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Flow of partially molten crust controlling construction, growth and collapse of the Variscan orogenic belt: the geologic record of the French Massif Central

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Abstract – We present here a tectonic-geodynamic model for the generation and flow of partially molten rocks and for magmatism during the Variscan orogenic evolution from the Silurian to the late Carboniferous based on a synthesis of geological data from the French Massif Central. Eclogite facies metamorphism of mafic and ultramafic rocks records the subduction of the Gondwana hyperextended margin. Part of these eclogites are forming boudins-enclaves in felsic HP granulite facies migmatites partly retrogressed into amphibolite facies attesting for continental subduction followed by thermal relaxation and decompression. We propose that HP partial melting has triggered mechanical decoupling of the partially molten continental rocks from the subducting slab. This would have allowed buoyancy-driven exhumation and entrainment of pieces of oceanic lithosphere and subcontinental mantle. Geochronological data of the eclogite-bearing HP migmatites points to diachronous emplacement of distinct nappes from middle to late Devonian. These nappes were thrusted onto metapelites and orthogneisses affected by MP/MT greenschist to amphibolite facies metamorphism reaching partial melting attributed to the late Devonian to early Carboniferous thickening of the crust. The emplacement of laccoliths rooted into strike-slip transcurrent shear zones capped by low-angle detachments from c. 345 to c. 310 Ma is concomitant with the southward propagation of the Variscan deformation front marked by deposition of clastic sediments in foreland basins. We attribute these features to horizontal growth of the Variscan belt and formation of an orogenic plateau by gravity-driven lateral flow of the partially molten orogenic root. The diversity of the magmatic rocks points to various crustal sources with modest, but systematic mantle-derived input. In the eastern French Massif Central, the southward decrease in age of the mantle- and crustal-derived plutonic rocks from c. 345 Ma to c. 310 Ma suggests southward retreat of a northward subducting slab toward the Paleotethys free boundary. Late Carboniferous destruction of the Variscan belt is dominantly achieved by gravitational collapse accommodated by the activation of low-angle detachments and the exhumation-crystallization of the partially molten orogenic root forming crustal-scale LP migmatite domes from c. 305 Ma to c. 295 Ma, coeval with orogen-parallel flow in the external zone. Laccoliths emplaced along low-angle detachments and intrusive dykes with sharp contacts correspond to the segregation of the last melt fraction leaving behind a thick accumulation of refractory LP felsic and mafic granulites in the lower crust. This model points to the primordial role of partial melting and magmatism in the tectonic-geodynamic evolution of the Variscan

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orogenic belt. In particular, partial melting and magma transfer (i) triggers mechanical decoupling of subducted units from the downgoing slab and their syn-orogenic exhumation; (ii) the development of an orogenic plateau by lateral flow of the low-viscosity partially molten crust; and, (iii) the formation of metamorphic core complexes and domes that accommodate post-orogenic exhumation during gravitational collapse. All these processes contribute to differentiation and stabilisation of the orogenic crust.

Keywords: Variscan belt / French Massif Central / flow of partially molten crust / orogenic magmatism / orogenic plateau / Gravitational collapse

Résumé – Impact du fluage de la croûte partiellement fondue sur la construction, la croissance et l'effondrement de la ceinture orogénique Varisque : l'enregistrement géologique du Massif Central français. Nous présentons dans ce papier un modèle géodynamique-tectonique pour la genèse et le fluage des roches partiellement fondues et le magmatisme au cours de l'évolution orogénique Varisque du Silurien au Carbonifère supérieur basé sur une synthèse des données géologiques du Massif Central Français. La subduction de la marge du Gondwana hyper-étirée est enregistré par des roches mafiques et ultramafiques affectées par un métamorphisme en faciès éclogitique. Ces éclogites forment pour certaines des boudins-enclaves dans des migmatites felsiques avec des reliques de faciès granulitique de HP retrogradées en faciès amphibolitique, ce qui atteste de la subduction de la marge continentale suivie d'une relaxation thermique et d'une décompression. Nous proposons que la fusion partielle à HP ait déclenché le découplage mécanique entre la plaque plongeante et les unités continentales partiellement fondues. Ceci a permis l'exhumation de ces roches gravitairement instables qui ont entrainé sur leur passage des blocs de lithosphère océanique et de manteau sous-continental. Les données géochronologiques disponibles sur les migmatites de HP contenant des éclogites indique une mise en place diachronique de nappes du Dévonien moyen au Dévonien Supérieur. Ces nappes ont chevauché un assemblage de métapélites et d'orthogneiss affectées par un métamorphisme de MP/MT allant du faciès schistes verts à amphibolite atteignant localement la fusion partielle et attribué à l'épaississement crustal du Dévonien supérieur au Carbonifère moyen. La mise en place de laccolithes enracinés dans des zones de cisaillement décrochantes et surmontés de détachements à faible pendage de c. 345 à c. 310 Ma est synchrone de la propagation vers le Sud du front de déformation Varisque marqué par le dépôt de sédiments détritiques dans les bassins d'avant-pays. Nous attribuons ces éléments à la croissance horizontale de la ceinture Varisque associée à la formation d'un plateau orogénique par fluage latéral de la racine orogénique partiellement fondue sous l'effet de la force gravitaire. La diversité des roches magmatiques témoigne d'une variété des sources crustales avec une contribution relativement modeste mais systématique de magmas issus du manteau. Dans la partie Est du Massif Central Français, la décroissance vers le Sud des âges de mise en place des magmas dérivés à la fois du manteau et de la croûte suggère le retrait d'un panneau plongeant vers le Nord vers la bordure libre constituée par la Paléotethys et située au Sud de la ceinture Varisque. La destruction de la chaine Varisque à la fin du Carbonifère est principalement le résultat de l'effondrement gravitaire accommodé par l'activation de détachements à faible pendage et l'exhumation-cristallisation de la racine orogénique partiellement fondue formant des dômes d'échelle crustale à cœur de migmatites de BP entre c. 305 et 295 Ma, concomitante au fluage latéral des unités de la zone externe de la chaine. Les derniers magmas extraits de la zone de fusion partielle forment des dykes et des laccolithes mis en place dans des détachements à faible pendage laissant derrière eux une croûte inférieure constituée de l'accumulation de granulites réfractaires de composition felsique à mafique. Ce modèle met en valeur le rôle primordial de la fusion partielle et du magmatisme sur l'évolution tectonique-géodynamique de la ceinture orogénique Varisque. En particulier, la fusion partielle et le transfert de magma (i) déclenchent le découplage mécanique entre le panneau plongeant et les unités subductées, permettant ainsi l'exhumation de ces dernières, (ii) favorisent le développement d'un plateau orogénique par fluage latéral de la croûte partiellement fondue de faible viscosité sous l'effet de la gravité, (iii) conduisent à la formation de metamorphic core complex et de domes qui accommodent l'exhumation post-orogénique au cours de l'effondrement gravitaire de la chaine. Tous ces processus contribuent à la différenciation et à la stabilisation de la croûte orogénique.

Mots clés : Ceinture Varisque / Massif Central Français / fluage d'une croûte partiellement fondue / magmatisme orogenique / plateau orogenique / effondrement gravitaire

1 Introduction

Migmatites and granites are the main constituents of the continental crust and their petrogenesis and emplacement are intimately linked to orogenic evolution (Thompson and Connolly, 1995; Sawyer, 1998; Brown, 2001; Foster *et al.*, 2001; Vanderhaeghe, 2009; Sawyer *et al.*, 2011; Weinberg, 2016; Závada *et al.*, 2018). Various heat sources have been proposed to cause high-temperature metamorphism and partial melting of orogenic roots comprising an increase in radioactive heat production of the thickened crust, an increase in the basal heat flux associated with delamination of the lithospheric mantle and heat advection through the emplacement of mantle-derived magmas (Houseman *et al.*, 1981; England and Thompson, 1984;

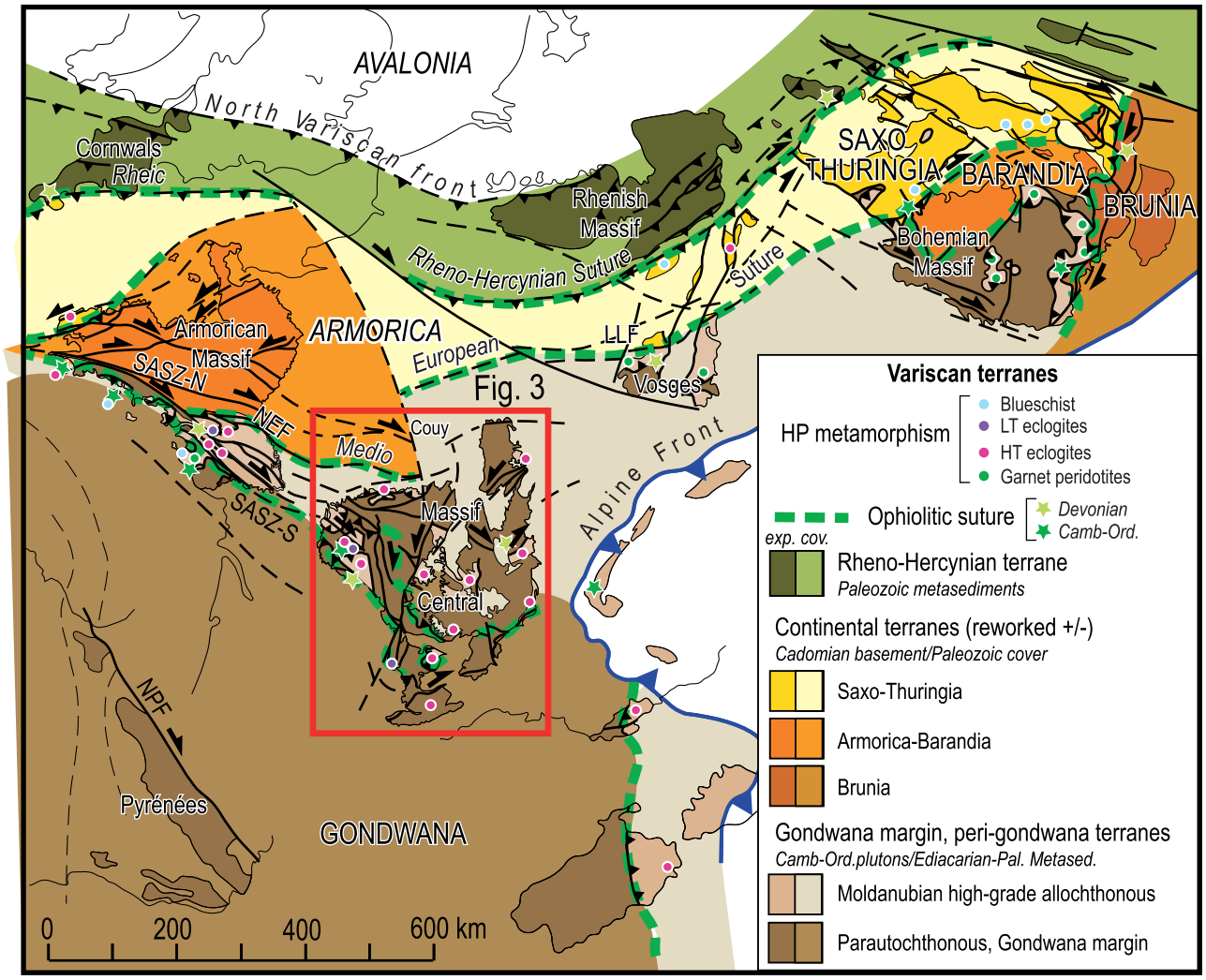


Fig. 1. Tectonic map of the Variscan belt in Western Europe. Continental terranes, Avalonia, Saxo-Thuringia, Armorica-Barandia, Brunia, are separated by ophiolitic sutures, namely the Rheic suture and the Medio-European suture, to the north and south of Armorica respectively. The internal zone of the Variscan belt comprises high-grade nappes overlying a parautochtonous unit belonging to the northern margin of Gondwana.

Henk *et al.*, 2000; Annen and Sparks, 2002; Vanderhaeghe *et al.*, 2003; Vanderhaeghe and Duchêne, 2010; Ueda *et al.*, 2012). In turn, partial melting has a profound impact on the rheology at the scale of the rock and at the one of the entire crust (Vigneresse *et al.*, 1996; Brown and Solar, 1998; Solar *et al.*, 1998; Rosenberg, 2001; Vanderhaeghe and Teyssier, 2001a, 2001b; Gébelin *et al.*, 2006; Schulmann *et al.*, 2008; Vanderhaeghe, 2009), which is expressed by an intimate link between deformation and melt/solid segregation (Sawyer, 1994; Brown and Rushmer, 1997; Brown and Solar, 1998; Weinberg and Searle, 1998; Vanderhaeghe, 1999; Hasalová *et al.*, 2008; Hasalova *et al.*, 2011; Weinberg *et al.*, 2013). Partial melting potentially triggers mechanical decoupling of the subducted continental crust from the downgoing slab as it has been proposed for example in the Norwegian Caledonides or the Variscan Bohemian Massif (Labrousse *et al.*, 2011; Gordon *et al.*, 2016; Závada *et al.*, 2018). Partial melting has also been identified as the key parameter controlling lateral flow of the deep root of orogenic belts through the activation of vertical shear zones (Solar *et al.*, 1998; Weinberg and Mark, 2008) leading to the formation of orogenic plateaux (Vanderhaeghe and Teyssier, 2001a, 2001b; Vanderhaeghe *et al.*, 2003; Gerbault *et al.*, 2005; Cagnard *et al.*, 2006; Chardon *et al.*, 2009). Finally, the ubiquitous presence of large domes cored by migmatites in the exhumed roots of orogenic belts (Whitney *et al.*, 2004; Vanderhaeghe, 2009) as well as the spatial-temporal correlations between the emplacement of granitic laccoliths and the activation of low-angle detachments (Lister and Baldwin, 1993; Vanderhaeghe, 1999; Searle *et al.*, 2009; Whitney *et al.*, 2013) suggest that the presence of a partially molten crust and the migration of granitic melts controls the behaviour of the orogenic crust during orogenic gravitational collapse.

The Variscan belt of Western Europe (Fig. 1) has long been recognized as particularly rich in migmatites and granitoids (*e.g.* Zwart, 1967) and is thus the perfect target to investigate the impact of partial melting and magmatism on orogenic evolution. The large spread of radiochronological ages obtained on migmatites and magmatic rocks (from c. 390 Ma to c. 290 Ma) and the wide variety of petrological and geochemical characteristics of the magmatic rocks indicate that the 100 Ma long tectonic history of the Variscan belt has been punctuated by the emplacement of magmas

implying the contribution of both the crust and the mantle (Letterrier, 1978; Cuney *et al.*, 1990; Solgadi *et al.*, 2007; Bussien *et al.*, 2008; Couzinié *et al.*, 2014; von Raumer *et al.*, 2014; Laurent *et al.*, 2017). In addition to the identification of the sources and geodynamic context of these magmas, arises the question of the impact of low-viscosity and low-density silicate melts on the dynamic evolution of the Variscan orogen.

Despite the significant exposure of migmatites and granitoids, their implication on the tectonic evolution of the Variscan belt has not been fully explored, to the noticeable exceptions of some papers on the French Massif Central (Malavieille *et al.*, 1990; Burg and Vanderhaeghe, 1993; Costa and Rey, 1995; Vanderhaeghe *et al.*, 1999) and Central Iberia, the Vosges, and Bohemia (Henk, 2000; Henk *et al.*, 2000; Schulmann *et al.*, 2008, 2014; Lardeaux *et al.*, 2014; Rubio Pascual *et al.*, 2016). The goal of this paper is to discuss the impact of partial melting and magmatism on the tectonic evolution of the Variscan orogenic belt of Western Europe based on a synthesis of structural, petrological, geochemical, geochronological and sedimentological data available for the Variscan basement of the French Massif Central. This region offers a unique section through the Variscan crust that recorded, from Silurian to Permian, a prolonged history of burial and exhumation associated with the construction and destruction of the belt, respectively. The tectonic evolution is particularly marked by the generation of migmatites under HP, MP and LP metamorphic conditions and by varied plutonic rocks emplaced from the middle Devonian to the early Permian. This history is complemented by the P-T-t record of lower crustal xenoliths brought back to the surface by Cenozoic volcanoes and by unmetamorphosed to low-grade volcano-sedimentary series deposited from the middle Devonian (Givetian) to the Permian that constrain the topographic evolution of the belt.

In this paper, we propose a new geodynamic model for the generation and flow of partially molten rocks and magmas during orogenic evolution from construction by tectonic accretion of subducted continental units followed by lateral growth of the orogenic belt associated with construction of an orogenic plateau and eventually to gravitational collapse. This geodynamic model is also nourished by new data recently published in companion papers comprising (i) Lu-Hf tracing of igneous and detrital zircon in gneisses and plutonic rocks (Chelle-Michou *et al.*, 2017; Couzinié *et al.*, 2017, 2019), (ii) U-Pb dating of zircon and monazite by LA-ICP-MS on the Carboniferous plutonic rocks (Chelle-Michou *et al.*, 2017; Laurent *et al.*, 2017) and (iii) a detailed petrogenetic model for these granitoids (Moyen *et al.*, 2017).

2 Geology of the French Massif Central: a window through the Variscan belt

2.1 The Variscan belt: continental blocks, oceanic sutures, allochthonous terranes and paleogeographic reconstructions

The Variscan belt has been first defined as a post-Cambrian and pre-Permian mobile belt based on analysis of stratigraphic unconformities, structures and nappes (Suess, 1883; Bertrand, 1887). It is extending from East Asia to the tip of South America running through Central Europe and along the edges of North America (Matte, 2001). Paleomagnetic data indicate that the Variscan belt formed as a consequence of the convergence between Laurussia (Laurentia + Baltica) and Gondwana resulting in the Pangea supercontinent (Scotese and McKerrow, 1990; Unrug, 1997; Tait *et al.*, 2000). However, the number of oceanic sutures and the former sizes of the oceanic basins are discussed as developed below.

Pioneer work correlating data from the eastern (Bohemia) and western (Iberia) terminations of the belt led to (i) the definition of the main geological-tectonic zones, (ii) the identification of the principal Paleozoic tectonic events based on the relationship between structures and Ediacaran to Carboniferous sedimentary deposits in the external zone and along the foreland, and (iii) the recognition of high-grade nappes in the internal zone (Stille, 1924; Kossmat, 1927; Gaertner, 1937; Demay, 1948; Gèze, 1949). The relationship between sedimentation and deformation, best exposed along its external domains, allowed the identification of continental blocks such as Avalonia, Armorica, Saxo-Thuringia, Barrandia and Brunia, all of which preserve Cambrian unconformities more or less affected by Variscan deformation and metamorphism (Matte, 1986, 1991; Franke and Engel, 1986; Franke, 1989, 2000; Kroner and Romer, 2013). These continental blocks are separated by oceanic sutures marked by ophiolitic assemblages or mélanges. All authors agree on the Rheic suture, also called the Lizard-Rheno-Hercynian suture, that corresponds to the former Rheic Ocean, to the south of Avalonia and to the north of Saxo-Thuringia and Armorica (Fig. 1) (Matte, 1991; Franke, 2000; Ballèvre *et al.*, 2014; Franke *et al.*, 2017). The nature of the terranes and the presence of sutures south of Armorica is however debated. Despite uncertainties, we favor the existence of multiple sutures (designated as "secondary sutures" on Fig. 1) based on (i) the presence of ultramafic and mafic high-pressure rocks of different ages at different structural levels (Girardeau *et al.*, 1986; Dubuisson *et al.*, 1989; Faure *et al.*, 1997; Bosse *et al.*, 2000; Ballèvre *et al.*, 2009; Berger *et al.*, 2006, 2010a; Lardeaux, 2014; Lardeaux *et al.*, 2014; Lotout *et al.*, 2018), and (ii) the occurrence of remnants of subordinate Devonian rift and/or oceanic basins (Sider and Ohnenstetter, 1986; Skrzypek *et al.*, 2012).

In the French Massif Central, until the middle of the 20th century, the prevailing model attributed the high-grade granitic-gneisses to a crystalline basement and the para-gneisses and schists to a sedimentary cover deposited from the Neoproterozoic throughout the Paleozoic (Jung, 1953; Roques, 1971). In the absence of geochronological data, metamorphism was considered as polycyclic, the basement being metamorphosed during the Neoproterozoic, and then, together with its sedimentary cover, during the Caledonian and the Variscan orogenies (Forestier, 1961; Chenevoy and Ravier, 1971; Roques, 1971). This view has been profoundly modified first by the results of absolute dating demonstrating ubiquitous Variscan reworking (Gebauer *et al.*, 1981; Pin and Lancelot, 1982; Rolin *et al.*, 1982; Duthou *et al.*, 1994). Another turning point was to interpret the felsic/mafic gneisses with a tholeiitic signature, defined as the Leptynite-Amphibolite Complex (LAC), as remnants of ophiolites (Forestier, 1961; Briand and Piboule, 1979; Cabanis *et al.*, 1983; Maillet *et al.*, 1984; Mercier *et al.*, 1985; Piboule and Briand, 1985; Briand *et al.*, 1988; Dubuisson *et al.*, 1989; Pin, 1990). In the Armorican Massif, ophiolites define the Medio-European suture also

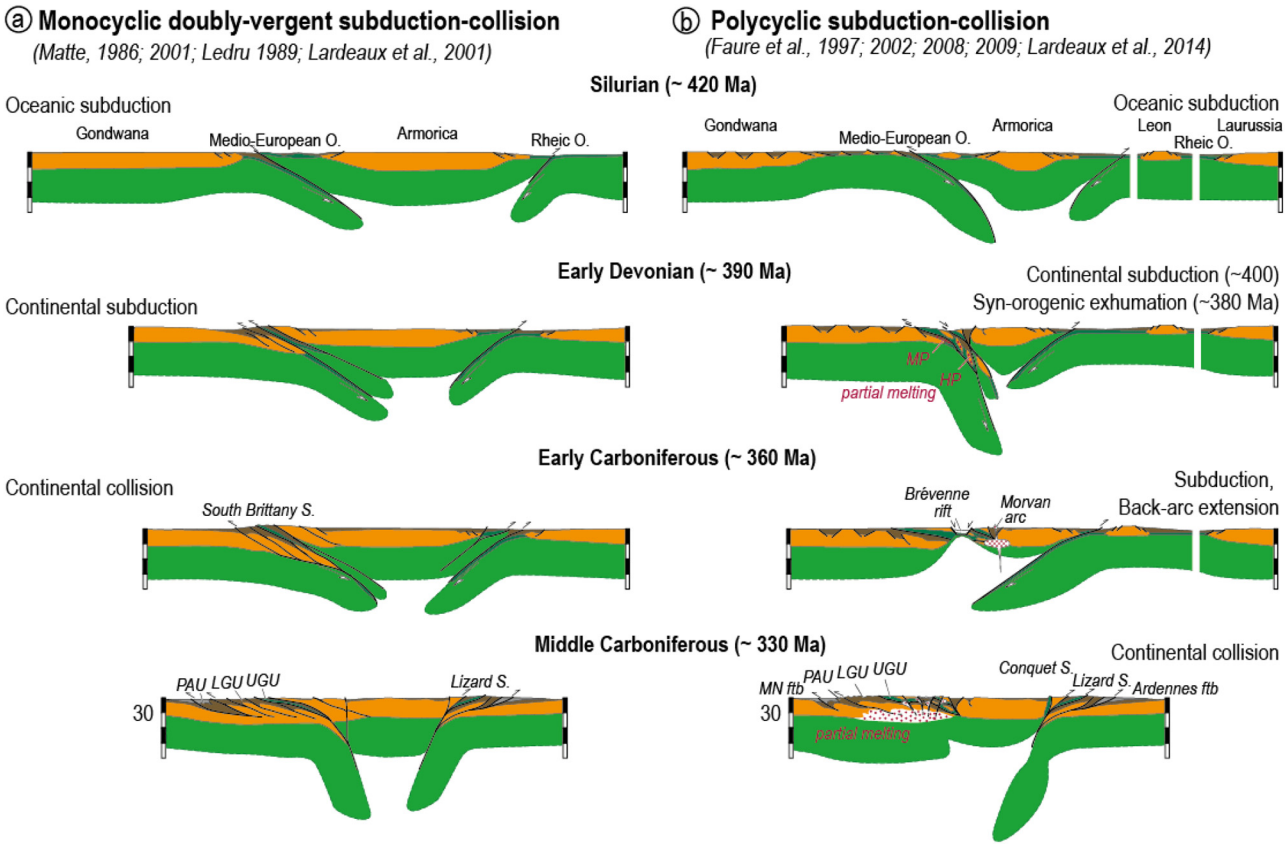
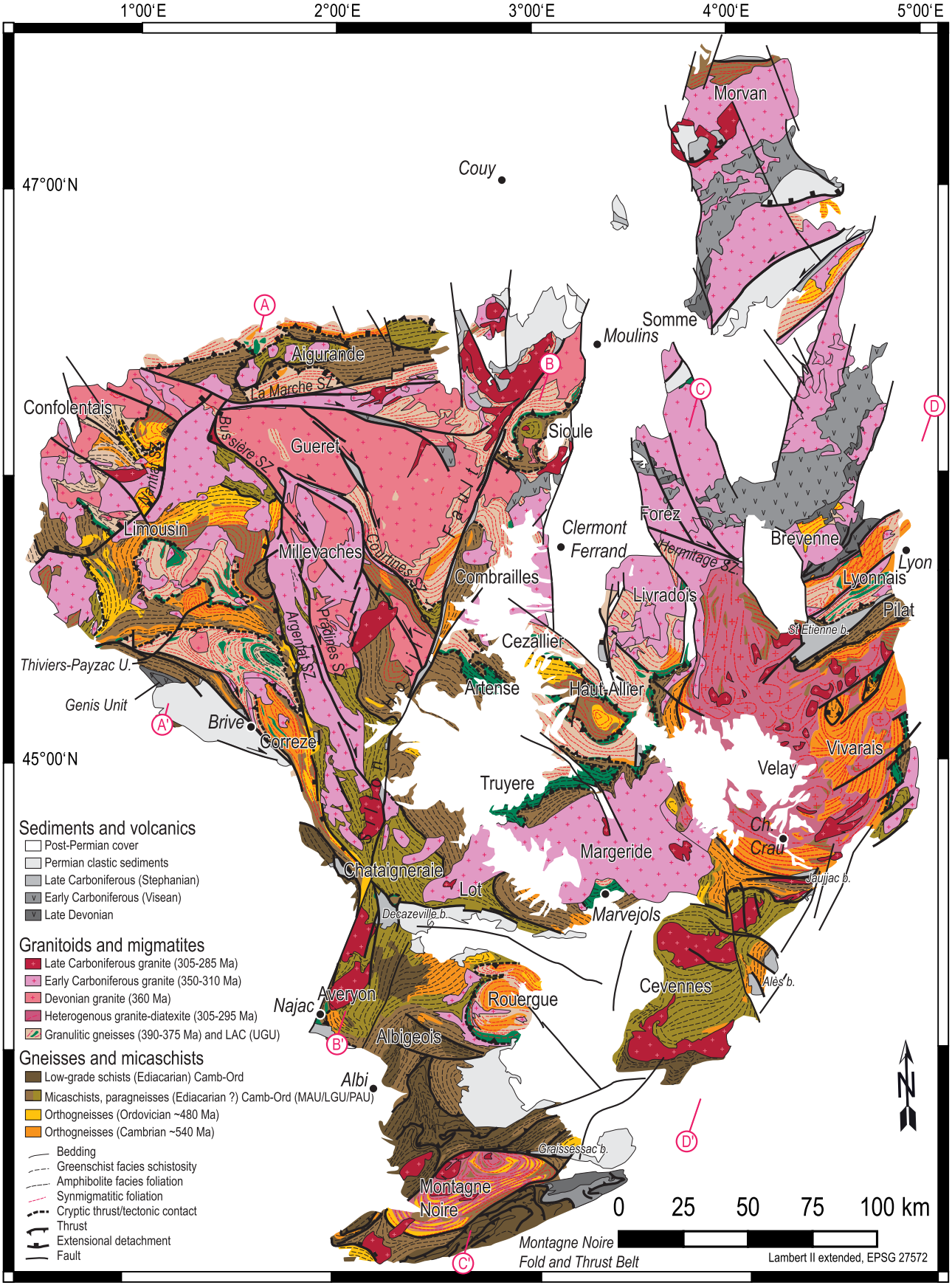


Fig. 2. Geodynamic-tectonic models and paleogeographic reconstructions for evolution of the Variscan belt of Western Europe. A. The double subduction model (modified after Matte, 1986, 1991, 2001). B. The polycyclic model (modified after Faure *et al.*, 1997, 2002, Faure et al., 2009a, 2009b and Lardeaux *et al.*, 2014). C. Single (Rheic) Ocean model of Paris and Robardet (1990); Martínez Catalán *et al.* (2001); Nance *et al.* (2010). D. Mutliple Oceans (Rheic, Medio-European, ...) model of Tait *et al.* (1997); Matte (2001); Stampfli and Borel (2004); Domeier and Torsvik (2014).

referred to as the Galicia-South Brittany suture, or the Eo-Variscan suture (Bernard-Griffiths and Cornichet, 1985; Hanmer, 1977; Faure *et al.*, 1997; Ballèvre *et al.*, 2009). This suture corresponds to the former Medio-European Ocean (also designated as the Galicia-Massif Central Ocean or the Paleotethys Ocean) that is located to the south of the Armorica-Barrandia continental block (Matte, 1986, 2001; Pin, 1990; Stampfli *et al.*, 2013) (Fig. 1).

Based on this analysis, most authors agree that the Variscan belt of Western Europe results from tectonic accretion of the Avalonia and Armorica ribbon-shaped continental terranes and the closure of intervening oceanic basins, marked by (i) the Iapetus-Tornquist suture north of Avalonia, (ii) the Rheic/Rheno-Hercynian suture between Avalonia and Armorica (Matte, 2001; von Raumer *et al.*, 2003) and (iii) the Medio-European suture between Armorica and Gondwana (Matte, 1986, 2001; Pin, 1990; Stampfli *et al.*, 2013) (Figs. 2A and 2B). All models invoke closure of the Iapetus Ocean during the Ordovician concomitantly to the rapid opening of the Rheic Ocean (*e.g.* Hamilton and Murphy, 2004) by reactivation of a Neoproterozoic suture along the northern Gondwana margin (Linnemann *et al.*, 2007). The driving force for this oceanisation has been attributed either to slab pull from the northward subducting Iapetus (Murphy *et al.*, 2006) or to roll-back of a southward subducting slab beneath the Gondwana margin (Martínez Catalán *et al.*, 2009). Paleogeographic reconstruction differ for the early Ordovician period with regard to the position of Armorica that has implications on the existence and size of the Medio-European Ocean (Tait *et al.*, 2000; Matte, 2001; Martínez Catalán *et al.*, 2007, 2009; Faure *et al.*, 2008; Ballèvre *et al.*, 2009; Shail and Leveridge, 2009; Nance *et al.*, 2010; Torsvik *et al.*, 2012; Kroner and Romer, 2013; Stampfli *et al.*, 2013; Lardeaux, 2014; Lardeaux *et al.*, 2014; Schulmann *et al.*, 2014; Skrzypek *et al.*, 2014; Edel *et al.*, 2018). Indeed, sedimentologic and paleontological data lead to paleogeographic reconstructions indicating a position close to the South Pole for Gondwana together with Avalonia and Armorica, and between the tropics and the equator for Laurentia and Baltica (Paris and Robardet, 1990; Robardet *et al.*, 1993; Fortey and Cocks, 2003; Robardet, 2003). This is consistent with paleomagnetic data indicating an Iapetus Ocean at least 3000 km wide (Tait *et al.*, 2000; Cocks and Torsvik, 2002; Hamilton and Murphy, 2004). On the other hand, some paleomagnetic data indicate that Armorica remained attached to the Gondwana margin until the Devonian (Kössler *et al.*, 1996), which is consistent with the continuity of benthic faunas from Armorica to the northern margin of Gondwana (Robardet, 2003) while other paleomagnetic data indicate that Armorica moved toward Laurussia during the Ordovician (Tait *et al.*, 2000), implying closure of the Rheic Ocean and opening of a 2000–3000 km wide Medio-European Ocean (Tait *et al.*, 1997; Cocks and Torsvik, 2006; Shaw and Johnston, 2016). As a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Courtines S.
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Argentat SZ
Pagnes S.
Thiviers-Payzac U.
Genis Unit
Brive
Correze
Artense
Haut-Allier
Vivarais
Velay
Truyere
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Crau
Margeride
Chataigneraie
Lot
Jaujac b.
Decazeville b.
Marvejols
Cevennes
Alès b.
Najac
Averyon
Rouergue
Albigeois
Albi
Graissessac b.
Montagne
Noire
Montagne Noire
Fold and Thrust Belt
0 25 50 75 100 km
Lambert II extended, EPSG 27572
N
Sediments and volcanics
Post-Permian cover
Permian clastic sediments
Late Carboniferous (Stephanian)
Early Carboniferous (Visean)
Late Devonian
Granitoids and migmatites
Late Carboniferous granite (305-285 Ma)
Early Carboniferous granite (350-310 Ma)
Devonian granite (360 Ma)
Heterogenous granite-diatexite (305-295 Ma)
Granulitic gneisses (390-375 Ma) and LAC (UGU)
Gneisses and micaschists
Low-grade schists (Ediacarian) Camb-Ord
Micaschists, paragneisses (Ediacarian ?) Camb-Ord (MAU/LGU/PAU)
Orthogneisses (Ordovician ~480 Ma)
Orthogneisses (Cambrian ~540 Ma)
Bedding
Greenschist facies schistosity
Amphibolite facies foliation
Synmigmatitic foliation
Cryptic thrust/tectonic contact
Thrust
Extensional detachment
Fault

result, two paleogeographic reconstructions clash, one favoring a large Medio-European Ocean between Gondwana and a continental ribbon including Armorica (Matte, 2001; von Raumer *et al.*, 2003; Stampfli and Borel, 2004; Domeier and Torsvik, 2014; Domeier, 2016), while the other considers at most a small immature rift in this region and infer that the large oceanic realm is the Rheic Ocean (Martínez Catalán *et al.*, 2007; Nance *et al.*, 2010; Kroner and Romer, 2013) (Figs. 2C and 2D). On the other hand, tectonic reconstructions based on geological data implying multiple rifts and/or oceanic basins in between Armorica and Gondwana (Girardeau *et al.*, 1986; Dubuisson *et al.*, 1989; Faure *et al.*, 1997; Lardeaux, 2014; Lardeaux *et al.*, 2014), correspond to an intermediate proposition.

2.2 The main lithologic-tectonic units of the French Massif Central

The French Massif Central is one of the largest exposures of the Variscan belt of Western Europe. Its geology is synthesized with reference to 1:1 000 000 scale map (Chantraine *et al.*, 1996, 2003) and to the lithologic-tectonic units defined on the basis of their distinct lithological, structural, metamorphic and geochronological record (Burg and Matte, 1978; Matte, 1986; Ledru *et al.*, 1989; Quenardel *et al.*, 1991; Faure *et al.*, 2009a; Lardeaux, 2014). According to these authors, the French Massif Central is made of (i) low- to high-grade metamorphic nappes with a Devonian to Carboniferous tectonic record, (ii) late Devonian to late Carboniferous plutonic rocks, (iii) late Devonian to Carboniferous volcanic and carbonate to clastic sedimentary rocks affected by low-grade metamorphism, and (iv) unconformable late Carboniferous and Permian detrital sediments (Fig. 3). The French Massif Central is subdivided into a western part and an eastern part by the NNE-SSW trending Sillon Houiller Fault (Arthaud and Matte, 1975; Feybesse, 1981) (Fig. 3). The latter crosscuts a set of NW-SE to NNW-SSE trending dextral shear zones that is particularly well-developed in the western part of the French Massif Central and connects to the South Armorican shear zone (Lerouge and Quenardel, 1988; Gébelin *et al.*, 2007). The nappe pile is also cross-cut by low-angle detachements (Malavieille *et al.*, 1990; Burg *et al.*, 1993; Faure, 1995; Gardien *et al.*, 1997; Bellot, 2007).

2.2.1 Metamorphic nappes

The interpretation of the LAC as a suture marking the boundary between an Upper Gneiss Unit (UGU) and a Lower Gneiss Unit (LGU) led to the reinterpretation of the structure of the FMC in terms of nappe stacking (Burg and Matte, 1978; Ledru *et al.*, 1989) but also to comparisons between the Variscan belt of Western Europe and the Himalaya-Tibet orogen (Dewey and Burke, 1973; Mattauer and Etchecopar, 1976; Burg and Matte, 1978; Autran and Cogné, 1980; Bard *et al.*, 1980; Matte, 1986, 1991). Since its first description, the definition of the LAC has fluctuated and appears to cover a variety of rocks, with emphasis either on the bimodal magmatic association or on the high-pressure metamorphism affecting the mafic and ultramafic rocks (see discussion in Santallier *et al.*, 1988). In addition, the LAC has been recognized at different structural positions and characterized by various metamorphic conditions and ages that led to the addition of a Middle Allochthonous Unit (MAU) in an intermediate position between the UGU and LGU (Girardeau *et al.*, 1986; Dubuisson *et al.*, 1989; Berger *et al.*, 2010a, 2010b; Lotout *et al.*, 2018). The proposed superposition of the UGU (and of the MAU) over the LGU relies on contrasted metamorphic record delineating an inverted metamorphic gradient and locally on the identification of tectonic contacts (Faure *et al.*, 1979; Burg *et al.*, 1984). Based on these characteristics, the main units of the metamorphic nappe stack are, from top to bottom (Tab. 1):

- The Upper Gneiss Unit (UGU): It is made of garnet/cordierite-bearing diatexites associated with metatexites derived from orthogneisses and paragneisses with relics of granulite facies mineral parageneses. It has recorded a typical maximum pressure of 10 kbar for a temperature up to 900 °C retrogressed into amphibolite facies and greenschist facies pointing to decompression and cooling (Audren *et al.*, 1987; Lardeaux *et al.*, 2001; Schulz *et al.*, 2001; Bellot and Roig, 2007; Schulz, 2009) (Fig. 4). Geochronological data are consistent with a Devonian to early Carboniferous age for these HP granulite facies migmatites (Duthou *et al.*, 1981, 1994; Lafon, 1986; Schulz, 2014; Do Couto *et al.*, 2016). The Upper Gneiss Unit contains boudins and enclaves of the Leptynite Amphibolite Complex (LAC) that have preserved HT eclogitic relics first discovered in the Haut-Allier and in the Rouergue (Forestier, 1961; Lasnier, 1968; Nicollet, 1977) but then found in most if not all of the LAC enclosed in the UGU (Burg and Matte, 1978; Gardien and Lardeaux, 1991; Mercier *et al.*, 1991a, 1991b; Gardien, 1993). These eclogites have typically recorded PT conditions of c. 15 kbar for c. 750 °C (Santallier, 1981; Le Breton *et al.*, 1986; Godard, 1990; Bellot and Roig, 2007) but more extreme conditions above 28 kbar are reported in the Lyonnais (Lardeaux *et al.*, 2001) (Fig. 4). The few available geochronological data for the French Massif Central have served to propose a late Silurian to Devonian age for this HT eclogite facies metamorphism (Pin and Lancelot, 1982; Ducrot *et al.*, 1983; Paquette *et al.*, 1995; Do Couto *et al.*, 2016).
- The Middle Allochthonous Unit (MAU): Identified in Limousin, it consists mainly of micaschists associated with an ophiolitic assemblage that is similar to the Leptynite Amphibolite Complex. In contrast to the Upper Gneiss Unit, the LAC of the MAU is marked by relics of LT

Fig. 3. Geological map of the French Massif Central (modified after Chantraine *et al.*, 2003). Metamorphic rocks comprise (i) a low-grade metasedimentary sequence attributed to the Lower Paleozoic (Cambrian to Lower Carboniferous), (ii) micaschists and paragneisses of uncertain age but considered as Neoproterozoic to Lower Paleozoic deposits, (iii) orthogneisses with a Cambrian or Ordovician age. The Middle Allochthonous Unit, the Parautochtonous Unit and the Lower Gneiss Unit are made of these metasedimentary rocks and orthogneisses. The Upper Gneiss Unit is characterized by relics of granulite facies metamorphism and by enclaves-boudins of mafic and ultramafic rocks affected by eclogite facies metamorphism, designated as the Leptynite-Amphibolite Complex (LAC). The color scheme of magmatic rocks is indicative of their age. Granitoids are distinguished according to their petrologic types in Figure 6.

Table 1. Geochronological constraints on emplacement or deposition of pre-Variscan rocks in the French Massif Central. 1 = Melleton *et al.*, 2010; 2 = Alexandrov *et al.*, 2001; 3 = Alexandre, 2007; 4 = Lafon, 1986; 5 = Bernard-Griffiths, 1975; 6 = Bernard-Griffiths *et al.*, 1977; 7 = Gebauer *et al.*, 1981; 8 = Berger *et al.*, 2010b; 9 = Lasserre *et al.*, 1980; 10 = Paquette *et al.*, 1995; 11 = Pin and Lancelot, 1978; 12 = Pin and Lancelot, 1982; 13 = Maurel *et al.*, 2003; 14 = Faure *et al.*, 2017; 15 = Lotout *et al.*, 2017; 16 = Ducrot *et al.*, 1979; 17 = Cocherie *et al.*, 2005; 18 = Pitra *et al.*, 2012; 19 = Roger *et al.*, 2004; 20 = Lescuyer and Cocherie, 1992; 21 = Trap *et al.*, 2017; 22 = Couzinié *et al.*, 2017; 23 = Caen-Vachette, 1979; 24 = Bé Mézémé *et al.*, 2006; 25 = R'Kha Chaham *et al.*, 1990; 26 = Couzinié *et al.*, 2017; 27 = Chelle-Michou *et al.*, 2017; 28 = Duthou *et al.*, 1981.

Region	Location	Rock type	Method	Age (Ma)	Refs
West French Massif Central					
Aigurande		Migmatitic paragneiss	U-Pb Zircon LA-ICPMS	< 558 ± 9	1
Limousin	Thiviers–Payzac Unit	Metasandstone	U-Pb Zircon LA-ICPMS	< 564 ± 9	1
	Cornil	Paragneiss	U-Pb Zircon LA-ICPMS	< 573 ± 12	1
	Seilhac	Paragneiss	U-Pb Zircon LA-ICPMS	< 523 ± 4	1
	Mllevache	Micaschist (S & E Argentat)	U-Pb Zircon LA-ICPMS	< 604 ± 16; < 631 ± 18	1
	Aubazine	Micaschist	U-Pb Zircon LA-ICPMS	< 593 ± 4	1
	Vergonzac	Leptynite	U-Pb Zircon ion probe	525 ± 12	2
	Thaurion	Orthogneiss	U-Pb Zircon ion probe	457 ± 23	3
	Moulin du Chambon	Orthogneiss	U-Pb Zircon LA-ICPMS	529 ± 4	1
	Meuzac	Orthogneiss	U-Pb Zircon LA-ICPMS	451 ± 5	1
	Saut du Saumon	Orthogneiss	U-Pb Zircon LA-ICPMS	501 ± 5	1
	Tulle	Orthogneiss	U-Pb Zircon LA-ICPMS	470 ± 11	1
	Aubazine	Orthogneiss	U-Pb Zircon LA-ICPMS	475 ± 11	1
	Pont de Vaur	Orthogneiss	U-Pb Zircon LA-ICPMS	464 ± 9	1
	Meuzac and St Yriex-La-Perche	Calc-alkaline orthogneiss	U-Pb Zir / Rb-Sr (WR)	495 ± 8; 468 ± 8	4, 5
	Saut-du-Saumon	Calc-alkaline orthogneiss	Rb-Sr (whole rock)	476 ± 22; 461 ± 22	5, 6
	Thaurion	Calc-alkaline orthogneiss	Rb-Sr (whole rock)	514 ± 24	6
	Clair vivre	Metarhyolite	U-Pb Zircon LA-ICPMS	475 ± 6	1
	Sauviat	Mafic gneisses	U-Pb Zircon TIMS	496 +25/-17	7
	Roche-l'Abeille	Zoisite–eclogite	U-Pb Zircon LA-ICPMS	473 ± 6	8
East French Massif Central					
Haut-Allier	Saint-Flour	Metaleucogranite	Rb-Sr whole rock	569 ± 17	9
Rouergue	La Bessenoits	Norite	U-Pb Zircon TIMS	481 ± 1	10
	La Bessenoits	Eclogite	U-Pb Zircon TIMS	475 ± 18	10
	Palanges	Orthogneiss	U-Pb Zircon TIMS	600 ± 10	10
	Caplongue	Diorite	U-Pb Zircon TIMS	557 +12/-10	4
Lot	Picades	Diorite	U-Pb Zircon TIMS	540 ± 15	11
	Marvejols	Metarhyolite	U-Pb Zircon TIMS	478 ± 6	12
	Marvejols	Metagabbro	U-Pb Zircon TIMS	484 ± 7	12
	Marvejols	Amphibolic gneiss	U-Pb Zircon TIMS	487 ± 6	12
Lévézou	Pomayrols	Metagranodiorite	U-Pb Zircon ion probe	519 ± 15	13
	Pomayrols	Metagranodiorite	Ar-Ar Biotite	533.1 ± 11.4	13
	Pinet	Orthogneiss	U-Pb Zircon ion probe	477.0 ± 5.2	14
	Pinet	Orthogneiss	U-Pb Zircon ion probe	474.8 ± 3.6	14
	Pinet	Orthogneiss	U-Pb Zircon LA-ICPMS	466.6 ± 3.3	15
	Pinet	Orthogneiss	U-Pb Zircon LA-ICPMS	468.2 ± 2.7	15
	Pinet	Orthogneiss	U-Pb Zircon LA-ICPMS	470.5 ± 5.2	15
	Pinet	Orthogneiss	U-Pb Zircon LA-ICPMS	465.6 ± 2.6	15
Mt Noire	Plaisance	Orthogneiss	U-Pb Zircon TIMS	532 ± 13	16
	Somail	Orthogneiss	U-Pb Zircon ion probe	471 ± 4	17
	Saint-Eutrope	Orthogneiss	U-Pb Zircon LA-ICPMS	455 ± 2.2	18
	Gorges d'Héric	Orthogneiss	U-Pb Zircon TIMS	450 ± 6	19
	Pont-de-Larn	Orthogneiss	U-Pb Zircon TIMS	456 ± 3	19
	Sériès	Metadacite	U-Pb Zircon	545 ±15	20
	Albine	Orthogneiss	U-Pb Zircon LA-ICPMS	472.1 ± 2.8	21
	Albine	Orthogneiss	U-Th-Pb Monazite LA-ICPMS	470.4 ± 4.7	21
	Lodève	Metasandstone	U-Pb Zircon LA-ICPMS	< 574.0 ± 6.1	22
	Lodève	Metarhyolite	U-Pb Zircon LA-ICPMS	542.5 ± 0.7	22
	Col du Layrac	Metarhyolite	U-Pb Zircon LA-ICPMS	537.1 ± 2.5	22
	Orbiel	Metasandstone	U-Pb Zircon LA-ICPMS	< 602.5 ± 7.3	22
Pilat		Metarhyolite	Rb-Sr whole rock	545 ± 14	23
Velay	Puylaurent	Migmatite	U-Th-Pb Monazite microprobe	543 ± 25 / 550 ± 86	24
	Arc-de-Fix	Orthogneiss	Rb-Sr whole rock	528 ± 9	25
	St Privat d'Allier	Orthogneiss	U-Pb Zircon LA-ICPMS	541.8 ± 3.1	26
	Col de Meyrand	Orthogneiss	U-Pb Zircon LA-ICPMS	542.5 ± 3.1	26
	Labastide-Puylaurent	Orthogneiss	U-Pb Zircon LA-ICPMS	541.4 ± 2.3	26
	Langogne	Orthogneiss	U-Pb Zircon LA-ICPMS	545.9 ± 4.3	26
	Tournon	Orthogneiss	U-Pb Zircon LA-ICPMS	482.2 ± 3.8; 477.6 ± 2.2; 481.4 ± 2.5	27
	Tournon	Amphibolite	U-Pb Zircon LA-ICPMS	486.4 ± 3.1	27
	Tournon	Granite (orthogneiss prot.)	U-Pb Zircon LA-ICPMS	550.2 ± 3.1; 544.3 ± 3.1	27
	Tournon	Migmatitic paragneiss	U-Pb Zircon LA-ICPMS	< 550	27
Lyonnais	Saint-André-la-Côte	Granulite	Rb-Sr whole rock	497 ± 8	28

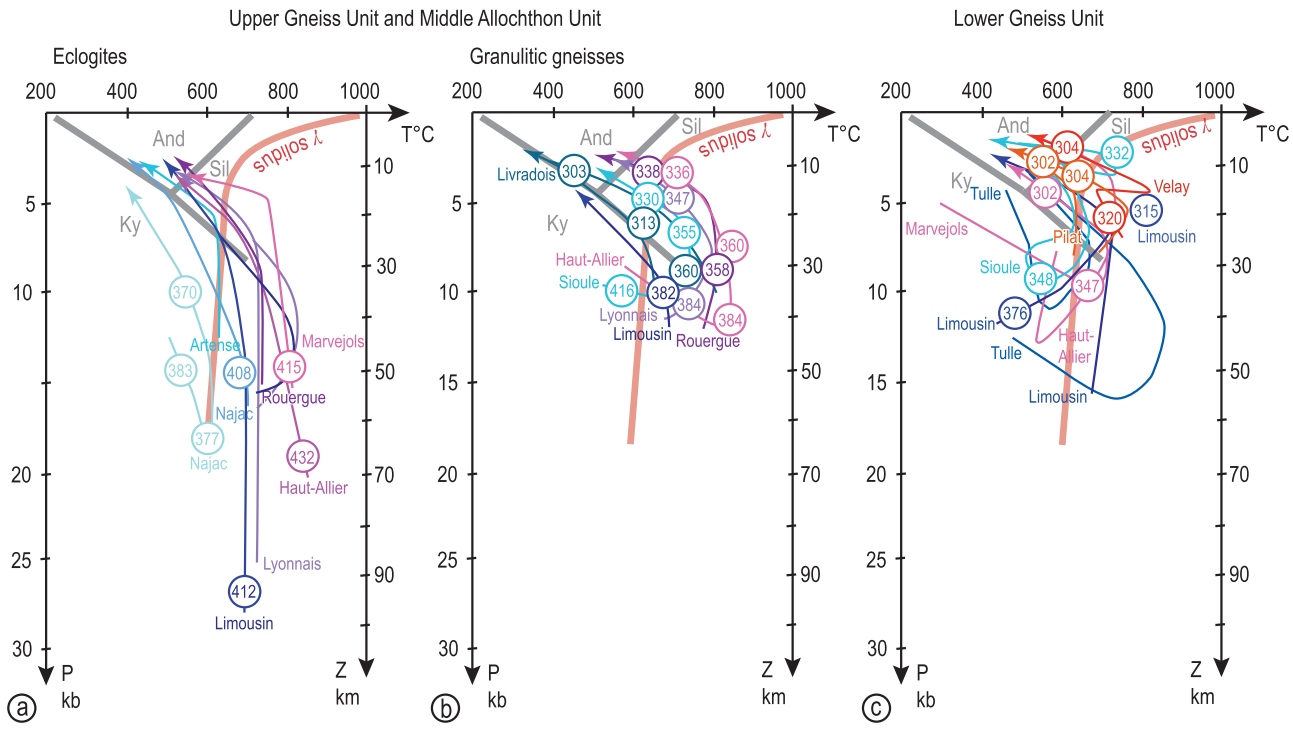

Fig. 4. Synthetic P-T-t paths of the Upper Gneiss Unit, Middle Allochthonous Unit, and of the Lower Gneiss Unit. The Upper Gneiss Unit is made of granulitic migmatites enclosing mafic and ultramafic enclaves of the Leptynite-Amphibolite Complex, whereas the Middle Allochthonous is not migmatitic. A. The Leptynite-Amphibolite Complex contains UHP and eclogitic relics dated at the transition from late Silurian to late Devonian as indicated by the numbers in the circles (c. 432 to c. 377 Ma). B. These rocks are retrogressed into the granulite facies dated from the middle to the late Devonian (c. 384 to c. 360 Ma) in the migmatitic gneisses of the Upper Gneiss Unit. C. The Lower Gneiss Unit comprises rare HP/LT rocks in the Limousin dated at c. 376 Ma. Rocks of the Lower Gneiss Unit have also recorded early Carboniferous (348–320 Ma) and late Carboniferous (304–302 Ma) LP amphibolite facies metamorphism.

eclogite facies metamorphism (Girardeau *et al.*, 1986; Dubuisson *et al.*, 1989; Berger *et al.*, 2010a, 2010b). The maximum pressure recorded by a garnet-kyanite assemblage is 29 kbar but the temperature did not exceed 660 °C consistent with subduction to 100 km depth (Berger *et al.*, 2010a) (Fig. 4). The pressure peak in Najac is 18 kbar and the temperature only reached 600 °C (Lotout *et al.*, 2018). These rocks have then been retrogressed into amphibolite facies. Published geochronological data for this LT eclogite facies metamorphism point to a late Silurian age in Central Limousin (Berger *et al.*, 2010a) and middle Devonian in Najac (Lotout *et al.*, 2018).

– The Lower Gneiss Unit (LGU): It is made of micaschists, paragneisses and felsic orthogneisses with minor carbonates and mafic rocks. The LGU is affected by greenschist to amphibolite facies metamorphism depicting a Carboniferous Barrovian MP/MT gradient reaching partial melting locally masked by retrogression into greenschist facies (Nicollet, 1978; Burg *et al.*, 1984, Burg *et al.*, 1989a, 1989b; Schulz *et al.*, 2001; Gébelin *et al.*, 2009; Gardien *et al.*, 2011) (Fig. 4).

– The Para-Autochtonous Unit (PAU): It is made of micaschists, paragneisses and orthogneisses affected by pervasive Carboniferous greenschist facies metamorphism locally preserving relics of amphibolite facies (Bellot and Roig, 2007) (Fig. 4).

These high-grade nappes, identified throughout the French Massif Central, are structurally overlain by Metamorphic Upper Units (MUU) with limited lateral extent:

– The Thiviers-Payzac Unit: It marks the western edge of the Limousin (Fig. 3). It is made of Cambrian-Ordovician metasedimentary rocks (Bellot and Roig, 2007). The lower part of the Thiviers-Payzac Unit is composed by an assemblage of metagabbros, metadolerites and pyroxene-bearing layered amphibolites (Santallier, 1981; Bellot and Roig, 2007) suspected to represent an ophiolitic mélange.

– The Génis Unit: It overlies the Thiviers-Payzac Unit (Fig. 3). It is composed of unmetamorphosed gabbro, dolerite, basalt and cherts (Cabanis *et al.*, 1983; Maillet *et al.*, 1984) – associated with Ordovician-Devonian sericite micaschist and middle Devonian limestones (Guillot and Doubinger, 1971; Guillot and Lefevre, 1975). This assemblage has been interpreted to represent a middle Devonian ophiolitic mélange (Ledru *et al.*, 1989) or a late Devonian – early Carboniferous olistostrome reworking a Devonian ophiolite (Faure *et al.*, 2009a).

– The Somme Unit: It is exposed south of the Morvan (Fig. 3). It is characterized by middle to late Devonian unmetamorphosed weakly deformed sedimentary and volcanic rocks (Delfour *et al.*, 1989). Marine carbonates of Givetian and Frasnian age alternate with calc-alkaline volcanics and volcaniclastics associated with massive

sulphide deposits and are capped by Famennian clastic sediments (Delfour *et al.*, 1989). This association is consistent with the construction of a magmatic arc along a convergent active margin (Faure *et al.*, 2008).

– The Brévenne Unit. It is located south of the Morvan and north of the Monts du Lyonnais (Fig. 3). It comprises ultramafics, gabbros, pillow basalts, siliceous sedimentary rocks and massive sulphide deposits attributed to a late Devonian ophiolitic sequence (Bébien, 1971; Sider and Ohnenstetter, 1986; Pin, 1990; Bitri *et al.*, 1999; Leloix *et al.*, 1999; Pin and Paquette, 2002; Milési and Lescuyer, n.d.). Volcanics display contrasting low-K calc-alkaline to tholeiitic signatures, suggesting an emplacement in an immature back-arc basin (Bébien, 1971; Pin and Lancelot, 1982; Sider and Ohnenstetter, 1986; Pin, 1990; Pin and Paquette, 1997). These magmatic rocks have been dated at 366 ± 5 Ma and 358 ± 1 Ma by U-Pb on zircon (Pin and Paquette, 1997).

2.2.2 Protoliths age for the high-grade rocks, basement of the Devonian to Carboniferous volcanic and sedimentary units

The first proposed ages for the different lithological units exposed in the French Massif Central relied on relative chronology based on stratigraphy, biostratigraphy and cross-cutting relationships (Jung, 1953; Roques, 1971). The intensity of metamorphism and deformation affecting rocks forming the UGU, MAU, and LGU precludes the identification of fossils in high-grade metasedimentary rocks and the recognition of initial magmatic-sedimentary contacts. Thus, protoliths age determination relying mostly on analogies with stratigraphic ages determined in other regions are subject to caution. Recent age determinations based on radiometric dating of inherited zircon grains (distinguished from Variscan metamorphic zircon) provide (i) a maximum age (the youngest age obtained on inherited grains) for the deposition of the sediments protoliths of paragneisses, and (ii) a crystallization age for magmatic rocks, protoliths of orthogneisses, and/or amphibolites and other mafic metaplutonics. Ages spreading from the late Neoproterozoic (Ediacaran) to the early Paleozoic (Cambrian to Ordovician) have been attributed to most of the metasedimentary sequences (Franke, 2000; Chantraine *et al.*, 2003; Linnemann *et al.*, 2007). Protoliths ages of metamorphic rocks (Pin and Duthou, 1990; R'Kha Chaham *et al.*, 1990; Duthou *et al.*, 1994; Melleton *et al.*, 2010; Chelle-Michou *et al.*, 2017; Couzinié *et al.*, 2017, 2019; Lotout *et al.*, 2018) (Fig. 5) indicate (i) an Ediacaran to Ordovician age for metasediments deposited along the former margin of the Gondwana continent, (ii) Ediacaran, Cambrian and Ordovician ages for orthogneisses, and (iii) a Cambrian to Ordovician age for the mafic and ultramafic rocks (Tab. 2). According to these data, the only identified Proterozoic basement in the French Massif Central corresponds to the paragneisses and orthogneisses with Ediacaran protoliths.

2.2.3 Migmatites and granulites

In addition to the HP granulite facies migmatites that are part of the UGU, MP and LP migmatites, developed to the expense of late Neoproterozoic to early Paleozoic paragneisses and orthogneisses, are exposed at the lowest structural level of the nappe pile in the Limousin, Velay and Montagne Noire (Williamson *et al.*, 1996; Downes *et al.*, 1997; Ledru *et al.*, 2001; Gébelin *et al.*, 2009; Barbey *et al.*, 2015; Villaros *et al.*, 2018). In the Limousin, PT conditions of 850–750 °C and 5–6 kbar have been estimated for the cordierite-bearing migmatitic gneisses and associated lenses of leucosomes of the Millevaches massif in the Limousin dated at c. 315 Ma (Gébelin *et al.*, 2009). In the Montagne Noire, migmatites coring the Caroux dome have recorded P-T conditions of 6 kbar and 720 °C (Rabin *et al.*, 2015). They contain magmatic zircon with U-Pb ages spreading from c. 330 to c. 300 Ma (Franke *et al.*, 2011; Faure *et al.*, 2014; Roger *et al.*, 2015). In the Velay dome, migmatites display contrasting P-T conditions and ages as a function of their structural position. Along the margin of the dome, migmatites have recorded partial melting with biotite remaining stable at a pressure over 5 kbar for a temperature over 750 °C (Montel *et al.*, 1992). These migmatites contain monazite that yield microprobe U-Pb ages ranging from c. 329 to 314 Ma (Mougeot et al., 1997; Cocherie et al., 2005; Bé Mézémé *et al.*, 2006). In contrast, migmatites coring the Velay dome have recorded fluid-absent biotite melting in the cordierite stability field with P-T estimates of 2–5 kbar and 760–850 °C (Montel *et al.*, 1992; Barbey *et al.*, 1999, 2015; Villaros *et al.*, 2018). These migmatites display a Rb-Sr whole rock age of 298 ± 8 Ma (Rb–Sr whole-rock, Caen-Vachette *et al.*, 1981) and contain monazite dated at 301 ± 5 Ma by U-Pb (Mougeot et al., 1997).

The nature of the lower crust underlying these migmatites is documented by xenoliths included in late Variscan plutonic rocks and in Cenozoic basaltic lavas. Biotite-sillimanite enclaves incorporated in diorite intrusive in the southern margin of the Velay dome have recorded P-T conditions of 8–10 kbar for 700–800 °C (Montel, 1985). The main mineral paragenesis of felsic and mafic granulites xenoliths in Cenozoic lavas indicate a pressure of 8–10 kbar for a temperature of 700–800 °C followed by isothermal decompression at 5–6 kbar (Leyreloup, 1974; Downes and Leyreloup, 1986). A few metaigneous xenoliths have preserved relics pointing to a pressure as high as 14 kbar for a temperature of c. 900 °C. These granulites contain zircon grains that yield U-Pb ages ranging from 320 to 280 Ma (Downes *et al.*, 1991). The geochemical signatures of the granulites with a metasedimentary protolith indicate a refractory or residual character while the mafic and felsic metaigneous granulites display characteristics of a calc-alkaline liquid and of a cumulate, respectively (Dupuy *et al.*, 1979; Downes *et al.*, 1990; Vielzeuf and Vidal, 2012). The representation of the deep part of the cross sections (Fig. 8) is in part based on these characteristics.

2.2.4 Late Devonian to Carboniferous plutonic rocks

The c. 70 to 80 Ma-long magmatic activity recorded by plutonic and minor volcanic rocks of the French Massif Central is characterized by an extreme variety of petrological types and geochemical signatures. In this section, we describe these petrologic and geochemical characteristics and discuss their significance integrating their spatial distribution and their ages of emplacement (Tab. 3). The petrology and geochemistry of granitoids, as described in the 1/1 000 000 geological map of

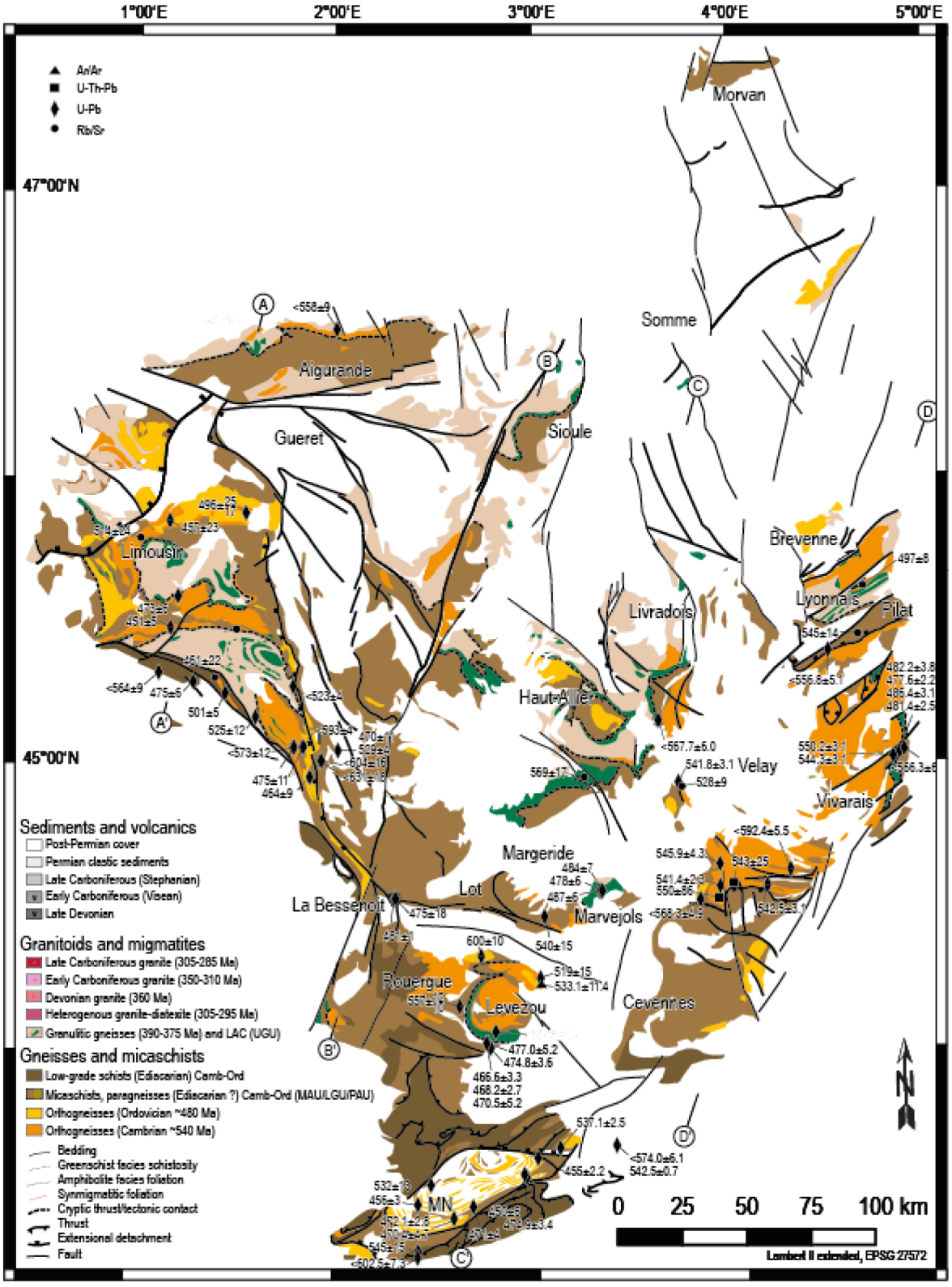

Fig. 5. Geochronological constraints on the emplacement and deposition ages of pre-Variscan rocks. For orthogneisses, the emplacement age corresponds to the Rb-Sr whole rock isochron age (circles) or the the youngest U-Pb, U-Th-Pb age obtained on magmatic zircon or monazite. For paragneisses, a maximum deposition age is provided by the youngest inherited age. Cambrian and Ordovician orthogneisses do not appear associated with a given nappe but are found throughout the French Massif Central.

Table 2. Geochronological data on Variscan magmatic rocks in the Western part of French Massif Central. 1 = Boutin and Montigny, 1993; 2 = Petitpierre and Duthou, 1980; 3 = Rolin *et al.*, 1982; 4 = Gébelin *et al.*, 2007; 5 = Roig *et al.*, 1996; 6 = Choukroune *et al.*, 1983; 7 = Berthier *et al.*, 1979; 8 = Duthou, 1978; 9 = Cartannaz *et al.*, 2007a, 2007b; 10 = Cartannaz, 2006; 11 = Bé Mézémé, 2005; 12 = Ducrot *et al.*, 1983; 13 = Berger *et al.*, 2010a; 14 = Duthou, 1978; 15 = Rolin *et al.*, 2009; 16 = Bernard-Griffiths *et al.*, 1977; 17 = Lafon, 1986; 18 = Faure *et al.*, 2008; 19 = Pin and Paquette, 2002; 20 = Bernard-Griffiths *et al.*, 1985; 21 = Bertrand *et al.*, 2001; 22 = Thiéry, 2010; 23 = Holliger *et al.*, 1986; 24 = Joly, 2007; 25 = Alexandrov *et al.*, 2000; 26 = Lafon and Respaut, 1988; 27 = Cuney *et al.*, 2002; 28 = Gébelin, 2004; 29 = Roig *et al.*, 2002; 30 = Monié *et al.*, 2000; 31 = Faure *et al.*, 2009b; 32 = Thiéry *et al.*, 2009; 33 = Gébelin *et al.*, 2009. B. Geochronological data on Variscan magmatic rocks in the Eastern part of French Massif Central: 34 = Costa and Maluski, 1988; 35 = Costa, 1990; 36 = Hottin and Calvez, 1988; 37 = Do Couto *et al.*, 2016; 38 = Faure *et al.*, 2002; 39 = Schulz, 2009; 40 = Pin (unpublished) cited in Duthou *et al.*, 1984; 41 = Pin and Barbarin (unpublished) cited in Duthou *et al.*, 1984; 42 = Saint-Joanis, 1975; 43 = Kosztolanyi, 1971; 44 = Vialette (unpublished) cited in Duthou *et al.*, 1984; 45 = Laurent *et al.*, 2017; 46 = Cocherie, 2007; 47 = Gardien *et al.*, 2011; 48 = Schulz, 2014; 49 = Couturié *et al.*, 1979; 50 = Respaut, 1984; 51 = Pin, 1979; 52 = Isnard, 1996; 53 = Lafon and Respaut, 1988; 54 = Pin, 1981; 55 = Pin and Lancelot, 1982; 56 = Legendre *et al.*, 2009; 57 = Costa, 1989; 58 = Paquette *et al.*, 1995; 59 = Pin, 1981; 60 = Maluski and Monié, 1988; 61 = Duguet, 2003; 62 = Thiéry, 2010; 63 = Delfour and Guerrot, 1997; 64 = Choulet *et al.*, 2012; 65 = Pin and Paquette, 1997; 66 = Faure *et al.*, 2002; 67 = Duthou *et al.*, 1994; 68 = Costa *et al.*, 1993; 69 = Gay *et al.*, 1981; 70 = Feybesse *et al.*, 1995; 71 = Duthou *et al.*, 1998; 72 = Caen-Vachette *et al.*, 1984; 73 = Gourgaud, 1973; 74 = Cocherie, 2007; 75 = Bé Mézémé *et al.*, 2006; 76 = Mougeot *et al.*, 1997; 77 = Bouilhol *et al.*, 2006; 78 = Bé Mézémé, 2005; 79 = Couzinié *et al.*, 2014; 80 = Costa unpublished cited in Malavieille *et al.*, 1990; 81 = Didier *et al.*, 2013; 82 = Batias and Duthou, 1979; 83 = Briand *et al.*, 2002; 84 = Caron, 1994; 85 = Doublier *et al.*, 2006; 86 = Monié *et al.*, 2000; 87 = Vialette *et al.*, 1979; 88 = Brichau *et al.*, 2008; 89 = François, 2009; 90 = Vialette and Sabourdy, 1977; 91 = Hamet and Mattauer, 1977; 92 = Mialhe, 1980; 93 = Chauvet *et al.*, 2012; 94 = Maluski *et al.*, 1991; 95 = Franke *et al.*, 2011; 96 = Doublier *et al.*, 2015; 97 = Whitney *et al.*, 2015; 98 = Faure *et al.*, 2014; 99 = Roger *et al.*, 2015; 100 = Faure *et al.*, 2010; 101 = Pitra *et al.*, 2012; 102 = Matte *et al.*, 1998; 103 = Franke *et al.*, 2011; 104 = Poilvet *et al.*, 2011.

Region	Location	Rock Type	Method	Age ± 2σ (Ma)	Refs
East Massif Central (wesrtern part)					
Couy-Sancerre		Amphibolite (LAC)	Ar-Ar Amphibole	385.5 ± 8.4; 379.4 ± 8.2	34
		Bt-grt orthogneiss +/- mylonitic	Ar-Ar Biotite	390 ± 7; 382.5 ± 7.6	34
		Trachy-andesite	Ar-Ar Biotite	301.6 ± 6.3	34
		Greenschist facies mylonite	Ar-Ar Biotite	317.1 ± 6.4; 336	35, 36
		Lamprophyre dike	Ar-Ar Biotite	301.5 ± 6.2; 292	35, 36
Sioule		Kyanite-garnet granulitic paragneiss	U-Th-Pb Mo microprobe,U-Pb Zr SIMS	416 ± 15; 362 ± 14; 343 ± 2; 328 ± 2	37
		Staurotite micaschist	U-Th-Pb Monazite microprobe	363 ± 8	37
		Migmatitic gneiss	U-Th-Pb Monazite microprobe	363 ± 4.5	37
		Biotite-sillimanite gneiss	U-Th-Pb Monazite microprobe	354 ± 7	37
		Two-mica gneiss	U-Th-Pb Monazite microprobe	351 ± 5	37
		Sill gneiss	Ar-Ar Mu; Ar-Ar Bio	332.2 ± 1.2; 331.6 ± 1.2; 334.2 ± 1.6; 333.2 ± 1.2	38
		Granite	Ar-Ar Biotite	336 ± 1.6; 322.3 ± 1.2	38
		Orthogneiss (encl. in granite)	Ar-Ar Biotite	321.4 ± 1.2	38
		Mylonite Ste Catherine Fault	Ar-Ar Biotite	337.6 ± 1.6	38
		Gneiss	Ar-Ar Muscovite; Ar-Ar Biotite	333.3 ± 1.6; 334.6 ± 1.6	38
		Micaschist	Ar-Ar Muscovite	330.8 ± 1.6	38
		Staurolite micaschist	Ar-Ar Muscovite	332.1 ± 1.6	38
		Staurolite garnet micaschist	Ar-Ar Muscovite	328.6 ± 1.6	38
		Kyanite Garnet gneiss	U-Th-Pb Monazite microprobe	337 ± 9; 330 ± 14	39
		Sill Bt gneiss	U-Th-Pb Monazite microprobe	343 ± 11 to 328 ± 15	39
		Staurolite Garnet micaschist	U-Th-Pb Monazite microprobe	333 ± 18; 327 ± 12	39
Forez	Saint-Julien-la-Vêtre	Granite	Rb-Sr whole rock	340 ± 20	40
	L'Hermitage	Granite	Rb-Sr whole rock	329 ± 14	41
	Saint-Dier d'Auvergne	Granite	Rb-Sr whole rock	330 ± 26	42
	Mayet-de-Montagne	Granite	Rb-Sr whole rock	318 ± 15	43
	Bois-Noirs; Charollais	Granite	Rb-Sr whole rock	346 ± 8; 346 ± 19	44
	Pierre-qui-Vire	Granite	Rb-Sr whole rock	323 ± 4	44
	Mayet-de-Montagne	Granite	Rb-Sr whole rock	297 ± 11	44
	Château-Montgilbert	Granite	Rb-Sr whole rock	282 ± 8	44
	Bois-Noirs	Granite	U-Pb Zircon ID TIMS	341 ± 15	43
		Bt granite; Porph. Bt granite	U-Pb Zircon LA-ICPMS	336,9 ± 1,8; 332 ± 2 ± 2	45
		Bt-Am granodiorite; Bt-Am Qz-diorite	U-Pb Zircon LA-ICPMS	330,1 ± 1,3 ; 321,2 ± 1,2	45
		Bt-Ms Leucogranite	U-Pb Zircon LA-ICPMS	325,7 ± 1,3	45
	Gumières	Granite	U-Pb Zircon LA-ICPMS	313 ± 2	46
Livradois		Porph. Bt-Crd granite; Bt granite	U-Pb Zircon LA-ICPMS	318,3 ± 2,6 ; 317.8 ± 1,3 ; 314,5 ± 1,7 ; 315.4 ± 0,9	45
		Vaugnerite	U-Pb Zircon LA-ICPMS	309,7 ± 1,2	45
		Monzogranite; Granite	U-Pb Zircon LA-ICPMS	315 ± 4; 311 ± 18	47
		Diatexite	U-Th-Pb Monazite microprobe	360 ± 4	47
Haut-Allier		Eclogite	U-Pb Zircon TIMS	432 +20 -10	12
		Kyanite Garnet gneiss	U-Th-Pb Monazite microprobe	337 ± 9; 332 ± 11	48
		Garnet Sill Bt mylonite	U-Th-Pb Monazite microprobe	339 ± 8	48
		Staurolite Garnet micaschist	U-Th-Pb Monazite microprobe	332 ± 16	48
Margeride		Granite	Rb-Sr whole rock	323 ± 12	49
		Granite	U-Pb Zircon ID TIMS	334 ± 9	50
		Granite	U-Pb Monazite ID TIMS	314 ± 3	51
	Chambon-le-Château	Granite	U-Pb Monazite ID TIMS	311 ± 6	52
	Saint-Christophe-d'Allier	Leucogranite	U-Pb Monazite ID TIMS	305 ± 14	52
	Grandrieu	Leucogranite	U-Pb Monazite ID TIMS	305 ± 4	53
		Vaugnerite	U-Pb Zircon LA-ICPMS	313,2 ± 2,5; 309,4 ± 1,5	45
		Porph. Bt-Crd granite	U-Pb Zircon LA-ICPMS	312,9 ± 2	45
	St-Christophe-d'Allier	Bt-Ms leucogranite	U-Pb Zircon LA-ICPMS	312,7 ± 2,3	45
	Grandrieu	Bt-Ms leucogranite	U-Pb Zr LA-ICPMS; U-Pb Mo LA-ICPMS	311 ± 1,1 ; 309.3 ± 1,2	45
Marvejols		Orthogneiss	U-Pb Zircon TIMS	346 ± 8	54
		Paragneiss	U-Pb ZrTIMS; U-Pb Mo TIMS	345 ± 2; 344 ± 3	51
		Pegmatite; Amphibolite gneiss	U-Pb Zircon TIMS	344 ± 13; 340 ± 4	55
Lot		HP trondhjemite	U-Pb Zircon TIMS	415 ± 6	55
		Staurolite-Garnet micaschist	U-Th-Pb Monazite microprobe	382 ± 6 to 370 ± 6	56
		Mylonite	Ar-Ar Biotite; Ar-Ar Muscovite	358.4 ± 3.6; 339.8 ± 3.5	57
		Staurolite-Garnet micaschist	Ar-Ar Biotite; Ar-Ar Muscovite	351.1 ± 3.5; 342.3 ± 3.5	57
Rouergue		Eclogite	U-Pb Zr Pb evapo; Sm-Nd WR	413 ± 23; 408 ± 7	58
	Pinet	Granite	U-Pb Zircon	360 ± 20	59
	Pinet	Orthogneiss	U-Pb Zircon	346 ± 7	60
	Tremouille	Mylonite de granite	Ar-Ar muscovite; Ar-Ar biotite	343 ± 2; 339 ± 2	61
	Pinet	Granite	Ar-Ar muscovite/biotite	342 ± 2	61
	Savennes	Granite	U-Pb Zircon	336 ± 3	62
		Micaschist	Ar-Ar Mu; Ar-Ar Bio	337,7± 3,4; 333,4 ± 3,9; 343,6 ± 3,5; 297,9 ± 3,0	35
		Orthogneiss	Ar-Ar Mus; Ar-Ar Bio	300,3 ± 3,1; 302,5 ± 3,2	35
Lévézou		Metagabbro	U-Pb Zircon TIMS	367 ± 10	55

Table 2. (*continued*)

Region	Location	Rock Type	Method	Age ± 2σ (Ma)	Refs
East Massif Central (eastern part)					
Morvan		Microgranite	U-Pb Zircon Pb evaporation	345 ± 10	63
		Leucogranite (deformed)	U-Th-Pb Monazite zircon; Ar-Ar Biotite	318 ± 7; 299.6 ± 6	64
		Leucogranite	U-Th-Pb Monazite zircon; Ar-Ar Biotite	321 ± 3; 317 ± 5; 306,4 ± 8	64
		Mylonite	Ar-Ar Muscovite	303,9 ± 6; 299.8 ± 6; 298.2 ± 6	64
Brévenne		Metarhyolite; Trondhjemite	U-Pb Zircon TIMS	366 ± 5; 358 ± 1	65
		Phyllite	Ar-Ar Muscovite	337.0 ± 4.9	66
		Mylonitic gneiss	Ar-Ar Muscovite	336.9 ± 4.9	66
Lyonnais		Migmatite	Rb-Sr whole rock	384 ± 16	67
		Retrogressed eclogite	Ar-Ar Amphibole	339.3 ± 3.8	68
		Orthogneiss	Ar-Ar Muscovite	337.7 ± 3.5	68
		Synkinematic granite	Ar-Ar Muscovite; Ar-Ar Biotite	349.1 ± 3.2; 333.4 ± 3.1; 345.6 ± 3.2; 341 ± 3.1; 338.4 ± 3.1;	68
		Retrogressed granulite	Ar-Ar Biotite	339.0 ± 3.1	68
		Synkinematic granite	Rb-Sr whole rock	332 ± 10	69
		Pegmatite in synkinematic granite	U-Pb Zircon Pb evaporation	331 ± 12	70
	Salt-en-Donzy	Bt granite	U-Pb Zircon LA-ICPMS	337,4 ± 1	45
		Vaugnerite	U-Pb Zircon LA-ICPMS	335,7 ± 2,1; 333,9 ± 1,4	45
Pilat		Granite Pilat	Rb-Sr whole rock	342 ± 8	71
	Gouffre d'Enfer	Deformed leucogranite	Rb-Sr whole rock	322 ± 9	72
		Granite	Rb-Sr whole rock	297 ± 9	73
		Granite	U-Pb Zr LA-ICPMS; U-Th-Pb MoEMP	304 ± 4; 322 ± 3	74
		Two-mica granite	U-Pb Zr LA-ICPMS; U-Th-Pb MoEMP	289 ± 6; 340 ± 5	74
Velay		Leucogranite	U-Th-Pb Monazite microprobe	333 ± 6; 318 ± 5; 311 ± 5.3	75
		Migmatite	U-Th-Pb Monazite microprobe	323.3 ± 2.9; 322 ± 7; 320 ± 5	75
		Paragneiss	U-Pb Monazite ID TIMS	314 ± 5	76
		Velay granite	U-Pb Monazite ID TIMS	301 ± 5	76
		Metapelite leucosome	U-Th-Pb Monazite microprobe	310.7 ± 2	77
		Micaschist; Paragneiss	Ar-Ar Biotite	309.8 ± 3; 307.5 ± 3.4	77
		Vaugnerite	U-Pb Zircon LA-ICPMS	320,5 ± 1,8; 318,9 ± 1,8; 306,6 ± 2,4; 305,9 ± 1,7; 301,5 ± 1,4; 299,1 ± 1,3	45
		Bt-Amph granodiorite	U-Pb Zircon LA-ICPMS	332,1 ± 0,7	45
		Bt-Crd Velay granite	U-Pb Monazite LA-ICPMS	302.8 ± 1,3	45
		Granite	U-Th-Pb Monazite microprobe	325 ± 4; 324 ± 4; 318 ± 3	78
		Velay granite	U-Pb Monazite LA-ICPMS	305.9 ± 1.4	79
		Late granite	U-Pb Zr LA-ICPMS; U-Pb Monazite LA-	303.9 ± 6.5; 303.7 ± 3.1	79
		Mylonite	Biotite	313 ± 6	80
		Microgranite	U-Pb Monazite LA-ICPMS	307 ± 2; 297 ± 4	81
Vivarais	Saint-Ciergues/Vienne	Granite	Rb-Sr whole rock	337 ± 13	82
	Vivarais	Granite	Rb-Sr WR; U-Pb Zr ID TIMS	351 ± 23; 341,0 ± 6,5	83
		Vaugnerite	U-Pb Zircon LA-ICPMS	307,8 ± 1,6; 307,3 ± 1,3	45
		Porph. Bt granite	U-Pb Zircon LA-ICPMS	322,2 ± 1,5 ; 321,1 ± 1,1	45
		Porph. Bt-granodiorite	U-Pb Zircon LA-ICPMS	321,9 ± 1,3	45
Cévennes		Amphibolite	Ar-Ar Amphibole	343.1 ± 4.4	84
		Micaschist	Ar-Ar Muscovite; Ar-Ar Biotite	341.6 ± 2.4; 335.7 ± 8.3	84
		Quartzite	Ar-Ar Muscovite	332.0 ± 2.4	84
		Porph. Bt-Amph granite	U-Pb Zircon LA-ICPMS	302,5 ± 0,9	45
		Porph. Bt-granite	U-Pb Zircon LA-ICPMS	298,9 ± 1,8	45
		Gneiss	Ar-Ar Muscovite; Ar-Ar Biotite	333.3 ± 1.6; 334.6 ± 1.6	38
		Stau micaschist; Micaschist	Ar-Ar Muscovite	332.1 ± 1.6; 330.8 ± 1.6	38
		Quartzite	Ar-Ar Muscovite	343.6 ± 3.5	85
		Slate; Silty slate	Ar-Ar Muscovite	341.2 ± 7.0; 337.7 ± 3.4; 334.1 ± 6.8; 334.0 ± 6.9	85
	Bougès	Granite	U-Pb Mo ID TIMS; Ar-Ar Bio. Rb-Sr wr	315 ± 4; 311 ± 3; 295 ± 15	86,87
	Pt-de-Montvert	Granite	Ar-Ar Biotite	309 ± 3	86
	Finiels	Granite	U-Pb Mo ID TIMS; U-Pb Zr ID TIMS	305 ± 5; 303 ± 3; 307 ± 11	86,88,89
	Finiels	Granite	Rb-Sr whole rock	291 ± 11	87
	Liron	Granite	U-Pb Zircon ID TIMS	307 ± 3	88
	St-Guiral	Granite	U-Pb Zircon ID TIMS	305.9 ± 2.4; 301 ± 4	88
	Aigoual	Granite	U-Pb ZrID TIMS; Rb-Sr WR	304 ± 12; 298 ± 9	88, 90
	Aigoual-St Guiral	Granite	Rb-Sr whole rock	279 ± 15	91
	Borne	Granite	Rb-Sr WR, Ar-Ar Biotite	315 ± 5; 310 ± 3	92, 86
	Laubies	Adamellite	Rb-Sr WR; U-Pb Mo ID TIMS	286 ± 11; 307 ± 5	87, 89
	Finiels	Pegmatite	Ar-Ar Muscovite	301,2 ± 3,1	93
		Aplite; Aplite-pegmatite	Ar-Ar Muscovite	306,4 ± 3,2; 306,5 ± 3,1; 301,6 ± 3,1	93
		Granite	Ar-Ar Muscovite	305,1 ± 3,1	93
		Lode	Ar-Ar Muscovite	304,8 ± 2.7 Ma	93
		Quartz vein	Ar-Ar Muscovite	310,5 ± 2,8; 303,3 ± 2,6; 313,5 ± 2,5; 307,5 ± 2,6	93
Montagne Noire		Sandstone	Ar-Ar Musco, Ar-Ar Bio	333.4 ± 3.9; 297.0 ± 2.7	57, 94
		Orthogneiss; Mylonitic orthogneiss	Ar-Ar Musco, Ar-Ar Bio	300 ± 3; 316 ± 4; 297.0 ± 2.8	94
		Paragneiss	Ar-Ar Bio; Ar-Ar Musco	303 ± 3; 303 ± 3	94
		Marble	Ar-Ar Muscovite	297.3 ± 2.7; 309.8 ± 2.8	94
		Banded gneiss	Ar-Ar Bio; Ar-Ar Musco	311 ± 4; 308.0 ± 2.9; 309.0 ± 2.9	94
		Amphibolite	Ar-Ar Biotite	311 ± 4	94
		Staurolite micaschist	Ar-Ar Biotite	308 ± 2.8	94
		Pegmatite; Pegmatite weakly deformed	K-Ar Muscovite	295.2 ± 3.8; 293.9 ± 6.8; 297.2 ± 5.3; 293.3 ± 3; 292 ± 4.4	95
		Migmatic orthogneiss	K-Ar Muscovite	294.3 ± 5.8	95
		Granite undeformed	K-Ar Muscovite	294.3 ± 6.0	95
		Silty slate	K-Ar Muscovite	326.8 ± 6.7	57
		Mylonite	Ar-Ar Muscovite	333.0 ± 3.4	57
		Orthogneiss	Ar-Ar Bio; Ar-Ar Musco	302.5 ± 3.2; 300.3 ± 3.1	57
		Micaschiste	Ar-Ar Biotite	297.9 ± 3.0	57
		Fine-grained meta-aplite	U-Pb Monazite ID TIMS	313 ± 1	95
		Slate	K-Ar White mica (fine fraction)	307.2 ± 8.8; 274.7 ± 5.7; 206.8 ± 4.8; 194.8 ± 4.4; 305.3 ± 6.2 to 280.6 ± 5.9	96
		Post-tectonic pegmatite	K-Ar White mica (fine fraction)	280.8 ± 5.8	96
		Eclogite	U-Pb Zircon LA-ICPMS	315.2 ± 1.6	97
		Eclogite	U-Pb Zr SHRIMP/ SIMS; Rt SIMS	314.5 ± 2.5 ; 311 ± 2; 308 ± 4	98
		Orthogneiss	U-Pb Monazite ID TIMS	308 ± 3	99
		Migmatite	U-Pb Zircon SIMS	305 ± 6	100
		Orthogneiss	U-Pb Monazite LA-ICPMS	294.4 ± 4.0	101
		Undeformed granite; Gt-granite	U-Th-Pb Monazite EMP	333 ± 6: 327 ± 7; 320 ± 3; 318 ± 4	100
		Deformed granite	U-Pb Zr ID TIMS; U-Pb Mo ID TIMS	327 ± 5	102
		Aplite dyke	U-Pb ID TIMS Mo/Zr	313 ± 1/ 309 ± 3	103
		Gt-granite	U-Pb Zircon SIMS	305 ± 10	100, 99
		Deformed granite	U-Pb Mo ID TIMS, LA-ICPMS	303 ± 10; 304 ± 2; 301 ± 2	99
		Undeformed granite	U-Pb Zircon SIMS	299 ± 8	100
		Undeformed Gt-granite	U-Pb Mo LA-ICP-MS; U-Pb Xe LA-ICP-MS	299 ± 2; 298 ± 2	99
		Synkinematic Gt-granite	U-Pb Mo LA6ICP6MS. U-Pb zR	294 ± 1; 294 ± 3	104

Table 3. Pressure-Temperature-time data constraining the evolution of metamorphic rocks of the French Massif Central. UGU = Uppper Gneiss Unit, LGU = Lower Gneiss Unit, PAU = Para-autochtonous Unit, EU = Upper Unit, GU/TPU/St SU = Thyviers Payzac- Genis Unit-St Savadour, PFTB = Paleozoic Fold Thrust Belt (Mt Noire). The pressure is expressed in kbar, the temperature in degrees Celius and the ages are given in Ma. In bold are U-Pb on zircon, in italic are Ar-Ar ages on micas, underlined ages are whole rock Rb-Sr ages and the doubly underlined are U-Th- Pb ages on monazite. 1 = Costa and Maluski, 1988; 2 = Burg *et al.*, 1989a, 1989b; 3 = Boutin and Montigny, 1993; 4 = Berger *et al.*, 2010a; 5 = Berger *et al.*, 2010b; 6 = Santallier, 1981; 7 = Ducrot *et al.*, 1983; 8 = Bellot and Roig, 2007; 9 = Gébelin, 2004; 10 = Costa, 1992; 11 = Melleton *et al.*, 2009; 12 = Lafon, 1986; 13 = Godard, 1990; 14 = Audren *et al.*, 1987; 15 = Schulz *et al.*, 2001; 16 = Schulz, 2009; 17 = Do Couto *et al.*, 2016; 18 = Delor *et al.*, 1986; 19 = Lotout *et al.*, 2018; 20 = Faure *et al.*, 2008; 21 = Delor *et al.*, 1986; 22 = Joanny *et al.*, 1989; 23 = Bodinier and Burg, 1981; 24 = Burg *et al.*, 1986; 25 = Delor *et al.*, 1987; 26 = Burg and Leyreloup, 1989; 27 = Costa, 1990; 28 = Mercier *et al.*, 1991a, 1991b; 29 = Briand *et al.*, 1988; 30 = Lardeaux *et al.*, 2001; 31 = Dufour, 1985; 32 = Pin and Lancelot, 1982; 33 = Costa *et al.*, 1993; 34 = Gardien, 1990; 35 = Gardien and Lardeaux, 1991; 36 = Gardien, 1993; 37 = Gardien *et al.*, 2011; 38 = Schulz, 2014; 39 = Schulz *et al.*, 1996; 40 = Santallier 1981; 41 = Bellot, 2001; 42 = Gébelin *et al.*, 2007; 43 = Caen-Vachette *et al.*, 1984; 44 = Vitel, 1988; 45 = Briand and Gay, 1978; 46 = Briand, 1978; 47 = Burg *et al.*, 1984; 48 = Costa, 1989; 49 = Montel *et al.*, 1992; 50 = Barbey *et al.*, 2015; 51 = Monier, 1980; 52 = Autran and Guillot, 1978; 53 = Caron, 1994; 54 = Arnaud *et al.*, 2004; 55 = Faure *et al.*, 2010; 56 = Faure *et al.*, 2014; 57 = Roger *et al.*, 2015; 58 = Maluski *et al.*, 1991; 59 = Matte *et al.*, 1998; 60 = Rabin *et al.*, 2015.

			tectonic events															
			HP (oceanic crust)			HP (continental crust)			Collision			Exhumation						
	Locality	Lithology	P	T	age	P	T	age	P	T	age	P	T	age	P	T	age	refs
UGU	***West French Massif Central***																	
	Couy-Sancerre	amphibolite				11-16.5	500-700	*383±8-385±8*	8-10.5	650-900		6-7	600					1, 2
	Aigurande	amphibolite						*381±5-389±8*										3
	Limousin	Ky-Zo eclogite	29 ± 3	660 ± 65	**412±10 ;**							5±2	670 ± 35					4
	Limousin	Ky-Cor-amphibolite							10±1	800-820±36								5
	Limousin	eclogite			**432+20/-10**	15-20	650-750		11± 1	650-750		8.5	700-750		8.5	W < 700		6,7
	Limousin	metabasite				17 ± 1	700 ± 50											8
	Limousin	metapelite	16	830		12 ± 1	750 ± 50		7±1	610 ± 50	362 ± 4 *-352 ± 7*							9,10,11
	Limousin/Mille	migmatite/granulite				6-10	650-750	**382± 5**			*348.5± 4.1*			*334.3±3.1-309.2± 2.4*				12,10
	East French Massif Central																	
	Morvan	eclogite				11-16	500-800					4±2	700					13
	La Sioule	Gneiss			416±15	9 ± 1	550 ± 50		11.5 ± 1	760 ± 50	363±5-348±21	6±1	750 ± 50	330±14	5 ± 1	650 ± 50		14,15,16,17
	Najac	Glau-eclogite				11 -16	650-730					7	600-650					18,17
	Najac	eclogite				15-20	560-630	***382.8± 1-376.7± 3.3***	11	560	**369± 13**							19
	Rouergue	eclogite				15 -20	680-760	408±6				4-7	550-650					20, 21,22
	Rouergue	Sta/Ky paragneiss				11-14	740-860		9	800	*355.3-348.8± 3,5*	3-4	520-660					23,24,22
	Vibal klippe	metagranodiorite				10-14	740-860		8.5-9.5	750-820	*347.7±3.6-353.1±3.5*	3.5-4.5	550-660	*338± 3.4*				24,25,26,27
	Artense	eclogite				> 15	700-740		10-12	720-780		6-7.5	650-700					26, 28
	Marvejols	eclogite				> 15.5	690±40	**415±6**	10-12	800-850	*363±2.4-346±4*			**344±13**				27, 28,29
	Lyonnais	Coe-eclogite	P>28	700-800														30
	Lyonnais	eclogite				16.5-18	700-750		10-13.5	750-850		6.5-8.5	650-740	*338-337*				31
	Lyonnais	Ky/Sill paragneiss				>10	650-750	384±16	7.5-10.5	750-850	*349-345*	3.5-4.5	650	*339-335*	< 4	500-600		32, 33,34
	Maclas	Zo Eclogite				14-16	700-770		10-13	750-800		< 5	480-575		< 3	300-400		35
	Tournon	Ky-eclogite							11-15	650-750		5-8	500-650		2.5-5	300-400		36
	Livradois	Ky/Sil-Grt paragneiss							8-10	625-800	**360**	5-6	550-720	*315 -311*	3-4	300-400	*307-300*	37
	Haut-Allier	eclogite				20	850± 50	**432+20/-10**	15	800		7.5	700		5	500		7, 38
	Haut-Allier	Sill-Grt gneiss				8	600	> 384	11-13	700-800	360	5-10	700–750	336±7				29, 39
LGU	***West French Massif Central***																	
	Limousin (Tulle	eclogite/gneiss	16	700± 50		9.5	825-850		6	650	*-352± 7*, **352± 2**, 357± 4-365± 5			332-336, *335-337*, **317± 3**				40, 12,9, 8, 11
	Limousin	metabasite				15.6	700											8
	Limousin	migmatitic gneiss				11-12	400-500		10± 1	600-650	378-374±5; *356±7*	6 ± 1	700 ± 20	36-332; *337-335* ; **317±1**	3-4	550		20,8, 11
	Limousin	migmatitic gneiss										5-6± 1	760-840± 50	**316±2-315±4**				41, 8, 42,11
	East French Massif Central																	
	La Sioule	Gneiss	3.5 ± 1	500 ± 50		4 ± 1	650 ± 50		9	550	341± 19-351± 5	7 ± 1	650 ± 50	335-329± 10	4 ± 1	600 -700		16,39, 38,17, 11
	La Sioule	micaschists							10 ± 1	600 ± 50								16,39;38, 17,11
	Pilat	micaschistes							8	570-700		4-5.5	700-780	**322± 9-*313***	2.5-3	500-550	*300*	36,27, 43, 44
	Marvejols	micaschists				5	300		10	650	*351-342±3.5*	7.5	700		4-3	550		45, 46, 47, 48
	Marvejols	metadiorite									*351.8±1.3*							48
	Vibal klippe	metapelite							7-8.5	400-450	*349.5-351.5± 3.6*	5-6.5	550-620		4.5-5.5	500		24,27
	Haut-Allier	K-Feld/Sil gneiss	9-12	600-650		12-15	580-650		8-12	610-680		5-9	600-750		2.5-7	600-750		39, 38
	Ardèche	migmatitic gneiss							8 to 10	700-800		5	720	**325-314**	3.5 ± 0.5	760-850	**304**	49,50
PAU	***West French Massif Central***																	
	Limousin	metapelites							9	490		5.7	520		4.9	605		51, 15, 8
	Limousin	micashists							4-9	650-750		9	850					52, 51,15, 8
	East French Massif Central																	
	La Sioule	micaschists							7 ± 1	450 ± 50	363± 8	8 ± 1	600 ± 50	333±18-327±12				16, 39, 38, 17
	Haut-Allier	micaschists				2,5-5	550-600		5.5-8	600-650		7-10	650-700		4-7	610-660		16, 39, 38
	Cevennes	micaschists							6 -9 ± 1.3	615 -655	*343.1± 4.4*	4.5	500					53, 54, 55
MUU	***West French Massif Central***																	
	GU/TPU/St SU	Sta/Grt metapelite							5-9	570-670	350-360							38,39
	East French Massif Central																	
	La Sioule	Micaschistes							7 ± 1	450 ± 50		8 ± 1	600 ± 50					16, 38,39
		Metapelite							7.9 ± 1.2	641 ± 32								16,38,39
PFTB	***East French Massif Central***																	
	Mt Noire	eclogite				14.5	725± 25	**359.5 ±4.7**						**315.2 ±1.6**				55; 56, 57
		Migmatitic gneiss							6.5 ± 0.5	750 ± 50	327± 5, **324 ± 3**	4 ± 1	680 ± 50	*316-320*			*308-297,*	58
		Micachists							6.5 ± 0.5	630 ± 20								58, 59, 60, 57

France (Chantraine *et al.*, 2003) follows the classification by Barbarin (1999). Four types are distinguished (Fig. 6):

- Calc-alkaline granitoids equivalent to the amphibole-rich calc-alkaline granitoids (ACG) of Barbarin (1999) include tonalites, granodiorites and granites. In addition to amphibole, they may contain pyroxene, and frequently include enclaves and small volumes of gabbro to diorites (*i. e.* more mafic terms of the same series). They are essentially similar to arc granitoids typically attributed to fractional crystallization of an enriched mafic magma.
- Peraluminous granites and leucogranites correspond to muscovite or muscovite + biotite bearing granites sensu-stricto equivalent to the muscovite-bearing peraluminous granitoids (MPG) of Barbarin (1999). They are attributed to relatively cold (< 850 °C, water present- or muscovite breakdown) melting of metasediments (Gardien *et al.*, 1995; Villaros *et al.*, 2018) and might represent the first melt extracted from the partially molten source at the onset of partial melting.
- Peraluminous granites to granodiorites, corresponding to the cordierite-bearing peraluminous granitoids (CPG) of

Barbarin (1999). They probably relate to relatively hot (≥ 850 °C, biotite breakdown) melting of a continental felsic source (ortho or paragneisses) (Gardien *et al.*, 1995; Barbey *et al.*, 1999; Villaros *et al.*, 2018). They might represent a partially molten source with a high-melt fraction (*i.e.* diatexites) implying inefficient melt and/or magma extraction but possibly also some solid settling.

– High-K sub-alkaline granitoids, *i.e.* K-feldspar porphyritic calc-alkaline granitoids (KCG) of Barbarin (1999). They are porphyritic granites to granodiorites, commonly amphibole-bearing, and they typically contain abundant accessory minerals such as apatite and titanite. They contain micro-granular mafic enclaves, and are associated with intermediate plutonic rocks (diorites, to tonalites, to monzodiorites) of similar, "vaugneritic" (see below) composition to which they are probably petrogenetically related (Moyen *et al.*, 2017).

In addition, granites and migmatites are associated with mafic but potassic plutonic rocks locally known as "vaugnerites" (Michon, 1987; Sabatier, 1991). Vaugnerites range from diorites to syenites and consist of amphibole, biotite, clinopyroxene, plagioclase, rare orthopyroxene, interstitial K-feldspar and quartz (Sabatier, 1991). Vaugnerites are K-, LILE- and LREE-rich mafic to intermediate rocks, pointing to an origin by partial melting of a mantle source enriched by the addition of crustal components, probably during earlier subduction (Rapp *et al.*, 2010; Couzinié *et al.*, 2014, 2016). They form the most mafic components of the KCG suites. Interestingly, they are undistinguishable from CPG and MPG from an isotopic point of view (Sr, Nd or Hf) (Williamson *et al.*, 1992; Couzinié *et al.*, 2016; Moyen *et al.*, 2017).

The study of vaugnerites and their counterparts in other orogenic settings worldwide indicate that their characteristics unlikely result from the crustal contamination of basaltic magma on their way to the surface and are rather primarily inherited from a mantle source enriched by crustal components (Williams, 2004; Laurent *et al.*, 2011, 2014; Prelević *et al.*, 2012; Campbell *et al.*, 2014; Couzinié *et al.*, 2016). It should be mentioned that vaugnerites are similar to the "durbachites" described in other parts of the Variscan belt (Sabatier, 1991; von Raumer *et al.*, 2014). Such rock types are present in most if not all orogenic settings elsewhere in the world where they are called "appinites", "redwitzite", "high Sr-Ba granitoids" (Fowler *et al.*, 2001) or "sanukitoids" in an Archean context (Martin *et al.*, 2005; Heilimo *et al.*, 2010). In the FMC, the isotopic similarity between vaugnerites and crust-derived granites shows that the crustal component was derived from the local crust, probably during (continental) subduction shortly prior to melting (Couzinié *et al.*, 2016; Moyen *et al.*, 2017). A similar model is proposed for the c. 345 Ma old KCG granitoids (the Blatna suite) of the Bohemian Massif (Janousek and Holub, 1997; Janoušek *et al.*, 2004), suggesting that KCG may derive from similar petrogenetic processes as vaugnerites and typically represent their differentiated products. However, this is not so clear for the FMC where KCG may also derive from interactions between vaugnerites and melts derived from the local crust, such as CPG and MPG (Solgadi *et al.*, 2007; Laurent *et al.*, 2017; Moyen *et al.*, 2017). In either case, KCG are genetically linked to the vaugnerites so they are classified together with them in the following as "mantle-derived" granitoids.

2.2.5 Carboniferous volcanic and sedimentary deposits

In the northern part of the French Massif Central, cystalline rocks are locally capped by middle Carboniferous (Visean: c. 347–325 Ma) volcanic and marine deposits, as exemplified in the Sioule, Morvan and Brévenne regions, implying that they were exhumed and below sea-level at this time (Bertaux *et al.*, 1993; Franke, 2014). In the southern part of the French Massif Central, Devonian to mid-Carboniferous (Visean) carbonates and turbidites are unconformably deposited on plutonic rocks and Ediacaran to Ordovician orthogneisses and paragneisses, in an underfilled foreland basin at the front of a propagating, low-grade fold-and-thrust system (Franke and Engel, 1986; Souquet *et al.*, 2003). Namurian (c. 330–325 Ma) olistoliths and probably Westphalian (c. 325–304 Ma) turbidites and coarse conglomerate deposits attest for the erosion of a growing mountain belt to the north (Engel *et al.*, 1978, 1981; Engel, 1984).

Clastic sediments associated with minor volcanics of late Carboniferous (Stephanian) and Permian ages are unconformably deposited on top of the crystalline rocks in extensional basins associated with strike-slip shear zones marking the waning stages of the Variscan orogeny (Ménard and Molnar, 1988; Van Den Driessche and Brun, 1992; Becq-Giraudon, 1993; Becq-Giraudon *et al.*, 1996). Presence of coal in the Stephanian basins attests for a high-geothermal gradient (Copard *et al.*, 2000), which could be attributed to the juxtaposition of the sediments to high-grade rocks freshly exhumed along low-angle detachments. Permian basins are typically wider than Stephanian ones suggesting progressive peneplanation of the Variscan topography at the end of the Carboniferous.

In summary, the superposition of the UGU over the MAU, LGU and PAU define an inverted metamorphic gradient with HP granulite facies migmatites overlying amphibolite facies paragneisses and orthogneisses with locally preserved LT eclogites. The structural, petrological and geochronological record of these nappes document a diachronous history of burial, exhumation and emplacement spreading from the late Silurian to the Devonian. The top of the nappe pile is locally marked by Metamorphic Upper Units (MUU). The lowest structural level is composed of MP to LP migmatites exposed in the Limousin, and in the Velay and Montagne Noire domes. The nappe pile is dissected by strike-slip shear zones and low-angle detachments. It is intruded by plutonic rocks with ages ranging from late Devonian to late Carboniferous-Permian. These crystalline rocks are capped by volcanic and sedimentary rocks deposited in intramontane and foreland basins with ages also ranging from late Devonian to Permian. The detailed structural relationships between these different lithological units and the timing of geological events is further presented in the next section.

2.3 Architecture and P-T-t record of nappes of the western and eastern French Massif Central

As stated above, the identification of the LAC as a suture led to the revival, after the pioneer proposition of Demay (1948), of the nappe concept in the French Massif Central and several models have been proposed ever since. The early tectonic model (Burg and Matte, 1978; Matte, 1986) highlights

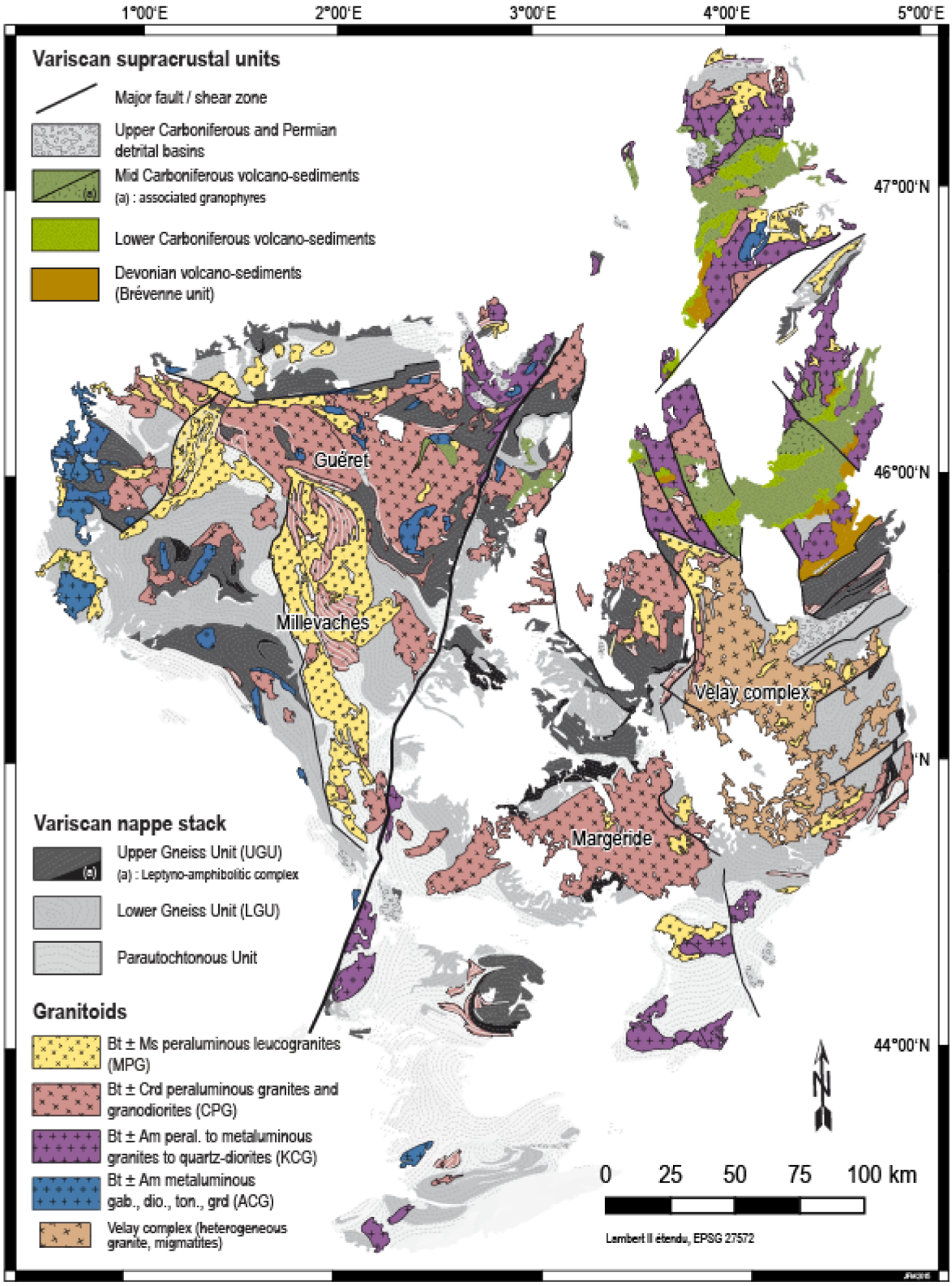

Fig. 6. Petrology of granitoids of the French Massif Central. Plutons are distinguished on the basis of the petrology of their dominant facies according to the classification of Barbarin (1999). ACG-type (calc-alkaline granites) are interpreted as arc magmas originated in an Andean-type continental margin by partial melting of an enriched mantle contaminated by the crust of the upper plate and/or mixed with crutal magmas. MPG-type (or muscovite-bearing peraluminous granites) are attributed to muscovite dehydration- or water present melting of a dominantly metasedimentary source. CPG-type (or cordierite-bearing peraluminous granites) are attributed to biotite dehydration melting of orthogneisses. KCG-type (or K-rich calc-alkaline granites) typically contain abundant micromafic enclaves and are attributed to mixing between magmas generated by partial melting of the crust and a magma generated by partial melting of an enriched lithospheric mantle represented by Mg-K diorites (the so-called vaugnerites).

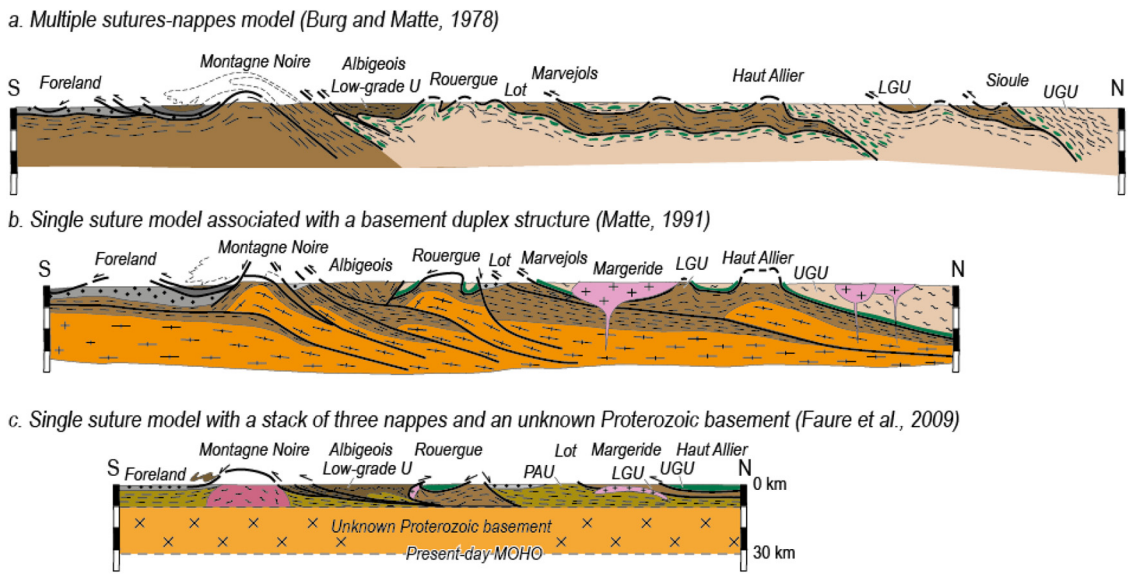

Fig. 7. Cross sections depicting the previously proposed nappe structure. A. Multiple sutures-nappe model (modified after Burg and Matte, 1978). B. Single suture model associated with a basement duplex structure (Matte, 1991). C. Single suture model associated with a stack of three nappes and an "unknown Proterozoic basement" (Faure *et al.*, 2009a, 2009b).

three distinct nappes cored by the migmatites of the UGU; namely from north to south, the Sioule, the Haut Allier – Marvejols, and the Rouergue nappes (Fig. 7). In this model each outcropping zone of the UGU and associated LAC corresponds to a locally rooted nappe that, in turn delineates a suture and thus a former oceanic basin. In contrast, subsequent models (Faure *et al.*, 2009a; Matte, 1991, 2001; Lardeaux, 2014) propose that these three nappes form only one with the LAC representing a single ocean rooted beneath the Paris Basin. Consequently, the discontinuous outcrops of the UGU with enclaves of LAC are interpreted as klippes.

The high-grade nappes are characterized by a penetrative composite foliation resulting from superimposed structures and metamorphic parageneses that is typically parallel to the tectonic contacts. This foliation is dominantly shallow dipping (Burg and Matte, 1978; Matte, 1986; Faure *et al.*, 2009a) but is locally steeply dipping such as in the Livradois or in the Monts du Lyonnais (Feybesse *et al.*, 1988; Lardeaux and Dufour, 1987; Gardien *et al.*, 1990, 2011). Away from strike slip shear zones, the lineation associated with this composite foliation is dominantly E-W to WNW-ESE trending in the western part of the French Massif Central and in the Sioule region but is dominantly N-S to NNE-SSW trending in the eastern part (Faure *et al.*, 2009a). Moreover, this foliation is in place affected by regional upright folding such as in the Limousin (Burg and Matte, 1978; Girardeau *et al.*, 1986; Matte, 1986). The structure of the nappe pile is blurred by numerous granitic plutons and original contacts are reworked by thrusts, strike-slip shear zones, low-angle detachments and high-angle normal faults. This complex structural record and the scarcity of outcrops impedes the identification of the original tectonic contacts between the nappes in most places. Nevertheless, in order to discuss the tectonic evolution of potentially distinct nappes, in the following sections, we review available data regarding the structural position and P-T-t record of the lithological-tectonic units presented above distinguishing the Western and Eastern parts of the French Massif Central separated by the Sillon Houiller Fault (Figs. 8–10).

2.3.1 Western French Massif Central (W-FMC)

In the northern part of the W-FMC, the Aigurande region is exposing metamorphic rocks unconformably overlain by Mesozoic sediments of the Paris Basin to the north and is delimited by the La Marche shear zone to the south (Fig. 8 cross section AA'). Metamorphic rocks present a polyphased structural and metamorphic history associated with an inverted metamorphic gradient characterized by the superposition, from top to bottom, of the UGU, the LGU and PAU (Quenardel and Rolin, 1984; Faure *et al.*, 1990). At the top of the nappe pile, the UGU is dominated by diatexites and metatexitic orthogneisses and paragneisses with rare quartzites. These rocks display a dominant garnet-sillimanite-cordierite mineral paragenesis with relics of kyanite that attest for HP partial melting followed by retrogression during decompression. The amphibolite facies foliation of these migmatites is associated with top-to-the SE sense of shear criteria considered to record nappe emplacement (Faure *et al.*, 1990). The boundary between the UGU and the LGU is marked by boudins of eclogitic amphibolites and of ultramafics attributed to the LAC. Amphibolites that are part of the LAC, yield $^{40}Ar/^{39}Ar$ dates on amphibole at 389 ± 8 Ma interpreted as the age of amphibolite facies metamorphism (Boutin and Montigny, 1993). A mylonitic shear zone underlines the contact between the migmatitic units of the LGU and micaschists attributed to the PAU (Faure *et al.*, 1990). This contact was first interpreted as a thrust responsible for burial of the PAU beneath the LGU (Quenardel and Rolin, 1984). In contrast, retrogression of the garnet-biotite dominant foliation of the micaschists associated with top-to-the NE kinematic criteria has been reinterpreted as reflecting exhumation of the PAU during a period of regional extension estimated at 325–312 Ma based on syntectonic

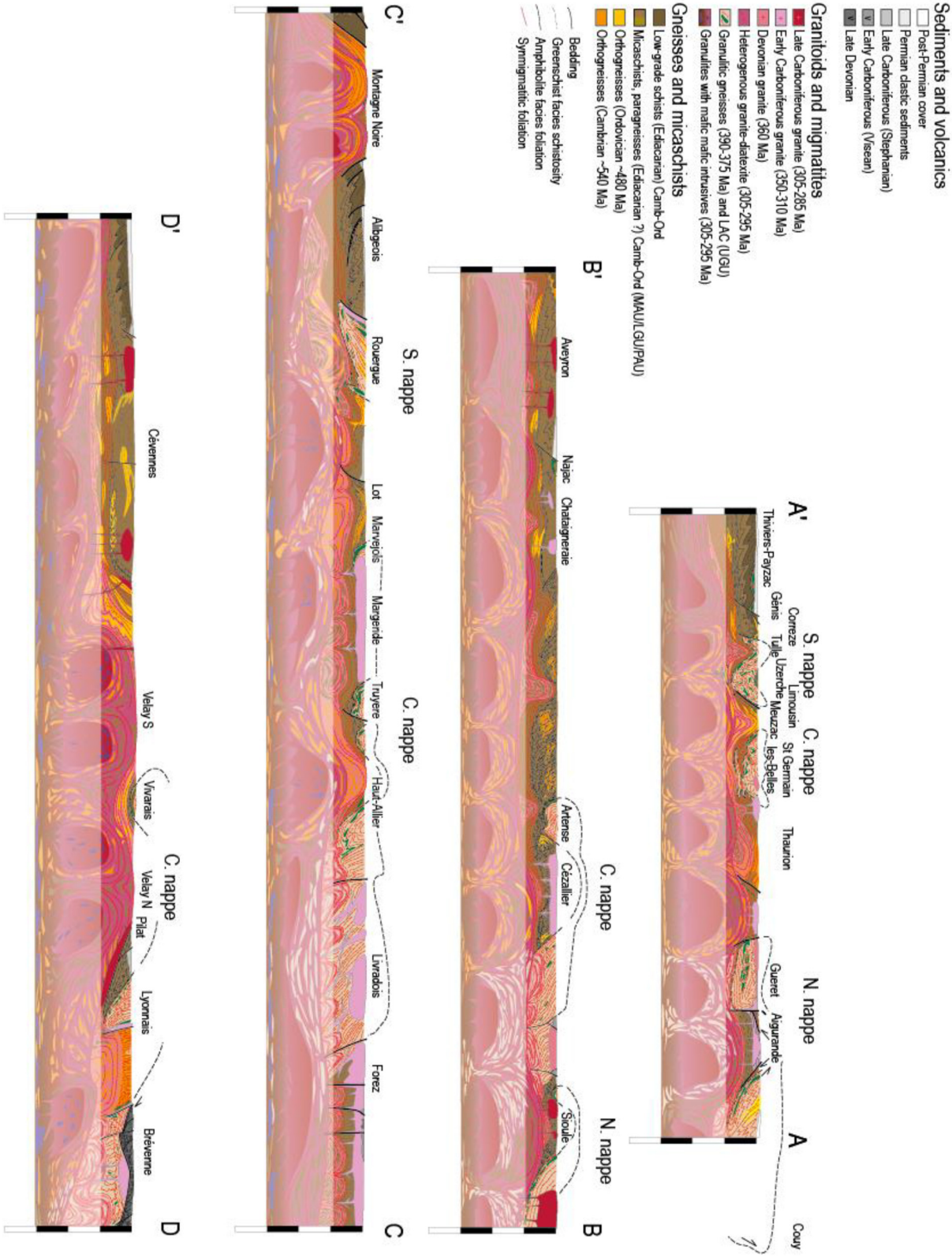

Fig. 8. Cross sections of the French Massif Central. The location of the cross sections (A-A', B-B', C-C', and D-D') is indicated on the geological map Figure 2. Same legend as Figure 3 with the addition of a granulitic lower crust intruded by mantle-derived mafic magmas. The upper part of the sections is constrained by field observations. The shaded lower part of the sections is less constrained and is based on scarce geophysical data that allow the prolongation of some structures at depth and on exposed sections of the Variscan lower crust in the Southern Alps (Ivrea Zone) and in Calabria.

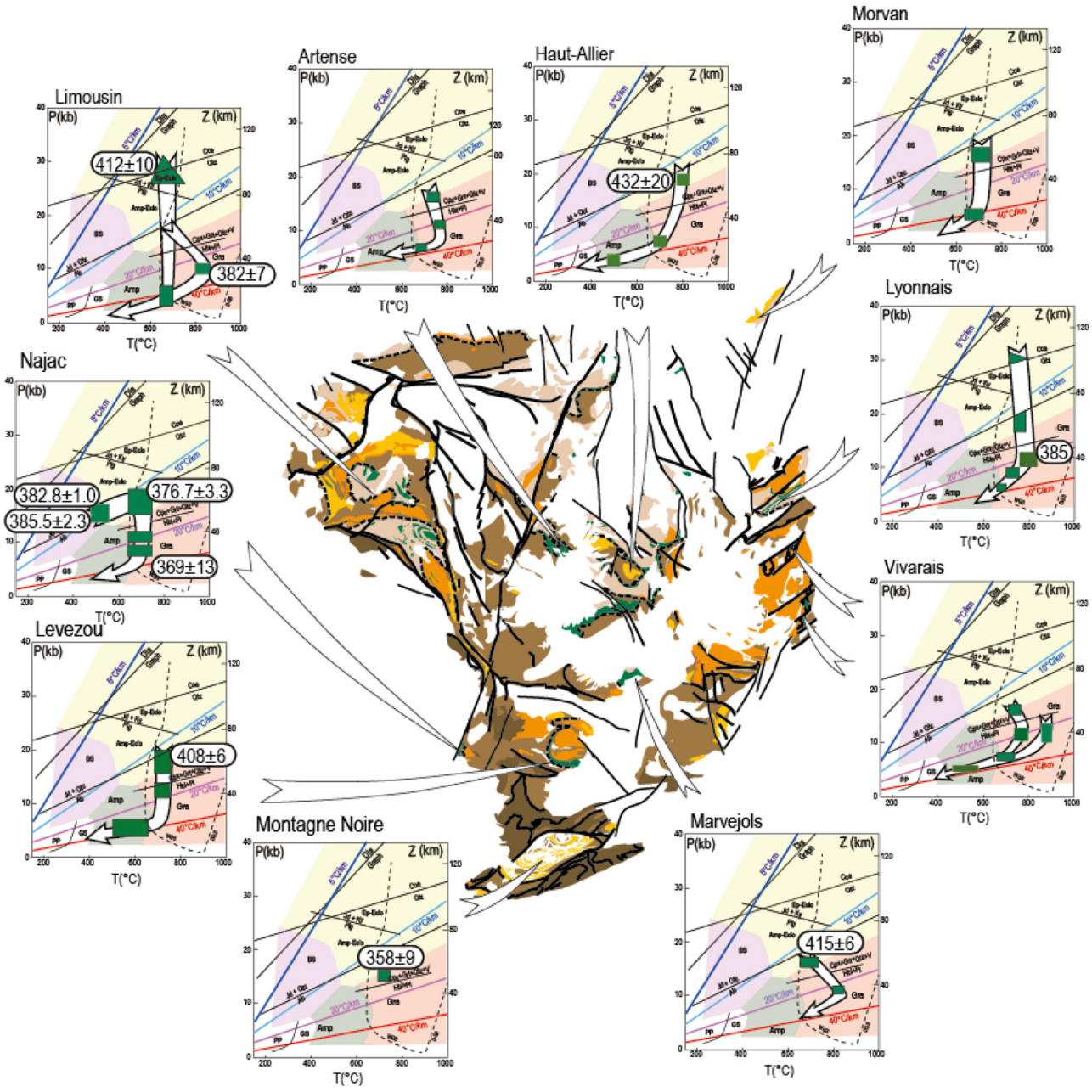

Fig. 9. P-T-t constraints on the metamorphic history of the Upper Gneiss Unit and of the Middle Allochthonous Unit. The Leptynite-Amphibolite Complex is characterized by HT eclogite facies metamorphism retrogressed into granulite facies by isothermal decompression and then into amphibolite facies by a decrease in temperature. Granulite facies to amphibolite facies metamorphism is also recorded in the migmatitic gneisses hosting the LAC. The PT path is depicted by the white arrows and numbers correspond to radiometric ages.

leucogranites emplacement (Faure *et al.*, 1990). It is noteworthy that these micaschists of the PAU contain relics of kyanite and staurolite attesting for a so far undated MP/MT amphibolite facies metamorphism before retrogression into greenschist facies.

To the north of the FMC, the crystalline basement beneath the Paris Basin has been sampled in the Couy deep borehole down to 3500 m (Fig. 1). Granulite facies migmatites of the UGU are associated with metabasites attributed to the LAC with a Cambrian-Ordovician protolith as constrained by a Sm-Nd isochron of 494 ± 17 Ma and a U-Pb zircon date of 497 ± 13 Ma (Pagel *et al.*, 1992). These rocks display a NE-SW trending foliation steeply dipping to the SE. The granulite facies mineral paragenesis yield a pressure ranging from 15 to 9 kbar and a temperature from 900 to 650 °C. Retrogression into the amphibolite facies is recorded at c. 6 kbar for c. 600 °C (Burg *et al.*, 1989a, 1989b; Ballèvre and Balé, 1992). Amphibolites yield an Rb-Sr isochron of 387 ± 2 Ma interpreted as dating high-grade metamorphism. $^{40}Ar/^{39}Ar$ ages on amphibole and biotite from granulite facies amphibolites and

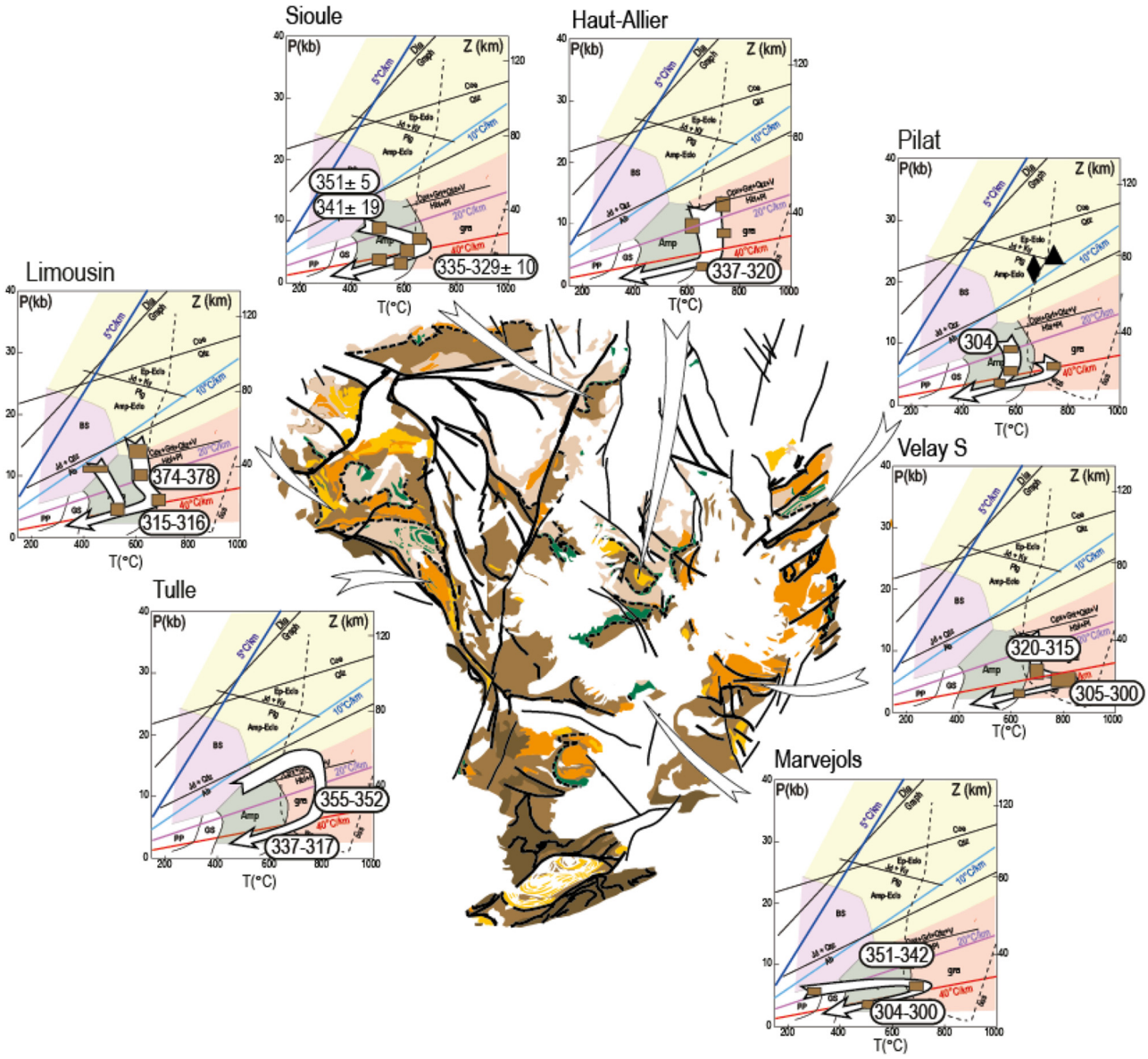

Fig. 10. P-T-t constraints on the metamorphic history of the Lower Gneiss Unit. The P-T-t paths of orthogneisses and paragneisses of the LGU indicate first an increase in temperature followed by isobaric cooling. This is particularly well illustrated by the P-T-t path of the south Velay which is characterized by a HT/LP gradient. The PT path is depicted by the white arrows and numbers correspond to radiometric ages.

orthogneisses, respectively range from c. 385 Ma to c. 379 Ma and point to rapid cooling below 300 °C before the end of the Devonian (Costa and Maluski, 1988). Accordingly, the P-T-t record of the UGU sampled in the Couy deep borehole is similar to the one of the UGU exposed in the Aigurande region and these rocks are attributed to the same nappe that will be designated as the northern nappe in the following.

South of the Aigurande region, the northern Limousin region exposes a slightly different nappe package. The UGU is mainly made of migmatitic paragneisses with ubiquitous relics of HP metamorphism expressed as eclogites and numerous garnet amphibolite boudins (Le Breton *et al.*, 1986). Below, the LGU exposed in the core of the Thaurion and Meuzac antiforms (Fig. 8, section AA') is dominated by amphibolite facies orthogneisses with some paragneisses. In addition to the high-grade units recognized in the Aigurande region, several authors have identified a Middle Allochthonous Unit (MAU) stacked in between the UGU and LGU (Girardeau *et al.*, 1986; Dubuisson *et al.*, 1989; Berger *et al.*, 2010a, 2010b). The UGU contains eclogite facies metabasites attributed to the LAC yielding U-Pb zircon ages pointing to a crystallization of their protolith between c. 489 and c. 475 Ma. The eclogitic UHP event is dated at 412 ± 10 Ma followed by a resetting potentially linked to partial melting and retrogression into the granulite facies at 382 ± 7 Ma (Berger *et al.*, 2010a), which is also consistent with previous whole rock Rb-Sr isochrons from c. 385 to c. 375 Ma (Duthou, 1978; Duthou *et al.*, 1994), U-Pb on zircon at 383 ± 5 Ma (Lafon, 1986) and U-Th-Pb on monazite between c. 378 and c. 374 Ma (Faure *et al.*, 2008). The relationship between this nappe pile and the one exposed

in the Aigurande region is not clearly identified but the differences displayed by their cooling histories point to distinct exhumation histories. In the following, the nappe exposed in the northern Limousin will be designated as the Central nappe.

In the southern Limousin the nappe pile is deformed in a serie of upright folds designated as the Uzerche synform and the Tulle antiform (Ledru *et al.*, 1989) (Fig. 8, section AA'). The UGU is dominated by granulite facies migmatitic paragneisses with eclogitic mafic boudins yielding peak metamorphic conditions at c. 15 kbar and c. 750 °C (Santallier, 1981; Bellot and Roig, 2007). In a lower structural position, migmatitic paragneiss and orthogneiss that contain boudins/enclaves of eclogites and garnet-spinel peridotites with peak P-T conditions at c. 15 kbar and c. 700 °C similar to the ones of the UGU (Santallier, 1981; Ledru *et al.*, 1989; Bellot and Roig, 2007). These eclogitic boudins have been first attributed to the LGU but could be part of the MAU according to their structural position and P-T record. Structurally below these rocks, migmatitic paragneisses display a syn-migmatitic foliation underlined by cordierite-sillimanite-bearing leucosomes that document a retrograde P-T path from c. 9.5 kbar at c. 850 °C to c. 6 kbar at c. 600 °C and locally to c. 3.5 kbar at c. 550 °C (Bellot and Roig, 2007). These migmatites yield a U-Pb age on zircon at 382 ± 5 Ma interpreted as the age of partial melting (Lafon, 1986) and a variety of $^{40}Ar/^{39}Ar$ ages on micas as well as U-Th-Pb ages on monazite spreading from c. 350 Ma to c. 315 Ma that might reflect progressive exhumation and cooling, or partial reseting owing to recrystallization, during the Carboniferous (Costa, 1992; Gebelin *et al.*, 2004; Melleton *et al.*, 2009). The high-grade nappes are overlain by the Thiviers-Payzac Unit and by the Génis Unit (Guillot and Doubinger, 1971; Guillot and Lefevre, 1975; Santallier, 1981; Bellot and Roig, 2007) that are affected by a prograde Barrovian metamorphic gradient with peak conditions at c. 9 kbar for c. 750 °C at the lowest structural level. The Thiviers-Payzac Unit is intruded by pre-tectonic calc-alkaline dolerite dykes dated at 363 ± 10 Ma by K-Ar on whole rock (Bellot and Roig, 2007). The presence of high-grade rocks of the UGU sandwiched in between lower-grade rocks is interpreted to correspond to vertical extrusion of the high-pressure UGU into an orogenic wedge affected by Barrovian metamorphism (Bellot and Roig, 2007), as envisioned in models of Chemenda *et al.* (1996) or Escher and Beaumont (1997). According to these data, the South Limousin UGU is characterized by a younger cooling history than the North Limousin one, which is used to define what will be referred as the southern nappe in the following.

The oldest Variscan plutonic rocks identified in the Western part of the French Massif Central are late Devonian and display a variety of petrological and geochemical signatures. Small plutons emplaced into the UGU (ACG type of Barbarin 1999), with a composition ranging from gabbro to granodiorite and signatures from calc-alkaline to tholeiitic, define a broadly linear trend referred to as the "Limousin tonalite line" (Peiffer, 1986; Cuney *et al.*, 1990, 1993). These rocks first yielded TIMS U-Pb zircon ages of 379 ± 19 Ma and 355 ± 2 Ma (Bernard-Griffiths *et al.*, 1985) and have since provided more precise ages of 365 ± 3 Ma and 360 ± 1 Ma by the same method (Pin and Paquette, 2002). In contrast, the contemporaneous Guéret pluton (Turpin *et al.*, 1990) is a cordierite-bearing peraluminous granite (CPG in the nomenclature of Barbarin, 1999) dated in the late Devonian (Berthier *et al.*, 1979). It forms a c. 1 km thick laccolith overlying the cordierite-bearing migmatitic gneisses of the UGU (Lameyre *et al.*, 1988; Dupis *et al.*, 1990; Gébelin *et al.*, 2006). These plutonic rocks are cross-cut by a system of E-W to NW-SE trending dextral shear zones including the La Marche, Courtine and Pradines shear zones that started their activity at about 350 Ma as attested by $^{40}Ar/^{39}Ar$ on syntectonic biotite in the Aigurande plateau (Gébelin *et al.*, 2007). These shear zones control the syntectonic emplacement of CPG and MPG plutons from 345 to 310 Ma (Lafon and Respaut, 1988; Lerouge and Quenardel, 1988; Alexandrov *et al.*, 2001; Gébelin *et al.*, 2007, 2009; Rolin *et al.*, 2009, 2014), bounded at their roof by detachment zones (Faure and Pons, 1991; Gébelin *et al.*, 2007).

Leucogranites are interpreted to be generated by partial melting of a metasedimentary middle crust (Cuney *et al.*, 1990; Williamson *et al.*, 1996; Moyen *et al.*, 2017; Villaros *et al.*, 2018). This is consistent with their structural position relative to their host rocks, as exemplified by the Millevaches laccolith rooted into cordierite-bearing migmatitic paragneisses that have been affected by partial melting under MP/MT amphibolite facies conditions (6 kbar for 850 °C) as attested by leucosomes localized in strike-slip shear bands (Gébelin, 2004; Gébelin *et al.*, 2006, 2009). This high-grade metamorphism and partial melting has been dated at 315 ± 4 Ma and 316 ± 2 Ma, coeval with the syntectonic emplacement of leucogranites in the Pradines dextral strike-slip shear zone at 313 ± 4 Ma (Gébelin *et al.*, 2009). The dextral strike-slip shear zones are cross-cut by high-angle normal faults and low-angle detachments such as the NE-SW trending Nantiat and Bussière shear zones and the N-S trending Argentat shear zone (Fig. 3) (Gébelin *et al.*, 2007, 2009). The footwall of these detachment zones represented sites of strong (meteoric) fluid-rock-deformation interactions during the late Carboniferous (Dusséaux, 2019; Dusséaux *et al.*, 2019). Exhumation along these low-angle mylonite zones is constrainted to be middle (Visean) to late Carboniferous (Stephanian) in age, by argon thermochronology (Alexandrov *et al.*, 2000; Roig *et al.*, 2002; Gébelin, 2004; Gébelin *et al.*, 2007; Rolin *et al.*, 2014). The activity of these shallow dipping detachments and strike-slip shear zones, which are part of the Sillon Houiller Fault, controlled the deposition of late Carboniferous coal-bearing sediments in small extensional and pull-apart basins (Feybesse, 1981; Thiéry *et al.*, 2009). The onset of deposition in these basins during the Visean is confirmed by a fireclay dated at 332 ± 4 Ma by U-Pb TIMS on zircon in northern Limousin (Bruguier *et al.*, 1998). The Permian clastic sedimentary deposits of the Brive basin unconformably overlie these late Carboniferous deposits and mark the end of the Variscan tectonic activity in this region.

Although scarce, available geophysical data for the W-FMC provide some constraints on the deep crustal structure. Gravity data indicate that most plutons are laccoliths with an average thickness of about 1 km but that can locally reach up to 3 km (Gébelin *et al.*, 2006; Joly *et al.*, 2008, 2009). As a complement, seismic data allow to identifiy the prolongation of surface structures at depth (Bitri *et al.*, 1999). In the upper crust, the main feature is that most reflectors appear to match the projection of the dominantly shallow-dipping high-grade fabric parallel to lithological-tectonic contacts identified at

the surface. These reflectors are only crosscut and offset by high-angle faults and low-angle detachments. For example, high-angle faults separating the North and South Limousin and affecting high-grade rocks coring the Meuzac antiform, are offsetting reflectors marking the contacts between the UGU, MAU, LGU and PAU and are rooted into a high reflectivity zone at 10 km depth. Similarly, the Argentat shear zone corresponds to a several km thick zone of reflectors shallowly dipping to the West rooting into a reflective zone at about 10 km depth. Accordingly, the Argentat shear zone might be interpreted as the breakaway zone of a low-angle detachment rooted in the brittle-ductile transition. These high reflectivity zones are overlying a c. 10 km thick seismically transparent middle crustal zone with a relative low density that has been interpreted to be composed of granitic material (Bitri *et al.*, 1999). Alternatively, this middle crust, coring low amplitude (few km) and long wavelength (tens of km) dome-shaped structures, could be composed by migmatites, as it has been proposed for similar structures detected beneath low-angle detachments in the South Armorican Massif (Bitri *et al.*, 2010). Beneath this transparent middle crustal zone, the lower crust is typically marked by its high reflectivity from c. 20 km down to the Moho at c. 30 km depth (Bitri *et al.*, 1999). These characteristics are used to constrain the deep part of the cross sections (Fig. 8) beyond information provided by surface outcrops.

2.3.2 Eastern French Massif Central (E-FMC)

The continuity of the nappes from the W-FMC to the E-FMC across the Sillon Houiller Fault is not easily established. Nevertheless, as for the W-FMC, the P-T-t record of high-grade rocks of the E-FMC points to the diachronous emplacement of several distinct nappes.

In the northern part of the E-FMC, the position of the late Devonian Brévenne back-arc, to the south of the Morvan arc represented by the late Devonian Somme Unit, has been used to infer a southward subduction of the Rheic Ocean along a continental active margin (Faure *et al.*, 1997, 2008). Sparse outcrops of retrogressed eclogites, serpentinised peridotites and amphibolites affected by HP metamorphism are characteristic of the UGU (Gardien *et al.*, 1988; Godard, 1990). The timing of exhumation of these high-grade rocks and their structural relationships with the Devonian volcanic-sedimentary sequences are ill-defined. However, it has been proposed that they were already exhumed before the middle Devonian at the time of formation of the Morvan arc and Brévenne back-arc (Faure *et al.*, 1997, 2008). In that case, the UGU exposed in the Morvan region might correspond to the northern nappe described in the W-FMC. Because of these uncertainties, this part of the French Massif Central is not represented on cross sections of Figure 8.

In the Sioule area (Fig. 8, section BB'), the Variscan basement shows a dominant shallow-dipping composite foliation deformed in a broad antiform cored by granitic plutons and displaying an inverted metamorphic gradient (Faure *et al.*, 1993, 2002). The top of the nappe pile is made of cordierite-bearing diatexites and migmatitic orthogneisses and paragneisses that have recorded isothermal decompression from 12–13 kbar to 2–3 kbar at 650–700 °C. Both lithologies display a composite foliation bearing a NE-SW trending lineation (Audren *et al.*, 1987; Schulz *et al.*, 2001; Schulz, 2009). Serpentinite boudins and granulitic relics allow to assign these rocks to the UGU (Ravier and Chenevoy, 1979). Metamorphic monazite with a U-Th-Pb EPMA age at 416 ± 15 Ma is attributed to HP metamorphism (Do Couto *et al.*, 2016) but retrogression under amphibolite facies has not been dated. The contact with the lower-grade underlying micaschists attributed to the PAU has first been interpreted as a thrust (Burg and Matte, 1978; Ledru *et al.*, 1989) but has been then attributed to an extensional detachment reflecting exhumation of the PAU during Visean regional extension dated at 337–336 Ma by Ar thermochronology on mica and amphibole of syntectonic granites (Faure *et al.*, 1993, 2002). Despite uncertainties on the timing of exhumation of the UGU in the Morvan and Sioule regions, we propose to consider that they are part of the same northern nappe exhumed, at least partly, during the late Devonian as previously proposed by Faure *et al.* (Faure *et al.*, 1997, 2008). The southern boundary of the Sioule-Morvan high-grade nappe is marked by a dextral strike-slip corridor (Hermitage shear zone) crossing the Forez and Brévenne regions and localizing the emplacement of syntectonic MPG plutons dated from 332 ± 2 to 326 ± 2 Ma (U-Pb on zircon, Laurent *et al.*, 2017). These high-grade metamorphic and plutonic rocks are capped by Visean undeformed volcanics, volcaniclastics and granophyres represented by the "tufs anthracifères" series dated at 336 ± 5 Ma by a Rb-Sr isochron (Carrat and Zimmermann, 1984; Sider and Ohnenstetter, 1986; Delfour *et al.*, 1989; Leloix *et al.*, 1999; Faure *et al.*, 2002). A similar age of 332 ± 2 Ma has been obtained by U-Pb TIMS on zircon from a rhyolite sampled in the Decazeville basin (Bruguier *et al.*, 1998). These Visean volcanic rocks are locally associated with marine deposits, which has been used to propose that the high-grade rocks of the nappe pile were exhumed but remained below sea-level at this time (Franke, 2014).

South of the Hermitage shear zone, several fragments of the UGU, composed of migmatitic paragneisses and orthogneisses grading from metatexites to diatexites, are exposed in the Combrailles, Cézallier, Artense, Livradois, Truyère, Haut-Allier, Lyonnais and Vivarais regions (Feybesse *et al.*, 1988; Lardeaux and Dufour, 1987; Gardien, 1993; Gardien and Lardeaux, 1991; Mercier *et al.*, 1991a, 1991b; Gardien *et al.*, 2011) (Fig. 8, sections BB', CC', DD'). We propose here that these litho-tectonic units are part of the central nappe. The migmatitic gneisses of the UGU yield whole rock Rb-Sr isochrons ranging from 385 to 375 Ma in the Lyonnais (Duthou *et al.*, 1981, 1994) and a monazite age of 360 ± 4 Ma by U-Th-Pb EMPA in the Livradois (Gardien *et al.*, 2011; Vanderhaeghe *et al.*, 2013). These ages are tentatively interpreted to record the transition from an early stage of HP granulite facies (at least 10 kbar for c. 800 °C) followed by decompression to 6 kbar. In the northern root zone of this nappe, exposed in the Lyonnais and Livradois, the NE-SW trending regional foliation of the UGU migmatites is steeply dipping to the north (Lardeaux and Dufour, 1987; Feybesse *et al.*, 1988; Gardien *et al.*, 1990, 2011) (Fig. 8, sections CC', DD'). North of the Livradois, these migmatites display a penetrative C/S fabric consistent with a top to the south sense of shear (Koné, 1985; Gardien *et al.*, 2011; Vanderhaeghe *et al.*, 2013). To the north of the Lyonnais, the late Devonian volcanic-sedimentary series of the Brévenne unit are characterized by upright folds with an NNE-SSW trending axial planar schistosity under greenschist facies metamorphism (Fig. 8 section DD'). The contact between the Brévenne Unit and the UGU of the Lyonnais is marked by transposition of previous structures into

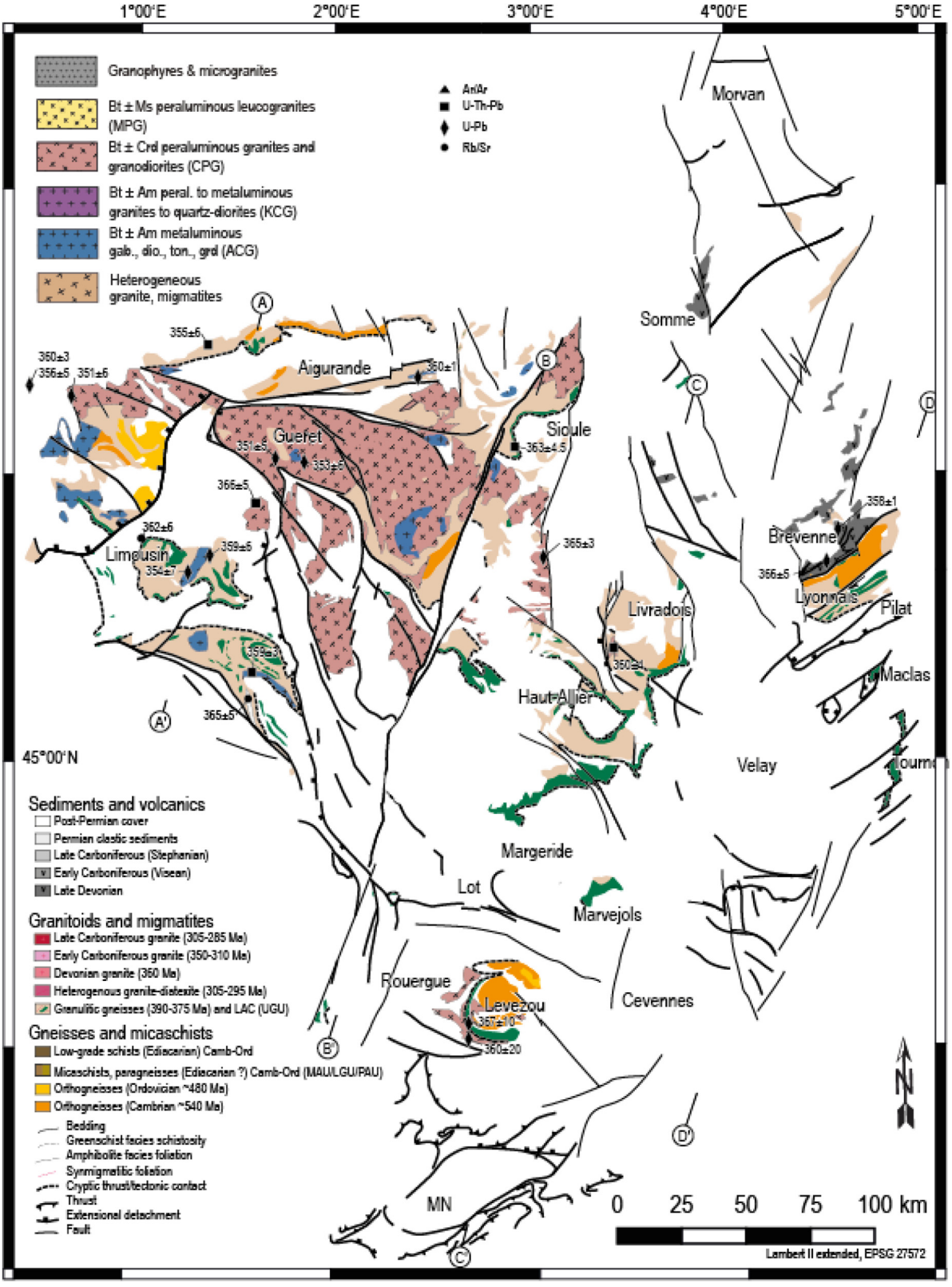

Fig. 11. Late Devonian to Early Carboniferous magmatism. The western part of the French Massif Central is dominated by plutonic rocks of the ACG-type and CPG-type while the eastern part of the French Massif Central also comprises volcanics with a tholeiitic to calc-alkaline signature.

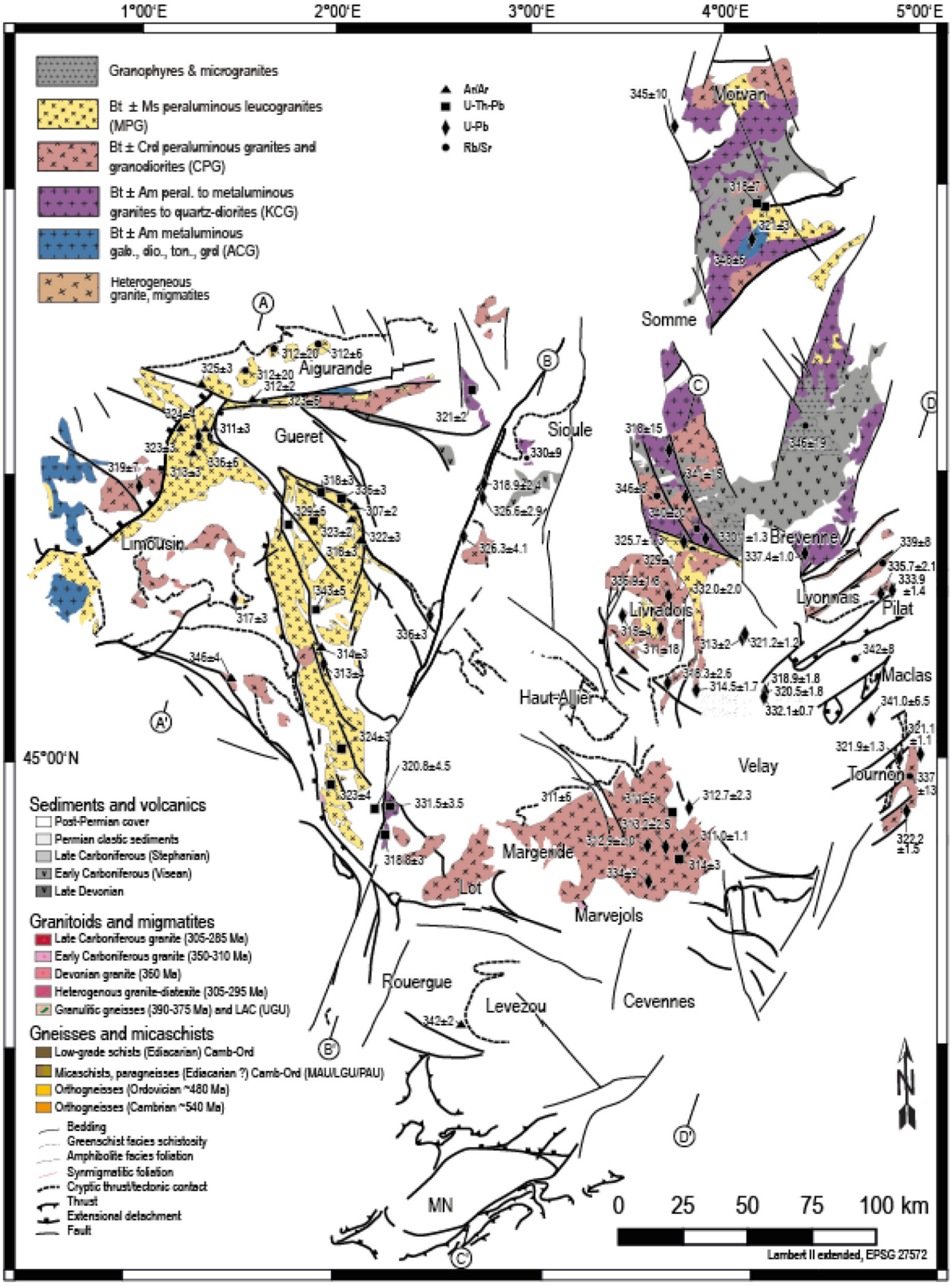

Fig. 12. Middle Carboniferous magmatism. Magmatic rocks with ages ranging from c. 345 to c. 310 Ma are widespread throughout the northern part of the French Massif Central indicating the presence of a partially molten source at depth during this period. Plutonic rocks display a variety of geochemical signatures encompassing MPG-type, CPG-type, and KCG-type pointing to the contribution of crustal and mantle sources.

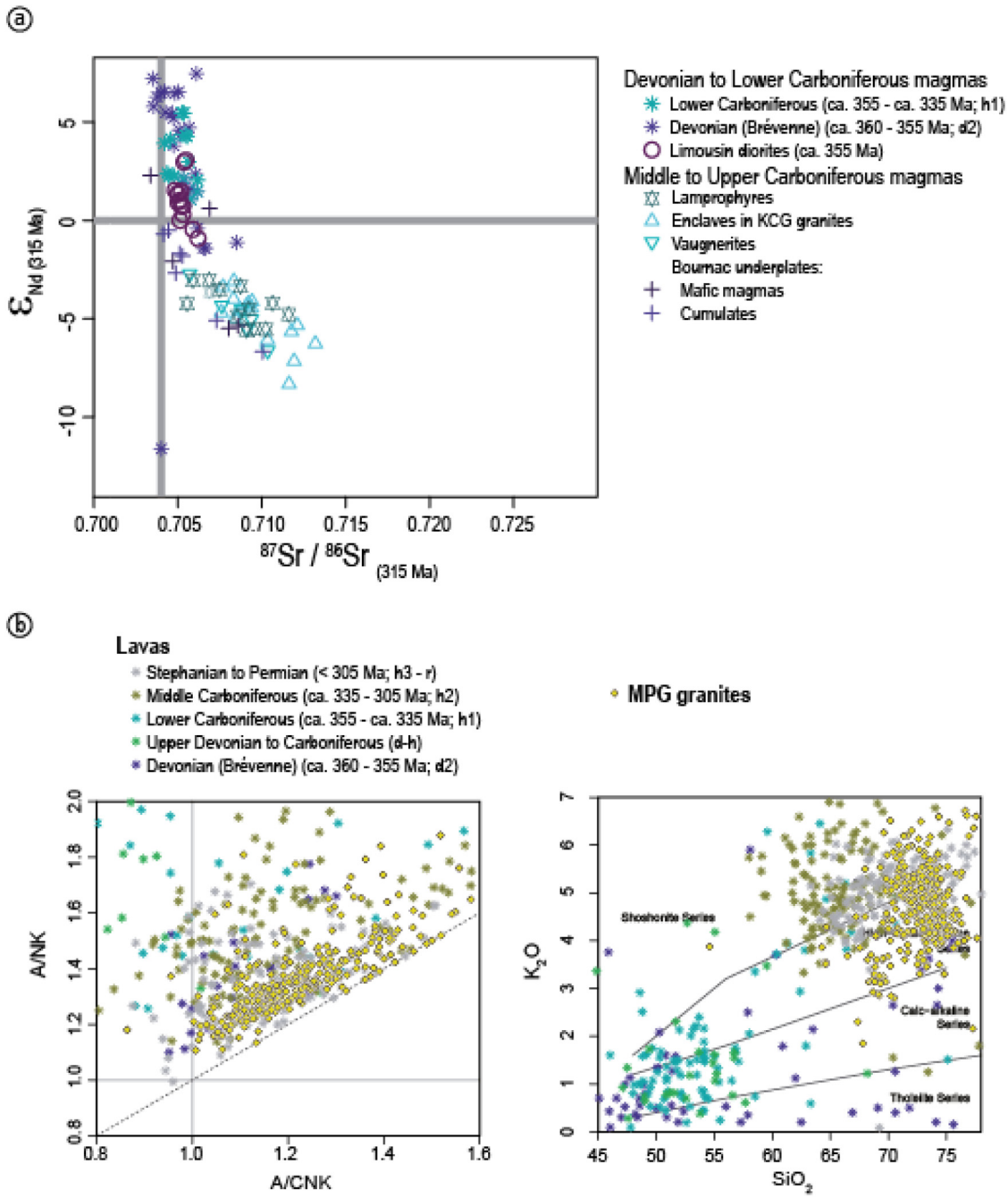

Fig. 13. Geochemistry of magmatic rocks of the French Massif Central. a) Two mantle sources in the Massif Central (calculated at 315 Ma, an average between the c. 335 Ma lavas and the ca 305 Ma lamprophyres and vaugnerites): note the clear difference between the pre-335 mafic magmas (lavas from the Brévenne Unit (Pin and Paquette, 1997) and diverse lavas from NE Massif Central (Pin and Paquette, 2002)), and the post-335 Ma lavas (lamprophyres: (Agranier 2001); enclaves in granites (Pin, 1990) and vaugnerites (Williamson *et al.*, 1992); underplated mafic magmas (or cumulates) found as enclave in the Cenozoic Bournac volcano (Downes *et al.*, 1990)). b) Change in the nature of the lavas, in Shand (1943) A/CNK *vs.* A/NK and Peccerillo and Taylor (1976) SiO_2–K_2O diagrams. Pre-335 Ma lavas are mafic and metaluminous, whereas post-335 Ma lavas are felsic, high-K and peraluminous, essentially similar to MPG granites forming at the same age.

NE-SW trending shallow-dipping shear zone (Feybesse *et al.*, 1988), also delineated by a syntectonic granite displaying a C/S fabric consistent with a top to the NW sense of shear (Feybesse *et al.*, 1988; Leloix *et al.*, 1999). Deformation of this granite is dated at 339–337 Ma by $^{40}Ar/^{39}Ar$ on recrystallized muscovite (Faure *et al.*, 2002), which is consistent with both Rb-Sr whole rock isochrons obtained by Gay *et al.* (1981) on the syntectonic granite and by Vialette (1973) on genetically linked hypovolcanics (Leloix *et al.*, 1999; Faure *et al.*, 2002), giving ages at 339 ± 8 and 336 ± 5 Ma respectively. These data

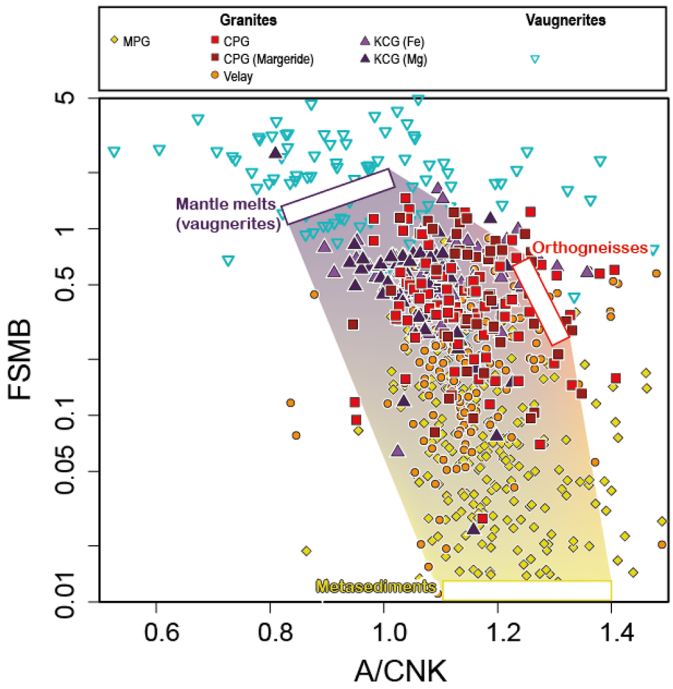

Fig. 14. Geochemical characteristics of magmatic rocks exposed in the East French Massif Central. Summary of the geochemical characteristics of E-FMC granitoids, in a A/CNK (molar $Al_2O_3/CaO + Na_2O + K_2O$ diagram, Shand 1943) *vs.* FSMB ((FeOt + MgO) × (Sr(wt.%) + Ba(wt.%)) diagram (Laurent *et al.*, 2014). This diagram separates granitoids related to different sources (Moyen *et al.*, 2017), and shows that KCG are primarily related to the differentiation of vaugnerites (with minor crustal components occasionaly); MPG are related to a metasedimentary source; CPG are generated from a source dominated by orthogneisses, but with more common involvement of either a metasedimentary component (particularly pronounced in the Velay complex) or a mafic component (*e.g.* the Margeride granite).

suggest that at least part of the exhumation of the UGU in this region occurred during the early Carboniferous and was associated with top to the NW shearing. In the Livradois (Fig. 8, section CC'), the southern part of the migmatitic UGU nappe is cut by dextral-reverse transcurrent shear zones and associated syntectonic peraluminous granodiorite and leucogranite plutons (CPG and MPG) dated by TIMS U-Pb on zircon at 315 ± 4 and 311 ± 18 Ma, respectively (Solgadi *et al.*, 2007; Gardien *et al.*, 2011; Vanderhaeghe *et al.*, 2013), which provides a maximum age for the exhumation of these rocks. The geochronological data obtained on the HP migmatites of the UGU in the Lyonnais and Livradois are significantly younger than the ones obtained in the Sioule area and we propose to attribute these rocks to the central nappe.

In the Haut-Allier area (Fig. 8, section CC'), the foliation of the UGU flattens to the south and delineates a dome cored by migmatites attributed to the LGU (Burg and Matte, 1978; Gardien *et al.*, 2011). In the Artense, Truyere, and Marvejols regions, amphibolite facies paragneisses attributed to the LGU and greenschist facies micaschists attributed to the PAU define an inverted metamorphic gradient with respect to the overlying UGU (Ledru *et al.*, 1989; Mercier *et al.*, 1991a). Amphibolites of the UGU contain thin tonalitic to trondhjemitic layers interpreted to reflect high-pressure partial melting (Nicollet and Leyreloup, 1978; Pin and Lancelot, 1982). This high-pressure metamorphism has been dated by zircon TIMS U-Pb analyses at 432 + 20/− 10 Ma in the Haut Allier (Ducrot *et al.*, 1983), 415 ± 6 Ma in Marvejols (Pin and Lancelot, 1982) and at 413 ± 23 and 408 ± 7 by Pb-Pb on zircon and a Sm-Nd whole rock and garnet isochron respectively in the Rouergue (Paquette *et al.*, 1995). Retrograde amphibolite facies metamorphism is recorded by lower intercepts defined by discordant U-Pb zircon data at 345–340 Ma obtained on paragneisses and amphibolites (Pin and Lancelot, 1982). The UGU-LGU contact is intruded by the Margeride laccolithic composite pluton (Couturié *et al.*, 1979; Couturié and Caen-Vachette, 1980; Talbot *et al.*, 2005). The main porphyritic monzogranite yields U-Pb zircon dates of 334 ± 9 Ma (Respaut, 1984) and of 313 ± 2 Ma (Laurent *et al.*, 2017) and a U-Pb on monazite of 314 ± 3 Ma (Pin, 1979). The leucogranitic facies cross cutting the monzogranite is dated by various methods from 311 to 298 (Couturié and Caen-Vachette, 1980; Lafon and Respaut, 1988; Monié *et al.*, 2000; Laurent *et al.*, 2017). In the Vivarais (Fig. 8, section DD'), several klippes of UGU made of migmatites including amphibolite enclaves overly paragneisses and orthogneisses of the LGU, outlining an inverted metamorphic gradient (Gardien, 1993). Rocks of the UGU have recorded HT eclogitic to HP granulitic metamorphic conditions up to 15 kbar at c. 800 °C, followed by retrogression at 5 kbar at c. 550 °C (Gardien, 1993). The HP migmatitic gneisses and amphibolites of the UGU contain zircon with metamorphic rims dated by U-Pb at 351.5 ± 3.0 Ma and 343.5 ± 2.6 Ma, respectively and interpreted to represent retrogression of the eclogite into amphibolite facies after tectonic accretion during continental collision (Chelle-Michou *et al.*, 2017). The underlying paragneisses display low-pressure granulite facies metamorphism associated with widespread partial melting dated at ca. 308 Ma (Chelle-Michou *et al.*, 2017). These zones in the Vivarais, Marvejols and Rouergue, with an inverted metamorphic gradient might correspond to the southern tip of the UGU central nappe.

To the south of the Rouergue, the Najac eclogites have recorded a pressure of 15–20 kbar and a temperature of 560–630 °C (Lotout *et al.*, 2018). Eclogite-facies metamorphism is dated by U-Pb on zircon at 385.5 ± 2.3 Ma, by Lu-Hf on garnet cores at 382.8 ± 1.0 Ma, and by a Sm-Nd amphibole-garnet-whole rock isochron of 376.7 ± 3.3 Ma. Subsequent exhumation and cooling below c. 500 °C are constrained by an apatite U-Pb age at 369 ± 13 Ma. The maximum temperature reached by these eclogites is significantly lower than the ones recorded by eclogites enclosed in the granulite facies migmatites of the UGU. Moreoever, geochronological data available for the Najac clogites point to burial coeval with the UGU central nappe exposed in the Haut-Allier, Marvejols and Rouergue, but also for a much older exhumation. These data suggest that the Najac eclogites are part of a nappe equivalent to the MAU, which has a different P-T-t history than the UGU.

The Velay and Montagne Noire migmatite domes correspond to the lowermost exposed structural level of the E-FMC (Figs. 4 and 8 section CC', DD'). These migmatites originated by partial melting of paragneisses and orthogneisses under MP to LP conditions at the bottom of the nappe pile from c. 320 to c. 300 Ma (Montel *et al.*, 1992; Williamson *et al.*, 1996; Downes *et al.*, 1997; Barbey *et al.*, 1999, 2015;

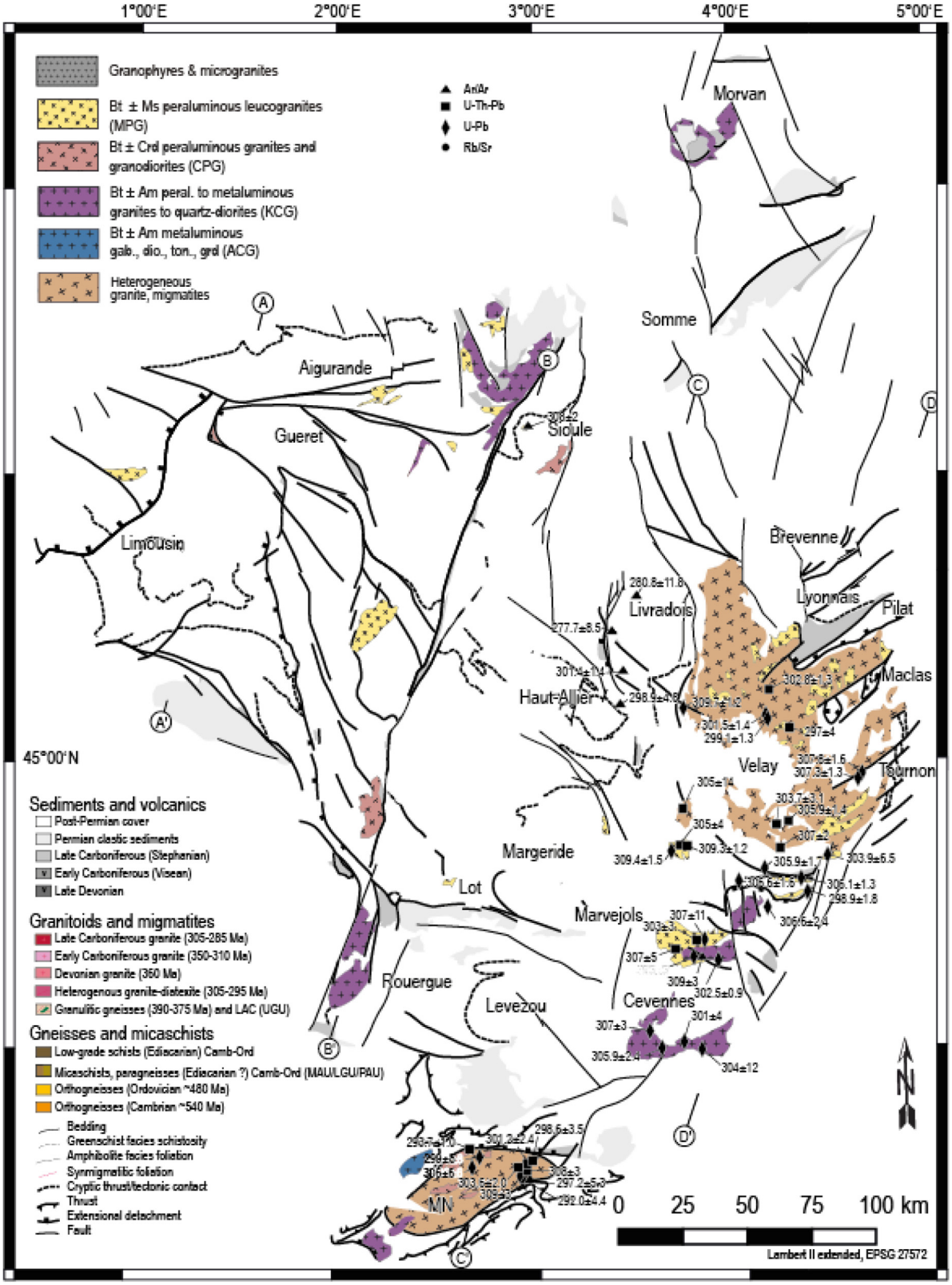

Fig. 15. Late Carboniferous-Permian magmatism. Magmatic rocks with ages ranging from c. 305 to c. 295 Ma are localized along the Sillon Houiller and are present as plutons and in the core of large migmatite domes (Velay, Montagne Noire) in the eastern part of the French Massif Central. The presence of plutonic rocks to the south of the French Massif Central suggests that the partially molten source has migrated since the Lower Carboniferous from the internal to external zone of the Variscan belt. The combination of MPG-type, CPG-type and KCG-type granites emplaced during this period is consistent with the contribution of crustal and mantle sources and is interpreted as reflecting the impact of southward slab retreat that is more pronounced beneath the eastern part of the French Massif Central.

Ledru *et al.*, 2001; Villaros *et al.*, 2018) and contain dismembered enclaves of vaugnerites (Michon, 1987; Sabatier, 1991; Ledru *et al.*, 2001; Couzinié *et al.*, 2014). The 100 km-wide, first-order Velay dome is delineated by the foliation of the surrounding paragneisses and orthogneisses (Lagarde *et al.*, 1994). The synmigmatitic foliation defines subdomes with an average diameter of 10–20 km and characterized by a radial distribution of the HT mineral lineation (Ledru *et al.*, 2001). Accordingly, the Velay dome is a crustal-scale structure interpreted to represent the exhumed middle part of the orogenic crust. The western boundary of the dome is subvertical and its southern part is overturned toward the south (Burg and Vanderhaeghe, 1993; Vanderhaeghe *et al.*, 1999; Ledru *et al.*, 2001). Along the eastern side of the dome, in the Vivarais region, the symigmatitic foliation is shallow-dipping and small klippen of the HP migmatites belonging to the UGU central nappe, as described above, are exposed above LGU grading into MP to LP migmatites (Gay *et al.*, 1982; Gardien, 1993; Gardien and Lardeaux, 1991; Chelle-Michou *et al.*, 2017). The superposition of the HP migmatites attributed to the UGU on top of the LGU is inferred to represent an inverted metamorphic gradient preserved from the time of the nappe emplacement. In turn, the downsection transition from mid-amphibolite facies metamorphism documented in the LGU just beneath the UGU to MP and LP migmatites of the Velay dome corresponds to a normal metamorphic gradient marked by an important increase in temperature with depth.

The northern part of the Velay dome is delimited by the Pilat mylonitic low-angle detachment intersected by high angle cataclastic normal faults (Malavieille *et al.*, 1990; Gardien *et al.*, 1997). Heterogeneous granite (*i.e.* diatexites) in the core of the dome shows a relatively tight cluster of U-Pb ages on zircon and monazite, in the range of 307 ± 2 to 301 ± 5 Ma (Mougeot *et al.*, 1997; Couzinié *et al.*, 2014; Chelle-Michou *et al.*, 2017; Laurent *et al.*, 2017). Magmatic zircon grains and rims with ages ranging from 340 to 300 Ma (Chelle-Michou *et al.*, 2017; Laurent *et al.*, 2017) point to a protracted history of zircon growth and/or dissolution-reprecipitation in these diatexites. To the north of the Velay the Gouffre d'Enfer syntectonic granite, emplaced within the Pilat detachment, yielded an unprecise whole rock Rb-Sr age of 322 ± 26 Ma (Caen-Vachette *et al.*, 1984; Vitel, 1988). To the south of the Velay dome, a Rb-Sr isochron of 302 ± 4 Ma has been obtained for the Rocles syntectonic granite (Caen-Vachette *et al.*, 1981) emplaced in a detachment that has been overturned later on (Burg and Vanderhaeghe, 1993; Vanderhaeghe *et al.*, 1999; Bouilhol *et al.*, 2006). U-Th-Pb ages by EMPA on monazite of 324 ± 4 Ma and 325 ± 5 Ma have also been obtained for the the Rocles granite (Bé Mézémé, 2005; Bé Mézémé *et al.*, 2006), which overlap with a more reliable U-Pb zircon LA-ICPMS age of 320.3 ± 3.8 Ma (Couzinié, 2017). This suggests that while the Rocles granite was emplaced at c. 320 Ma, the Rb-Sr system was probably reset at 302 Ma. Migmatites and heterogeneous granite of the core of the dome are intruded by small plutons and dykes of CPG/MPG with sharp contacts designated as late-migmatitic (Montel and Abdelghaffar, 1993) dated by U-Th-Pb on monazite (LA-ICPMS) from 307 ± 2 to 297 ± 4 Ma (Didier *et al.*, 2013). They are characterized by an aluminous and potassic signature and are rich in rounded enclaves of metapelites and of microdiorite suggesting a metapelitic source together with a contribution from a magma generated by partial melting of an enriched mantle (Villaros *et al.*, 2018). Microgranites with similar chemical signatures have yielded identical U-Th-Pb EMPA ages on monazite at about 300 Ma (306 ± 12, 291 ± 9 Ma) but also at about 255 Ma (257 ± 8 and 252 ± 11 Ma), which points to either a Permian crystallisation or to hydrothermal perturbation at this time (Montel *et al.*, 2002). High-angle normal faults rooting in the low-angle detachments, delimit the late Carboniferous St. Etienne, Jaujac and Alès extensional basins filled by coarse detrital sediments including clasts from the migmatites and granites interbedded with volcanic deposits (rhyolitic ash fall tuffs and accretionary lapilli) and coal-bearing sediments (Becq-Giraudon *et al.*, 1996).

The Montagne Noire is characterized by a dome structure with a core of migmatitic gneisses and a mantle of low-grade metasedimentary rocks (Gèze, 1949; Arthaud *et al.*, 1966; Ellenberger, 1967; Engel *et al.*, 1978, 1981; Demange, 1980; Demange and Jamet, 1985). Migmatites and orthogneisses in the core of the dome display a prolate finite strain ellipsoid indicative of constriction with a subhorizontal long axis parallel to the axis of the elliptical shape dome (Echtler and Malavieille, 1990; Matte *et al.*, 1998; Rabin *et al.*, 2015). Migmatites coring the Caroux dome in the Montagne Noire have recorded P-T conditions of 6 kbar and 720 °C (Rabin *et al.*, 2015) and they are juxtaposed to low-grade LP/HT micaschists (Thompson and Bard, 1982; Demange and Jamet, 1985). Magmatic zircon from the migmatites yield U-Pb ages spreading from c. 330 to c. 300 Ma (Franke *et al.*, 2011; Faure *et al.*, 2014; Roger *et al.*, 2015). Migmatites contain mafic enclaves that have preserved relicts of eclogite facies metamorphism (Demange, 1980; Faure *et al.*, 2014). Zircon grains from the eclogite facies rocks yield two age peaks, one at c. 360 Ma and the other at c. 315 Ma, with a few discordant ages pointing at an early Paleozoic heritage (Faure *et al.*, 2014; Whitney *et al.*, 2015). Faure *et al.* (2014) attribute the 360 Ma age to eclogite facies metamorphism whereas Whitney *et al.* (2015), based on REE signatures of the different zircon zones, argue that eclogite facies is recorded by the 315 Ma age. The Montalet syntectonic granite emplaced along the northern side of the Montagne Noire yield a U-Pb age on zircon of 294 Ma (Poilvet *et al.*, 2011). This syntectonic granite is juxtaposed to the late Carboniferous Graissessac basin along a mylonitic to cataclastic detachment (Van Den Driessche and Brun, 1992). Many different models have been proposed for the Montagne Noire, the dome structure having been interpreted as (i) an anticline developed by horizontal shortening (Matte *et al.*, 1998) (Fig. 7), (ii) a ductile layer exhumed in a pull-apart basin (Nicolas *et al.*, 1977; Rey *et al.*, 2011; Whitney *et al.*, 2015), (iii) a diapir (Charles *et al.*, 2009), (iv) an eroded antiformal stack (Malavieille, 2010) or (v) a Metamorphic Core Complex formed as a consequence of gravitational collapse of the Variscan belt during convergence (Echtler, 1990; Echtler and Malavieille, 1990; Aerden, 1998; Aerden and Malavieille, 1999) or during regional extension (Van Den Driessche and Brun, 1992).

3 Previous tectonic-geodynamic reconstructions and debated issues

In this section, we present the various tectonic-geodynamic reconstructions that were proposed at the scale of the Variscan

belt with a focus on the French Massif Central, with the aim of identifying robust features but also to point at the discrepancies and shortcomings.

3.1 Monocyclic doubly-vergent orogen model

Early geodynamic reconstructions at the scale of Western Europe invoked a doubly-plunging subduction system based on the presence of the two major suture zones described above, namely the Rheic suture and the Medio-European suture, and opposite vergence of structures on the northern and southern sides of the orogenic belt (Matte, 1986, 1991, 2001) (Fig. 2A). According to the latest version of this model, Silurian subduction of Ordovician oceanic basins along the southern branch of the Variscan Belt was followed by Devonian continental subduction and Carboniferous collision between Laurussia and Gondwana (Matte, 2001). This model, mostly relying on a synthesis of structural, metamorphic and sedimentary data, provides a first order tectonic-geodynamic framework for the Variscan belt. In contrast, other geodynamic models assuming that Armorica remained attached to the north Gondwana margin do not include the closure of a Medio-European Ocean (*e.g.* Nance *et al.*, 2010) and thus fail to account for the presence of ophiolitic assemblages to the south of Armorica. Still, the reconstructions proposed by Matte (1986, 1991, 2001) elude some key features including (i) the presence of a late Devonian arc and back-arc association in the Vosges (Skrzypek *et al.*, 2012) and the Eastern Massif Central (Somme and Brévenne Units, see above); (ii) the mechanisms of exhumation of eclogites and migmatites, and, most of all, (iii) syn-orogenic partial melting and magmatism that are notably absent from the cross sections despite the vast exposed surface represented by migmatites and granites. Note also that in the scenario proposed by Matte (1986, 1991, 2001), the HP rocks of the UGU are issued from the southern margin of Armorica, *i.e.* the upper plate relative to Silurian-Devonian subduction. Accordingly, from their position, it is unclear how these rocks could have been buried to granulite facies and then exhumed back to the surface.

3.2 Polycyclic orogenic model

Faure *et al.* (1997) refined the geodynamic model elaborated by Matte (1986, 1991, 2001) in order to account for the late-Devonian magmatic arc and back-arc inferring a southward subduction of the Rheic Ocean based on the relative position of the Somme Unit to the north of the Brévenne Unit (Fig. 3). These authors propose a polcyclic model for the tectonic evolution of the Variscan belt in Western Europe with two distinct orogenic phases (Fig. 2B). The first orogenic phase is associated with northward oceanic subduction during the Silurian and Devonian leading to the closure of the Medio-European Ocean followed by continental subduction during the early Devonian and exhumation of the UGU before the late Devonian. This model provides an explanation for high-pressure metamorphism, which is attributed to burial of rocks from the Gondwana margin that first have been dragged with the downgoing plate and then decoupled from it allowing their exhumation. It should be noted that mafic and ultramafic rocks of the LAC are described by Faure *et al.* (2008) as part of the UGU but are not considered to represent an ophiolite, which is at odds with the interpretations of most authors. For example, to explain the intimate association of mafic and felsic HP rocks, Lardeaux (2014) proposes that the UGU and the LAC represent the formerly thinned continental margin of Gondwana (Fig. 2B). Irrespective of these differences, all these authors invoke a second orogenic phase associated with southward subduction of the Rheic Ocean during the late Devonian beneath an upper plate, made of the exhumed, HP UGU nappe. The latter undergoes extension as attested by the late Devonian Brévenne back-arc rift basin (Fig. 2B). In this model, partial melting of the UGU is attributed to retrogression owing to decompression during syn-orogenic exhumation whereas partial melting of the underthrusted LGU is interpreted to be caused by burial beneath the UGU (Fig. 2B). At the lithospheric scale, a high-velocity anomaly beneath the Paris Basin detected in tomographic models is proposed to represent a remnant of this southward subducting slab (Averbuch and Piromallo, 2012). As an alternative, Lardeaux *et al.* (2001) advocated that the late Devonian Brévenne back-arc basin was opened above a northward subducting slab (corresponding to the former Medio European Ocean) at the time of exhumation of the UGU and was closed as a consequence of collision between Armorica and Gondwana. Despite differences in the polarity of subduction, all these authors attribute Carboniferous deformation, metamorphism and magmatism in the French Massif Central to crustal thickening owing to post Devonian continental collision followed by delamination of the lithospheric root beneath the orogenic belt (Lardeaux *et al.*, 2001; Faure *et al.*, 2002; Lardeaux, 2014; Lardeaux *et al.*, 2014). This model considers implicitely that the UGU represents a single nappe exhumed and emplaced above the LGU before the opening of the late Devonian Brévenne back-arc basin.

3.3 Collision *versus* syn-orogenic extension during the Carboniferous

The tectonic-geodynamic setting leading to the construction-evolution of the Variscan belt has also been actively debated for the Carboniferous period. The mid- to late-Carboniferous is marked by (i) regional-scale strike-slip shear zones and a NW-SE trending stretching lineation parallel to the belt throughout the French Massif Central (Arthaud and Matte, 1975; Mollier and Bouchez, 1982; Lardeaux and Dufour, 1987; Gébelin *et al.*, 2007, 2009); (ii) the exhumation of metamorphic rocks and the emplacement of syntectonic plutons beneath low-angle detachements (Faure and Pons, 1991; Roig and Faure, 2000); and (iii) fold and thrust belts in the foreland of the Variscan belt as exemplified in the Ardennes (Sintubin *et al.*, 2009) and in the Montagne Noire (Echtler, 1990). These features have been interpreted as reflecting either lateral escape of crustal blocks during progressive construction of the orogenic belt following continental collision (Arthaud and Matte, 1975; Matte, 1986; Burg *et al.*, 1987; Lardeaux and Dufour, 1987; Gébelin *et al.*, 2007), syn-orogenic extension of the thickened orogenic crust (Burg *et al.*, 1993; Faure, 1995), or syn-convergent extension (Gébelin *et al.*, 2009).

For the late Carboniferous-Permian period, gravitational collapse of the Variscan belt has been recognized through the development of a rift system superimposed on the thickened crust (Ménard and Molnar, 1988) and by the identification of

low-angle detachments in the French Massif Central (Malavieille *et al.*, 1990; Burg *et al.*, 1993; Faure, 1995; Gardien *et al.*, 1997; Vanderhaeghe *et al.*, 1999; Bouilhol *et al.*, 2006). For the same late Carboniferous period, the prevailing tectonic-geodynamic model for the nearby Pyrénées, south of the FMC, favours a context of transpression (Gleizes *et al.*, 1997; Laumonier *et al.*, 2010; Denèle *et al.*, 2014; Cochelin *et al.*, 2017) although models invoking regional extension have also been proposed (Wickham *et al.*, 1987; Gibson, 1991). On the other hand, a synthesis at the scale of western Europe reveals that the late Devonian to early-mid Carboniferous (Visean) sedimentary record, preserved locally in the internal zone and in the foreland of the Variscan belt, is dominated by platform carbonates and pelagic deposits, which is not in favour of the presence of a Tibetan-type elevated orogenic plateau for this time period and questions the pertinence of the concept of orogenic collapse applied to the Variscan belt (Franke, 2014). Nevertheless, these Visean carbonate deposits have not been identified in the intermediate part of the French Massif Central, in between the Brévenne region and the Montagne Noire. The near absence of late Devonian to middle Carboniferous deposits in the W-FMC, contrasts with their abundance in the E-FMC and suggests either that it was at higher altitude at this time or that these deposits have been eroded. At last, as pointed by Franke *et al.* (2011), it should be noted that foreland deposits are underlain in the Montagne Noire and in the Pyrénées by rocks affected by HT/LP metamorphism and deformation during the Variscan orogeny, which are not typical characteristics of external zones of orogenic belts.

3.4 Impact of partial melting and magmatism on Variscan tectonics?

Despite the predominance of plutonic and migmatitic rocks in the French Massif Central, and more generally in the Variscan belt (Zwart, 1967), early tectonic models partly eluded the relationships between HT metamorphism, magmatism and orogenic evolution (Matte, 1986, 1991). During the 1980s, progress on experimental petrology and thermodynamic modelling (Wyllie, 1977; Vielzeuf and Holloway, 1988; Spear and Cheney, 1989; Gardien *et al.*, 1995) has allowed to identify the P-T conditions of partial melting during orogenic evolution and discuss their tectonic-geodynamic significance (England and Thompson, 1984; Thompson and Connolly, 1995). In the French Massif Central, partial melting has been identified throughout the high-grade nappe pile and is associated with HP, MP and LP metamorphism. High-pressure granulite to amphibolite facies migmatites dated from the early to the middle Devonian are interpreted to record either partial melting during exhumation of the UGU (Faure *et al.*, 1997, 2008) or to magmatic arc accretion (Lardeaux, 2014). Intermediate pressure migmatites typically associated with Barrovian metamorphism with ages spreading from the middle Devonian to the middle Carboniferous (from c. 370 to c. 310 Ma) are interpreted as reflecting continental collision marked by nappe emplacement (Montel *et al.*, 1992; Ledru *et al.*, 1994; Faure *et al.*, 2008; Barbey *et al.*, 2015) and/or a mantle heat supply owing to asthenospheric upwelling as a consequence of lithospheric delamination (Faure *et al.*, 2002, 2009a). The last partial melting event is characterized by low-pressure migmatites and granites exposed in large domes is attributed to a temperature increase caused by the emplacement of mantle-derived magmas (vaugnerites) during late-orogenic collapse (Montel *et al.*, 1992; Ledru *et al.*, 1994; Barbey *et al.*, 2015). Each of these migmatite types are therefore dominantly regarded as recording discrete, short-lived events of partial melting associated with prograde metamorphism. This is in conflict with the fact that the solubility of accessory minerals in silicate liquids during melting and crystallization is positively correlated with temperature (Harrison and Watson, 1983; Watson and Harrison, 1983; Boehnke *et al.*, 2013). Consistently, thermodynamic modelling shows that zircon and monazite, the most common geochronometers in migmatites, preferentially crystallize during the retrograde (cooling) path and only seldom preserve a record of the prograde path (Kelsey *et al.*, 2008; Yakymchuk and Brown, 2014).

The discrepancies beween tectonic and geodynamic models proposed for different parts of the Variscan belt of Western Europe illustrate the difficulty in tracking the continuity of terranes and sutures. They potentially point to a non-cylindrical structure marked by discontinuous ribbon-shaped continental terranes separated by immature oceanic basins. Furthermore, these discrepancies reflect differences in the interpretation of the geological record in terms of metamorphism, magmatism and deformation. Until now, the existing models have failed to integrate the impact of partial melting and of the generation of magmatic rocks on orogenic evolution. We hereby provide a novel synthetic model for the geodynamic-tectonic evolution of the Variscan belt integrating most of the existing data summarized in the previous paragraphs. In contrast with previous models, we emphasize the pivotal role of protracted partial melting and magmatism on the rheology of the orogenic crust and thus on the tectonic-geodynamic evolution of the Variscan belt.

4 New model for the geodynamic-tectonic evolution of the Variscan belt of Western Europe

4.1 Pre-Variscan configuration: the North Gondwana hyper-extended margin

As presented in Section 2.1, the relative position of the cratons, the numbers and sizes of continental terranes and oceanic basins, and the polarity of subductions are all actively debated owing to discrepancies between paleomagnetic and paleobiostratigraphic data, and to uncertainties in tectonic reconstructions. The ophiolitic assemblages with different protoliths and peak ages as well as contrasting peak temperatures identified in the French Massif Central, in the Armorican Massif, and in the Vosges (Hanmer, 1977; Bernard-Griffiths and Cornichet, 1985; Girardeau *et al.*, 1986; Santallier *et al.*, 1988; Burg *et al.*, 1989a, 1989b; Dubuisson *et al.*, 1989; Mercier *et al.*, 1991a; Bosse *et al.*, 2000; Lardeaux *et al.*, 2001; Ballèvre *et al.*, 2009; Berger *et al.*, 2010a; Skrzypek *et al.*, 2012; Lotout *et al.*, 2018), might represent different sutures that might have corresponded to former rift and/or oceanic basins separating former crustal blocks. This scheme is consistent with the pre-Variscan record of the micaschists, paragneisses and orthogneisses forming the UGU, MAU, LGU and their relative para-autochthon exposed in the

French Massif Central and the Pyrenées (Fig. 5, Tabs. 1–3). Namely, Ediacaran sediments intruded by Cambrian granitic plutons represent a Cadomian basement for the thick detrital sedimentary sequences of lower Paleozoic age deposited during the post-Pan-African dislocation of the Gondwana continent (Duthou *et al.*, 1981, 1984; R'Kha Chaham *et al.*, 1990; Alexandrov *et al.*, 2001; Chelle-Michou *et al.*, 2017; Couzinié *et al.*, 2017, 2019). Other orthogneisses with intrusive contacts (dyke networks, contact metamorphism) of Ordovician age, represent former laccoliths emplaced during extension along the northern margin of the Gondwana continent (Lasnier, 1968; Bernard-Griffiths, 1975; Bernard-Griffiths *et al.*, 1977; Duthou *et al.*, 1981, 1984; R'Kha Chaham *et al.*, 1990; Pin and Marini, 1993; Barbey *et al.*, 2001; Deloule *et al.*, 2002; Roger *et al.*, 2004; Cocherie *et al.*, 2005; Castiñeiras *et al.*, 2008; Melleton *et al.*, 2010; Lotout *et al.*, 2017). The calc-alkaline to tholeiitic chemical signature of the LAC also suggests an emplacement of this bimodal magmatic suite in a continental to oceanic rift environment during the Cambrian-Ordovician (Pin and Lancelot, 1982; Bodinier *et al.*, 1986; Briand *et al.*, 1995; Chelle-Michou *et al.*, 2017). Pre-Neoproterozoic rocks, such as the Archean to Paleoproterozoic Icartian gneisses exposed in the northern Armorican Massif (D'Lemos *et al.*, 1990; Le Corre *et al.*, 1991), have not been identified in the French Massif Central. As already mentioned by other authors (Bouchardon *et al.*, 1989; Pin, 1990; Faure *et al.*, 1997; Lardeaux, 2014; Franke *et al.*, 2017), these data are consistent with the development of a thinned continental margin with one or several immature rifts and/or oceanic basins along the hyperextended northern continental margin of the Gondwana craton.

Accordingly, a two-stage geodynamic model is proposed for the pre-Variscan configuration of the French Massif Central. During the Cambrian (Figs. 16A and 17A), subduction of the Iapetus Ocean along the Gondwana margin was marked by the emplacement of calc-alkaline plutonic and volcanosedimentary rocks (D'Lemos *et al.*, 1990; Le Corre *et al.*, 1991). Crustal extension and opening of rifts at the rear of this active margin during the Ordovician might have been favoured by retreat of the Iapetus slab leading to the opening of the Medio-European Ocean (Figs. 16B and 17B). Such a hyper-extended margin might have spread over several hundred kilometres from the Ordovician to early Silurian and might conciliate the apparent contradiction between paleomagnetic reconstructions implying a distance of more than 2000 km between Gondwana and Laurussia during the Ordovician and paleontologic data pointing to small communicating basins. Accordingly, the Variscan orogenic belt is essentially made of a reworked continental crust made of a Cadomian basement affected by post Pan-African Ordovician hyper-extension, intruded by granitoids and covered by thick volcanic-sedimentary series. Reworking of this hyper-extended margin occurred as a consequence of convergence between Laurussia and Gondwana from the Silurian to the Carboniferous (Figs. 17C–E).

4.2 Late Silurian to Devonian subduction and HP partial melting of terranes issued from the North Gondwana margin

As described in the previous sections, the oldest evidence for the onset of the Variscan orogenic cycle corresponds to the HP metamorphism identified in mafic and ultramafic rocks of the LAC (Fig. 4) pointing to subduction of these units (Lasnier, 1968, 1971; Pin and Vielzeuf, 1983; Bouchardon *et al.*, 1989; Gardien *et al.*, 1990). The presence of UHP mineral assemblages in the LAC of the Lyonnais (Lardeaux *et al.*, 2001) and Limousin (Berger *et al.*, 2010a, 2010b), argues for burial of these units to a depth of more than 100 km. Nevertheless, two types of eclogites are distinguished, namely (i) HT eclogites that are forming enclaves-boudins into migmatites of the UGU as exemplified in the Aigurande, north Limousin, Sioule, Livradois, Lyonnais, Rouergue regions (Pin and Vielzeuf, 1983; Dufour, 1985; Burg *et al.*, 1989a, 1989b; Gardien, 1990; Gardien *et al.*, 1990; Lardeaux *et al.*, 2001; Faure *et al.*, 2008); and (ii) LT eclogites that are hosted by micaschists not affected by partial melting as illustrated by the MAU exposed in south Limousin or in Najac (Berger *et al.*, 2010a; Lotout *et al.*, 2018). According to the few available geochronological data, subduction of these units is diachronous and occurred from the late Silurian to the Devonian (Fig. 18A–C) (Pin and Lancelot, 1982; Ducrot *et al.*, 1983; Paquette *et al.*, 1995; Berger *et al.*, 2010a; Do Couto *et al.*, 2016; Lotout *et al.*, 2018).

A similar nappe pile has been described in the South Armorican Massif, with the distinction of HT and LT eclogites (Ballèvre *et al.*, 2009). The core of the Champtoceaux nappe is made of granulite facies migmatitic gneisses, with enclaves of ultramafic rocks with HT eclogite facies relics (Marchand, 1981; Ballèvre *et al.*, 1987, 2002; Godard, 2001). These rocks overlay lower grade orthogneisses and micaschists that contain mafic boudins with LT eclogite facies relics. LT eclogites and blueschist facies rocks of the Ile de Groix are in a similar structural position as the MAU in the FMC and have been interpreted to represent the suture of the Galicia-South Brittany Lower Paleozoic Ocean. $^{40}Ar/^{39}Ar$ and Rb-Sr dating of blueschist facies rocks, yield c. 360 Ma for the metamorphic peak attributed to subduction of this ocean at the Devonian-Carboniferous transition. Greenschist facies retrogression of these rocks reflects cooling and exhumation dated in the early Carboniferous as constrainted by ages ranging from 355 to 340 Ma (Bosse *et al.*, 2000, 2005; Paquette *et al.*, 2017).

Mafic-ultramafic enclaves with relictual HT eclogitic facies metamorphism enclosed in granulite facies migmatites was also identified in other Variscan massifs. In the Vosges, garnet-lherzolite belonging to a subcontinental lithospheric mantle exhumed from more than 150 km are present in the varied gneiss unit dominated by granulite facies migmatitic gneiss (Altherr and Kalt, 1996; Brueckner and Medaris, 2000; O'Brien and Rötzler, 2003). The Bohemian massif also comprises large mafic and ultramafic bodies enclosed in high-grade gneisses (Kusbach *et al.*, 2012). In the French Massif Central, ages interpreted to record eclogite facies peak metamorphism are typically 20 to 30 Ma older to the ones attributed to granulite facies metamorphism and partial melting of their host migmatitic paragneisses and orthogneisses (Duthou *et al.*, 1981, 1994; Pin and Lancelot, 1982; Chelle-Michou *et al.*, 2017).

The significance of this association and of this age gap is debated. The question is whether it represents (i) a pre-metamorphic association reflecting intrusion of mafic magmas into the crust or tectonic accretion of oceanic and continental terranes, (ii) a syn-metamorphic extrusion of mantle into the lower crust, (iii) or a subduction of the continental crust and

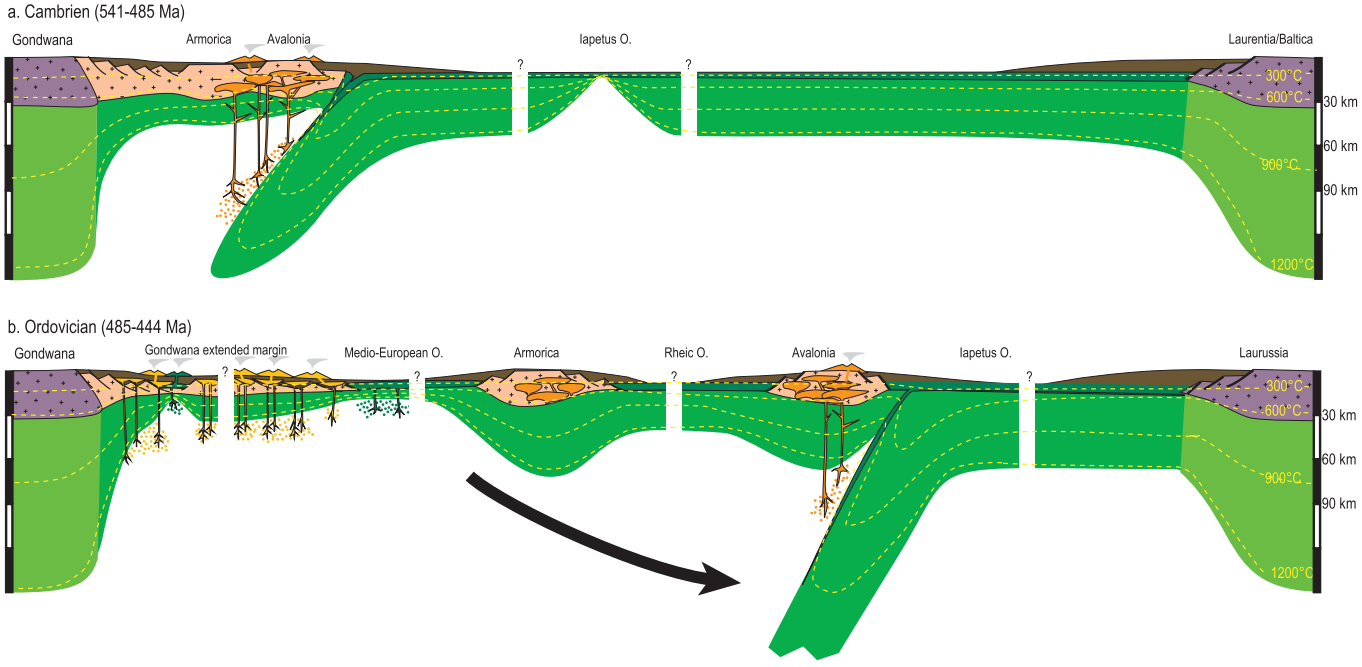

Fig. 16. Pre-Variscan geodynamic configuration. A. During the Cambrian, the Gondwana margin is marked by the emplacement of calc-alkaline magmas attributed to an enriched mantle source above a subducting slab. The size of the Iapetus is about 2000–3000 km wide. B. During the Ordovician, the Avalonia and Armorica continental ribbons are separated from the Gondwana margin. The Rheic Ocean corresponds to the future Rheic suture exposed in southern Great Britain. The Medio-European Ocean corresponds to the Leptynite-Amphibolite Complex forming boudins and enclaves in high-grade nappes of the Moldanubian allochthonous terrane (see Fig. 3). The tholeitic to calc-alkaline signature of the LAC is interpreted as reflecting an emplacement of the magmatic protoliths in a back-arc or immature oceanic setting. Alkaline magmas intrusive in Ediacarian sedimentary sequences correspond to orthogneisses preserved in the LGU and PAU and are attributed to opening of a series of rifts leading to hyperextension of the Gondwana margin. These features are consistent with retreat of the southward plunging Iapetus slab that will eventually lead to tectonic accretion of Avalonia to the Laurussia craton.

mixing of mantle and crustal units. Tectonic-geodynamic models attributing the succession of eclogite and granulite facies metamorphism to oceanic subduction followed by continental collision (Matte, 1986; Girardeau *et al.*, 1986; Dubuisson *et al.*, 1989; Ledru *et al.*, 1989; Lardeaux *et al.*, 2001) provide an explanation for the HP metamorphic condition but do not account for the systematic incorporation of the LAC into the migmatitic UGU. Models invoking a vertical extrusion of the mantle into the partially molten granulitic lower crust account for the presence of mafic and ultramafic rocks into the migmatitic continental rocks but do not propose a driving force for such a process (Kusbach *et al.*, 2012). A more appealing proposition is that pieces of suprasubduction mantle might be incorporated into the orogenic belt during relamination of orogenic crust by flow of partially molten crustal units decoupled from the downgoing slab (Lexa *et al.*, 2011; Kusbach *et al.*, 2015). Another option is that the association of remnants of an oceanic suture together with lithospheric mantle into granulite facies migmatitic gneisses, was achieved by mixing of subducted units into the mantle (O'Brien and Rötzler, 2003; Faure *et al.*, 2008). In this latter scenario, granulite-facies partial melting of the UGU would be driven either by decompression of the UGU during syn-orogenic exhumation (Faure *et al.*, 2008) or owing to thermal relaxation about 30 Ma after subduction (O'Brien and Rötzler, 2003). We concur to the latter proposition as it will be developed in the next section.

4.3 Middle Devonian to early Carboniferous syn-orogenic exhumation of the partially molten subducted crustal units with mantle enclaves

The geological record of the middle Devonian to early Carboniferous period is marked by the association of HT eclogites and HP granulite-facies migmatites of the UGU. These are only present south of the Nort-sur-Erdre Fault in the Armorican Massif and of the Lalaye-Lubine Fault in the Vosges Massif (Fig. 1), which delineate the main suture south of the Armorica-Barrandia continental block (Faure *et al.*, 1997). North of this suture, the inprint of Variscan metamorphism is absent or limited. The typical retrogression and transposition of the granulite facies mineral assemblage and foliation of the UGU into an amphibolite facies foliation records isothermal decompression caused by rapid exhumation (Pin and Vielzeuf, 1983; Dufour, 1985; Burg *et al.*, 1989a, 1989b; Gardien *et al.*, 1990; Mercier *et al.*, 1991a, 1991b; Lardeaux *et al.*, 2001; Faure *et al.*, 2008) (Fig. 4). The position of the exhumed high-grade nappes relative to the Nort-sur-Erde Fault and Lalaye-Lubine Fault implies that this suture was reworked as a steep syn-orogenic detachement allowing the exhumation of the continental units previously entrained in subduction and then decoupled from the slab (Figs. 18B and 18C). The inverted metamorphic gradient at the contact between the UGU and the LGU (Nicollet, 1978; Burg *et al.*, 1984; Burg *et al.*, 1989a, 1989b; Schulz *et al.*, 2001) suggests

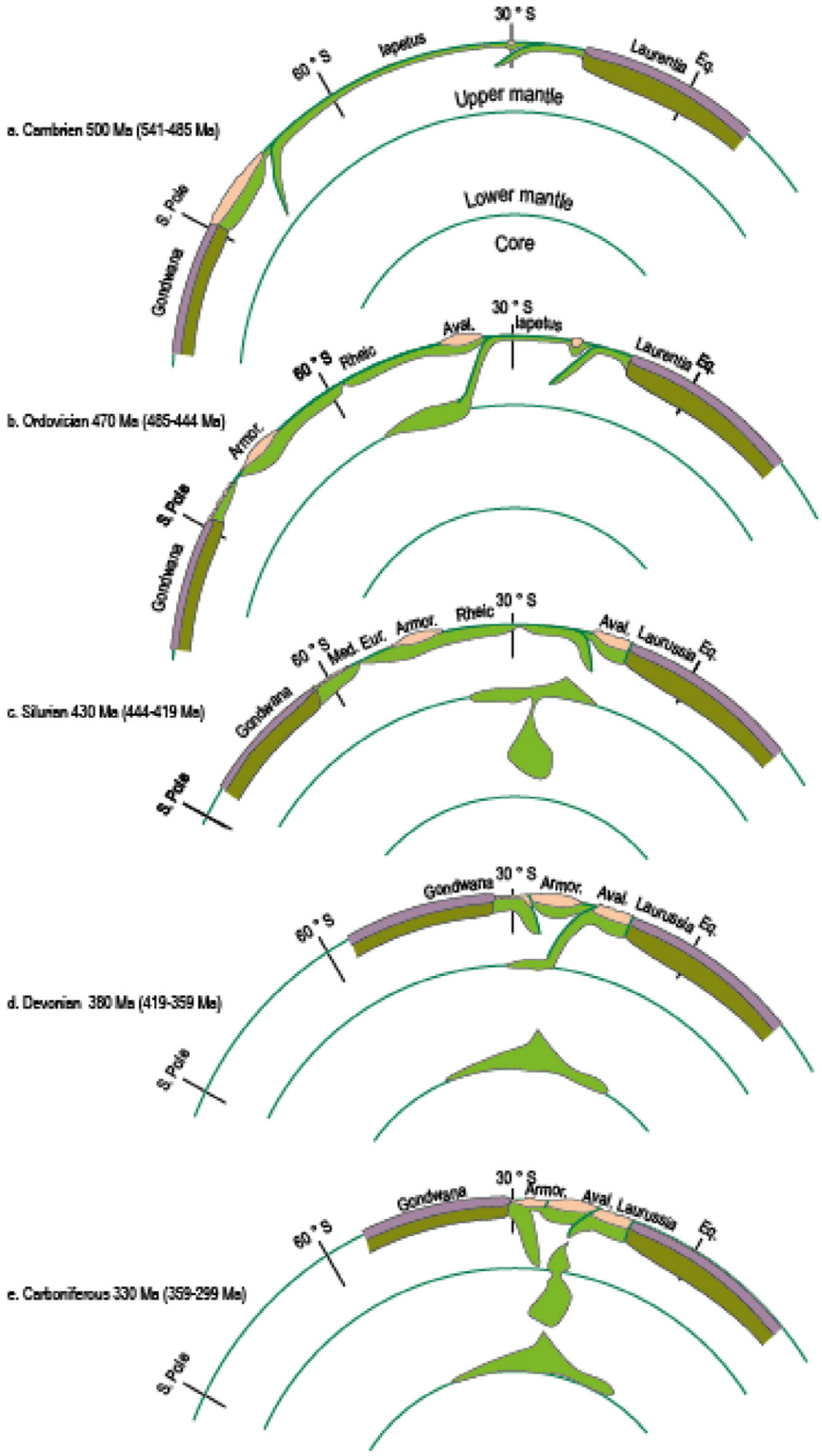

Fig. 17. Plate scale geodynamic reconstruction for the Paleozoic (modified after Domeier, 2016; Domeier and Torsvik, 2014; Matte, 2001). A. Cambrian 500 Ma (541–485 Ma). The Gondwana margin is at the South Pole, Laurentia is at the Equator and the Iapetus Ocean is at least 3000 km wide. The Gondwana margin is an active plate boundary marked by subduction of the Iapetus. B. Ordovician 470 Ma (485–444 Ma). The margin of Gondwana is marked by hyperextension resulting in the separation of Avalonia and Armorica and the opening of the Rheic and Medio-European Oceans. C. Silurian 430 Ma (444–419 Ma). The Iapetus Ocean has closed and Avalonia has been tectonically accreted to Laurussia. The Rheic Ocean started to subduct beneath the margin of Laurussia and Medio-European Ocean, between Armorica and Gondwana is at its maximum width. D. Devonian 380 Ma (419–359 Ma). Armorica is bounded by subduction zones with opposite vergence resulting in the formation of the Variscan belt. E. Carboniferous 330 Ma (359–299 Ma). The Variscan orogenic front progresses from the hinterland to the foreland in association with slab retreat.

that the exhumation of the UGU is associated with burial of the LGU. This is consistent with transposition of the granulite facies foliation of the UGU into an amphibolite facies synmigmatitic foliation (Forestier, 1961; Burg and Matte, 1978) and with the absence of HP/HT eclogitic relicts in the LGU. Thrusting of the UGU over the LGU is locally corroborated by kinematic data indicating a top-to-the SE sense of shear (Faure *et al.*, 1979, 2009a; Burg *et al.*, 1984). However, this contact is in many places reworked and retrogressed into a greenschist facies fabric associated with a top-to-the NW sense of shear attributed to regional extension leading to exhumation of the LGU and of the PAU (Faure *et al.*, 1979, 2008, 2009a).

Available geochronological and stratigraphic data indicate that exhumation of the UGU started before the late Devonian with the emplacement of the northern nappe exposed in the Aigurande plateau, the Morvan area, and sampled in the Couy borehole (Costa and Maluski, 1988; Godard, 1990; Boutin and Montigny, 1993). The exhumation of the UGU forming the central and southern nappe (Limousin, Sioule-Combrailles, Livradois – Haut-Allier, Lyonnais) is bracketed between the late Devonian and the Visean and thus postdates the exhumation of the northern nappe (Pin and Lancelot, 1982; Melleton *et al.*, 2009; Gardien *et al.*, 2011; Do Couto *et al.*, 2016; Chelle-Michou *et al.*, 2017). Migmatitic paragneisses from the Limousin and the Sioule display a subhorizontal foliation bearing a NW-SE trending lineation mostly associated with top-to-the-NW kinematic criteria interpreted to accommodate syn-orogenic exhumation of the UGU (Bellot and Roig, 2007; Do Couto *et al.*, 2016). In the Livradois, the foliation of the migmatites attributed to the UGU is steeply-dipping and is associated with dextral top-to-the SE kinematic criteria interpreted to record extrusion of the UGU (Gardien *et al.*, 2011; Vanderhaeghe *et al.*, 2013). Such a mechanism of vertical extrusion for the formation of high-grade nappes is consistent with the interpretation of the Champtoceaux nappe, in the Armorican Massif, as a fold nappe (Ballèvre *et al.*, 2009) and has also been proposed to account for the structure of the varied gneiss unit in the Vosges (Skrzypek *et al.*, 2014) and the Bohemian Massif (Schulmann *et al.*, 2014).

Several lines of reasoning suggest that the multiple nappes model is more coherent with the hyperextended margin model made of thinned continental blocks separated by small immature oceanic basins than with a pre-Variscan configuration characterized by a single, large oceanic domain between Gondwana and Armorica. First, the inverted metamorphic isograds, requiring limited thermal relaxation after underthrusting, fits better with a model considering a system of several small nappes with at most a few tens of kilometres of lateral expansion, rather than the case of a single, several hundred kilometres long nappe. Indeed, thermal-mechanical modelling of orogenic evolution indicates that inverted metamorphic/thermal gradients are not sustainable for more than about 100 km equivalent to about 10 Ma with a convergence rate of 1 cm/yr (Huerta *et al.*, 1996; Henry *et al.*, 1997; Vanderhaeghe *et al.*, 2003). Moreover, the multiple nappes model predicts diachronous HP metamorphism, which seems to be confirmed by the currently available geochronological data. Finally, the absence of large volumes of calc-alkaline magmatism associated with subduction initiation and steady-state subduction further suggests that forced subduction of several hyper-extended basins is a more likely scenario than the spontaneous subduction intiation of a mature oceanic crust (see McCarthy et al., 2018).

Following this rationale, following other authors, we propose that the construction of the Variscan orogenic belt was achieved by tectonic accretion of continental units that were previously subducted and then decoupled from the downgoing slab (Faure *et al.*, 1997, 2008; Lardeaux *et al.*, 2001) rather than by continental collision and indentation and thickening of the overriding plate as proposed in early tectonic reconstructions (Matte, 1986; Franke, 1989; Ledru *et al.*, 1989). Again, available geochronological data for the UGU and LAC are consistent with partial melting at high-pressure (10–20 kbars) of paragneisses, orthogneisses and amphibolites c. 20 to 30 Ma after subduction (Nicollet and Leyreloup, 1978; Duthou *et al.*, 1981, 1994; Pin and Lancelot, 1982; Chelle-Michou *et al.*, 2017). Although such data are scarce and of unequal robustness from a nappe to another, this time span is broadly consistent with that required for thermal relaxation after burial (England and Thompson, 1984; Vanderhaeghe *et al.*, 2003). Following models advocated for the tectonic accretion of HP mafic-ultramafic rocks enclosed in migmatitic units (O'Brien and Rötzler, 2003; Labrousse *et al.*, 2011; Gordon *et al.*, 2016; Závada *et al.*, 2018), we propose that partial melting of subducted units forming the protolith of the UGU triggered their mechanical decoupling from the slab. In this scenario, mafic and ultramafic enclaves would represent fragments of previously subducted oceanic crust and lithospheric mantle entrained by the buoyant and low-viscosity, partially molten rocks, on their way back towards the surface. This process corresponds to syn-orogenic exhumation by vertical extrusion of the partially molten nappes. According to this proposition, the UGU represents the part of the thinned continental margin that has been subducted and then decoupled from the downgoing slab, while the LGU represents the part of the former continental margin that was underthrusted beneath the UGU during its syn-orogenic exhumation. The age gradient for retrogression and cooling of the UGU, ranging from c. 385 Ma in the north to c. 340 Ma in the south, is consistent with progressive exhumation of nappes successively decoupled from a north-vergent and southward-retreating subduction slab (Fig. 18). We defined here a northern, central and southern nappe but this proposition and the number of nappes and of repeated UGU/LGU alternations remains to be clarified. Another consequence of partial melting of subducted fertile continental units might be the percolation of felsic melts into the suprasubduction mantle wedge, contributing to its enrichment in incompatible elements. Such a process might explain the signature of mafic magmas emplaced during the Carboniferous, as described in the next section.

4.4 Late Devonian exhumation of nappes in between retreating slabs

The geological record of the late Devonian period (Figs. 11, 18B and 18C) is marked by a great diversity of information that is difficult to reconcile in a single geodynamic context. In the northern part of the French Massif Central, plutonic and volcanic rocks (ACG) exposed respectively in the Somme and

Limousin regions have been interpreted as a continental magmatic arc (Pin and Paquette, 1997; Faure *et al.*, 2008). The tholeiitic to calc-alkaline volcanic rocks of the Brévenne Unit have been attributed to a back-arc rift basin (Bébien, 1971; Pin and Lancelot, 1982; Sider and Ohnenstetter, 1986). Rocks of the same age and geochemical signatures exposed in the Central Bohemian Plutonic Complex have been interpreted as arc magmas originated in an Andean-type continental margin (Janousek and Holub, 1997; Janoušek *et al.*, 2004; Schulmann *et al.*, 2009). The positive ε_{Nd} of these magmatic rocks points to a dominant juvenile contribution (Fig. 13A). However, structural, metamorphic and geochronologic record demonstrate that the late Devonian is also marked by (1) the exhumation of the central nappe in the Limousin and Livradois (Bellot and Roig, 2007; Melleton *et al.*, 2009; Gardien *et al.*, 2011; Do Couto *et al.*, 2016); and (2) the emplacement of cordierite-bearing peraluminous granite laccoliths (CPG) (Berthier *et al.*, 1979; Pin and Paquette, 1997; Bertrand *et al.*, 2001; Cartannaz, 2006; Gébelin *et al.*, 2009). The crust-derived Guéret-type plutons formed through melting of dominantly metasedimentary sources, possibly with the contribution of a mafic igneous lower crust (Downes and Duthou, 1988; Downes *et al.*, 1997). These data imply that the end of opening of the Brévenne rift and the construction of the Morvan continental arc are coeval with partial melting of subducted continental units. Furthermore, this activity is contemporaneous to deposition of detrital sediments and carbonates in the underfilled southern foreland basin at the front of a propagating thrust system, currently exposed in the Pyrénées (Franke and Engel, 1986; Souquet *et al.*, 2003).

To the south of Armorica, geochronological data obtained on blueschists exposed in the Ile de Groix and on low-temperature eclogites at the base of the Champtoceaux nappe indicate that high-pressure metamorphism attributed to subduction occurred at about 370–360 Ma (Bosse *et al.*, 2000, 2005; Paquette *et al.*, 2017). North of the Nort sur Erdre fault, the Saint Georges sur Loire unit, a late Silurian to early Devonian back-arc basin, affected by blueschist facies metamorphism, has also potentially been subducted at this time (Ledru *et al.*, 1986; Cartier *et al.*, 2001). Mid to late Devonian subduction, but with a southward dip, is likewise recorded north of the Medio-European suture, in the Saxo-Thuringian terrane to the north of the Vosges and of the Bohemian Massif (Schulmann *et al.*, 2014; Skrzypek *et al.*, 2014). In the Vosges Massif the "ligne des Klippes" represents an immature oceanic basin opened during the late Devonian and inverted in the Lower Carboniferous (Skrzypek *et al.*, 2012). North of Armorica, in South West England, the Lizard suture represents an early Devonian immature oceanic domain obducted during the early Carboniferous (Floyd and Leveridge, 1987; Clark *et al.*, 1998; Shail and Leveridge, 2009).

Accordingly, late Devonian extension in the internal zone of the Variscan belt occurred in an overall context of plate convergence as implied by subduction/exhumation of nappes, foreland propagation of deformation and deposition of clastic sediments. Therefore, two geodynamic scenari are evoked to account for this extension, namely (i) opening of a back-arc associated with northward subduction of the Medio European Ocean being contemporary with the southward subduction of the Rheic Ocean followed by continental collision (monocyclic model, Matte, 1986; Ledru *et al.*, 1989; Lardeaux *et al.*, 2001), or (ii) renewed extension of the Eo-Variscan orogenic belt associated with southward subduction of the Rheic Ocean after closure of the Medio European Ocean by northward subduction (polycyclic model, (Pin, 1990; Leloix *et al.*, 1999; Faure *et al.*, 1997, 2009a; Lardeaux, 2014; Lardeaux *et al.*, 2014). The cooling ages obtained on the UGU of the Aigurande plateau indicates that at least some of the high-grade nappes were exhumed to the surface before late Devonian rifting and emplacement of the Brévenne volcanics, which is more consistent with the polycyclic model.

Alternatively, to resolve the apparent discrepancy between an overall context of plate convergence and local extension, we propose that late Devonian geodynamics was characterized by convergence accommodated by subduction but also by retreat of the northern (Rheic) and southern (Medio-European) slabs. This explains simultaneous closure of immature oceanic basins entrained in subduction, tectonic accretion of ribbon-shaped terranes and extension of the upper plate. Hence, the exhumation of previously subducted continental units might have occurred without substantial erosion owing to the opening of space toward the surface in between the retreating slabs as envisioned in the conceptual models of Vanderhaeghe and Duchêne (2010). In this scenario, the top to the NW kinematic criteria marking the contact between the Brévenne Unit and the UGU of the Monts du Lyonnais might have accommodated the last stage of syn-orogenic exhumation of the high-grade nappe as proposed for the exhumation of the UGU in the Limousin at the same period (Bellot and Roig, 2007).

However, this model does not fully account for lateral variations of the tectonic context, evidenced by exhumation of nappes and emplacement of peraluminous granites in the western French Massif Central coeval with opening of a continental to oceanic rift in its eastern part. Two directions are proposed for future reflexion. The first one would be to consider a context of oblique plate convergence, which might allow for opening of pull-apart basins along releasing bends and concomitant burial and exhumation of tectonic units along restraining bends. The second one would be to infer differential retreat between the western and eastern side of the French Massif Central that might have been accommodated by a precursor of the Sillon Houiller strike-slip fault (Fig. 3). Slab retreat potentially controls the tectonic-magmatic geological history of the French Massif Central throughout the Carboniferous as described in the following sections.

4.5 Carboniferous (c. 345–310 Ma) building of an orogenic plateau by lateral flow of the partially molten orogenic root

The Carboniferous (345–310 Ma) geological record of the FMC is marked in the northern part by E-W to NW-SE trending regional-scale dextral strike-slip shear zones and orogen-parallel stretching localizing the emplacement of mantle and crust-derived magmas and in the southern part by thrusts and folds in the Cévennes, Albigeois and Montagne Noire, coeval with deposition of clastic sediments in the foreland (Figs. 1, 3, 12, 18D) (Arthaud and Matte, 1975; Engel, 1984; Feist and Galtier, 1985; Arnaud and Burg, 1993; Faure *et al.*, 1999). The strike-slip shear zones, exemplified in the Limousin (Faure and Pons, 1991; Mollier and Bouchez, 1982; Roig and Faure, 2000; Gébelin *et al.*, 2007, 2009), in the Forez (Barbarin and Belin, 1982), in the

Livradois (Gardien *et al.*, 2011; Vanderhaeghe *et al.*, 2013), and in the Lyonnais (Lardeaux and Dufour, 1987), merge to the northwest with the South Armorican shear zone (Lerouge and Quenardel, 1988; Carlier De Veslud *et al.*, 2004; Gébelin *et al.*, 2007; Rolin *et al.*, 2009, 2014). As presented above, these strike-slip shear zones have been interpreted either to record a period of transpression (Lardeaux and Dufour, 1987; Gébelin *et al.*, 2007) or to reflect the transition from collision to orogen-parallel extension (Ledru and Autran, 1987; Faure *et al.*, 1993, 2009b; Roig and Faure, 2000).

After a 10 Ma gap from c. 355 to c. 345 Ma, magmatism proceeded with the emplacement of plutonic and volcanic rocks throughout the middle Carboniferous (Fig. 12). In Section 3.4, following previous authors (Williamson *et al.*, 1996, 1997; Barbey *et al.*, 2015; Laurent *et al.*, 2017; Moyen *et al.*, 2017), MPG and CPG (and their volcanic counterparts) are proposed to derive from a mixed crustal source comprising ortho- and paragneisses from the LGU. Partial melting of the orogenic root at this time is documented by MP migmatites dated at c. 315 Ma underlying the Millevaches granitic laccolith (Gébelin *et al.*, 2009) and by MP migmatites mantling the Velay dome with ages ranging from c. 330 to c. 315 Ma (Mougeot *et al.*, 1997; Cocherie *et al.*, 2005; Bé Mézémé *et al.*, 2006). Although volumetrically less abundant, mantle-derived magmatism is expressed almost exclusively in the East Massif Central (only a few occurences are described in Limousin) by the presence of widespread vaugnerites, forming decimeter- to kilometer-sized bodies intimately associated with the granites and migmatites. The dual geochemical character of vaugnerites (low SiO_2, high Mg# together with elevated K, LILE and LREE contents), as well as their Sr-Nd-Pb-Hf isotope signatures (Turpin *et al.*, 1988; Couzinié *et al.*, 2016), is consistent with partial melting of a lithospheric mantle that was previously enriched in incompatible elements (Sabatier, 1991; Solgadi *et al.*, 2007; von Raumer *et al.*, 2014 Couzinié *et al.*, 2016). The variety of the geochemical signatures of some granitoids and the fact that they contain micromafic enclaves indicate a mixture of crustal-derived and mantle-derived magmas, as illustrated in the Livradois (Solgadi *et al.*, 2007). This model would be particularly relevant to explain the origin of the compositionally intermediate KCG and, to a lesser extent CPG. The Margeride granite, for example, shows an intermediate signature, interpreted as reflecting interaction with mafic melts (Williamson *et al.*, 1992; Laurent *et al.*, 2017). Collectively, granites exposed in the eastern French Massif Central show the implication of different sources that are progressively affected by partial melting as the temperature of the orogenic root increases (Fig. 14). Geochronological data indicate that (i) granites and vaugnerites emplaced together from c. 340 to c. 300 Ma and (ii) there is a progressive younging of U-Pb emplacement ages of both granites and vaugnerites from the North (Forez, Lyonnais) to the South (Cévennes) in the considered time period, pointing to the southward migration of a lithospheric-scale thermal anomaly resulting in both crust- and mantle melting (Laurent *et al.*, 2017).

In the North-Eastern Massif Central, the extrusive equivalents of the granitoids record a drastic shift in composition during the middle Carboniferous. They change from mafic, low to medium-K calc-alkaline to felsic and high K (potassic rhyolites, and associated microgranites), broadly similar to MPG in composition. These rhyolites are middle to upper Visean in age as constrained by a U-Pb zircon age of 336.9 ± 3.2 Ma (Cartannaz *et al.*, 2007a), identical within uncertainty to the age of the underlying granitoids (Laurent *et al.*, 2017). Moreover, both the early, and the middle Carboniferous magmatic rocks do include some mantle-related components, with nevertheless clear differences in the nature of the mantle component between these two periods (Fig. 14A). Up to the early Carboniferous (before c. 345–340 Ma), the isotopic composition of the mantle-derived magmatic rocks (late Devonian Brévenne and lower Carboniferous series) are on the mantle array, consistent with an asthenospheric mantle source. On the other hand, the middle (and late) Carboniferous mantle-derived magmatic rocks (vaugnerites and lamprophyres) are shifted towards "crustal" compositions, reflecting the growing influence of a recycled crustal component in the mantle below the French Massif Central (Fig. 13). A similar and coeval evolution is described in the Bohemian Massif (Janousek and Holub, 1997; Janoušek *et al.*, 2004). In the French Massif Central, there is not only a temporal evolution, but also a spatial distribution of mantle sources. While the enriched mantle is centered on the Velay complex, the non-enriched mantle domain is located in the Northern part of the region (Beaujolais and Morvan). Similarly, different mantle compositions are still featured today in mantle xenolith from Cenozoic volcanoes (Lenoir *et al.*, 2000), displaying a comparable spatial distribution. Furthermore, the volumetrically more abundant Cenozoic magmatism occurs in the domain where the mantle is more enriched (and probably more fertile).

The preservation of platform carbonates of Visean age in the northern part of the French Massif Central and around the Montagne Noire, indicates that these regions were below sea level at this time. Other sedimentary sequences of this period corresponds to the erosion products of subcontemporaneous volcanics and plutonics traping organic matter in continental basins delimited by strike-slip shear zones or normal faults (Bertaux *et al.*, 1993; Bruguier *et al.*, 1998; Thiéry *et al.*, 2009).

In order to reconcile all observations, we propose that exhumation of migmatites along strike-slip shear zones coeval with foreland propagation of the deformation front correspond to growth of an orogenic plateau by lateral flow of the partially molten orogenic root in a context of plate convergence associated with southward slab retreat (Figs. 17 and 18D). This plateau spreads from south of the Brévenne region to north of the Montagne Noire as constrained by the deposition of plateform carbonates. In this model, the partially molten orogenic root also flows toward the north beneath the former late Devonian Brévenne rift basin. Such horizontal flow, already proposed for the Vosges (Skrzypek *et al.*, 2014) and the Bohemian Massifs (Lexa *et al.*, 2011; Schulmann *et al.*, 2014; Kusbach *et al.*, 2015), explains the voluminous granitic magmatism observed at that time. The systematic occurrence of vaugnerites along with granitic magmas point to mantle melting that might be caused by decompression as a consequence of slab retreat.

4.6 Late Carboniferous to Permian (c. 305–295 Ma) gravitational collapse and exhumation of the partially molten root of the Variscan orogenic belt

The late Carboniferous (Figs. 15 and 18E) is marked by regional scale extension of the Variscan belt of Western Europe (Ménard and Molnar, 1988), which is particularly illustrated in the French Massif Central by the activation of low-angle detachments (Malavieille *et al.*, 1990; Van Den Driessche and Brun, 1992; Burg *et al.*, 1993; Faure, 1995; Gardien *et al.*, 1997; Vanderhaeghe *et al.*, 1999; Bouilhol *et al.*, 2006) controlling the exhumation of migmatites in the core of domes such as the Velay in the central-east French Massif Central (Dupraz and Didier, 1988; Burg and Vanderhaeghe, 1993; Ledru *et al.*, 2001) and the Montagne Noire in the southern French Massif Central (Gèze, 1949; Nicolas *et al.*, 1977; Echtler and Malavieille, 1990; Van Den Driessche and Brun, 1992; Rabin *et al.*, 2015; Trap *et al.*, 2017) (Fig. 3).

The HT/LP metamorphic conditions recorded by the migmatites coring the Velay and Montagne Noire domes and by the lower crustal granulites have been classically interpreted in terms of a sudden increase in temperature at the end of the Carboniferous (Marignac *et al.*, 1980; Dupraz and Didier, 1988; Lardeaux *et al.*, 2001; Ledru *et al.*, 2001; Couzinié *et al.*, 2014; Barbey *et al.*, 2015). However, such a catastrophic event is not required by the data. Indeed, as discussed in the previous section, (i) the oldest ages obtained on migmatites in the Limousin and around the Velay and Montagne Noire domes, and (ii) the coeval emplacement of granitic plutons and vaugnerites indicates that the crust and the mantle were already partially molten as early as 340 Ma ago and remained so throughout the Carboniferous (Laurent *et al.*, 2017; Vanderhaeghe *et al.*, 1999). A similar time range has been proposed for the duration of the partial melting event in the Variscan crustal segment exposed in the Ivrea-Verbano Zone (Guergouz *et al.*, 2018) but also for the root of the Grenville orogenic belt (Turlin *et al.*, 2018). The continuous magma extraction from a partially molten source at depth results in the emplacement of granitic plutons (CPG, MPG) at higher structural level in combination with the entrainment of source material, which fully explains their chemical characteristics (Villaros *et al.*, 2018). Final crystallization of migmatites is constrained by the ages of late-migmatitic dikes at c. 297 Ma in the Velay (Montel *et al.*, 2002; Didier *et al.*, 2013) and by the emplacement of a syntectonic granite at c. 294 Ma in the Montagne Noire (Poilvet *et al.*, 2011).

The size of the Velay and Montagne Noire domes, *i.e.* several tens of km in diameter, indicates that they are crustal-scale features (Van Den Driessche and Brun, 1992; Burg and Vanderhaeghe, 1993; Ledru *et al.*, 2001). This view of a pervasively partially molten orogenic root is corroborated by the diversity of the protoliths (orthogneisses, paragneisses, amphibolites...) that have molten to form the migmatites (Downes and Duthou, 1988; Williamson *et al.*, 1992; Downes *et al.*, 1997; Ledru *et al.*, 2001; Barbey *et al.*, 2015; Rabin *et al.*, 2015). Moreover, the fact that the domes are circumscribed by the foliation of the host paragneisses and orthogneisses (Lagarde *et al.*, 1994; Echtler and Malavieille, 1990; Mattauer *et al.*, 1996) and by the syn-melting foliation of the migmatites (Burg and Vanderhaeghe, 1993; Ledru *et al.*, 2001; Rabin *et al.*, 2015) indicates that the migmatites correspond to a mechanically coherent partially molten body. In the Velay, the synmigmatitic foliation delineates subdomes of about 10–20 km in diameter and bears a radially distributed HT mineral lineation pointing to the role of gravitational instabilities (Ledru *et al.*, 2001; Vanderhaeghe, 2009). Such subdomes have been described in Naxos Aegean domain and interpreted as reflecting crustal-scale convection (Kruckenberg *et al.*, 2011; Vanderhaeghe *et al.*, 2018). In the Montagne Noire, migmatites in the core of the dome display a prolate finite strain ellipsoid indicative of constriction with a subhorizontal long axis parallel to the axis of the elliptical shape dome, which is coeval with exhumation of the core of the dome (Echtler and Malavieille, 1990; Van Den Driessche and Brun, 1992; Mattauer *et al.*, 1996; Aerden and Malavieille, 1999; Charles *et al.*, 2009; Rabin *et al.*, 2015). Following this rationale, the development of crustal-scale migmatite domes at 305–295 Ma marks the time at which the long-lived, partially molten lower-middle crust cooled rapidly as a consequence of rapid exhumation owing to gravitational collapse. If crustal thinning was faster than thermal relaxation, isothermal decompression of the migmatites would result in an increase of the geothermal gradient as observed in the E-FMC (Montel *et al.*, 1992; Barbey *et al.*, 1999, 2015; Ledru *et al.*, 2001).

To explain the protracted melting of the root of the Variscan orogenic crust, one may invoke the effects of an increase in radioactive heat production of the thickened crust, combined with the increase in mantle heat flux owing to the southwards removal of the lithospheric mantle slab underneath the FMC. Coeval crustal thickening and lithospheric mantle thinning is the best case scenario to produce a high geothermal gradient in the continental crust (Vanderhaeghe and Duchêne, 2010) that might last for several tens of Myrs (Ueda *et al.*, 2012). This model is also supported by the nature and spatial/temporal evolution of granitoid and vaugnerite magmatism (Moyen *et al.*, 2017; Laurent *et al.*, 2017). In addition to the thermal input at the base of the orogenic crust, partial melting might also be enhanced by exhumation, as dehydration melting reactions are crossed during decompression (Thompson and Connolly, 1995).

In the external zone of the Variscan belt, specifically in the Montagne Noire area, migmatites are present beneath and deform a metasedimentary sequence affected by recumbent folds and low-grade metamorphism. This is paradoxal as this scheme does not match the classical model of thermal relaxation after nappe stacking (Franke *et al.*, 2011). Moreover, the deposition age of the protolith of part of the metasedimentary sequence (Visean to Namurian) overlaps with the geochronological record of HT/LP metamorphism and granitic intrusion, spreading from c. 330 to c. 300 Ma. In order to resolve this paradox, we propose that sediment deposition, HT/LP metamorphism and granite emplacement were indeed coeval but occurred in laterally remote units that were subsequently juxtaposed owing to lateral horizontal flow of the partially molten orogenic root beneath the sedimentary rocks and their upper crustal basement (Figs. 18E and 19). In this scenario, the migmatites coring the Montagne Noire dome represent partially molten rocks that were located beneath the orogenic plateau since the early Carboniferous and have flown laterally from the internal to the external zone in the late Carboniferous. The migmatites and associated granites were then exhumed, cooled and juxtaposed to the metasedimentary

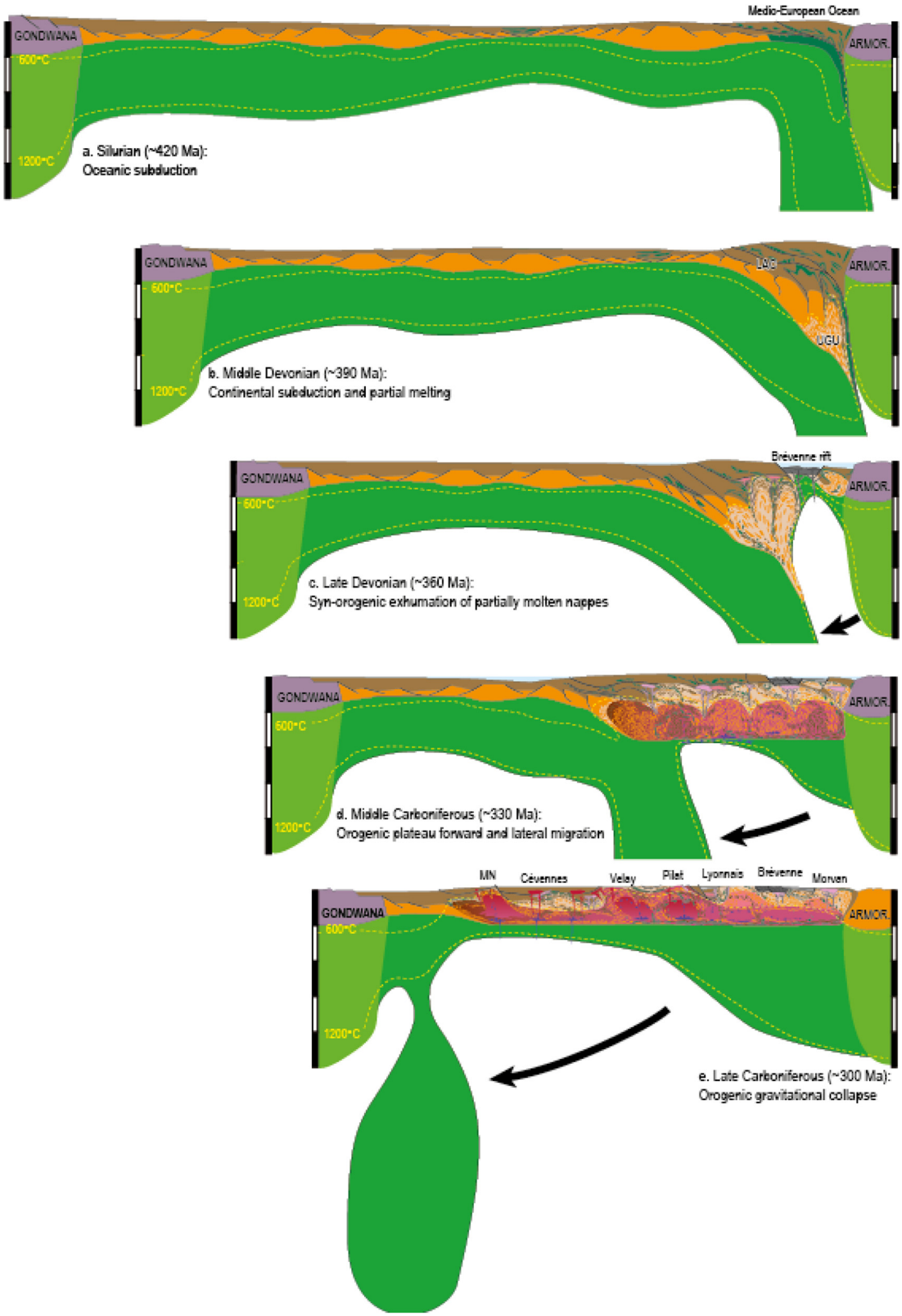

Fig. 18. Geodynamic-tectonic model of the Variscan bel exposed in the French Massif Central. A. Silurian (c. 420 Ma) subduction of the Medio-European Ocean. B. Middle Devonian (c. 385 Ma) subduction and partial melting of the hyper-extended northern continental margin of the Gondwana craton. C. Late Devonian (c. 365 Ma) slab retreat, opening of the Brévenne rift and syn-orogenic exhumation of high-grade partially molten nappes. D. Lower Carboniferous (c. 330 Ma) development of an orogenic plateau by lateral flow of partially molten orogenic root in a context of plate convergence and southward slab retreat. E. Late Carboniferous (c. 300 Ma) gravitational collapse of the Variscan belt in a context of southward slab delamination accommodated by lateral and upward flow of the partially molten orogenic root concomitant with brittle extension of the upper crust.

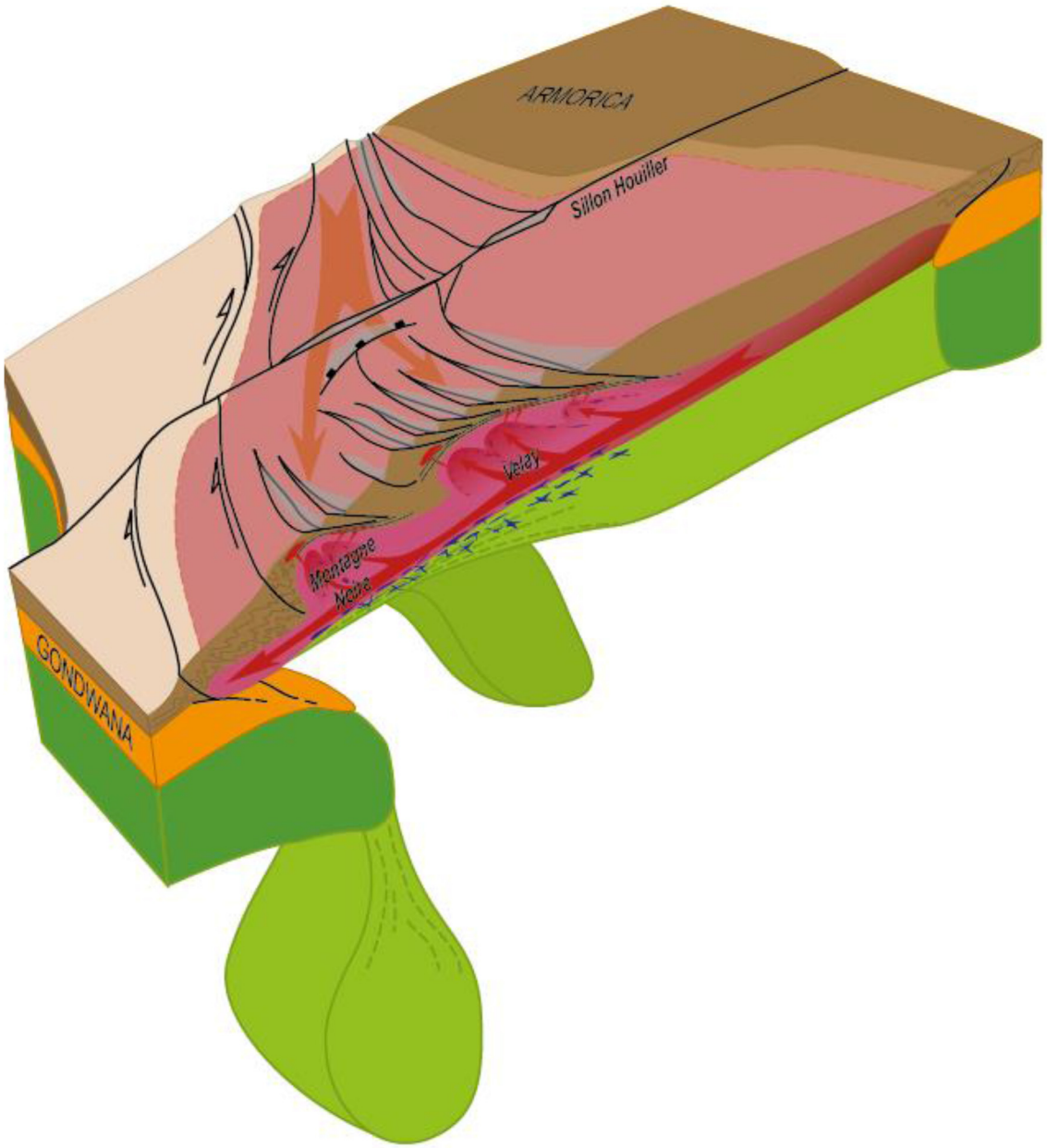

Fig. 19. 3D model for the late Carboniferous crustal and lithospheric scale structure of the Variscan belt beneath the French Massif Central. Gravitational collapse is accommodated by (i) lateral flow of the partially molten orogenic root from the western to the eastern side of the French Massif Central and from the internal to the external zone toward the south, and (ii) upward flow to form migmatite domes within Metamorphic Core Complexes. The Sillon Houiller accommodates differential slab retreat between the eastern and western parts of the French Massif Central.

nappes along a detachment. The Variscan basement exposed in the Axial Zone of the Pyrenees and in the North Pyrenean Massifs displays similar geological features (de Saint Blanquat, 1993; Gleizes *et al.*, 1997; Cochelin *et al.*, 2017) and the partially molten orogenic root might have flown toward the foreland beneath the current day Pyrenees providing an explanation for their peculiar Carboniferous-Permian structural and metamorphic record.

Comparison between the eastern and the western part of the FMC shows that large, late Carboniferous migmatite domes are only exposed in the eastern part of the FMC, which points to the Sillon Houiller as a major tectonic divide between these two parts of the FMC, at least during the late orogenic tectonic evolution. The Sillon Houiller corresponds to a subvertical sinistral strike-slip shear zone (Grolier and Letourneur, 1968; Arthaud and Matte, 1975) cross-cuting the Lower to Middle Carboniferous transcurrent strike-slip shear zones. It is in places sealed by Visean volcanics, and localizes the deposition of late Carboniferous to Permian clastic sediments accompanied with the emplacement of rhyolite at the onset of extension (Bonijoly and Castaing, 1984; Joly *et al.*, 2008, 2009; Lapierre *et al.*, 2008; Thiéry *et al.*, 2009). Scarce U-Pb data indicate an onset of deposition in some basins as early as 330 Ma (Bosmoreau and Decazeville Basins), but most ash beds yield

ages of 300–295 Ma that constrain a predominance of syntectonic intramontane basins (Jaujac, Bosmoreau, Alès, Bertholène, Graissessac and Roujan-Neffies basins) during the late Carboniferous (Bruguier *et al.*, 1998, 2003). In the Livradois, cooling of the migmatites and granites is recorded by argon thermochronology on micas and K-feldspar between 307 and 300 Ma. It is associated with exhumation along a top-to the west low-angle detachment that controls the deposition of coal-bearing sediments in the Brassac basin (Gardien *et al.*, 2011; Vanderhaeghe *et al.*, 2013). The discordant contact of these deposits with the LGU (locally migmatitic) and UGU attests that these metamorphic units reached surface exposure at the end of Carboniferous and that exhumation and crystallization of the partially molten orogenic crust and of crustal melts was essentially terminated by 295 Ma.

In the western Massif Central, this period is marked by ductile-brittle detachments such as the Argentat fault that also accommodate a component of strike-slip displacement (Bellot and Roig, 2007). Accordingly, the activity of the Sillon Houiller straddles the transition from the orogenic plateau development to gravitational collapse of the Variscan belt. The limited lateral offset of the Sillon Houiller compared to its the length is consistent with its role as a transfer fault accommodating a larger amount of N-S extension in the eastern part of the French Massif Central relative to the western part (Burg *et al.*, 1990). The presence of migmatite domes solely in the eastern part of the French Massif Central is consistent with this model. Currently, except for a slight variation beneath the Cenozoic rift, the continental crust displays a constant thickness of c. 30 km on both sides of the Sillon Houiller (Ziegler and Dèzes, 2006). This suggests that, at the time of orogenic gravitational collapse, the larger amount of surface extension in the eastern French Massif Central was compensated in the orogenic root by flow of the partially molten rocks from the northern and western French Massif Central toward the Velay and Montagne Noire dome in the southeastern part of the French Massif Central. Moreover, the presence of migmatites in the Montagne Noire and in the Pyrenees, beneath the foreland sedimentary sequence affected by recumbent folds and low-grade to HT/LP metamorphism, also suggests that the partially molten orogenic root has flown toward the foreland. This model provides a potential explanation for the enigmatic high geothermal gradient identified in the external zone and for propagation of crustal thickening in the foreland beneath supracrustal rocks. Our model is also compatible with the shallow northward plunge (0–30°) of the mineral and stretching lineation displayed along the Sillon Houiller (Grolier and Letourneur, 1968; Bonijoly and Castaing, 1984).

The P-T-t record of the lower crust documented by felsic and mafic granulitic xenoliths with a maximum pressure of 14 kbar and a temperature of 900 °C followed by near isothermal decompression (Leyreloup, 1974; Montel, 1985; Downes and Leyreloup, 1986) is consistent with a hot and thick orogenic crust that has then been affected by thinning. U-Pb ages on zircon from the granulites from 320 to 280 Ma cover the transition from crustal thickening to gravitational collapse (Downes and Leyreloup, 1986; Costa and Rey, 1995). The geochemical characteristics of the granulites suggest that they represent a mixture of (i) resisters (rocks that were not prone to melt), (ii) solid residues after melt extraction, (iii) cumulates (iv) and residual melts (Dupuy *et al.*, 1979; Pin and Vielzeuf, 1983; Vielzeuf *et al.*, 1990; Downes *et al.*, 1997), which is complementary to the evidences for crustal-derived magmas emplaced at higher structural levels. Such features are also identified in exposed sections of the Variscan lower crust in the Ivrea Zone (Percival, 1992; Barboza *et al.*, 1999; Bea and Montero, 1999; Schaltegger and Gebauer, 1999; Guergouz *et al.*, 2018) or in Calabria (Schenk, 1980, 1981, 1989).

4.7 Pertinence of the proposed geodynamic-tectonic model compared to physical modelling of the dynamics of orogenic belts

In this section, we assess the significance of the geological record of rocks forming the Variscan belt exposed in the French Massif Central in terms of the thermal-mechanical evolution of orogenic belts as investigated by physical modelling.

Eclogites, which are the oldest metamorphic rocks identified in the French Massif Central, and are present at the highest structural level of the nappe pile, have recorded HP/LT conditions. Such conditions imply burial at more than 30 km depth and more rapidely than the effect of thermal diffusion, typically a subduction rate of more than 1 cm/yr (Huerta *et al.*, 1996; Henry *et al.*, 1997).

modelling of the thermal evolution of orogenic belts has shown that a time delay of 20 to 30 Myrs after crustal thickening is required for thermal diffusion and heat production through natural decay of radioactive isotopes to lead to significant partial melting of the orogenic root (England and Thompson, 1984; Thompson and Connolly, 1995). This 20 to 30 Myrs gap is consistent with the geochronological record of HT eclogites and granulites preserved in the UGU. In turn, the thermal impact of removal of the lithospheric mantle root is more rapid and dramatic in terms of increase in temperature in the crust (Houseman *et al.*, 1981; Arnold *et al.*, 2001). Thinning of the lithospheric mantle is so efficient that it has been proposed as a mechanism to account for HT/LP metamorphism in back-arc basins marked by a relatively thin crust (Collins, 2002). In the case of a convergent plate boundary marked by slab retreat and tectonic accretion, both the radioactive heat production and the mantle heat flux are increased concomitantly, which is the most favorable scenario for a hot orogenic root (Sandiford and Powell, 1990; Vanderhaeghe and Duchêne, 2010; Arnold *et al.*, 2001). In such a case, thermal relaxation after removal of the lithospheric mantle occurs over about 100 Myrs (Ueda *et al.*, 2012), which is roughly the duration of HT metamorphism and magmatism invoked in the geodynamic-tectonic model presented in this paper.

Exhumation of rocks entrained in subduction entails mechanical decoupling of these rocks from the downgoing slab, which in turns indicates that their buoyancy reached their mechanical strength (Chemenda *et al.*, 1996; Escher and Beaumont, 1997; Warren *et al.*, 2008). In turn, partial melting might be particularly efficient in decreasing the strength of buried rocks and thus favouring their decoupling from the downgoing slab and their exhumation.

The presence of a low-viscosity orogenic root is causing horizontal flow of the thickened crust (Artyushkov, 1973; Molnar and Lyon-Caen, 1988; Bird, 1991; Royden, 1996).

This horizontal flow, driven by the gravity force associated with lateral variations of the weight of the crustal column, occurs preferentially toward a free boundary or a mechanically weak zone. In the case of an advancing plate boundary, *i.e.* indentation, horizontal flow occurs preferentially laterally and is associated with the activation of strike-slip shear zones (Royden, 1997; Cagnard *et al.*, 2006). The low-viscosity layer might also flow in the direction of convergence, toward the foreland (Henk, 2000; Vanderhaeghe *et al.*, 2003). The presence of a low-viscosity layer also impedes the maintenance of an irregular topographic surface (Artyushkov, 1973), which leads to the formation of an orogenic plateau (Molnar *et al.*, 1993; Vanderhaeghe *et al.*, 2003). If the zone of weak crust is maintained along its boundaries by stronger crustal sections, the orogenic plateau might be maintained (Vanderhaeghe *et al.*, 2003; Cook and Royden, 2008). In the contrary, horizontal flow of the low-viscosity orogenic root will lead to redistribution of the orogenic crust until total decay of the gravity force (Rey *et al.*, 2001). The style of extension is controlled by the rheology of the crust and thus its temperature (Buck, 1991; Rey *et al.*, 2009).

Given its low density and low viscosity, a partially molten orogenic root is susceptible to develop diapiric Rayleigh-Taylor instabilities (Ramberg, 1968; Talbot, 1979; Perchuk *et al.*, 1992; Weinberg and Schmeling, 1992; Cruden *et al.*, 1995) and even convective instabilities (Weinberg, 1997; Vanderhaeghe *et al.*, 2018).

5 Conclusion

The structural, petrological, geochemical and geochronological record of the French Massif Central provides an archive of the thermal-mechanical evolution of the Variscan belt in Western Europe and documents the impact of partial melting and magmatism during orogenic evolution, as summarized in the following and in Figures 18 and 19.

The pre-Variscan paleogeography (Figs. 16 and 17) is marked by hyper-extension of the northern margin of the Gondwana supercontinent, evidenced by the coeval emplacement of alkaline granitoids and of tholeiitic to calc-alkaline bimodal mafic-felsic magmas of the Leptynite Amphibolite Complex during Ordovician times (485–460 Ma). This setting is particularly favorable for trapping of voluminous detrital sediments and the emplacement of alkaline magmas that might represent the protoliths of the main portion of the metagreywackes, metapelites and orthogneisses forming the UGU, MAU, LGU and PAU.

The presence of HT eclogite facies mafic and ultramafic enclaves of the Leptynite Amphibolite Complex into the migmatitic HP granulites of the UGU indicates subduction of the immature oceanic crust (Fig. 18A) together with continental ribbons (Fig. 18B). The 20–30 Ma difference in age between the eclogite-facies metamorphism recorded by the LAC corresponds to the time required for thermal relaxation and partial melting. Partial melting potentially triggered decoupling of the UGU from the downgoing slab allowing for the syn-orogenic exhumation of the partially molten UGU entraining pieces of mafic and ultramafic rocks forming the LAC and representing previously subducted oceanic lithosphere and/or part of the suprasubduction mantle. The percolation into the suprasubduction mantle of felsic melt segregated from the partially molten UGU would have possibly contributed to its enrichment in HFSE, REE and LILE required to form the source of the later vaugnerites.

During the Devonian-Carboniferous transition, opening of a rift in the internal zone of the Variscan belt is accompanied by the emplacement of the c. 360 Ma ACG and low-K calc-alkaline to tholeiitic magmas of the Brévenne Unit and Limousin tonalitic line. This is coeval with thrust propagation in the external zone and deposition of detrital sediments in the foreland that we tentatively attribute to the outward propagation of the orogenic belt in a context of slab retreat (Fig. 18C). Such a context might have facilitated syn-orogenic exhumation of the buoyant and low-viscosity partially molten felsic units previously dragged with the subducting slab.

Regional scale transcurrent shear zones and foreland propagation of thrusts accommodate the development of an orogenic plateau by gravity-driven lateral flow of the partially molten orogenic root, owing to a major Carboniferous thermal anomaly of lithospheric extent. This is indeed associated with high-temperature/medium-pressure metamorphism and the emplacement of syntectonic plutons from 345 to 310 Ma (Fig. 18D). The diversity of the geochemical signatures of the magmatic rocks encompassing MPG, CPG and their volcanic equivalents, KCG and Mg-K vaugnerites indicates a contribution of both the crust and the mantle. The latter along with the southward younger emplacement ages of these magmatic rocks is consistent with progressive retreat toward the south of the northward plunging slab during the Carboniferous.

The late Carboniferous gravitational collapse of the Variscan orogenic crust (Fig. 18E) is accommodated by extension of the upper crust and by lateral flow and exhumation of the partially molten root. This is marked by the formation of crustal-scale domes cored by LP migmatites and heterogeneous granites coeval with the emplacement of syntectonic laccoliths in the footwall of low-angle detachments. These are complementary to a refractory granulitic lower crust formed by protracted high-temperature metamorphism, partial melting and melt/solid segregation.

According to this new model consistent with physical modelling, continuous and protracted presence of melt in the root of the orogenic crust plays a crucial role in the tectonic evolution of the Variscan belt by (i) triggering syn-orogenic exhumation of subducted continental units decoupled from the downgoing slab; (ii) controlling the formation and lateral development of an orogenic plateau; and finally, (iii) guiding the formation of metamorphic core complexes during orogenic gravitational collapse. Crustal melting starts with segregation of melts from the subducted oceanic and continental units in the Devonian. Subsequently during the Carboniferous, the emplacement of plutons and volcanics during the building of the orogenic plateau has a contribution from the partially molten crust and from the mantle. The maintenance of a partially molten crust for several tens of Myrs is probably favored by the combined effects of radioactive heat production and increasing mantle heat flux owing to removal of the lithospheric mantle slab. It ended with the extraction of differentiated magmas and crystallization of the collapsed partially molten orogenic root. The contrasting Carboniferous geological record between the Western and Eastern French Massif Central separated by the Sillon Houiller is consistent

with a more pronounced slab retreat in the East toward the Paleotethys free boundary. The Eastern part of the French Massif Central is indeed characterized by (i) the abundance of Mg-K diorites (vaugnerites) and KCG-type granites indicating the contribution of mantle-derived magmas, and (ii) a widespread extension associated with the development of the Velay and Montagne Noire migmatite domes (Fig. 19).

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