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ABSTRACT

In the Variscan French Massif Central and Massif Armoricain, the tectonic significance of a widespread NW-SE trending stretching lineation, coeval with medium pressure-medium temperature metamorphism, is an open question. Based on a structural analysis in the Southern part of the Massif Central, we show that this top-to-the-NW shearing is a deformation event, referred to as D2, that followed a D1 top-to-the-South shearing Devonian phase, and was itself re-deformed by a Late D3 Visean-Serpukhovian southward thrusting event. We date the D2 phase at 360 Ma (Famennian-Tournaisian boundary). In the Massif Armoricain, D2 is the "Bretonian phase" recorded in the metamorphic series and sedimentary basins. Geodynamically, D2 is related to a general northwestward shearing during the Laurussia-Gondwana collision, which occurred after the closure of the Rheic Ocean, as indicated by the emplacement of the Lizard ophiolitic nappe in Britain. The left-

lateral Nort-sur-Erdre fault accommodated the absence of ductile shearing in Central Armorica.

Keywords: Variscan belt, Bretonian phase, French Massif Central, Massif Armoricain

1. Introduction

It is widely acknowledged that the Variscan Belt of Western Europe formed as a result of the multiple collisions that occurred between Gondwana to the South and Laurussia to the North, from Early Devonian to Carboniferous times.These collisions stacked together continents and micro-blocks such as Armorica or Mid-German Crystalline Rise that had been previously drifted from Gondwana (e.g. Holder and Leveridge, 1986; Pin, 1990; Matte, 1986, 2001; Franke, 2000; Faure et al., 2005, 2008; Lardeaux et al., 2014). In the French Massif Central (FMC, Fig. 1A), a polyphase syn-metamorphic deformation is well documented (e.g. Faure et al., 2009 and enclosed references). By analogy with the Himalayas, it was initially proposed that a ductile south-directed shearing, active from Late Devonian to Middle Carboniferous accommodated the nappe stacking with younging from North to South (e.g. Mattauer 1974; Mattauer and Etchecopar, 1977; Matte, 1986; Ledru et al., 1989). Top-to-the-South shearing is indeed well established in the southern part of the French Massif Central (Montagne Noire and Cévennes, Fig. 1) –where it is referred to as a “D3 event”, but more to the North and West, in Lot, Rouergue, Lyonnais, Sioule and Limousin, the dominant structure is instead a NW-SE stretching lineation with a top-to-the-NW shearing. The tectonic significance of this NW-SE deformation and its relations with the widespread southward D3 shearing are not clear. According to Brun and Burg, (1982) and Burg et al., (1987), the top-to-the-NW shearing would be due to a combination of southward thrusting and sinistral wrenching during the ibero-armorican oroclinal bending. Mattauer et al., (1988) considered this deformation as a consequence of extensional tectonics, whereas Bouchez and Jover (1986), Friedrich et al., (1988), Faure et al. (2005), and Bellot and Roig (2007) argued that it corresponds to a nappe stacking. This event is referred to as the "D2 event" (Faure et al., 2009).

Here we present structural and dating data in the Rouergue-Albigeois (Fig. 1B) area, which allow us to discriminate and date the S- and NW-ward displacement events (D3 and D2). We report similar observations in the Massif Armoricain. We propose a geodynamic interpretation of the D2 event in the two massifs in the general framework of the Laurussia-Gondwana continental collision.

2. The architecture of the Southern Massif Central

The French Massif Central stack of metamorphic nappes belongs to the northern Gondwana margin. From top-to-bottom, the following units are recognized: 1) the Upper Gneiss Unit, 2) the Lower Gneiss Unit, 3) the Para-Autochthonous domain, 4) the Fold-and-Thrust Belt, and 5) the Southern Foreland. South of the Margeride pluton, the nappe architecture exhibits several particularities, which we describe below (Figs. 1, 2).

2.1 The Upper Gneiss Unit (UGU) crops out as several klippes (Marvejols, Vibal, Lévézou, Najac, and Decazeville). It is made of an association of felsic-mafic-ultramafic rocks and sedimentary rocks, called the leptynite-amphibolite complex. This complex experienced a high pressure-medium temperature (HP/MT) metamorphism (Nicollet and Leyreloup, 1978; Burg et al., 1986, 1989; Bodinier and Burg, 1980-1981) at 415±5 Ma (U/Pb) or 408±7 Ma (Sm/Nd), thus in Late Silurian-Early Devonian (Pin and Lancelot, 1982; Paquette et al., 1995). During their exhumation, most of the eclogites were retrogressed in the amphibolite facies and the melting of the Al-rich part produced migmatite. Due to its circular shape in map view and the abundance of anatexites in its center, the southernmost Lévézou klippe has long been considered as a diapiric dome (Collomb, 1970; Burg, 1987; Collomb and Meyzindi, 1991). However, structural and gravimetric data show that the amphibolites and migmatites are not rooted in the Lower Gneiss Unit but rather overlie it (Matte, 1986; Bayer and Hirn, 1987). The UGU klippes have thus been displaced to the SW. As a matter of fact, northwestward overturned folds deform the UGU foliations. As we explain below, they are attributed to the D2 deformation phase.

2.2. The Lower Gneiss Unit (LGU) consists of metagreywackes and metapelites that never experienced any HP/MT metamorphism. Several plutons that intrude the LGU, such as the Caplongue diorite (557±10 Ma, U/Pb on zircon, Lafon, 1984), the Rodez alkaline granite, and the Pinet and Comps porphyritic monzogranites, have been transformed into augen orthogneiss.

2.3. The Para-autochthonous Unit (PAU), well exposed in Cévennes, consists of a thrust sheet-imbrication of greenschist facies metapelites, quartzites, and metagrauwackes with subordinate layers of conglomerate, felsic and mafic lava, and rare intrusions (Pin and Marini, 1993; Caron, 1994). In the Albigeois area, the PAU has been subdivided into the S^{t}-Sernin-sur-Rance and the S^{t}-Salvi-de-Carcavès nappes (Guérangé-Lozes and Guérangé, 1984; Guérangé-Lozes, 1987; Guérangé-Lozes and Burg, 1990). The lithostratigraphy of these two nappes is similar, with, from base to top, Cambrian greywacke, rhyolite and ignimbrite, Ordovician white quartzite, and black metapelite. However, a biotite-garnet ±staurolite assemblage is fairly common in the former but is absent in the latter.

2.4. The Fold-and Thrust Belt, developed in the Montagne Noire and the Viganais, is composed of unmetamorphozed fossiliferous Paleozoic sedimentary rocks terminated by a Late Visean to Serpukhovian turbiditic basin. The series have been deformed,by South-directed thrust sheets and km-scale recumbent folds (Gèze, 1949; Arthaud, 1970; Engel et al., 1980-81). The Montagne Noire axial zone is a migmatitic dome that cross-cuts the folds and thrusts. This area is beyond the scope of this paper.

3. Polyphase shearing in the Southern Massif Central

The pervasive foliation developed in the UGU, LGU, and PAU units results from three synmetamorphic ductile deformations, D1, D2, D3, each associated with specific kinematics and P-T conditions. The three deformation phases are described below from the youngest to the oldest.

3.1. The D3 Carboniferous southward thrusting phase. Spectacular km-scale, southward overturned recumbent folds characterize the Paleozoic Fold-and-Thrust Belt (e.g. Arthaud, 1970, Arthaud and Matte, 1977). In the Southern Montagne Noire, folding is coeval with horizontal cleavage and rare N-S to N30E trending mineral and stretching lineation (Fig. 1). A more dominant lineation exists, that strikes NE-SW (Lee et al 1988; Echtler and Malavielle, 1990). This NE microstructure is a late feature since it overprints the already deformed series. The NE lineation is coeval with a HT/LP metamorphic event that has been related to the doming of the axial zone (e.g. Courtillot et al., 1986; Echtler and Malavieille, 1990; Faure et al. 2014). In the Northern Montagne Noire and the S^{t}-Salvi-de-Carcavès nappe, the submeridian stretching lineation is coeval with a top-to-the-S sense of shear (Brunel et al., 1974; Guérangé-Lozes, 1987). In map view, the basal thrust of the D3 S^{t}-Salvi-de-Carcavès nappe truncates the bedding surface (Figs. 1, 2). The D3 event recognized in the PAU series in Cévennes and at the base of the UGU series in Marvejols is dated at ca 335-325 Ma and 340-335 Ma, respectively (Pin and Lancelot, 1982; Caron, 1994; Faure et al., 2001). Therefore, the D3 event is clearly younging southward. Moreover, the D3 structures are locally overprinted by a top-to-the-north shearing related to the Late Carboniferous extensional tectonics (Arnaud and Burg, 1993) that are not considered here (cf. Faure et al., 2009 for details).

3.2. The D2 Early Carboniferous top-to-the-NW shearing phase. The main deformation of the S^{t}-Sernin-sur-Rance nappe is characterized by a flat-lying foliation and a NW-SE trending mineral and stretching lineation ascribed to the D2 phase. Near Naucelle (Fig. 1), top-to-the NW shear criteria coeval with a biotite-garnet-staurolite metamorphism is observed (Fig. 3C, E, F; Burg et al., 1986; 1989). A flat-lying mylonitic fabric with NW-SE trending folds with axes parallel to the stretching lineation developed during the ductile shearing that accommodated the tectonic superposition of the S^{t}-Sernin-sur-Rance nappe upon the LGU (Fig. 3A, B). Further east, the dip of the foliation increases progressively to become SW east of Naucelle, and vertical south of the Lévézou klippe. The kinematic consistency from a top-to-the-NW shearing developed in the flat-lying foliation to dextral one observed in vertical surfaces with subhorizontal stretching lineation suggests a wrench-thrust structure. The D2 deformation phase is not recognized in the S^{t}-Salvi-de-Carcavès nappe and farther south, but in contrast, it is clearly observed in the north in the LGU, and to a lesser extent, in the UGU units.

3.3. The D1 early southwestward shearing phase. The D2 top-to-the-NW shearing event was preceded by an earlier deformation phase that is well observed in the UGU and LGU series, in the S^{t}-Sernin-sur-Rance and S^{t}-Salvi-de-Carcavès nappes in the Rouergue area. Where the units are not deformed by the later D2 and D3 events, a N-S to N30°E trending stretching lineation is observed, associated with intrafolial folds and top-to-the-SW shearing (Figs. 1, 3D). Yet, at many places, the D2 NW-SE trending folds deformed this early mineral lineation (Fig. 3A,B D). In the S^{t}-Sernin-sur-Rance nappe, km-scale S-verging recumbent folds appear re-deformed by the D2 deformation, and hence are attributed to the D1 phase (Guérangé-Lozes, 1987). The D1 top-to-the-S stretching lineation is observed in the Rodez orthogneiss of the LGU series, and in the UGU gneiss, amphibolite and migmatite of the Lévézou and Vibal klippes.

The foliated Pinet orthogneiss has recorded both the D1 and the D2 deformation events. Although the D2 NW-SE lineation is dominant in many places (Fig. 1, Burg and Teyssier, 1983), an older N-S trending D1 mineral lineation is observed where the D2 overprint is lacking. Petro-structural analysis documents a top-to-the-south shearing coeval with a high-temperature deformation, whereas low-temperature top-to-the-NW shear bands are ascribed to the D2 phase (Fig. 3D, Duguet and Faure, 2004).

4. Chronological constraints

4.1 Timing of the polyphase shearing in the Southeast Massif Central. Due to their similar submeridian trend and top-to-the-South sense of shear, the D1 and D3 deformation events have been so far considered as the result of a single, long duration intracontinental shearing period, operating during the "Himalayan thrusting" (Mattauer, 1974, Mattauer and Etchecopar, 1977). However, we have shown that the D1 and D3 events are diachronous since they are separated in time by nearly 40 Ma. The age of the D3 event is well constrained as this event deforms the Late Visean-Early Serpukhovian (330-325 Ma) syntectonic flysch basin of the Southern Montagne Noire. Muscovite populations from the Mendic orthogneiss and the S^{t}-Salvi-de-Carcavès nappe metasandstone yield ^{40}Ar/^{39}Ar ages of 330±-3 Ma and 333±4 Ma, respectively (Costa, 1990). These Visean ages are similar to those available in the Cévennes area (Caron, 1994; Najoui et al., 2000).

The biotites, muscovites and amphiboles aligned along the NW-SE lineation reveal ^{40}Ar/^{39}Ar ages in the range 354-346 Ma. Since the closure temperature of micas is lower than that of the metamorphic climax, the above ages provide the minimum age of the D2 event. In the S^{t}-Sernin-sur-Rance nappe, muscovites from quartzites yield a 345±3.5 Ma age. In the UGU and LGU series, biotites, muscovites and amphiboles yield consistent ^{40}Ar/^{39}Ar ages in the range 354-346 Ma (Costa, 1990). The age of the D1 event is still poorly constrained with only one $^{40}Ar/^{39}Ar$ muscovite age of 380±10 Ma (Guérangé-Lozes, 1987).

Whatever the precise absolute age of the three D1, D2 and D3 events, their relative timing allows us to draw an interpretative general cross-section (Fig. 2). The top-to-the-SW D1 structures were folded in the Late Devonian-Early Carboniferous by the northwestward D2 deformation. Later, during the Middle Carboniferous, the D3 southward shearing event re-deformed the whole stack. This new interpretation makes the Pinet orthogneiss a pre-D1 pluton.

4.2. New zircon U-Pb age of the Pinet orthogneiss. The Pinet orthogneiss is a monzogranite or syenogranite foliated in a variable way, that includes both nearly undeformed facies at local spots, and mylonitic to ultramylonitic shear zones at other spots. A detailed petro-structural study of the Pinet orthogneiss has revealed that the pluton experienced two deformation phases, ascribed to the D1 and D2 events (Duguet and Faure, 2004). The early deformation phase is coeval with a pervasive post-solidus planar fabric and a N-S striking lineation. The second deformation phase is characterized by a local foliation cross-cutting the previous one, and a NW-SE striking lineation with top-to-the-NW shearing. Zircon populations in the granite yielded a TIMS U-Pb age of ca 360±20 Ma (Pin, 1981), whereas a biotite single grain was dated at 346±7 Ma using the $^{40}Ar/^{39}Ar$ method (Maluski and Monié, 1988).

We separated zircon concentrates from two samples (FR 41 and FR 42) of the porphyritic orthogneiss, located along the Tarn river, at 44° 03' 16.27"/002° 45' 56.35" and 44° 02' 43.57"/002° 46' 47.70", respectively. We applied analytical procedures and data reduction as in Li et al. (2009) and Do Couto et al. (2016). Cathodoluminescence images of the zircon grains show a well developed oscillatory zoning representative of a magmatic origin of the grains (Fig. 5).

Zircons from the two rock samples yield consistent Ordovician ages of 477±5 Ma and 475± 4 Ma (Fig. 5); these ages are interpreted as dating the emplacement of the porphyritic granite. This new result shows that the Pinet orthogneiss is not a syn-kinematic pluton emplaced during the D1 or D2 events, but instead formed in the Early Ordovician pre-orogenic magmatism phase that is widespread in the Variscan belt. The ca 350 Ma $^{40}Ar/^{39}Ar$ age of post-folial biotite corresponds to the D2 event.

5. Discussion-conclusion

5*.1. Significance of the three D1, D2 and D3 tectono-metamorphic events.* The D1 event is recognized in the Lyonnais, Sioule, Limousin, and Plateau d'Aigurande areas of the Massif Central. It is is coeval with the Middle Devonian (385-375 Ma) migmatization, that was interpreted as the result of the exhumation of the HP rocks of the UGU series (cf Faure et al., 2008 for details).

The Late Devonian-Early Carboniferous (360-350 Ma) D2 event with a top-to-the-NW shearing is also recognized in many places of the Massif Central (Fig. 6). In the LGU series of Marvejols (Fig. 1), biotites from metadiorite and micaschist, aligned along the NW-SE lineation, yield consistent $^{40}Ar/^{39}Ar$ ages of 352±2 and 351±3 Ma (Costa, 1990). The Limousin, Sioule and Plateau d'Aigurande series are affected by a consistent medium temperature-medium pressure metamorphism coeval with a top-to-the-NW shearing (e.g. Floc'h 1983; Bouchez and Jover, 1986; Friedrich at al., 1988; Faure et al., 1990, 1993, 2005; Roig and Faure, 2000; Bellot and Roig, 2007). Since the $^{40}Ar/^{39}Ar$ dates are very sensitive to the temperature, the monazite U-Th-Pb chemical chronometer that records high temperature events has also been carried out in the UGU, LGU, and PAU metapelites of Limousin and Sioule areas (Melleton et al., 2009; Do Couto et al., 2016). The 360-350 Ma ages yielded by the syn-D2 metamorphic monazites confirm the Famennian-Tournaisian age of the D2 event.

Furthermore, in eastern Massif Central, the Brévenne ophiolitic nappe was emplaced from SE to NW under amphibolite facies conditions, before the unconformable deposition of the Early Visean (i.e. 345 Ma) Le Goujet, terrigenous formation (Leloix et al., 1999). Thus the Brévenne ophiolitic nappe formed also during the D2 event.

The D3 event is identified only in the South Massif Central. The Visean to Serpukhovian southward migration from middle to shallow crustal levels is acknowledged since a long time as the consequence of the post-collisionnal nappe stacking (Matte, 1986; Ledru et al., 1989, Faure et al., 2009).

5.2. Geodynamic significance of the D2 event in the French Variscan segment. In the southern Massif Armoricain that belongs to the metamorphic zone of the Variscan chain, the D2 synmetamorphic shearing event is recognized in Vendée and south Brittany coast (Burg, 1981; Cannat and Bouchez, 1986; Fig. 6). There, an E-W to NW-SE striking mineral lineation develops on a flat-lying foliation, coeval with a MP/MT metamorphism characterised by a biotite-garnet-staurolite assemblage. Top-to-the-NW shearing shown by asymmetric pressure shadows and shear bands is conscpicuous.

More to the North, in Central Armorica, top-to-the-NW shearing is described only in the S^{t}-Georges-sur-Loire and Lanvaux units (Bouchez and Blaise, 1976; Diot et al., 1983; Cogné et al., 1983; Faure and Cartier, 1998; Cartier et al., 2001; Cartier and Faure, 2004). The pre-Visean age of the deformation is attested by the age of the terrigenous deposits of the Ancenis basin that did not record the D2 event. Therefore, the top-to-the-NW shearing, that is widespread in the Massif Armoricain and South Massif Central, is a major feature of the Variscan orogeny.

The MP/MT D2 metamorphism dated at ca 360 Ma, is coeval with the Devonian-Carboniferous "Bretonian phase" long recognized in the central part of the Massif Armoricain, through the Tournaisian unconformity and the widespread erosion of the Late

Devonian formations (e.g. Stille, 1929 in Rolet, 1982). In the 70's and 80's, on the basis of the gentle folding of the pre-Tournaisian formations, and the small unconformity angle (lower than 20°), the Bretonian phase was considered as a km-scale upright folding coeval with vertical movements, responsible for erosion and clastic sedimentation in the Laval and Châteaulin basins (e.g. Cogné 1965, 1974; Pelhâte, 1971; Paris et al., 1982; Houlgatte et al., 1988, Le Gall et al. 1992; Fig. 6). However, recumbent folds, ductile shear zones, and low angle thrust faults identified in the Brest area (Rolet et al., 1986) allow us to reassess the importance of the Bretonian phase.

The Variscan orogeny is the consequence of the closure of the Rheic ocean, and subsequent collision of Laurussia that was driven by a southward oceanic and then continental subduction below Gondwana. The Rheic suture is today hidden below the English Channel, but the Lizard ophiolitic nappe of SW Britain that overthrusts to the NNW the Laurussia foreland at ca 360 Ma is a remnant of the Rheic Ocean (e.g. Holder and Leveridge, 1986; Le Gall and Darboux, 1986; Sandeman et al., 1994). Therefore we argue here that the ductile and synmetamorphic, top-to-the-NW, shearing observed in the French Massif Central and South Armorica, and more broadly the Famennian-Tournaisian deformation ascribed to the Bretonian phase, are the result of the collision between Laurussia and Gondwana. Top-to-the NW shearing observed at the microtectonic scale results of the Variscan collision.

Although close to the Rheic suture, (Fig. 6), the syn-metamorphic ductile deformation does not exist in Central Armorica. A possible explanation would be to consider the contrasted mechanical behaviour between the Massif Central - South Armorican domain with a widespread D2 event, and the Central Armorican domain where D2 is absent. Due to its crustal rigidity, possibly related to the Neoproterozoic Cadomian orogeny, and the thick sub-continental mantle lithosphere, the Central Armorican domain behaved as a rigid plate characterized by sinistral wrenching, responsible for the opening of the Châteaulin and Laval basins (Fig. 7). In its southern margin, along the Nort-sur-Erdre strike-slip fault, and the S^{t}-

Georges-sur-Loire and Lanvaux units, the sinistral shearing accommodated the decoupling between the ductile and brittle domains (Cogné et al., 1983; Diot et al., 1983; Lardeux and Cavet, 1994; Faure et al., 1997; 2005; Cartier et al., 2001; Cartier and Faure, 2004). This interpretation, which is at variance to the previous geodynamic models (e.g. Ballèvre et al., 2009), provides a satisfactory solution for the significance of the D2 event in the French Variscan orogen.

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Figure Captions

Fig. 1: A Insert showing the Variscan belt in France. NASZ: North Armorican Shear Zone, NBSASZ: North Branch of the South Armorican Shear Zone, SBSASZ: South Branch of the South Armorican Shear Zone, NPF: North Pyrenean Fault, MGCR: Mid-German Crystalline Rise. B: simplified structural sketch of the French Massif Central (purple areas: Upper Gneiss Unit; the Lower Gneiss Unit and Para-Autochtonous Unit are not distinguished). C: Structural map of the S part of the French Massif Central with emphasis on the compressional structures. Syn- to late orogenic extensional structures are not considered here. Captions are the same as for Fig. 2.

Fig. 2: Crustal scale cross-section through the Montagne Noire-Rouergue area (location in Fig. 1). The bulk architecture results of three shearing events, D1, D2, and D3, with different ages and displacement directions.

Fig. 3: Field and thin section photographs showing D1 and D2 deformation in the S^{t}-Sernin-sur-Rance nappe and Lower Gneiss Unit. A: NW-SE trending D2 fold (L2) reworking an early NE-SW trending L1 lineation; B: NW-SE trending "a-type" fold deforming the L1

lineation; C: Low-temperature D2 top-to-the-NW shear zone reworking the foliated Pinet granodiorite; D: N-S striking intrafolial D1 fold; E: Thin section of staurolite porphyroblast with top-to-the-NW, D2, asymmetric biotite pressure shadows; F: Garnet with top-to-the NW, D2, pressure shadows.

Fig. 4: Cathodoluminescence images of representative zircons for SIMS U–Pb dating. White ellipses indicate the in-situ analytical spots of $^{206}Pb/^{238}U$ age (shown nearby the spot). SIMS spots are 30 μm in length for scale.

Fig. 5: Zircon ion-probe U-Pb age of the Pinet orthogneiss. Samples FR 41 and FR 42 are located at 44° 03' 16.27"/002° 45' 56.35", and 44° 02' 43.57"/002° 46' 47.70", respectively.

Fig. 6: Structural map of the French-Britain segment of the Variscan belt with emphasis on the D2 NW-SE shearing developed from Albigeois up to the Lizard nappe. The Late Carboniferous, south-directed, D3 event develops in southern Massif Central (Cévennes and Montagne Noire). At the scale of the entire Variscan belt, a top-to-the-North-directed deformation, characterized by thrust and faults, deforms the Ardenne Massif and the northern Variscan front.

Fig. 7: 3D Schematic geodymamic interpretative model to account for the tectonic difference between the Massif Central-Massif Armoricain areas dominated by the top-to-the D2 synmetamorphic ductile shearing, and the Central Armorican Domain, where D2 deformation is represented by brittle structures only. This difference in rheological behaviour can be explained by a tectonic decoupling between the two domains. The Neoproterozoic Cadomian orogeny, and the thick subcontinental lithosphere mantle may explain the rigid behaviour of the Central Armorican Domain in which the brittle deformation is associated with the opening

of the Châteaulin and Laval basins. The left-lateral Nort-sur-Erdre strike-slip fault can be seen as a transfer fault between the S. Gondwana and Central Armorican domains.

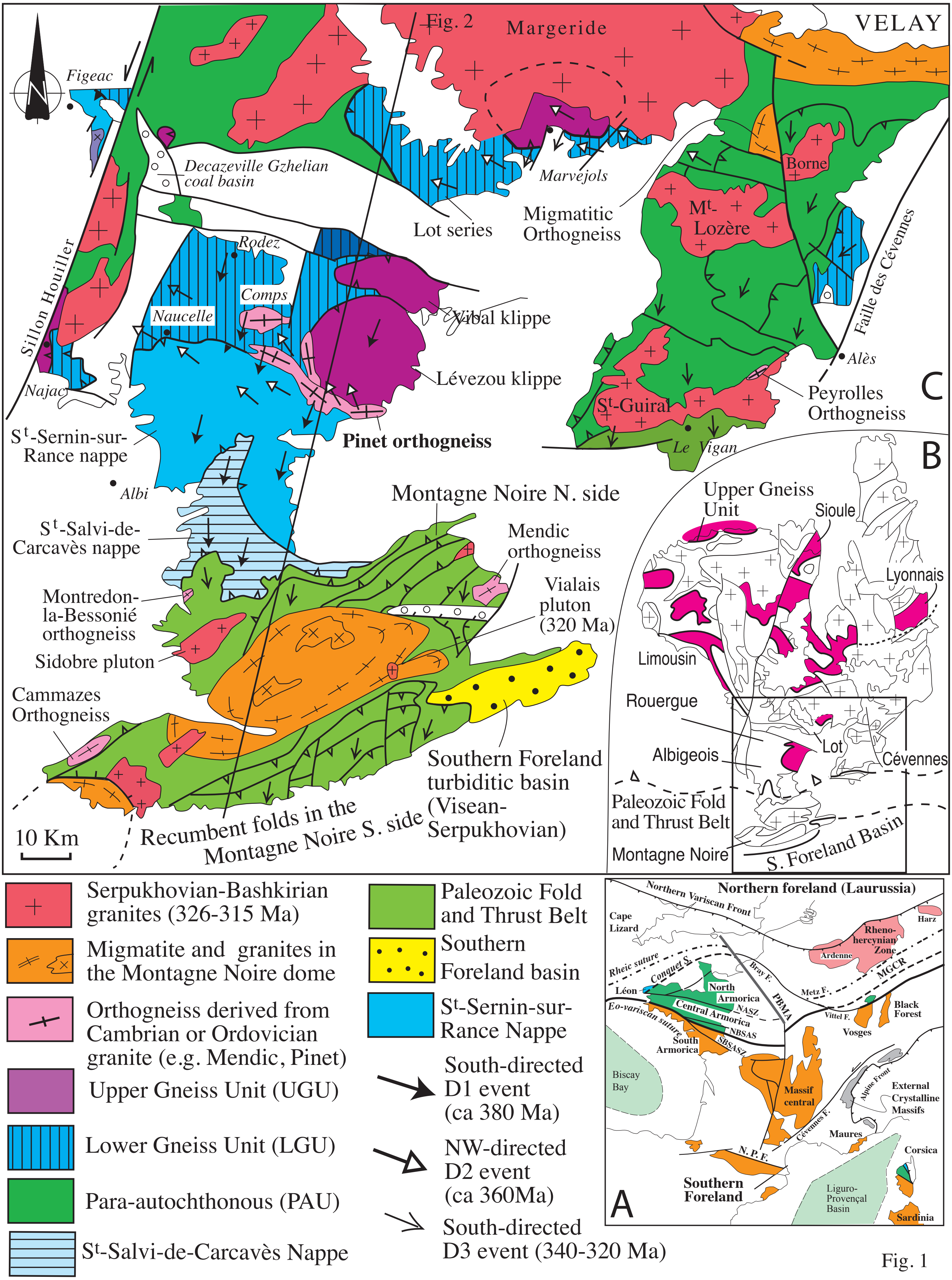
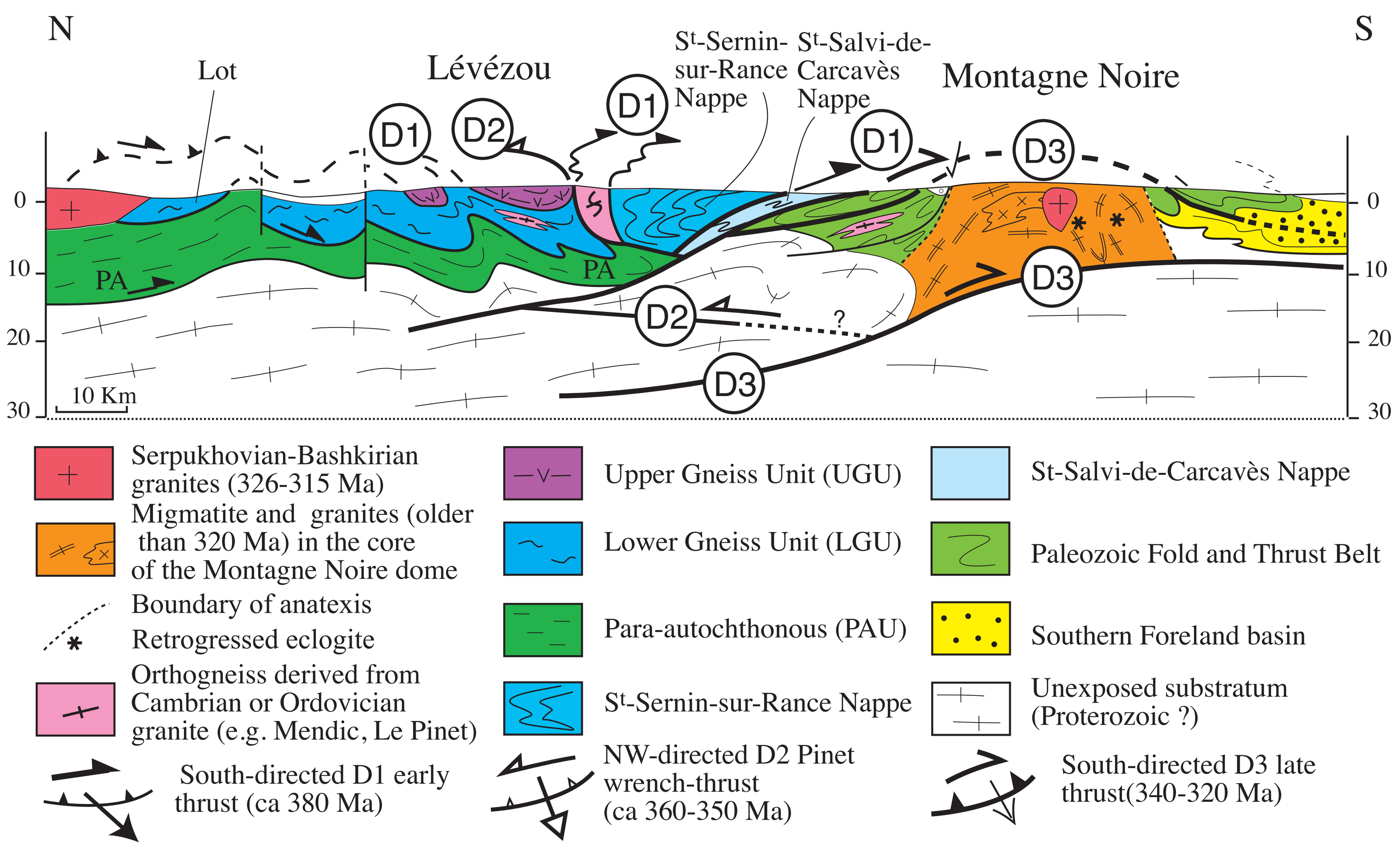


Fig. 2
Margeride
VELAY
Figeac
Decazeville Gzhelian coal basin
Marvejols
Lot series
Migmatitic Orthogneiss
Borne
Mt-Lozère
Faille des Cévennes
Sillon Houiller
Rodez
Comps
Naucelle
Vibal klippe
Lévezou klippe
Najac
Alès
Peyrolles Orthogneiss
St-Guiral
Le Vigan
C
St-Sernin-sur-Rance nappe
Pinet orthogneiss
B
Albi
Montagne Noire N. side
Upper Gneiss Unit
Sioule
St-Salvi-de-Carcavès nappe
Mendic orthogneiss
Lyonnais
Montredon-la-Bessonié orthogneiss
Vialais pluton (320 Ma)
Limousin
Sidobre pluton
Cammazes Orthogneiss
Rouergue
Lot
Albigeois
Cévennes
Southern Foreland turbiditic basin (Visean-Serpukhovian)
Paleozoic Fold and Thrust Belt
Recumbent folds in the Montagne Noire S. side
10 Km
Montagne Noire
S. Foreland Basin
Serpukhovian-Bashkirian granites (326-315 Ma)
Migmatite and granites in the Montagne Noire dome
Orthogneiss derived from Cambrian or Ordovician granite (e.g. Mendic, Pinet)
Upper Gneiss Unit (UGU)
Lower Gneiss Unit (LGU)
Para-autochthonous (PAU)
St-Salvi-de-Carcavès Nappe
Paleozoic Fold and Thrust Belt
Southern Foreland basin
St-Sernin-sur-Rance Nappe
South-directed D1 event (ca 380 Ma)
NW-directed D2 event (ca 360Ma)
South-directed D3 event (340-320 Ma)
Northern foreland (Laurussia)
Northern Variscan Front
Cape Lizard
Rheno-hercynian Zone
Harz
Ardenne
Rheic suture
Conquet S.
Bray F.
MGCR
Léon
North Armorica
NASZ
Metz F.
PBMA
Eo-variscan suture
Central Armorica
NBSAS
Vittel F.
Black Forest
South Armorica
SBSASZ
Vosges
Biscay Bay
Massif central
Alpine Front
External Crystalline Massifs
Cévennes F.
N. P. F.
Maures
Corsica
Southern Foreland
Liguro-Provençal Basin
Sardinia
A

Fig. 1



N
S
Lot
Lévézou
Sᵗ-Sernin-sur-Rance Nappe
Sᵗ-Salvi-de-Carcavès Nappe
Montagne Noire
D1
D2
D3
PA
10 Km
0
10
20
30
Serpukhovian-Bashkirian granites (326-315 Ma)
Migmatite and granites (older than 320 Ma) in the core of the Montagne Noire dome
Boundary of anatexis
Retrogressed eclogite
Orthogneiss derived from Cambrian or Ordovician granite (e.g. Mendic, Le Pinet)
South-directed D1 early thrust (ca 380 Ma)
Upper Gneiss Unit (UGU)
Lower Gneiss Unit (LGU)
Para-autochthonous (PAU)
Sᵗ-Sernin-sur-Rance Nappe
NW-directed D2 Pinet wrench-thrust (ca 360-350 Ma)
St-Salvi-de-Carcavès Nappe
Paleozoic Fold and Thrust Belt
Southern Foreland basin
Unexposed substratum (Proterozoic ?)
South-directed D3 late thrust(340-320 Ma)

Fig. 2

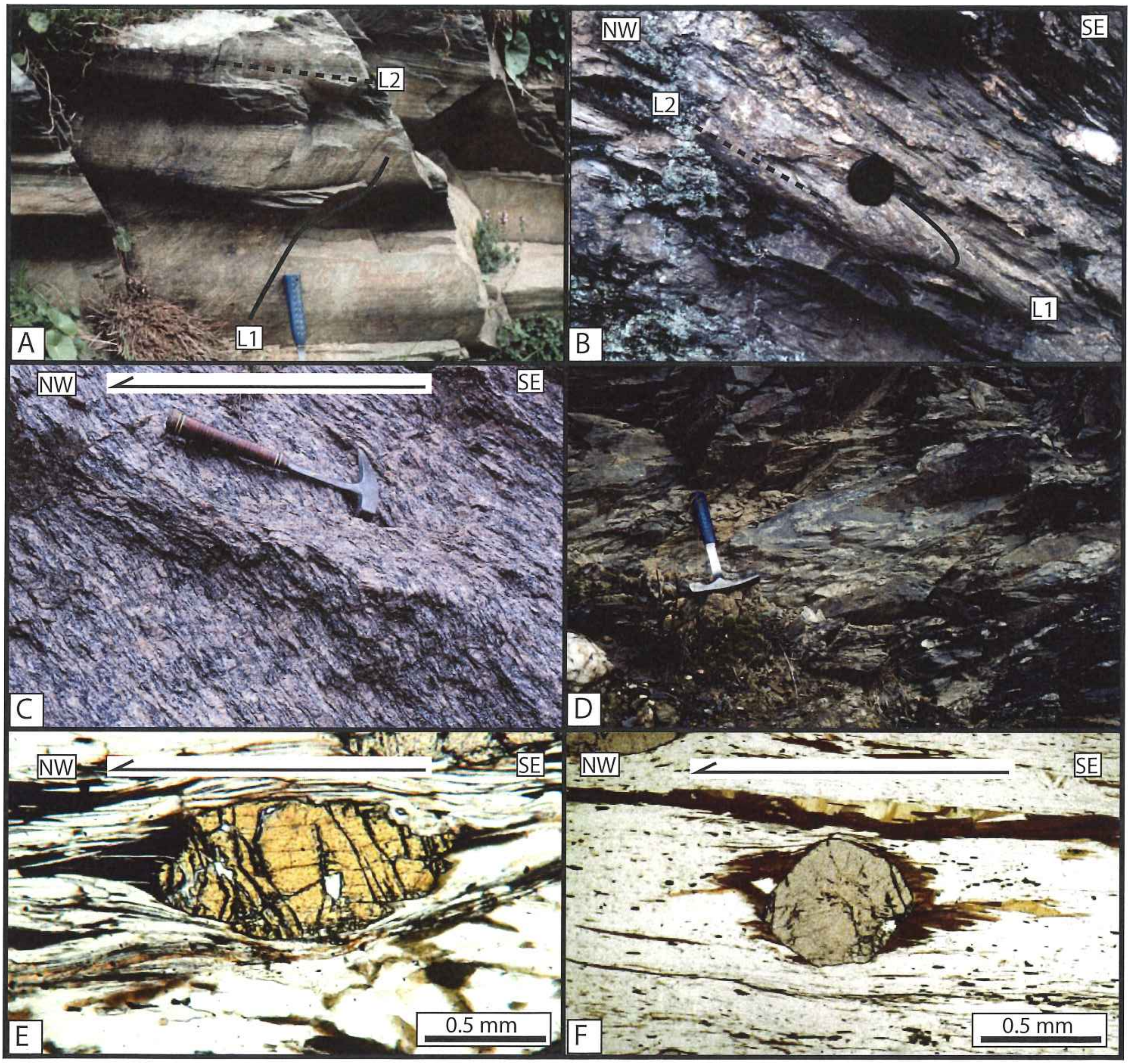
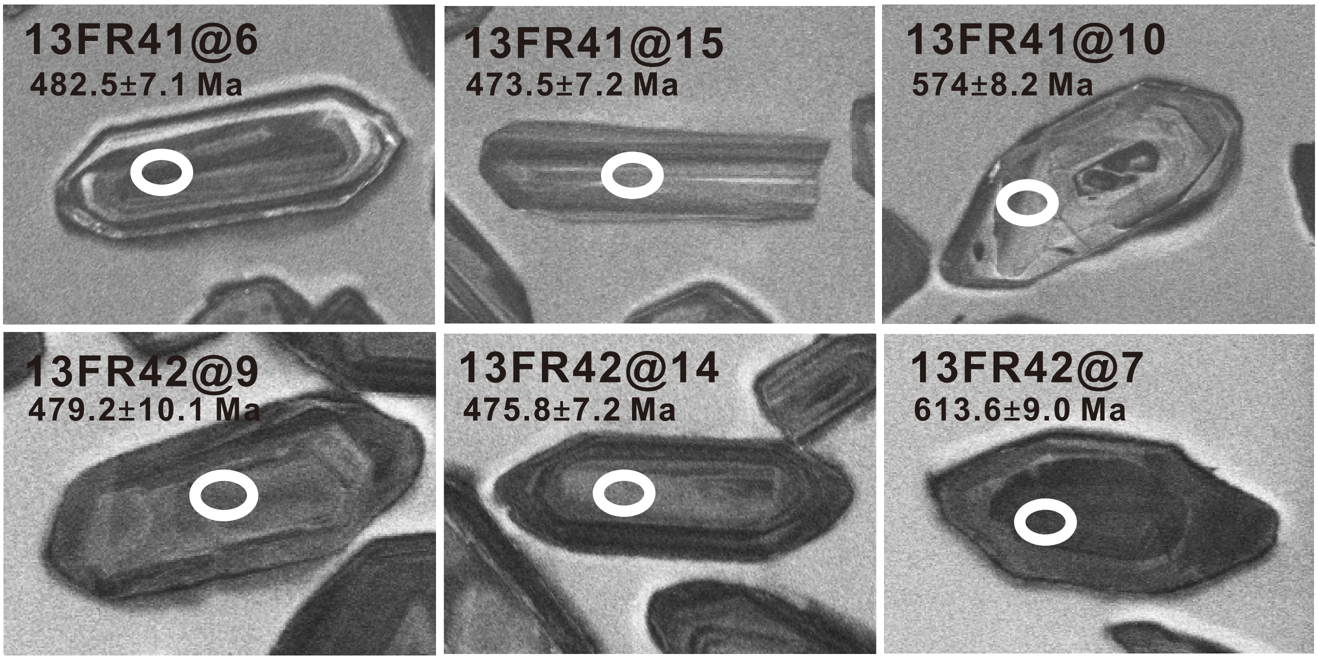


Fig. 3



13FR41@6
482.5±7.1 Ma
13FR41@15
473.5±7.2 Ma
13FR41@10
574±8.2 Ma
13FR42@9
479.2±10.1 Ma
13FR42@14
475.8±7.2 Ma
13FR42@7
613.6±9.0 Ma

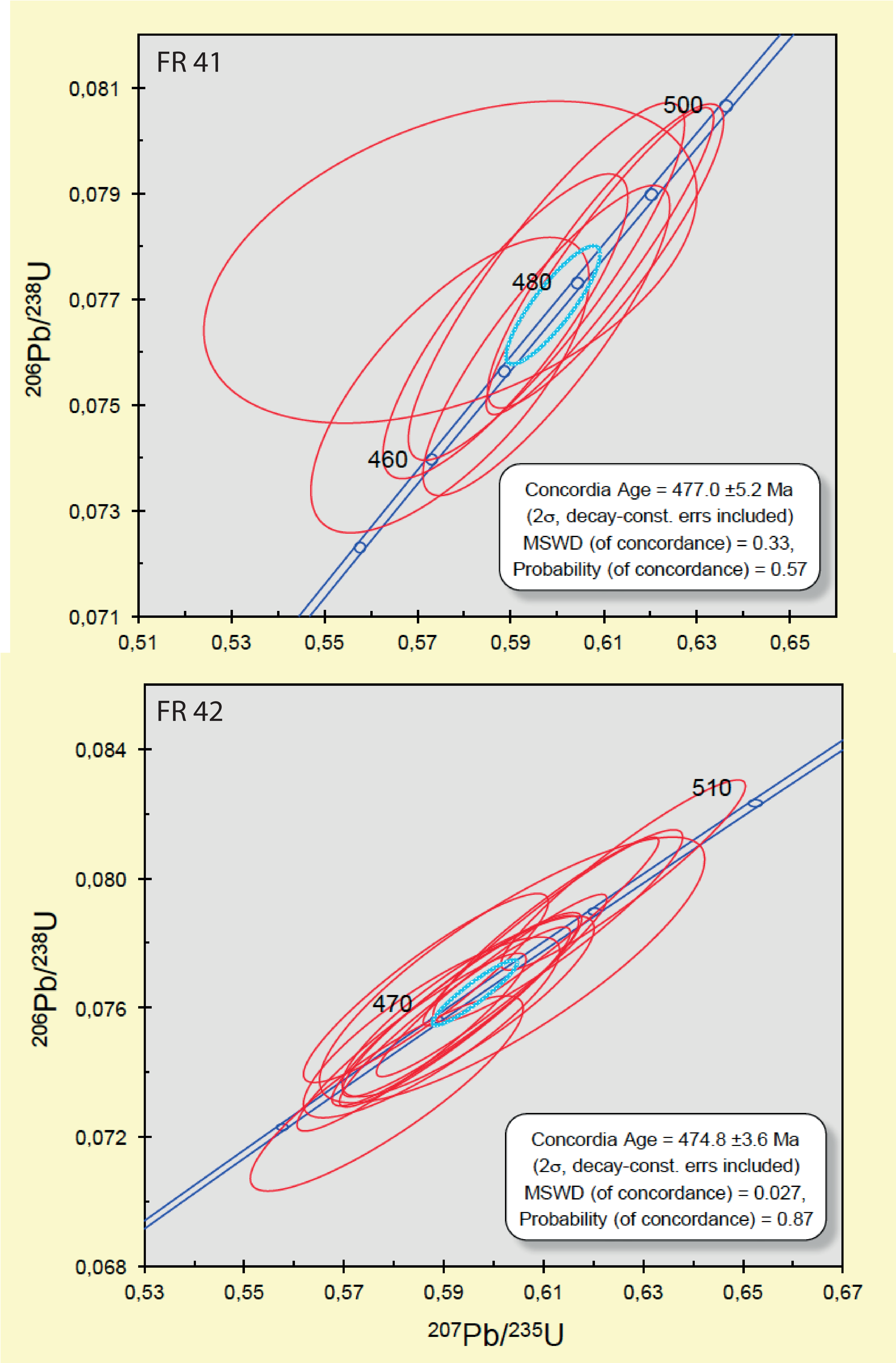
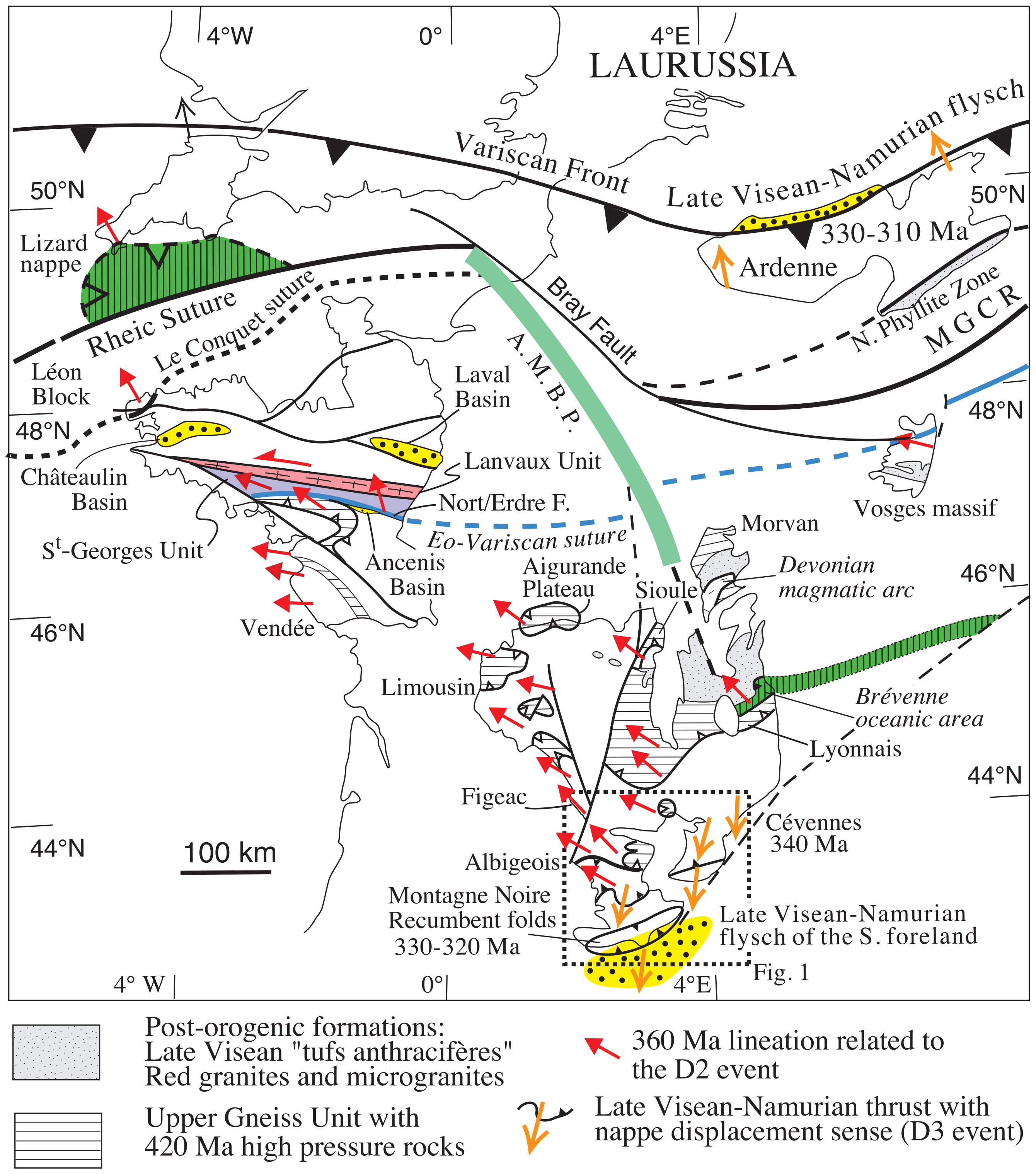

FR 41
0,081
0,079
0,077
0,075
0,073
0,071
0,51
0,53
0,55
0,57
0,59
0,61
0,63
0,65
$^{206}Pb/^{238}U$
500
480
460
Concordia Age = 477.0 ±5.2 Ma
(2σ, decay-const. errs included)
MSWD (of concordance) = 0.33,
Probability (of concordance) = 0.57
FR 42
0,084
0,080
0,076
0,072
0,068
0,53
0,55
0,57
0,59
0,61
0,63
0,65
0,67
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
510
470
Concordia Age = 474.8 ±3.6 Ma
(2σ, decay-const. errs included)
MSWD (of concordance) = 0.027,
Probability (of concordance) = 0.87

Fig. 5



LAURUSSIA
Variscan Front
Late Visean-Namurian flysch
330-310 Ma
Ardenne
N. Phyllite Zone
M G C R
Lizard nappe
Rheic Suture
Le Conquet suture
Bray Fault
A. M. B. P.
Léon Block
Laval Basin
Lanvaux Unit
Châteaulin Basin
Nort/Erdre F.
Eo-Variscan suture
St-Georges Unit
Ancenis Basin
Vosges massif
Morvan
Devonian magmatic arc
Aigurande Plateau
Sioule
Vendée
Limousin
Brévenne oceanic area
Lyonnais
Figeac
Cévennes 340 Ma
Albigeois
Montagne Noire Recumbent folds 330-320 Ma
Late Visean-Namurian flysch of the S. foreland
Fig. 1
100 km
4°W
0°
4°E
50°N
48°N
46°N
44°N
Post-orogenic formations:
Late Visean "tufs anthracifères"
Red granites and microgranites
Upper Gneiss Unit with 420 Ma high pressure rocks
360 Ma lineation related to the D2 event
Late Visean-Namurian thrust with nappe displacement sense (D3 event)

Fig. 6

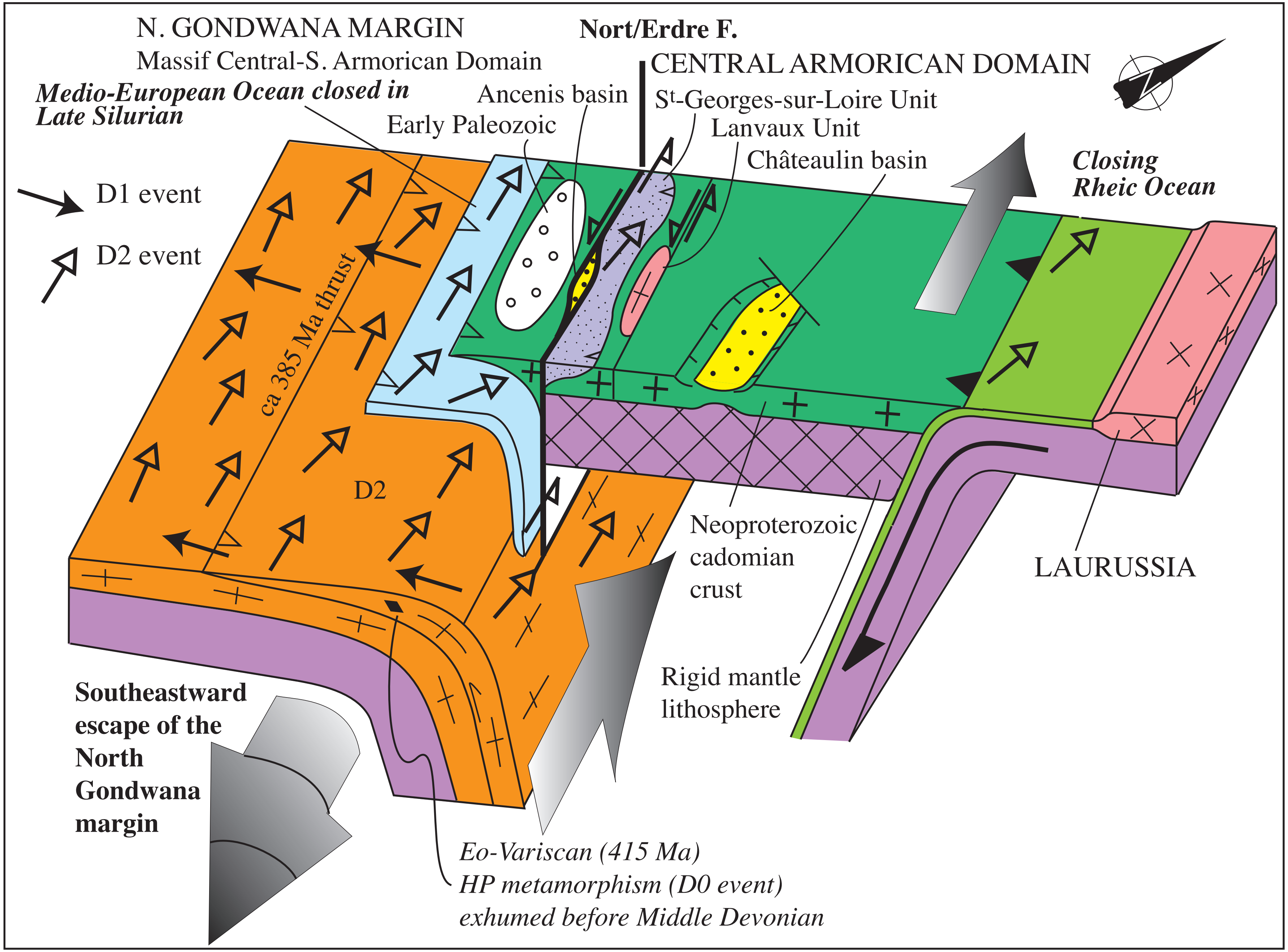

N. GONDWANA MARGIN
Massif Central-S. Armorican Domain
Nort/Erdre F.
CENTRAL ARMORICAN DOMAIN
Medio-European Ocean closed in Late Silurian
Ancenis basin
Early Paleozoic
St-Georges-sur-Loire Unit
Lanvaux Unit
Châteaulin basin
Closing Rheic Ocean
D1 event
D2 event
ca 385 Ma thrust
D2
Neoproterozoic cadomian crust
LAURUSSIA
Rigid mantle lithosphere
Southeastward escape of the North Gondwana margin
Eo-Variscan (415 Ma) HP metamorphism (D0 event) exhumed before Middle Devonian

Fig. 7