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Paleozoic tectonic evolution of medio-Europa from the example of the French Massif Central and Massif Armoricain

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Abstract: The French Massif Central and Massif Armoricain belong to three tectonic and paleogeographic domains of the Medio-Europa Variscan Orogen. The entire Massif Central and southern part of the Massif Armoricain belong to the North Gondwana margin, the Central Armorican Domain is a part of Armorica microcontinent and the Léon Domain is a piece of another microcontinent. The N. Gondwana margin and Léon Domain are made of a stack of metamorphic nappes, conversely, the Central Armorican Domain consists of a Proterozoic basement built up by the Neoproterozoic Cadomian orogeny and a Paleozoic sedimentary cover weakly deformed by upright folds related to wrenching. The architecture of the North Gondwana margin results of three main tectonic-metamorphic events that follow an early Late Silurian (ca 415 Ma) high-pressure metamorphism whose associated structures are poorly documented. The Early Devonian D1 event is responsible for top-to-the-SW nappes coeval with migmatization and exhumation of high-pressure rocks around 385-380 Ma. The Late Devonian-Early Carboniferous D2 event is a top-to-the-NW shearing coeval with an intermediate pressure-temperature metamorphism dated around 360-350 Ma. The Visean D3 event is a top-to-the-south shearing widespread in the south Massif Central whereas in north Massif Central, D3 corresponds to the onset of synorogenic extension. The Variscan Belt is also characterized by a widespread magmatism. The Early-Middle Devonian calc-alkaline magmatism is related to the southward subduction of the Rheic Ocean. The Carboniferous magmatic events are the crustal melting response of D2 and D3 tectonic events. Late Visean, Namurian and Westphalian magmatic stages are coeval with extensional tectonics controlled by NW-SE stretching. These structural, metamorphic and magmatic events are replaced in a geodynamic evolution model involving two cycles of microcontinent drifting, rewelding and continental collision.

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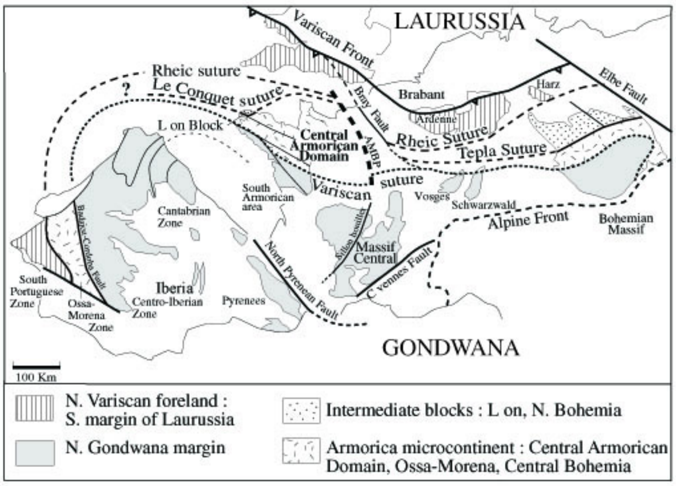
Introduction

It is now well acknowledged that the middle part of the European continent was built up in Paleozoic times by the welding of three continental masses, namely Baltica, Laurentia and Gondwana and several intervening microcontinents such as Avalonia or Armorica (e. g. Matte, 1986, 2001; Van der Voo, 1993; Paris and Robardet, 1990; Tait et al., 1997; Cocks, 2000; Franke, 2000; Robardet, 2003; Von Raumer et al. 2003). This process led to the formation of the thousands kilometers long and hundreds kilometers wide Variscan orogen which is often compared to the Cenozoic Alpine-Himalayan orogen. Within this bulk framework, the precise timing and geodynamic significance of the tectonic-magmatic-metamorphic events are still controversial. This paper aims to critically review the available database for the French Massif Central and Massif Armoricain. A geodynamic scenario that places emphasis on a polycyclic evolution characterized by an Early Paleozoic (Cambrian to Early Devonian) cycle of rifting and convergence of microcontinents and a Late Paleozoic (Devonian to Late Carboniferous) cycle corresponding to the true continental collision is proposed.

Large scale architecture of the French Massif Central and Massif Armoricain

In France, pre-Permian rocks crop-out in several massifs such as Ardenne, Vosges, Massif Armoricain, Massif Central, and also in the basement of the Cenozoic Alpine and Pyrenean Belts (Figure 1). The Massif Central and Massif Armoricain are the largest ones, less reworked by recent tectonics and thus the most representative of the French Paleozoic Massifs. In these two areas, three tectonic and paleogeographic domains are recognized, namely from South to North (Figure 1): 1) the North Gondwana margin is represented by the entire Massif Central and the South part of the Massif Armoricain, 2) the Armorica microcontinent corresponds to the Central Armorican Domain, and 3) another microcontinent is identified in the Léon Domain. In spite of observation gaps, such as the Iberia-Armorican orocline or Central European plain, these domains can be traced from South Spain up to Bohemia. Nevertheless, the correlations between Iberia and Bohemian Massif are still controversial. Such a discussion is beyond the scope of this paper that focuses on the French Massif Central and Massif Armoricain.

Figure 1. General zonation of the Medio-European Paleozoic Belt



General zonation of the Medio-European Paleozoic Belt showing the place of the Massif Central and Massif Armoricain in Western Europe. Correlations with Iberia and Central Europa remain hypothetic.

The North Gondwana margin

The North Gondwana margin is represented by the southern part of the Massif Armoricain and the entire Massif Central (Figures. 1, 2, 3, 4). Both areas experienced the same tectonic evolution. However, in southern Brittany, the primary nappe structure characterized by a flat-lying foliation and stacked units, is obscured by subvertical faults belonging to the dextral South Armorican Shear Zone. Although important for the understanding of the bulk tectonic framework, the South Armorican Shear Zone is a late structure active in Namurian-Westphalian times as shown by the syntectonic leucogranitic plutons (Berthé et al., 1979). The estimated total offset of 50-80 km does not significantly alter the general reconstruction of the N. Gondwana Margin with respect to the Central Armorican Domain. The stacked units recognized in the Massif Central and southern Massif Armoricain are presented from bottom to top (Ledru et al., 1989; Le Corre et al., 1991; Colchen and Rolin, 2001, Faure et al., 2004 and enclosed references).

i. The foreland basin, along the southernmost part of the Massif Central, is a Middle Carboniferous (Visean-Namurian) turbiditic basin widely developed southward below the coastal plain of the Mediterranean Sea and up to the Pyrénées. In the Montagne Noire, proximal turbiditic facies consists of wild flysch including kilometer-scale olistoliths of Paleozoic sedimentary rocks coming from the next unit. In Vendée (southernmost part of the Massif Armoricain), crops out a Tournaisian-Visean olistostrome with Silurian radiolarian cherts and limestones but its structural setting is not well understood yet (Colchen and Poncet, 1989).

ii. The Paleozoic Fold and Thrust Belt consists of weakly or un-metamorphosed rocks displaced to the South, as thrust sheets or kilometric-scale recumbent folds well developed in the Montagne Noire area but absent in the Massif Armoricain. The Cambrian-Ordovician rocks are unconformably overlain by terrigeneous rocks and platform carbonates of Devonian and Early Carboniferous age. Silurian rocks are almost lacking.

iii. The Para-autochthonous Unit to the North, overthrusts the Paleozoic sedimentary series. It is formed by greenschist to lower amphibolite facies metapelites, quartzites, and a small amount of limestone and amphibolite. This Para-autochthonous Unit is widely exposed in Cévennes, Albigeois and Vendée. In the north of the Massif Central, the Para-autochthonous Unit crops out in tectonic windows surrounded by the Lower Gneiss Unit. In Cévennes and Vendée, this unit is underlain by partly migmatized orthogneiss derived from alkaline granites.

iv. The Lower Gneiss Unit (LGU) is composed of medium pressure/medium temperature metagreywackes, metapelites and metarhyolites intruded by numerous alkaline porphyritic granitoids of Cambrian to Early Ordovician age transformed into augen orthogneiss during the tectonic-metamorphic events.

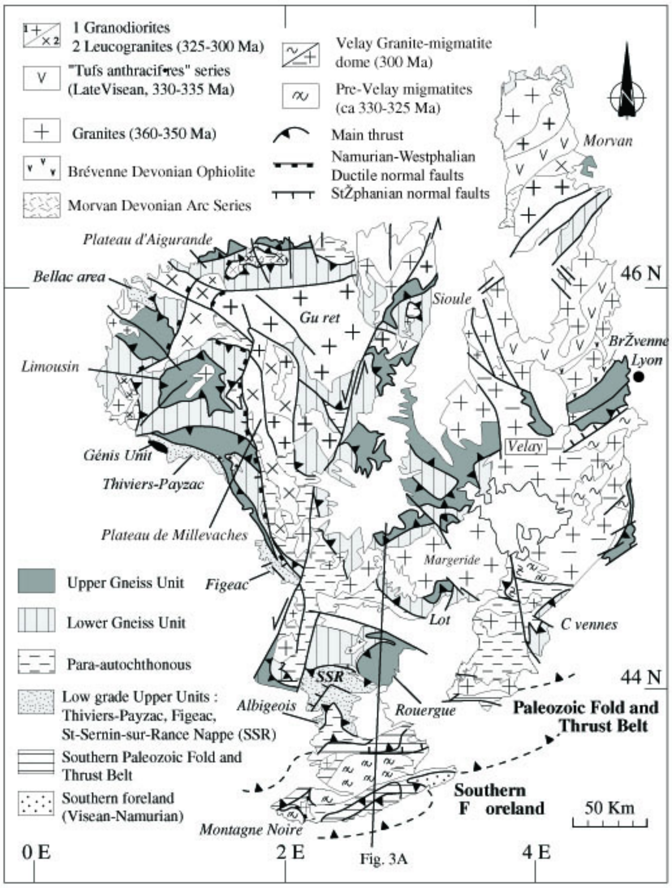
v. The Upper Gneiss Unit (UGU) forms the overlying nappe. It is made of rocks which experienced the higher metamorphic pressure, locally reaching coesite-eclogite facies near Lyon (Marchand, 1981; Godard, 1988; Lardeaux et al., 2001). The protoliths of the UGU, partly similar to those of the LGU, include metasediments and granitoids. Moreover, the UGU is also characterized by a bi-modal magmatic association, called the "leptynite-amphibolite complex" interpreted as formed during the rifting that led to the separation of Armorica from North Gondwana. In the Massif Central, rare Early Ordovician metagabbros and serpentinized ultramafics are considered by some authors as remnants of the Medio-European Ocean (e. g. Dubuisson et al., 1989). However, it is worth to note that ophiolitic nappes deformed and metamorphosed during the devonian D1 event (cf. belowsection 3) are not recognized in the Massif Central. Conversely, in the Baie d'Audierne, at the western end of the Massif Armoricain, metabasites (basalts, gabbro, amphibolite, eclogite), mafic volcanic-sedimentary rocks and serpentinized peridotites are considered as ophiolitic remnants of the Early Paleozoic Medio-European Ocean (Ballèvre et al., 1994). Glaucophane-garnet +/- lawsonite micaschists found in the Bois de Céné and Ile de Groix are sub-units of the Upper Gneiss Unit. Blueschists are very rare in the Massif Central. The upper part of the UGU consists of migmatites formed by the partial melting of pelitic and quartzo-feldspathic rocks. In these rocks, mafic restites are retrogressed eclogites.

vi. The Thiviers-Payzac Unit is the highest tectonic unit of the allochthonous stack in the Massif Central. It is formed by Cambrian metagraywackes, rhyolites and quartzites. Conversely to the underlying UGU, the Thiviers-Payzac Unit never experienced the high pressure metamorphism. The allochthony of the Thiviers-Payzac Unit with the underlying UGU established on the basis of metamorphic and structural observations (e. g. Floc'h, 1983; Roig, 1997; Duguet, 2003) is also supported by seismic lines (Bitri et al., 1999). It is worth noting that this uppermost unit is lithologically and structurally similar to the Para-autochthonous Unit that crops out in the southern Massif Central (i. e. St-Sernin-sur-Rance Nappe, Guérangé-Lozes, 1987; Figure 2). In Vendée, the Thiviers-Payzac Unit is represented by graywacke, rhyolite, quartzite and siltite that form the Chantonnay syncline (Figure 3). Due to a metamorphic overprint weaker than in the Massif Central, preserved Cambrian and Silurian-Devonian fossils allow to assess the stratigraphic age of this unit (Wyns et al., 1989).

vii. The Brévenne Unit consists of oceanic rocks (pillow basalts, diabase dykes, gabbros, ultramafics and siliceous sedimentary rocks) of Devonian age interpreted as an ophiolitic nappe (Pin et al, 1982; Sider and Ohnenstetter, 1986; Pin and Paquette, 1998) overthrust to the NW upon pre-Devonian gneiss in Latest Devonian-Early Carboniferous (Faure et al., 1997; Leloix et al., 1999). In the South Limousin, some small outcrops of gabbro, mafic metavolcanics (sometimes pillowed), radiolarian cherts, siliceous red shales and Middle Devonian limestones form the Génis Unit. The structural and paleogeographic setting of the Génis Unit is not yet settled. Although sometimes considered as an ophiolitic nappe (e. g. Ledru et al., 1989), the lack of outcrop continuity suggests that the Génis Unit might be a Late Devonian-Early Carboniferous olistostrome reworking oceanic rocks similar to those of the Brévenne Unit.

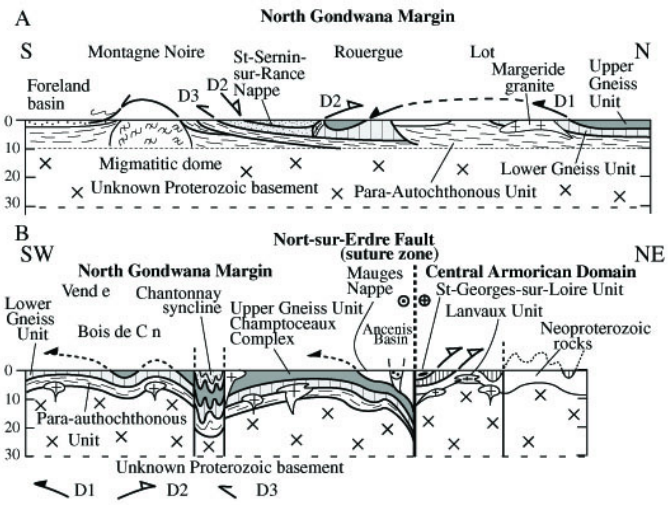
viii. The peculiarities of the Southern Massif Armoricain. The Brévenne Unit is not recognized in the Massif Armoricain, however, the south part of this massif exhibits two specific features. Firstly, east of Nantes, the Mauges Nappe (Cogné, 1974; Figures 3, 4) consists of Neo-Proterozoic micaschists unconformably covered by Cambrian-Ordovician unmetamorphosed terrigeneous rocks and acidic lava flows (Cavet et al., 1966). The Mauges Nappe overthrusts high pressure metamorphic rocks and migmatites of the Champtoceaux complex correlated with the UGU. It is worth noting that the South part of the Massif Armoricain is the only place in the whole French Variscan Massifs where a basement nappe overlies the Upper Gneiss Unit. Secondly, north of the Loire estuary, high temperature metamorphic rocks, migmatites and granitoids form the «Cornouailles Anticline» (Cogné, 1974; Audren, 1986; Figure 4). The bulk structure of this complex area and its relationships with other units of the Massif Armoricain remain poorly understood. The boundary between the North Gondwana Margin and the Central Armorican Domain corresponds to the Nort-sur Erdre fault which is the place of the Early Paleozoic suture zone reworked by strike-slip tectonics (cf section 3).

Figure 2. Structural map of the French Massif Central



Structural map of the French Massif Central.

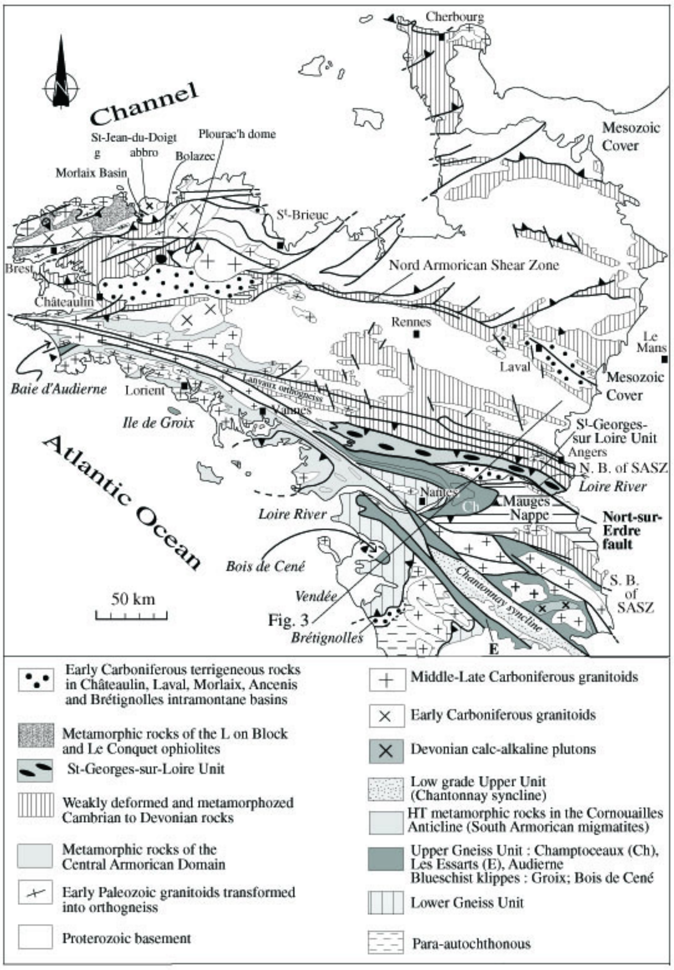
Figure 3. Crustal scale cross section of the Massifs



A: Crustal scale cross section of the Massif Central (located in Figure 2)

B: Crustal scale cross section of the Massif Armoricain (located in Figure 4). Both sections, drawn at the same scale, show the stack of nappes and polyphase deformation.

Figure 4. Structural map of the French Massif Armoricain



Structural map of the French Massif Armoricain (modified from Le Corre et al., 1991 and Rolet et al., 1994). Thin lines in the Upper Gneiss Unit are the main orthogneiss bodies metamorphosed under eclogite facies.

The Central Armorican Domain forms the main part of the Massif Armoricain

It consists of a Proterozoic basement built up during the Neo-Proterozoic (or Cadomian) orogeny, unconformably covered by a Cambrian to Early Carboniferous sedimentary cover and intruded by numerous Carboniferous plutons. The Central Armorican Domain is limited to the South, from the North Gondwana margin by the Nort-sur-Erdre fault and to the North, from the Léon Block by the Conquet suture (Figures 1, 4). To the northeast, the boundary of the Central Armorican Domain is hidden below the Channel. In agreement with Rolet et al. (1986), two subareas are distinguished in the Central Armorican Domain.

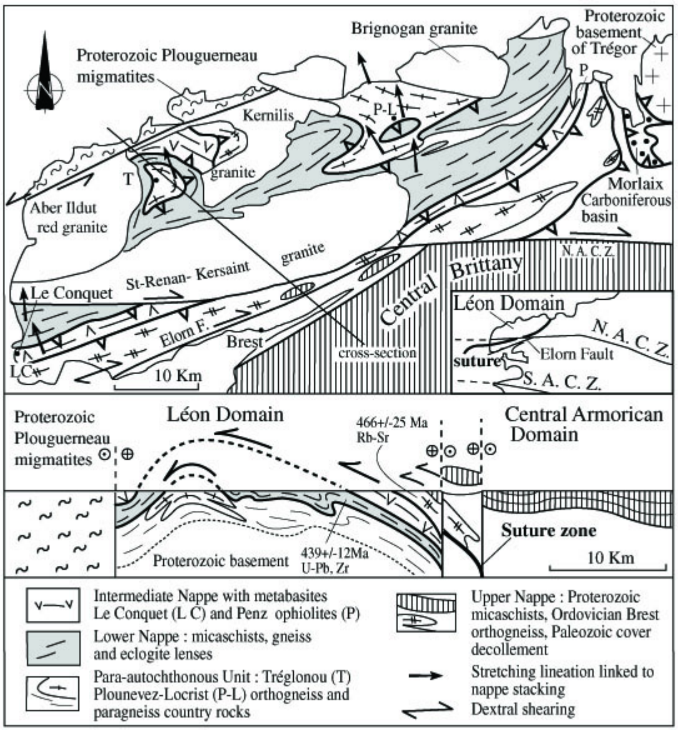
i. The eastern area, around Rennes and in Normandy, consists of a Proterozoic basement deformed and metamorphosed during the Neo-Proterozoic Cadomian orogeny unconformably overlain by a Paleozoic sedimentary cover. During the Paleozoic times, this eastern area experienced a relatively weak deformation characterized by upright folds with subvertical cleavage coeval with low to middle temperature metamorphism. These structural and metamorphic features are related to granite emplacement along the North and South Armorican Shear Zones. From the North Armorican Shear Zone to Cherbourg, the Paleozoic rocks unconformably overlying the Proterozoic basement are gently deformed by E-W to NE-SW trending south-vergent synclines coeval with basement-cover decollements (Rolet et al., 1994).
ii. The western area, east of Brest, experienced stronger Paleozoic tectonics and metamorphism than the eastern area. Horizontal displacements and locally staurolite-kyanite-garnet metamorphism took place before the sedimentation of the Early Carboniferous Chateaulin basin (Rolet et al., 1994). As suggested by early workers (e. g. Cogné, 1974) and discussed below in section 5, this Late Devonian-Early Carboniferous event, called Bretonian phase, played an important role in the geodynamic evolution of the Central Armorican Domain.

The southern part of the Central Armorican Domain, north of the Nort-sur-Erdre fault, is formed by a peculiar unit called the St-Georges-sur-Loire Unit (Figure 3). Recent petrological, and structural works show that the St-Georges-sur-Loire Unit consists of a southern olistostrome subunit of Middle to Late Devonian age and a northern terrigeneous subunit (Cartier et al., 2001). The olistoliths are Silurian radiolarian cherts, Devonian limestones, mafic pillow lavas, gabbro and pyroclastics, Cambrian (?) rhyolites and undated grauwackes. Both sub-units are overthrust to the north upon the Lanvaux anticline formed by Cambrian-Ordovician sedimentary rocks and the Lanvaux Ordovician orthogneiss. The tectonic significance of the St-Georges-sur-Loire Unit will be discussed in section 5. In the following, the Central Armorican Domain will be considered as a part of the Armorica microcontinent which corresponds to a continental stripe drifted from Gondwana in Ordovician and rewelded to it in Late Silurian.

The Léon Domain

The Léon Domain forms the NW part of the Massif Armoricain (Figures 1, 4). In spite of numerous Carboniferous plutons partly hidding the structural relationships between the units, an antiformal stack of nappes is presently recognized (Le Corre et al., 1989; Rolet et al., 1994; Figure 5). From bottom to top, the structure of the Léon Domain consists in the following succession.

Figure 5. Structural map and cross section of the Léon Block



Structural map and cross section of the Léon Block (adapted from Rolet et al., 1994). For clarity, the Carboniferous granites are unpatterned in the map and not represented in the cross section.

i. The Para-autochthonous Unit corresponds to paragneiss intruded by augen orthogneiss (Tréglonou and Plounevez-Lochrist) which emplacement is dated at 385+/- 8 Ma by Rb-Sr method on whole rock, and 400+/-40 Ma by U-Pb method on zircon fractions (Cabanis et al., 1979). Both the augen gneiss and country rocks experienced migmatization but its age is still unknown.

ii. The Lower Nappe is formed by biotite-garnet-sillimanite gneiss that enclose eclogitic rocks mostly retrogressed into amphibolite and derived from gabbro or basalt. Pyroxenites and serpentinites crop out locally. P-T conditions for the eclogitic metamorphism are estimated around 14-15 kbar, and 650-700°C respectively. U/Pb dates from zircons provide an age of 439+/-12 Ma which is considered as that of the high pressure metamorphism (Paquette et al., 1987).

iii. The Intermediate Nappe or Penzé-Le Conquet ophiolitic nappe consists of ortho- and paraderived amphibolite, metagabbro, serpentinite, biotite-garnet-staurolite micaschist and metachert. These rocks which are interpreted here as remnants of an oceanic area that separated the Léon Domain and the Central Armorican Domain form Le Conquet suture (Figures 1, 4)

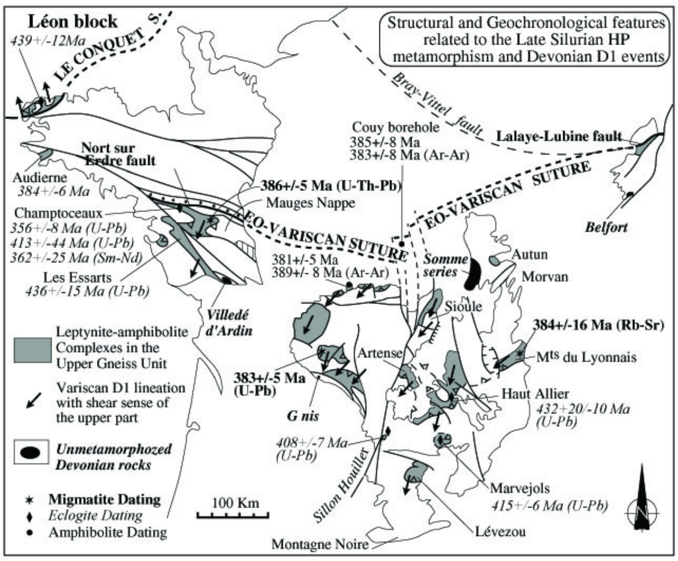
iv. The Upper Nappe consists of Late Proterozoic micaschists intruded by Ordovician granodiorites, presently deformed into orthogneiss (e. g. Brest orthogneiss) dated around 466+/-25 Ma by Rb-Sr method on whole rock (Cabanis et al., 1979). Weakly deformed Ordovician white quartzite and pelite form the Paleozoic cover of the Proterozoic basement. A north directed decollement separates the Paleozoic cover from its Proterozoic basement (Figure 5).

This stack of nappes is cut by the dextral strike-slip Elorn fault which is a branch of the North Armorican Shear Zone. The main ductile deformation coeval with nappe stacking in the Léon Block is characterized by a N-S to NNW-SSE trending stretching lineation with top-to-the-N (or NW) shear criteria observed from the Para-autochthonous Unit up to the Penzé-Le Conquet Ophiolitic nappe (Figure 4). A second ductile deformation is restricted to the dextral Elorn wrench fault. The top-to-the-North shearing is presently undated, however, it is older than the emplacement of the Early Visean St-Renan-Kersaint granite (ca. 340 Ma) and younger than the Ordovician quartzite of the Upper Nappe, an Early Carboniferous age (ca. Tournaisian) is likely. The Léon Domain has been considered as the western part of the Upper Gneiss Unit of the South part of the Massif Armoricain located west of the Baie d'Audierne area and translated to the North by the Elorn strike-slip fault (e. g. Balé and Brun, 1986; Le Corre et al., 1989). Such an interpretation is not supported by available data. Near the Penzé river, at the NE termination of the Léon Domain (Figure 5) such a strike-slip fault is not recognized. Conversely, the conspicuously developped low angle, south dipping foliation and NNW-SSE lineation suggest rather that the Central Armorican Domain overthrusts the Léon Domain. Therefore, the Penzé-Le-Conquet ophiolitic nappe rooted in Le Conquet suture separates the Léon Domain from the Central Armorican Domain.

Tectonic-Metamorphic Evolution of the Massif Central-Massif Armoricain

Four main ductile and syn-metamorphic phases can account for the tectonic evolution of the French Paleozoic Massifs. The earliest one is coeval with the high (to ultra high) pressure metamorphism recorded in the eclogite facies rocks of the UGU (Figure 6). Although most of high pressure rocks are mafic ones, jadeite orthogneiss are locally found (e. g. Lasnier et al., 1973; Ballèvre et al., 1994). Similar physical conditions of 18-20 Kb and 650-750°C are computed from UGU eclogites both in the Massif Central and in the Massif Armoricain (Figure 7 , cf Lardeaux et al., 2001, and Godard, 2001 for reviews of the Massif Central and Massif Armoricain eclogitic metamorphism respectively). Available radiometric dates range around 415 Ma (Pin and Peucat, 1986). Since the high pressure rocks are blocky relics within amphibolite facies rocks or migmatites, the structural information is quite rare. The following three events are better documented.

Figure 6. Synthetic map of the Massif Central

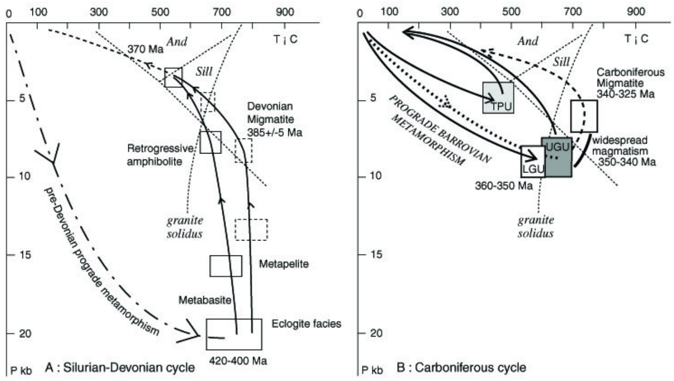


Synthetic map of the Massif Central and Massif Armoricain showing the structural, metamorphic and geochronological elements related to the Late Silurian HP metamorphism and the following Devonian D1 event. In the Upper Gneiss Unit and Léon Block, the available radiometric dates, stretching lineation and related top-to-the-SW kinematics are presented (see text for discussion).

The Early to Middle Devonian D1 event

This tectonic-metamorphic event is coeval with the crustal melting of the Si-Al rich rocks (i. e. pelites and granitoids) of the Upper Gneiss Unit, whereas mafic rocks remain as amphibolite restite in migmatites. The migmatisation is dated of Middle Devonian : 384+/- 16 Ma by Rb/Sr method on whole rock in the Lyonnais (Duthou et al., 1994); 383+/-5 Ma by U/Pb method on zircon fractions in Limousin (Lafon, 1986); and 386+/-6 Ma by chemical U/Th/Pb method on monazite single grain in the Champtoceaux Complex (Cocherie et al., in press; Figure 6). P-T estimates from garnet-plagioclase and garnet-biotite pairs provide metamorphic conditions of 7+/- 0.5 kb and 700+/-50°C respectively (Mercier et al., 1991; Roig and Faure, 2000, Figure 7).

Figure 7. Various P-T-t paths



Various P-T-t paths showing the two metamorphic-tectonic cycles experienced by the Massif Central and South Massif Armoricain rocks. A: Silurian-Devonian cycle due to continental subduction and collision of N. Gondwana margin below Armorica. Crustal rocks forming the Upper Gneiss Unit are metamorphosed in eclogite facies around 420-400 Ma (i. e. Late Silurian-Early Devonian) and exhumed around 390-380 Ma (Early-Mid Devonian). During this exhumation, the mafic protoliths are retrogressed into amphibolites whereas the metapelites and orthogneiss are easily melted to produce migmatites. B: P-T paths related to the Carboniferous cycle in different units. TPU: Thiviers-Payzac Unit, UGU: Upper Gneiss Unit, LGU: Lower Gneiss Unit. Petrology and geochronology indicate 360-350 Ma age for the prograde intermediate pressure-intermediate temperature metamorphism. Retrogression of these units is poorly documented, except for the 340-325Ma anatexis.

Structurally, the flat-lying migmatitic foliation exhibits a NE-SW trending (N30 to N60E) mineral and stretching lineation marked by fibrolitic sillimanite or biotite in migmatites and biotite or amphibole in mafic rocks. Shear criteria indicate top-to-the-SW displacement (Floc'h, 1983; Faure et al., 1997; Roig and Faure, 2000). Locally, the migmatitic texture is totally overprinted by a mylonitic fabric. 40Ar/39Ar ages of 381+/-5 Ma and 389+/-8 Ma from hornblende in amphibolite in the Plateau d'Aigurande (Boutin and Montigny, 1993) or 385+/-8 Ma and 383 +/- 8 Ma on amphibolite and biotite respectively from gneiss recovered in the Couy borehole (Figure 6 ; Costa and Maluski, 1988) correspond to the age of this syntectonic metamorphism. In agreement with thermal modelling (e. g. England and Thompson, 1986) these radiometric ages support an isothermal decompression leading to crustal melting nearly 30 Ma after the development of the high pressure metamorphism. A high thermal gradient of ca. 50°/km and a 3-4 mm/y exhumation rate are computed.

As already pointed out, (Faure et al., 1997), in Morvan (Figure 2), the nearby occurrence of Middle Devonian unmetamorphosed and undeformed rocks (Delfour, 1989) and eclogitic relics in migmatite (Godard, 1990) suggests that, at least in North part of the Massif Central, the high pressure rocks were already exhumed before Middle Devonian. Other undeformed Middle to Late Devonian sedimentary rocks crop out from Vendée to Vosges (Figure 6) however their structural setting along late faults does not allow us to observe an unconformable contact. The lack of large Devonian clastic deposits implies that the exhumation of the HP Variscan metamorphics was dominantly a tectonically assisted process.

The Late Devonian-Early Carboniferous D2 event

Since structural and metamorphic D2 features differ in the North Gondwana margin and in the Central Armorican Domain, these two areas are presented successively.

i) In the Massif Central and the South part of the Massif Armoricain, the major structure related to this stage is a NW-SE trending stretching lineation (Figure 8) widespread in the Lower Gneiss and Para-autochthonous Units but less developped in the Upper Gneiss Unit. The NW-SE lineation is also observed in the Thiviers-Payzac and Brévenne Units. Whatever the tectonic unit, the foliation along which the NW-SE lineation develops is flat-lying or dipping at a low-angle. This Early Carboniferous lineation must not be mistaken with another NW-SE stretching lineation coeval with the emplacement of synkinematic Namurian-Westphalian plutons during the syn-orogenic extension (cf. section 5.5).

Figure 8. Synthetic map of the Late Devonian-Early Carboniferous D2 event

Synthetic map of the Late Devonian-Early Carboniferous D2 event in Massif Central and Massif Armoricain characterized by top-to-the-NW ductile shearing and pre-Late Visean Guéret-type plutonism. T and SG are Tréban and St-Gervais granites respectively. These two plutons are the continuation of the Guéret massif east of the Sillon Houiller fault. Available U-Pb, Ar-Ar and Rb-Sr ages for granitoids and metamorphic rocks are also shown. A. M. B. P.: Magnetic Anomaly of Paris Basin.

Thermo-barometric constraints are well established in the Limousin and Rouergue (Floc'h, 1983; Feix, 1988; Burg et al., 1989; Bellot, 2001, Duguet, 2003; Figure 7). In the Upper Gneiss Unit, syn-D1 metamorphic minerals, such as kyanite, are found either as inclusions in garnet or plagioclase or as cataclazed grains boudinaged along the NW-SE stretching lineation. Syn-D2 minerals, such as biotite, garnet, plagioclase crystallized along the NW-SE lineation indicate 7-10 kb and 600-700°C. Paragneiss belonging to the Lower Gneiss Unit provide nearly similar conditions of 8-10 kb and 550-600°C. In the LGU, amphibolites which never experienced the high-pressure event indicate 8-10 kb and 700-800°C (Santallier, 1981). In the uppermost Thiviers-Payzac Unit, biotite-garnet +/- staurolite commonly crystallize along the NW-SE stretching. P-T conditions of 4-6 kb and 400-500°C respectively are computed. At the scale of the whole Massif Central, the thermobarometric constraints support a prograde middle pressure/middle temperature metamorphism coeval with the NW-SE stretching.

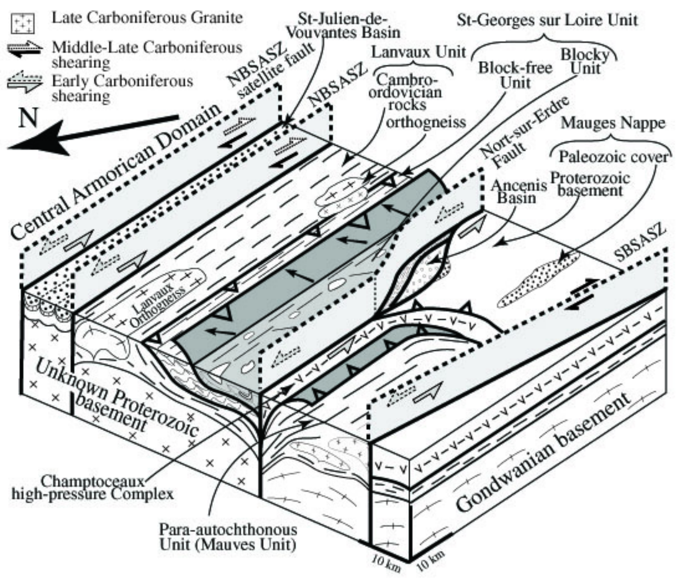
Top-to-the-NW ductile shearing is dominant from southeast Massif Central up to the South part of the Massif Armoricain (Figure 8 ; Brun and Burg, 1982; Bouchez and Jover, 1986; Burg et al., 1987; Friedrich et al., 1988). Moreover, in the Rouergue area, a kilometer-scale flat lying synmetamorphic ductile shear zone, called the “Naucelle thrust”, (Figure 8) transports to the NW the Para-autochthonous Unit of the Albigeois area upon the Lower Gneiss Unit. This northwestward shearing reworks D1 structures, such as NE-SW trending isoclinal folds and stretching lineations (Duguet and Faure, 2004). However, in some places such as Marvejols or S. Limousin, top-to-the-SE displacements are also recognized but the timing of these displacements remains poorly documented. For instance, in Limousin, it has been shown that this top-to-the-SE shearing is a late deformation related to the Late Carboniferous syn-orogenic extensional tectonics (Roig, 1997).

Top-to-the-NW shearing is also well developped in the Brévenne ophiolitic nappe, in particular, at the nappe base, a mylonitic shear zone with isoclinal folds parallel to the NW-SE stretching lineation develops (Leloix et al., 1999). This deformation is dated as pre-Visean (i. e. older than 345 Ma) by the Early Visean unconformity (the so-called Le Goujet conglomerates). The syn-D2 middle pressure/middle temperature metamorphism is dated by 40Ar/39Ar method on biotite, muscovite and amphibole between 360 and 350 Ma (Maluski and Monié, 1988; Costa, 1989, Costa, 1991-92; Figure 8). A general interpretation of the Late Devonian-Early Carboniferous D2 event will be discussed in section 5.5.

ii) In the Central Armorican Domain, several lines of evidence argue for the existence of a Late Devonian-Tournaisian event known as the “Bretonian phase”. From Brest area up to the Laval basin, stratigraphic and sedimentological works show that erosion of the Ordovician to Devonian series was very active during Early Carboniferous (e. g. Darboux et al., 1988; Paris et al., 1982; Rolet, 1982; Rolet et al., 1994). At depth, the western part of the Central Armorican Domain experienced a regional middle pressure /middle temperature metamorphism with biotite-garnet-staurolite assemblage older than the thermal contact metamorphism related to the Carboniferous Pontivy granite which is dated at 344+/-8 Ma (Rolet et al., 1994). This “Bretonian metamorphism” is attributed to crustal thickening, however, its age and associated structures are still unknown. Thin skin thrusting is described in Brest and Plourac’h areas (Rolet et al., 1986, 1994; Darboux and Le Gall, 1988, Figure 4).

More to the SE, the weakly or unmetamorphosed Devonian block-in-matrix series of the St-Georges sur Loire Unit overthrust the Lanvaux Unit to the North (Cartier et al., 2001). Top-to-the-NW shearing and left-lateral wrenching on flat-lying and vertical foliations respectively is recognized in the Lanvaux orthogneiss and its metasedimentary host rocks (Faure and Cartier, 1998). This event is older than the Middle Carboniferous dextral strike-slip of the S. Armorican Shear Zone and younger than Middle Devonian which is the age of the deformed sedimentary rocks. In the Central Armorican Domain, wrench tectonics lasting from Late Devonian to Middle Carboniferous are the main structural feature. The boundary between the N. Gondwana margin and the Central Armorican Domain, i. e. the Nort-sur-Erdre Variscan suture zone, (cf section 2) is reworked by a left-lateral shearing along which the Ancenis basin opens as a sinistral pull-apart in Tournaisian and Visean times (Diot, 1980; Dubreuil, 1986; Figure 9).

Figure 9. Schematic block diagram showing the geometric and kinematic relationships



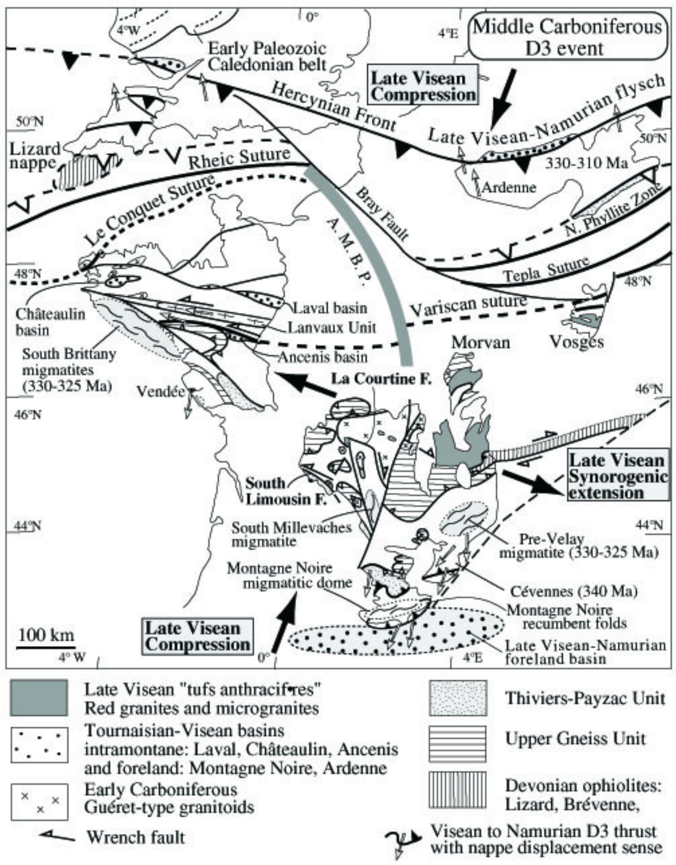
Schematic block diagram showing the geometric and kinematic relationships between the Central Armorican Domain and the N. Gondwana margin in the southern part of the Massif Armoricain.

A consequence of the Late Devonian-Tournaisian D2 event is the thermal resetting of the geochronometers. Sm-Nd measurements of eclogites in the Champtoceaux Complex (Figures 3,4) yield a 360 Ma age (Bosse et al., 2000). This date does not comply with other ages of the high-pressure metamorphism of the Upper Gneiss Unit. Moreover, the migmatite that forms the upper part of the Champtoceaux Nappe and encloses mafic restites derived from eclogites is dated at 386+/-5 Ma (Cocherie et al. in press; cf section 3.1). Therefore, this 360 Ma age does not corresponds to the crystallization of the HP minerals. The geological significance of the 360 Ma ages recovered in the S. Brittany eclogites remains unclear. A possible interpretation would be a resetting duing the D2 tectonic-metamorphic event.

The Middle Carboniferous D3 event

Ductile syn-metamorphic D3deformation is only recognized in the southern parts of the Massif Central and Massif Armoricain (Figure 10). In the southern third of the Massif Central, the Para-autochthonous Unit of Cévennes and Albigeois area experienced its first syn-metamorphic deformation at ca 340-335 Ma (e. g. Arthaud and Matte, 1974; Caron 1994; Faure et al., 2001 and therein references, Figure 10). More to the south, southward verging recumbent folds and thrusts of the Paleozoic series are dated of Late Visean-Early Namurian (ca. 325 Ma) by the syn-orogenic sediments in a flexural type foreland basin (e. g. Engel et al., 1981; Feist and Galtier, 1985). This progressive southward younging of the shearing tectonics coeval with the development of flat-lying foliations, N-S trending stretching lineation and top-to-the south displacement have been put forward for an Himalayan-style nappe stacking (Mattauer, 1975). This model accounts only for the Visean tectonic evolution of the southern outer part of the belt. However, the transition between the Early Carboniferous top-to-the-NW shearing and Middle Carboniferous top-to-the South shearing remains unclear. The D3 event is also recognized in the Vendée area of the southern massif Armoricain where a Tournaisian olistostrome is involved in southward shearing (Colchen and Poncet, 1989).

Figure 10. Middle Carboniferous D3 Event



NNE-SSW compression is active in the northern (SW England, Ardenne) and southern (Montagne Noire) forelands whereas NW-SE synorogenic extension develops in the northern part of the Massif Central. In the Massif Armoricain, left-lateral wrenching accommodates the extensional regime. Middle Carboniferous migmatites of north Cévennes, Montagne Noire, south Brittany are also pictured. A. M. B. P.: Magnetic Anomaly of Paris Basin

In the Central Armorican Domain, the Middle Carboniferous D3 event is recorded by the syn-tectonic chaotic sedimentation of the Châteaulin, Laval and Ancenis basins which are located along wrench faults (Figures 4, 10). Most of authors assume that these basins are dextral pull aparts (e. g. Darboux and Le Gall, 1988; Houlgatte et al., 1988; Le Gall et al., 1992; Rolet et al., 1994). If a Late Carboniferous dextral reworking is demonstrated by sheared sedimentary rocks and plutons (e. g. Berthé et al., 1979), a Visean dextral wrenching is not supported by data. Indeed, the opening of these basins probably begins already in Tournaisian and continues with the same characteristics in Visean. The left-lateral ductile shearing older than the Late Carboniferous dextral one is well documented for the Ancenis basin (see above section 3.2) and also described along the Lanvaux orthogneiss (Cogné et al., 1983; Faure and Cartier, 1998). Therefore, in the present state of knowledge, a syn-sedimentatry left lateral strike-slip motion controlling the sedimentation of the Châteaulin and Laval bassins would be in agreement with the whole kinematic picture of the Massif Armoricain (Figure 10). In the northern Massif Central, the D3 event corresponds to the onset of syn-orogenic extension. Since it is coeval with magmatic activity, it will be presented in the following sections 4.3 and 5.6.

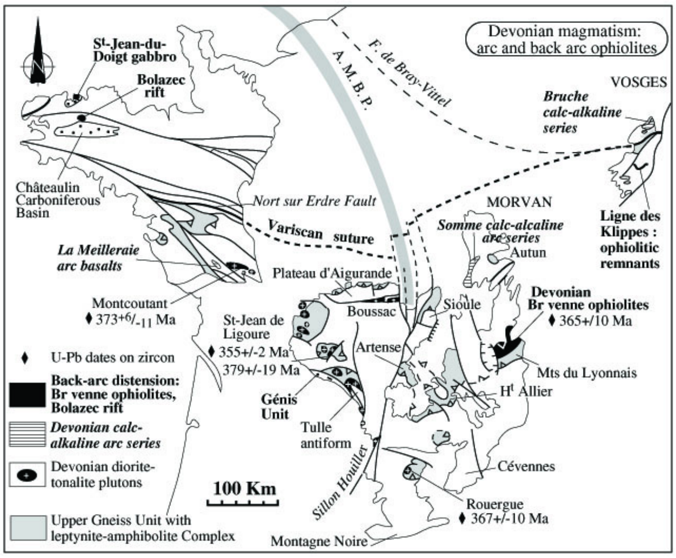
A structural outline of the Variscan magmatism

Alike all the Variscan areas, the Massif Central and Massif Armoricain are characterized by a voluminous magmatism, mainly derived from crustal melting. Several generations of granitoids and migmatites are recognized (e.g. Duthou et al., 1984). They are presented below in the chronological order with emphasis on the tectonic settings. The pre-orogenic magmatism is not discussed here. Cambrian and Early Ordovician alkaline granitoids and volcanic rocks are ductilely deformed, metamorphozed with their country rocks and included in the stack of nappes.

The Middle to Late Devonian magmatism

Although involved in the D2 and younger events, several kinds of Devonian magmatic rocks are recognized both in the North Gondwana margin and in the Central Armorican Domain (Figure 11). Conversely to the subsequent magmatic events, the Devonian one exhibits a significant mantle contribution (e. g. Pin and Duthou, 1990; Shaw et al. 1993; Pin and Paquette, 2002).

Figure 11. Synthetic map of the Devonian magmatism



Synthetic map of the Devonian magmatism with diorite arc plutons, calc-alcaline volcanic-sedimentary series (Morvan and Vendée), and back-arc related rocks: Brévenne ophiolites, Bolazec rift, St-Jean-du-Doigt gabbro, Génis greenrocks, Ligne des Klippes. Available radiometric dates are also shown.

i) Calkalcaline volcanic, volcani-clastic and plutonic rocks form the Somme series in the NE Massif Central (Figure 11). Famennian-Frasnian terrigeneous siltstone, sandstone and conglomerate with volcanic clasts are interlayered with calc-alkaline andesite and trachyte, and contains massive sulfide deposits (Bebien and Gagny, 1981; Pin et al., 1982; Delfour, 1989). The very contact is not observed, however, regional geology suggests that the Somme series unconformably overlies D1 migmatites and metamorphic rocks. A similar volcaniclastic series is recognized in the Vosges (e. g. Ikene et al., 1991; Rizki et al., 1992). In Vendée, the Middle Late Devonian basalts of la Meilleraie (Figure 11), overlying Eifelian-Givetian terrigeneous rocks, crop-out in the core of the Chantonnay syncline (Wyns et al., 1989). The calc-alkaline mineralogy and the arc tholeiite geochemical signature of those volcanic rocks indicate that they belong to a magmatic arc related to subduction zone (Thiéblemont and Cabanis, 1986).

ii) Arc plutons such as diorite, tonalite and gabbro, crop-out as twenty-kilometer scale plutons widespread in southern Massif Armoricain and western Massif Central (Figure

11). Most of the plutons are laccoliths that exhibit the same solid-state flat-lying foliation and NW-SE trending lineation than their metamorphic host rocks showing that both rocks experienced the D2 event. U/Pb zircon ages as old as 370-380 Ma are measured in the Limousin (Bernard-Griffith et al., 1985, Pin and Paquette, 2002), in Vendée (Cuney et al., 1993, Bertrand et al., 2001) and Rouergue (Pin and Piboule, 1988). The youngest ages around 360-350 Ma attest for an isotopic resetting during the Early Carboniferous D2 tectonics. The calc-alkaline petrology and geochemistry of the diorites led many authors (e. g. Didier and Lameyre, 1971; Bernard-Griffith et al., 1985; Peiffer, 1986; Shaw et al., 1993) to interpret these rocks as markers of a north-dipping subduction zone. A comprehensive view in terms of arc-back-arc system related to a southward dipping subduction has been proposed (Faure et al., 1997, see section 5. 4).

Because of the same Late Devonian age and calc-alkaline geochemistry of the volcanic series and the diorites, we suggest that all these rocks formed in the same magmatic arc. The diorite-tonalite plutons and the volcanic-sedimentary rocks represent the deep and shallow levels of the arc respectively. An objection might arise due to the large spatial distribution of the dioritic plutons. However, it is worth noting that the present width does not correspond to the Devonian one since the diorite plutons are involved into D2 and D3 tectonics, thus they are not rooted in their present outcroping site. Moreover, the Late Carboniferous extensional tectonics (see section 5.7) also contributed to enlarge the distance between all the plutons.

iii) Ophiolites are recognized in eastern Massif Central in the Brévenne area. Oceanic rocks emplaced in Middle and Late Devonian as shown by the 365+/-10 Ma U/Pb age on zircon from acidic volcanics coeval with the mafic magmatic rocks (Pin and Paquette, 1998). Remnants of Devonian mafic magmatic rocks with a tholeiitic signature and deep sea sedimentary rocks (siliceous shales, radiolarian cherts, rare limestone) are found in South Vosges, in the "Ligne des Klippes" (Schneider et al., 1990). The Devonian mafic rocks and siliceous sedimentary rocks of the Génis Unit attest also for the existence of a Middle to Late Devonian oceanic basin. These Devonian rocks are distinct from those of the UGU which experienced the Silurian high pressure metamorphism. Devonian tholeitic and alkali basalts and dolerite crop out around the St-Jean-du-Doigt gabbro or in close association with siliceous sedimentary rocks in Bolazec rift (Figures 4, 11; Cabanis et al., 1982).

The pre-Late Visean magmatism

An aluminous magmatism, widespread in the north part of the Massif Central and more scattered in the Massif Armoricain took place before Late Visean (Figure 8). The biotite-cordierite Guéret monzogranite which is taken as the type lithology yields a Rb/Sr whole rock age of 356+/-10 Ma (Berthier et al., 1979). The Early Visean age (350-340 Ma) of these plutons complies with stratigraphic constraints since the Late Visean volcanic-terrigeneous "Tufs anthracifères" formation unconformably covers the Guéret massif. In the Limousin area, structural studies dealing with the Guéret-type granitoids show that they exhibit magmatic to solid state fabrics with a SE-NW trending mineral lineation (e. g. Bouchez and Jover, 1986; Roig et al., 1996, 1998). The deformation is dated around 346+/-4 Ma by 40Ar/39Ar method on biotite (Roig et al., 1996). The NW-SE trend consistency between the metamorphic lineation in the host rocks and the magmatic lineation in the plutons suggests that the same strain field was present when the Guéret-type plutons emplaced. Therefore, the pre-Late Visean magmatism can be considered as a late increment of the D2 event.

In the Massif Armoricain, Early Carboniferous granites crop out along the South Armorican Shear Zone (e. g. Pontivy, 344+/-8 Ma); in Central Brittany (Huelgoat, 336+/-13 Ma), or in Léon (St-Renan, 330-340 Ma; e. g. Le Corre et al., 1991). The crustal source of this pre-Late Visean magmatism is well acknowledged, but its structural setting and geodynamic significance remain poorly documented. Crustal thickening due to the D2 event appears as a likely mechanism to trigger the melting.

The Late Visean Magmatism

This magmatism, well developed in the northern and western parts of the Massif Central (Figures 2, 10), consists in aerial products with lava flows, ignimbrites, pyroclastic deposits, called “Tufs anthacifères series”, rhyolitic to dacitic dykes, hypovolcanic microgranites and coarse grained red granites. Geochemistry indicates that crustal melting was triggered by heat input from the mantle. Moreover, a mantle contribution to the source of magma is also likely (Pin and Duthou, 1990). The lower crust or upper mantle thermal input is responsible for a resetting of the isotopic systems. The 40Ar/39Ar ages of ca 335 Ma widespread in the pre-Visean metamorphic rocks of the northern Massif Central are due to such an overprint (Bruguier et al., 1998;

Faure et al., 2002). The structural analysis of dykes indicates that NW-SE stretching of the crust controls their emplacement. This deformation, related to the early stage of orogenic collapse,is coeval with the D3 event (Faure, 1995; cf. section 5).

In the northern Cévennes, the Para-autochthonous Unit is underlain by migmatitic gneiss called the pre-Velay migmatites (Faure et al., 2001; Figure 10). The anatexis is dated between 333 and 324 Ma by the chemical U/Th/Pb method on monazite (Be Mezème et al., 2002). Similar ages are yielded by the migmatites and cordierite granites of the Montagne Noire Axial Zone (Figures 2, 3). The granitic-migmatitic dome that overprints southward overturned kilometer-scale Visean-Namurian recumbent folds, remains a controversial structure (cf. details in Soula et al., 2001). Gneiss, migmatites and granitoids exhibit a ENE-WSW (N50-70E) trending stretching lineation parallel to the dome long axis. This gneiss dome has been variously interpreted as : i) a transcurrent shear zone (Nicolas et al., 1977; Echtler and Malavieille, 1990); ii) an anticlinal stack (Mattauer et al. 1996, Matte et al., 1998); iii) a diapir (Schuilling, 1960; Faure and Cottereau, 1988); or iv) a metamorphic core complex (Van den Driessche and Brun, 1991-92). Even if ductile normal faulting coeval to the Late Carboniferous extension is clearly established along the northern side of the dome, an extensional setting for the crustal melting is not demonstrated yet. Pre-Velay migmatites are also developed but not well characterized in other parts of the Massif Central such as in South Millevaches. The migmatites widespread all along the south coast of the Massif Armoricain, in Vendée and Anticlinal de Cornouailles probably belong also to the same Late Visean event (Figures 4, 10).

The Namurian-Westphalian magmatism

This ca 325-310 Ma event corresponds to the main period of magma production. Porphyritic monzogranites and biotite-muscovite leucogranites form the two main types of plutons (Didier and Lameyre, 1971). The two types were derived from different magmas, but field relationships and geochronology show that they were emplaced coevally. Petro-structural and AMS studies of numerous Namurian-Westphalian plutons show that these bodies are characterized by a conspicuous NW-SE trending mineral, and stretching lineation. The same trend is also inferred from contact minerals in the pluton host rocks. In the Limousin, leucogranite plutons are often bound by ductile normal faults which also exhibits NW-SE trending hot slickenlines. This structural pattern is interpreted as the consequence of the syn-orogenic extensional tectonics of the Massif Central (Faure, 1995). In the Massif Armoricain, the Namurian-Westphalian plutonism is also widespread but dominantly located along hundred kilometers-scale dextral strike-slip faults (Figure 3). The South Armorican Shear Zone is worldwide famous since S-C structures have been first described there (Berthé et al., 1979).

The Stephanian magmatism

In the lower crust, the 310-290 Ma time is that of emplacement of the cordierite granite-migmatite Velay dome (Figure 2 , Malavieille et al., 1990; Ledru et al., 2002 and enclosed references). This huge thermal anomaly is probably the result of the interference between lithosphere-scale tectonics and asthenosphere-scale diapiric ascent. The Velay dome is bounded to the north by the Pilat detachment fault which is characterized by N-S to NNE-SSW slickenlines. Moreover, numerous dykes, acidic tuf, ash layers and more rarely alkaline basalts associated with terrigeneous formations crop out in most of the coal basins (cf. Faure, 1995 for details). It is now well accepted that the Late Carbonifeous magmatism occurred during the late orogenic extension of the Variscan Belt (cf. section 5.7).

A possible geodynamic scenario

The above presented data allow us to discuss a geodynamic evolution model. Several models involving the Massifs Central and Armoricain have been already proposed (e. g. Matte, 1986; Paris and Robardet, 1990; Robardet et al., 1994; Tait et al., 1997; Cocks, 2000; Robardet, 2003). Presently, two types of scenario are invoked. 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 the later model, an Early Paleozoic cycle, from Cambrian to Early Devonian, is related to the opening and closure of the Medio-European Ocean and correlatively the drifting and rewelding of Armorica to Gondwana. Then, a second orogenic cycle, from Middle Devonian to Carboniferous, accounts for the closure of the Rheic Ocean and the collision of Gondwana and Laurussia. The structural and magmatic data presented in sections 3 and 4 support the polycyclic model developed in the following.

The Early Ordovician breaking of the north Gondwana margin

From Early Cambrian to Ordovician, the Massif Central and Massif Armoricain belong to Gondwana. The Central Armorican and Léon Domains are pieces of two micro-continents progressively drifted from the North Gondwana margin. The numerous alkaline granitoids found in the Para-autochthonous Unit, LGU and IGU (e. g. Duthou et al., 1984) and also in Léon (Tréglonou, Plounevez-Lochrist) or in Central Armorica (Brest, Lanvaux or Douanenez) argue for an Early Ordovician rifting. In the Para-autochthonous Unit, alkaline mafic volcanics (locally with pillow lavas), diabase dykes, gabbro intrude the grauwacke-pelite series (Pin and Marini, 1993). In the UGU, the bimodal magmatism of the leptynite-amphibolite complex is interpreted as the consequence of crustal thinning and oceanisation. The oceanic basin, is variously called South Armorican Ocean (Paris and Robardet, 1990), or Massif Central Ocean (e. g. Matte, 1986). Since this domain probably extends farther east up to Bohemia, the name of “Medio-European Ocean” will be used here. The width of this ocean is presently unknown. Since Ordovician faunas appear quite similar between N. Gondwana and Armorica, the existence of the Medio-European Ocean is questionned (e. g. Robardet, 2003). However, a narrow Medio-European Ocean did not act as a significant paleobiogeographic barrier. Indeed, as discussed in the next section, the Medio-European ocean closed in Late Silurian. Thus, the duration of this oceanic domain lasted less than 80 Ma from Early Ordovician to Late Silurian, and its width can be assumed whatever the opening and closing rates, ranging between 500 and 1000 km. The resemblance of Cambrian facies between Montagne Noire-Rouergue and Normandy although located in N. Gondwana and Armorica respectively can be easily understood since at that time, the two areas still belong to the same Gondwana continent. Paleomagnetism could help to solve this question, however, up to know all attempts show remagnetization of those Early Paleozoic series. As a matter of fact, the Ordovician rifting led to the formation of continental stripes such as Avalonia, Armorica, Léon drifted from Gondwana.

The Silurian subduction and closure of the Mid-European Ocean

On the basis of available dates of the high-pressure metamorphism (Figure 6 , section 3), the Medio-European Ocean closed in Late Silurian by 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 (for a discussion of this problem, see Faure et al., 1997). The 440 +/-12 Ma age of the high pressure metamorphism in the Léon Domain (cf section 2. 3), suggests that continental subduction of this microcontinent might have occurred in Early Silurian, i. e., earlier than the collision of the North Gondwana Margin with the Central Armorican Domain. However, the date of collision between Léon and Armorica is not settled yet.

The existence of the Mauges basement nappe overlying the high-pressure Champtoceaux Complex in the South part of the Massif Armoricain (Figures 3, 4) supports a collision model. However, in the Central Armorican Domain, the lack of any disturbance in the Silurian-Devonian sedimentation and the Famennian unconformity observed near Angers (Lardeux, 1969) shows that this domain did not experienced any deformation before Late Devonian. The deep sea origin of Silurian radiolarite and arc derived magmatic rocks recovered as olistoliths in the St-Georges-sur-Loire olistostrome, led Cartier et al., (2001) to consider that a rift basin (called the Layon Rift) separated Armorica from an island arc installed upon a continental basement : the Mauges microblock. The complete closure of the Layon rift will occur only in Late Devonian-Early Carboniferous during D2 event. Therefore, in the Massif Central-Massif Armoricain area, the Early Paleozoic tectonics between Armorica and Gondwana corresponds to a continental subduction and collision of the N. Gondwana margin below an island arc.

The Devonian exhumation and anatexis of the eo-Variscan HP rocks

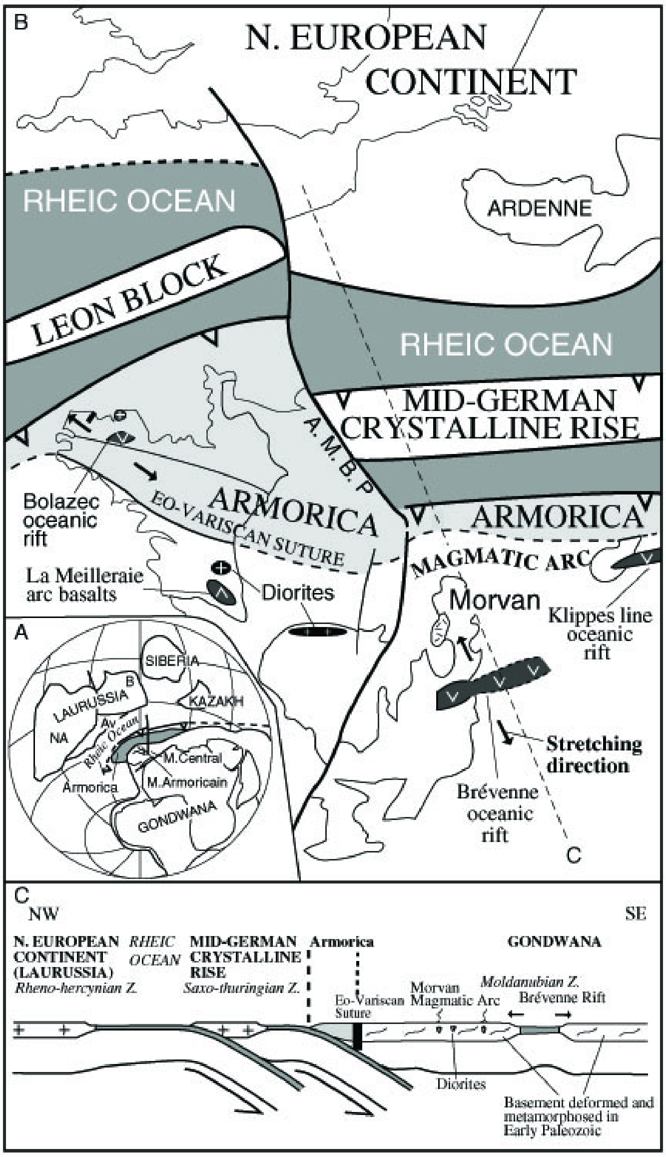
Subduction of oceanic and continental rocks is followed by their exhumation in Early to Middle Devonian, around 390-385 Ma. The D1 event (section 3.1) coeval with pervasive retrogression of the high-pressure rocks of the UGU and migmatisation of the pelitic parts occurred at that time.

The exhumation mechanism is not well understood yet. A buoyancy driven model accommodated by southwestward thrusting and normal faulting (e. g. Chemenda et al., 1995) is a likely mechanism to be tested by further works.

The Middle-Late Devonian active margin of N. Gondwana

According to faunal distribution, paleomagnetism and geodynamic reconstructions, (e. g. Tait et al., 1997; Paris and Robardet, 1990; Robardet et al., 1994; Matte, 2001; Robardet, 2003) in Late Silurian-Early Devonian, an oceanic basin called «Rheic Ocean», of ca 1500-2500 km width, separated the North Gondwana margin from Laurussia (Figure 12 A). The Middle-Late Devonian magmatic arc and back-arc basins observed both in N. Gondwana margin and Central Armorican Domain show that at that time these two paleogeographic and tectonic domains already behaved as a single plate. The Late Devonian geodynamic setting is the southward subduction and subsequent closure of the Rheic Ocean that separated Laurussia (i. e. North America-Baltica-Avalonia already welded by the Early Paleozoic Caledonian Orogeny) and Gondwana-Armorica, also rewelded by the Early Paleozoic Variscan Orogeny, to the North and South respectively (Figure 12).

Figure 12. Reconstruction of the Late Devonian paleogeodynamics



A: Global reconstruction showing the active margin of Gondwana (in Laurussia, Av: Avalonia,

B: Baltica, NA: north America; simplified from Robardet, 2003). B: Close up of the study area.

C: Corresponding lithosphere scale cross section.

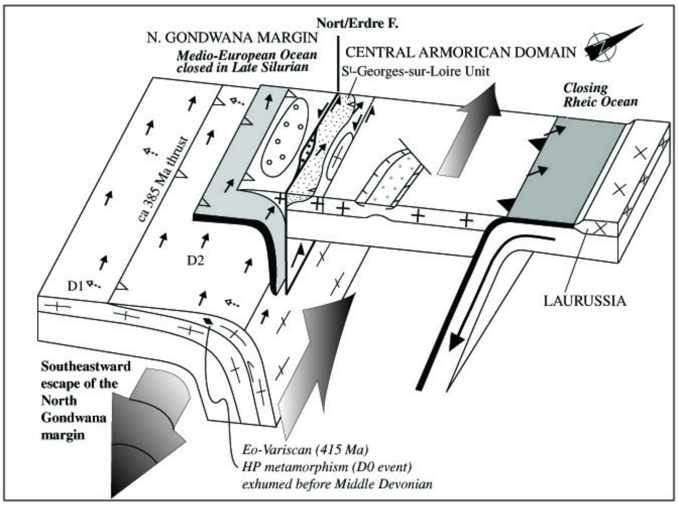
The Late Devonian-Early Carboniferous closure of the Rheic Ocean

The closure of the Rheic Ocean will control the development of the D2 tectonics (see section 3.2, Figure 8). A general understanding of the Massifs Central and Armoricain tectonics requires to take into consideration the tectonics of SW England. On the basis of 40Ar/39Ar dates on metamorphic amphibole in the thrust sole, the Lizard ophiolitic nappe emplaced to the North in Late Devonian (ca 366-360 Ma, e. g. Le Gall and Darboux, 1986; Holder and Leveridge, 1986; Sandeman et al., 1995; Cook et al., 2002). Seismic profiling through the English Channel shows that the Lizard ophiolitic nappe is rooted into the Channel gravimetric and magnetic anomaly that can be considered as the Rheic suture (Figure 8). In turn, the ophiolitic nappe is overthrust by basement rocks belonging to the Léon Block (Le Gall, 1990). The Lizard ophiolite is sometimes rapported to the Rheno-Hercynian basin which, in Germany, opened in Mid Devonian along the trace of an Ordovician precursor : the Rheic Ocean assumed to be closed in Early Devonian (Franke, 2000). Along the SW England-Massif Armoricain transect, the available data do not support the existence of such an Early Devonian suture overprinted by a Late Devonian one. Therefore, in the present state of knowledge, the Late Devonian-Early Carboniferous closure of the Rheic ocean appears as the simplest interpretation. East of the Paris Basin Magnetic Anomaly (AMBP), a similar N-NWward directed stack of nappes is recognized along the "Nord de la France" seismic line south of the Ardenne Carboniferous Variscan thrust front (Cazes et al., 1985; Figure 8). The suture zone recognized east of the Bray fault might be correlated to the Rheic suture. Nevertheless, a comprehensive discussion of the whole system is beyond the scope of this paper.

The tectonic significance of the NW-SE trending D2 stretching lineation with top-to-the-NW shearing is one of the most puzzling problem of the Paleozoic evolution in the French massifs. Models involving a progressive rotation of shearing trends from transverse to longitudinal to the belt have been proposed (e. g. Brun and Burg, 1982; Burg et al., 1987). However, the Middle to Late Devonian distension is not taken into account. Moreover, the 20 Ma gap between the top-to-the-SW (D1) and top-to-the-NW (D2) shear events is hardly compatible with the model of a progressive and continuous rotation of shear trends. An extensional setting has also been invoked (Mattauer et al., 1988) but this interpretation is based on a misunderstanding between the D2 lineation and the Namurian-Westphalian stretching direction associated to the synconvergence extensional tectonics (Faure, 1995; cf section 3.2). Although similar in trend and often in kinematics, these two diachronous lineations differ by their P-T conditions of deformation. Moreover, the extensional model with a top-to-the-NW shearing cannot account for the tectonic superposition of the Thiviers-Payzac Unit above the Upper Gneiss Unit. In the South Massif Armoricain, the overthrust of the Mauges nappe upon the Upper Gneiss Unit precludes a northerly origin of the Thiviers-Payzac Unit from the Central Armorican Domain. Northwestward thrusting, as suggested by Bouchez and Jover, (1986); or Friedrich et al., (1988) complies with the prograde middle pressure/middle temperature metamorphism and the per-aluminous Guéret-type magmatism (section 4. 2).

A lithosphere-scale model linking the top-to-the-NW shearing on flat-lying foliations in the Massif Central and left-lateral wrenching in the Massif Armoricain is presented here (Figure 13). During the closure of the Rheic Ocean and subsequent collision, the lithosphere of the North Gondwana margin is extruded to the Southeast. The Silurian Nort-sur-Erdre suture is reactivated as left-lateral wrench fault, and the St-Georges-sur-Loire Unit is overthust to the NW. This boundary accounts for the lack of widespread flat-lying ductile deformation in the Central Armorican Domain and the development of left-lateral wrenching in the St-Georges olistostrome and Lanvaux Unit. In the Central Armorican Domain, the deformation is not distributed penetratively in the whole crust but instead is localized along belt-parallel strike-slip faults. This rigid behaviour of the Central Armorican Domain may be a consequence of the Neo-Proterozoic (or Cadomian) orogeny responsible for a general strain hardening of the Central Armorican crust. Conversely, the crust of the North Gondwana margin which never experienced the Neo-Proterozoic tectonics, but was already heated by the Devonian magmatism deforms penetratively.

Figure 13. Late Devonian-Tournaisian D3 geodynamics



Interpretative block diagram of the Late Devonian-Tournaisian D3 geodynamics in the Massif Central and Massif Armoricain. The top-to the-NW shearing in the North Gondwana Margin is coeval with the left-lateral wrenching in the Central Armorican Domain while the Rheic Ocean is closing by southward subduction. The top-to-the-NW ductile deformation is interpreted as an effect of a SEward escape of the North Gondwana Margin during the closure of the Rheic Ocean and subsequent Gondwana-Laurussia collision.

The Middle to Late Carboniferous intracontinental tectonics

After the Tournaisian collision, intracontinental tectonics characterizes the Middle Carboniferous evolution of the Variscan Belt. The time interval from 340Ma to 290 Ma can be divided into a first period during which compression and extension regimes are both active and a second one during which extension controls the tectonic activity.

i) The Late Visean is a key period since the orogenic core, i. e. the central and northern parts of Massif Central or the entire Massif Armoricain, is characterized by the onset of syn-orogenic extension whereas, D3 compression is still going on both in the south Massif Central and in the northern foreland of SE England orArdenne (Figure 10). In the northern foreland, the Middle Carboniferous tectonics are characterized by northward directed thrusts with hundred kilometers displacement as shown by seismic lines (Cazes et al., 1985; Raoult and Melliez, 1987; Le Gall, 1990 and enclosed references). Those nappes are rooted in the eastern equivalent of the Rheic suture which is reworked by the dextral Bray fault.

The Late Visean period corresponds also to a huge magmatism that spreads out from north Limousin to south Vosges (Figures 2, 10). This magmatism is a direct consequence of the Early Carboniferous stage of crustal thickening (e. g. Pin and Duthou, 1990). In order to account for the high temperature magmatism and the mantle contribution, a lithospheric delamination model has been speculated (Faure et al., 2002).

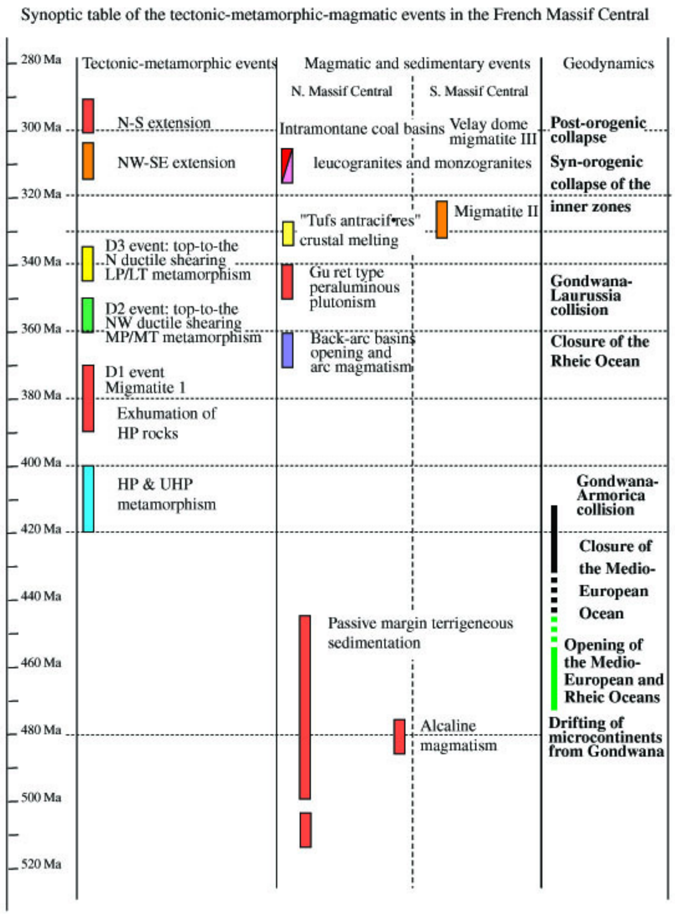
ii) Extensional tectonics develops in Late Carboniferous (Namurian-Stephanian). As in most orogens, the evolution of the Variscan Belt ends with extensional tectonics that accommodates crustal re-equilibration. In the Massif Central, two stages have ben distinguished (e. g. Faure and Becq-Giraudon, 1993; Burg et al., 1994; Faure, 1995 and enclosed references). The syn-orogenic (325-310 Ma) stage is represented by NW-SE stretching as shown by the development of planar and linear fabrics developed in syntectonic plutons. As discussed in the previous section, the NE-SW trending acidic dykes of the Tufs Anthracifères in the North part of the Massif Central show that extensional tectonics initiated earlier in Late Visean.

The late orogenic stage (310-290 Ma) is associated to N-S to NNE-SSW maximum stretching of the crust responsible for the opening and infill of intramontane coal basins either by half-grabens or pull apart (for further details, see Faure, 1995). The Late Carboniferous high temperature granulites scavenged by Tertiary volcanoes that form the layered lower crust observed in the seismic lines are also the result of the syn-extension thermal input (Pin and Vielzeuf, 1983).

Conclusion

In spite of still disputed points, the Massif Central and Massif Armoricain are amongst the most studied places of the Middle Europa Paleozoic areas. The main tectonic, metamorphic, magmatic and sedimentary events are dispayed in chronological order in a synthetic table (Figure 14). The above presented scenario with two rifting-subduction-collision cycles accounts for the available lithologic, structural, metamorphic, magmatic and geochronologic data. Although often compared, the Paleozoic Variscan Belt significantly differs from the Himalayan one in the sense that collision is not restricted to two large continental masses such as India and Tibet but involves also several microcontinents. A modern analogue of such a complex pattern of island arcs, microcontinents and marginal seas between two converging continents could be found in the SW Pacific between SE Asia and Australia. One of the most striking features is that the two main ductile and synmetamorphic events, called here D1 and D2, are separated by about 25 Ma during which intra- or back arc rifting took place. The southward directed recumbent folds and thrusts well documented in the South Massif Central develop in Middle Carboniferous during the D3 event, do not appear as representative of the lithospheric convergence at the scale of the whole belt. Indeed, in the present orientation frame, the southward subduction of the Rheic Ocean below the northern margin of Gondwana is the major geodynamic feature of the Variscan orogeny. Lastly, conversely to the Alpine Collision Belt, the Variscan Belt is caracterized by a voluminous crustal melting giving rise to migmatites and plutons. Comparisons with the other segments of the same belt, such as Iberia or Bohemia, and even with coeval orogens such as Appalachians or Urals, would provide new insights and tests for this model.

Figure 14. Synoptic table



Synoptic table of the tectonic, metamorphic, magmatic and sedimentary events recorded in the Variscan French Massif Central and their interpretative geodynamic setting.

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