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Abstract. The Variscan French Massif Central experienced two successive stages of extension from Middle Carboniferous to Early Permian. In the northern Massif Central, the first stage began in the late Visean, immediately after nappe stacking, and is well recorded by Namurian-Westphalian synkinematic plutonism. The Middle Carboniferous leucogranites widespread in the NW Massif Central (Limousin and Sioule area) were emplaced within a crust extending along a NE-SW direction. At the same time, the hanging wall or "Guéret extensional allochton" moved toward the SE. Several examples of the synextensional plutonism are also recognized in central Limousin: Saint Mathieu dome, La Porcherie, and Cornil leucogranites. These examples illustrate the relationship between granite emplacement and crustal scale deformation characterized by NW-SE stretching and NE-SW shortening. In the central and southern Massif Central (Cévennes, Châtaigneraie, and Margeride areas), plutonism is dominantly granodioritic and exhibits the same structural features: NW-SE maximum stretching and overturning to the SE. Middle Carboniferous (Namurian-Westphalian) extension was parallel to the Variscan belt both in the Massif Central and southern Armorican area. This extensional regime was active from the late Visean in the north,while compression dominated in the southernmost domains (Montagne Noire and Pyrenées). The second extensional stage occurred from Late Carboniferous to Early Permian. This event was responsible for the opening of intramontane coal basins, brittle deformation in the upper crust, and ductile normal faulting localized on the margin of cordierite granite-migmatite domes. Data from the coal basins show that the half-graben is the dominant structural style, except for basins located along submeridianal left-lateral faults which have pull-apart geometries. Late Carboniferous extension occurred along the NE-SW direction. The NE-SW maximum stretching direction can be found in the whole Massif Central but is more developed in the eastern part. The extensional direction is transverse to the general trend of the belt, and top-to-the-NE shearing is dominant. Correlations of these two extension directions with neighboring Variscan massifs are discussed.

Introduction

Late orogenic extension is presently recognized in most collisional belts. Crustal thickening, which is caused by nappe stacking and is responsible for partial melting at deep levels, induces gravitational instability. According to mass balance deductions from the peripheral molasse basins and the uplift rate, erosion alone appears unable to denude the main part of the upper crust and to exhume the deepest parts of the orogen [*Thompson and Ridley*, 1987; *Dewey*, 1988]. Extension removes the instability by reducing the thickness of the crustal root and allowing the continental crust to recover a standard thickness of about 30 km.

The Variscan Belt of Western Europe is interpreted as a collisional belt between the northern Laurussia and southern Gondwana continents [*Dewey and Burke*, 1973, *Matte*, 1986]. In the French Massif Central, which belongs to Gondwana, the Variscan orogenic events range from Late Silurian (circa. 410 Ma), which is the average age for the high-pressure metamorphism, up to Late Carboniferous-Early Permian (ca 300 Ma) which is the deposition time of the late-orogenic, frequently coal-bearing, intramontane molassic sediments. Crustal thickening in the Massif Central is well documented [*Ledru et al.*, 1989 and references therein] by (1) south verging deep seated metamorphic nappes, (2) high pressure metamorphism, and (3) crustal melting and magmatism.

The width of similar tectonic zones is nearly 4 times larger in the Massif Central than in the nearby Armorican massif. Such a sudden change, occurring within a few tens of kilometers, suggests either paleogeographic variations that are not recorded in the rock facies or differential modifications of the initial compression-related structures. The tectonic zonation seems to have been dilated in the Massif Central. Indeed, extensional tectonics due to gravity collapse of the thickened crust has been described in many places of the Massif Central, [e.g., *Mattauer et al.*, 1988; *Ménard and Molnar*, 1988; *Van den Driessche and Brun*, 1989, 1991; *Faure*, 1989; *Echtler and Malavieille*, 1990; *Malavieille et al.*, 1990; *Faure et al.*, 1990; *Faure and Pons*, 1991]. As pointed out by *Faure and Becq-Giraudon* [1993], post-Variscan extension in the Massif Central can be subdivided chronologically and structurally into two successive stages. The Middle Carboniferous (late Visean-Namurian-Westphalian, 330-315 Ma) extensional period is characterized in the north Massif Central by a NW-SE maximum stretching direction and a NE-SW intermediate axis of finite strain. It is followed by a second extensional stage in Late Carboniferous (Stephanian)-Early Permian (Autunian) times characterized by a NE-SW maximum stretching axis and a NW-SE intermediate axis. This paper aims to show the spatial superposition and the temporal succession of the two extensional regimes. New structural data and previous metamorphic, magmatic, and sedimentary data are synthetized and reinterpreted in the frame of this model.

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The Middle Carboniferous NW-SE extension

In spite of lack of Namurian-Westphalian sedimentary basins in the Massif Central, evidence for extensional tectonics of this age is found in the ductile crust by a conspicuous synmetamorphic deformation and the shape of numerous syntectonic plutons (Figure 1). In the Massif Central, two groups of Carboniferous granitoids are recognized, namely, leucogranites and granodiorite-monzogranite associations [*Didier and Lameyre*, 1969]. The former is more common in the northern Massif Central, whereas the latter is widespread in the central and southern parts. In the following, examples from several parts of the Massif Central are presented to show how Middle Carboniferous syntectonic granitoids recorded the regional extensional deformation during their emplacement.

Northern Massif Central

The Guéret extensional allochton. Ductile extension is well demonstrated in the NW part of the Massif Central, or Limousin area. Northern Limousin (Figure 2) is occupied by the Guéret massif, which consists of pre-upper Visean cordierite-bearing granitoid, migmatite, and gneiss radiometrically dated around 360 Ma by the Rb-Sr method on whole rock [*Berthier et al.*, 1979]. The granitoid and metamorphic rocks that bear a subhorizontal foliation are geometrically underlain by flat-lying mica schist and gneiss (Figure 3). To the east, the Guéret massif is sharply truncated by the Sillon Houiller fault. Due to the 60 to 70 km Stephanian left-lateral offset of this fault, the Guéret massif and underlying Chavanon series are found in the Tréban massif and Sioule metamorphic series respectively [*Grolier and Letourneur*, 1968; *Grolier*, 1971b].

The Guéret massif is surrounded by the Plateau d'Aigurande metamorphic series to the north, the Brame-Saint Sylvestre-Saint Goussaud leucogranites to the west and SW and by the Chavanon metamorphic series to the south (Figure 2). In this last area, migmatite of the Guéret massif overlies biotite-sillimanite gneiss and mica schist with a subhorizontal contact refolded by NW-SE upright folds. In other places, the boundary between the Guéret massif and the surrounding units is marked by a subvertical ductile contact. The left-lateral Marche fault connects to the west with the N-S trending Bussière-Madeleine fault, which, in turn, connects to the SE with the NW-SE right-lateral, Arrènes-La Courtine wrench fault [*Mollier and Lespinasse*, 1985; *Lespinasse et al.*, 1986]. On the Guéret side of these faults, the sense of shear is sometimes unclear because an earlier ductile fabric formed in pre-Visean times is reactivated in the Middle Carboniferous deformation. In fact, the Guéret massif appears surrounded and underlain by a kilometer scale listric surface, with vertical or high-angle dips at ground level to the west becoming progressively lower angle to subhorizontal at depth and to the east (Figure 3). The term "Guéret extensional allochton" [*Faure and Pons*, 1991] will be used in the following. The Bussière-Madeleine fault exhibits a NW-SE (N120°E to N130°E) "hot striation" marked by muscovite, quartz ribbons, and sometimes sillimanite fibers. Its present geometry indicates a normal motion, the Guéret massif being downfaulted with respect to the Brame granite. Similar NW-SE trending hot slickensides and mineral lineations occur in all the ductile faults that bound the Guéret allochton. Shear criteria consistently indicate a top-to-the-SE motion for the Guéret allochton with respect to the surrounding units.

The time of the displacement is given by the radiometric age of the syntectonic leucogranitic plutons: 318±5 Ma (Rb-Sr method on whole rock) for the Saint Sylvestre pluton [*Duthou et al.*, 1984] and 324±18 Ma (U-Pb method on zircon and monazite) for the Brame pluton [*Hollinger et al.*, 1986]. The syntectonic character of the leucogranites is observed in the field, hand specimen, and thin section by the progressive evolution at the scale of each pluton, from a mylonitic fabric in the pluton cortex to a magmatic fabric (i.e., oriented texture with weak or no plastic strain) in the core [*Mollier and Bouchez*, 1982; *Faure and Pons*, 1991]. To the west and SW, the Guéret extensional allochton is bounded by the Namurian leucogranites of Brame, Saint Sylvestre, and Saint Goussaud. This last pluton is asymmetric with a subvertical northeastern side and a gently dipping southwestern one. It has an elliptical outcrop shape with its long axis parallel to the right-lateral Arrènes fault and also to the regional stretching lineation in the host rock mica schist. The Saint Goussaud pluton intrudes the Devonian stack of nappes. The early tectonic contact between the mica schist and orthogneiss, which is parallel to the regional foliation, is refolded by SW verging low-angle axial planar microfolds. These structures are interpreted as drag folds related to the emplacement of the Saint Goussaud massif. The contact is therefore a detachment fault (Figure 3).

The Brame massif is the largest syntectonic leucogranite in northern Limousin. Structural analysis, in agreement with gravimetric data [*Audrain et al.*, 1989; *Vasseur et al.*, 1990] shows that the pluton is asymmetrically rooted to the east, below the Guéret massif, and overturned to the west-NW. Whatever its attitude, the foliation bears a N120°E to 130°E mineral and stretching lineation. The present boundaries of the Brame pluton are the Nantiat and Bussières-Madeleine normal ductile faults to the west and east, respectively. In both cases, the leucogranite exhibits a mylonitic fabric with S-C structures. Hot slickensides on the C surface are parallel to the NE-SW stretching lineation. The relative displacement corresponds to a rise of the Brame pluton with respect to the Guéret massif and the west Limousin metamorphic series. Inside the pluton, magmatic structures formed before full crystallization of the magma [e.g. *Hutton*, 1988; *Paterson et al.*, 1989] are parallel to the mylonitic ones. In particular, the mineral lineation exhibits the same NW-SE trend whatever its presolidus or postsolidus origin.

The Plateau d'Aigurande metamorphic series. Ductile extensional tectonics of Namurian-Westphalian age, related to the SE motion of the Guéret allochton, were first described in the Plateau d'Aigurande metamorphic series and the syntectonic leucogranites [*Faure et al.*, 1990; *Dumas et al.*, 1990]. The Plateau d'Aigurande is an antiformal stack of pre-Visean nappes [*Quenardel and Rolin,* 1984]. The WSW-ENE trending antiform is due to the emplacement of several leucogranite plutons (e.g., Crozant, Measnes, Orsennes, and Crevant) dated around 312 Ma by the whole rock Rb-Sr method [*Petitpierre and Duthou*, 1980; *Rolin et al.*, 1982]. The shape of the Plateau d'Aigurande plutons is characterized by a downward tail pointing to the SE, eccentric to the south, and by a flat cap with recumbent peripheral lobes. Such a shape is

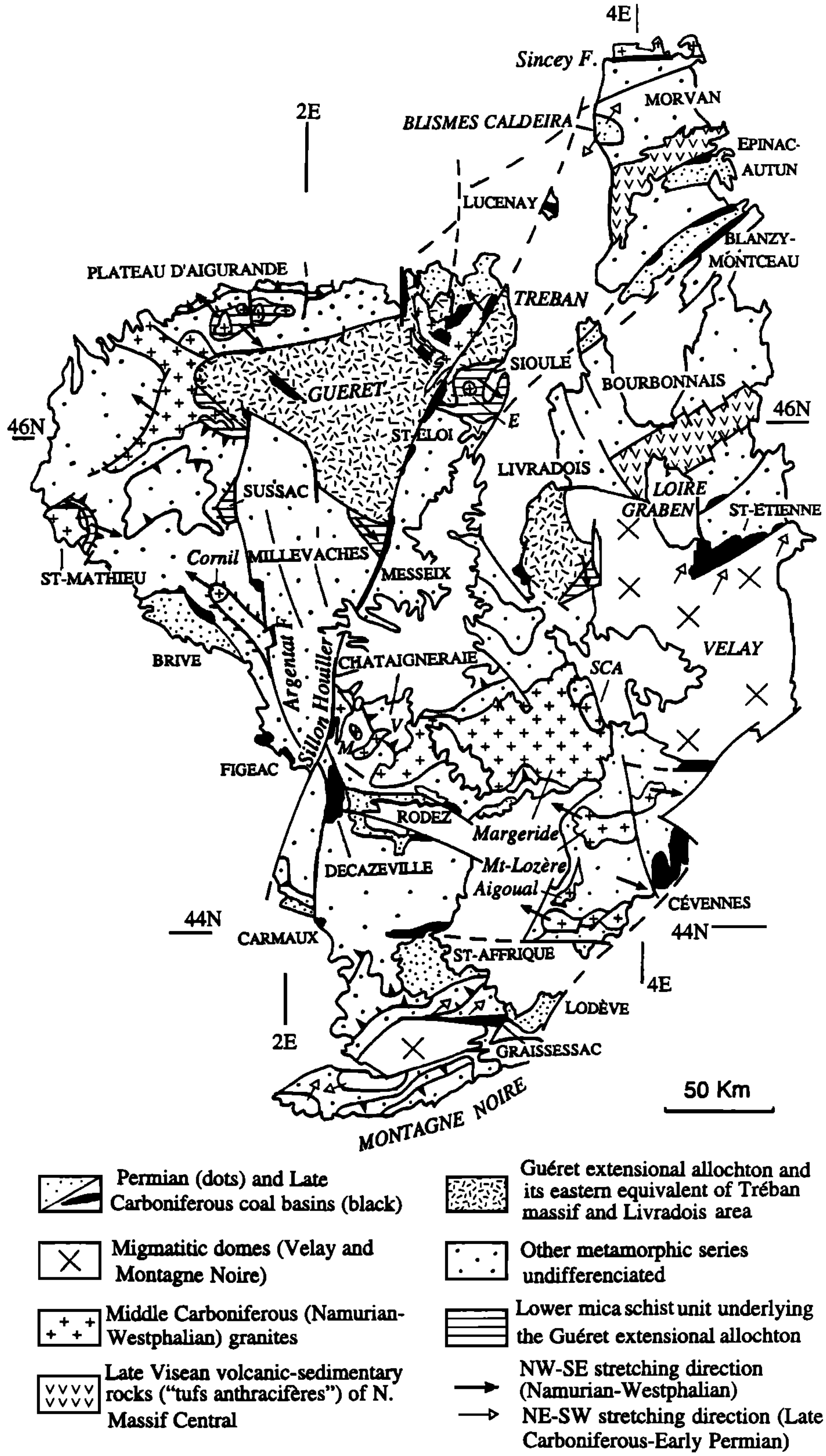

Figure 1. General map of the French Massif Central with emphasis on the Carboniferous extensional structures. Abbreviations are E, Echassières; SCA, Saintt Christophe d'Allier; V, Veinazès; and M, Marcolès.

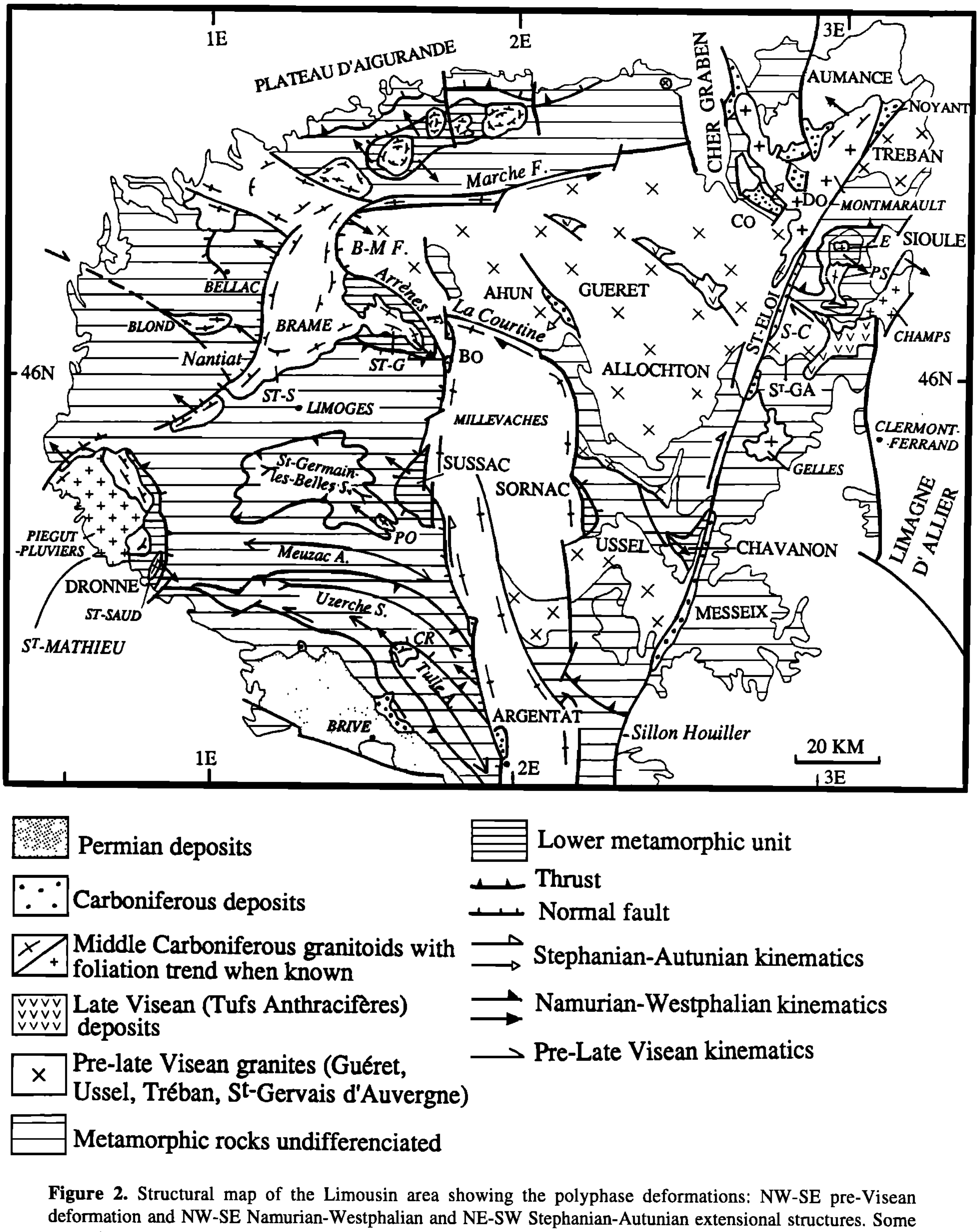

Figure 2. Structural map of the Limousin area showing the polyphase deformations: NW-SE pre-Visean deformation and NW-SE Namurian-Westphalian and NE-SW Stephanian-Autunian extensional structures. Some early thrusts are reactivated as normal faults. Granitic plutons are ST-G, Saint Goussaud, ST-S, Saint Sylvestre; PO, Porcherie; CR, Cornil; E, Echassières; PS, Pouzol-Servant; ST-GA, Saint Gervais d'Auvergne. B-MF is Bussières-Madeleine normal fault. S-C is Sainte Christine fault. Coal basins are Co, Commentry; Do, Doyet; Bo, Bosmoreau.

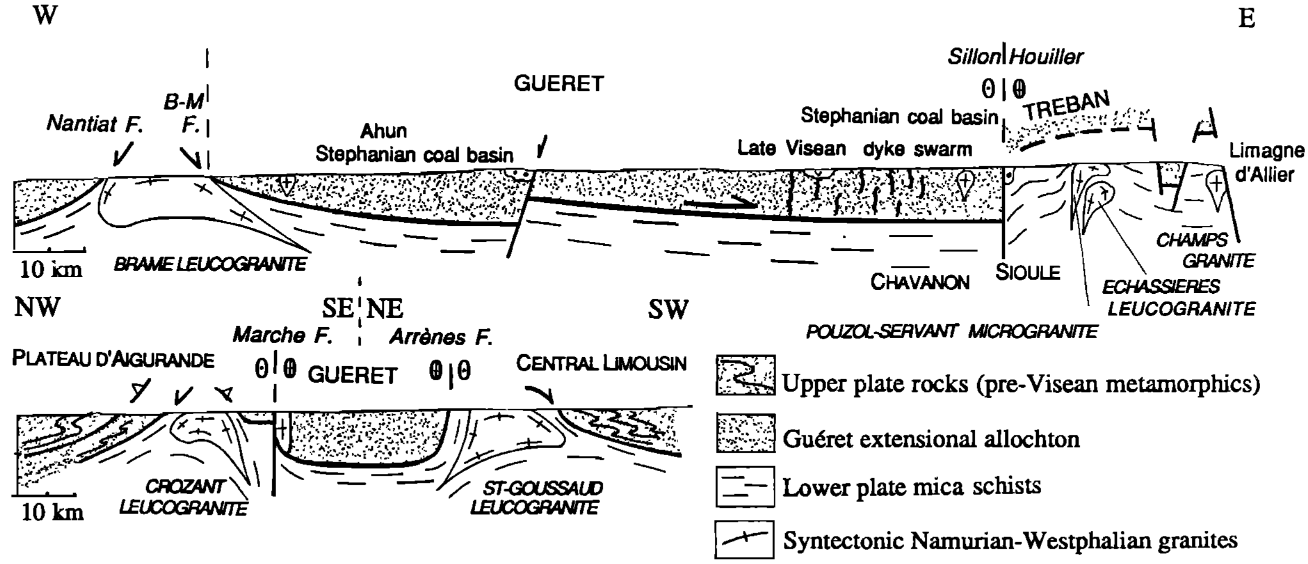

Figure 3. Cross sections through the Guéret extensional allochton.

in agreement with vertical shortening as the cause of the flattened top of the pluton, as is to be expected for magmatic bodies emplaced within an extending crust. The leucogranites have oblique tails rooted at about 3-4 km from the Marche fault, and they are overturned to the NW. The NW-SE direction that appears to control the upper flow direction of the leucogranite is also the regional direction of maximum stretching in the host rock.

The northwestern margin of the plutons is locally mylonitized. S-C relationships along the N120°E trending stretching lineation in the mylonite indicate a downward motion (to the NW) of the host rock with respect to the granite. A similar motion is shown in the contact aureole by asymmetric biotite pressure shadows around garnet and shear bands and also in the mica schist-gneiss host rock even when contact metamorphism is absent. The same NW-SE stretching lineation is observed in the oriented leucogranite and its mylonitic cortex, in the contact aureole, and in the mica schist and gneiss country rocks forming the lower unit (Figure 2) [*Quenardel and Rolin*, 1984; *Faure et al.*, 1990]. Conversely, the upper unit of the Plateau d'Aigurande metamorphic series, which consists of gneiss, amphibolite, and migmatite, exhibits a Devonian NE-SW stretching lineation [*Boutin and Montigny*, 1993]. However, this upper unit is devoid of the NW-SE ductile deformation related to the Namurian-Westphalian extension. Early thrusts are reworked as "detachment faults." Along the northern flank of the antiform, in the detachment hanging wall, the Devonian foliation is folded into post folial folds, overturned to the NW, that are interpreted as drag folds related to the northwestward decollement of the upper plate during extension (Figure 3). In the footwall, kinematic analysis along the NW-SE lineation shows a divergent motion away from the antiform axis, namely, top-to-the-NW shearing and top-to-the-SE shearing in the northern and southern limbs, respectively [*Faure et al.*, 1990]. This extensional ductile deformation is coeval with a conspicuous retrogression of the mica schist-gneiss lower unit. Most of the shear criteria are marked by chloritized micas or retrogressive shear bands. This event is recorded by K-Ar measurements on hornblende which provide ages between 330 and 300 Ma [*Cantagrel*, 1973].

The Chavanon and Sioule metamorphic series. The Chavanon series and its eastern equivalent, the Sioule series, are characterized by an inverted metamorphic zonation [*Grolier*, 1971a]. From top to bottom, the subhorizontal metamorphic rocks consist of cordierite granite, (Guéret and Tréban granites respectively to each series), migmatite, biotite-sillimanite gneiss, two-mica-sillimanite paragneiss, and biotite-muscovite ± staurolite mica schist (Figure 2). The biotite-sillimanite gneiss and two-mica paragneiss boundary is interpreted as a thrust surface. The same polyphase evolution is observed in both areas. The oldest deformation is characterized by NE-SW (N30°E-60°E) trending mineral and stretching lineations and intrafolial folds. At the southern end of the Sioule area, the metamorphic foliation makes contact with the vertically foliated Saint Gervais granodiorite by the right-lateral ductile wrench fault of Sainte Christine [*Belin*, 1981]. The ductile deformation is dated as pre-Visean by the unconformity of late Visean volcanic sedimentary rocks of the "Tufs anthracifères" formation [*Grolier*, 1971a; *Vennat*, 1982]. The right-lateral wrench at the southern boundary of the Chavanon series cannot be dated since late Visean rocks are lacking. The flat-lying foliation of the Sioule and Chavanon metamorphic series also bears a NW-SE mineral and stretching lineation well developed in the lowermost mica schist sequence and in the two-mica-sillimanite paragneiss [*Grolier*, 1971a; *Feybesse and Teygey*, 1987]. The kinematics of this NW-SE deformation which is coeval to the retrogression of an earlier medium pressure-medium temperature metamorphism indicate top-to-the-SE shearing [*Faure et al.*, 1993].

The difference between the Sioule and Chavanon series is the Carboniferous magmatism. In the Sioule series, the Echassières leucogranite occupies the core of an antiform. A $^{40}Ar/^{39}Ar$ age of 308±2Ma (Namurian) on lepidolite [*Cheilletz et al.*, 1992] is in agreement with Rb-Sr whole rock age of 300-312 Ma [*Duthou and Pin*, 1987]. The Echassières pluton has been interpreted as an injected pluton filling a N60°E left-lateral pull-apart [*Gagny et al.*, 1984]. However, this model does not fit with the asymmetric shape of the pluton. To the east and SE parts of the massif, the granite foliation is flat lying (dip about 10-20°E) and concordant with the host staurolite mica schist, whereas to the west and NW, the foliation dips more steeply, about 40-60°, to the NW. In the horizontal plane, the massif has a slightly elliptical section with a NW-SE long axis. In the vertical NW-SE section plane, the pluton is rooted to the NW and overturned to the SE in agreement with the Bouguer gravimetric anomaly for this area [*Vigneresse et al.*, 1985]. Linear structures are more difficult to observe, but, as is usual in most plutons, the best developed joint set corresponds to the "cross joint" [e.g., *Balk*, 1937; *Marre*, 1982], which is the plane normal to the stretching lineation. In the Echassières massif, most of the joints (aplitic dykes, quartz veins, and ore bearing veins) are oriented N10°E to N30°E, in agreement with the N110-120°E stretching lineation in the host rocks. The three-dimensional shape and the internal structure of the Echassières leucogranite show that it is a syntectonic body which experienced NW-SE stretching, vertical shortening, and southeastward overturning during its emplacement.

The Pouzol-Servant microgranite is also an asymmetric body with a steep western margin and a flat-lying eastern margin concordant with the surrounding mica schist. This boundary is well observed along the Sioule valley. There, numerous shear criteria, such as sigmoidal quartzo-feldspathic lenses and asymmetric boudins of microgranite dykes, indicate a top-to-the-SE sense of shear [*Faure et al.*, 1993]. The Pouzol-Servant microgranite is an injected massif which was emplaced within a N-S to N20°E gash opened as the same time as the NW-SE stretching. Evidence of magmatism related to brittle stretching is also provided by the numerous N20°E to N40°E trending microgranite dykes of late Visean to Namurian age [*Vennat*, 1982].

The NW-SE structural trend is also the axial direction for millimeter to kilometer scale postfolial upright folds which are assumed to be coeval with the stretching parallel to their axes. Consequently, the strain ellipsoid is qualitatively characterized by a vertical maximum shortening, a NW-SE maximum stretching and an intermediate NE-SW shortening axis. Such a prolate shape of the strain ellipsoid is representative of a constrictional bulk finite strain.

The Montmarault area. Due to poor outcrop conditions, the NE corner of the Guéret extensional allochton is the less studied part of the northern Limousin structure. There, the Guéret massif is intruded by the Montmarault granitic complex (Figures 2 and 4) which is a composite massif with mainly pink porphyritic granite and related small granodiorite and leucogranite plutons [*Truland et al.*, 1990]. The Montmarault granite is petrologically similar to the "red granites" of the Bourbonnais area, dated between 330 and 320 Ma by Rb-Sr and U-Pb methods [*Binon and Pin*, 1989]. The same Middle Carboniferous age is likely for the Montmarault complex. The NW boundary of the eastern arm of the Montmarault pluton is mylonitized. Along the N150°E trending stretching lineation, shear criteria indicate a downward motion of the host rock with respect to the granite (Figure 4). The mylonitization occurred during or after the

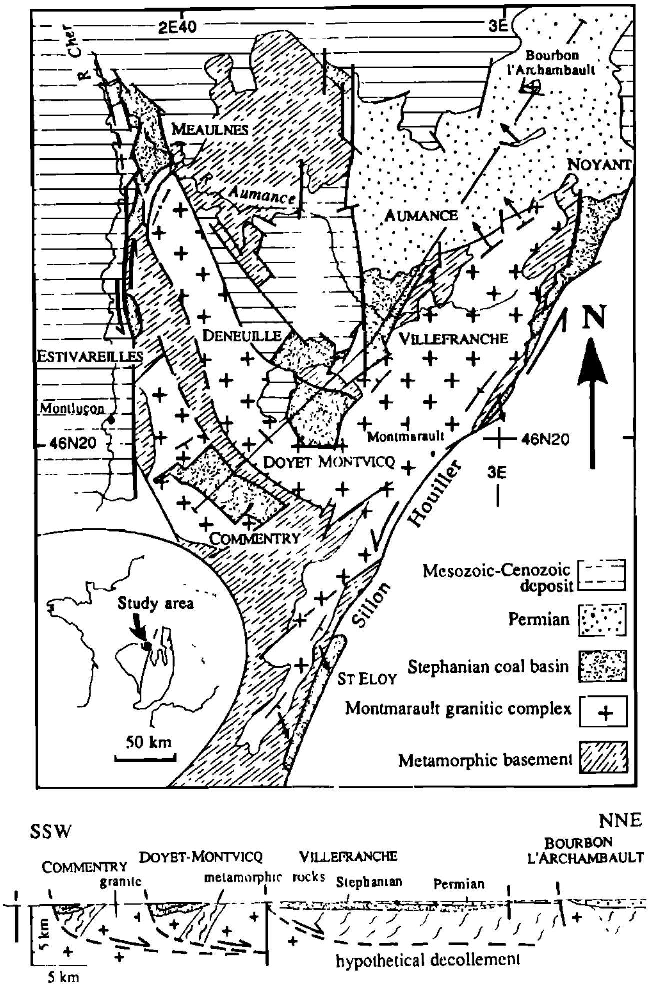

Figure 4. Structural map of the Montmarault area and cross section from Commentry to Bourbon l'Archambault showing the NE-SW extensional setting of the Late Carboniferous coal deposits. Along the Sillon Houiller, the basins are left-lateral pull-aparts, west of the Sillon Houiller the half-graben structure predominates. Commentry, Doyet-Montvicq, and Villefranche basins opened upon metamorphic basement and the Middle Carboniferous Montmarault granite which experienced a synemplacement ductile deformation. A ductile detachment fault is assumed at depth. When known, foliation and lineation trends are put inside the Montmarault granite. Solid arrows indicate the sense of shear of the upper part both in the granite mylonite (south of Bourbon l'Archambault) and the host rock (west of Saint-Eloi).

Namurian, which is the assumed age of the granite crystallization and before the deposition of Early Permian (Autunian) sandstone that covers the foliated granite [*Turland et al.*, 1990]. Inside the Montmarault granitic complex, NW-SE linear preferred orientations marked by elongated xenoliths have been recognized [*Barbarin et al.*, 1985]; (also personal observations, 1993). In the metamorphic rocks, along the eastern contact of the granite, our preliminary investigations show a top-to-the-SE sense of shear along the N120°E to N150°E stretching lineation. Some additional structural data of the Montmarault complex will be discussed below when dealing with the formation of coal basins and Stephanian-Autunian extension.

In conclusion, the Guéret extensional allochton is one of the widest late orogenic structures of the Massif Central. The architecture of a syntectonic pluton results from the interplay between regional tectonics and ballooning due to pluton dynamics [*Brun and Pons*, 1981]. The northern Limousin leucogranites provide various examples of shape and emplacement kinematics controlled by NW-SE stretching during the collapse of the Guéret allochton. The Brame pluton, overturned toward the NW, experienced an antithetic motion with respect to the general tectonic motion. Conversely, the Echassières body behaved synthetically like the surrounding rocks. The weak ellipticity of the Plateau d'Aigurande or Echassières plutons suggests that the ballooning force was strong enough to balance the regional stretching, whereas in the case of the Saint Goussaud pluton the ballooning force was unable to oppose the regional stress field.

West of the Nantiat fault, the metamorphic series also experienced ductile extensional tectonics. North of Bellac, the pre-Devonian "Lanneau migmatite" is bound to the west by a normal ductile fault along which several small gneissic leucogranites exhibit S-C structures (the west side moving down) [*Santallier and Floc'h*, 1989]. East of the Oligocene graben of the "Limagne d'Allier," NW-SE trending ductile extension is not described. However, in the Livradois area (Figure 1), conspicuous dynamic retrogression of the metamorphic series [*Forestier*, 1963] and top-to-the-SE ductile shearing in syntectonic granitic bodies [*Mouctar*, 1985] are tentatively interpreted here as formed during the Middle Carboniferous extension.

Central and Southern Limousin

Besides the Guéret allochton, which shows the structural relationship between granite emplacement and regional extensional tectonic setting, several isolated areas in central and southern Limousin also support this interpretation. They will be briefly examined.

The Saint Mathieu dome. In the westernmost part of the Limousin, the Saint Mathieu area exhibits a subcircular structure partly hidden below the Mesozoic cover (Figure 2). This dome reworks the pre-Visean stack of nappes. The lowermost unit or Dronne mica schist is intruded by two types of Namurian-Westphalian granitoids [*Floc'h*, 1979, 1983], namely, the Piegut-Pluvier porphyritic granodiorite dated around 325±17 Ma (Rb-Sr method on whole rock) and the Saint Mathieu-Saint Saud leucogranite, dated around 315±17 Ma by the same method [*Duthou and Dutreuil*, 1978]. The leucogranite that surrounds the Saint Mathieu dome presents a well marked magmatic mineral preferred orientation evolving to a mylonite along the granite boundaries. Whereas the foliation strike marks the annular shape of the dome, the mineral and stretching lineations trend consistently NW-SE with a variable dip all around the dome. S-C relationships and other shear criteria show a top-to-the-NW motion along the NW side of the dome (the host rock moves downwards with respect to the granite). There, the granite-metamorphic contact is reworked by a left-lateral strike-slip fault in brittle conditions. Along the eastern side of the dome, the Saint Saud leucogranite and its peripheral aplitic dykes are foliated and lineated; shear criteria indicate top-to-the-SE motion. However, E-W to NW-SE stretching lineation is conspicuous in the Dronne mica schist. Most of the shear criteria which indicate a top-to-the W-SW sense of shear [*Floc'h*, 1983] predate the deformation related to the granite emplacement. Although it is unknown, the age of this deformation is likely to have been pre-Visean as discussed below.

The Porcherie leucogranite-Sussac antiform. In central Limousin, the Porcherie porphyritic leucogranite (Figure 2) intrudes the metamorphic series in the Saint Germain-les-Belles synform [*Ledru and Hottin*, 1984]. The foliation bears a well-marked E-W to NW-SE (N80°E to N120°E) mineral and stretching lineation, coeval to the magma crystallization but becoming post-solidus in character along the margins. This deformation is a Namurian-Westphalian event, since U/Pb dating on monazite gives an age of 317±3 Ma [*Lafont and Respaut*, 1988].

NE of the Porcherie granite, a lower mica schist unit, equivalent to the Dronne unit, outcrops in the core of the Sussac brachyantiform (Figure 2) [*Mouthier*, 1976]. The contact between the mica schist unit and the Limousin gneisses is classically interpreted as a refolded NW vergent thrust [e.g., *Floc'h*, 1983; *Ledru et al.*, 1989]. Top-to-the-NW shear criteria are observed along the NW-SE stretching lineation. Although it cannot be demonstrated here, it is likely that at least a part of these microstructures, which occur in chlorite-sericite retrogressive conditions, were formed during the Carboniferous extension. Consequently, the mica schist-gneiss thrust contact is considered to have been reworked as a normal fault with west side moving down.

Evidence for NE-SW synextension shortening. In the southern Limousin, postfolial NW-SE to E-W trending upright folds have long been recognized [e.g., *Grolier*, 1971b; *Floc'h*, 1983]. From north to south the folds are Sussac, Meuzac, and Tulle antiforms, and the Saint Germain-les-Belles and Uzerche synforms (Figure 2). The Limousin leucogranites always outcrop in the core of the antiforms. It is obvious for the Saint Mathieu dome and the Cornil granodiorite. This pluton (CR in Figure 2) occupies the core of the Tulle antiform. Rb-Sr dating on whole rock gives a Namurian-Westphalian age of 317±15 Ma [*Bernard-Griffiths and Vachette*, 1970]. Emplacement kinematics of the Cornil granite is not available, but preliminary survey shows the occurrence of a NW-SE mineral lineation and magmatic textures. The upright folding is coeval to the greenschist facies retrogression of mica schist and gneiss of the lower unit. Chlorite-albite-actinolite assemblages formed at the expense of higher-grade minerals. In the present state of knowledge, an extensional setting for the Cornil granite emplacement appears the most likely. The Porcherie pluton occupies an antiformal second-order fold within the Saint Germain-les-Belles synform. No large granitic massif appears in the Meuzac antiform; however, few leucogranite masses are found, and the existence of an underlying body is suspected on geophysical grounds. The same geometry is described for the plateau d'Aigurande and Sioule metamorphic series (see above, Figure 3) and has been considered as evidence for a diapiric emplacement of the leucogranites [*Lameyre*, 1982, 1984]. The pluton rise is responsible for refolding the stack of nappes and the thrust contacts. The lower mica schist unit is presently observed in tectonic "windows" which are in fact the "footwall" of extensional allochtons coeval to granite emplacement. The interference, already considered in the case of the north Limousin area, between granite ballooning and regional deformation is responsible for the bulk postmetamorphic structure of the south Limousin. On one hand, the plutonism creates the doming of the metamorphic series, and on the other hand, the regional strain field, characterized by NE-SW shortening and NW-SE stretching, is responsible for the NW-SE orientation of the upright folding (Figure 5). When the regional shortening is weaker than the ballooning push, a brachyantiform, as in the case of the Saint Mathieu dome, will develop.

The Argentat fault and Massif de Millevaches. It has long been proposed [*Grolier*, 1971b; *Lameyre*, 1982; *Floc'h*, 1983] that the Argentat fault is a vertical thrust contact between the Limousin nappes and the Millevaches metamorphic series (Figure 2). The Argentat fault has also been considered as a normal fault [*Lameyre*, 1984; *Ledru and Autran*, 1987; *Mattauer et al.*, 1988]. Along the fault, mylonitic foliation dips steeply (60-70°) to the west and bears a stretching lineation trending to N330°E on average. Shear bands and other criteria indicate a dextral-normal motion, the Limousin gneiss moved downward with respect to the Millevaches massif [*Feix et al.*, 1987]. Although earlier deformations cannot be ruled out, this ductile deformation likely took place in Namurian times since mylonitization occurs within retrogressive conditions in the Limousin gneiss (temperature of 300-400°C, pressure of 2kb, *Feix et al.*, 1987). Moreover, mylonite pebbles similar to the mylonitic rocks observed along the fault are found in the Stephanian coal basins that are distributed along the Argentat fault. A widespread cataclastic deformation responsible for a normal-sinistral motion overprints the ductile deformation [*Labernardière*, 1970]. The tectonic significance of this brittle structure will be discussed in the following section.

East of the Argentat fault, the Millevaches massif presents a wide variety of metamorphic and granitic rocks. Leucogranites are among the youngest plutonic rocks; a few Rb-Sr datings on whole rock indicate late Visean to Namurian ages (335 to 330 Ma [*Monier*, 1980]). The leucogranite frequently occupies the core of N-S to NW-SE antiforms. When present, the planar preferred orientation of granite minerals is generally parallel to the host rock foliation, and a N-S to NW-SE mineral lineation has been recognized. This structural pattern is correlated with the diapiric emplacement of leucogranite and the ductile dextral-normal motion of the Argentat fault (Figure 5).

Southern and Central Massif Central

The Cévennes area. The southeastern part of the Massif Central, or Cévennes area (Figure 1), is a wide mica schist domain which experienced prograde greenschist facies metamorphism and nappe stacking in Late Devonian-Early Carboniferous. The two plutons of Mont Lozère and Aigoual-Saint Guiral-Liron intrude the subhorizontal mica schist series (Figure 6). The emplacement of these massifs has been variously interpreted as synorogenic, late tectonic, or post tectonic [e.g., *Gèze*, 1949; *De Waard*, 1949; *Prager*, 1965; *Van Moort*, 1966] (also work of F. Arthaud, discussed by

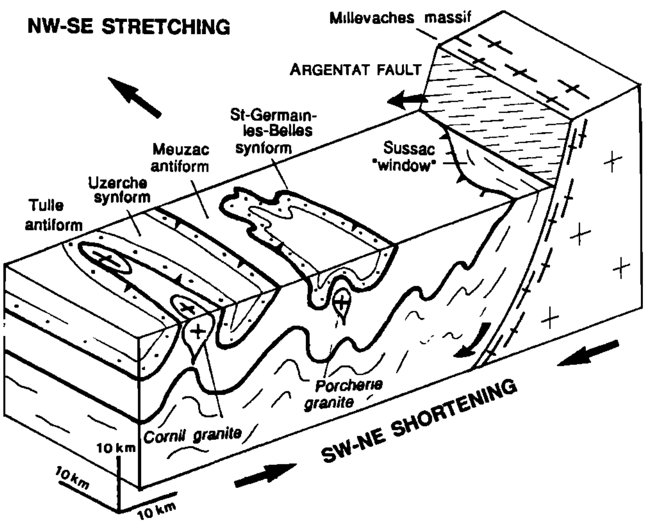

Figure 5. Schematic interpretation of the south Limousin showing the relationships between postfoliation upright folding, pluton emplacement, and normal-right lateral wrench motion along the Argentat fault.

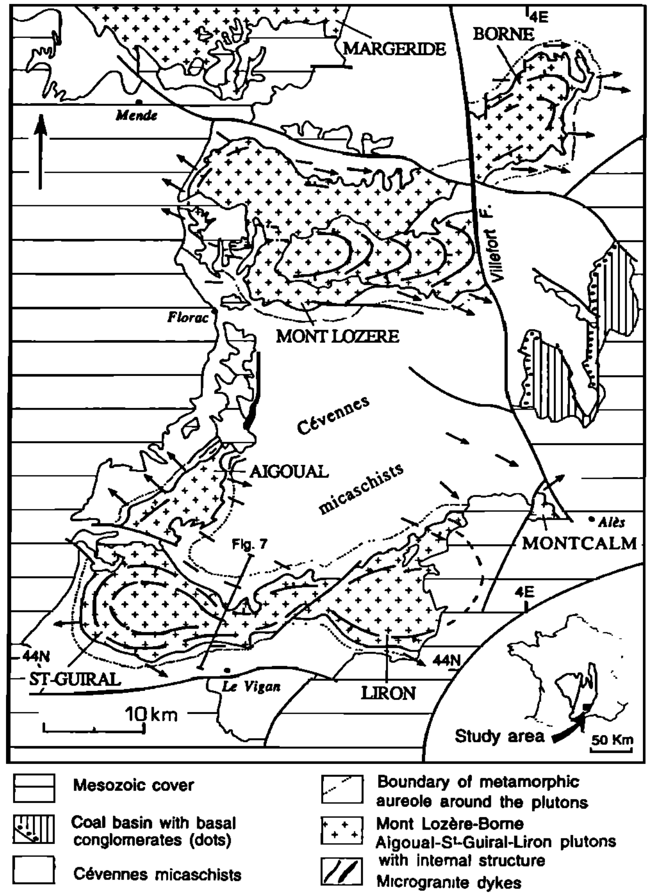

Figure 6. Structural map of the Cévennes area with emphasis of the late structures related to granite emplacement. Bar is stretching lineation related to pluton emplacement; arrows indicate the sense of shear of the upper part, both in the granite and the host rock.

Alabouvette [1988]). The synorogenic interpretation was in fact understood as coeval with a south verging compression. The Aigoual-Saint Guiral-Liron massif is made solely of porphyritic granodiorite, whereas the Mont Lozère consists of several petrographic facies among which the porphyritic granodiorite of Pont-de-Montvert forms the largest pluton [*Van Moort*, 1966]. The Borne massif, which is left laterally offset to the north by the Villefort fault, corresponds to the eastern termination of the Pont-de-Montvert pluton. Due to its richness in structural markers, such as schlieren, aplitic joints, xenoliths, and K feldspar megacrysts, the porphyritic facies is the most suitable for structural analysis [*Fernandez*, 1977; *Mialhe*, 1980; *Faure et al.*, 1992].

The Mont Lozère and Aigoual-Saint Guiral-Liron plutons present common structural features. The foliations make E-W elongated ellipses, the long axis of which are parallel to the mapped shape of the two massifs. In the Mont Lozère massif, the same planar and linear mineral preferred orientations cross through the lithological boundaries. This shows that the synemplacement deformations of all the facies are coeval. The plutons have an asymmetric shape in the submeridianal vertical plane [*Fabre*, 1877]; in their northern side, the granite foliation dips gently to the north, whereas it is subvertical along the southern side (Figure 7). The same asymmetry is found in the mica schist in close vicinity of the plutons. Along the northern side, the N90°E to N130°E trending centimeter to meter folds are overturned to the south and along the southern side, upright microfolds without overturning predominate. These folds, which consistently indicate a N-S shortening, progressively fade out away from the granite. As proposed in other examples [e.g., *Pons et al.*, 1991; *Paterson et al.*, 1991], here also we interpret the microfolds observed in the surroundings of the granitic massifs as due to pluton ballooning and not to a compressional event of regional extent.

Inside the granite, the mineral lineation, defined by xenolith and biotite clots, has a near E-W trend. The strain ellipsoid has been calculated using the shape of mafic xenoliths. All the points fall in the prolate field; the Flinn parameter, ranging from 1.6 to 15, indicates a constrictional finite strain (Figure 8). Brittle stretching shown by boudinaged xenoliths and K feldspar megacrysts is found in the Pont-de-Montvert pluton. Submeridianal cross joints are conspicuous; some of them, in the Mont Lozère pluton, form large N-S trending cliffs. N-S to N30°E trending aplitic dykes are, by far, the most abundant of the joint sets. They correspond to cross joints [*Balk*, 1937; *Marre*, 1982]. As the filling is the same granitic material, it is likely that stretching occurred during crystallization of the pluton. In the northwestern end of the Aigoual massif, microgranitic texture predominates. This massif terminates in the north at kilometer to meter-scale N-S trending microgranite dykes (Figure 6). This submeridianal to NE-SW dyke swarm is consistent with an E-W to NW-SE stretching. The microgranite veins can be compared to tension gashes opened by NW-SE brittle stretching and filled by injected microgranite during the Carboniferous extension.

A N80°E to N150°E lineation is well developed in the contact metamorphic aureole. North of Le Vigan, cherty limestone presents a well-developed E-W boudinage, but macroscopic evidence of stretching is rare. In the field, this lineation appears as a crenulation and mineral lineation of biotite and andalusite; under the microscope, boudinaged andalusite and quartz pressure shadows at the extremities of biotite porphyroblasts also show stretching in this direction. Several generations of contact minerals can be recognized on the basis of the degree of their preferred orientation. The latest andalusite crystals are randomly oriented, but earlier ones are stretched and others are involved in the crenulation wrinkles. Therefore contact minerals are syntectonic to posttectonic with respect to granite emplacement. Along the northern and southern sides of the two massifs, shear criteria (pressure shadows, sigmoidal biotite, shear bands, and asymmetric quartz lenses) dominantly indicate a top-to-the-east sense of shear. However, even in gneissose granite where stretching lineation is well marked, shear criteria are difficult to assess. These observations are in agreement with a significant component of coaxial strain (i.e., stretching without shearing)

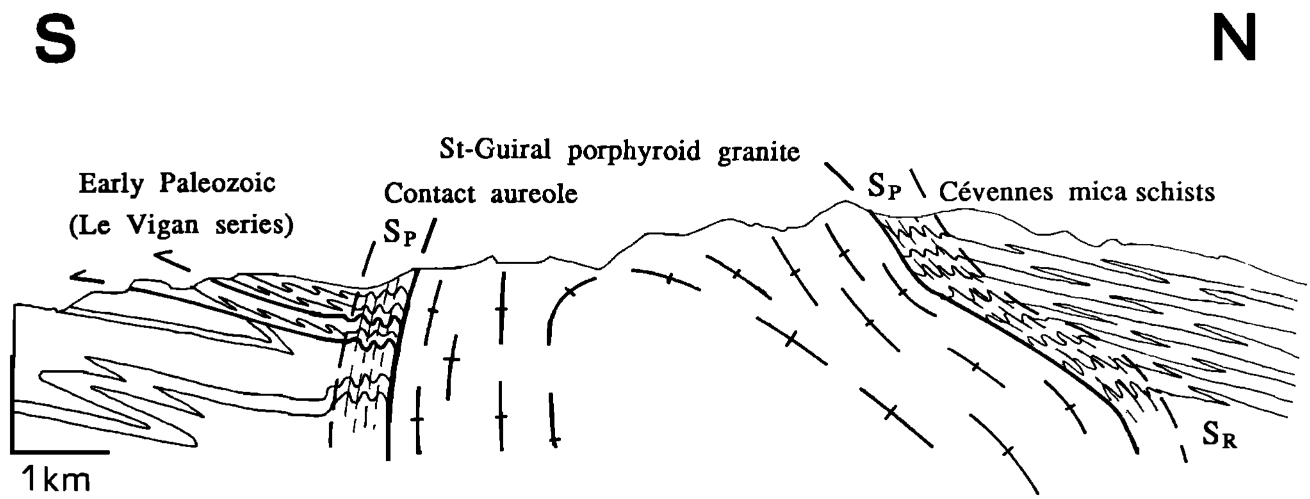

Figure 7. Cross section through the Saint Guiral granite (adapted from work of Arthaud as discussed by Alabouvette [1988]). S_R is regional foliation in the Cévennes mica schists; Sp is pluton-related foliation in the contact auréole.

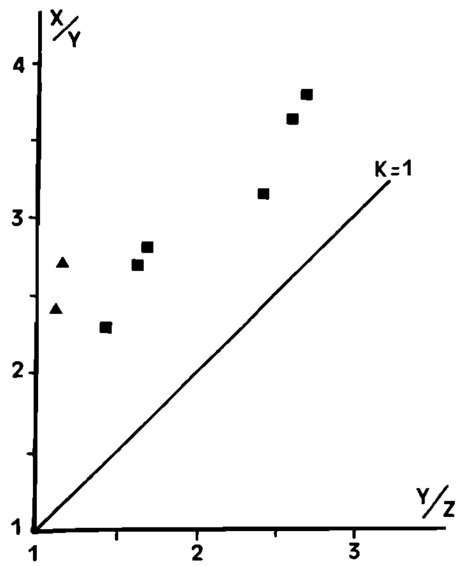

Figure 8. Flinn diagram showing the prolate shape of the mafic xenoliths. Triangles are Mont Lozère; squares are Aigoual-Saint Guiral massifs measured by J.F Babinault and I. Lucas.

in the medial part of the plutons. In the western termination of the Aigoual-Saint Guiral-Liron massif, the lineation dips steeply toward the NW (N330°E), and the host rock moved downward. The eastern end of the Mont Lozère massif can be observed around the Borne massif. There the lineation dips about 50-60°E, host mica schists moved downward with respect to the granite [*Faure et al.*, 1992]. Along the northern and NW boundaries of the Mont Lozère, the nonporphyritic granite is locally mylonitized [*Fabre*, 1877]. S-C relationships indicate right-lateral and normal motions (host rock moving downwards to the NW) in the north and NW sides, respectively (Figure 6). As a whole, the kinematic picture related to granite emplacement indicates an E-W stretching and divergent kinematics at the extremities of the plutons. However, the top-to-the-SE shear is dominant over the top-to-the-NW shear. These kinematics indicate that the two plutons are overturned to the SE; the opposite shear senses at their western extremities are related to pluton ascent around the root zone.

The Bouguer gravimetric anomaly map for this area shows that the lowest minima are located in the western part of both massifs (Figure 9). This suggests that the granites are rooted to the west, in agreement with the kinematics. A sketch of the general three-dimensional shape of the Cévennes plutons is depicted in Figure 10. Although a vertical shortening coeval with granite emplacement cannot be strictly proven, the shape of the plutons, their internal structure, the E-W ductile stretching, and emplacement-related kinematics better agree with an extensional tectonic setting than a compressional one in which N-S stretching lineation would be expected.

In the mica schists outside the contact metamorphic aureole, NW-SE trending structures are rare. However, meter to millimeter scale upright microfolds and crenulations are described [*De Waard*, 1949]. In the SE part, top-to-the-SE penetrative shear bands are locally well developed (Figure 6). The age of these structures is unknown, but their geometry and kinematics correspond to normal ductile faults with the SE side moving down. West of Alès, the Montcalm massif (Figure 6) presents an anomaly in this consistent NW-SE trend. In this area, the andalusite mica schists of the contact aureole have a N50°E lineation with top-to-the-NE sense of shear (normal geometry). This unusual pattern is interpreted here as due to normal motion along the Villefort fault. The NE stretching suggests that this deformation might be related to the Late Carboniferous opening of the Cévennes coal basins (see below).

On the basis of available Rb-Sr dates on whole rock and biotite or feldspar separates, the age of the Cévennes pluton ranges from 280 to 315 Ma [*Hamet and Mattauer*, 1977; *Vialette and Sabourdy*, 1977; *Mialhe*, 1980]. The youngest radiometric ages (280-290 Ma, Autunian) are certainly too young, since Stephanian-Permian detrital rocks overlie the Pont-de-Montvert pluton [*Deroin et al.*, 1990]. A Middle Carboniferous age, close to the Rb-Sr whole rock age of 315±5 Ma in the Borne massif [Mialhe, 1980], is likely. Such a date would be in good agreement with the extensional setting proposed above and also with the chronological and structural data for the Margeride-Châtaigneraie area.

The Margeride-Châtaigneraie area. The Margeride massif is the largest post-Visean plutonic complex in the Massif Central (Figure 1). The available radiometric ages (U-Pb zircon of 334±7 Ma [*Lafont and Respaut*, 1988], Rb-Sr whole rock of 322±12 Ma [*Couturié et al.*, 1979], and U-Pb monazite of 314±3 Ma [*Pin*, 1980]) indicate a staggering of magmatic events from late Visean to Westphalian, in agreement with the variety of granitic types [*Couturié*, 1977]. The main facies is a porphyritic monzogranite with several

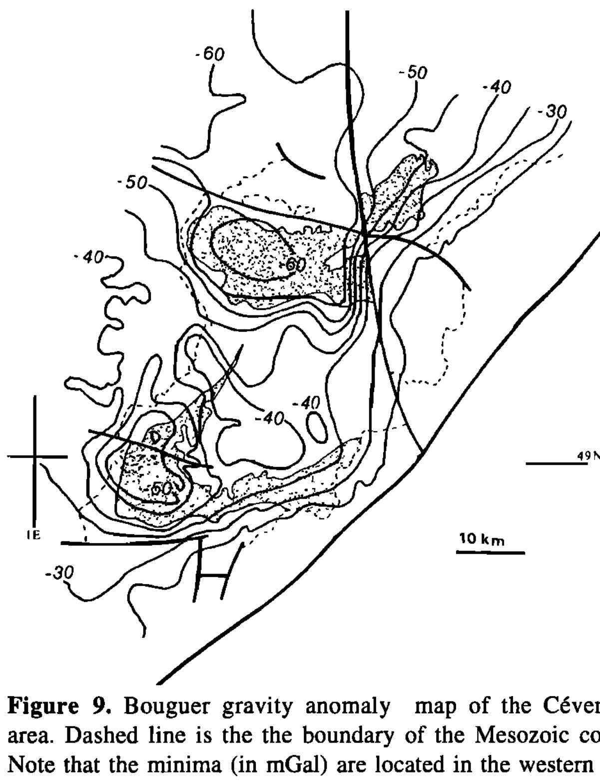

Figure 9. Bouguer gravity anomaly map of the Cévennes area. Dashed line is the the boundary of the Mesozoic cover. Note that the minima (in mGal) are located in the western part of the two plutons.

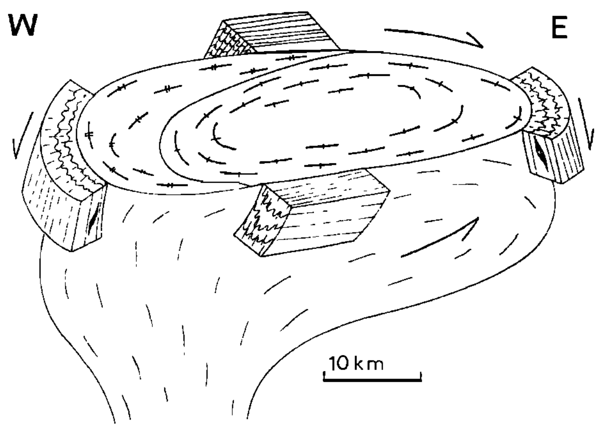

Figure 10. Inferred shape of the Cévennes plutons and their emplacement kinematics.

NE-SW trending rows of small leucogranite bodies. The Margeride massif is a subhorizontal slice 4 to 8 km thick that extends laterally several kilometers below the host rock mica schists. Gravimetric data show NNE-SSW trending light anomalies which are interpreted as feeder zones of the Margeride granite [*Petrequin*, 1979; *Bayer* et al., 1982]. The NNE-SSW direction is subperpendicular to the maximum stretching direction of Middle Carboniferous age recognized all over the Massif Central. The laccolithic shape of the Margeride massif [*Couturié*, 1977] with its recumbent margins is in agreement with vertical shortening. According to *Laboue* [1982], the granitic fabric was formed during pluton emplacement. Structural analysis shows that N60°E and N140°E imbricate fabrics are widespread, but internal structure of the Margeride massif is presently not available. Our local observations along the northern contact show that contact metamorphic minerals such as andalusite or biotite are sometimes oriented N120-130°E. Shear criteria indicate a normal fault motion (the host rock is downfaulted with respect to the granite) in agreement with the kinematics established in the granitic northern margin [*Laboue*, 1982]. Moreover, as already pointed out in the case of the Saint Mathieu area, deformation related to granite emplacement is weak and subparallel to an older lineation of sillimanite or biotite [*Burg and Matte*, 1978] with which it must not be confused. In the thermal aureole of the southern margin of the pluton, mica schists exhibit a subhorizontal foliation with NW-SE mineral lineations of biotite, albite, and cordierite. Although the contact minerals are oblique to the regional foliation, they are deformed and indicate a top-to-the-NW shear. Due to submeridianal folding related to the Velay dome (Figure 1), the laccolith footwall may be observed in the eastern margin. There, plastic deformation of quartz is limited to the melanocratic facies in the basal part of the pluton. In the same area, the Saint Christophe d'Allier leucogranite (SCA in Figure 1) exhibits a well marked sub-solidus fabric with a NW-SE mineral and stretching lineation. Evidence of divergent shearing, namely, top-to-the-NW shear in the NW part and top-to-the-SE in the SE part can be observed. Top-to-the-NW shear bands are also well developed in orthogneiss within the underlying country rocks. Moreover, as the magmatic and ductile deformations are found on a subhorizontal foliation, the related compressional or extensional setting is difficult to settle. Owing to the space problem, the emplacement of such a thick body, around 10 km, is easier to understand in terms of extensional tectonics.

Between the western end of the Margeride pluton, or Entraygues appendix, and the Sillon Houiller, the Châtaigneraie metamorphic series is intruded by the granitic bodies of Omps, Boisset, Marcolès, Veinazès, and Soulaque from west to east (Figures 1 and 11). All these massifs are porphyritic monzogranites petrologically similar to the Margeride pluton [*Joubert*, 1978; *Feybesse*, 1981]. Rb-Sr whole rock dates of 320 Ma, 315±15 Ma, 313±13 Ma, and 292±10 Ma for the Veinazès, Marcolès, Omps, and Boisset granites respectively, (the ages have been recalculated with $\lambda = 1.42\ 10^{-11}$ year^{-1}), support this comparison [*Vivier and Lasserre*, 1973; *Duthou et al.*, 1986]. The western side of the Omps granite experienced a postsolidus brittle-ductile deformation related to the wrench faulting along the Sillon Houiller [*Feybesse*, 1981]. However, the internal structure of the Omps and Boisset plutons and NW-SE stretching lineation in the host rock suggest that granite emplacement could be related to the Middle Carboniferous extension before the activity of the Sillon Houiller fault.

Among the Namurian-Westphalian granites, the Veinazès pluton (Figure 11) presents peculiar features. This massif exhibits a strongly anisometric shape with a NE-SW long axis almost perpendicular to the usual NW-SE stretching trend of the Namurian-Westphalian extension. In contrast to other plutons, andalusite, biotite, or cordierite in the contact mica schist are almost unoriented; static crystallization is dominant. When present in the contact aureole, the foliation is at high angle to the granite boundary but is parallel to the regional foliation. The Veinazès pluton crosscuts the regional structures such as NW-SE foliation, NE-SW lineation, and early thrusts [*Joubert*, 1978; *Bogdanoff et al.*, 1989] without any structural accordance. Within the pluton, the planar structure, marked by xenoliths and biotite, dips steeply and follows the pluton shape; lineation is rare and subvertical. In thin section, quartz is weakly deformed by undulose extinction and polygonization, and zoned plagioclase with syneusis figure is common. These textural features indicate that the mineral preferred orientation in the Veinazès pluton was acquired before the full crystallization of the magma [e.g., *Hutton*, 1988; *Paterson et al.*, 1989]. Along the margins, mylonite is completely lacking. The center of the foliation ellipse is located to the NE, which corresponds to the biotite-cordierite leucocratic facies. The Bouguer gravity anomaly [*Joubert*, 1978] shows a minimum also centered in the NE end of the pluton suggesting that this area is the pluton root zone. These lines of evidence support our conclusion that the Veinazès granite is an injected pluton that filled a NE-SW trending kilometer scale "tension gash" which opened in agreement with the Namurian-Westphalian strain field.

As in the Limousin, in the southern and central Massif Central, most of the Middle Carboniferous porphyritic monzogranites present synemplacement structures characterized by a NW-SE stretching. Granite shape, internal structures, and emplacement kinematics are in agreement with an extensional setting.

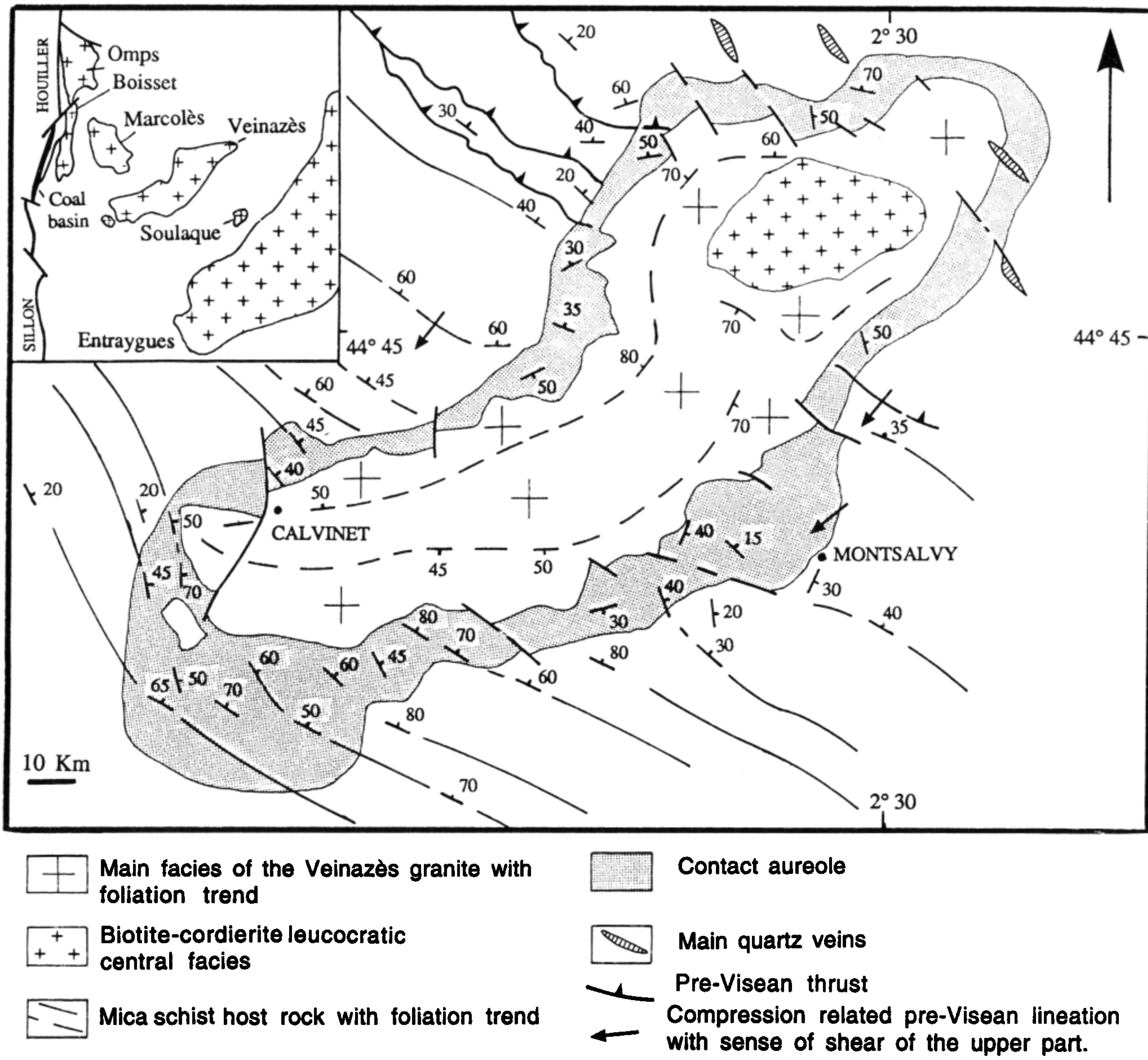

Figure 11. Structural map of the Veinazès pluton in the Châtaigneraie area showing its crustal scale "tension gash" shape, mapped with the collaboration of A. Chauvet.

Middle Carboniferous Extension Versus Compression

In the Massif Central, the emplacement of the Namurian-Westphalian granitoids follows a tectonic control. All the plutons discussed above have a mineral preferred orientation that began to form during the crystallization of the magma under a regional strain and continued in the postsolidus state after complete crystallization [*Hutton*, 1988]. The planar and linear structures are in continuity with the regional ones in the host rock. Frequently, the pluton margins are mylonitized, and emplacement-related plastic strain can be also recognized in the metamorphic aureole. In spite of a lack of precise radiometric dating of igneous and contact metamorphic minerals, the Middle Carboniferous plutons of the French Massif Central exhibit the structural features established for syntectonic plutons [e.g., *Hutton*, 1988; *Paterson et al.*, 1991; *Pons et al.*, 1991]. At the scale of the Massif Central, the NW-SE trend corresponds to the maximum stretching direction. The northwestward or southeastward overturning of each individual pluton depends on the local tectonic setting. The NE-SW direction corresponds to a shortening direction as shown by large-scale upright folding and the crenulation lineation. Evidence for vertical shortening can be inferred from the pluton shapes, in particular from the peripheral recumbent lobes. Top-to-the-SE displacement as in the Guéret extensional allochton and the Cévennes plutons appears dominant at the NW and SE extremities of the Massif Central, whereas top-to-the-NW shear is well developed in the southern Limousin. Metamorphic retrogression of the lowermost mica schist unit also occurred during the synmagmatic NW-SE stretching. These lines of evidence show that regional deformation, granite emplacement, and retrogression are coeval and related to the decompression of the stack of nappes. An extensional setting is most likely to account for all these events.

Although crustal thinning was active in Namurian-Westphalian times, the onset of this tectonic regime is not fully constrained by the plutonism. Indeed, the late Visean is a major chronological boundary in the history of the Massif Central. In the north, around Roanne, the late Visean "Tufs anthracifères" series is characterized by the association of sedimentary and volcanic rocks dominated by acidic lavas, ignimbrite, and pyroclastic rocks. Near Boen (Figure 12), microgranite dykes, granophyre, and granite are closely associated with the volcanic-sedimentary series. Petrological and geochemical work [e.g., *Leistel and Gagny*, 1984] has shown that all the magmatic rocks are cogenetic. They belong to a single volcanic plutonic event formed by crustal melting. The effusive part was emplaced along NE-SW trending fractures that form a NE-SW graben, the "Loire synclinorium trough." The granite-granophyre-microgranite dykes present a subvertical N70°E trending planar mineral preferred orientation corresponding to magma flow during their emplacement [*Leistel and Gagny*, 1984]. Thus the tectonic setting of the late Visean magmatism is in agreement with a NW-SE stretching of the crust. Although occurring in brittle conditions, this deformation can be considered as the beginning of the Middle Carboniferous extensional regime in the Massif Central. Due to its greater mobility, the emplacement of the volcanic magma in the upper crust would precede the slowest granitic ascent.

However, in late Visean times, extensional tectonics did not prevail all over the belt (Figure 13). In the southernmost area, or Montagne Noire (Figure 1), kilometer scale south verging recumbent folds were emplaced in the latest Visean-early Namurian [*Feist and Galtier*, 1985]. The Paleozoic series is underlain by mica schist and gneiss of the "axial zone." It is likely that during the recumbent folding of the sedimentary series, the Proterozoic-Early Cambrian substratum also underwent a compressional event recorded by (1) a Namurian $^{40}Ar/^{39}Ar$ age of 316±4 Ma from banded gneiss [*Maluski et al.*, 1991], (2) a medium pressure/medium temperature metamorphism (i.e., eclogitic facies and kyanite) [*Demange*, 1985], and (3) possibly, ductile deformation [*Van den Driessche and Brun*, 1991; *Cassard et al.*, 1993]. Evidence for compression at this time is also reported in the Pyrenées [*Vissers*, 1992]. Therefore, as suggested by *Mattauer et al.* [1988], compression in the outer zone is coeval to extension in the inner zone. This tectonic pattern is similar to the Himalayas [*Burg et al.*, 1984] or the northern Apennines [*Carmignani and Kligfield*, 1990] where granitic plutons were emplaced within an extensional setting while compression was still active in the foreland. In the Massif Central, the transition zone from compressional to extensional tectonics is not precisely located since it moved southward with time. In Namurian-Westphalian times, this transition zone lay approximately around the Margeride massif. This may account

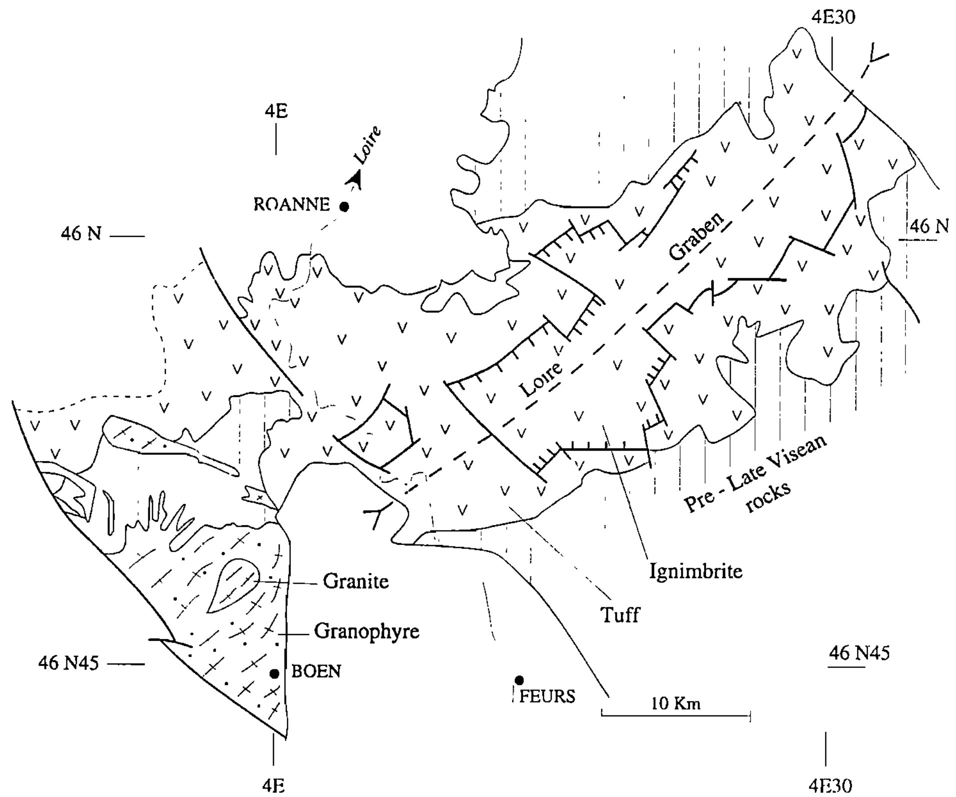

Figure 12. Late Visean extensional setting of the ignimbrite and tuff formations (Tufs anthracifères) in the Loire graben (adapted from *Leistel and Gagny* [1984]).

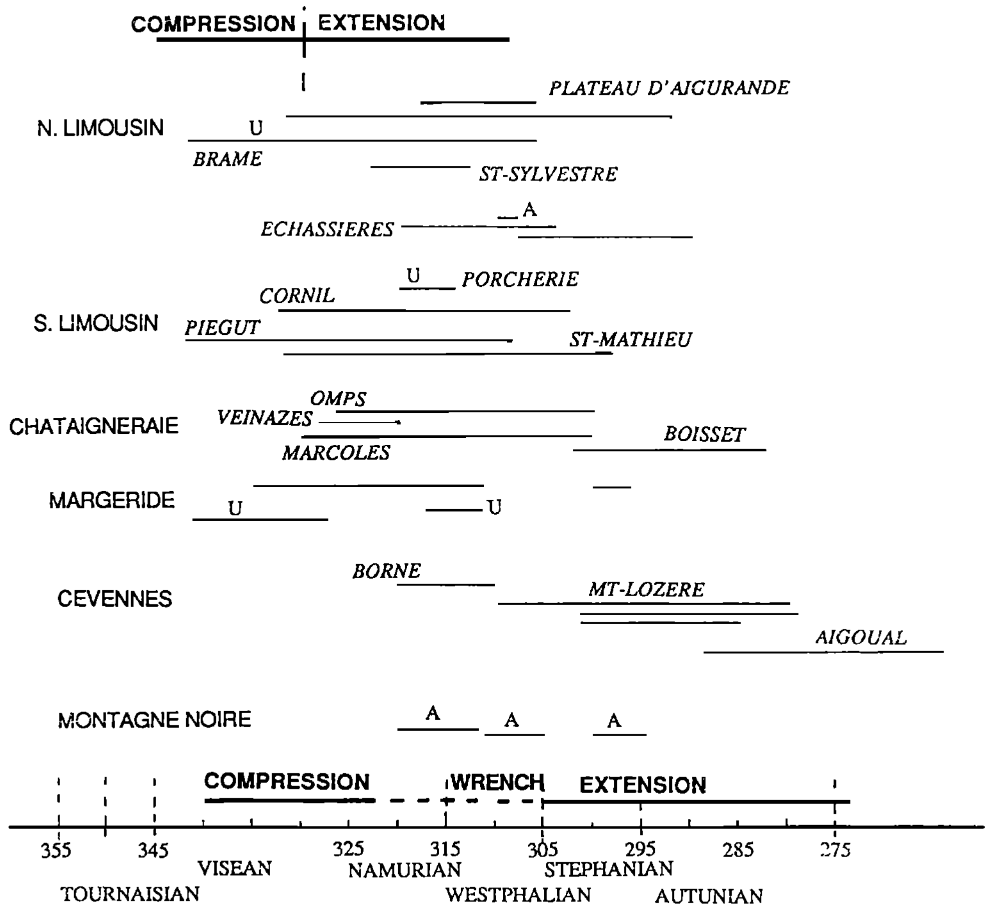

Figure 13. Timing of granite emplacement in the Massif Central in relation with the N. to S. migration of stress fields. A and U stand for $^{40}Ar/^{39}Ar$ and U/Pb methods, respectively; others are Rb/Sr ages recalculated with $\lambda = 1.42\ 10^{-11}$ year^{-1} (references in the text).

for the difficulty in clarifying the tectonic setting of this pluton. Indeed, according to radiometric ages, it is conceivable that early Margeride granites were emplaced when compression was still active, and the latest leucogranitic intrusions were emplaced during the onset of extension.

The NW-SE trend is a conspicuous structural trend in the Massif Central, but it cannot be systematically attributed to Middle Carboniferous extension. NW-SE wrench faults [*Ledru and Autran*, 1987] and NW-SE stretching lineation lying on a subhorizontal foliation, for example in the Guéret massif and Limousin metamorphic series [*Floc'h*, 1983; *Bouchez and Jover*, 1986] formed in pre-late Visean times, are documented. When chronological markers are lacking, the distinction between the pre-Visean and Namurian-Westphalian deformations is difficult to assess. One key is given by the study of the PT path of metamorphic rocks since their pre-Visean deformation occurs with a progressive metamorphism and their retrogression occurs during extensional tectonics during uplift of the nappes [e.g., *Faure et al.*, 1990, 1993].

The Late Carboniferous-Early Permian Extension

Stephanian-Autunian extensional tectonics have been already recognized [e.g., *Mattauer et al.*, 1988; *Ménard and Molnar*, 1988; *Van den Driessche and Brun*, 1989; 1991; *Echtler and Malavieille*, 1990; *Malavieille et al.*, 1990]. This deformation is responsible for intramontane coal basins and granite-gneiss domes. This section emphasizes structural features showing that the maximum stretching trends NE-SW.

NE-SW Extensional Features in the Upper Crust

Opening dynamics of the coal basins. In the Massif Central, Late Carboniferous (Stephanian) to early Permian (Autunian) sediments consist of continental to lacustrine deposits trapped within several tens of basins ranging from less than one to several hundred square kilometers (Figure 1). There is presently some uncertainty regarding the precise location of the Stephanian-Autunian boundary due to the isolated character of the basins and the slow evolution of plants used as stratigraphic indicators. Indeed, Autunian-type spores are found inside typical Stephanian deposits, even in the type locality of Saint Etienne, and Stephanian-type ferns are found inside the Autunian formations of the Autun basin [*Broutin et al.*, 1986]. Therefore the accurate dating of deformation phases and their correlation from one basin to another are questionable.

The boundary between the Stephanian and Permian deposits is in some places conformable (e.g., Brive and Lucenay), and in other it is unconformable; (e.g., Aumance, Decazeville, and Lodève) the latter occurrences have been taken as the mark of a tectonic event [*Grolier*, 1971b]. However, evidence for a compressional event associated with an erosive discontinuity is lacking. Presently, the angular unconformity is better understood in terms of tilted blocks [*Van den Driessche and Brun*, 1989; *Legrand et al.*, 1991]

The structural control of the opening and sedimentary infill of the late Paleozoic basins is well established [*Vetter*, 1986]. Several stress fields have been derived on the basis of relative chronology of brittle structures and "Stephanian" stratigraphy. Emphasis has been placed on the strike-slip motion assumed to be due to a NW-SE compressive stress field. In this scheme, coal and clastic deposits filled pull-apart basins [*Arthaud and Matte*, 1975; *Gélard et al.*, 1986; *Bonijoly and Castaing*, 1984; *Lerouge*, 1988; *Blès et al.*, 1989]. In fact, the pull-apart model is limited to N-S trending faults, and the dominant structural pattern of these is the half-graben. This geometry is in agreement with an extensional setting [*Gibbs*, 1984]. The azimuth of the border faults allows a classification [*Faure and Becq-Giraudon*, 1993].

The submeridianal faults: In the Late Carboniferous, the Sillon Houiller and the Argentat fault moved as brittle left-lateral wrench faults along which several small pull-apart basins opened (Figure 2) [*Labernardière*, 1970]. Structural and sedimentological studies in the Saint Eloi, Messeix, Decazeville, Bosmoreau, and Argentat basins show the syntectonic character of the sediment infill. The opening of pull-apart basins along the N-S trending faults is in agreement with a NNE-SSW (to NE-SW) maximum stretching direction [*Gélard et al.*,1986; *Robert et al.*, 1988]. In some cases, (e.g., Decazeville, Messeix, Saint Eloi) en échelon folds indicate a NW-SE shortening in agreement with a N-S trending left-handed pull-apart. N-S folds indicate an E-W to NE-SW shortening; however, because of lack of stratigraphic markers, the age of this secondary folding is unknown. In the Messeix basin, folding occurred after coalification, which itself is related to the Late Carboniferous thermal regime [*Robert et al.*, 1988]. Thus a post-250 Ma (Late Permian) age for the E-W shortening appears likely.

NW-SE trending faults: The Commentry, Doyet-Montvicq, Deneuille, and Aumance basins (Figure 4) have a typical half-graben structure, documented by mining [*Fayol*, 1888; *Freytet*, 1960]. The border fault is systematically located to the SW side of these basins. There, decameter to hectometer scale brittle shear zones, formed at the expense of Devonian metamorphics and the Middle Carboniferous Montmarault granite, bear NE-SW downdipping slickensides. This structure is in agreement with the tilted block pattern found in extensional basins. The arrangement of detrital material close to the border fault supports a synsedimentary activity. The Aumance basin is the northernmost Stephanian-Autunian basin of this area. The unconformity between NE-SW folded "Stephanian" and flat-lying "Autunian" sandstone was interpreted as evidence for a deformation phase [*Grolier*, 1971b]. However, NW-SE shortening does not support a compressional event since vertical shortening is predominant. Lower Permian clastic formations are synextensional deposits controlled by two sets of NE-SW and NNW-SSE trending normal faults [*Bonnion et al.*, 1983; *Turland et al.*, 1990]. Although border faults are hidden below the Mesozoic rocks, radial extension is invoked as opening dynamics for the Aumance basin.

Our preliminary data show that the Ahun basin (Figure 2) is also a half-graben controlled by a NE-SW opening direction. The main difference from the northern Guéret coal fields is that the border normal fault dips to the SW.

Stephanian nappes were recognized in the Cévennes coal basin [*Gras*, 1970] and taken as evidence for a Carboniferous compression [*Blès et al.*, 1989]. These nappes are reinterpreted as gravity-driven sheets that slid along the coal measures [*Délénin et al.*, 1988]. Although west verging reverse faults of unknown age do exist, they merely indicate a NNW-SSE shortening. The Cévennes basin is divided into western and eastern subbasins by the Rouvergue ridge, which formed before or during deposition of the Late Carboniferous rocks. The western subbasin is a half-graben bounded by a normal fault to the-NE, but a normal offset along the Villefort fault cannot be ruled out, as suggested by the top-to-the-NE ductile deformation west of Alès (Figure 6). The structure of the Cévennes basin is in agreement with NE-SW stretching and NW-SE shortening.

E-W trending faults: The Graissessac basin has also a half-graben geometry with a southern E-W trending normal-dextral border fault (slickensides trend N50°E). Structure in the Late Carboniferous sediments shows that the basin infill is related to the activity of this fault [*Becq-Giraudon*, 1973; *Echtler and Malavieille*, 1990]. In the Lodève basin, Early Permian beds unconformably overlie the Stephanian deposits. As the same NE-SW to N-S maximum stretching direction is found in Permian rocks [e.g., *Santouil*, 1980], this unconformity is now interpreted in terms of synsedimentary intrabasinal tilt [*Van den Driessche and Brun*, 1989]. Farther north, the opening of the Saint Affrique Permian basin, which presents similar structures, is controlled by the reactivation of Variscan thrusts [*Legrand et al.*, 1991].

NE-SW trending faults: This trend is well developed in the eastern Massif Central. It controls the opening of basins such as Saint Etienne, Blanzy-Montceau, and Epinac-Autun. The Saint Etienne basin is bounded by the normal fault of Pilat characterized by N-S to NE-SW slickensides [*Malavieille et al.*, 1990]. The Stephanian "nappes" in the Saint Etienne basin must be reinterpreted as thin skin sheets due to gravity sliding. In the Blanzy-Montceau basin, normal-dextral faults control the deposition of coal measures [*Vallé et al.*, 1988]. The early extensional deformation structures are erased by a Tertiary deformation [*Feys and Gand*, 1983]. Structural data from the Epinac-Autun basin are scarce. According to *Marteau* [1983], a NW-SE to E-W shortening characterizes the late Stephanian tectonics, whereas N-S Autunian extension is responsible for a half-graben structure with an E-W trending normal fault, located south of the Autun basin.

Brittle deformation outside the coal basins. Late Carboniferous-Early Permian brittle deformation in the upper crust is widespread in the Massif Central, for instance in the Marche [*Lerouge and Quenardel*, 1985], Millevaches [*Labernardière*, 1970], Châtaigneraie [*Blès et al.*, 1982], Margeride [*Dutartre*, 1981]. Normal faults, microgranite dykes, joints, and quartz veins have been used to derive a succession of stress fields. According to the authors mentioned above, early-middle and late Stephanian times are characterized in the Massif Central by N-S to E-W compression, respectively, followed by a N-S Autunian extension. These stress field determinations do not provide the $\sigma_2-\sigma_1/\sigma_3-\sigma_1$ ratio needed to estimate the relative magnitude of the three principal stresses. The brittle strain data allow estimation of a N-S to NE-SW maximum finite elongation and an E-W to NW-SE maximum finite shortening. Strain estimate along the vertical axis is generally not considered.

In the NE Massif Central, the Late Carboniferous-Permian acidic volcanism of Blismes (Figure 1), occurred within an elliptical caldera with a NNW-SSE long axis [*Carpena et al.*, 1984]. Microtectonic analysis of the brittle deformation shows that before Mesozoic tectonics, the volcaniclastic sequence records a Permian extensional stress field with a N-S maximum stretching direction and a Late Carboniferous extensional stress field with N130°E and N40°E trends for σ_1 and σ_3 respectively [*Carpena et al.*, 1984]. These directions are the orientation of the maximum and minimum horizontal stresses, the vertical principal stress being in fact σ_1. The small difference in modulus between σ_1 and σ_2 may account for the high frequency of strike-slip faults together with normal faults.

In spite of the difficulty of accurate dating, late Paleozoic brittle deformations in the Massif Central are consistent with an extensional stress field characterized by NE-SW to N-S maximum stretching.

Extensional Ductile Deformation in the Lower Crust

The Late Carboniferous ductile deformation is localized within granite-migmatite domes (Figure 1).

The Velay dome is the largest late orogenic deep seated structure in the Massif Central (see *Dupraz and Didier*, [1988] for an extensive bibliography). A high temperature metamorphism (4-5 kbar and 800±50°C) developed at the expense of the Devonian structures, through migmatization and anatexis [*Montel et al.*, 1992]. The cordierite (± garnet) Late Carboniferous Velay granite dated at 298-274 Ma on the basis of whole rock Rb-Sr age [*Caen-Vachette et ai.*, 1982] is an anatectic massif coeval to the doming. Extensional tectonics are well documented in the northern margin of the Velay dome, along the Pilat detachement fault. The $^{40}Ar/^{39}Ar$ dating supports a late Westphalian-Stephanian age for the cooling and uplift of the metamorphic pile [*Costa*, 1991]. The structure of the Velay dome is the result of the interference of a radial shortening due to the horizontal expansion of the granite during its emplacement and a vertical shortening related to the regional late Variscan extension. [*Lagarde et al.*, 1993].

The axial zone of the Montagne Noire is a gneissic dome recognized since *Gèze* [1949]. Cordierite-garnet granitoids and migmatites occupy the core of an ENE-WSW elongated elliptical structure. N50°E to N70°E stretching lineation is conspicuous in both the migmatite and gneiss-mica schist envelope. Divergent kinematics, namely, top-to-the-NE and top-to-the-SW shears at the NE and SW terminations of the dome, respectively, and coaxial strain between are well known. The axial zone dome is variously interpreted as a basement antiformal stack, diapir, or strike-slip-related or pure extensional core complex [e.g., *Schuilling*, 1960; *Beaud*, 1985; *Faure and Cottereau*, 1988; *Echtler and Malavieille*, 1990; *Van den Driessche and Brun*, 1989, 1991; *Cassard et al.* 1993]. Indeed, if Late Carboniferous ductile deformation in the footwall of the Graissessac basin is supported by structural and radiometric data, in the dome core the $^{40}Ar/^{39}Ar$ age of 316±4 Ma on biotite [*Maluski et al.*, 1991] indicates also a Namurian event coeval with recumbent folding before doming. Therefore the Late Carboniferous extension followed a Middle Carboniferous compression in the axial zone of the Montagne Noire.

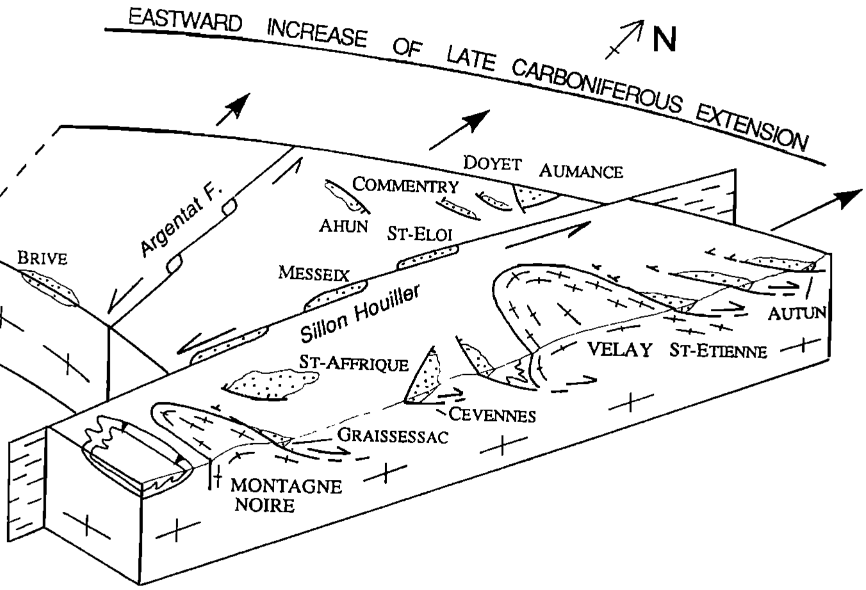

Figure 14. Schematic representation of the Late Carboniferous-Early Permian extension due to doming and basins opening. The west to east increase of extension rate is accomodated by the Sillon Houiller and Argentat fault.

Discussion

The Late Carboniferous-Early Permian extension, recognized in the whole Massif Central, is responsible for the massif's present width. NE-SW maximum stretching, transverse to the general trend of the belt, increases from west to east (Figure 14). In the eastern part, extension caused doming and opening of more than 10 coal basins. In the Limousin area, brittle NE-SW stretching is recorded in the basement of the coal basins, but neither granite-migmatite dome nor ductile deformation of late Carboniferous age is reported. West of the Sillon Houiller, coal basins are few and are smaller than those to the east. The submeridianal strike-slip faults of the Sillon Houiller and the Argentat fault might be interpreted as tear faults to accomodate the variable amount of extension on both parts of the Massif Central [*Burg et al.*, 1990]. A minimum estimate of stretching is provided by the cumulative length of the pull-apart basins parallel to the fault. In the case of the Argentat fault it is about 10 km, whereas it reaches more than 95 km for the Sillon Houiller. The Sillon Houiller that stretches along more than 500 km is the major late orogenic structure of the Massif Central [*Grolier and Letourneur*, 1968]. However, ductile deformation related to wrenching is rare, and a pre-Stephanian activity of the Sillon Houiller is not demonstrated. Therefore, as the initiation of such a large fault in Late Carboniferous time only seems very unlikely, we tentatively suggest here that, owing to its N20°E trend, the "Proto-Sillon Houiller" was initiated during Middle Carboniferous as a normal fault. Our preliminary results in the Montmarault area (Figure 4) support this interpretation.

The Middle Carboniferous NW-SE extension is quite different. It is a diachronous event that started in late Visean in the northern Massif Central and later reached the Cévennes area (Figure 15). In late Visean, in the Montagne Noire, recumbent folds emplaced with a NNE-SSW stretching lineation but elongation occurred also along the E-W direction. The related strain ellipsoid lies in the oblate field. In the north Massif Central, the finite strain ellipsoid has a prolate shape, since NW-SE maximum stretching is coeval with NE-SW shortening. In terms of finite strain, the relationships between NW-SE extension in the north Massif Central and NNE-SSW compression in the Montagne Noire can be qualitatively seen as an exchange between the X and Y finite strain axes in the horizontal plane; the axis of maximum shortening Z remains vertical.

Although ductile normal faults with N-NE to S-SW stretching have been recently described in the southern part of the Armorican massif [*Gapais et al.*, 1993], the Armorican massif is characterized, in Carboniferous time, by right-lateral strike-slip motion and synkinematic granite emplacement. Along the southern Armorican shear zone, maximum shortening trends NE-SW, and vertical finite elongation is small since deformation is close to simple shear [*Berthé et al.*, 1979]. The transition from wrench to extensional tectonics can be seen as an exchange between Y and Z axes in the vertical plane normal to the trajectory followed by the X axis along the Armorican shear zone (Figure 15).

Late orogenic extensional tectonics are not limited to the Massif Central. To the east, ductile normal faulting and syntectonic plutonism of Visean to Namurian age is found in

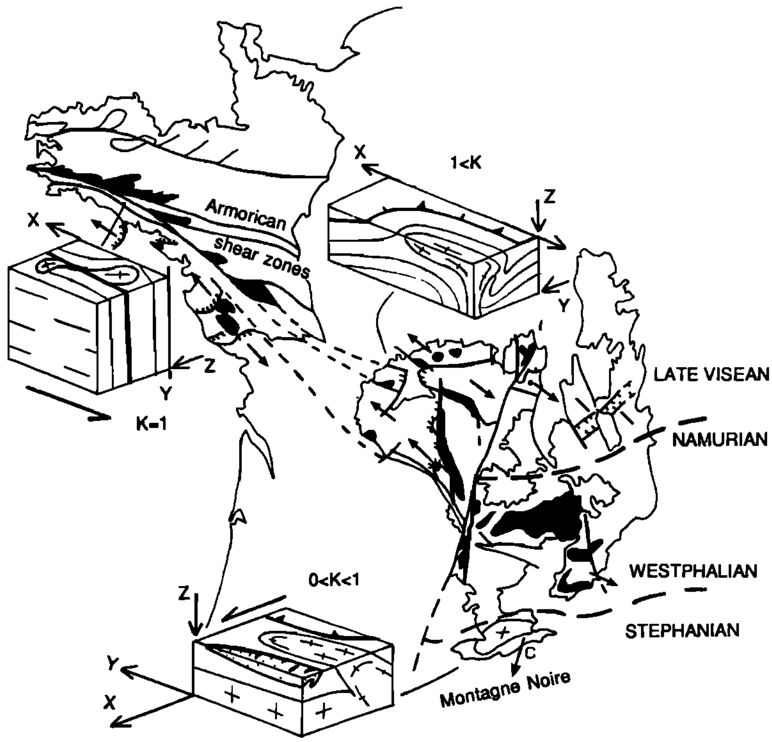

Figure 15. Relationships between wrench, extension, and compression in the southern Armorican-Massif Central branch of the Variscan belt. Late Visean, Namurian, Westphalian, and Stephanian correspond to the age of begining of extension which is shifted to the south with time. Solid areas are the main Carboniferous plutons used as crustal strain markers. Bar indicates the stretching direction; arrows show the sense of shear of the upper part.

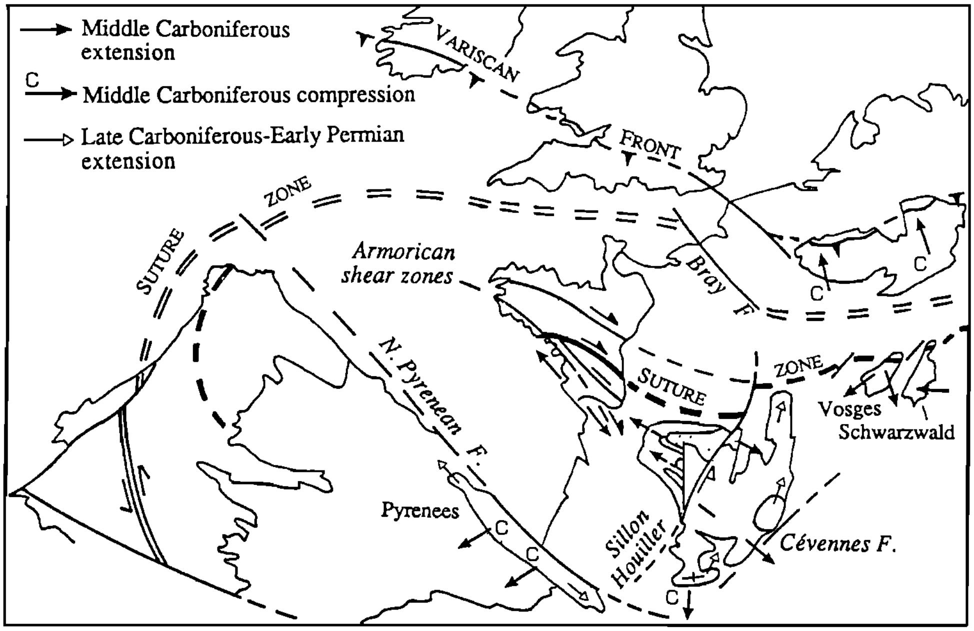

Figure 16. The two stages of extensional tectonics of the Massif Central located within the W. European Variscan Belt. Note the discrepancy in azimuth for the Late Carboniferous-Early Permian extension directions in the Massif Central and Pyrénées.

the Vosges and Schwarzwald [*Rey et al.*, 1991; *Echtler and Chauvet*, 1991]. However the extension direction is at variance: E-W in Schwarzwald, NW-SE in eastern Vosges and NE-SW in western Vosges. Late orogenic extensional tectonics are also described in the Variscan Pyrénées [e.g., Vissers, 1992], but a discrepancy remains with respect to the extensional pattern in the other Variscan massifs. In the Pyrenées, extension started during the early Stephanian with a NW-SE maximum stretching direction. This trend is almost perpendicular to the trend described in the Massif Central (Figure 16). Systematic structural studies and accurate dating of these events are still needed.

Conclusion

Several lines of evidence support a Late Carboniferous-Early Permian extensional stress field in the French Massif Central. The NE-SW trend is the maximum stretching direction that controlled (1) the opening of intramontane coal basins which exhibit a typical half graben geometry, (2) the formation of pull-apart troughs along the tear faults, (3) the uplift of granite-migmatite domes, (4) the localization of ductile deformation along normal or normal-wrench faults, and (5) the brittle faulting widespread in the upper plate metamorphic rocks. At the scale of the whole massif, extension appears to be asymmetric since top to the NE shear is predominant. Last, the Carboniferous-Permian unconformity is not evidence for a compressional event in the Massif Central. This tectonic style has been compared to the Basin and Range Province of the western United States [*Ménard and Molnar*, 1988; *Malavieille*, 1993].

The Middle Carboniferous extensional tectonic regime presents contrasting characters. In spite of lack of upper crustal strain markers, extension is well recorded by its structural, metamorphic, and plutonic effects in the deep crust. A conspicuous ductile stretching occurred along the NW-SE trend and in the same time, NE-SW horizontal shortening produced large-scale antiforms and synforms. These two finite strain directions controlled the emplacement and shape of the intrusions. The synkinematic granitoids exhibit typical features such as asymmetric shape, recumbent peripheral lobes, and NW-SE lineation formed in subsolidus to postsolidus states, which reflect the dynamics of the extending crust.

The Middle Carboniferous extension is a diachronous event which propagated southward. The temporal transition between the two orthogonal extensional tectonic regimes remains to be studied from the point of view of stress and strain fields. Two possibilities are tentatively suggested here for the strain history. First, the X and Y axes of the finite strain ellipsoid which lay in the horizontal plane rotated around the vertical Z axis from Middle Carboniferous (late Visean) to Early Permian (Autunian). Second, the finite strain axes remained fixed in direction but varied in modulus; thus the X and Y strains underwent a transient stage of flattening strain ($X=Y$). The understanding of the Variscan extensions in the Massif Central will be greatly improved by the increase of the accuracy of radiometric dating.

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