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Special Issue Some applications of LA-ICP-MS U-Pb geochronology: A tribute to Jean Louis Paquette
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Short-lived active margin magmatism preceding Variscan collision in the Western French Massif Central

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Abstract – This paper presents and discusses new geochronological and petrological data on a suite of calc-alkaline plutons composed predominantly of diorites and tonalites from the West Massif Central. Their petrochemical fingerprints are compatible with partial melting of a hydrous mantle wedge followed by fractional crystallization of amphibole and plagioclase before final emplacement between 5 and 8 kbar within the continental upper plate of a subduction system. In situ U-Pb zircon dating on tonalites yields a fairly narrow age range of 365−354 Ma (including uncertainties) for igneous crystallization. These calc-alkaline plutons imply active margin magmatism near the Devonian-Carboniferous boundary and are contemporaneous with the back-arc magmatism and HP metamorphism as dated by recent studies. However, such isolated igneous bodies do not form a transcrustal magmatic arc but rather represent dispersed plutons emplaced within less than 30 Myr when all data from the Variscan belt of France are considered. In Limousin, they intrude migmatitic paragneisses and retrogressed eclogites from the Upper Gneiss Unit (UGU), suggesting that the high pressure rocks were already exhumed at 19−30 km depth before 365 Ma. Moreover, the diorites and tonalites are never found within units below the UGU. It therefore suggests that these tectono-metamorphic units of the Western French Massif Central were piled up after 354 Ma. Altogether these results support the monocyclic model for Variscan geodynamics in the French Massif Central, with the transition between oceanic subduction and continental collision taking place between Upper Devonian and Lower Carboniferous.

Keywords: Subduction / calc-alkaline magmatism / arc / Upper Devonian / diorite / tonalite

Résumé – Courte pulsation du magmatisme de marge active avant la collision continentale varisque dans le Massif central français occidental. Cette étude apporte de nouvelles contraintes géochronologiques et pétrologiques sur une série de plutons calco-alcalins composés principalement de diorites et de tonalites et situés Massif central occidental. Leur signature pétro-géochimique implique la fusion partielle d'un coin mantellique hydraté suivie de la cristallisation fractionnée d'amphibole et de plagioclase avant la mise en place finale entre 5 et 8 kbar dans la plaque continentale supérieure d'un système de subduction. La datation U-Pb in situ des zircons provenant des tonalites donne une gamme d'âge de 365 à 354 Ma (erreurs incluses) interprétée comme représentant la cristallisation magmatique des zircons. Ces plutons calco-alcalins proviennent d'un magmatisme de marge active à la limite Dévonien-Carbonifère et sont synchrones du magmatisme d'arrière-arc et du métamorphisme de haute pression datés par des études récentes. Ces intrusions ne forment cependant pas un arc magmatique d'échelle crustale mais représentent plutôt des plutons dispersés qui se sont mis en place en moins de 30 millions d'années si l'on considère toutes les données disponibles, réévaluées et robustes pour la chaîne varisque en France. Dans le Limousin, ces plutons intrudent notamment les paragneiss migmatitiques et les éclogites rétromorphosées de l'Unité Supérieure des Gneiss, ce qui suggère que les roches de haute pression étaient déjà exhumées à une profondeur de 19-30 km avant 365 Ma. En outre, les diorites et les tonalites n'ont pas été observées dans les

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unités situées sous l'Unité Supérieure. Cela indique que les unités tectoniques du Massif central occidental ont été empilées après 354 Ma. Ces résultats soutiennent donc le modèle monocyclique de la géodynamique varisque dans le Massif central français où la transition subduction océanique/collision continentale se produit entre le Dévonien supérieur et le Carbonifère inférieur.

Mots clés : subduction / magmatisme calco-alcalin / arc / Dévonien supérieur / diorite / tonalite

1 Introduction

The West European Variscan belt (Fig. 1) is the result of the convergence between two supercontinents, Laurussia and Gondwana, ultimately leading to their collision starting in the Early Carboniferous. This convergence is chiefly accommodated by the subduction of the Rheic Ocean, which separated the Avalonian terrains from the Gondwanan margin. However, the number, palaeogeography, lifetime and even the existence of other oceanic domains are poorly constrained and these uncertainties lead to various geodynamic models of pre-Carboniferous convergence and subductions (compare Kroner and Romer, 2013 and Franke *et al.*, 2017; or for the western branch, Lardeaux *et al.*, 2014 and Ballèvre *et al.*, 2014). These models (see Vanderhaeghe *et al.*, 2020 for a recent review) can be subdivided into those involving (i) one single ocean (generally the Rheic, see von Raumer and Stampfli, 2008; Kroner and Romer, 2013), (ii) several (up to three) oceanic basins (Matte, 2001; Franke *et al.*, 2017), (iii) monocyclic continuous subduction zones (see Matte 1986, 2001, 2007; Ballèvre *et al.*, 2014) or (iv) polycyclic subduction-collision models involving northward subduction of an oceanic lithosphere until the Silurian-Lower Devonian (generating the so-called eo-variscan event/suture) and southward subduction of another oceanic domain during Middle Devonian to Lowermost Carboniferous times (Faure *et al.*, 2005, 2008, 2009; Lardeaux *et al.*, 2014). More specifically, the identification of the subducted ocean(s) located along the southern Variscan domain is debated. It is referred to as the Galicia, (South) Brittany and Massif central ocean (or a combination of these appellations; Matte, 1986; Matte *et al.*, 2001, 2007), the Rheic ocean (von Raumer and Stampfli, 2008; Nance *et al.*, 2010; Kroner and Romer, 2013), or a branch of the Rheic ocean (Paris and Robardet, 1998) or the Saxo-thuringian ocean (Franke *et al.*, 2017).

Considering that paleo-geographic and paleo-kinematic data are less robust for Paleozoic orogens compared to Cenozoic ones (see for example Jolivet *et al.*, 2021), the evolution of pre-orogenic subductions is strongly based on the sedimentological, petrological and tectonic records acquired by either high pressure metamorphic units or supra-subduction complexes. One of the key arguments to favor/support a particular model is the age of the high pressure event(s). Recent dating performed on high pressure rocks (see Paquette *et al.*, 2017; Lotout *et al.*, 2018, 2020; de Hoÿm de Marien *et al.*, 2023) suggest that eo-variscan 430-390 Ma ages obtained in the past for the HP metamorphism in the French Massif Central (see Faure *et al.*, 2009) are artifacts and that most if not all the eclogites and related HP units could be related to a single Upper Devonian-Lowermost Carboniferous high pressure event as it is generally recognized in the Armorican massif (Bosse *et al.*, 2000, 2005; Ballèvre *et al.*, 2014). There is less ambiguity on the age of supra-subduction magmatism spanning from 379 to 355 Ma for calc-alkaline plutons (Bernard-Griffith *et al.*, 1985; Cuney *et al.*, 1993; Bertrand *et al.*, 2001; Pin and Paquette, 2002; Fig. 1) and Middle Devonian to Lowermost Carboniferous for basaltic and felsic lavas with arc and back-arc affinities (Sieder and Ohnenstetter, 1986; Pin and Paquette, 1997; Pin and Paquette, 2002; Fig. 1). Published zircon U-Pb ages indicates that calc-alkaline plutons in the French Massif Central emplaced within about 30 Myr near the Devonian-Carboniferous transition (Bernard-Griffiths *et al.*, 1985; Pin and Paquette, 2002). However, this time span is sometimes interpreted as covering two successive geological events considering that the plutonic rocks are locally sheared and recrystallized (Faure *et al.*, 1997; Bellot and Roig, 2007). These authors suggest that igneous crystallization of diorites and tonalites occurred between 380−360 Ma while the 360−355 Ma ages represent deformation and recrystallization during the so-called D2 tectono-metamorphic event (Faure *et al.*, 2009), despite the fact that original geochronological studies interpreted all the ages as dating igneous emplacement.

This contribution focuses on a suite of calc-alkaline plutons called the Tonalitic Line of Limousin and grossly aligned on a NW-SE strike from Vendée (SE Amorican massif) to SW French Massif central. We will discuss the nature of Late Devonian magmatism in Western French Massif central (Fig. 1) in the light of new ages and petrological data combined to published results. We will also discuss the implications for the pre-collisional evolution of the West European Variscan belt considering that the calc alkaline plutons could represent a single short-lived magmatic pulse preceding the stacking of the main litho-tectonic units.

2 Geological setting

The French Massif central belongs to the internal units of the Moldanubian zone of the Western Variscan belt (Faure *et al.*, 2009; Lardeaux *et al.*, 2014; Martinez-Catalan *et al.*, 2021; Fig. 1). This belt formed after Cambro-Ordovician rifting of the Northern Gondwanan margin and opening of (an) oceanic domain(s), an event is coeval with the formation of large volume of predominantly felsic magmatic rocks now forming Furongian-Ordovician orthogneiss in metamorphic units. The Devonian convergence, accommodated by subduction between Laurussia and Gondwana, is evidenced by numerous eclogites whose age have been re-evaluated recently at Middle Devonian to Lowermost Carboniferous times (Lotout *et al.*, 2018, 2020; Benmammar, 2021; de Hoÿm de Marien *et al.*, 2023). Final collision of continental blocks occurred during the Lower Carboniferous and triggered a massive phase of syn- to late-orogenic, dominantly silicic magmatism derived from crustal and mantle sources and lasting from about 360 Ma to 300 Ma (Vanderhaeghe *et al.*, 2020).

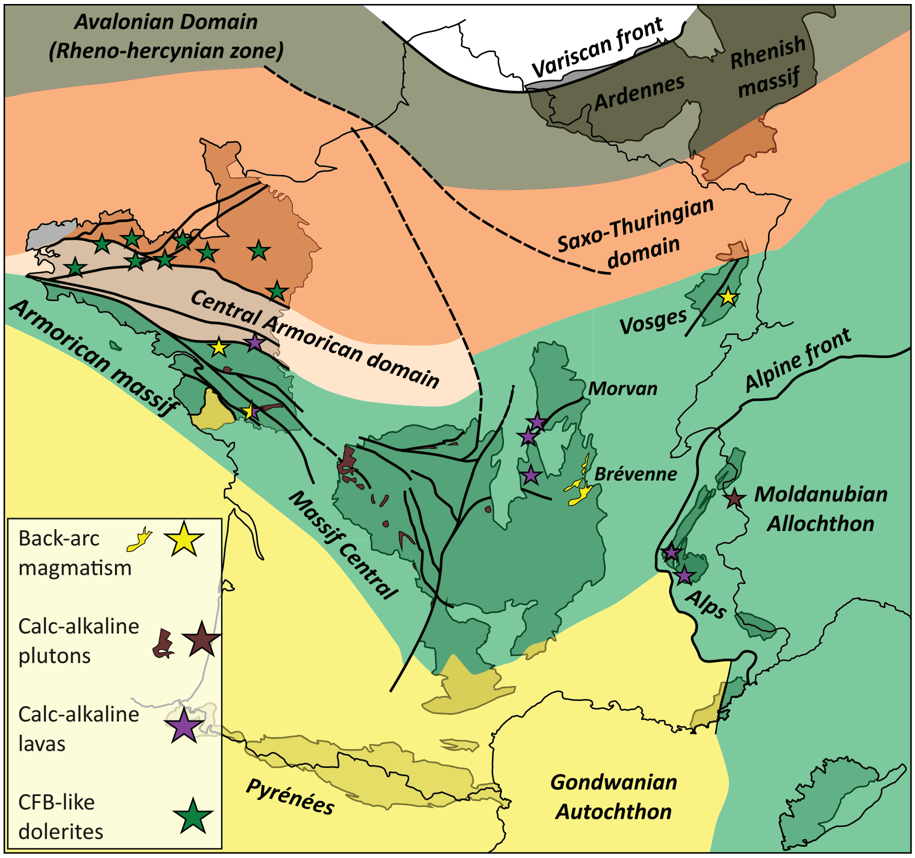

Fig. 1. Map of the Variscan belt in France showing the main Devonian-Early Carboniferous magmatic markers for subduction (Variscan zones modified after Ballèvre *et al.*, 2014).

Middle to Upper Devonian igneous rocks supposedly emplaced in a supra-subduction setting (Fig. 1) form isolated massifs in the internal part of the Variscan belt and especially in the French Massif Central, the neighboring South Armorican zone, the Vosges (Skrzypek *et al.*, 2012) and Paleozoic crystalline massifs of the Alps (Bertrand *et al.*, 2000; Guillot and Ménot, 2009; Guillot *et al.*, 2012; Bergomi *et al.*, 2017). In the Armorican massif, Devonian subalkaline basaltic to rhyolitic rocks occur in low grade Upper allochthonous units in Vendée (basalt and andesite of La Meilleraie interpreted either as arc or back arc magmatism: Thiéblemont and Cabanis, 1986; Ducassou *et al.*, 2011) and at St Georges sur Loire (undated but assumed to be Silurian or Devonian; Cartier and Faure, 2004; Ducassou *et al.*, 2011). In the French Massif central Fammenian to Tournaisian supra-subduction zone magmatism is documented in Morvan (basalt and andesites of the Somme Unit; Pin and Paquette, 2002) and in the so-called Brévenne ophiolite (bimodal volcanic and plutonic basaltic-rhyolitic associations of the Brévenne Unit; Sieder and Ohnenstetter, 1986; Pin and Paquette, 1997; Leloix *et al.*, 1999). However, the most striking expression of this Middle to Late Devonian magmatic episode is the Tonalite Belt of Limousin (Didier and Lameyre, 1971) underlined by diorite and tonalitic plutons extending from Vendée to southwestern French Massif Central (Bernard Griffith *et al.*, 1985; Pfeiffer, 1986; Shaw *et al.*, 1993; Cuney *et al.*, 2001a, 2001b; Pin and Paquette, 2002; Figs. 1 and 2a). The present study focuses on Western Massif Central plutons (Fig. 2a) that intruded either into the Upper Gneiss Unit (UGU) made of migmatitic paragneiss with numerous lenses of retrogressed eclogites (Pfeiffer 1986) or into the uppermost amphibolite facies Leyme unit for the Figeac and St Céré massifs representing the southernmost occurrences of these plutonic associations (Pfeiffer, 1985, 1986; Duguet *et al.*, 2007). Pin and Paquette (2002) also described two similar igneous complexes in the Northern French Massif Central (Aydat and La Marche plutons). It is worth to note that diorite-tonalite plutons are never found in the greenschist facies metapelites of the Parautochtonous nor in the amphibolite facies orthogneiss and metapelites (with very rare eclogitic lenses) of the Lower Gneiss Unit (LGU).

A representative example of the Tonalitic belt in Limousin is the St Féréole-Tulle massif (Fig. 2b Peiffer, 1986). It has a curved morphology parallel to the tectonic contact between the LGU and UGU (Floc'h, 1983; Bellot and Roig, 2007) and intrudes the migmatitic paragneiss and retrogressed eclogites belonging to the UGU (Fig. 2b). Pfeiffer (1986) describe different lithologies from hectometer to kilometer-size hornblendite and hornblende gabbro clusters to diorite and tonalite forming the main mass of plutons. The textural fabrics vary from igneous with euhedral plagioclase, subhedral amphibole and interstitial quartz and biotite to a deformed porphyroclastic gneiss recrystallized under solid state. Metamorphic foliations of gneissic diorites are subparallel

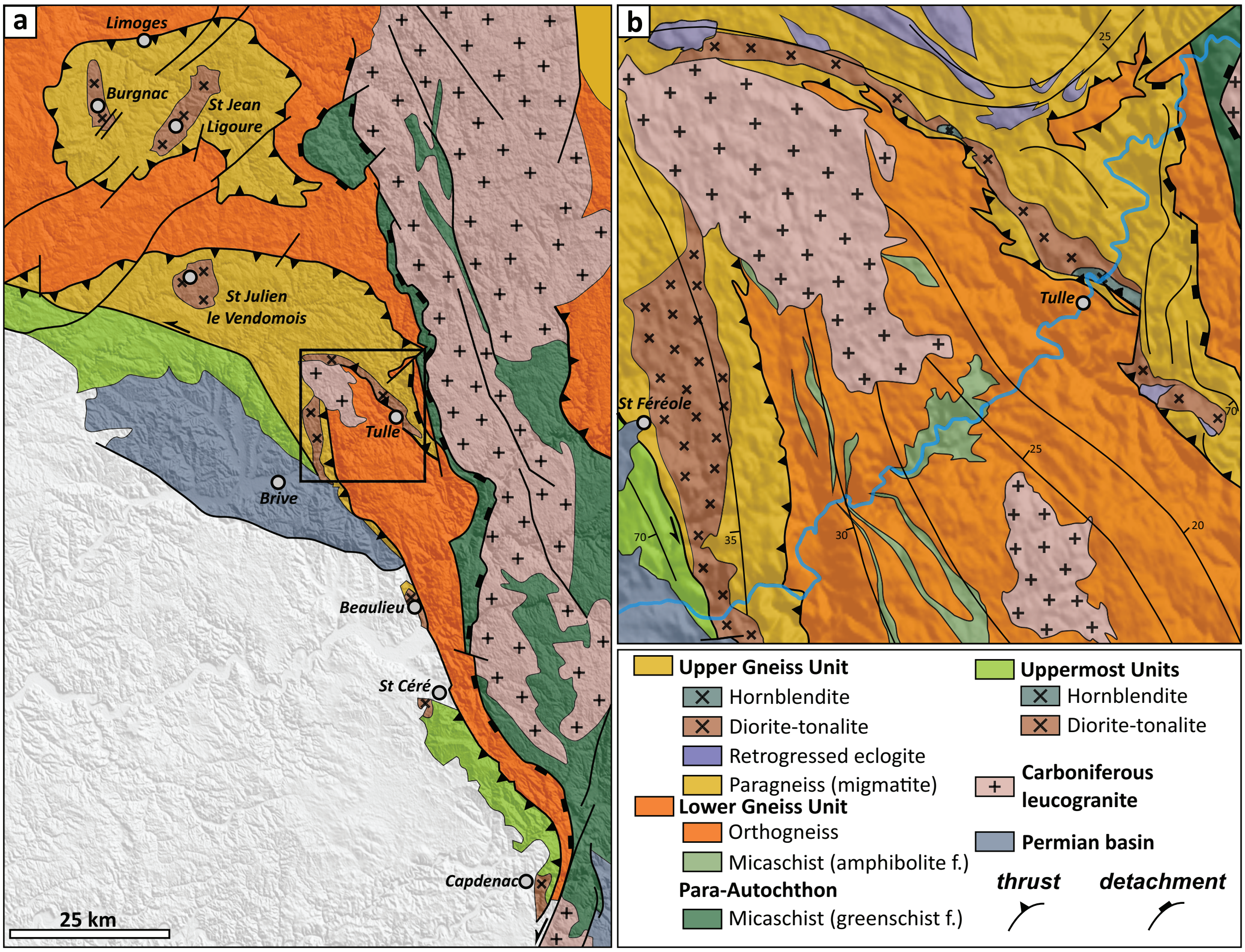

Fig. 2. Geological maps showing the location of calc-alkaline plutons and their relation with tectono-metamorphic units. (a) Simplified geological map of the Limousin area adapted from published BRGM maps, the position of studied plutons is indicated together with samples labels. (b) Zoom on the St-Féréole-Tulle massif located within UGU but near the LGU/UGU contact. Foliation trajectories from Bellot and Roig (2007).

to those measured in host gneisses (Pfeiffer, 1986), *i.e.* fabrics that are related to the D2 deformation event (Bellot and Roig, 2007; Faure *et al.*, 2009). The bulk structure of the magmatic body resembles an unrooted laccolith transposed into the foliation of host paragneisses (Pfeiffer, 1986).

Available geochronological data (U-Pb zircon by ID-TIMS or SHRIMP) for the emplacement of diorites and tonalites range from 379 to 355 Ma (Bernard Griffiths *et al.*, 1985; Cuney *et al.*, 1993; Bertrand *et al.*, 2001; Pin and Paquette, 2002). All authors converge to interpret these dates as representing igneous crystallization ages.

3 Sampling and analytical methods

Seven massifs were sampled from the central Limousin to the Lot Valley in southwestern Massif Central (Tab. 1, Fig. 2a), including, from NW to SE (Pfeiffer, 1987 and Fig. 2): Burgnac (sample labels: BIA, FRO), Saint Jean de Ligoure (SJL, SHB, SPL), Saint Julien le Vendômois (SAJ), Tulle-Saint Féréole (JAM, TUL, MAR), Beaulieu-sur-Dordogne (DBD, BEA), Saint-Céré (STC) and Capdenac (FIG, DCAP). They belong to the Upper Gneiss Unit, except for St-Céré and Capdenac which were ascribed to the amphibolite-facies Leyme unit structurally above the UGU.

Mineral chemical data (Tab. S1) were acquired with a SXFive Cameca electron microprobe hosted by the "Centre de microcaractérisation Raimond Castaing" in Toulouse, France. The beam voltage and current were set at 15 kV and 10 nA, respectively and calibration was done with a set of natural silicate and oxide standards. Major and trace-elements on pulverized bulk rocks were analyzed at the Central Analytical Facilities (CAF) of the Stellenbosch University, South Africa. Rock powders were dried, mixed with lithium metaborate and fused to produce glass beads. Major elements were measured by XRF while trace-elements were analyzed by LA-ICP-MS on the same glass beads. Relative standard deviations between measured and reference values for international standards (BE-N, BHVO, JG-1) analyzed by XRF is around 20% for oxides <0.1 wt%, below 5% for oxides <5 wt% and below 1% for oxides >10 wt%. Relative accuracy on trace-elements (monitored with secondary standard BHVO) is typically around 0.2−10%, the highest values representing either some specific elements (Nb, Ta, Pb) or low concentrations (<1 µg/g).

Table 1. Location, name, structure and modal proportion of samples used in this study.

Rock type	Sample	Massif	UTM X	UTM Y	Structure	Hbl	Plag	Fe-Ti oxide	Biotite	Quartz	Epidote	Apatite
Hbldite	TUL3	Tulle/St Féréole	403507	5015030	Igneous	98.0	1.5	0.5				
Hbldite	JAM10	Tulle/St Féréole	404298	5014202	Igneous	100						
Hbl Gabbro	JAM11	Tulle/St Féréole	404298	5014202	Igneous	59.5	31.0	9.5				
Hbl Gabbro	TUL1	Tulle/St Féréole	403507	5015030	Igneous	54.5	41.0	4.5				
Diorite	SPL	St Jean Ligoure	376295	5058019	Deformed	22.5	60.0	4.0	10.0	2.0		1.5
Qz diorite	BEA1	Beaulieu	407251	4982188	Igneous	25.0	52.5	2.0	12.0	8.0		0.5
Qz diorite	BEA2	Beaulieu	407659	4980817	Igneous	26.0	52.5	2.5	11.5	7.0		0.5
Qz diorite	DBD	Beaulieu	407204	4982545	Igneous	24.0	48.5	4.0	13.0	10.0		0.5
Qz diorite	BIA	Burgnac	356430	5062803	Igneous	21.0	50.0	2.0	16.0	10.5		0.5
Qz diorite	FRO	Burgnac	355494	5062118	Deformed	19.0	52.0	2.0	16.5	10.0		0.5
Qz diorite	SAJ12A	St Julien	372827	5031982	Igneous	13.5	54.0	2.0	15.0	12.5	2.5	0.5
Qz diorite	SAJ13	St Julien	372827	5031982	Igneous	18.5	54.0	1.5	14.0	10.0	1.5	0.5
Qz diorite	TUL2	Tulle/St Féréole	403507	5015030	Deformed	12.5	54.0	1.5	16.0	12.5	3.0	0.5
Tonalite	DCAP	Capdenac	430056	4936533	Gneissic	10.5	47.5		24.5	17.0		0.5
Tonalite	FIG	Capdenac	428117	4932678	Igneous	2.0	50.5	0.5	25.0	18.5	3.0	0.5
Tonalite	MAR1	Tulle/St Féréole	389666	5009461	Deformed	10.5	54.0	1.5	16.5	16.0	1.0	0.5
Tonalite	MAR2	Tulle/St Féréole	389666	5009461	Deformed	7.5	55.5	2.0	17.0	14.5	3.0	0.5
Tonalite	SHB	St Jean Ligoure	370973	5065249	Deformed	15.5	52.5	1.0	15.5	15.0		0.5
Tonalite	SJL	St Jean Ligoure	368521	5060793	Deformed	12.5	45.0		24.5	13.0	4.0	1.0
Tonalite	STC	St Céré	410120	4963275	Igneous	5.0	50.0	1.0	21.5	21.0	1.0	0.5

Nd-Sr isotopic data was obtained at GET-OMP according to the following procedure: 100 mg of whole rock powder was weighed in a teflon beaker and dissolved in a mixture HF/HNO_3/HCl 2:1:1. Nd and Sr were extracted from the matrix using a combination of Sr-Spec, Thru-spec and Ln-Spec resins. An equivalent of 500 ng Sr and 150 ng Nd were run on a Thermo Scientific Triton+ mass spectrometer. NBS987 and La Jolla isotopic standards were regularly run during the measurements. Standard reproducibility for $^{143}Nd/^{144}Nd$ ratio is 0.510858 ± 18 (n = 50) for La Jolla and 0.710248 ± 35 (n = 70) for $^{87}Sr/^{86}Sr$ ratio of NBS987. However, part of the samples (TUL1, DBD, SAJ12A, SJL, AUB1) were run following Li *et al.* (2010) procedure, *i.e.* with Sm isobaric corrections. For those, Sm-corrected $^{145}Nd/^{144}Nd$ ratios are indicated and Sm-doped JNdi standards were run, they give a $^{143}Nd/^{144}Nd$ ratio of 0.512108 ± 8 and $^{145}Nd/^{144}Nd$ ratio of 0.348406 ± 5. Typical procedural blanks are 50 pg for Nd and 150 pg for Sr.

Zircons were separated with routine magnetic and heavy-liquid methods and mounted in epoxy. They were imaged with cold cathode optical cathodoluminescence at the University of Mons using a Cambridge Image Technology model 8200 Mk5 system. U-Pb analyses were done at Géosciences Montpellier, France (platform AETE-ISO of the OSU OREME) with a Teledyne G2 excimer laser probe coupled to a ThermoFinnigan Element XR high-resolution ICP-MS. The pre-ablation blank signal was acquired during 15s followed by about 30 s of ablation (spot size of 25 µm, repetition rate of 4 Hz, fluence of 6 J/cm^2) and signal acquisition (see Bruguier *et al.*, 2017 for further details). Pb/U and Pb/Pb isotopic ratios were calibrated against primary reference zircon G91500 (Wiedenbeck *et al.*, 1995). Secondary standards GJ-1 (slightly discordant with an upper intercept TIMS age at 608.5 ± 1.5 Ma; Jackson *et al.*, 2004) and Plesovice (concordant TIMS age at 337.1 ± 0.4 Ma; Sláma *et al.*, 2008) were analyzed every five unknowns and yielded a concordia age of 604 ± 3 Ma (n = 15) and 339 ± 2 Ma (n = 13), respectively. Every zircon sample mount was analyzed with 25 laser spots. Only analyses with regular ablation spectra (*i.e.* similar in trend to standards, with gently decreasing counts per second and gently increasing Pb/U isotopic ratios during ablation) were selected for further processing. Irregular spectra characterized by abrupt drop(s) or increase(s) in signal (probably due to ablation on fractures or mineral inclusions) were systematically discarded. Raw data were reduced with the software Glitter. For spots yielding regular ablation spectra, the signal was integrated from about 5 s after laser ignition to about 3 s before laser shut off. Reduced and calibrated results were plotted and calculated with IsoplotR (Vermeesh, 2018). Two uncertainties are quoted with Concordia ages, following the recommendation of Horstwood *et al.* (2016). The first one is based on weighted mean statistic and is given by IsoplotR along with MSWD for concordance and equivalence. The second one (written into brackets) integrates the excess variance (1.6%) calculated on the basis of long term analysis of a secondary reference material (here GJ1) in the laboratory, including the uncertainties on primary reference material (here 91500) and also the errors on decay constants. Note that the obtained dates will be discussed with the second uncertainty, this allow better comparison of results obtained in different laboratories.

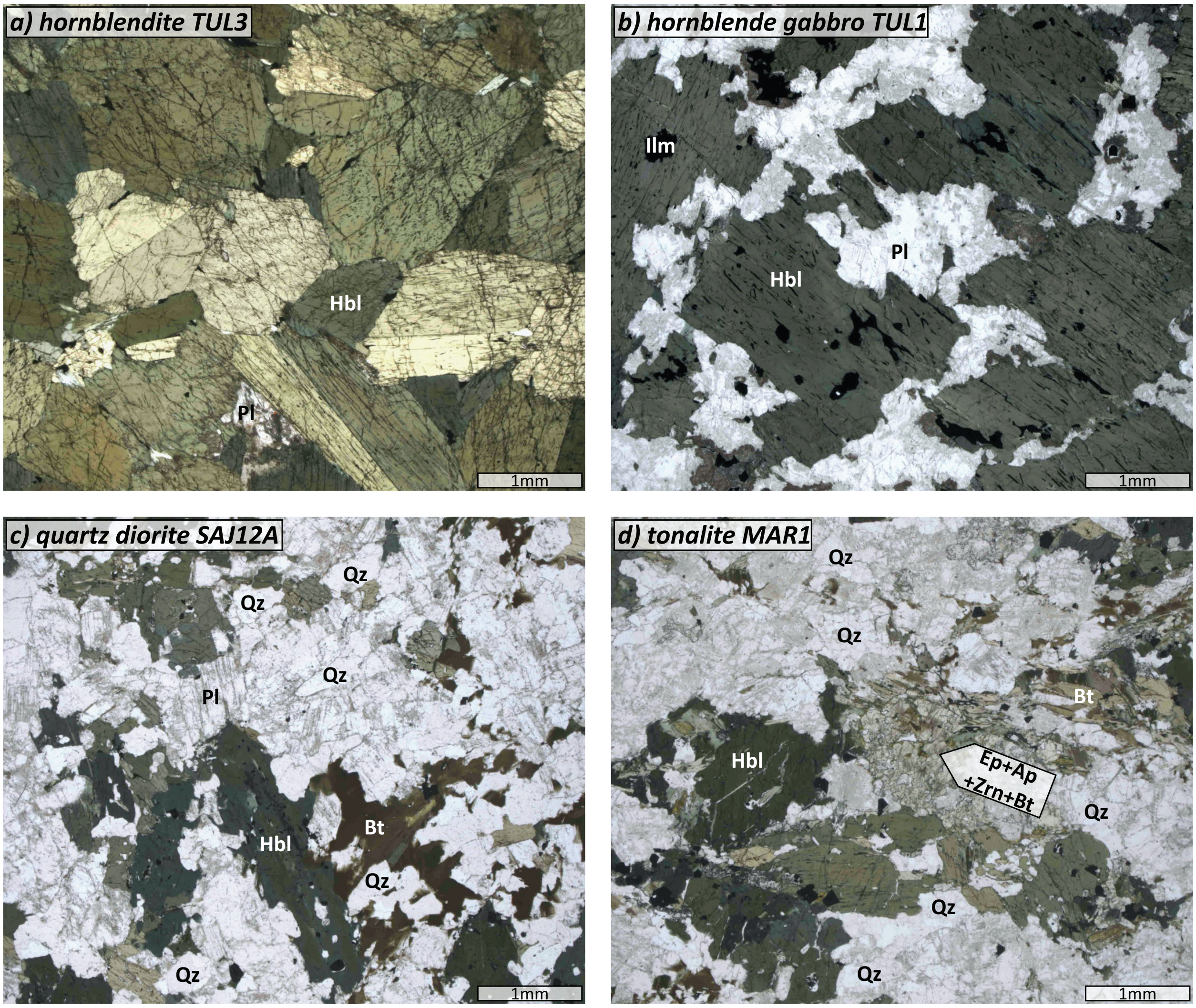

Fig.3. Representative microphotographs of hornblendite TUL3 (a), hornblende gabbro TUL1 (b), hornblende-biotite quartz diorite SAJ12A (c) and hornblende-biotite tonalite MAR1 (d). Despite post-magmatic alteration, igneous textures are generally preserved (a, b, c) but a weak foliation can develop locally (d). Note the interstitial epidote-apatite-zircon-biotite cluster in sample MAR1 (d).

4 Petrography, mineral chemistry and thermobarometry

Hornblendites have been sampled in the Tulle massif (Tab. 1, Fig. 2, samples TUL3 and JAM10). They consist of subhedral coarse (up to 1 cm wide) pargasite (98–99 vol.%) showing minute brown lamellar Schiller exsolutions of Fe-Ti oxides with interstitial anhedral altered plagioclase (~1 vol.%) and ilmenite often included in amphibole (Fig. 3a, Tab. 1). The latter has high Mg# (60–63), low Si (6.05–6.30 apfu) and variable Ti (0.11–0.22 apfu) (Fig. 4). All plagioclase grains are altered into epidote-albite associations and their composition could not be determined.

Hornblende-gabbro samples in the Tulle massif (TUL1 and JAM11) have 31–41 vol.% plagioclase, 54–60 vol.% amphibole and 5–9 vol.% Fe-Ti oxides (Tab. 1). Hornblende form coarse (2–3 mm wide) subhedral grains with Fe-Ti oxide inclusions and plagioclase is present as a mosaic of submillimetric euhedral altered crystals (Fig. 3b). Pargasite has lower Mg# (50–55), Si (5.90–6.25 apfu) and Ti (0.08–0.15 apfu) compared to hornblendites and plagioclase is calcic ($An_{85\text{-}92}$).

Other samples were classified as ***diorite***, ***quartz diorite*** and ***tonalite*** according to their normalized volumetric amount of quartz in the quartz-plagioclase subsystem (<5%, between 5 and 20% and >20%, respectively) but they generally share similar textural features (Figs. 3c and 3d). They show variable amounts of amphibole (from 2 to 20 vol%), plagioclase (48–60 vol.%), biotite (10–25 vol.%) quartz (2–21 vol.%) with minor epidote (0–4 vol.%), apatite (<1.5 vol.%) and Fe-Ti oxides (<4 vol.%) (Tab. 1). In samples with perfectly preserved igneous textures (BEA, FIG, DBD, SAJ12A, SAJ13, STC; Fig. 3c) plagioclase is millimetric, tabular euhedral and zoned. It also occurs as small euhedral inclusions into amphibole and biotite. Amphibole is coarse (1–3 mm) but systematically interstitial into the network of plagioclase tabs and contains numerous inclusions of Ti-magnetite. Biotite forms large anhedral flakes with amphibole and rare epidote

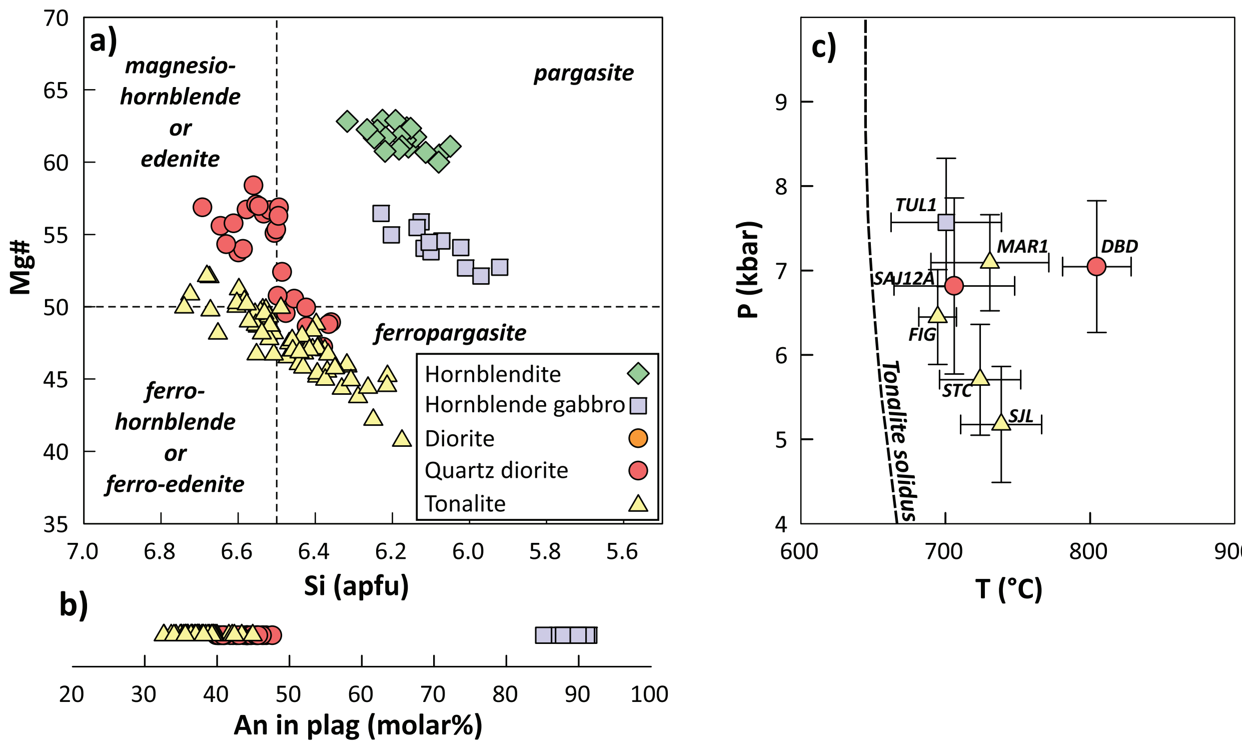

Fig.4. Mineral composition and thermobarometry. a) Composition and classification of amphiboles (a); composition of plagioclases (b) and average P-T results per sample calculated with amphibole only and amphibole-plagioclase thermobarometers (see text) (c). The error bars represent the 1σ standard deviation of individual pressures and temperatures calculated for each sample.

inclusions. The latter is commonly associated with biotite, apatite, quartz and zircon in interstitial clusters (particularly in tonalites). Localized deformation and recrystallization is observed in some samples (BIA, FRO, MAR1, MAR2, SHB, SJL; SPL Fig. 3d). The texture locally becomes porphyroclastic with elongated grains of amphibole and biotite surrounding partly recrystallized porphyroclasts of plagioclase. Plagioclase recrystallized along its rims, locally exhibiting a mortar texture and some large grains show undulatory extinction with development of subgrains, but igneous concentric zoning is still preserved. Undeformed zones are preserved with similar textures to those described previously. DCAP sampled in the active quarry of the Capdenac massif is a porphyroclastic gneiss with almost no relic of the original igneous texture except for large zoned plagioclase grains. Amphibole in quartz diorite is on average slightly more magnesian (Mg#: 58–47) and Si rich (6.35–6.70 apfu) compared to amphibole in tonalites (Mg#: 41–53; 6.20–6.75 Si pfu). Similar variations are observed for biotite (Mg#: 54–63 in quartz diorite and 49–54 in tonalites). There is no systematic differences in composition between amphibole from deformed versus undeformed samples. However, a small fringe of actinote can develop around hornblende in some deformed samples. Plagioclase is on average more calcic in quartz diorite (An_{39-48}) than in tonalites (An_{32-45}) (Fig. 4).

The amphibole-plagioclase barometer of Molina *et al.* (2015) and the amphibole-only thermometer of Liao *et al.* (2021) were used to estimate pressure and temperature of crystallization. They can be applied on a wide range of bulk and mineral compositions (although not for hornblendites in which plagioclase is totally altered) and have the following calibration uncertainties: ±35 °C for Liao *et al.* (2021) and ±1.5 to ±2.3 kbar for Molina *et al.* (2015). About 100 amphibole-plagioclase pairs were used for thermobarometry and results range from 4.5 to 8.5 kbar and 640–840 °C. When looking at averages per sample (Fig. 4), most calculated pressures fall within 5–8 kbar corresponding to middle or lower crustal depths (19–30 km) and 700–800 °C, *i.e.* temperature above the water-saturated tonalitic solidus (Schmidt and Thompson, 1996). Considering the large uncertainties on pressure estimations all the calculated pressures for diorites and tonalites are equivalent within errors. There are therefore no systematic differences between samples affected by solid-state deformation/recrystallization (MAR1, SJL) and those with igneous textures (FIG, SAJ12A, DBD, STC) or when comparing those found in the so called eo-variscan Leyme units (FIG, STC) to plutons from the Upper Gneiss Unit (MAR1, SJL, SAJ12A, DBD).

5 Geochemistry

Rocks belonging to the Tonalite belt of Limousin form a typical low-Ti, normal to high-K calc-alkaline suite (Tab. S2, Fig. 5). Hornblendites and hornblende gabbros are cumulates characterized by low SiO_2 (40–43 wt%), high Al_2O_3 (16–23 wt%) and high MgO (8–12.5 wt%) (Fig. 6). They display the typical REE profile of amphibole segregates with a slight depletion in LREE compared to HREE

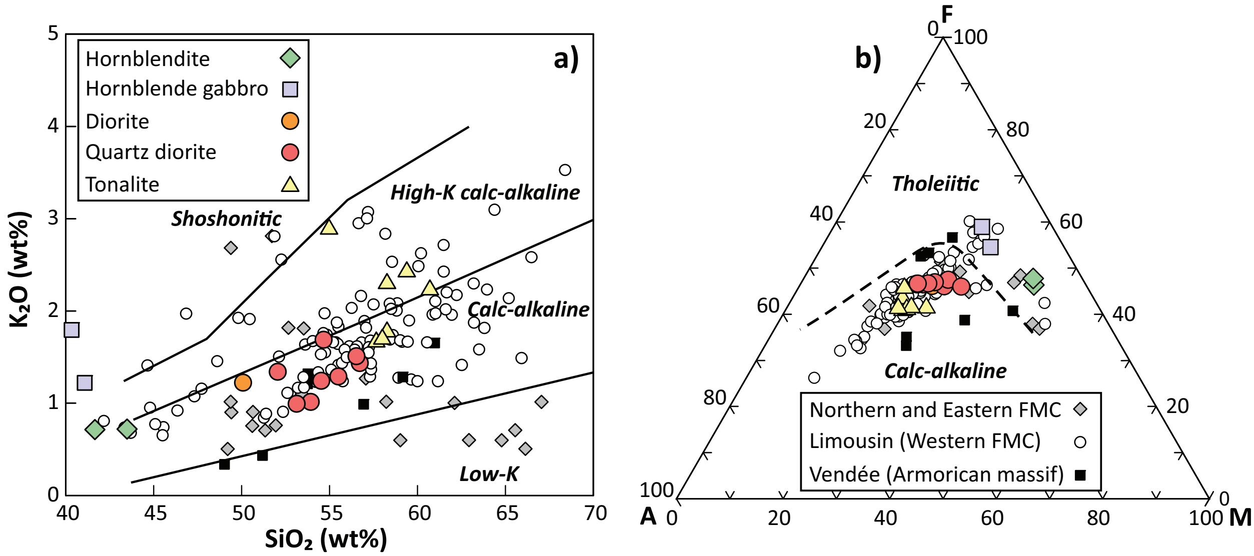

Fig.5. Classification of Late Devonian – Early Carboniferous calc-alkaline plutonic rocks from the French Massif Central and the Armorican Massif in the K_2O-SiO_2 diagram (a) and the AFM triangle plot (b). Literature data (white, black and grey symbols) are from Pfeiffer (1986); Shaw *et al.*, (1993); Cuney *et al.*, (2001) and Pin and Paquette (2002).

($(La/Yb)_N$: 0.59–1.10) accompanied by a weak negative Eu anomaly (Eu/Eu*: 0.68–0.95, with Eu* = $(Sm*Gd)^{0.5}$ (Fig. 7). They are depleted in very incompatible elements (especially in Th and U relative to Nb) compared to quartz diorites and tonalites, but share similar concentrations in Y and HREE (Fig. 7). Diorite (50 wt% SiO_2; Mg#: 49), quartz diorites (52–54 wt% SiO_2; Mg#: 49–54) and tonalites (54.5–60.7 wt % SiO_2; Mg#: 44–53) form near linear trends in Harker diagrams (Fig. 6) marked by a decrease in TiO_2, Al_2O_3, CaO and a slight increase in K_2O with increasing differentiation. In most cases, when these sublinear trends are extrapolated toward low SiO_2 values, they reach a composition of cumulate hornblende gabbros (Fig. 6). In REE and multi-element diagrams (Fig. 7), they are enriched in very incompatible elements (LREE, Rb, Ba, Th, U) with negative anomalies in Nb-Ta (Nb/Nb*: 0.12-0.67 with Nb*: $(Th*La)^{0.5}$) and Ti, features recalling typical basic to intermediate arc lavas (Fig. 7). On average, the LREE enrichment and the magnitude of the Nb and Ti negative anomalies increases from diorite to tonalites (Fig. 7). The amplitude of the negative Eu anomaly also gently increases from diorite (Eu/Eu*: 0.94) to quartz-diorites (Eu/Eu*: 0.83–1.02) and tonalites (Eu/Eu*: 0.71–0.86).

The Sr-Nd isotopic composition of 10 representative samples (Fig. 8, Tab. S3) lies between 0.7050–0.7061 for initial $^{87}Sr/^{86}Sr$ and +0.2 to +2.0 for εNd. These values are similar to those reported by Shaw *et al.* (1993) for the Limousin Tonalite Belt but have slightly lower εNd compared to diorite and tonalites from the Northern and Eastern Massif Central (Pin and Paquette, 2002) (Fig. 8). Two UGU paragneisses have also been analyzed to test crustal assimilation, they plot between εNd −1 to −2 and $^{87}Sr/^{86}Sr$ 0.7095–0.7115 (Fig. 8).

6 Zircon U-Pb geochronology

Three samples were selected for U-Pb dating on the basis of their geographical position and the amount of deformation/recrystallization (Fig. 9, Tab. S4). SJL is a tonalite from the Saint Jean de Ligoure massif located in northwest Limousin. This sample shows evidences for localized deformation and recrystallization but no macroscopic planar foliation. MAR1 is from the central Tulle-St Féréole massif. It is more affected by deformation than SJL as it shows a faint macroscopic gneissic fabric. FIG comes from the southernmost Capdenac massif and has perfectly preserved igneous textures at macroscopic and microscopic scales.

SJL yielded euhedral zircon crystals with elongation ratios around 1:3 and very regular oscillatory zoning (Fig. 9a). However, the grains were fractured with numerous minute inclusions of apatite (green on CL images), quartz (generally orange red) and epidote (black). Very few grains had a small (<10 µm wide) resorbed bright core that could not be analyzed. On the 25 spots made on the zircons, 12 were disturbed by the presence of inclusions and fractures generating very irregular ablation spectra (with brutal drop or jumps of the signal for Pb, Th and U isotopes). The remaining, undisturbed, 13 analyses give a concordant date of 359 ± 2 (± 5) Ma (MSWD: 0.97; Fig. 9b) and high Th and U contents (180–560 ppm Th and 390–1200 ppm U) translating into Th/U ratios between 0.43 and 0.62. Zircons from MAR1 are all euhedral, coarse (up to 400 µm long) and either elongated (1:5) or stocky (1:2). A lot of grains display a less luminescent core with sector (and sometimes faint oscillatory) zoning but the bright mantle zones have concentric oscillatory zoning (Fig. 9a). 20 spots yielded regular ablation spectra and very similar ellipses with a concordia date of 359 ± 3 (± 5) Ma (MSWD: 0.35) (Fig. 9c). Th/U ratios are high (0.43–0.78) but Th and U content are rather low (30–100 and 53–150 ppm respectively) compared to SJL zircons. Note that spots within darker cores yielded the same age that those made in mantle zones with oscillatory zoning (Fig. 9a). FIG had euhedral, often elongated (1:4 to 1:5) zircons but smaller than in the two other samples (<200 µm in length). On CL images (Fig. 9a), they generally display darker core with subtle oscillatory

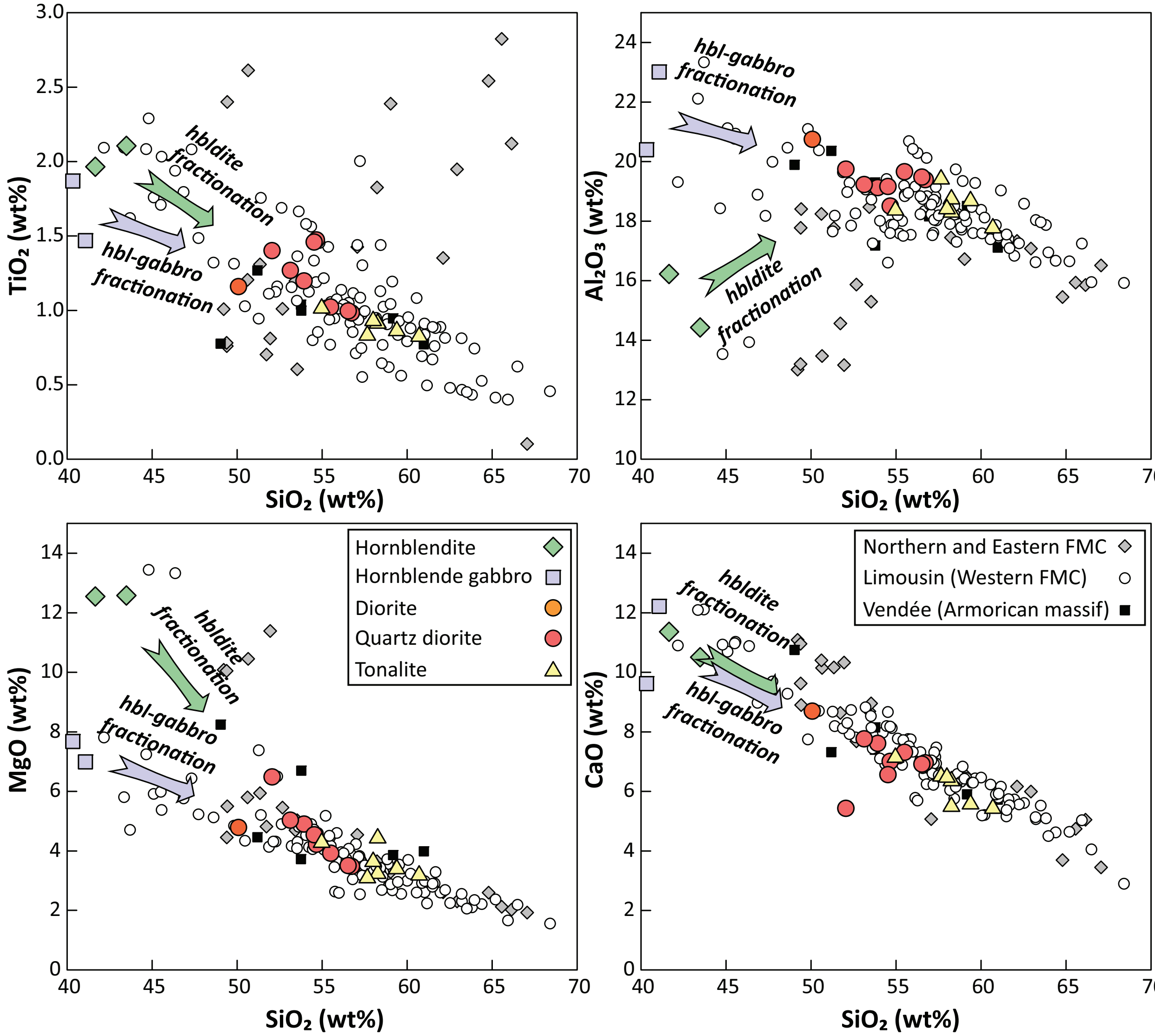

Fig.6. Harker diagrams showing major element composition of calc-alkaline plutons in the French Massif Central and the Armorican massif. Literature data (white, black and grey symbols) are from 1986 (Pfeiffer); Shaw *et al.* (1993); Cuney *et al.*, (2001) and Pin and Paquette (2002). Note the near linear trends drawn by diorites and tonalites extrapolating toward the composition of hornblende gabbros.

zoning and bright mantle/rims but no resorption textures between the zones. On the 25 spots made on the mount, 18 yielded regular ablation spectra with a concordia date of 360 ± 2 (± 5) Ma (MSWD: 1.1) (Fig. 9d). Th and U concentration were around 110–660 and 300–720 ppm respectively yielding Th/U ratios between 0.33 and 0.96. Similar ages were recovered on dark cores and on bright rims (Fig. 9a).

7 Discussion

7.1 Differentiation of a mantle-derived hydrous calc-alkaline suite at mid to lower crustal levels

The diorites and tonalites from the Western French Massif Central form a medium- to high-K calc-alkaline suite (Fig. 5). Occasional granodiorites are also mentioned (Pfeiffer, 1986) but none were analyzed in this study. Diorites, quartz-diorites and tonalites form nearly linear trends in major element variation diagrams (Fig. 6). The composition of these plutonic rocks can be interpreted as melts and not crystal segregates, as confirmed by the absence of positive Eu and Sr anomalies despite high modal plagioclase content. The liquid line of descent formed by diorites and tonalites in major element variation diagrams is controlled by the fractionation of hornblendites and hornblende gabbros assemblages (Fig. 6). The most primitive diorites and quartz-diorites have 50–54 SiO_2 wt%, Mg# around 49–54 and high alumina content, up to 20 wt% Al_2O_3 corresponding in composition to high alumina basalts and basaltic andesites found in volcanic arcs (Sisson and Grove, 1993). However, the quite low Mg#, compared to melt in equilibrium with mantle peridotite suggest that the most primitive samples were already slightly fractionated, as also confirmed by their quite low Ni and Cr contents (below 50

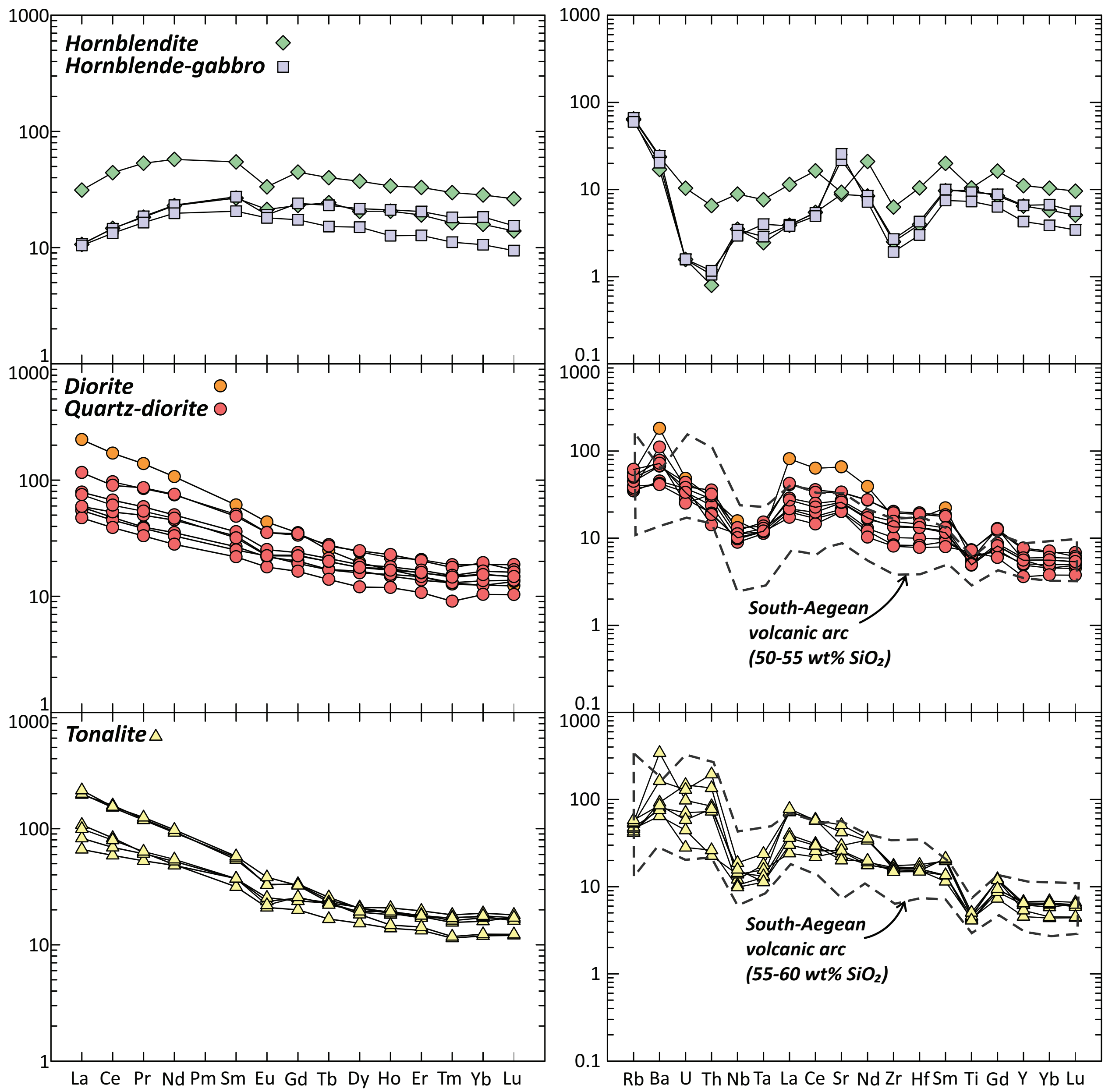

Fig.7. Chondrite-normalized REE patterns and primitive mantle normalized multi-element diagrams for the calc-alkaline plutonic rocks investigated in this study. The compositions of volcanic rocks from the South Aegean arc are extracted from the Georoc database. Normalization values are from McDonough and Sun (1995).

and 180 ppm respectively). The ubiquity of hornblende and titano-magnetite, even in the most primitive samples, with highly calcic plagioclase (up to 92 mol% An) in the hornblende gabbros is consistent with strongly hydrous oxidized parental magmas, typical of calc-alkaline suites found in continental magmatic arcs (Grove and Baker, 1984; Sisson and Grove, 1993). The trace element pattern of all samples except cumulates, also mimics volcanic rocks from calc-alkaline continental arcs (Fig. 7) with their typical Nb-Ta-Ti negative anomalies and their enrichment in fluid mobile elements (Rb, Ba, Sr, Pb). Moreover, near- but supra-solidus igneous epidote formed in interstitial clusters with biotite, zircon and apatite, also characterize hydrous, oxidized calc-alkaline magmas (Schmidt and Thompson, 1996; Schmidt and Poli, 2004). Considering that crystallization pressures determined with amphibole-plagioclase barometry are between 5 and 8 kbar for the French Massif Central diorites and tonalites (Fig. 4), supra-solidus late crystallization epidote probably indicate oxygen fugacities close to the NNO buffer (Schmidt and Thompson, 1996) during crystallization of tonalites.

Review of published (Shaw *et al.*, 1993) and new isotopic data (Fig. 8) highlight the remarkable homogeneity of initial Sr and Nd isotopic compositions for the Limousin massifs ($^{87}Sr/^{86}Sr$: 0.7040−0.7061 and εNd: −1 to +2). There is no systematic variations of Sr-Nd isotopic composition with the lithological nature and SiO_2 content (Fig. 8). Tonalites indeed

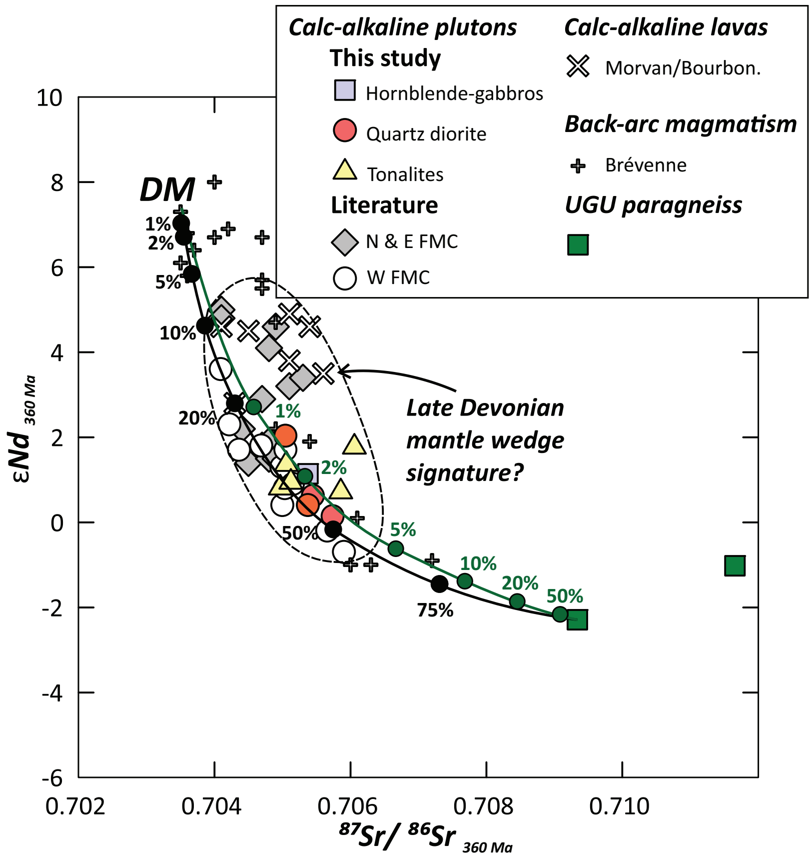

Fig.8. Sr-Nd isotopic diagram for calc-alkaline lavas/plutons from the French Massif Central (this study, Shaw *et al.*, 1993; Cuney *et al.*, 2001; Pin and Paquette, 2002) and for Brévenne back-arc magmatism (Pin and Paquette, 1997). Also shown, the composition of the Depleted Mantle (DM) at 360 Ma (calculated with the data of Salters and Stracke, 2004), the probable signature of the mantle wedge around 360 Ma as attested by calc-alkaline magmatism arc like magmatism. The green dotted mixing hyperbola represent mixing between Depleted Mantle and a UGU paragneiss to model mixing of the mantle source with sediments buried by subduction while the black mixing dotted curve simulates contamination of a depleted basalt by a UGU paragneiss to reproduce continental assimilation. Values in % indicate the relative mass of sedimentary component in the mix.

have similar compositions to diorites and to primitive hornblende gabbro cumulates. Testing crustal assimilation of UGU paragneiss hosting the diorites-tonalites plutons by depleted Brévenne back arc basalt, representing a contemporaneous depleted mantle component, to explain the isotopic signatures of the calc-alkaline plutonic suite yield unrealistic levels of contamination (20−60%; Fig. 8) to reproduce the composition of Limousin diorites and tonalites. Instead, calculating contamination of a 360 Myr-old depleted MORB mantle (using values of Salters and Stracke, 2004 recalculated at 360 Ma) by sediments buried by subduction (UGU paragneiss were taken as the 360 Ma sedimentary components) yields results around 2% (Fig. 8). Such level of crustal input into mantle wedge is in agreement with estimates made for recent primitive arc magmas (Chauvel *et al.*, 2009). Therefore crustal assimilation did not play a major role during differentiation of the Limousin diorite-tonalite suite. The isotopic compositions of the parental magmas are explained by melting of a mantle wedge contaminated by sediment-derived components buried by the slab with only a minor contribution of crustal assimilation as already suggested by various authors (Shaw *et al.*, 1993; Cuney *et al.*, 2001a; Pin and Paquette, 2002). Calc-alkaline lavas and plutons located in Northern and Eastern French Massif Central (FMC) have slightly different values (εNd: +1.5 to +5) probably representing a less contaminated mantle source or parental magma (Pin and Paquette, 2002). Globally, as proposed by Shaw *et al.* (1993), the focal zone represented by Late Devonian calc-alkaline plutons and lavas in the Sr-Nd diagram (Fig. 8) is the signature of the variously enriched Variscan mantle wedge under the French Massif Central around 360 Ma. Late Devonian magmatism with depleted isotopic signatures (εNd_i up to +8 and $^{87}Sr/^{86}Sr_i$ down to 0.7040) characterizes some basic and felsic volcanic rocks of the Brévenne area, interpreted as a former continental back-arc basin (Pin and Paquette, 1997; Fig. 8). The dichotomy of enriched signatures for tonalite and diorites similar to arc magmas versus depleted signatures at the Brévenne back arc is consistent with geochemical studies on modern arc-back arc systems (Pearce *et al.*, 2005; Pearce and Stern, 2006) describing a depleted mantle source at the back arc and an enriched mantle source below the arc.

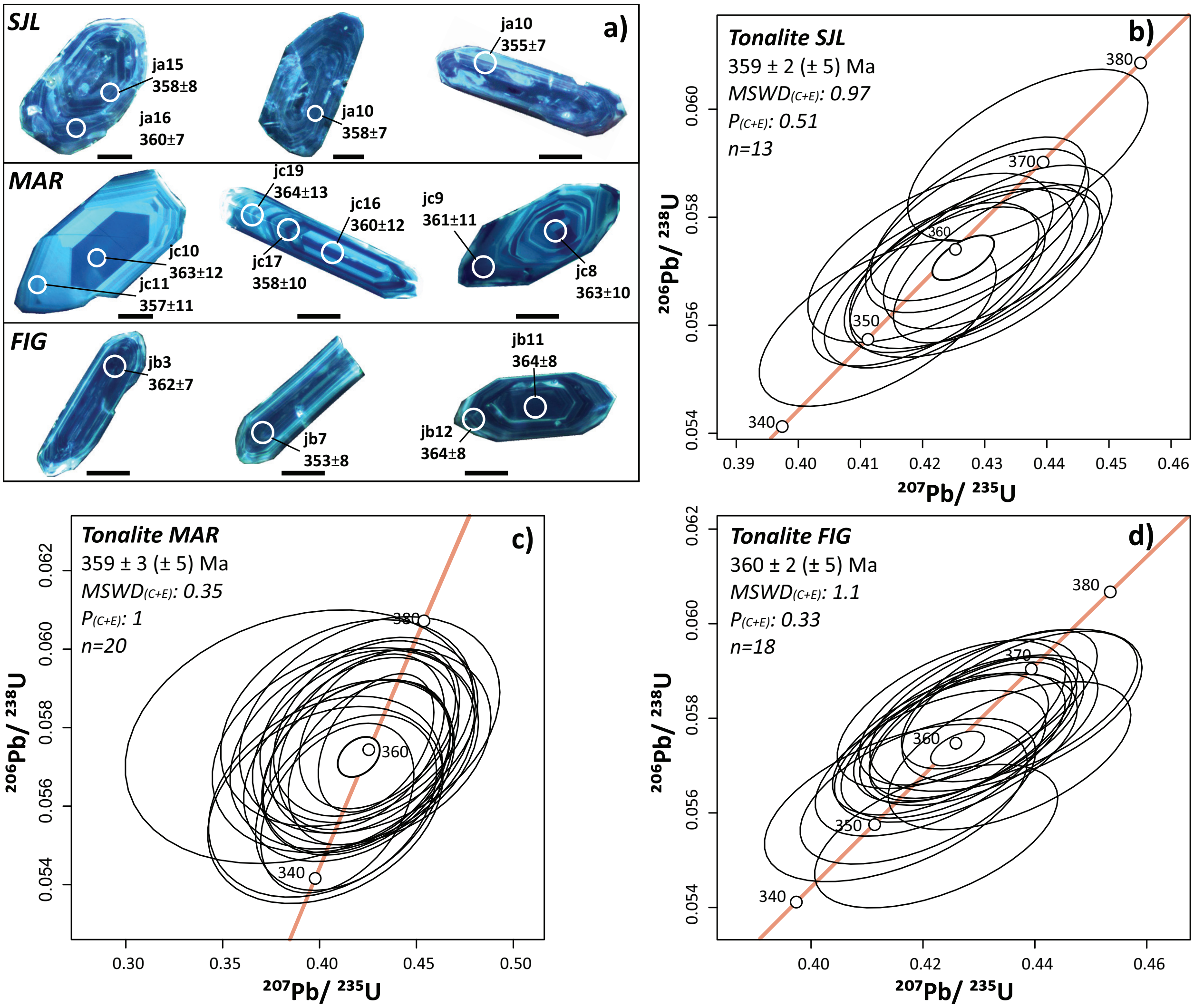

Fig.9. Results of in situ LA-ICP-MS U-Pb zircon dating. (a) Cathodoluminescence images of representative zircon grains. Scale bars represent a length pf 20 μm and the quoted ages in Ma are calculated from $^{206}Pb/^{238}U$ ratios. (b, c, d) Concordia plots for tonalites SJL, MAR and FIG, respectively. MSWD and *p*-value are for concordance and equivalence. The two uncertainties are reported as 2σ.

7.2 Short-lived Late Devonian-Early Carboniferous subduction in the French Massif Central?

New U-Pb zircon dating of tonalites from Limousin yield dates ranging between 365 and 354 Ma (uncertainties included, Fig. 9). Considering that zircons are euhedral, show typical oscillatory growth zoning of igneous zircons (Corfu, 2003; Fig. 9a) and have high Th/U ratios, we interpret these dates as igneous crystallization ages. The results obtained on three different plutons are equivalent within uncertainties, although they are variously deformed and recrystallized. No correlation between geographical position and age of emplacement can be assumed based on these data.

Published zircon ages (ID-TIMS and SHRIMP; Bernard-Griffiths *et al.*, 1985; Bertrand *et al.*, 2001; Pin and Paquette, 2002) on calc-alkaline plutons across the French Massif Central all converge to a magmatic event ranging from Late Devonian to Lowermost Carboniferous (379–355 Ma). Recalculation of all these published ages using IsoplotR (Vermeesch, 2018) to allow better comparison yielded very similar ages compared to published ones (Fig. 10), except for the strongly discordant data of Bernard-Griffiths *et al.* (1985). The latter made an assumption on a recent Pb Loss and obtained two anchored discordia built only with two data points each that yielded upper intercepts of 379 ± 19 Ma and 355 ± 2 Ma, interpreted as igneous crystallization ages. Different upper intercept ages were obtained after recalculation with IsoplotR without assuming recent lead loss: 358 ± 28 Ma and 353 ± 27 Ma. Considering the very large uncertainties and the fact that each discordia is based on two analytical points only, the ages published by Bernard-Griffiths *et al.* (1985) have been ignored in the following discussion. Bertrand *et al.* (2001) dated a diorite from the northwestern FMC (Fig. 1) by ID-TIMS and SHRIMP. Recalculated TIMS data are discordant but 5 zircon fractions out of 6 are perfectly aligned and yield a precise and statistically robust age of 359 ± 3 Ma (MSWD: 1.1). SHRIMP data are more dispersed (MSWD: 6) but equivalent within uncertainties (356 ± 7 Ma);

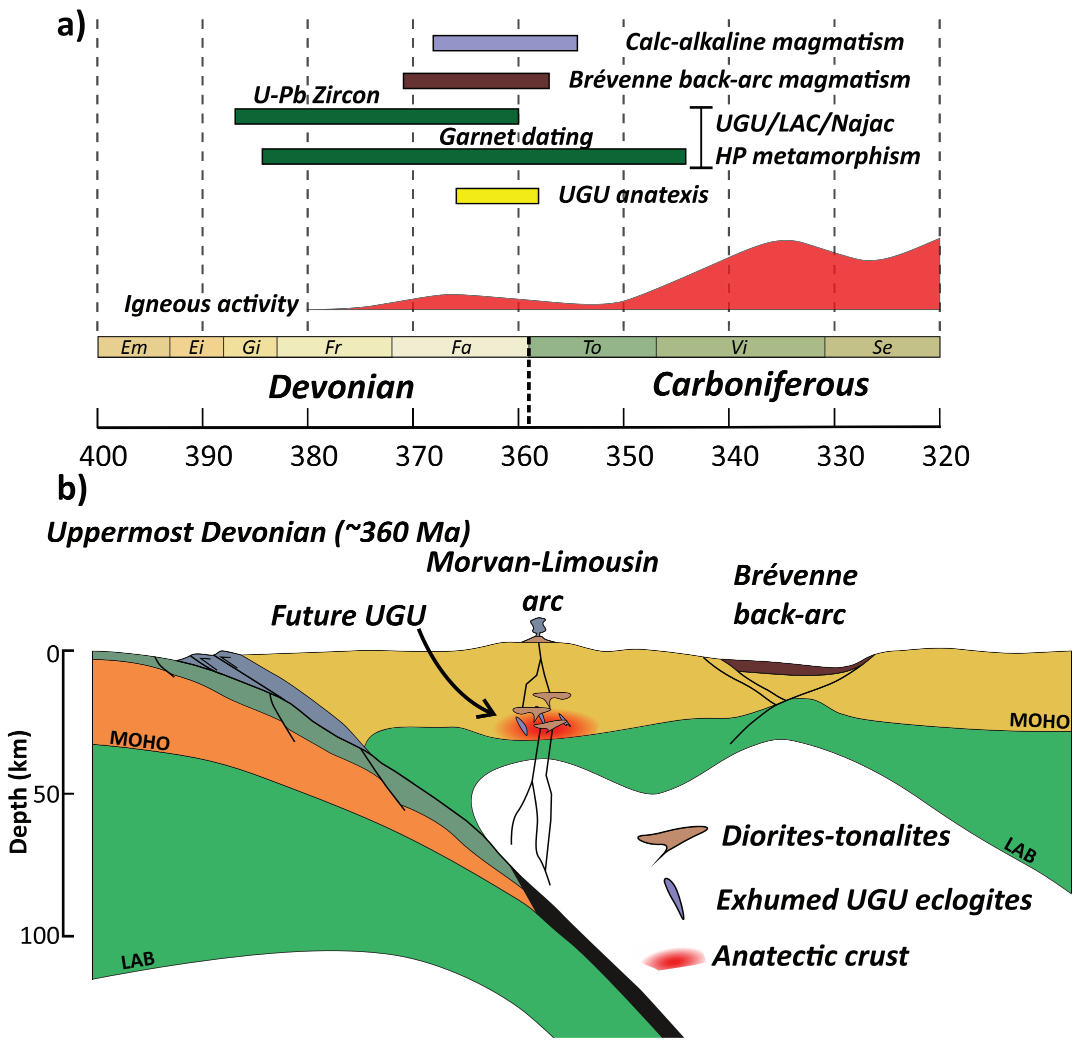

Fig.10. (a) Compilation of geochronological data obtained on petrological markers of Middle to Late Devonian subduction in the French Massif Central. U-Pb zircon on calc-alkaline magmatism are from Bertrand *et al.* (2001), Pin and Paquette (2002) and this study; age of Brévenne magmatism is from Pin and Paquette (1997), recent ages U-Pb zircon and Sm-Nd/Lu-Hf garnet ages obtained on eclogites are from Lotout *et al.* (2018, 2020) and de Hoÿm de Marien *et al.* (2023), UGU anatexis as dated by U-Th-Pb monazite chemical age is from Melleton *et al.* (2009) and the curve indicating the relative igneous activity is from Chopin *et al.* (2023) traced with data compiled by Vanderhaeghe *et al.* (2020). (b) Tentative snapshot of the geodynamic situation around 360 Ma for the Western French Massif Central, with emphasis on diorites-tonalites, eclogites and migmatitic rocks belonging to the UGU (see text for explanations).

TIMS results should thus be preferred. Combining these reviewed data, with our new results (365−354 Ma, uncertainties included) and the precise data from Pin and Paquette (2002) for the North and Eastern FMC diorites (368−359 Ma, uncertainties included), it can be suggested that active margin magmatism in the French Massif central is rather short lived (368−354 Ma). Interpretation of the apparent spread of ages into two successive events that are igneous crystallization around 380 Ma and metamorphic recrystallization around 360 Ma as done by Faure *et al.* (1997) and Bellot and Roig (2007) is therefore irrelevant. The new and the published precise U-Pb zircon ages should be interpreted as representing one single igneous event.

Similar expressions of Devono-Carboniferous calc-alkaline magmatism are also preserved as Fammenian lavas in Morvan (372−359; Pin and Paquette, 2002), in the Armorican massif (373 +6/−11 Ma; Cuney *et al.*, 1993) and the Variscan basement massifs of Western Alps (371−356 Ma; Bertrand *et al.*, 2000; Guillot *et al.*, 2012; Bergomi *et al.*, 2017). The ID-TIMS data of Cuney *et al.* (1993) could not be recalculated and checked because measured isotopic ratios were not published in a table. The discordia is traced with 3 points not perfectly aligned but with one falling on the concordia chord. Extension, sedimentation and magmatism related to a back-arc or arc setting locally forming incomplete and dismembered "ophiolites" (Figs. 1 and 10) or basaltic lava flows interbedded with Devonian sediments are also preserved in the Armorican massif (but the igneous products are not dated; Thieblemont and Cabanis, 1994; Ducassou *et al.*, 2011), the Eastern French Massif Central (371-357 Ma, uncertainties included; Sider et

Ohnenstetter, 1986; Ohnenstetter et Sider, 1988 ; Feybesse *et al.*, 1988 ; Pin et Paquette, 1997) and in the Vosges (372 ± 18 Ma; Skrzypek *et al.*, 2012).

Subduction activity in the French Massif central is moreover supported by markers of HP metamorphism (Faure *et al.*, 2009; Lardeaux *et al.*, 2014). The polycyclic view of the Variscan belt in FMC (Faure *et al.*, 1997) suggests that an early subduction event took place during a Late Silurian eo-variscan event. This is supported by dating of eclogites and related rocks yielding ages ranging from 430 to 390 Ma (Paquette *et al.*, 1995; Gebauer *et al.*, 1981; Ducrot *et al.*, 1983; Berger *et al.*, 2010). It is interesting to note that re-investigations of ID-TIMS zircon eo-variscan ages obtained by Paquette *et al.* (1995) on southern FMC eclogites with the in-situ LA-ICP-MS method (Paquette *et al.*, 2017) did not reproduced the eo-variscan Early Devonian ages. Moreover, recent geochronological investigations on FMC eclogites (including new investigations on previously dated occurrences) involving in situ U-Pb dating, Lu-Hf and Sm-Nd garnet dating (Lotout *et al.*, 2018, 2020; Benmammar, 2021; de Hoÿm de Marien *et al.*, 2023) all yielded Middle Devonian to Lowermost Carboniferous ages (Fig. 10). Eclogites from the Upper Allochthonous units (Upper Gneiss Unit, Leptyno-amphibolite complex and Najac HP-LT unit) have Givetian to Frasnian U-Pb zircon ages (387 to ∼360 Ma; Lotout *et al.*, 2018, 2022; Benmammar, 2021; De Hoÿm de Marien *et al.*, 2023). Finally, it must be emphasized that the sedimentary record in the South Armorican zone (including the presence of concordant 400 Ma inherited magmatic zircons) suggests that relief variations controlled by an active subduction started as early as Lower Devonian (Ducassou *et al.*, 2014).

Magmatic and metamorphic markers for subduction in the French Massif Central all range between 387 and 356 Ma (Fig. 10), suggesting at least *ca* 31 Myr of active subduction. This is short compared to orogenic systems characterized by long-lived subduction such as the Himalaya where at least 100 Myr of arc magmatism is recorded before collision (Burg and Bouilhol, 2019). This range is however comparable to the Western Alps, which is characterized by dispersed, short lived near-collision arc-like magmatism and 40 Myr long record of HP to UHP metamorphism (McCarthy *et al.*, 2020). The calc-alkaline lavas and plutons in French Massif Central do not underline a transcrustal magmatic arc formed during a protracted subduction event; they are dispersed and isolated, suggesting that magmatic inputs were low and sparse. According to the metamorphic and igneous records, it can be suggested that subduction in the French Massif Central was short lived and thus probably consumed a small oceanic basin and/or hyper-extended continental margin comparable to the Alpine example. It is worth to note that the presence of post-nappes Visean calc-alkaline magmatism is sometimes taken as an evidence for renewed subduction after the main Tournaisian collision event (Pin and Paquette, 2002). The same authors also suggest that this magmatism can form during the post-collisional period without active subduction, by remelting of the mantle previously enriched by the Devonian subduction.

7.3 Some implications for the Variscan evolution of the Western French Massif Central

Three key implications can be proposed for the Variscan evolution of Western French Massif Central on the basis of the study of dioritic and tonalitic plutons.

(i) These igneous bodies, emplaced in supra-subduction position, intruded UGU migmatites and retrogressed UGU eclogite at 19−30 km depth between 365 and 354 Ma in Limousin (Fig. 2). Therefore, UGU Limousin eclogites were subducted to about 60 km depth (Bellot and Roig, 2007), exhumed to crustal depths and accreted to the upper plate of the subduction system before 365 Ma while subduction was still ongoing (Fig. 10). A process of relamination of subducted crust has recently been proposed to explain the syn-subduction transfer from the lower plate to the upper plate of UGU eclogites (De Hoÿm de Marien *et al.*, 2023) but several other processes can be considered such as slab roll back (Faccenna and Brun, 2008) also supporting formation of the synchronous Brévenne back arc.

(ii) The migmatitic paragneisses hosting the Limousin eclogites were dated at 362 ± 4 Ma chemical U-Th-Pb monazite age; Melleton *et al.*, 2009). Anatexis occurred around 6−10 kbar and 700−800 °C (Bellot and Roig, 2007), *i.e.* grossly at the same conditions than diorites and tonalites crystallization (Fig. 4). Partial melting in the UGU paragneisses is thus concomitant with calc-alkaline plutonism, meaning that the metasediments were partially molten during the intrusion of tonalites and diorites (Fig. 10).

(iii) The calc-alkaline plutons are found in the UGU with two occurrences in the amphibolite facies Leyme unit Duguet *et al.*, 2007; see also Pfeiffer, 1986). The geological map of the St Féréole-Tulle massif (Fig. 2) and observations made by Pfeiffer (1986) clearly show that the shear zone separating LGU and UGU cuts across and deforms the igneous body while the latter is never found within LGU. These basic observations exclude the hypothesis of an early tectonic superposition of LGU and UGU during an Early Devonian eo-variscan event as proposed by Ledru *et al.* (1989), Faure *et al.* (2009) and Lardeaux (2014). Specifically, a Middle Devonian thrusting of eclogites-bearing UGU and LGU onto the low grade Parautochthonous unit in Limousin as proposed by Bellot and Roig (2007) is unlikely as Late Devonian calc-alkaline plutons are found in the upper allochthonous units only. Tectonic transport of UGU onto LGU and the Parautochtonous Unit consequently occurred after 365−354 Ma in the Western French Massif Central. According to the geochronological record of Variscan igneous activity in French Massif Central (Vanderhaeghe *et al.*, 2020; Chopin *et al.*, 2023; Fig. 10), the Late Devonian-Lowermost Carboniferous active margin magmatism was followed and partly coeval with crustal melting and emplacement of the single but huge granitic Guéret massif (359−351 Ma; Cartannaz *et al.*, 2007; Marcoux *et al.*, 2021) that is included within UGU (Gébelin *et al.*, 2006). The main phase of syn- to late-Variscan magmatism ignited in the Visean with both calc-alkaline and anatectic granites cutting across the mylonitic contacts between tectono-metamorphic units (Vanderhaeghe *et al.*, 2020). This igneous transition could probably mark the climax of Variscan collision, encompassing the stacking of units near the Tournaisian-Visean boundary.

8 Conclusions

Diorites and tonalites in Western Massif Central formed after partial melting of a hydrous mantle wedge and fractional crystallization in the crust controlled by segregation of plagioclase and amphibole. New U-Pb zircon ages support emplacement in the continental upper plate of an active subduction context around 365−354 Ma (uncertainties included). The plutons crystallized at middle to lower crustal depths (19−30 km) and intruded migmatites and exhumed retrogressed eclogites of the Upper Gneiss Unit but also amphibolite facies paragneiss of the so-called Leyme unit. Field data, published observations and geological maps indicate that calc-alkaline plutons emplaced before the final tectonic piling of the UGU onto LGU but after the exhumation of UGU eclogites.

The magmatic pulse represented by calc-alkaline plutons across the different Variscan massifs of France (371−356 Ma) is partly synchronous with Late Devonian-Early Carboniferous U-Pb zircon ages recently obtained for HP metamorphism in the French Massif Central (387−357 Ma). The available magmatic and metamorphic record suggest that the subduction was short lived (~30 Myr), suggesting either slow convergence rates and/or subduction of a small oceanic basin. Subduction and exhumation of UGU eclogites started before 365 Ma and active margin magmatism as represented by the diorites and tonalites argue that subduction was still ongoing between 365−354 Ma in the Western French Massif Central. All these results are against the existence of an eo-variscan event leading to an early superposition of LGU and UGU during Middle Devonian.

Further geochronological studies should focus on LGU eclogites that are not yet precisely dated and on the record of detrital zircons in clastic and volcaniclastic Devonian to Lowermost Carboniferous sediments. The latter may have preserved igneous and metamorphic Devonian detrital zircons witnessing former subduction-related units that are not currently cropping out.

Supplementary material

Table S1: Composition of amphibole and plagioclase plotted in Figure 4 and used for thermobarometry.
Table S2: Bulk rock major (wt%) and trace (?g/g) element contents of samples investigated in this study.
Table S3: Sr-Nd isotopic composition of representative samples, including host paragneisses.
Table S4: Results of LA-ICP-MS U-Pb dating.

The Supplementary Material is available at https://www.bsgf.fr/10.1051/bsgf/2024003/olm.

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