit, some of them are considered as hypovolcanic granites or volcaniclastic metasediments (Pin, 1981).

As seen in the first stops of D3 day, the Lot Series of the Lower Gneiss Unit is characterized by a subhorizontal foliation and a conspicuous NW-SE trending mineral and stretching lineation. This ductile deformation is coeval with an intermediate temperature-intermediate pressure metamorphism. Biotite, garnet, staurolite, andalousite and muscovite are widespread in the metapelites. The Marvejols area is often taken as an example of the inverted metamorphism developed in the footwall of the Upper Gneiss Unit overthrust (Fig. 24). ^{40}Ar/^{39}Ar dates on biotite and muscovite from the Lot Series micaschist yields 351±4 Ma and 342±4 Ma respectively (Costa, 1989). The tectonic significance of the NW-SE trending stretching lineation which is widespread throughout the Massif Central is not clearly settled yet.

The mylonitic zone at the base of the Upper Gneiss Unit is characterized by a N-S trending mineral and stretching lineation. In spite of intense recrystallization and post-kinematic annealing, top-to-the-south shearing can be observed. ^{40}Ar/^{39}Ar dating of synfolial biotite gives 358±4 Ma interpreted as the age of thrusting. Moreover, a late muscovite developed upon the early foliation is dated at 340±4 Ma (Costa, 1989).

In the Marvejols area, the Upper Gneiss Unit consists of a lower part called "leptynite-amphibolite" sequence and an upper part with migmatitic gneiss and micaschist. The leptynite-amphibolite sequence contains metamorphosed mafic rocks of magmatic or sedimentary origin such as metagabbro, metabasalt, amphibolite rare serpentinites and acidic rocks (i.e. leptynites) Meter to centimeter scale acidic-mafic alternations are probably of volcanic-clastic origin. Several U/Pb ages on zircon populations are available (Pin and Lancelot, 1982). Namely, an amphibolite boudin is dated at 487±6 Ma, and a coronitic metagabbro at 484±7 Ma. An orthogneiss intrusive in the paragneiss gives 478±6 Ma. These dates are interpreted as the evidence for an Ordovician magmatism related to the rifting of Armorica from Gondwana. Moreover, the 415±6 Ma age of zircon populations from a high-pressure trondhjemite is considered as the age of melting coeval with eclogite facies metamorphism. Pressure and temperature constraints on this rock are 16±4 kb and 800±50°C respectively.

Upper and Lower Gneiss Units stacking was followed by huge crustal melting produced under distinct P-T conditions (Fig. 25). The second part of the D3 and the whole D4 days are devoted to the observation of some manifestations of the Middle to Late Carboniferous crustal melting. From older to younger, three stages are distinguished.

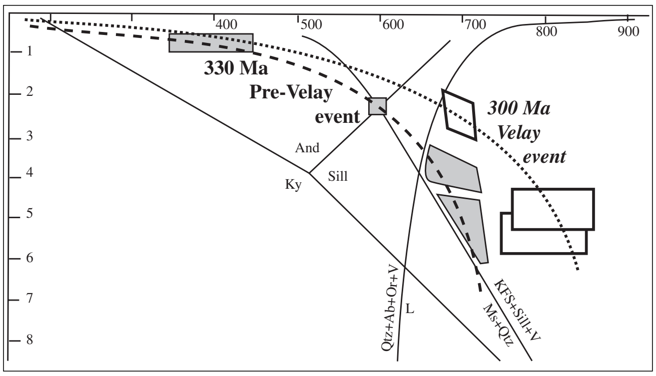


Fig. 25.- P-T paths of pre-Velay and Velay events constructed from metamorphic rocks sampled in the south part of the Velay area (simplified from Montel et al.*, 1992).*

1. Pre-Velay Cévennes migmatites, dated between 333 to 324 Ma by chemical U/Th/Pb method on monazite (Be Mezème, 2002) (Fig. 26).
2. Namurian-Westphalian plutonism dated around 320-315 Ma. This magmatism is characterized by porphyritic monzogranite (Margeride or Pont-de-Montvert-Borne plutons) and also by leucogranite (Signaux and Rocles plutons). Although distinct massifs derived from different magmas, field relationships show that these two magmatic types are coeval.

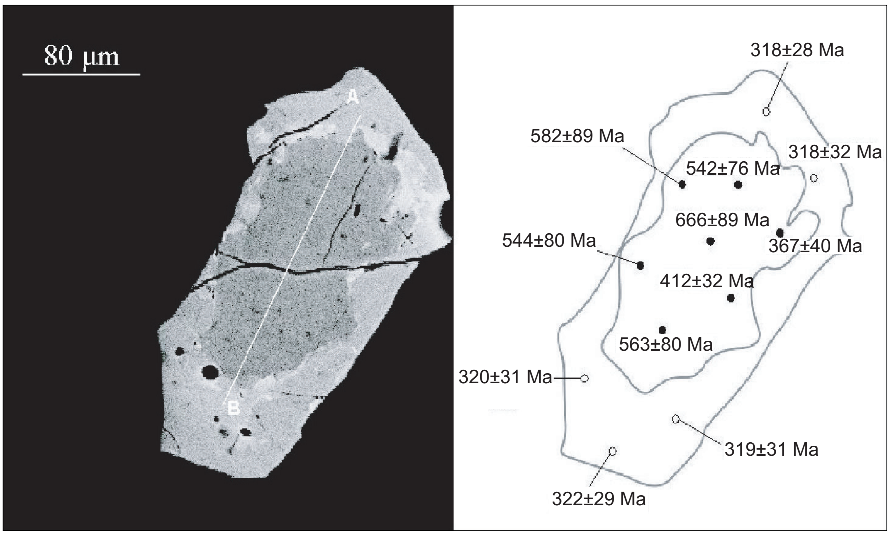


Fig. 26.- Example of ponctual dating on monazite single grain by U/Th/Pb chemical method (Be Mezème et al.*, 2003).*

3. Velay migmatites and cordierite granite dated around 300Ma. This large massif will be examined during D4.

B. Stop description

D3.1: Cambrian quartz-diorite. N88, East of Pont des Ajustons, S. of Marvejols

A fine-grained biotite-hornblende quartzdiorite originally intrudes micaschists (stop D3-2) belonging to the Lower Gneiss Unit. U/Pb dating on zircon populations gives a 540±12 Ma age (Pin and Lancelot, 1978) for the emplacement of this pluton. $^{40}Ar/^{39}Ar$ dates on biotite provide a 352 ± 1 Ma age corresponding to the tectonic event (Costa, 1989). This well foliated and lineated rock experienced a NW-SE deformation.

D3.2: Lower Gneiss Unit of the Lot series

The Lot series are composed of biotite-garnet ± staurolite micaschists originally intruded by porphyric granite and metadiorite. The flat lying foliation bears a conspicuous NW-SE mineral and stretching lineation, indicating a top to NW sense of shear (Color Plate 1, E). Biotite and muscovite $^{40}Ar/^{39}Ar$ ages are respectively 351 and 342±4 Ma (Costa, 1989). In the background, Early Jurassic limestones unconformably overly the metamorphic rocks.

D3.3: Augen orthogneiss within the Lot series. Pont de Pessil

The Lower Gneiss Unit includes augen orthogneiss with mylonitic fabric. In sections perpendicular to the foliation and parallel to the NW-SE lineation, asymmetric K-feldspar augen indicate a top-to-the-SE sense of shear. U/Pb date on zircon populations gives a lower intercept age of 346±8 Ma (Pin, 1981). An U/Th/Pb chemical age on monazite gives 370±12 Ma (Joly, unpublished data).

D3.4: Coronitic metagabbro belonging to the Upper Gneiss Unit. Le Croisier

The Upper Gneiss Unit outcrops North of Marvejols city. Metabasites, locally with mylonitic fabric, underwent the Eovariscan high-pressure metamorphism (Color Plate 1, F). However, due to the heterogeneity of deformation, magmatic textures are still preserved. This rock is dated by U/Pb method on zircon populations (upper intercept) at 484±7 Ma (Pin and Lancelot, 1982).

D3.5: Leptynite-amphibolite complex (Upper Gneiss Unit). Along the main road (N9)

This outcrop exposes a typical section of the “leptynite-amphibolite complex” made of alternations of mafic and acidic rocks considered as a volcanic-clastic formation. The foliation exhibits meter to decameter-size amphibolite boudins (Color Plate 2, A). Zircon populations from an amphibolite give a U/Pb age of 487±6 Ma age (upper intercept) interpreted as the rock formation age (Pin and Lancelot, 1982). The lower intercept at 340±4 Ma is close to the thermal event (ca. 345-330 Ma) that overprints the tangential tectonics.

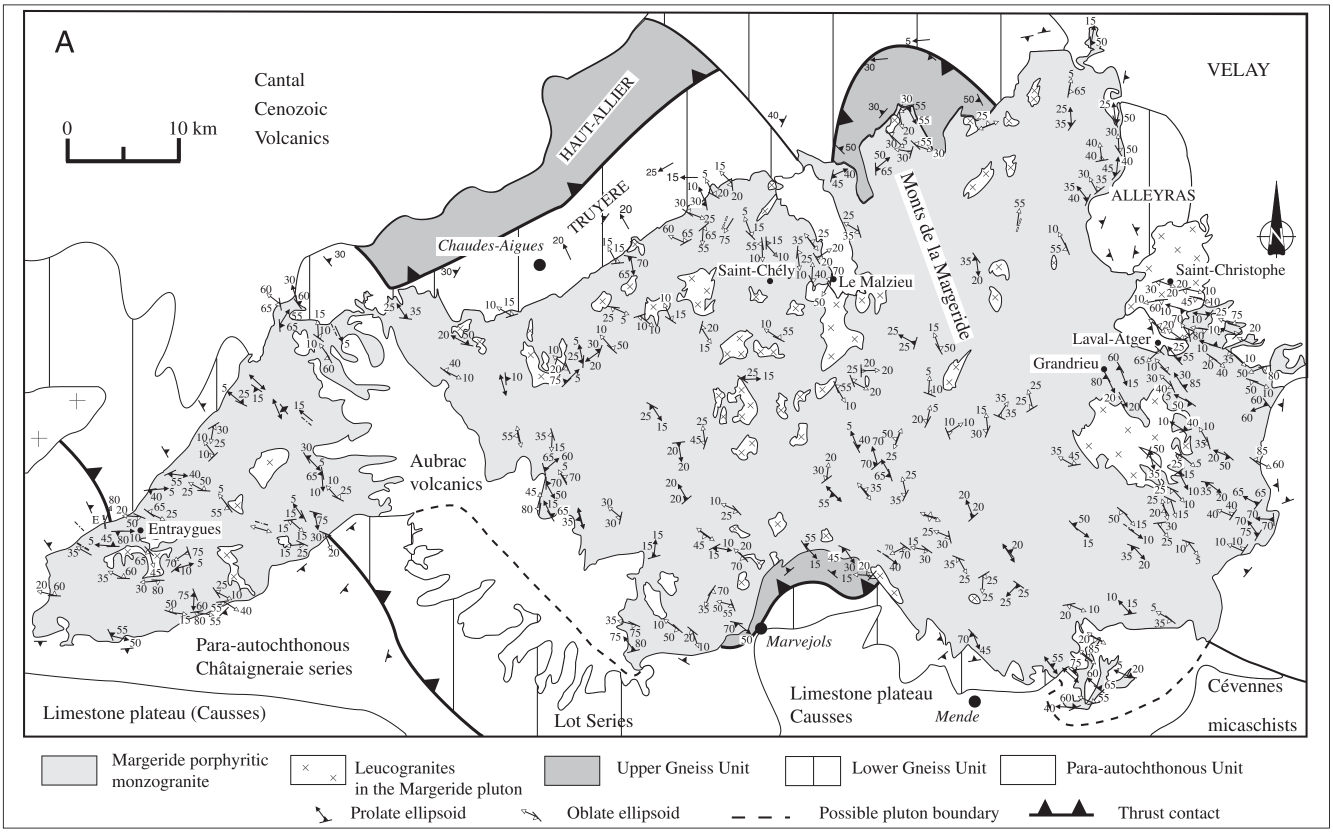
D3.6. Early Variscan migmatisation. Gorges du Val d’Enfer

The road runs from South to North in the leptynite-amphibolite complex which becomes migmatized northward. The migmatite is not dated here. By comparison with other places in the Massif Central, a ca 380 Ma age can be inferred.

D3.7: Middle Carboniferous Margeride pluton. Truc de Fortunio

Drive to St-Amans → Estables

The Margeride massif is one of the largest granitic pluton in the French Massif Central (3,200 km²). It consists mainly of a porphyritic monzogranite with large (up to 10 cm) K-feldspar megacrysts. On the basis of biotite content, three facies, namely dark, intermediate and light facies, are distinguished (Couturier, 1977). Nevertheless, more than 80% of the massif is made of the intermediate facies. Moreover, muscovite-K-feldspar leucogranite intrude the monzogranite. Most of the leucogranites are meter-scale dykes, but east of the massif the Grandrieu leucogranite represents a kilometer-sized pluton. The monzogranite yields a Rb-Sr whole rock age of 323±12 Ma (Couturier, 1977) and an isotopic dilution U/Pb monazite age of 314±3 Ma (Pin, 1979); the Grandrieu leucogranite is dated at 305±4 Ma (U/Pb method, Lafont and Respaut, 1988). The Margeride pluton is a subhorizontal of 4 to



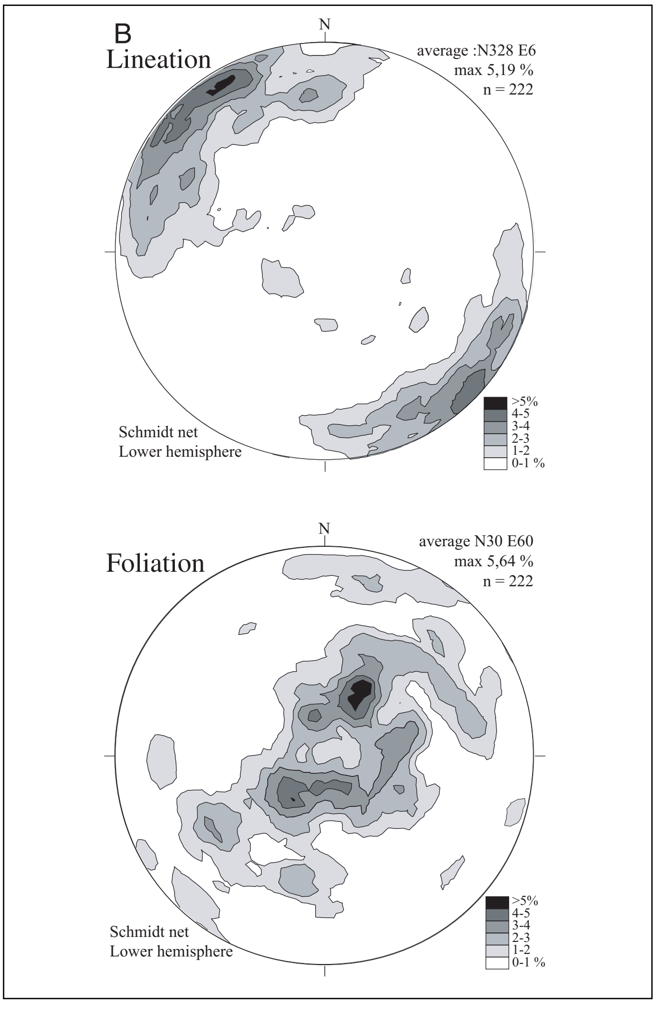


Fig. 27.- A: Map of the planar and linear structures in the Margeride pluton inferred from AMS study (from J.-Y. Talbot, unpublished).

B: Stereograms represent the magnetic lineation (K1) and the pole of foliation (K3).

8 km thick (Fig. 23). Petrostructural and AMS studies (J.-Y. Talbot, work in progress, Fig. 27) show a complex pattern of the foliation trajectories. Although the foliation trajectories do not show a consistent shape, at the scale of the whole pluton, the foliation presents a flat lying attitude. The lineation pattern exhibits a well-defined NW-SE trend. It is worth noting that such a trend is widespread throughout the whole Massif Central and corresponds to the maximum stretching direction of the Namurian-Westphalian syn-orogenic extension (Faure, 1985).

D3.8: Augen orthogneiss below the Para-autochthonous Unit

Drive to Châteauneuf-de-Randon → Montbel → NE of Belvezet

SE of the Margeride pluton, the Cévennes area exposes the para-autochthonous Unit of the Massif Central. Below the unconformity of the Mesozoic sedimentary rocks, an augen orthogneiss and its host rocks crop out in a tectonic window below the Para-autochthonous Unit (Cévennes micaschists). The augen orthogneiss exhibits a subhorizontal foliation and NE-SW trending stretching lineation. The age of the granitic magmatism is not determined here but assumed to be Early Cambrian (ca 550 Ma) by comparison with other orthogneiss in the Massif Central. The chemical U/Th/Pb age of 560±18 Ma in the core of monazites grains from migmatitic orthogneiss support this interpretation (cf. Stop D3-9).

D3.9: A few kilometers eastward, biotite, garnet (± cordierite) paragneiss and quartz-micaschist correspond to the orthogneiss host rock

D3.10: Migmatitic orthogneiss. Barrage de Puylaurent

To the east, the orthogneiss experiences a partial melting giving rise to diatexites. Locally the orthogneiss fabric remains well preserved. A chemical U/Th/Pb dates on monazite give 560±18 Ma and 324±6 Ma for the grains core and rim respectively (Be Mezème, 2002; Cocherie *et al.*, in press). The latter is interpreted as the age of migmatization.

D3.10: Boudinaged dykes of leucogranites

Pink granite dykes and leucogranite dykes intrude the metamorphic rocks. Muscovite dyke is dated by chemical U/Th/Pb method on monazite at 316±5 Ma (Be Mezème *et al.*, 2003; Fig. 26).

In Prévenchères, turn to the north (left) to Langogne. The road follows the brittle left-lateral Villefort fault of Permian age. South of La Bastide-Puylaurent, the road is located in the Para-autochthonous Unit (Schistes des Cévennes). From La Bastide Puylaurent, to Langogne, the migmatitic orthogneiss crops out again along the Allier river.

End of the 3rd day. Overnight in Langogne

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Day 4. The Velay dome (French Massif Central): melt generation and granite emplacement during orogenic evolution

The generation of large granite-migmatite complexes by crustal melting during orogeny is a process still discussed in particular because of the deep, inaccessible location of their production sites (Clemens, 1990; Brown, 1994). Moreover, the development of a partially molten middle crust during collision tectonics implies a major change in the rheology of the thickened crust and largely control its behaviour during orogenic collapse (Vanderhaeghe and Teyssier, 2001). Thus, the Variscan belt which exposes numerous granitic intrusions and large migmatitic complexes is of great interest to study the role of partial melting during orogenic evolution (Brown and Dallmeyer, 1996; Gardien *et al.*, 1997; Vanderhaeghe *et al.*, 1999). The Velay migmatite-granite dome located in the SE Massif Central (Figs. 28, 29, 30) offers a unique opportunity to examine the thermal conditions required for widespread crustal anatexis and the consequences of the presence of the generation of a large volume of partially molten rocks on the evolution of the Variscan orogenic crust.

The aim of the fourth day is to illustrate the melt generation and granite emplacement of the Velay dome in connection with the tectonic evolution of the Variscan belt, by showing:

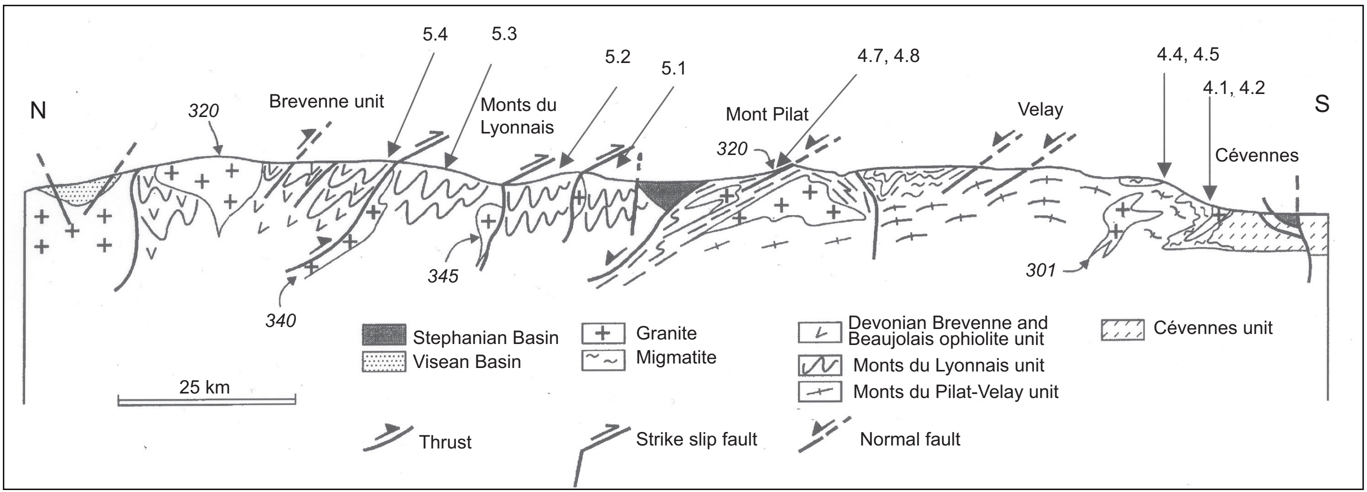

Fig. 29.- Simplified cross section through the eastern margin of the Massif Central showing the main tectonic units and their structural relationships, Day 4 and Day 5 localities. Ages of some granites are indicated as specific geochronological markers.

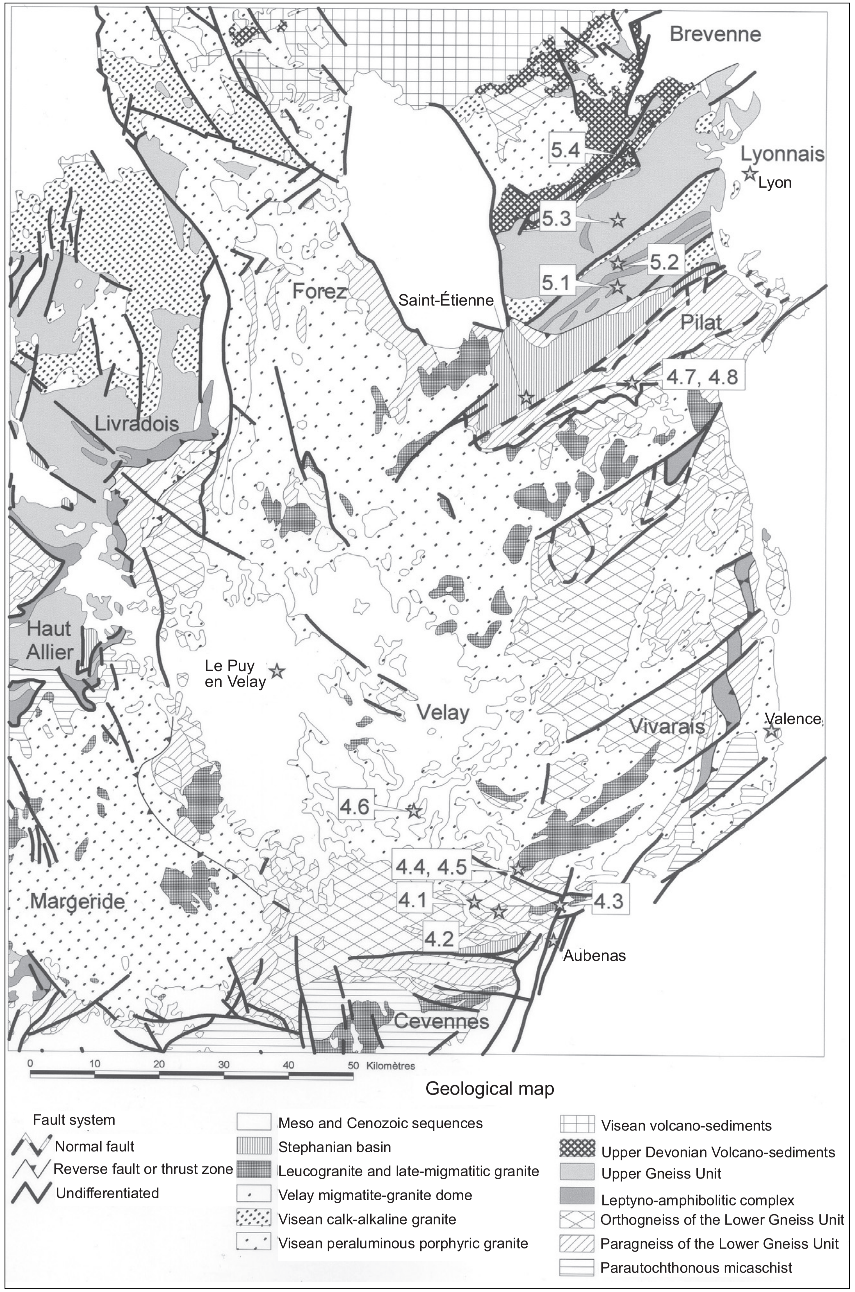

Fig. 28.- Simplified geologic map of the eastern margin of the Massif Central, Day 4 and Day 5 localities.

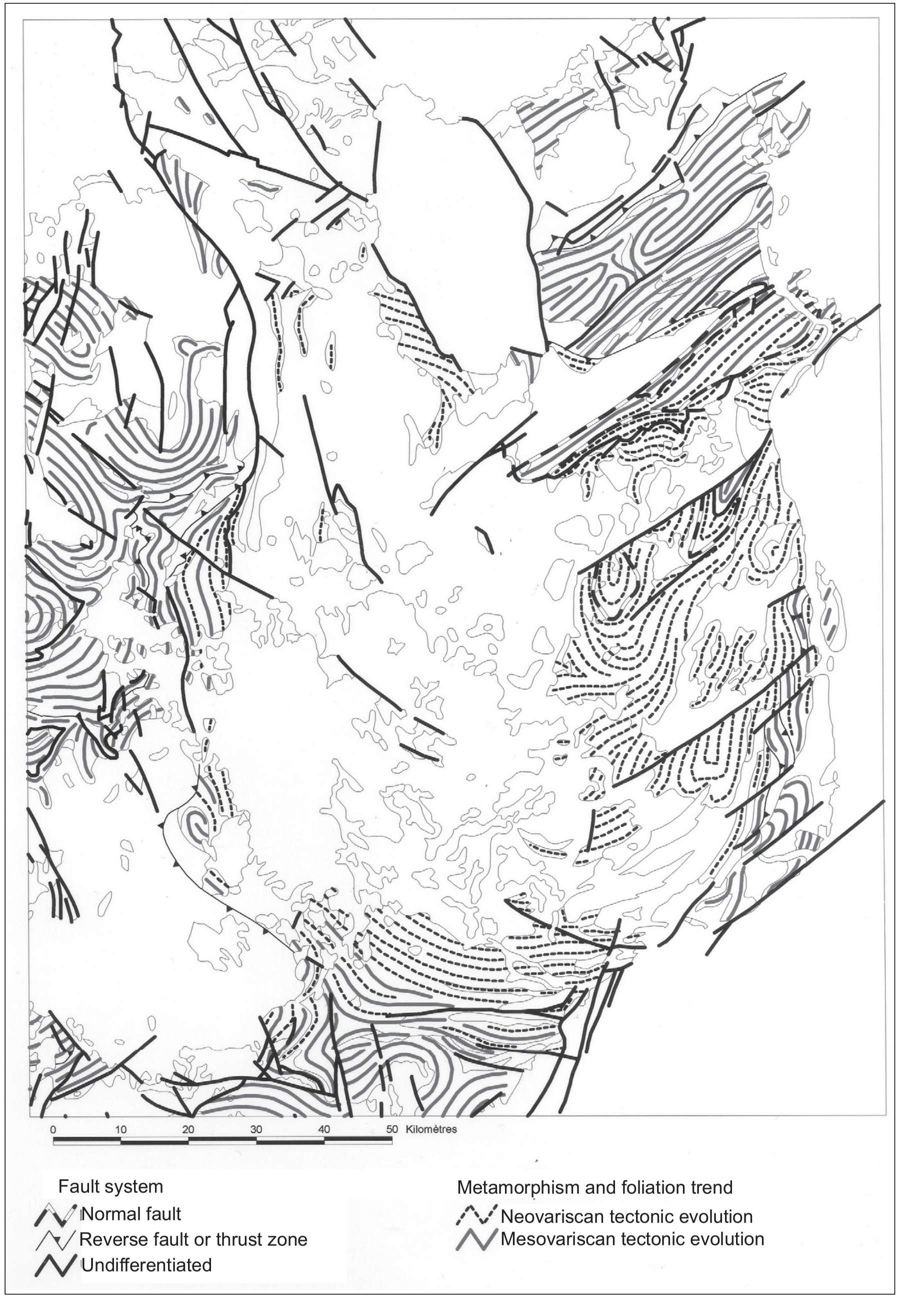

Fig. 30.- Extension of Meso and Neovariscan metamorphism and foliation trends within the host rocks of the Velay migmatite-granite dome.

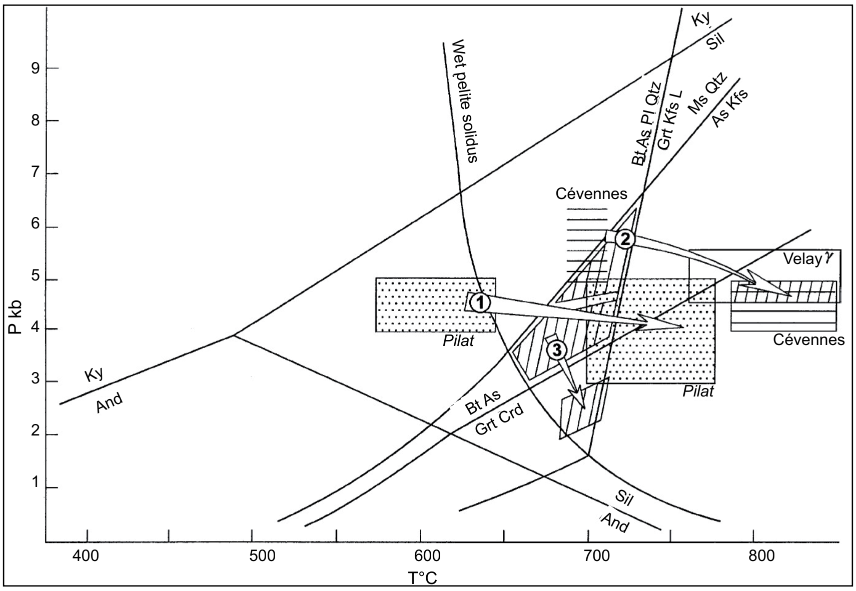

Fig. 31.- Pressure-temperature evolution from the gneisses to the Velay granite.

Mineral abbreviations: Ky=kyanite; Sil=sillimanite; And=andalusite; Cd=cordierite; Grt=garnet; Ms=muscovite; Qtz=quartz; Kfs=potassium feldspar; Pl=plagioclase; Bt=biotite; As=aluminium silicate; L=liquid. The transition from the M3 to the M4 metamorphic stage is indicated by arrows (1) in the Pilat micaschist (after Gardien *et al.*, 1990), (2) in the migmatitic orthogneiss and granite in the southern part of the dome (oblique-and horizontal-ruled boxes, after Gardien *et al.*, 1997 and Montel *et al.*, 1992), (3) in the migmatitic part of the southern host rocks of the Velay granite (oblique-ruled boxes, after Montel *et al.*, 1992).

- incipient stages of melting in the Late Neoproterozoic pre-tectonic granite and metasediments on the southern margin;
- the cordierite-bearing granites and migmatites;
- the relation between granite emplacement, extensional tectonics and formation of the Saint-Étienne Stephanian basin on the northern flank of the Velay dome.

A. Geological setting

The Velay dome (Figs. 28, 29), about 100km in diameter, is composed of peraluminous granites (about 70%) characterized by abundance of nodular and prismatic cordierite and by enclaves of gneisses (25%) and granites (5%) of various nature and size (Didier, 1973; Dupraz and Didier, 1988). Previous work in this area provided the following results and models.

- Montel *et al.* (1992) describe two successive stages of anatexis, first under water-saturated conditions with biotite stable followed by melting under biotite dehydration conditions.
- Burg and Vanderhaeghe (1993) proposed that the amplification of the Velay dome cored by migmatites and granites reflects gravitational instabilities within a partially molten middle crust during late-orogenic extension.
- Lagarde *et al.* (1994) suggested that the deformation pattern of the Velay dome records southward lateral expansion of the granites below the detachment zone of the Pilat, one of the major normal faults developed during the collapse of the Variscan belt (Malavielle *et al.*, 1990).
- Geochemical and petrological data published by Williamson *et al.* (1992); Montel *et al.* (1992) and Barbey *et al.* (1999), indicate that the Velay dome has followed a clockwise P-T-time evolution overprinted by a thermal peak due to the underplating of mafic magmas (Fig. 31).

According to Ledru *et al.*, 2001, structural, petrologic and geochronological data indicate that the formation of the Velay migmatite-granite dome results from the conjunction of several phenomena.

- Partial melting of the thickened crust started at about 340 Ma, while thrusting in the hinterland of the Variscan belt was still active, and ended during collapse of the orogenic crust at ~300 Ma. Crustal anatexis responsible for the generation of the rocks forming the Velay dome hence lasted about 40 Ma.
- Partial melting took place within a dominantly metasedimentary crustal layer dominated by fertile pelitic compositions. Melting reactions evolved from the water-saturated granitic solidus to destabilization of hydrous minerals and indicate that melting started at the end of the prograde metamorphic path and ended during decompression associated with exhumation of the migmatite-granite dome.
- Thermal relaxation and increased radioactive heat production following crustal thickening likely caused a rise in temperature during the evolution of the Variscan orogenic crust. However, it is proposed that heat advection from mantle-derived magmas and also asthenospheric upwelling coeval with orogenic collapse have provided the extra heat source required to melt a large volume of the thickened crust and generate the migmatites and granites of the Velay dome.

  The formation of the Velay dome, coeval with the activation of crustal-scale detachements, potentially corresponds to flow of a partially molten crustal layer in response to gravitational collapse.

Four main structural zones, that will be partially illustrated during this fourth day, are defined (Figs. 28, 30):

1. The host rocks. The Velay granite-migmatite dome is hosted by gneissic units stacked during the collision history of the Variscan belt (Ledru *et al.*, 1994a, b):

- the Upper Gneiss Unit, that contains remnants of Early Paleozoic oceanic or marginal basins is presently in an upper geometric position, this unit contains dismembered basic-ultrabasic complexes at its base overlain by gneisses derived from granites, microgranites, acid and basic volcanics, tuffs and grauwackes. Numerous eclogitic relics are preserved within basic layers marking an Eovariscan stage of lithospheric subduction (450-400 Ma). Structural and radiometric data show these rocks were exhumed from 90 km at 420-400 Ma to less than 30km at 360-380 Ma while subduction was still active (Lardeaux *et al.*, 2001);

- the north Gondwana continental margin is represented by (a) a Lower Gneiss Unit composed of metasediments derived from pelites and argilites, and augen orthogneiss (the “Arc de Fix”) originating from peraluminous porphyric granite dated at 528±9 Ma (Rb-Sr whole rock, R’Kha Chaham *et al.*, 1990), and (b) a mainly sedimentary parautochthonous sequence. This margin underwent a general medium-pressure metamorphism attributed to the thrusting of the Upper Gneiss Unit which occurred during Devonian, prior to 350 Ma in the internal zone (Mesovariscan period). The Lower Gneiss Unit is intruded by syn tectonic granites precursor of the Velay dome emplaced between 335-315 Ma, including magnesio-potassic plutons, the so-called “vaugnerite”. In the south (Fig. 2), the Cévennes micaschists are interpreted as the parautochthonous domain. Maximum P-T conditions during the metamorphic evolution are there estimated at 500°C, 5 kbar, with the muscovite-chlorite-garnet parageneses being synchronous with southward thrusting and a thickening estimated at about 15 km (Arnaud and Burg, 1993; Arnaud, 1997). The closure of micas to Ar diffusion has been dated at 335-340 Ma ($^{40}Ar/^{39}Ar$, Caron *et al.*, 1991).

2. The gneiss-migmatite zone, at the periphery and at the roof of the Velay dome. In the migmatites and in the gneissic hosts, the following melting reactions are identified (Fig. 31):

- the first melting stage developed under P-T conditions exceeding those for water-saturated quartz-feldspathic rocks, with biotite remaining stable: around 700°C, 4 kbar within the metamorphic envelope, 5 kbar in the granitic core (M3 stage of Montel *et al.*, 1992). The presence of corundum paragneiss enclaves confirms the initial presence of muscovite and the prograde character of this melting event (Aït Malek *et al.*, 1995). A U-Pb monazite date indicates a minimum age of 314±5 Ma (Mougeot *et al.*, 1997). High-K magnesian monzodiorite, with mantellic affinity are also dated at 313±3 and 314±3 Ma (^{207}Pb-^{206}Pb and U-Pb respectively on zircon, Aït Malek, 1997). They contain peraluminous xenoliths that record a first stage of isothermal decompression at 700-800°C, 8-10 kb, consistent with a source located more than 30 km deep, followed by a stage at 5-6 kb (Montel, 1985). In view of the water-saturated conditions, it is unlikely that large quantities of granite (i.e. < 10-20%) were produced and extracted at this stage (Patiño Douce and Johnston, 1990);
- the second stage of melting is characterized by high-temperature metamorphism in the cordierite stability field, with biotite destabilized: 760-850°C, 4.4-6.0 kbar (stage M4 of Montel *et al.*, 1992). Leucosomes were dated at 298±8 Ma based on Rb-Sr whole rock isochron (Caen-Vachette *et al.*, 1982), and Rb-Sr whole rock-biotite isochrons yield ages between 305 and 276 Ma (Williamson *et al.*, 1992). An age of 301±5 Ma was obtained for the homogeneous parts of the granite using the U-Pb monazite method (Mougeot *et al.*, 1997). Therefore, this second melting stage is considered to be generally synchronous with emplacement of the main cordierite-bearing granites. The volume of cordierite-bearing granites generated makes a case for massive partial melting at this stage, associated to destabilization of hydrous minerals.

3. The migmatite-granite domain. The various granites that appear in the Velay dome define a suite, with 3 main granite types distinguished according to age, structure, homogeneity, mineralogy and geochemistry:

- a heterogeneous banded biotite granite, found mainly on the western margin of the dome and locally on the southern and eastern margin. It corresponds to the first generated granite of the Velay suite. Foliation trajectories are in continuity with porphyric granites in the external rim of the dome suggesting continuity between these precursor granites and the development of the heterogeneous banded biotite granite;
- a main biotite-cordierite granite, in which several subtypes may be distinguished, in particular according to the cordierite habitus (Barbey *et al.*, 1999):
  - a heterogeneous banded granite with abundant enclaves. Most of these enclaves represent incorporated and partly assimilated pieces of the Lower Gneiss unit and precursor plutons originating from the host rocks, although some enclaves with refractory composition or granulite facies metamorphism have a lower crustal origin (Vitel, 1985). Cordierite may be prismatic, cockade-type or mimetic overprinting previous biotite-sillimanite assemblages. Most of the heterogeneous granites indicate mixing between melts of lower-crustal origin and melts from the para- and ortho-derived host rock (Williamson *et al.*, 1992),
  - a homogeneous leucocratic biotite-cordierite granite with mainly cockade-type cordierite. Its emplacement has been dated at 301±5 Ma using the U-Pb method on monazite (Mougeot *et al.*, 1997),
  - a homogeneous granite with biotite and prismatic cordierite as a primary ferromagnesian phase, with few enclaves. The heterogeneous and homogeneous granites with prismatic cordierite, with a high Sr content, have a mixed isotopic signature between the host rocks and a lower-crustal origin. The deep source is considered to be the melting of the lower mafic/felsic plutonic crust (Williamson *et al.*, 1992),
  - a leucocratic granite with cockade-type cordierite, without enclaves. The cordierite-quartz aggregates posdate primary biotite bearing assemblages and probably prismatic cordierite.

- the late magmatic activity that includes:
  - a homogeneous granite with K-feldspar porphyrocrysts and common prismatic cordierite, basic and micaceous inclusions (the Quatre Vios massif) (Fig. 10d). These granites are defined as late-migmatitic and are considered to be originated from melting of aluminous sediments at 4.5-5.5 kbar and 750-850°C, under water-undersaturated conditions and have a significant mafic component (Montel *et al.*, 1986; Montel and Abdelghaffar, 1993). Ages at 274±7 Ma (Rb/Sr whole rock, Caen Vachette *et al.*,

1984) are considered to be partially reset during Permian or Mesozoic hydrothermal event,

- Stephanian leucogranites, microgranite and aplite-pegmatite dykes, Permian rhyolites. Microgranite dykes have been dated at 306±12 and 291±9 Ma and a Permian hydrothermal event at 252±11 and 257±8 Ma (microprobe dating of monazite, Montel *et al.*, 2002).

4. The Stephanian intracontinental basin of Saint-Étienne. This basin is formed along the hanging wall of the Mont Pilat extensional shear zone (Malavieille *et al.*, 1990). The Mont Pilat unit, attributed to the lower gneissic unit at the scale of the French Massif Central consists of aluminous micaschists, metapelites, orthogneisses and amphibolites. This unit has a gently north-dipping foliation plane bearing a north-south stretching lineation. Numerous leucogranitic pods outcrop more or less parallel to this main foliation plane and have been dated at 322±9 Ma (Rb/Sr whole rock, Caen-Vachette *et al.*, 1984). Shear criteria, observed at different scales, are compatible with a top-north extension dated between 322 and 290 Ma ($^{39}Ar/^{40}Ar$, Malavieille *et al.*, 1990). This event was coeval with the progressive development of low pressure-high temperature metamorphic conditions (3-5 Kbar and 700-780°C, Gardien *et al.*, 1997).

B. Stop description (Fig. 28, 29)

D4.1: Meyras, Road from Le Puy-en-Velay to Aubenas, N102, Road cut

Stop D4.1 shows the incipient stage of melting within the orthogneiss of the Lower Gneissic Unit. An augen orthogneiss (the “Arc de Fix”), originating from peraluminous porphyric granite dated at 528±9 Ma (Rb-Sr whole rock, R’Kha Chaham *et al.*, 1990), constitutes an almost continuous rim around the Velay granite-migmatite dome. The melting is marked by the segregation of cordierite-free melts along the main inherited foliation and locally discordant cordierite-bearing granitic patches (Color Plate 2, B). Large phenocrists of K-feldspar attest of the porphyric type of the granite protolith while the foliation is marked by the elongation and crystallization of the quartzofeldspathic aggregates and biotite-rich melanosome. Magnesio-potassic dykes (the so-called “vaugnerite”) are intrusive and boudinated within the orthogneiss.

The progressive development of the anatexis and textural evolution in the transition from subsolidus annealing to melting process has been studied in detail in this zone by Dallain *et al.* (1999). Anatexis first develops with the resorption of quartz along the existing foliation. The breakdown of muscovite is then accompanied by the growth of sillimanite. Quartz-plagioclase aggregates are replaced by assemblages that are in equilibrium with the granite eutectic point, although K-feldspar aggregates are preserved. The breakdown of biotite is responsible for the production of melt beyond 30-50%, the value of the Rheological Critical Melt Percentage (Arzi, 1978). Leucosomes with cockade-type cordierite produced during this second melting stage tend to be discordant with the inherited structure. Structural orientations then become more varied as the leucosome proportion increases, with folds becoming abundant and randomly oriented.

D4.2: Pont de Bayzan, Road from Le Puy-en-Velay to Aubenas, N102, River banks of the Ardèche river

Stop D4.1 shows the incipient stage of melting within paragneiss of the Lower Gneissic Unit. The metagranite observed at the stop 4.1. is originally intrusive in sediments (pelites and argillites, including refractory quartz-rich and calcic layers). The location of early melting is controlled by foliation anisotropy (Macaudière *et al.*, 1992) and folding (Barraud *et al.*, 2003).

Numerous resisters from refractory layers preserve microstructure developed during the pre-migmatitic tectonic evolution that resulted in a composite foliation (named regionally S2) and polyphased folding (Color Plate 2, C). The outcrop is characterized by open folds that play an active role in the segregation of anatectic melts: cordierite-free leucosomes accumulate in saddle reef and axial planes of the folding that is attributed to S3 (Barraud *et al.*, 2003).

D4.3: Ucel, Road from Aubenas to Mezilhac, Road-cut

Stop D4.3 shows the unconformity of the Mesozoic sandstone over altered granite and biotite-sillimanite migmatitic paragneiss. The exhumation of the Velay granite-migmatite dome occurred during the Stephanian as boulders of granites and gneisses are found in the conglomerates of the Stephanian basin in the North and Prades basin in the South. Apatites in granite and migmatites yield a U-Pb age at 289±5 Ma that is interpreted as a cooling age during the uplift of the Velay region (Mougeot *et al.*, 1997). Finally, a regional unconformity is characterized at the base of the Trias sandstone and conglomerate. A recent and fresh road cut provides a spectacular illustration of this unconformity.

D4.4: Volane river, Road from Aubenas to Mezilhac, D578, Road-cut.

Stop D4.4 shows an hololeucocratic granite, with cockade-type cordierite, that represents one of the petrographic type of the Velay migmatite-granite dome (Color Plate 2, D). Detailed observation indicates that cordierite is formed at the expense of biotite, in the presence of a melt phase. Cordierite is formed from the early phase of melting to the end of the magmatic evolution of the Velay granite. However some garnets are present in cordierite nodules, indicating that, in that area, melting started in the garnet stability field.

D4.5: Volane river, Road from Aubenas to Mezilhac, D578, Road-cut

Stop D4.5 shows a late-migmatitic homogeneous granite and relations with migmatitic gneisses and heterogeneous cordierite-bearing granite. In the upper part of the outcrop, a late-migmatitic granite, the Quatre-Vios granite, is intruding the heterogeneous banded granite: it is a coarse grained peraluminous granite with prismatic cordierite and frequently oriented feldspar phenocrysts. It contains abundant mafic microgranular enclaves and sur-micaceous enclaves including biotite, garnet, cordierite, sillimanite, hercynite, ilmenite and rare plagioclase. This unusual mineralogy (absence of quartz and potash feldspar) and the corresponding chemical composition indicate that these enclaves are restites. P-T conditions calculated from this mineralogy yielded water-undersaturated conditions estimated at 4.5-5.5 kbar and 750-850°C. The mafic microgranular (biotite+plagioclase) enclaves correspond to frozen blobs of mafic magma. Locally, another type of late-migmatitic fine-grained granite, with typical acicular biotite and devoid of enclaves, crosscuts the Quatre-Vios granite.

In the lower part of the outcrop, another dyke of late-migmatitic granite is intrusive within migmatitic orthogneiss in which the second stage of melting is well marked by the biotite breakdown that produces Fe-rich garnet and cordierite. This zone is itself enclosed within the heterogeneous banded granite that contains a lot of enclaves of migmatitic paragneiss.

D4.6: Mont Gerbier-de-Jonc, Road from Mezilhac to Le Puy-en-Velay, D378, Sight seeing from the road

The Velay volcanism is made up of an eastern chain of Mio-Pliocene basaltic to phonolitic volcanoes and a western Plio-Quaternary basaltic plateau (Mergoil *et al.*, 1993). The road to Le Puy-en-Velay shows nice sight-seeing of this phonolitic chain that extends over more than 55km with more than 180 points of extrusion, emplaced between 14 and 6 Ma.

The Mont Gerbier-de-Jonc is known as the spring of the Loire river. It is a phonolitic protrusion that displays a rough prismatic jointing.

D4.7: Moulin de Sezigneux, Road from St Chamond to Le Bessat, D2, Road cut

The cordierite-andalusite-bearing micaschist of the Pilat Unit, seen at stop D4.7, displays extensional tectonics and HT-LP metamorphism within the Pilat series (Lower Gneissic Unit). This outcrop offers a good example of a low-pressure metamorphic unit, with micaschists and paragneisses intruded by syn-tectonic pegmatite dykes and pods. The main foliation plane is gently dipping to the North and shear criteria are well marked mainly around the pegmatitic pods indicating top to the North extensional tectonics. In the metamorphic rocks, the common mineralogy is: quartz + feldspars + biotite + andalusite and/or cordierite ± muscovite.

D4.8: Moulin de Sezigneux, Road from Saint-Chamond to Le Bessat, D2, River banks

Structure and metamorphism of the orthogneiss of the Lower Gneissic Unit are illustrated at stop D4.8. Ultramylonite and pseudotachylite textures are developed within the orthogneiss and S-C-C' structures indicate top to the North shear criteria compatible with extensional tectonics. Shear bands are underlined by syntectonic recrystallized biotites dated around 320-300 Ma ($^{40}Ar/^{39}Ar$). In the highly sheared parts of the outcrop ultramylonite bands and pseudotachylites are observable. The main foliation plane bears a north-south oriented stretching lineation. The metamorphic mineralogy is characterized by the association of quartz + feldspars + biotite + muscovite. Rare small-sized cordierites can also be observed.

End of the 4th day. Overnight in Saint-Étienne

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Day 5. High to ultra-high pressure metamorphism and arc magmatism: records of subduction processes in the French Massif Central

The main goal of Day 5 is to present the geological and petrological records of subduction processes in the eastern Massif Central that preceeded the development of the Velay migmatite-granite dome illustrated during Day 4. These records are: remnants of high to ultra-high pressure metamorphism in both crustal and mantle-derived lithologies in the Mont du Lyonnais unit, a partially preserved back-arc derived ophiolitic sequence, the Brévenne unit.

A. Geological setting

1. Eclogites and garnet peridotite from The Monts du Lyonnais unit (Fig. 32a).

The Monts du Lyonnais unit belongs to the upper gneissic unit (Lardeaux, 1989; Ledru *et al.*, 1994a). It comprises metasediments, orthogneisses (with protoliths of Ordovician age), leptynites (i.e. meta rhyolites), amphibolites and minor marbles. This unit also contains lenticular relics of either crustal (mafic and acid granulites, eclogites, Lasnier, 1968; Coffrant and Piboule, 1971; Dufour, 1985; Dufour *et al.*, 1985; Lardeaux *et al.*, 1989) or mantle origin (garnet and/or spinel bearing peridotites, Gardien *et al.*, 1988, 1990). Eclogites outcrop, in close association with garnet-bearing peridotites, in the southernmost part of the Monts du Lyonnais unit. Eclogites and related garnet amphibolites also occur in a similar structural situation farther north (in the Morvan unit, Godard, 1990) and also southeast of the Monts du Lyonnais unit (in the Maclas-Tournon area, Gardien and Lardeaux, 1991).

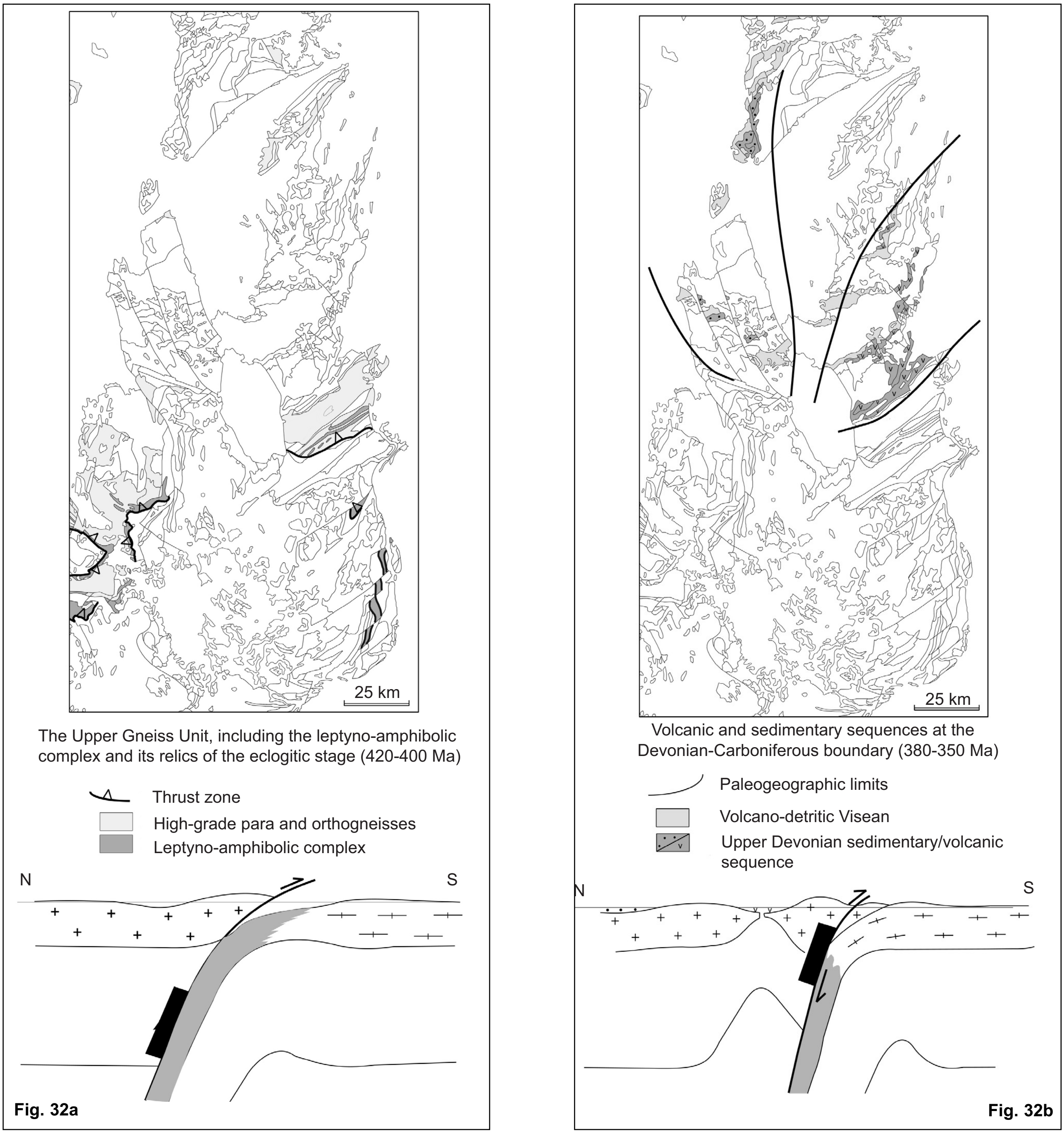

Fig. 32.- Geological maps of the eastern margin of the Massif Central through time showing the progressive edification of the belt. The geodynamic

In the Monts du Lyonnais unit, three ductile strain patterns were distinguished (Lardeaux and Dufour, 1987; Feybesse *et al.*, 1996) and related to high pressure and medium pressure metamorphic conditions:

- The relictual high-pressure structures.
- A main deformation imprint, contemporaneous with amphibolite facies conditions, corresponds to a NW-SE crustal shortening with a finite NNE-SSW stretching direction (Fig. 32b).
- A deformation event developed under a transpressional regime dated between 335 and 350 Ma (Rb/Sr whole rock, Gay *et al.*, 1981; $^{40}Ar/^{39}Ar$, Costa *et al.*, 1993) which is correlated to the main deformation within the Brévenne ophiolite in relation with its overthrusting (Fig. 32c).

With respect to this transpressive strain pattern, in the southern part of the Monts du Lyonnais unit, the eclogites outcrop exclusively in the strongly folded domains where they behave as rigid bodies in a deformed ductile matrix. We never found any eclogitic body within the shear zones. Therefore, the so-called Monts du Lyonnais Unit, corresponds to the tectonic juxtaposition of contrasted metamorphic domains interpreted as the transition from an

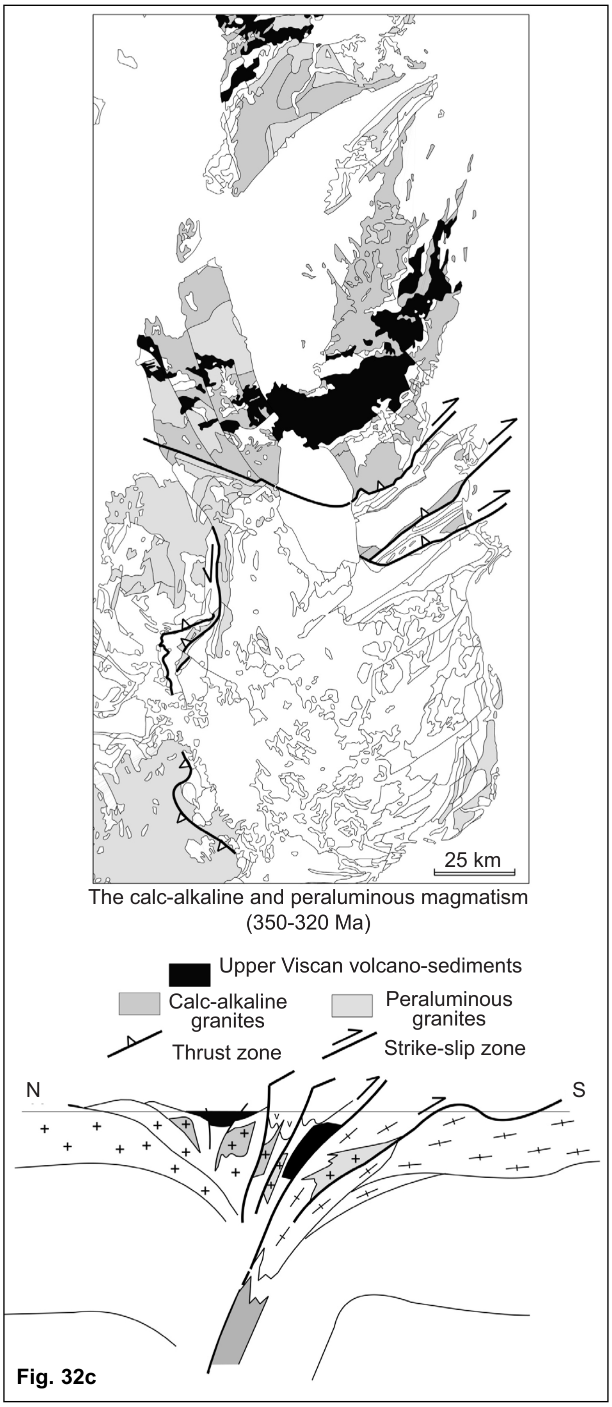

Fig. 32c

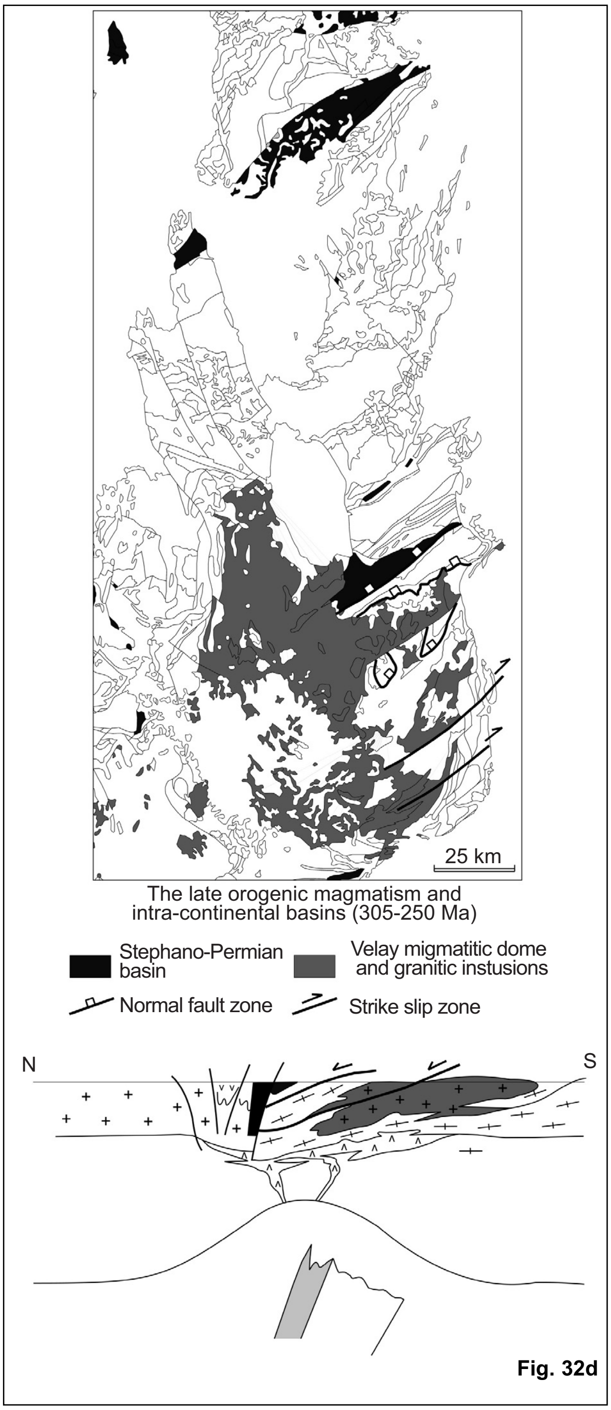

Fig. 32d

cartoons show the possible position of the Monts du Lyonnais eclogites during the four critical periods illustrated (a to d).

exhumed subduction complex to an uppermost back-arc ophiolitic system (Fig. 33).

2. The uppermost part of the magmatic arc: the Brévenne ophiolite (Fig. 32b).

The Devonian Brévenne ophiolitic unit consists of an association of metabasalts and metarhyolites together with intrusive intruded by trondhjemitic bodies (Peterlongo, 1970; Piboule *et al.*, 1982, 1983). The ophiolitic unit was initially emplaced in a submarine environment (Pin *et al.*, 1982; Delfour *et al.*, 1989). These intercalations are cut and overlain by intrusive gabbros and dolerites and by submarine basaltic lavas that, finally, are overlain by siltstones with pyroclastic intercalations (Milesi and Lescuyer, 1989; Feybesse *et al.*, 1996). A prograde greenschist to lower amphibolite facies metamorphism is recorded (Peterlongo, 1960; Fonteilles, 1968; Piboule *et al.*, 1982; Feybesse *et al.*, 1988). The Brévenne ophiolite underwent a polyphase deformation. An early event, well developed in the northern part of the unit, is characterized by a NW-SE stretching lineation with top to the NW shearing (Leloix *et al.*, 1999). During the second event, the ophiolitic unit is overthrusting the Monts du Lyonnais along a dextral trans-

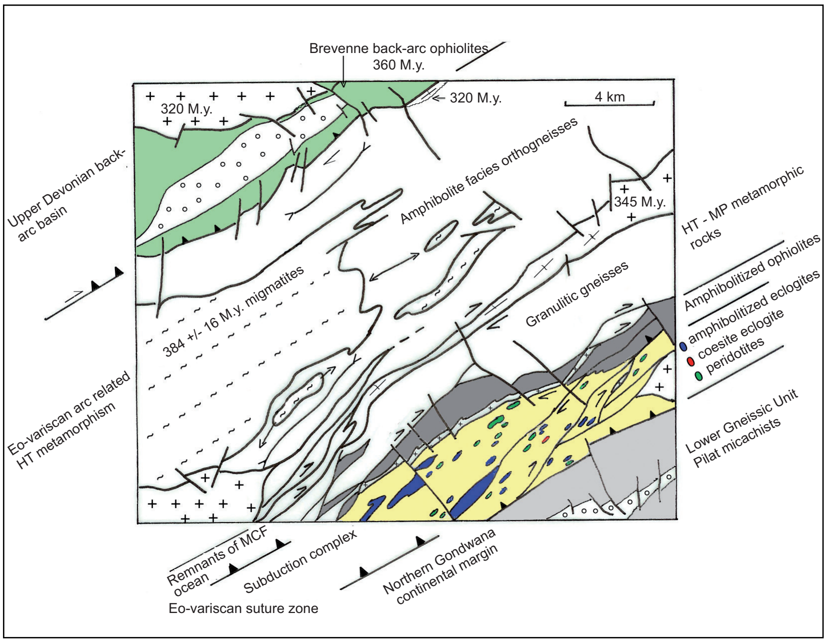

Fig. 33.- Structural sketch map of the Northeastern French Massif Central showing the geological units along a section from Pilat to Brévenne Units. The different tectono-metamorphic units are interpreted as remnants of a paleo-subduction zone.

pressional zone in which syntectonic granites emplaced between 340 and 350 Ma (Fig. 32c, Gay *et al.*, 1981; Feybesse *et al.*, 1988; Costa *et al.*, 1993). Subsequently, monzonitic granites of Namurian-Westphalian age and a contact metamorphism aureole postdate this tectonics (Delfour, 1989).

3. The development of the Velay migmatite granite dome and the collapse of the orogen (Fig. 32b).

The tectonic evolution of the eastern Massif Central is achieved during Westphalian and Stephanian. The formation of the Velay dome, coeval with the activation of crustal-scale detachements, potentially corresponds to flow of a partially molten crustal layer in response to gravitational collapse.

B. Stop description (Fig. 28, 29)

D5.1: The Bois des Feuilles, Road from Saint-Symphorien-sur-Coise to Rive de Gier, D2

This outcrop consists of garnet bearing peridotites and eclogites occuring as boudins within garnet sillimanite paragneisses. The coesite-bearing eclogite occurs in the southern part of the Monts du Lyonnais unit, near Saint-Joseph in the Bozançon valley (1/50.000 geological map “Saint-Symphorien-sur-Coise”, Feybesse *et al.*, 1996) in association with “common” eclogites and serpentinites. In the whole area, eclogites are preserved in low-strain lenses (meter scale boudins) wrapped by amphibolites or amphibolite facies paragneisses. For practical reasons (difficult access), we shall observed only garnet- peridotites and “common eclogites”.

Well-preserved peridotites occur as metric to decametric scale bodies within the paragneisses. In the less retrogressed samples, garnets in equilibrium with olivine, clinopyroxenes and orthopyroxenes can be observed. Frequently, garnets contain inclusions of spinels and pyroxenes, while in some samples spinels are replaced by coronas of garnet. These microstructures indicate an evolution from spinel to garnet lherzolite facies during a prograde metamorphic P-T path involving a strong pressure increase associated to a moderate temperature increase (Gardien *et al.*, 1990). In many samples, garnets are partly replaced by spinel and orthopyroxene while the porphyroclasts of olivine and pyroxenes are transformed into talc, amphibole, chlorite and serpentine. These mineralogical transformations document a retrograde evolution characterized first by a strong isothermal pressure decrease followed by both pressure and temperature decrease.

As a general rule, the eclogites from the Monts du Lyonnais unit are strongly retrogressed under granulite and amphibolite facies conditions and in 80% of the cases, the mafic boudins are composed of garnet bearing amphibolites with relics of eclogitic minerals. Petrographically, three types of eclogite facies rocks can be distinguished:

- fine-grained dark-colored kyanite- free eclogites;
- fine-grained light-colored, often kyanite-bearing eclogites;
- coarse-grained meta-gabbros (with coronitic textures) only partly reequilibrated under eclogite facies conditions.

As pointed out by various authors (Coffrant and Piboule, 1971; Coffrant, 1974; Blanc, 1981; Piboule and Briand, 1985), dark-coloured eclogites are iron and titanium rich (Fe0 + Fe_2O_3 near 13% and TiO_2 > 2%), Al-poor metabasalts (Al_2O_3 near 13-15%), while light-coloured eclogites have higher aluminium contents (Al_2O_3 near 17-20%), and higher average magnesium values but lower titanium contents (TiO_2 < 1,3%). Detailed geochemical investigations (Blanc, 1981; Piboule and Briand, 1985) have shown that these eclogites can be regarded as the variably fractionated members of a volcanic tholeiitic suite.

In the less retrogressed samples, the following mineral assemblages, representing the relicts of eclogite facies metamorphism, are recognized in the dark (1-2) and light (3-4) eclogites from the Monts du Lyonnais (Fig. 34):

- Garnet - omphacite - quartz - zoisite - rutile - apatite - sulfides,
- Garnet - omphacite - quartz - zoisite - colourless amphibole - rutile - sulfides,
- Garnet - omphacite - quartz (or coesite) - zoisite - kyanite - colorless amphibole - rutile,
- Garnet - omphacite - quartz - zoisite - kyanite - phengite - rutile.

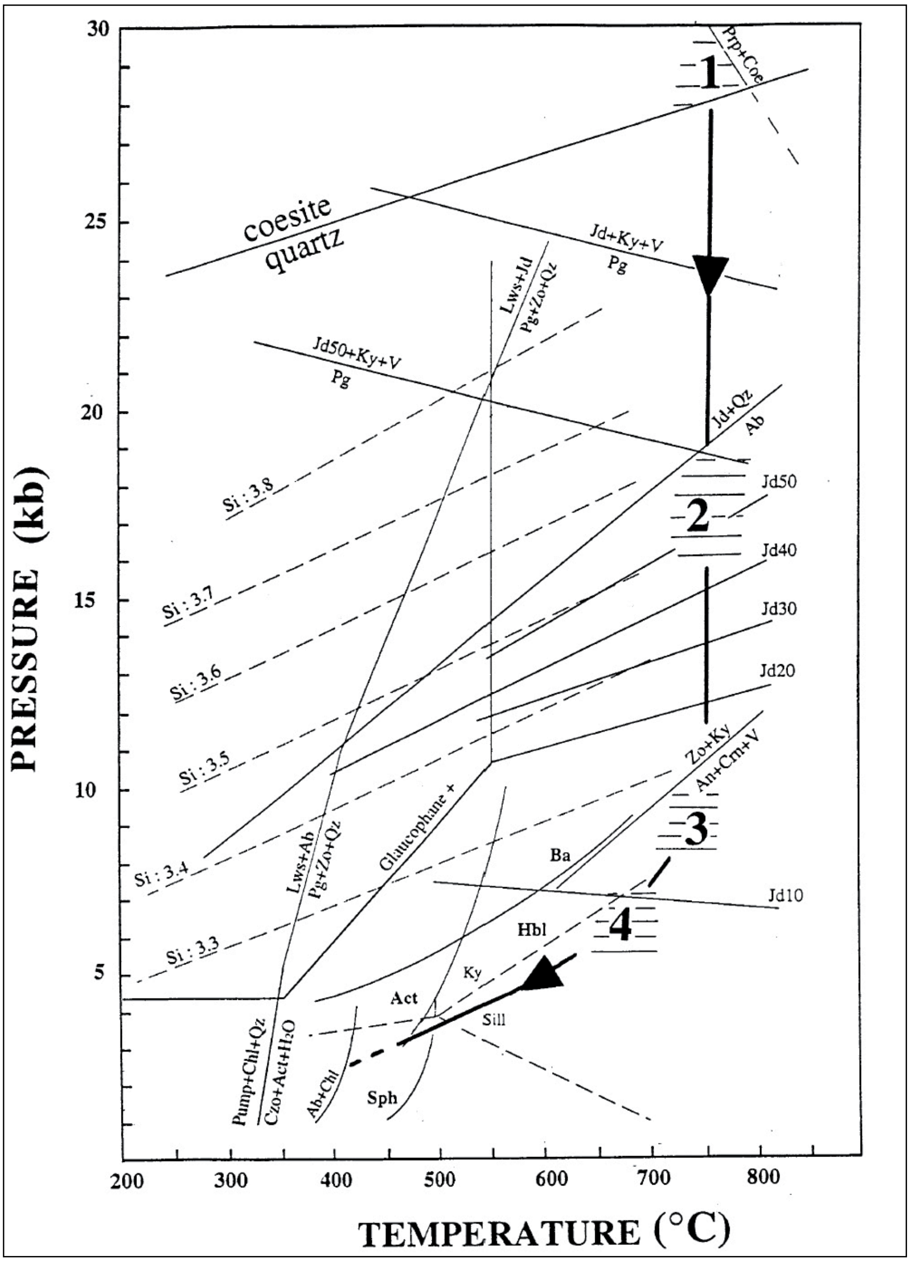

Fig. 34.- P-T path of the Monts du Lyonnais coesite-bearing eclogite (see detailed legend of the reactions in Lardeaux et al.*, 2001).*

Coesite and quartz pseudomorphs after coesite were exclusively detected as inclusions in two garnet grains within one sample of kyanite-bearing eclogite (Color Plate 2, E, F). SiO_2 polymorphs were distinguished optically, i.e. coesite was first positively identified relative to quartz by its higher refractive index, and then confirmed by Raman spectroscopy, by observation of the characteristics Raman lines 177, 271, 521 cm^{-1}. Only two coesite grains are preserved as relics and, generally, coesite is otherwise completely transformed into polycrystalline radial quartz (palisade texture) or into polygonal quartz surrounded by radiating cracks. The extremely rare preservation of coesite in the Monts du Lyonnais eclogites is clearly the result of the high temperature conditions (near 750°C, see details in Dufour *et al.*, 1985 and Mercier *et al.*, 1991) reached during decompression as well as the consequence of fluid influx (hydration) during retrogression. Indeed, the kinetics of the coesite —> quartz transformation are strongly temperature and fluid dependent (Gillet *et al.*, 1984; Van der Molen and Van Roermund, 1986; Hacker and Peacock, 1995; Liou and Zhang, 1996) and consequently in the studied area, coesite has been almost entirely transformed into quartz.

D5.2: Saint-André-la-Côte, Road from Saint-André-en-Haut to Mornant

Migmatites and granulitic rocks outcrop in the northern part of the Monts du Lyonnais. Near Saint-André-la-Côte village, mafic and acid granulite facies rocks are well exposed. In mafic granulites the following metamorphic assemblages are described (Dufour, 1985; Dufour *et al.*, 1985):

- Garnet + plagioclase + orthopyroxene + ilmenite,
- Garnet + plagioclase + amphibole + ilmenite,
- Clinopyroxene + orthopyroxene + plagioclase ± amphibole + ilmenite,
- Garnet + clinopyroxene + orthopyroxene + plagioclase ± amphibole + ilmenite.

In acid granulites (Dufour, 1982; Lardeaux *et al.*, 1989), the common mineralogy consists of quartz + plagioclase + K-feldspar + garnet + sillimanite ± spinel ± biotite. Kornerupine - bearing granulites have been also locally recognized in this outcrop (Lardeaux *et al.*, 1989).

In this northern part of the Mont du Lyonnais unit, the metamorphic imprint is typical for Intermediate Pressure granulite facies and there is no trace of eclogitic high-pressure facies metamorphism.

D5.3: Ste Catherine. Road from Ste Catherine to Saint-Symphorien-sur-Coise. Road D2

Stop D5.3 shows spectacular syn-tectonic granites emplaced within strike-slip shear zones, well dated at 350-345 Ma. The observed shear zone underlines the boundary between the granulite facies domain and the northern Monts du Lyonnais domain which is mainly composed of ortho and paragneisses metamorphosed under amphibolite facies conditions (Fig. 33). The road cuts allow the migmatitic orthogneisses to be observed and compared to syn-tectonic granites.

D5.4: Brévenne valley, road cut: bimodal magmatic sequence

Stop D5.4 shows different lithologies, like metabasalts, metarhyolites, metapyroclastites and metasediments, typical for the Brévenne ophiolitic unit. All the lithologies are metamorphosed under greenschist facies conditions. In mafic lithologies, the common mineralogy corresponds to an association of plagioclase + actinolite + chlorite + sphene ± calcite ± quartz.

The different lithologies are also deformed and involved into a regional scale fold system with sub-vertical axial planes. These folds are related to the regional transpressive regime which affects also the Monts du Lyonnais unit at around 350-340 Ma.

Recent geochemical investigations support the origin of the Brévenne ophiolitic sequence, during Devonian, in a back-arc basin developed upon the upper plate of a subduction system.

STOP D5.5: Pillow lavas of the Brévenne Unit. Road cut between L'Arbresle and Lozanne

This stop enhances outcrops of deformed and metamorphosed, but still recognizable, pillow lavas of basaltic compositions. The meta-basalts, associated with meta-tuffites, are transformed under greenschist facies conditions. They display a well-developed foliation plane, sometimes bearing, a stretching lineation marked by alignments of chlorites and/or actinolites.

End of the 5th day in Lyon (airport and railway station)

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Color plate 1

A: Moulin de Graïs recumbent fold in Devonian limestone with subhorizontal axial planar cleavage (stop D1-11).

B: Thin section of black chert (lydienne), near stop D1-11. The white ellipses are asymmetrically deformed radiolarians.

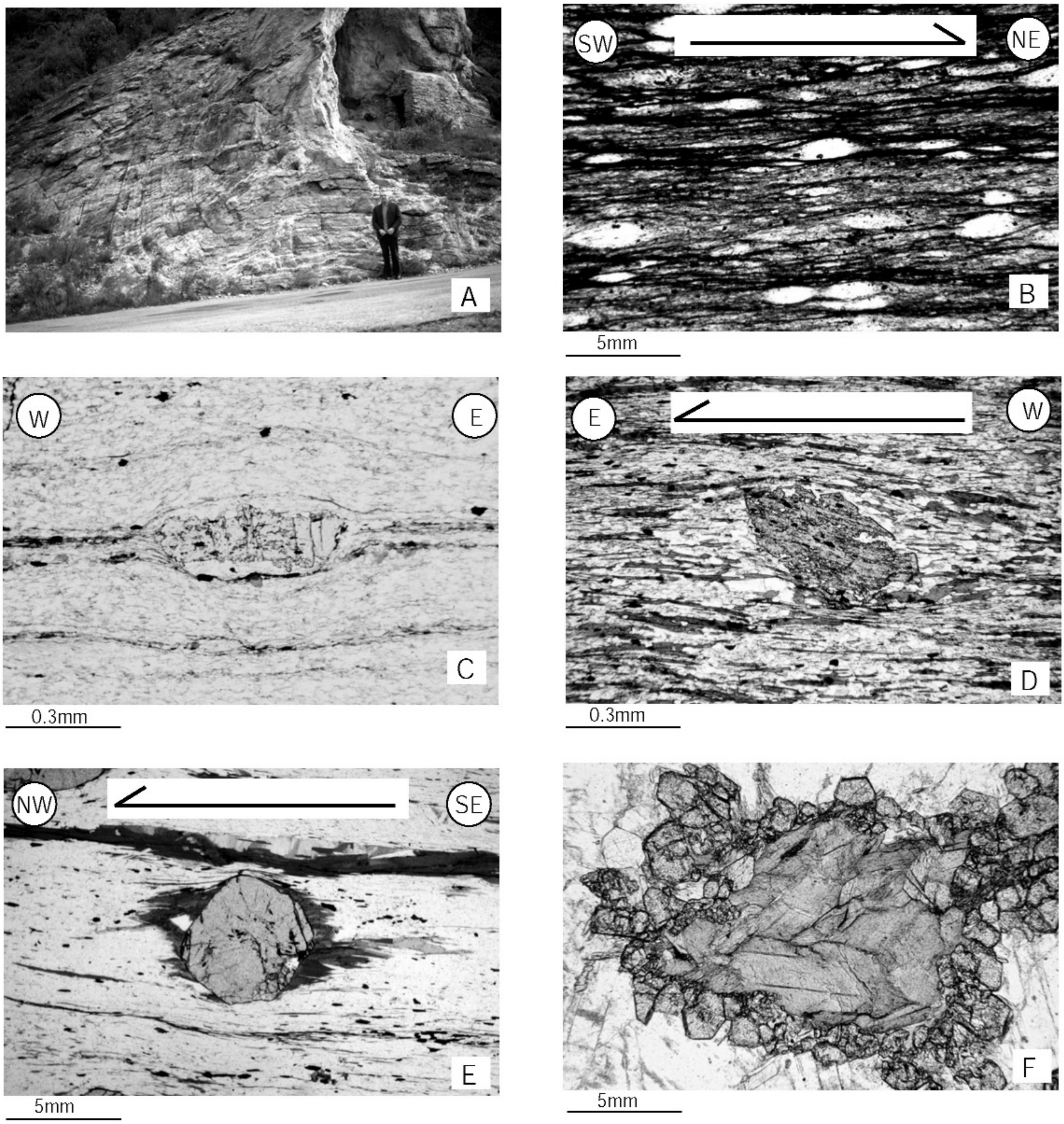
C: Thin section of micaschist in the Montagne Noire Axial Zone (west of stop D2-1). The symmetric shape of garnet porphyroblast suggests that this rock deformed in a coaxial flow.

D: Thin section of asymmetric staurolite porphyroblast in micaschist at the eastern end of the Montagne Noire Axial Zone (stop D2-3).

E: Thin section of micaschist of the Lot series (Lower Gneiss Unit) showing garnet porphyroblast surrounded by asymmetric biotite pressure shadows. (Lot river, west of Marvejols, stop D3-2).

F: This section of coronitic structure in eclogitic metagabbro, Marvejols (stop D3-4).

All thin sections are parallel to the stretching lineation and perpendicular to the foliation.


A
SW
NE
B
5mm
W
E
C
0.3mm
E
W
D
0.3mm
NW
SE
E
5mm
F
5mm

Color plate 2

A: Amphibolite boudins in the Leptynite-Amphibolite Complex of Marvejols (stop D3-5).

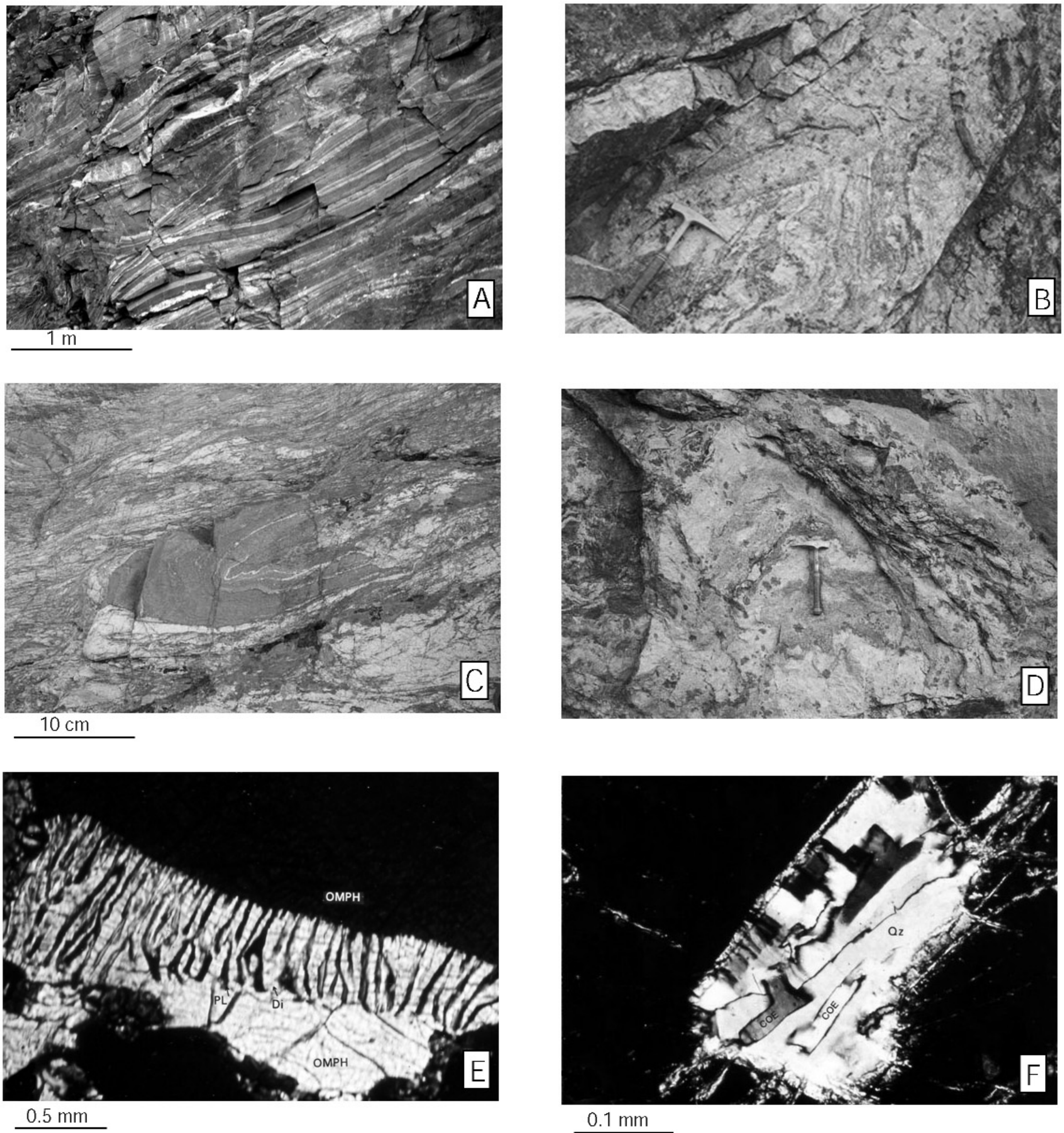
B: Incipient stage of melting within the orthogneiss of the Lower Gneissic Unit (Meyras, N102, stop D4-1).

C: Incipient stage of melting within paragneiss of the Lower Gneissic Unit (Pont de Bayzan, N102, stop D4-2). Isoclinal folding related to early tectonics is preserved within resisters.

D: Leucocratic granite, with cockade-type cordierite (Volane river, D578, stop D4-4).

E: Retrogressed eclogite with clinopyroxene-plagioclase symplectite developed at the expense of omphacite (stop D5-1).

F: Coesite grains preserved in a polycristalline quartz (near stop D5-1).


A
1 m
B
C
10 cm
D
OMPH
PL
Di
OMPH
E
0.5 mm
Qz
COE
COE
F
0.1 mm