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Pressure-temperature conditions and significance of Upper Devonian eclogite and amphibolite facies metamorphisms in southern French Massif central

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Abstract – The southwestern French Massif central in western Rouergue displays an inverted metamorphic sequence with eclogite and amphibolite facies units forming the top of the nappe stack. They are often grouped into the leptyno-amphibolite complex included, in this area, at the base of the Upper Gneiss Unit. We sampled garnet micaschists and amphibolites to investigate their metamorphic history with isochemical phase diagrams, thermobarometry and U-Pb zircon dating. Our results demonstrate that two different tectono-metamorphic units can be distinguished. The Najac unit consists of biotite-poor phengite-garnet micaschists, a basic-ultrabasic intrusion containing retrogressed eclogites and phengite orthogneisses. Pressure and temperature estimates on micaschists with syn-kinematic garnets yield a prograde with garnet growth starting at 380 °C/6–7 kbar, peak pressure at 16 kbar for 570 °C, followed by retrogression in the greenschist facies. The age of high pressure metamorphism has been constrained in a recent publication between ca. 383 and 369 Ma. The Laguépie unit comprises garnet-free and garnet-bearing amphibolites with isolated lenses, veins or dykes of leucotonalitic gneiss. Thermobarometry and phase diagram calculation on a garnet amphibolite yield suprasolidus peak P-T conditions at 710 °C, 10 kbar followed by retrogression and deformation under greenschist and amphibolite facies conditions. New U-Pb analyses obtained on igneous zircon rims from a leucotonalitic gneiss yield an age of 363 ± 3 Ma, interpreted as the timing of zircon crystallization after incipient partial melting of the host amphibolite. The eclogitic Najac unit records the subduction of a continental margin during Upper Devonian. It is tentatively correlated to a Middle Allochthon, sandwiched between the Lower Gneiss Unit and the Upper Gneiss Unit. Such an intermediate unit is still poorly defined in the French Massif central but it can be a lateral equivalent of the Groix blueschists in the south Armorican massif. The Uppermost Devonian, amphibolite facies Laguépie unit correlates in terms of P-T-t evolution to the Upper Gneiss Unit in the Western French Massif central. This Late Devonian metamorphism is contemporaneous with active margin magmatism and confirms that the French Massif central belonged to the continental upper plate of an ocean-continent subduction system just before the stacking of Mississippian nappes.

Keywords: Variscan / Rouergue / HP metamorphism / partial melting

Résumé – Évolution pression-température et implications des métamorphismes amphibolitique et éclogitique du Dévonien supérieur dans le sud du Massif central français. Les unités tectono-métamorphiques du sud-ouest du Massif central français, dans l'ouest du Rouergue, sont structurées selon

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une séquence métamorphique inverse où les unités du faciès éclogite et amphibolite se situent au sommet de l'empilement des nappes. Ces unités régionales sont généralement incorporées dans le complexe leptyno-amphibolique, formant la base de l'Unité des Gneiss Supérieurs. Suite à une étude comparative de l'histoire métamorphique des unités de Najac et de Laguépie, deux unités tectono-metamorphiques peuvent etre distinguées. L'unité de Najac est composée de métapélites à phengite-grenat pauvres en biotite, d'une intrusion basique-ultrabasique renfermant des éclogites rétromorphosées et des orthogneiss à phengite. Le grenat commence sa croissance vers 380 °C/6–7 kbar, suivi d'un pic de pression à 16 kbar et 570 °C et enfin d'une rétromorphose dans les conditions du faciès des schistes verts. L'âge du métamorphisme de haute-pression a été contraint récemment entre 383 et 369 Ma. L'unité de Laguépie est formée par des amphibolites avec ou sans grenat renfermant des lentilles isolées, des veines ou dykes de gneiss leucotonalitique. Les conditions P-T ont été estimées sur une amphibolite à grenat à 710 °C et 10 kbar pour la fusion partielle suivie d'une rétromorphose et une déformation dans les conditions du faciès des amphibolites et des schistes verts. Les datations U-Pb sur des bordures de zircons d'une veine de gneiss leucotonalitique donnent un âge de 363 ± 3 Ma, interprété comme marquant la cristallisation magmatique des zircons après l'initiation de la fusion partielle de l'encaissant amphibolitique. L'unité de Najac a enregistré la subduction d'une marge continentale au Dévonien supérieur. Elle peut être corrélée à un Allochthone Intermédiaire, compris entre l'Unité des Gneiss Inférieurs et l'Unité des Gneiss Supérieurs. Une telle unité intermédiaire est encore mal définie dans le Massif central français mais elle peut être un équivalent latéral des schistes bleus de Groix dans le Massif Armoricain. L'unité amphibolitique du Dévonien Supérieur de Laguépie est reliée en termes d'évolution P-T-t à l'Unité des Gneiss Supérieurs dans le Massif Central français occidental. Ce métamorphisme du Dévonien tardif est contemporain d'un magmatisme de marge active et confirme que le sud du Massif Central français appartenait à la plaque continentale supérieure d'un système de subduction océan-continent juste avant l'empilement des nappes durant le Mississippien.

Mots clés : Varisque / Rouergue / métamorphisme HP / fusion partielle

1 Introduction

The evaluation of pressure-temperature-time paths in orogenic belts is fundamental to reconstruct the geotectonic evolution before, during and after the orogenesis. Specifically, pre-collisional eclogite and blueschist high-pressure (HP) units formed in the subducting slab (Ernst, 2001) and amphibolite to granulite high-temperature (HT) units belonging to the upper plate (Hydmann *et al.*, 2005) may contain crucial information on the dynamics of pre-orogenic subductions (Brown, 2006). The stacking of these subduction-related HP and HT metamorphic rocks onto greenschist facies units during exhumation and/or collision can lead to the formation of inverted metamorphic sequences (Peacock, 1987) where metamorphic conditions increase upward in the tectonic stack and where the boundary between units is marked by localized deformation and sharp contrasts in metamorphic conditions.

Pioneer studies on the Variscan French Massif central (FMC) showed that pre-Visean metamorphic units have a complex tectonic distribution (see Burg *et al.*, 1984, 1989; Ledru *et al.*, 1989, 1994; Santallier *et al.*, 1994; Faure *et al.*, 2005, 2009; Lardeaux, 2014; Lardeaux *et al.*, 2014), with greenschist facies units forming the lowermost and uppermost parts of the tectonic pile (the para-autochthon and the so-called epizonal units, respectively). Amphibolite facies units locally preserving relic of eclogites and HP granulites rocks are classically grouped into the Lower Gneiss Unit (LGU) and the Upper Gneiss Unit (UGU) in the French Massif central (see Bellot and Roig, 2007) but investigations on the neighboring Armorican massif (Bosse *et al.*, 2000, 2005; Ballèvre *et al.*, 2009; Pitra *et al.*, 2010; Ballèvre *et al.*, 2014) pointed out the existence of a Late Devonian ophiolitic and eclogite/blueschist-bearing Middle Allochthon sandwiched between the upper and lower units. Berger *et al.* (2010a, 2010b) proposed to introduce a Middle Allochthon in the FMC located between LGU and UGU and composed of HP to UHP eclogites with host orthogneiss and micaschists but also of ophiolites marked by a post-oceanic equilibration in the granulite facies (Santallier *et al.*, 1994; Berger *et al.*, 2010b). This subdivision, still immature for the French Massif central, group together rocks with contrasted metamorphic evolutions. More detailed metamorphic petrology studies are thus needed to propose a better scheme of subdivision and coherent geodynamic interpretations. Furthermore, this metamorphic organization is not integrated in the most recent compilations on the metamorphic evolution of the French Massif central (Faure *et al.*, 2009; Lardeaux, 2014) in which most HP metamorphic rocks are included within the Upper Gneiss Unit encompassing the enigmatic leptyno-amphibolite complex (Santallier *et al.*, 1988). The latter is defined as a bimodal association of felsic and mafic gneisses frequently containing relics of eclogite and granulite facies rocks and often located at the base of UGU, sometimes in LGU. These apparent conflicting views are, on the one hand due to the poor quality of exposures in the French Massif central, and on the other hand to the lack of detailed quantitative metamorphic studies coupled to petrochronological investigations that are to propose robust pressure-temperature-time (P-T-t) paths.

Recent dating performed on eclogites from Southern Massif central yielded Upper Devonian to Lowermost Carboniferous ages (Lotout *et al.*, 2018, 2020) while the HP metamorphism and the closure of oceanic domains in the French Massif central are classically considered to be around 410–390 Ma (Eo-varican cycle or D0 event of Faure *et al.*, 2009; see also Lardeaux, 2014). Ages of HP metamorphism published between 1980 and 2000 have to be re-evaluated

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(Paquette *et al.*, 2017) and, more generally, petrochronological data on metamorphic units are required to better constrain the Devonian evolution of the French Massif central. These data are crucial to determine if the West European Variscan belt is polycylic and marked by two phases of convergence and ocean closure (Faure *et al.*, 2005, 2008, 2009; Lardeaux, 2014) or monocyclic with a single event of continental collision (Ballèvre *et al.*, 2009) or somewhere between the two endmembers models.

This paper addresses the question of the subdivision of amphibolite and eclogite facies metamorphic units and their geological meaning in southern French Massif central near Najac in Western Rouergue (Burg *et al.*, 1984, 1989). According to most authors, the metamorphic units in this area are thought to belong to the leptyno-amphibolite complex and are often integrated into the UGU (Lardeaux, 2014; Lotout *et al.*, 2018). Our study shows that their constitutive rocks display contrasted P-T-t-d histories. Therefore, we provide new P-T estimations on phengite-garnet micaschists from Najac and on migmatitic amphibolites from Laguépie. These results are coupled to U-Pb zircon dating in the latter unit and interpreted considering the new and robust multi-method ages provided by Lotout *et al.* (2018) on an eclogite from Najac.

2 Geological setting

The Variscan French Massif central consists of several tectono-metamorphic units that were stacked before the Visean (see Faure *et al.*, 2009; Lardeaux, 2014). Despite the poor quality of their exposures, the metamorphic units are well defined on geological maps and in the literature in Limousin, Haut-Allier and Rouergue domains (Dubuisson *et al.*, 1988; Ledru *et al.*, 1989; Ledru *et al.*, 1994; Burg *et al.*, 1989a). This stack is characterized by an apparent inverse metamorphic gradient, with amphibolite facies and eclogite facies units (Lower Gneiss and Upper Gneiss Units; LGU and UGU, respectively) commonly lying above greenschist units (Para-Autochthon; see Burg *et al.*, 1984; Lardeaux, 2014). At the scale of the French Massif central, the pre-Carboniferous tectono-metamorphic evolution is subdivided into three phases following (Faure *et al.*, 2005, 2008, 2009, 2017): D0 represent the Late Silurian/Early Devonian (420–400 Ma) HP metamorphic phase; D1 relates to amphibolite facies migmatitization in LGU and UGU associated with a top-to-the-southeast kinematics, it occurred during Middle and Upper Devonian (385–375 Ma); D2 (360–350 Ma) is marked by top-to-the-northwest kinematics under amphibolite facies conditions. However, recent petrochronological investigations performed by Lotout *et al.* (2018, 2020) yielded Upper Devonian to Early Carboniferous ages for HP metamorphism in southern French Massif central (Najac and Lévézou). These new findings suggest that the D1 and D2 phases as defined by Faure *et al.* (2009) are also contemporaneous with formation and exhumation of eclogites in southern French Massif central.

Outcrops of the Viaur and Aveyron valleys near Najac and Laguépie were described in details by Collomb (1970), Bodinier and Burg (1981) and Burg *et al.* (1984). The para-autochthon consists of greenschist facies metapelites (chlorite-muscovite ± biotite bearing) with rare intercalation of felsic, often meta-volcanic, orthogneiss (Fig. 1). The Lower Gneiss Unit is separated from the para-autochthon by a low angle mylonitic shear zone. It is made of orthogneiss representing former felsic plutons with rare lenses of amphibolite facies biotite-muscovite ± garnet metapelites. The contact with the Najac-Carmaux unit is not well exposed but it is interpreted as a thrust contact considering that the latter contains eclogite facies rocks that were not found in the Lower Gneiss Unit (see Burg *et al.*, 1984). The Najac-Carmaux klippe as defined by Burg *et al.* (1984) consists of an association of phengite-rich micaschists (often garnet-bearing, with minor amounts of biotite and locally accompanied by chloritoid and staurolite; Delor *et al.*, 1987), phengite-bearing porphyroclastic orthogneisses and basic-ultrabasic complexes known as the Najac and Laguépie massifs (Delor *et al.*, 1986; Bodinier *et al.*, 1986; Lotout *et al.*, 2018). Bodinier and Burg (1981) and Bodinier *et al.* (1986) interpret the eclogitic layered intrusion south of Najac as a former laccolith that intruded the precursor of micaschists and orthogneiss prior to high-pressure metamorphism. We observed small (max 10 cm width) xenolithic fragments of phengite orthogneiss included into eclogite facies metagabbros south of Najac, close to Mergieux. This supports the conclusion considering the Najac basic-ultrabasic massif as a former intrusion within the orthogneiss. Bodinier and Burg (1981) and Bodinier *et al.* (1986) also noted that the Najac eclogitic basic-ultrabasic massif and the Laguépie amphibolite recorded distinct metamorphic histories but so far, no metamorphic studies have been performed on the amphibolites.

Hereafter, the phengite micaschists, the phengite orthogneiss and the eclogitized basic-ultrabasic intrusion cropping out south of Najac will be grouped into the Najac unit because they display a similar metamorphic evolution (Fig. 1; Burg *et al.*, 1984; this study). The amphibolite massif west of Laguépie, devoid of HP mineral assemblage and showing evidence for incipient partial melting will compose the Laguépie unit. Both are either included within (1) the Najac-Carmaux klippe/unit by Burg *et al.* (1984) and tentatively correlated to the Groix and Bois de Céné units in the Armorican massif (Delor *et al.*, 1986), or (2) following Lardeaux (2014) and Lotout *et al.* (2018) they are part of the Leptyno-Amphibolite Complex (LAC) at the base of the Upper Gneiss Unit (Santallier *et al.*, 1994; Lardeaux, 2014). The Laguépie unit is bounded by normal and strike-slip faults, its position within or relative to the Najac unit remains unclear but the normal faults suggest it was structurally located above the Najac unit.

Metamorphic foliations in the Viaur and Aveyron valleys are dipping to the east (20–70° dip) except in the eastern part of the map (Fig. 1). They are affected by small scale overturned N-S folds with an axial plane facing west. Stretching lineations are generally trending N350 with low plunges (<10°). Asymmetric criterion for sense of shear are well expressed along the mylonitic band separating the para-autochthon and the Lower Gneiss Unit is top-to-the-north (D2 phase of Faure *et al.*, 2009). The eclogitic orthogneisses and micaschists of the Najac unit also carry a N280–300-trending stretching lineation with top-to-the-southeast kinematics (deduced from C/S structures and asymmetric feldspar porphyroclasts in orthogneisses).

Northeast of Najac, the whole metamorphic massif is intruded by the Carboniferous Villefranche de Rouergue

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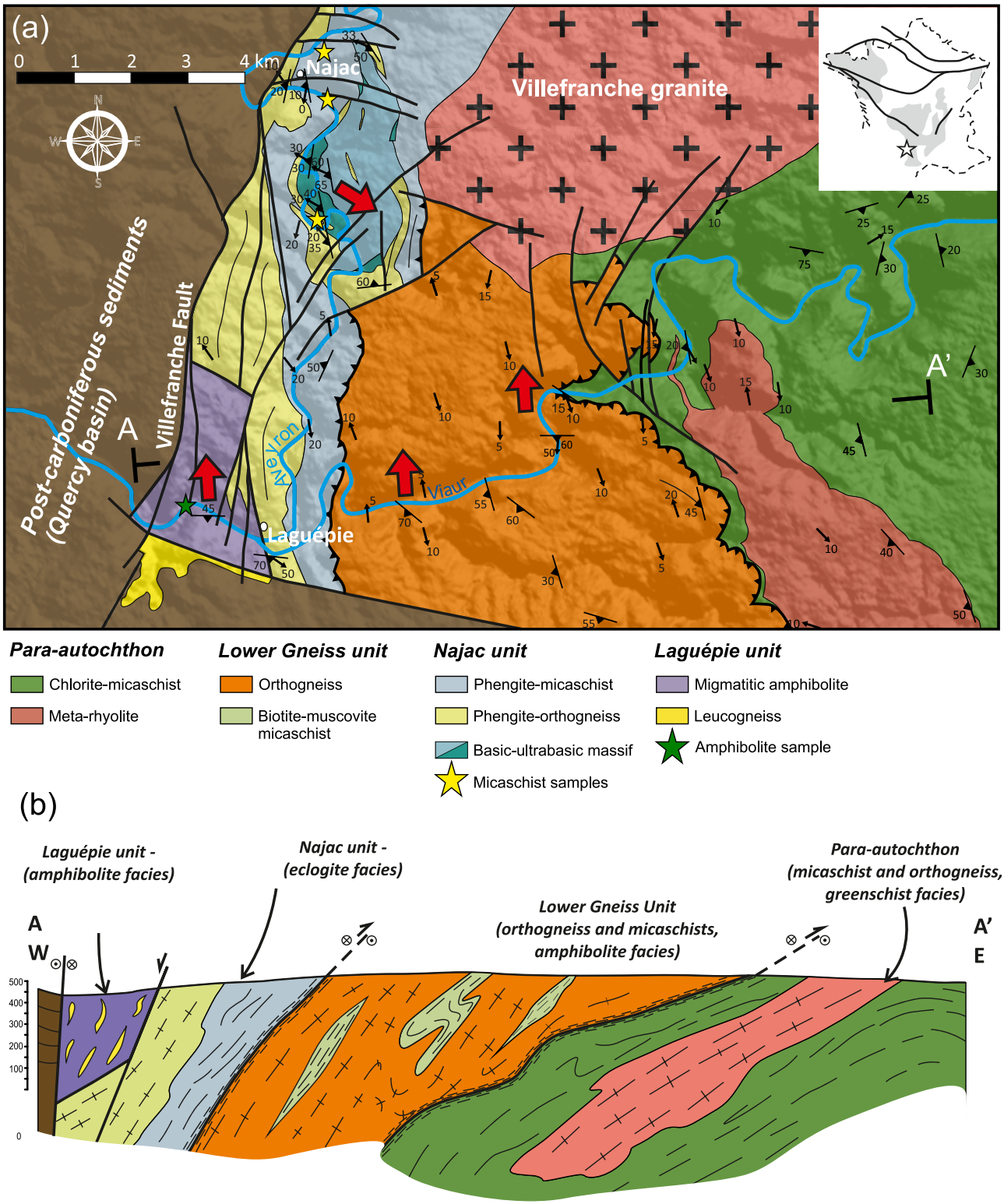


Fig. 1. Geological setting of the Najac and Laguépie units: (a) geological map modified after Burg *et al.* (1989a). The red arrows indicate the kinematics deduced from C'/C/S structures; (b) interpretative W-E cross section with indication of lithology and metamorphic facies for each unit.

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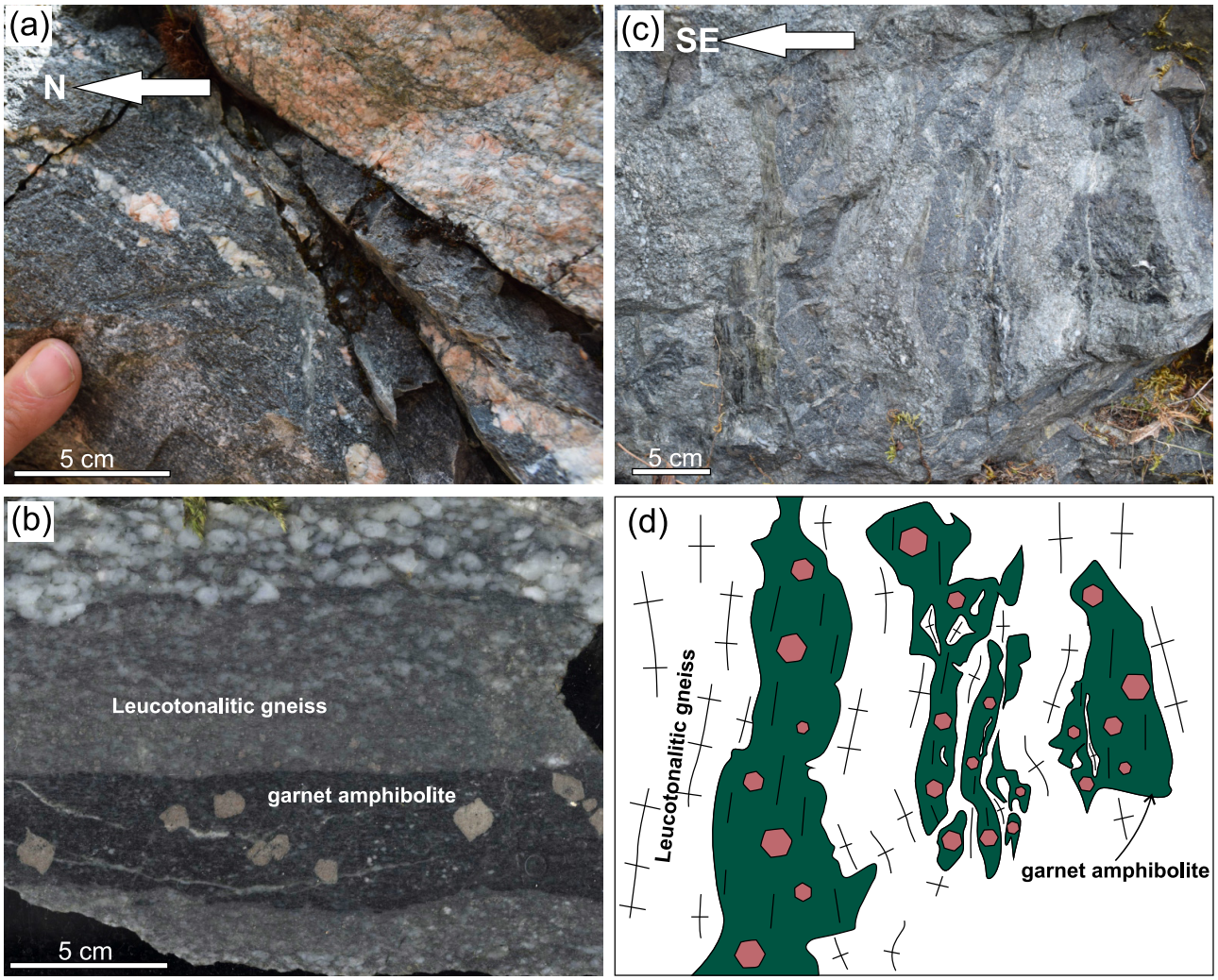


Fig. 2. Main macroscopic features of the Laguépie unit: (a) field photographs of leucotonalitic lenses into garnet-free amphibolite (AJAH9; 1,9558°E, 44,1485°N); (b) polished section of a garnet amphibolite within a quartz-feldspar-chlorite leucogneiss (AJAH8; 1,9602°E; 44,1468°N); (c) outcrop image of the complex relationship between garnet amphibolite lenses and leucotonalitic veins (1,9602°E; 44,1468°N). Note the crosscutting relationships and the cauliflower-like structure at the leucogneiss/amphibolite contact; (d) sketch of the outcrop image shown in (c).

granodioritic pluton (Burg *et al.*, 1989b). It is bounded by the Villefranche fault to the west, which separates the metamorphic units from the large Permian to Mesozoic Quercy basin and it is unconformably overlain by Permian and Cenozoic deposits to the south.

3 Samples description and mineral chemistry

In order to compare the metamorphic evolution of Najac and Laguépie units, we focus our study on several samples of phengite-garnet micaschists surrounding the basic-ultrabasic complex and on amphibolites and associated leucotonalitic gneisses at Laguépie. The orthogneisses around Najac are deformed but their mineral assemblage did not fully reequilibrate during metamorphism (except for some late kinematic Si-rich white micas); these samples were consequently disregarded in this study.

3.1 The Laguépie unit

Samples were collected in an abandoned quarry along the Aveyron valley, west of Saint Martin de Laguépie. The amphibolites are homogeneous amphibole-plagioclase rocks alternating with discontinuous leucotonalitic orthogneisses forming isolated lenses (several millimetres to 20 cm in width) (Fig. 2a). In the eastern side of the quarry, one outcrop exposes discontinuous and rounded levels of melanocratic garnet amphibolite wrapped into large veins of leucogneiss. Contacts between both lithologies can be either sharp or lobed, occasionally resembling cauliflower structures in migmatites (Burg and Vanderhaeghe, 1993) (Fig. 2b–d). The leucogneiss locally cuts across the melanocratic levels and it can also forms deformed lenses within the amphibolites (Fig. 2c). These observations suggest that the unconnected felsic lenses were formed *in situ* in the amphibolites while large felsic veins or dykes containing lobed fragments of garnet amphibolites are the

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results of melt drainage and segregation. Accordingly, these field observations suggest that the precursor leucotonalitic magma formed after incipient partial melting of the amphibolite.

The most common lithology of the Laguépie unit is an amphibolite made of amphibole, plagioclase and quartz. Plagioclase is commonly cloudy due to advanced sericitization and frequently contains epidote neoblasts (Fig. 3a, b). Amphibole porphyroclasts are pleiochroic from blue-green to brownish and small needles of light colored green amphibole are found at the contact with plagioclase (Fig. 3a, b). Quartz is common, but never exceed 10 vol.%. The texture is porphyroclastic with oblique localized cataclastic shear bands consisting of crushed chlorite, actinolite and albite grains (Fig. 3a). Secondary calcite and pyrite-chlorite veins cut across plagioclase and amphibole with aligned euhedral pyrite crystals is also commonly observed.

Garnet amphibolite levels consist of a mineral assemblage of plagioclase-amphibole-garnet ± titanite ± quartz ± k-feldspar with large (up to 3 cm width), subrounded, pre-kinematic porphyroclastic garnet rich in quartz inclusions (Fig. 3c). Elongated porphyroclasts of amphibole and plagioclase alternating with rare quartz ribbons define a foliation wrapping the garnet (Fig. 3c). Titanite, apatite, zircon and pyrite are the most common accessory phases. Retrogression is evidenced by the cloudy aspect of plagioclase, the development of light-colored amphibole needles rimming large brownish porphyroclastic grains, growth of chlorite within fractures cutting across garnet and thin cataclastic shear bands made of chlorite, albite and epidote.

Leucotonalitic gneisses consist of an assemblage of quartz-albite-chloritized biotite ± K-feldspar ± garnet and display an augen texture (Fig. 3d) with large porphyroclastic feldspars. Garnet are rounded and small (<1 cm) compared to those observed the amphibolite layer. Their modal abundance usually decreases from the contact with the amphibolite to the core of the leucocratic orthogneiss vein. Chlorite, probably replacing a former biotite, forms elongated domains aligned along the foliation or C−C' shear bands indicating a top-to-the-north sense of shear.

One amphibolite sample (LAG3b) and one garnet-amphibolite sample (AJAH08), collected close to a leucotonalitic vein, were analysed for their mineral composition. The garnet-free amphibolite LAG3b is made of oligoclase (X_{An}: 0.13–0.17) with albitic rims (X_{An}: down to 0.07). Amphibole appears as large brown-green crystals characterized by low-Ti (0.94–1.25 wt% TiO_2) magnesiohornblende (Mg#: 54–55, Si: 6.72–6.78 a.p.f.u., Fig. 4a) core surrounding Si-rich and Ti-poor thin rim (6.84–7.09 Si a.p.f.u.; 0.33–0.69 wt % TiO_2 Fig. 4a). Unaltered plagioclase grains in the garnet amphibolite AJAH08 are more calcic (X_{An}: 0.30–0.32) while altered grains are albitic (X_{An}: 0.07–0.10). The amphibole is also a low Ti (0.73–1.05 wt% TiO_2) tschermakite (Si 6.24–6.41 a.p.f.u., Mg#: 51–54, Fig. 4a), with thin magnesiohornblende rims (Si up to 6.78 a.p.f.u., Fig. 5a). A discrete chemical zoning was evidenced in a large garnet porphyroclast varying from Alm_{55}-$Spss_4Prp_{12}Grs_{29}$ to $Alm_{58}Spss_2Prp_{14}Grs_{25}$ (Fig. 4b). Amphibole inclusions into garnet show the same tschermakitic composition as the ones forming the matrix.

3.2 Micaschists of the Najac unit

Micaschists of the Najac units are homogeneous light gray-blue rocks displaying a penetrative planar fabric with poorly defined mineral lineation. Granoblastic and elongated quartz and plagioclase form millimeter-scale layers alternating with phengite-rich bands (Fig. 3a). Biotite is present in low volumetric proportions but is preferentially concentrated at the contact between garnet and white mica (Fig. 3e). In most samples, garnet forms minute (< 300 μm in diameter) subhedral grains within the phengitic layers and show pressure shadows filled with biotite and phengite (Fig. 3e). Garnet is rich in quartz and rutile inclusions sometimes delineating a foliation that can be parallel or oblique to the main planar fabric. NJC08 contains centimetric syn-kinematic fibrous snowball garnet porphyroblasts with quartz inclusions and enclosed into phengite stacks (Fig. 3f), substantiating that garnet growth occurred during deformation. Accessory minerals consist of rutile (partly transformed into ilmenite), apatite and zircon.

Garnet chemical zoning is obvious in sample NJC11 where compositions range from $Alm_{41}Spss_{27}Prp_2Grs_{30}$ in the core to $Alm_{66}Spss_4Prp_5Grs_{25}$ in the rim (Fig. 5b), while its Fe# decreases from core to rim (96 to 92). Garnet in NJC12a shows a more homogenous composition with core at $Alm_{68}Spss_4Prp_6Grs_{22}$ and a rim at $Alm_{72.5}Spss_{1.5}Prp_7Grs_{19}$ at nearly constant Fe# (91–93). White micas are phengitic with Si (per formula unit, on the basis of 11 oxygens) ranging from 3.30 to 3.40 in NJC08, 3.18 to 3.36 in NJC12a and 3.17–3.35 in NJC11; and Fe+Mg (a.p.f.u.) between 0.20 and 0.45. Phengite crystals with the lowest Si content are found close to biotite and in the rim of large grains. Biotite has generally low Ti (0.09–0.11 a.p.f.u) with Mg# varying from 0.45 and 0.50 and low Si (2.70–2.80 a.p.f.u.) in the three analyzed samples. Plagioclase is an oligoclase with X_{An} comprised between 0.14–0.16 in NJC11 and NJC12a.

4 Pressure-temperature estimations

4.1 Amphibolites from the Laguépie unit

Garnet amphibolite AJAH08 collected in the outcrop shown in Figure 2c, d was selected for detailed thermobarometric investigations because it contains garnet, a good tracer to recover P-T conditions. The sample's bulk composition has been calculated using modal proportions (estimated by pixel counting on thin section images) and core composition of unaltered rock forming minerals (garnet, amphibole, plagioclase, titanite and quartz). Two different estimations were made and the results were differing by less than 5% (relative) on the different oxides proportions. Phase diagrams were calculated with Perple_X (Connolly, 2009) in the system Na_2O-CaO-FeO-MnO-MgO-TiO_2-Al_2O_3-SiO_2-H_2O. Water content has been estimated on the basis of the modal proportion of amphiboles, considering they contain approximately 2 wt% H_2O. The calculation uses the thermodynamic database of Holland and Powell (2011, update ds62) and solid solution models adapted for amphibolite to granulite facies mafic rocks (see Green *et al.*, 2016). Ferric iron was not considered because its content in minerals (estimated by stoichiometry) is very low and no oxides containing ferric iron

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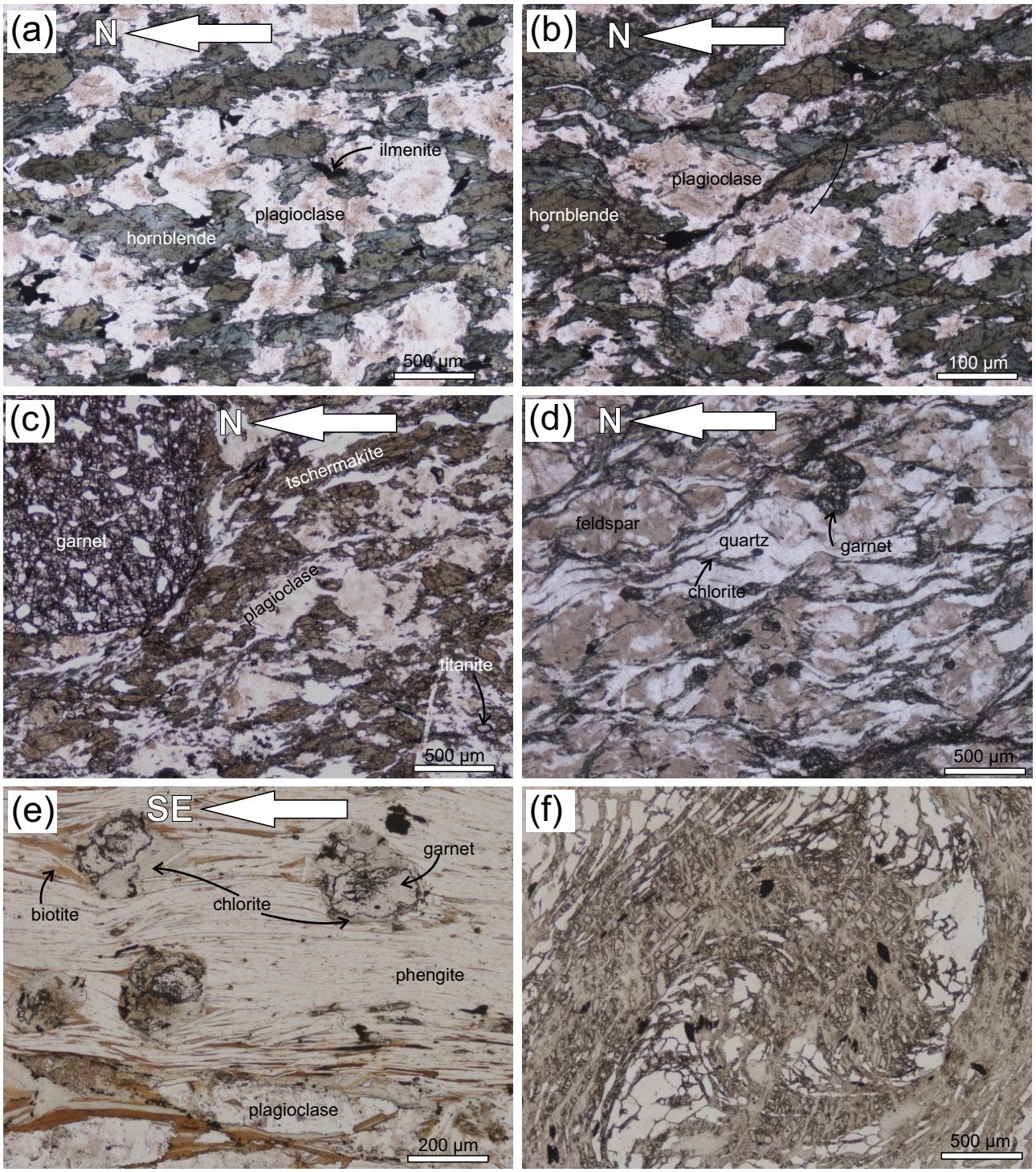


Fig. 3. Photomicrographs of representative samples from the Najac and Laguépie units. Laguépie samples: (a) amphibole-plagioclase-ilmenite amphibolite LAG3b representing the dominant lithology of the Laguépie amphibolite (1,9558°E, 44,1485°N); (b) chlorite-epidote-albite shear band oblique to the main foliation and indicating a top to the north sense of shear (sample LAG3b); (c) garnet amphibolite AJAH08 with foliation molded around the garnet porphyroclast; (d) leucogneiss from sample AJAH08 showing a porphyroclastic augen texture. Note the C/S structure marked by chlorite formed after soldification and cooling of the leucotonalitic orthogneiss; (e) Representative texture of the Najac unit garnet-phengite micaschists (sample NJC12a; 1.9754°E, 44,2159°N). Note the pressure shadows filled with biotite and phengite around garnet indicating that the high pressure assemblage is syn-kinematic. Greenish chlorite partly replaces garnet and biotite in all samples; (f) large porphyroclastic snowball and skeletal garnet from sample NJC11 (1,9693°E; 44,2196°N), again showing that the high-pressure mineral assemblage developed during deformation.

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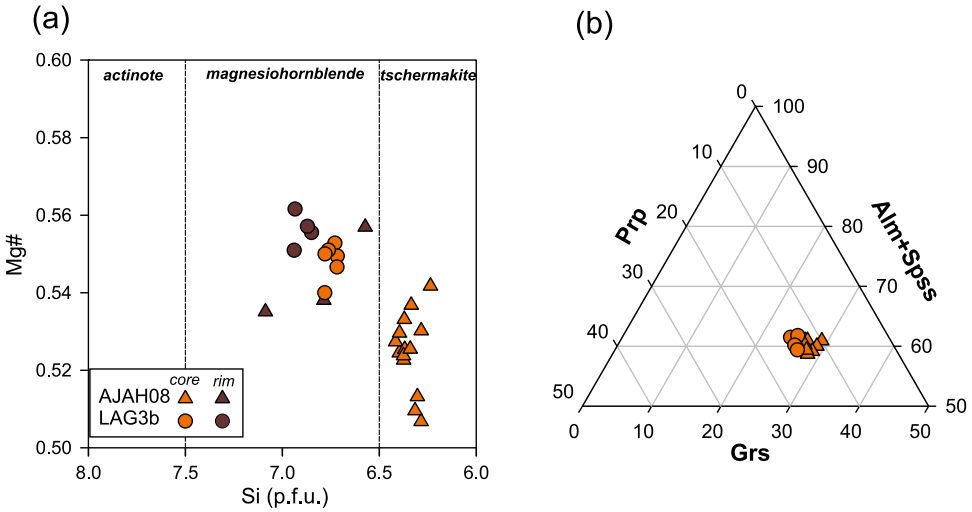


Fig. 4. Minerals compositions in the amphibolites from the Laguépie unit: (a) amphibole composition in the classification diagram by Leake *et al.* (1997); (b) garnet compositions in AJAH08.

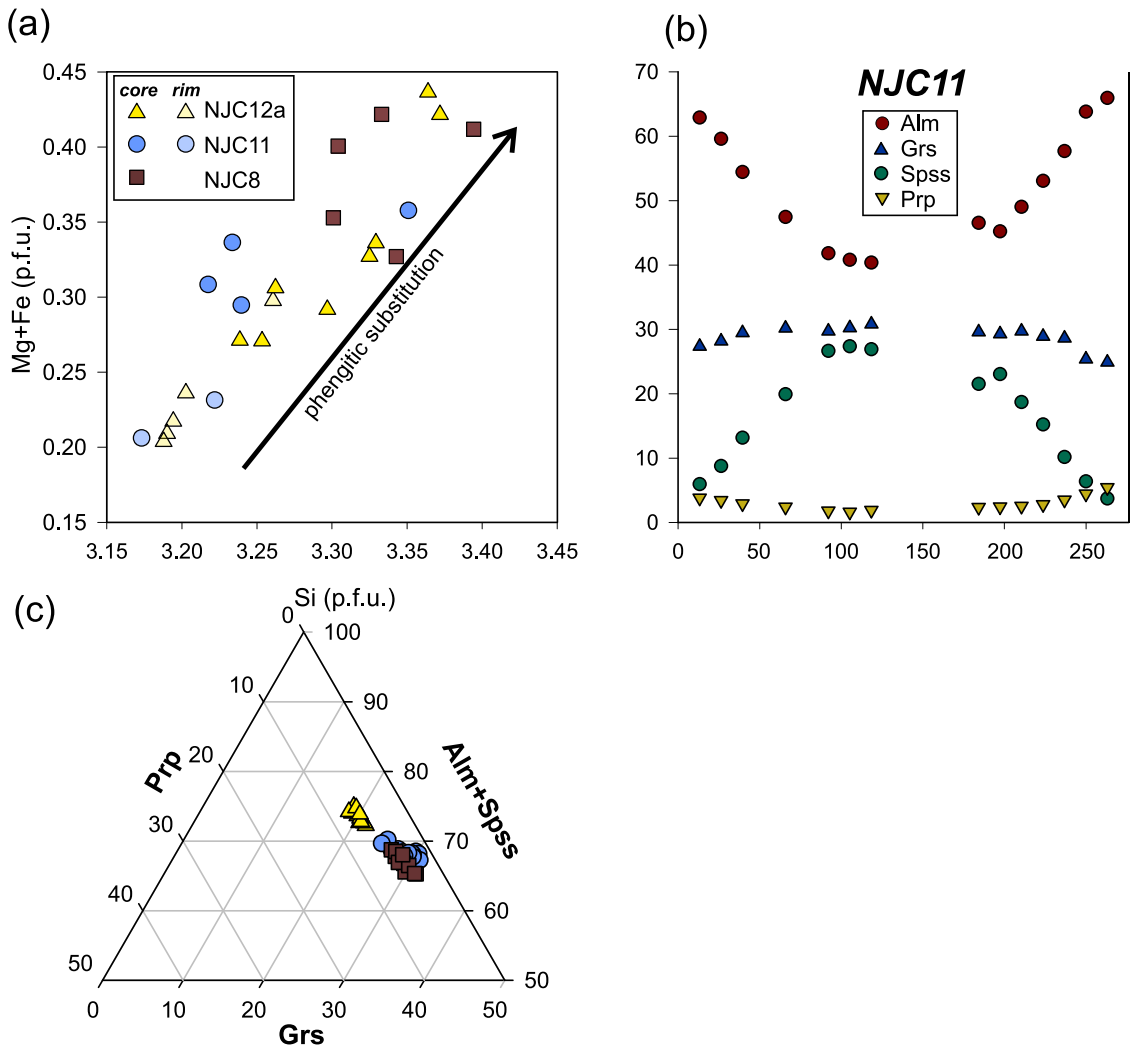


Fig. 5. Minerals composition in the micaschists from the Najac unit: (a) Si *versus* Fe+Mg diagram for white micas showing the phengitic substitution; (b) garnet zoning profile in NJC11; (c) garnet composition for three representative samples (NJC8, NJC11 and NJC12a).

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Na_2O	MgO	Al_2O_3	SiO_2	CaO	TiO_2	FeO	MnO	H_2O
3.76	4.30	17.69	54.22	8.90	1.12	8.36	0.18	0.84

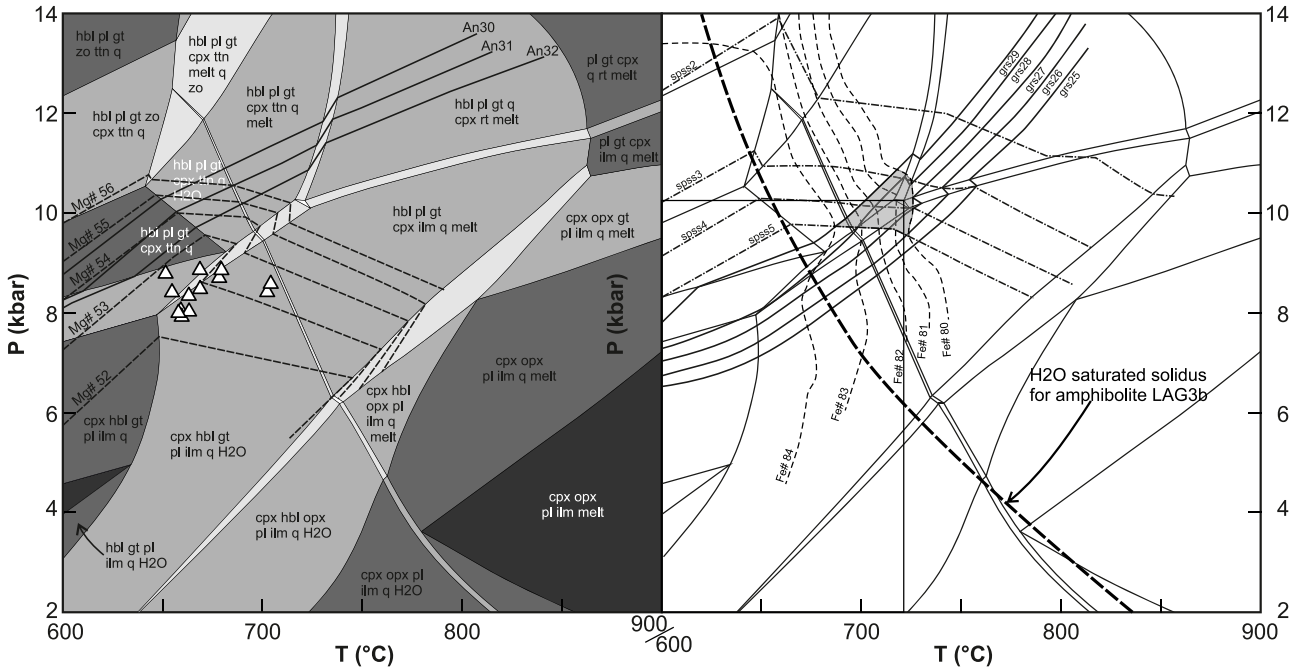


Fig. 6. Isochemical phase diagram built for the bulk composition of the garnet amphibolite in sample AJAH08 of the Laguépie unit: (a) phase diagram also showing the isopleth for XAn in plagioclase and Mg# of amphibole (corresponding to composition determined with the electron microprobe). The small triangles represent the results of garnet-amphibole plagioclase-quartz thermobarometry; (b) Fe#, grossular and spessartine isopleths in garnet corresponding to composition measured by electron microprobe. Also shown is the vapor-saturated solidus for the amphibolite LAG3b.

were observed. The mineral assemblage observed in the garnet amphibolite AJAH08 (plagioclase-amphibole-garnet ± titanite ± quartz) cannot be reproduced in the isochemical phase diagram because the calculation systematically predicts the presence of small amounts (<4 vol.%) of clinopyroxene in fields where amphibole, garnet and plagioclase are stable. This can be a consequence of retrograde metamorphism that has transformed clinopyroxene into amphibole or inaccuracies of the calculated model. Garnet, plagioclase, amphibole, quartz and titanite without orthopyroxene, epidote, ilmenite or rutile coexist between 8 and 14 kbar and 600 and 740 °C (Fig. 6). X_{An} and Mg# isopleths for plagioclase and amphibole, respectively, cross between 8 and 10 kbar at 600–700 °C in fields where low amounts of clinopyroxene are predicted (<4 vol.%) (Fig. 6). The overlapping zone of various garnet isopleths (Fe#, grossular, spessartine contents) yields P-T conditions of 710 ± 15 °C and 10 ± 1 kbar (Fig. 6). As the garnet cores display higher Fe# (up to 84) and grossular content (up to 29 mol%) compared to the rim (Fe# down to 80 and 26 grossular mol%), the slight zoning observed in garnet could trace a small increase in temperature from 690 to 730 °C at nearly constant pressure (Fig. 6). This P-T domain locates close to the ilmenite-titanite and ilmenite-rutile phase transitions but also clinopyroxene (<4 vol.%) and melt present (<2 vol.%) fields (Fig. 6); consequently, it lies above the vapor-present solidus calculated for the amphibole-plagioclase-ilmenite amphibolite LAG3b. It is worth to note that the calculated phase diagram closely reproduces the observed modal proportion of garnet (7 vol.%) around 700 °C and 10 kbar.

Application of garnet-amphibole-plagioclase-quartz barometry (Kohn and Spear, 1990) with hornblende-plagioclase thermometry (Holland and Blundy, 1994) yields 640–700 °C, 8–9 kbar. LAG3b plagioclase amphibole pairs yield similar albeit slightly lower temperature conditions of 640–680 °C at a fixed pressure of 9 kbar. The magnesiohornblende and albitic rims in AJAH08 equilibrated at lower temperature (480–560 °C).

4.2 Micaschists from the Najac unit

Sample NJC11 and NJC12a were selected for isochemical phase diagram calculations. They were calculated in the system Na_2O-K_2O-FeO-MnO-MgO-TiO_2-Al_2O_3-SiO_2-H_2O using the Holland and Powell (1998) thermodynamic database revised in 2002, with solid solution models from Tajcmanova *et al.* (2009) for biotite, Newton *et al.* (1980) for plagioclase, Holland and Powell (1998) for garnet, Coggon and Holland (2002) for white mica, Holland and Powell (1998) for chlorite. We ignored ferric iron because calculated Fe^{3+} in silicates (by charge balance or stoichiometry) is systematically very low and Fe^{3+} bearing oxides are absent. Before drawing the isochemical section using the bulk rock composition measured by XRF spectrometry (CAF service, Stellenbosch University, South Africa), we tested different bulk water content using T-X sections because calculated pyrope content in garnet is

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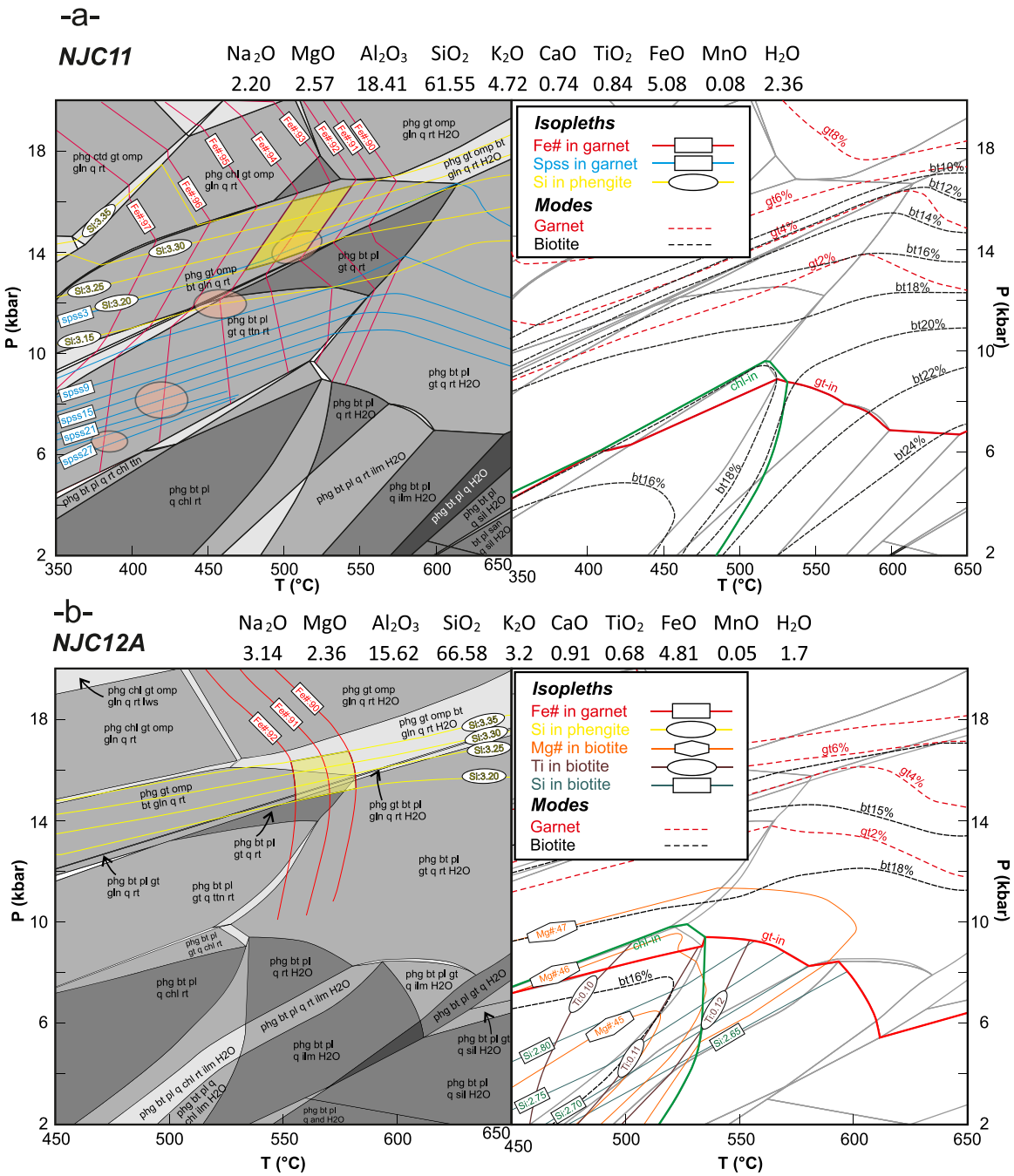


Fig. 7. Isochemical phase diagrams computed for compositions corresponding to garnet micaschists from the Najac unit: (a) sample NJC11 used to determine the prograde P-T path; (b) sample NJC12a used to determine the peak P-T conditions and the retrograde path. Garnet in/out and chlorite in/out curves are indicated in bold to better localize the retrogression in greenschist facies conditions.

extremely sensitive to bulk rock H_2O content. The best results, *i.e.* convergence of garnet isopleths and reproduction of the observed mineral assemblages, were obtained with the H_2O content calculated using the micas modal proportion and considering a H_2O content of ~5 wt% in white mica.

Garnet in NJC11 preserved a well-developed bell shaped Mn profile. Core composition (spss: 27mol% and Fe#: 96) are in equilibrium in greenschist facies conditions (360–400 °C, 6–7 kbar) slightly above the garnet-in phase boundary in a field where muscovite, biotite, plagioclase, garnet, titanite and rutile are in equilibrium (Fig. 7a). Intermediate compositions between core and rim draw a linear prograd path passing at 420 °C/8 kbar and 460 °C/12 kbar. Garnet rims equilibrated at 510 ± 20 °C and 14 ± 1 kbar in a field where phengitic mica, biotite, plagioclase, garnet, quartz and rutile are stable with minor amounts of sodic amphibole and clinopyroxene (Fig. 7a). Computed modal proportion for garnet and biotite are low (<6 vol.% and <10 vol.%, respectively). Isopleths of Si content in phengite (3.20–3.35 p.f.u.) and of Fe# in garnet (93–94) cross at 510 ± 30 °C and 15 ± 2 kbar.

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The field corresponding to the high-pressure assemblage observed in NJC12a (phengite-quartz-biotite-garnet-plagioclase-rutile) lies within 500–570 °C and 13–16 kbar under vapor under-saturated conditions (Fig. 7b). Free H_2O coexist with the observed assemblage at higher temperatures. At higher pressure conditions, the formation of sodic amphibole and pyroxene appears as a result of plagioclase and biotite breakdown while titanite is stable below 13–14 kbar and 520–560 °C (Fig. 7b). Calculated Fe# in garnet is temperature sensitive. Measured values (90–92) correspond to temperatures ranging between 520 and 585 °C for 10 and 20 kbar of pressure (Fig. 7b). These isopleths cross those representing measured Si content in white mica (3.18–3.36 a.p.f.u.) in a narrow P-T domain centered at 570 ± 15 °C and 16 ± 1 kbar (Fig. 7b). Our calculation predicts minor amounts of sodic pyroxene and amphibole (<10 vol.%), despite these ones were not observed in any micaschist samples. It can be due to retrogression of these phase or to inaccuracies of the thermodynamic calculations. Calculated grossular content in this P-T domain (0.20–0.28, increasing with decreasing pressure) is slightly above those determined with electron-microprobe (0.18–0.22). The pressure conditions at which measured and calculated grossular content are overlapping (0.20–0.22) are around 17 kbar. Low-Si (2.72–2.78 a.p.f.u.) biotite with Mg# of 45–48 and Ti between 0.10 and 0.11 p.f.u. is in equilibrium between 460–520 °C and 2–7 kbar (Fig. 7b); this is consistent with the presence of chlorite in the retrograde assemblage and the higher modal amounts of biotite calculated in greenschist facies conditions (around 16 vol.%) compared to eclogitic conditions (<10 vol.%). Biotite stable in the eclogite facies has much higher calculated Si content (>2.90 a.p.f.u.), compositions that were not observed in our samples.

5 Zircon U-Pb geochronology

The age of high-pressure, low temperature metamorphism in the Najac eclogite has been recently determined by multi-method geochronology (prograde path at 385–383 Ma, HP peak at 377 ± 3 Ma, exhumation around 369 ± 13 Ma; Sm-Nd and Lu-Hf isochron plus U-Pb zircon and apatite dating by Lotout *et al.*, 2018) but the age of amphibolite facies metamorphism in the Laguépie amphibolite has not been constrained. A large leucotonalitic lens (AJAH09, 20 × 30 cm) included into the amphibolite was sampled, from which about 40 zircon grains were extracted using heavy liquids and magnetic separation techniques at the Geosciences Environnement Toulouse laboratory.

Zircon images were acquired using a cold-cathode optical cathodoluminescence (CL) at the University of Mons using a Cambridge Image Technology model 8200 Mk5 system. They are generally small (length <200 μm), with minute quartz and apatite inclusions. These zircons show two different textures (Fig. 8a):

– cores of subhedral elongated grains or crystal fragments with dark shade (CL or transmitted light) displaying chaotic or no zoning and being often cracked with fractures extending into the rims. These features are typical of metamict zircons (Corfu *et al.*, 2003);
– luminescent part, often light brown and translucent, riming the dark cores and showing oscillatory growth zoning. These rims are usually 15 to 50 μm large and are relatively rare compared to dark zircon cores. These luminescent rims were also found as isolated fragments.

U-Pb analyses were performed at Géosciences Montpellier (University of Montpellier, France) using a Teledyne G2 excimer laser probe coupled to a ThermoFinnigan Element XR high-resolution ICP-MS (AETE-ISO regional facility of the OSU OREME). The probe was set at 25 μm diameter, with an ablation frequency of 4 Hz and a fluency of 6 J/cm^2. More details on analytical setup can be found in Bosch *et al.* (2011). Unknowns were calibrated against zircon 91500 standard reference material and GJ-1 was used as secondary standard (both reference materials were analyzed before and after each 5 unknowns). U-Pb ages and common Pb corrections were calculated using the IsoplotR code by Vermeesch (2018). Twelve analyses of GJ-1 zircon yield an upper intercept of 605 ± 14 Ma with 606 ± 7 Ma and 598 ± 5 Ma for the average $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ages, respectively. This is in good agreement with the recommended values, *i.e.* an upper intercept of 608.5 ± 1.5 Ma calculated from slightly discordant ID-TIMS analyses (Jackson *et al.*, 2004).

Dark metamict cores are U-rich (often >1000 ppm and up to 4650 ppm) and yield strongly discordant U-Pb ellipses (Fig. 8b; Tab. 1). The ablation spectra were moreover irregular and consequently, none of the analyzed zircon cores were used to calculate an age. About 15 spots were shot in the luminescent zoned rims but only 9 were not contaminated by the U-rich metamict cores or by apatite inclusions in depth (evidenced by irregular ablation spectra and/or a continuous increase in U or Pb count rates). These analyses show regular ablation spectra for the $^{206}Pb/^{238}U$ ratios (*i.e.* comparable to those of reference zircons 91500 and GJ-1) but more irregular ones for those involving ^{207}Pb. U contents range between 420 and 1044 ppm and Th/U ratios (Tab. 1) are on average slightly higher (0.02–0.04) compared to cores (Th/U: 0.01–0.02 with one analysis at 0.04). The data are discordant (1 to 14% of discordance, 4 ellipses are overlapping Concordia) with $^{206}Pb/^{238}U$ ages ranging between 356 ± 9 Ma and 374 ± 9 Ma and $^{207}Pb/^{235}U$ ages between 370 ± 12 Ma and 419 ± 14 Ma. Age calculation using a discordia regression line for rim analyzes yields a lower intercept at 363 ± 3 Ma (MSWD = 2) (Fig. 8c). The weighted average of $^{206}Pb/^{238}U$ common Pb corrected age is slightly older at 365 ± 3 Ma (Fig. 8d; Tab. 1).

6 Discussion

6.1 Two distinct tectono-metamorphic units with contrasted P-T paths

The Najac and Laguépie units are grouped into a single tectono-metamorphic unit by different authors (Burg *et al.*, 1984, 1989; Lardeaux, 2014; Faure *et al.*, 2017; Lotout *et al.*, 2018) but we show hereafter that they display different metamorphic histories and ages.

The Najac unit encompasses the eclogitic basic-ultrabasic massif, the phengite-bearing orthogneiss and the phengite-garnet micaschists (Fig. 1). Micaschists record early garnet

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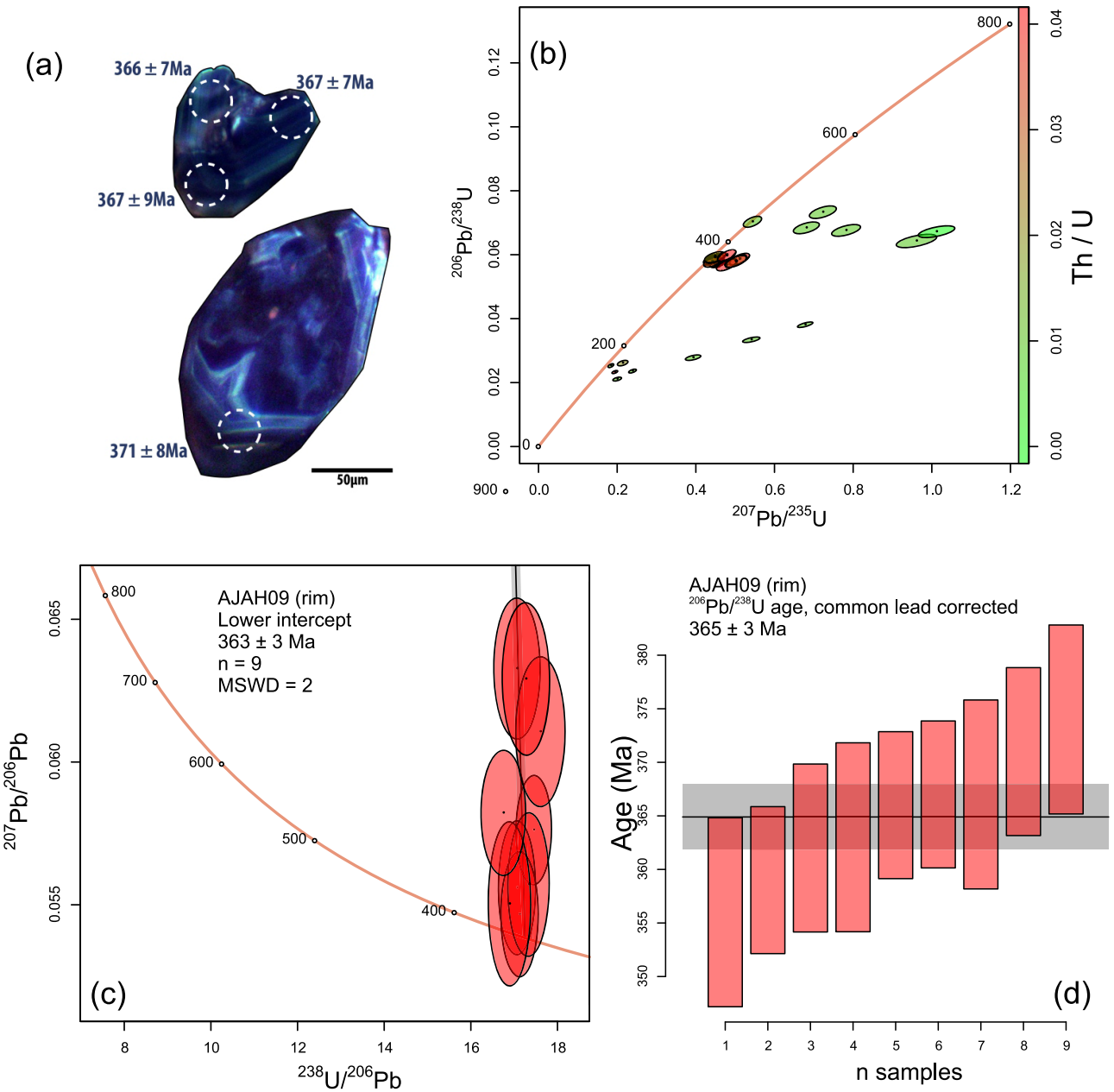


Fig. 8. Results of U-Pb zircon dating for leucogneiss AJAH09 of the Laguépie unit: (a) CL images showing the texture of zircon with dark resorbed metamict cores and luminescent oscillatory zoned rims. Some representative spots made on rims are indicated with their $^{206}Pb/^{238}U$ age; (b) Concordia diagram showing all the U-Pb analyses. Color range corresponds to Th/U ratio values. The rim data are the sub-concordant ellipses just below 400 Ma; (c) regression of rim U-Pb data in a Tera-Wasserburg plot; (d) weighted average of $^{206}Pb/^{238}U$ common lead corrected ages obtained in zircon rims.

nucleation around 360–400 °C, 6–7 kbar (Fig. 7a) followed by syn-kinematic growth (Fig. 7a) and equilibration of garnet rims and phengite around 510–570 °C and 14–17 kbar (~340 °C/GPa) in the eclogite facies (Fig. 7a, b). Late- to post-kinematic biotite and chlorite developed preferentially around garnet (Fig. 7b) and are indicative of retrogression in the greenschist facies at 460–520 °C and 2–7 kbar (Fig. 7b). Lotout *et al.* (2018) obtained slightly higher peak conditions for an eclogite from the basic-ultrabasic Najac massif (600 °C, 18 kbar; Fig. 9) but similar thermal gradient at peak pressure (330 °C/GPa) (Fig. 9). Multi-methods dating performed by Lotout *et al.* (2018) on an eclogite from Najac constrained the age of prograde evolution around 383–385 ± 3 Ma and the pressure peak at 377 ± 3 Ma (Fig. 9). The P-T path determined for the Najac unit (Fig. 9) is different than those determined for the paragneisses and micaschists of the Lower Gneiss and Upper Gneiss units in Limousin and French Massif central (Bellot and Roig, 2007; Faure *et al.*, 2009; Lardeaux, 2014; Do Couto *et al.*, 2016), both showing pervasive recrystallization in the amphibolite facies (600–700 °C, 5–10 kbar) during Devonian D1 and D2 events (Faure *et al.*, 2009).

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Table 1. Results of U-Pb zircon dating on leucogneiss sample AJAH09.

Sample		Pb* (ppm)	Th (ppm)	U (ppm)	Th/U	$^{207}Pb/^{206}$ Pb ratio	±2σ	$^{207}Pb/^{235}U$ ratio	±2σ	$^{206}Pb/^{238}U$ ratio	±2σ	Rho	$^{207}Pb/^{235}U$ age	±2σ	$^{206}Pb/^{238}U$ age	±2σ	Disc (%)
ab2	Rim	56	27	1044	0.03	0.0576	0.0021	0.455	0.015	0.0573	0.0011	0.57	381	10	359	7	6
ab7	Rim	31	18	572	0.03	0.0556	0.0025	0.449	0.018	0.0586	0.0012	0.51	377	13	367	7	3
ab8	Rim	36	21	674	0.03	0.0546	0.0024	0.440	0.017	0.0584	0.0012	0.53	370	12	366	7	1
ab21	Rim	32	17	616	0.03	0.0558	0.0027	0.443	0.019	0.0577	0.0013	0.51	373	14	362	8	3
ab26	Rim	25	8	476	0.02	0.0550	0.0029	0.449	0.022	0.0592	0.0014	0.49	377	15	371	8	2
ac_5	Rim	32	20	472	0.04	0.0581	0.0024	0.479	0.019	0.0597	0.0015	0.63	397	13	374	9	6
ac_6	Rim	39	21	564	0.04	0.0633	0.0028	0.511	0.021	0.0586	0.0015	0.63	419	14	367	9	14
ac_7	Rim	27	17	424	0.04	0.0611	0.0029	0.478	0.021	0.0568	0.0015	0.60	397	15	356	9	11
ac_9	Rim	48	18	703	0.03	0.0629	0.0029	0.502	0.022	0.0579	0.0015	0.61	413	15	363	9	14
ab1	Core	127	23	3123	0.01	0.129	0.004	0.678	0.016	0.0381	0.0007	0.72	526	10	241	4	118
ab4	Core	100	160	4302	0.04	0.060	0.002	0.194	0.006	0.0233	0.0004	0.58	180	5	148	3	21
ab11	Core	102	27	4268	0.01	0.053	0.002	0.184	0.006	0.0253	0.0005	0.57	171	5	161	3	6
ab12	Core	82	5	645	0.01	0.269	0.010	2.888	0.088	0.0777	0.0019	0.79	1379	23	483	11	186
ab13	Core	250	12	1598	0.01	0.493	0.014	7.296	0.175	0.1074	0.0019	0.74	2148	21	658	11	227
ab14	Core	299	13	2350	0.01	0.323	0.010	3.278	0.081	0.0737	0.0013	0.73	1476	19	458	8	222
ab15	Core	64	6	662	0.01	0.184	0.006	1.804	0.052	0.0713	0.0015	0.71	1047	19	444	9	136
ab16	Core	106	16	3126	0.01	0.118	0.005	0.541	0.018	0.0334	0.0007	0.64	439	12	212	4	107
ab19	Core	46	9	691	0.01	0.084	0.004	0.782	0.030	0.0676	0.0015	0.58	586	17	421	9	39
ab20	Core	58	6	855	0.01	0.072	0.003	0.723	0.028	0.0733	0.0016	0.57	552	16	456	10	21
ab22	Core	161	14	2613	0.01	0.056	0.002	0.544	0.019	0.0703	0.0014	0.57	441	12	438	8	1
ab24	Core	105	34	4653	0.01	0.074	0.003	0.239	0.008	0.0236	0.0005	0.59	218	7	150	3	45
ab25	Core	22	4	314	0.01	0.108	0.005	0.961	0.042	0.0643	0.0017	0.59	684	22	402	10	70
ab29	Core	114	74	3555	0.02	0.060	0.003	0.214	0.011	0.0261	0.0007	0.50	197	9	166	4	19
ab30	Core	66	4	964	0.00	0.109	0.005	1.012	0.038	0.0672	0.0015	0.59	710	19	419	9	69
ab32	Core	139	15	1656	0.01	0.237	0.009	1.777	0.061	0.0544	0.0011	0.61	1037	22	341	7	204
ab33	Core	110	10	1875	0.01	0.072	0.003	0.681	0.027	0.0684	0.0015	0.55	528	16	427	9	24
ab34	Core	123	43	4198	0.01	0.103	0.005	0.393	0.016	0.0278	0.0007	0.58	336	12	176	4	91
ab35	Core	71	24	3585	0.01	0.069	0.003	0.200	0.009	0.0211	0.0005	0.52	185	7	135	3	37

The Laguépie unit comprises garnet-bearing amphibolite, garnet-free amphibolite and a leucotonalitic orthogneiss forming isolated lenses and, sporadically, veins and dykes within amphibolites (Fig. 2). The isolated, unconnected leucotonalitic lenses, the lobed contact between the garnet amphibolite and the leucotonalite magma as well as the sodic nature of the felsic material support that it formed after partial melting of the amphibolite. Garnet in the amphibolite sample AJAH08 preserves core to rim zoning attesting for isobaric (~10 kbar) heating from 690 to 730 °C (Fig. 6). The main plagioclase-garnet-amphibole-quartz-ilmenite-melt assemblage equilibrated around 700–730 °C at 10 ± 1 kbar. (~720 °C/GPa; ~20 °C/km) on a garnet-amphibolite residue. These conditions are just above the vapor-present solidus calculated for the bulk composition of garnet-bearing and garnet-free amphibolites from Laguépie. Retrogression is evidenced by the development of low-Al magnesiohornblende rims around tschermakite in equilibrium with oligoclase and epidote ($T_{Hbl\text{-}Pl}$ around 510–580 °C) in the epidote-amphibolite and/or greenschist facies. The porphyroclastic texture of garnet, amphibole and plagioclase and the crystallization of albite, chlorite and actinolite whithin cataclasic shear zones were acquired in the amphibolite and greenschist facies, respectively. Solid state deformation characterized by a top-to-the-north sense of shear (the D2 event of Faure *et al.*, 2009) affected the Laguépie unit during retrogression in P-T conditions corresponding to the amphibolite and greenschist facies after the partial melting event. U-Pb ages of luminescent and zoned zircon rims in a leucotonalitic lens from Laguépie unit (sample AJAH09) yield an age of 363 ± 3 Ma (Fig. 8; Tab. 1) which is interpreted as the timing of felsic magma crystallization following partial melting of the amphibolite.

Our petrological and chronological study demonstrates that these two units have contrasted pressure-temperature-time-deformation histories (Fig. 9) and cannot be assigned to a single tectono-metamorphic unit. The implications of this result are discussed below.

6.2 Correlations with tectono-metamorphic units of the Western European variscan belt

The metamorphic units of the FMC are characterized by contrasted P-T evolutions. The metapelites of the para-autochthon have a metamorphic evolution within the greenschist facies locally reaching amphibolite facies near

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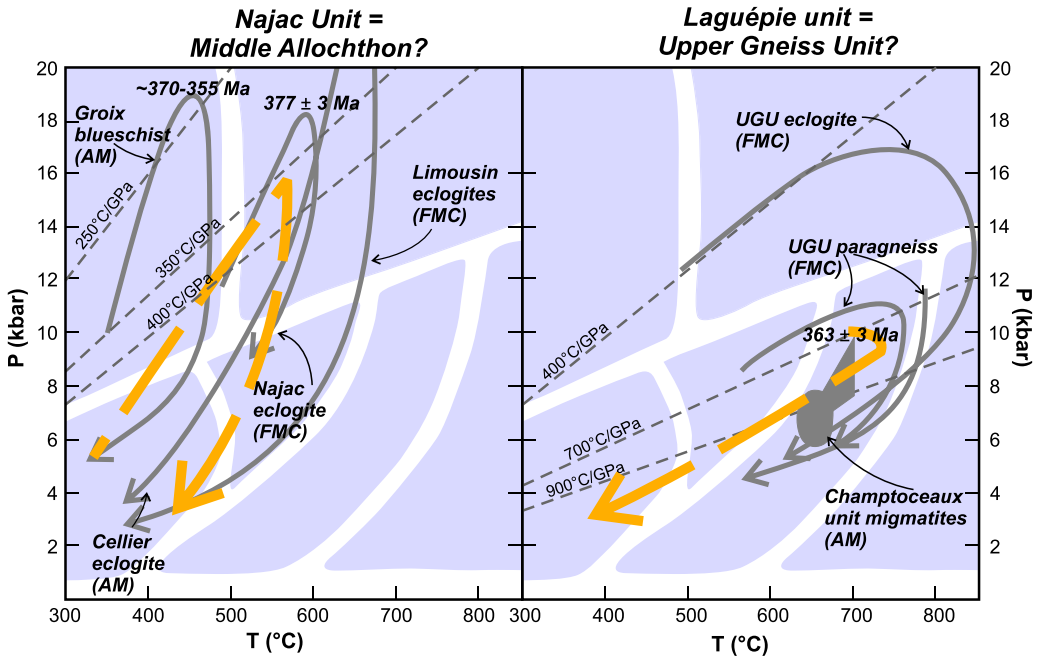


Fig. 9. Proposed P-T path (orange arrows) for the Najac and the Laguépie units. Grey P-T paths are from the literature: Groix blueschists from Ballèvre *et al.* (2003), Cellier éclogites from Ballèvre *et al.* (2014); Najac éclogite from Lotout *et al.* (2018); UGU eclogite from Bellot and Roig (2007); UGU paragneiss from Bellot and Roig (2007) and Schulz *et al.* (2009), Champtoceaux migmatites after Pitra *et al.* (2010). Age of the HP metamorphism in the Groix Island from Bosse *et al.* (2005), age of pressure peak in the Najac eclogite from Lotout *et al.* (2018).

large Carboniferous plutons (Bellot and Roig, 2007). Both the Lower Gneiss (Lower Allochthon by Santallier *et al.*, 1994) and Upper Gneiss Units (Bellot and Roig, 2007; Lardeaux, 2014; called Middle Allochthon by Santallier *et al.*, 1994) display evidences for pervasive recrystallization in the amphibolite facies, around 600–750 °C, 5–10 kbar (see Faure *et al.*, 2009; Do Couto *et al.*, 2016) after a phase of high pressure metamorphism, mostly recorded in the UGU. The uppermost epizonal units (called Upper Allochthon by Santallier *et al.*, 1994) are poorly characterized, they are mostly considered as greenschist facies meta-sedimentary and meta-igneous rocks (Roig *et al.*, 1996; Lardeaux, 2014). The nappe stack in the southern Armorican massif is either described similarly to the FMC by Faure *et al.* (2005, 2008) or subdivided into various allochthons by Ballèvre *et al.* (2009, 2014). In both the FMC and AM, a Middle Allochthon has been defined on the basis of its structural position within the nappe stack and the metamorphic conditions recorded by its constitutive rocks. Berger *et al.* (2010a) described zoisite and kyanite eclogites (~660 °C, 29 kbar) exhumed at temperatures below 650 °C. They are located close to the contact between LGU and UGU and were included into a Middle Allochthon. Ballèvre *et al.* (2014) proposed to assign the Groix and Bois de Céné blueschists (<570 °C, up to 17 kbar and also devoid of recrystallization in the amphibolite facies, Ballèvre *et al.*, 2003) to a Middle Allochthon but its structural position is uncertain and debated (see Ballèvre *et al.*, 2009 and also Faure *et al.*, 2005). A Middle Allochthon would thus define as a unit comprising cold HP rocks devoid of Late Devonian amphibolite facies recrystallization and located between LGU and UGU.

The *Najac unit* is often included within the Upper Gneiss Unit on maps published by several authors (Lardeaux, 2014; Faure *et al.*, 2017; Lotout *et al.*, 2018). However, the UGU, containing most of retrogressed eclogite lenses in the FMC (formed during the 420–400 Ma D0 event of Faure *et al.*, 2009), also include migmatitic paragneisses having experienced temperatures up to 700–750 °C (Middle Devonian D1 event of Faure *et al.*, 2008, 2009) followed by retrogression in the amphibolite facies (Upper Devonian D2 event; Faure *et al.*, 2009). The P-T path of the Najac unit is unusual in the French Massif central (Fig. 9; see Bellot and Roig, 2007; Faure *et al.*, 2009 and Lardeaux, 2014 for reviews on the metamorphic structure and evolution of the French Massif central). Rocks forming the Najac unit have not recorded the D1 and D2 amphibolite facies metamorphic phases preserved in LGU and UGU and instead preserve high-pressure, low temperature (340 °C/GPa at peak pressure) event contemporaneous with a top-to-the-southeast sense of shear. High-pressure rocks included in the Middle Allochthon of the FMC and the AM display metamorphic evolutions similar to the one of the Najac unit, i.e. a HP stage followed by an isothermal exhumation path without recrystallization in the amphibolite facies (Berger *et al.*, 2010a; Ballèvre *et al.*, 2003, 2014). Delor *et al.* (1986) described glaucophane relics in Najac eclogites and already proposed that they belong to the same tectono-metamorphic unit than the Groix and Bois de Céné units in the Armorican massif. High-pressure rocks from these Middle Allochthon occurrences in Brittany (Guiraud *et al.*, 1987; Ballèvre *et al.*, 2003) are characterized by a cold high pressure metamorphism (<500°, up to 18 kbar; 7–8 °C/km) followed by exhumation at low temperature (<500 °C) that compares to Najac micaschists

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(Fig. 9a). The base of the Lower Allochthon (Lower Gneiss Unit of Faure *et al.*, 2005) unit in the Armorican massif also contains eclogitic lenses and HP orthogneiss (in the Cellier unit) having quite similar peak conditions (600 °C, 2 GPa; 10 °C/km; Fig. 9a) (Ballèvre *et al.*, 2014) when compared to the Najac unit. However, they cannot be considered as the lateral equivalent of the Najac unit as the latter clearly thrusts over the Lower Gneiss Unit (Fig. 1).

Published ages for HP metamorphism in the Middle Allochthon are not strictly equivalent in different locations. Lotout *et al.* (2018) performed multi-method dating (U-Pb zircon and apatite; Sm-Nd and Lu-Hf isochrons) on a retrogressed eclogite from Najac and obtained Upper Devonian ages (383–369 Ma) interpreted as the age of high-pressure metamorphism. Sm-Nd, Rb-Sr and Ar-Ar geochronology by Bosse *et al.* (2005) also yielded 370–355 Ma for high pressure metamorphism and exhumation of the Groix blueschists. Berger *et al.* (2010a) proposed that the age of HP metamorphism in Middle Allochthon of Limousin is Lower Devonian but this is based on questionable and sparse ages obtained on thin uranium-poor zircon rims surrounding uranium-rich Ordovician cores. Upper Devonian (~380 Ma) ages were also obtained on these zircon rims but they were tentatively attributed to D1 Late-Devonian high temperature metamorphism recorded in Limousin (*cf.* Faure *et al.*, 2008; Melleton *et al.*, 2009) while the dated eclogite is almost not affected by retrogression. New careful analyses done in the zircon rims from the same sample investigated by Berger *et al.* (2010a) yielded younger Upper Devonian ages (work in progress).

Considering the metamorphic evolution, the age and the structural position (thrusting over the Lower Gneiss Unit) of the high-pressure Najac unit, we thus propose that it represents the lateral equivalent of the Groix and Bois de Céné unit in the Armorican massif and the Limousin eclogites of Berger *et al.* (2010a) and assign this unit to the Middle Allochthon Further exploration of phengitic, biotite-poor garnet micaschists and associated eclogites is needed in the French Massif central to better characterize a potential Middle Allochthon and to correlate it with well-known occurrences of the Armorican massif.

The *Laguépie unit* records amphibolite facies metamorphism peaking at 710–730 °C, 10 kbar, corresponding to metamorphic conditions obtained in the Upper Gneiss Unit elsewhere in the French Massif central (Burg *et al.*, 1984; Bellot and Roig, 2007; Schulz, 2009; Lardeaux, 2014; Do Couto *et al.*, 2016; Fig. 9b). The UGU hosts retrogressed eclogites enclosed into migmatitic paragneisses, formed during the D0 and D1 events, respectively (Faure *et al.*, 2009; Melleton *et al.*, 2009; Do Couto *et al.*, 2016). High pressure metamorphism and partial melting were followed by retrogression in the amphibolite facies around 600–700 °C, 5–10 kbar during the Upper Devonian/Lower Carboniferous D2 event (Faure *et al.*, 2009). Association of mafic and felsic rocks recrystallized in the amphibolite facies is common in the Leptyno-Amphibolite Complex (LAC), usually attributed to the UGU (see Ledru *et al.*, 1989, 1994 and Lardeaux, 2014) and more rarely to the LGU (Bellot and Roig, 2007). Mafic rocks from the LAC often display relict assemblages attesting for eclogite and HP granulite facies metamorphism (Santallier *et al.*, 1988) and their igneous precursors are thought to have been emplaced in an ocean-continent transition zone (Lardeaux, 2014). If the Laguépie unit belongs to the LAC, it must be envisaged that the some of the mafic-felsic associations can also originate after partial melting of a mafic precursor. The age of partial melting and felsic melt crystallization has been constrained at ca. 363 ± 3 Ma in the Laguépie unit. While Faure *et al.* (2009) usually ascribe the partial melting event to the 385–375 Ma Devonian D1 phase, U-Pb dating indicates that amphibolite facies (up to 730 °C) partial melting at Laguépie occurred during Late Devonian. It was followed by top-to-the-north shearing under amphibolite to greenschist facies conditions probably during Lowermost Carboniferous corresponding to the kinematic proposed for the D2 event (Faure *et al.*, 2017).

In the Armorican massif, robust P-T estimates by Pitra *et al.* (2010) yielded peak temperature above 650 °C at pressure conditions ranging from 8 to 11 kbar for migmatitic paragneisses of the eclogite and HP orthogneiss bearing Champtoceaux unit. However the structural position of this units is debated: Faure *et al.* (2005, 2008) include it into the UGU by correlation with FMC occurrences; Ballèvre *et al.* (2009) and Pitra *et al.* (2010) place it at the base of an Upper Allochthon while the upper parts of this allochthon involve a Cadomian basement with low grade metasediments and ophiolites (Faure *et al.*, 2005, 2008; Ballèvre *et al.*, 2009; Ducassou *et al.*, 2011). It is however included within the Lower Allochthon by Ballèvre *et al.* (2014) by correlation within Iberian massifs. The Laguépie and Champtoceaux units both yield peak temperature conditions around 700 °C and 10 kbar (Fig. 9). Their metamorphic evolutions are thus more comparable to the Upper Gneiss Unit in FMC, as suggested by Faure *et al.* (2005, 2008). Considering the conditions and age of amphibolite facies metamorphism (363 Ma) along with the deformation post-dating the anatectic stage, the Laguépie units correlates with the LAC in the FMC and the Champtoceaux Unit in the AM, that we tentatively ascribe to the Upper Gneiss Unit as defined in the literature (see Lardeaux, 2014; Fig. 9).

6.3 Geodynamic significance

The results presented in this study and those published recently by Lotout *et al.* (2018, 2020) are not compatible with the subdivision in tectono-metamorphic phases proposed by Faure *et al.* (2005, 2008, 2009). In these latter papers, the D0 phase correspond to the formation of HP units between 420 and 400 Ma during the closure of an oceanic domain separating Gondwana and Armorica. However, Lotout *et al.* (2018) provided Upper Devonian ages for the Najac eclogites and Lotout *et al.* (2020) obtained Upper Devonian to Early Carboniferous ages for HP metamorphism in Lévézou. These data suggest that HP metamorphism is younger in southern French Massif central compared to other occurrences (Pin and Lancelot, 1982; Ducrot *et al.*, 1983; Paquette *et al.*, 1995). Furthermore, partial melting in UGU as recorded in the Laguépie unit is usually ascribed to the 385–375 Ma D1 event by Faure *et al.* (2009) but it is dated at 363 Ma at Laguépie. It is however affected by the Late Devonian/Lower Carboniferous D2 top-to-the-north shearing (Faure *et al.*, 2017). These discrepancies suggest that either (i) new and old ages for HP

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metamorphism should be critically evaluated because dating HP metamorphism is a difficult and challenging task or (ii) metamorphic events are about 20 Myr younger in southern French Massif central compared to northern parts or (iii) that final collision between Armorica and Gondwana occurred during Upper Devonian/Early Carboniferous and not Lower Devonian, as suggested by Lardeaux (2014) and Ballèvre *et al.* (2009, 2014).

If we consider that Upper Devonian HP/LT metamorphism (Lotout *et al.*, 2018, 2020) is coeval with partial melting in UGU (Melleton *et al.*, 2009; this study) and active margin magmatism as represented by tonalites and diorites intruding the UGU (375–355 Ma; Bernard-Griffiths *et al.*, 1985; Shaw *et al.*, 1993; Bertrand *et al.*, 2001; Pin and Paquette, 2002); these data are compatible with an active subduction system forming a paired metamorphic belt during Late Devonian (Miyashiro, 1967; Brown, 2006). The Najac unit, comprising a basic/ultrabasic intrusion within orthogneisses and micaschists all metamorphosed under eclogite facies conditions, either represents fragments of a continental lower plate or the accretionary prism in the subduction system (proposed for the Groix blueschists, Ballèvre *et al.*, 2014). The UGU, and accordingly, the Laguépie unit, are, in this proposition, part of the upper plate of the subduction system, similarly to what has been proposed by Lardeaux (2014) and Lardeaux *et al.* (2014). Nappe stacking that caused superimposition of the Najac and Laguépie units occurred after 363 Ma, probably during the Early Carboniferous 345–335 Ma D3 phase of Faure *et al.* (2009) because the Najac micaschists were not affected by the Late Devonian 700 °C/10 kbar metamorphism observed at Laguépie.

7 Conclusion

Petrological investigations on metamorphic samples from the Najac and Laguépie units in the southwestern FMC reveal two distinct P-T evolutions. The Najac unit is characterized by syn-kinematic eclogitic metamorphism in micaschists and basic rocks implying subduction of a continental margin at the end of the Devonian (around 377 Ma) followed by cold exhumation in the greenschist facies. The Laguépie unit records amphibolite facies metamorphism (710 °C, 10 kbar) dated at 363 Ma and later affected by deformation and retrogression under amphibolite to greenschist facies conditions. These two units were formerly grouped into the leptyno-amphibolite complex belonging to the Upper Gneiss Unit. Comparison with tectono-metamorphic units in the French Massif central and the Armorican massifs suggest that the Najac unit can be integrated into the HP/LT Middle Allochthon while the Laguépie unit belongs to the Upper Gneiss Unit. The French Massif central consequently preserves the remnants of an Upper Devonian paired metamorphic belt, where the Middle Allochthon represent subducted material attached to the slab or within an accretionary prism while the Upper Gneiss Unit was located within the upper plate of the subduction system. Lower Carboniferous continental collision further led to the stacking of metamorphic units with contrasted pre-Carboniferous histories. The stack, in its current configuration, is showing an apparent inverted metamorphic gradient, well expressed in the Rouergue domain.

The structure of the tectono-metamorphic units near Najac can be considered as a reference for further studies on the structure and evolution of metamorphic units preserved in the French Massif central. Future investigations should focus on obtaining precise P-T-t paths on pre-Carboniferous metamorphic units belonging to the FMC and exploration of phengite-bearing biotite-poor garnet micaschists (locally enclosing eclogites) possibly marking a still poorly defined Middle Allochthon. Altogether, these results should be used to propose an integrated tectono-metamorphic framework that can be useful to test the different geodynamic scenarios proposed for the Variscan orogeny in Western Europe.

Supplementary material

Table S1. Tables of mineral chemistry for samples of Najac micaschists and Laguépie amphibolites.
The Supplementary material is available at https://www.bsgf.fr//10.1051/bsgf/2020033/olm.

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