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Structural, metamorphic and geochronological insights on the Variscan evolution of the Alpine basement in the Belledonne Massif (France).

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Abstract:

A structural and petrochronological study was carried out in the southern part of the Belledonne crystalline massif. A first tectonometamorphic event, Dx, corresponds to the eastward thrusting of the Chamrousse ophiolitic complex characterized by a low-temperature–moderate-pressure metamorphism reaching $0.535 \pm 0.045$ GPa and $427.5 \pm 17.5$ °C. A subsequent D1 deformation is defined by a penetrative S1 foliation that mostly dips towards the west and displays an E-W-to NE-SW-trending mineral and stretching lineation L1. D1 is associated with a top-to-the east shearing and is responsible for the crustal thickening accommodated by the eastward nappe stacking and the emplacement of the Chamrousse ophiolitic complex upon the Rioupéroux-Livet unit. This event is characterized by an amphibolite facies metamorphism ($0.58 \pm 0.06$ GPa; $608 \pm 14$ °C) that attains partial melting at the base of the nappe pile ($0.78 \pm 0.07$ GPa; $680.5 \pm 11.5$ °C). LA-ICP-MS U-Pb dating of monazite grains from the mica schists of the Rioupéroux-Livet unit constrain the age of D1 to $337 \pm 7$ Ma. The D2 tectono-metamorphic event is characterized by NE-SW trending, upright to NE-verging synfolial folding. Folding associated with D2 is pervasively developed in all lithotectonic units with the development of a steeply-dipping S2 foliation. In particular, D2 involves the uppermost weakly metamorphosed Taillefer unit. LA-ICP-MS U-Pb dating performed on detrital zircon grains shows that the Taillefer conglomerates was deposited during the Visean. A zircon SIMS U-Pb age of $352\pm 1$ Ma from a plagioglasse-rich leucocratic sill of the Rioupéroux-Livet unit is interpreted as the age of magmatic emplacement. Our results suggest that the D2 event took place between 330 Ma and 310 Ma. We propose a new interpretation of the tectonometamorphic evolution of the southern part of the Belledonne massif, focusing on the Middle Carboniferous stages of the Variscan orogeny.
Keywords: Variscan Belt, Alpine External Crystalline Massifs, Belledonne Massif, SIMS and LA-ICP-MS dating, Thermobarometry, zircon and monazite dating

1. Introduction

In Europe, the Variscan belt is interpreted as the result of a Devonian to Carboniferous continent-continent collision of Laurussia in the north, and Gondwana in the south, with several intermediate micro-continents trapped between them (Autran and Cogné, 1980; Ballèvre et al., 2009; Bard et al., 1980; Franke, 2000; Faure et al., 2005; Matte, 1986, 2007; Paris and Robardet, 1990; Stampfli et al., 2013; Tait et al., 1997, 2000; Von Raumer et al., 2003). The Variscan orogenic evolution is relatively well documented in the main crystalline massifs found in Iberia, the Armorican Massif, French Massif Central, Vosges, Ardennes, and the Bohemian Massif (Lardeaux et al., 2014; Stampfli et al., 2002, 2013) (Fig. 1A). The Variscan belt is also exposed through the Alpine Basement, as the East Variscan branch, with its External Crystalline Massifs (ECMs, Fig. 1B), which have been much less studied. While there are controversies concerning the timing of the main tectonometamorphic events and the correlations of the ECM’s distinct basement domains, several interpretations have already been proposed, with comparisons to the Maures-Tanneron Massif, the Corsica-Sardinia region, and other Variscan fragments of the Alps (Corsini and Rolland, 2009; Fernandez et al., 2002; Faure et al., 2014; Guillot et al., 2009; Guillot and Ménot, 2009; Rossi et al., 2009; Von Raumer et al., 2013). A first interpretation argues that the East Variscan branch resulted from a tectonic collage along a N030°E East Variscan Shear Zone (EVSZ) during late Carboniferous to Permian time (Corsini and Rolland, 2009; Guillot et al., 2009; Padovano et al., 2012). A second interpretation suggests that the Variscan massifs of the East Variscan branch first drifted from the Gondwana margin, and then accreted along the Armorica during early Paleozoic time (Stampfli et al., 2002; Von Raumer, 1998; Von Raumer et al., 2003, 2009, 2013, 2014, 2015).
This contribution presents new structural, P-T estimates and geochronological constraints (LA-ICP-MS U-Pb on zircon and monazite) for the southwestern Belledonne Massif, mostly along the Romanche Valley and surrounding areas (Fig 2). These results represent crucial records for the ECMs, enabling us to better define a relevant geodynamic model for the Variscan Orogen, particularly for Middle Carboniferous time.

2. Geology setting

2.1 The External Crystalline Massifs

The ECMs are composed of various Cambrian to Carboniferous metamorphic, plutonic and migmatitic rocks, mantled by late Carboniferous to Permian non-metamorphic sedimentary and volcanic series, which are in turn unconformably overlain by Mesozoic sedimentary rocks (Fig. 1B, Barfety et al., 2000; Guillot et al., 2009). Based on their structural and petrological differences, the ECMs can be divided into three domains. The easternmost domain consists of Variscan granites and migmatites (Fig. 1B). The central domain, which corresponds to SW Pelvoux, SW Belledonne and SW Aiguilles Rouges, consists of the Chamrousse Ophiolite, amphibolite facies metamorphic rocks, and the Visean volcano-sedimentary series (see details below). The westernmost domain (NW Belledonne) exhibits a micaschist series called the Série Satinée (e.g. Bordet and Bordet, 1963; Fig. 1B).

During the early Jurassic, continental rifting affected Pangea and led to the formation of hemi-grabens resulting in a local tilting of the Paleozoic basement along normal faults (Barfety et al., 1988; Lemoine, 1988). The Miocene deformation is very heterogeneous with localized steeply-dipping brittle-ductile shear zones that accommodated the Alpine NW-SE compression (Bellahsen et al., 2012, 2014, Bellanger et al., 2014, 2015; Marquer et al., 2006). The Miocene deformation is associated with a low-grade metamorphism, with from prehnite-pumpellyite to
greenschist facies conditions (Gratier et al., 1973). Except for this low-grade metamorphism and localized deformation along Alpine shear zones, the evidence of pre-Alpine, i.e., Variscan tectonometamorphic events is well preserved in the Belledonne Massif.

2.2 The main lithotectonic units in the Belledonne Massif

The Belledonne Massif is divided into three tectonic parts delimited by high-angle strike slip faults (Figs. 1B, 2; Barfety et al., 1972, 2000). To the NW, in the External Domain, the Série Satinée is bounded to the east by the Synclinal Median dextral strike-slip Fault (SMF) (Bordet and Bordet, 1963; Simeon, 1979). Based on a structural analysis, Simeon (1979) shows that the SMF records a polyphase history with a late-Variscan dextral strike-slip fault that was reworked by a reverse faulting and then a normal faulting during the Mesozoic and Alpine deformations respectively. The protolith for this series, which consists of alternations of low metamorphic grade quartz-feldspar sandstone and two-mica bearing micaschists, is considered to be a turbidite formation (Bordet and Bordet, 1963). East of the SMF, the Internal Domain of the Belledonne Massif is divided into two parts, on either sides of the Rivier-Belle Etoile fault (RBE, Fig. 1B). The NE part is composed of partly migmatitic volcanoclastic series intruded by Visean granitoids (Barfety et al., 2000; Debon and Lemmet, 1999). Scarce eclogitic relics are documented in the NE Belledonne, with a U-Pb zircon age of 395±2Ma, interpreted as defining the age of the HP event (Paquette et al., 1989). A similar Eo-Devonian HP event is invoked for the eclogites that crop out in the Aiguilles Rouges (Paquette et al., 1989). In the Argentera Massif, the HP event is younger, with Carboniferous ages ranging from 340 to 336 Ma (Rubatto et al., 2010). This contribution focuses on the SW part of the Belledonne Massif (Fig. 2). The following lithological or tectonic units are recognized: i) the Chamrousse ophiolitic complex; ii) the Rioupéroux-Livet volcanosedimentary unit; iii) the Allemont migmatitic unit; and iv) the Taillefer terrigenous-volcanic unit (Ménot, 1988a).
The Chamrousse ophiolitic complex (Bodinier et al., 1981; Carme, 1965a, 1970; Pin and Carme, 1987) consists of a well-preserved kilometer-scale ophiolite that may have formed in a back-arc basin at around 496 Ma (Ménot et al., 1988; Pin and Carme, 1987). Detailed mapping indicates that the ophiolitic succession is tectonically inverted with serpentinized ultramafic rocks that are underlain by gabbros and amphibolites (Bodinier et al., 1981). Pillow lavas, volcanic and sedimentary rocks occupy the lowermost position. The presence of ductile shear zones between each lithological sub-unit attests to the tectonic disruption and inversion of the ophiolitic sequence (Barfety et al., 1972, 1988; Carme, 1965a). A low pressure and high temperature (LP-HT) metamorphism estimated at 0.3-0.4 GPa and 500-600 °C is reported by (Guillot et al., 1992). These authors considered this LP-HT metamorphism to be contemporaneous with a rift-related intra-oceanic deformation defined by the development of NW-SE-trending lineation and top-to the NW shearing.

The Rioupéroux-Livet unit is composed of bimodal magmatic and volcano-sedimentary rocks (Ménot, 1988b). The magmatic portion includes felsic and mafic lavas; the graywackes in the volcanoclastic portion are intruded by trondhjemitic sills. These trondhjemites have been dated at 367-362 Ma by K/Ar on amphibole (Ménot et al., 1985, 1987; Ménot, 1986), and at 367±17 Ma and 352±55 Ma by U-Pb on zircon (Ménot et al., 1985; Ménot, 1988b). The volcano-sedimentary sequence exhibits an alternation of plagioclase-rich leucocratic beds, felsic metavolcanics, metapelites and rare marbles. Towards the east, the metapelitic layers thicken and become more abundant.

The Rioupéroux-Livet unit was interpreted as an active continental margin (Carme and Pin, 1987) whereas Ménot (1987, 1988b) argued for a continental extensional setting with a progressive change from mantle to crustal magmatic sources. An amphibolite facies metamorphism is recorded by garnet-staurolite-bearing micaschists with peak metamorphic P-T conditions of 0.8±0.2 Gpa and 590±60 °C (Fernandez et al., 2002; Guillot and Ménot, 1999).
A near isothermal decompression evolution down to P-T conditions of 0.7±0.2 Gpa and 590±60°C before a late retrogression under green schist facies conditions is reported (Fernandez et al., 2002; Guillot and Ménot, 1999). In view of the K-Ar dating on amphibolite (Ménot et al., 1987), and the granitoid emplacement ages (Debon et al., 1998), Guillot et al. (2009) considered that the amphibolite facies metamorphism is related to a nappe stacking event that occurred between 341 ± 13 Ma and 324 ± 13 Ma. The metamorphic gap observed between the Chamrousse ophiolitic complex and the Rioupéroux-Livet unit is explained by the thrusting of the former upon the latter along the Rioupéroux thrust (RT, Fig. 2).

East of the Rioupéroux-Livet unit, the Allemont migmatitic unit consists of a hundred-meter-thick anatectic zone with garnet-bearing metatexites, migmatitic gneisses and anatectic granites (Fig. 2, Guillot and Ménot, 1999). These rocks were interpreted as being formed during a late Carboniferous to Permian extensional tectonic phase coeval with crustal melting (Fernandez et al., 2002; Guillot and Ménot, 1999). The Rivier-Belle Etoile fault zone truncates the metatexites observed near Allemont, suggesting that their apparent thickness is probably underestimated (Fig. 5A).

The Taillefer unit is composed of terrigenous rocks, dominantly siltstones with graphitic layers, sandstones, conglomerates, and acidic volcanic rocks. On the basis of poorly preserved fossil plant fragments, the Taillefer unit was believed to be upper Visean in age (ca. 330 Ma) (Gibergy, 1968). However, a U/Pb zircon age of 336± 5 Ma was recently obtained for a granitoid intrusion within the Taillefer unit in the Pelvoux massif (Fréville, 2016). The Taillefer unit experienced a green schist facies metamorphism coeval with ductile deformation (Barfety et al., 1972). The Taillefer unit rocks unconformably overlie the Rioupéroux-Livet unit (Carme, 1965b), and both units were involved in the same tectonic-metamorphic event. On the basis of the geochemical tholeiitic signature with evidence for crustal contamination of the magmatic
rocks, the Taillefer unit was interpreted as a back-arc basin developed on a thin continental crust (Vivier et al., 1987).

As regards the tectonic history, several studies (Fernandez et al., 2002; Guillot et al., 2009; Guillot and Ménot, 2009) lead to the following evolution: (i) an early Devonian nappe emplacement represented in the SW Belledonne by a top-to-the-NNW thrusting related to an early obduction of the Chamrousse ophiolite complex; (ii) a Visean nappe stacking responsible for the back thrusting of the Chamrousse ophiolitic complex onto the Rioupéroux-Livet unit, and the top-to-the-ENE shearing within this unit; and (iii) a Westphalian-middle Stephanian extensional tectonics allowing the emplacement and metamorphism of the Allemont migmatitic unit.

3. Structural analysis

Macro- and microstructural investigations in the southwestern part of the Belledonne Massif enable the recognition of a succession of two main ductile deformation phases, called D1 and D2. In what follows the deformation features are described from the top to the bottom of the tectonic pile, and from west to east. Table 1 summarizes the structural features and the tectonic and metamorphic events identified in this study over the southwestern portion of the Belledonne Massif.

3.1 D1 deformation: Nappe stacking

The main planar fabric of the Chamrousse ophiolitic complex is defined as a metamorphic foliation S1, which mostly parallels the primary bedding, which may correspond to magmatic layering. S1 strikes N-S to NE-SW and dips mainly toward the west, but E- or SE-vergent post-folial folds may disturb the S1 dip (Figs. 2, 5, 6). S1 is superimposed on the deformation related to the rifting event and represented by a NW-SE trending lineation and top-
to-the-NW shearing described by Guillot et al. (1992). Along the tectonic contact between the Chamrousse and Rioupéroux-Livet units (i.e. the RT), and the low angle internal ductile thrust within the Chamrousse unit, $S_1$ becomes very penetrative and exhibits mylonitic fabrics (Fig. 3A). The $S_1$ planar fabric comprises an E-W- to NE-SW-trending mineral and stretching lineation $L_1$ (Fig. 6) that is well exemplified by elongated amphibole needles within amphibolite. Mafic boudins elongated along $L_1$ are also observed. Intra-folial folds ($F_1$) with axes parallel to $L_1$, are also seen. As with $S_1$, $L_1$ becomes more pronounced in the mylonitic zones that developed along the internal contacts in the Chamrousse ophiolitic complex, particularly between serpentinite and gabbro. These shear zones suggest a top-to-the-ENE motion (Fig. 3A).

In the western part of the Rioupéroux-Livet unit, the structural elements are similar to those described in the Chamrousse ophiolitic unit. The main planar fabric is a metamorphic foliation $S_1$ that strikes N-S to NE-SW and dips mainly toward the west (Figs. 3B, 3C, 3D, 3E, 5, 6). $S_1$ exhibits an E-W- to NE-SW-trending $L_1$ (Fig. 6) that defines the preferential orientation of elongated amphibole needles, biotite aggregates and elongated quartz within amphibolite and metapelite respectively (Fig. 3F). Along the $L_1$ and within the XZ plane, kinematic indicators observed in the field or in thin sections are in agreement with a top-to-the-E shearing (Figs. 3C, 3D, 7A, 7C).

$F_1$ isoclinal folds emphasized by the attitudes of several quartz-rich layers within the volcanosedimentary rocks are observed. $S_1$ and $F_1$ intrafolial folds strike N-S and dip gently to the west (Figs. 3B, 3D, 6). Furthermore, the $D_1$ fabric observed in the Rioupéroux-Livet reworked has an earlier bedding, ($S_0$), preserved as plagioclase-rich leucocratic layers in a few $F_1$ fold hinges (Figs. 3B, 8A).

In the easternmost part of the Rioupéroux-Livet unit, a $D_1$ strain gradient is documented by the progressive development of a mylonitic zone at the base of the unit (Fig. 3E, 5). Several
mylonitic bands, moderately westward-dipping (30° - 50°) and a decimeter to several meters thick, exhibit a pervasive E-W trending, stretching lineation (L1), along which top-to-the-E shear criteria, such as sigmoidal veins, drag folds and sigmoidal blasts are observed (Figs. 3C, 3D, 3E, 7C, 7D). These mylonitic bands correspond to a high-strain zone, approximately 1 km thick, here named the Allemont shear zone (ASZ) (Figs. 2, 5A). Thus along the eastern part of the Belledonne Massif, a D1 strain gradient increasing from west to east is observed. As described in the next section, the increase in metamorphic grade and the onset of partial melting is consistent with this east-directed strain gradient, which is interpreted here as being related to the D1 nappe stacking event.

Within the Allemont migmatitic unit the early D1 structural elements were partially erased during the melting, nevertheless when observed they exhibit the same geometric features as those described within the Rioupéroux-Livet unit. Moreover, the biotite and quartzo-feldspathic leucosomes define a preferred mineral orientation parallel to S1. In what follows, this planar structure is also considered to be coeval with the S1 observed in the Rioupéroux-Livet unit.

An early deformation attributed to S1, characterized by relict N-S-striking and westward dipping foliation, is also observed in the Série Satinée unit (Fig. 6). It is worth noting that the D1 event described here in several units is not observed in the Taillefer unit (Table 1).

### 3.2 NW-SE D2 shortening

In the southwestern part of the Belledonne Massif, in both the inner and outer branches, N000°E to N030°E striking, upright or slightly eastward overturned, km-scale F2 folds are observed (Fig. 2). These structures belong to the D2 deformation as S1 is folded along a broad N030°E trending sub-horizontal axis with sub-vertical or steeply westward dipping axial planes (Figs. 2, 4A, 4B, 4C, 6). Commonly, the F2 long limbs are moderately (20° to 40°) west dipping,
and the short limbs are sub-vertical (Fig. 5). At the centimeter- to decimeter-scale F2 folds tend to be more upright (Fig. 4A). The D2 deformation is responsible for a refolding of L1 in which the initial D1 E-W trend becomes parallel to a NE-SW direction (Figs. 3F, 8B, 8C). The D2 linear fabric is dominated by a NE-SW trending, weakly SW plunging L2 crenulation lineation that parallels the meter-scale F2 fold axes (Figs. 4D, 6). The L2 crenulation lineation is observed in the Chamrousse ophiolitic complex, the Rioupéroux-Livet unit and the Taillefer unit (Fig. 4D), as well as in the Série Satinée unit (Fig. 6).

D2 shearing with opposite kinematics, attested by mm- to cm-scale shear bands is recognized along F2 flanks (Figs. 4B, 4E, 4F, 7B and 8D). These opposite senses of shear, coeval with F2 folding, can also be seen at the microscopic scale (Fig. 7B). Owing to the geometry of F2 folds, with long flanks dipping toward the WNW, the apparent top-to-the-W sense of shear is preponderant (Figs. 4E, 8D). These shear bands are easily observed in the plane perpendicular to the L2 crenulation lineation (Fig. 8D). The Allemont migmatitic unit is also deformed by the D2 folding. Asymmetric pockets of melt (Figs. 4B, 4E) and shear bands (Figs. 4B, 4E, 4F) show a top-to-the-NW or top-to-the-SE shearing.

Within the Rioupéroux-Livet unit, S2 is subvertical and strikes NE-SW (Figs. 4C, 6). The S2 foliation is mostly observed near the hinge of F2. S2 is very penetrative in metapelitic layers and less so in the more competent volcanoclastic layers (Fig 4A, 4C, 8A). In the Rioupéroux-Livet unit near Allemont, a NW-SE-directed D2 shortening gradient is marked by the tightening of upright folds (Figs. 4A, 5B), and by the development of meter-scale S2 corridors along which the S0-1 foliation is transposed (Fig. 8C).

Within the Taillefer unit, an S2 slaty cleavage pervasively develops: it strikes NE-SW and dips steeply, predominantly to the NW. It is well recorded within the black shale sediment but may be observed in the terrigenous and volcanic rocks as well. The elongation of quartz pebbles defines an L2 stretching lineation with a NE-SW trend and moderate plunge. Since the planar
and linear structures observed in the Taillefer unit exhibit the same orientation as the D₂ structures recognized in the Rioupéroux-Livet unit, they are attributed to the D₂ event (Table 1).

In summary, two main phases of penetrative deformation are easily recognized along the Romanche valley, namely an earlier D₁ deformation event corresponding to an eastward nappe stacking, and a subsequent D₂ deformation event attributed to a general NW-SE-directed shortening.

4. Petrological analysis

Two samples from the Rioupéroux-Livet unit and one from the Allemont migmatitic unit were selected to place thermobarometric constraints on the deformation events described in the previous section. Sample locations are shown in figures 2 and 5. From west to east, the samples are i) a staurolite-garnet micaschist (MCE56Va), sampled near Livet (Figs. 2, 5A); ii) a kyanite-garnet micaschist (MCE240) from the eastern part of the Rioupéroux-Livet unit (Figs. 2, 5A); and iii) a garnet-bearing metatexite (MCE195a) that comes from the Allemont migmatitic unit (Figs. 2, 5A). Electron Microprobe Analyses were performed, using a CAMECA SX100 at the University of Lille, France. Results are presented in Table 2.

4.1 Sample petrography and mineral chemistry

Garnet-kyanite micaschist (MCE240)

Sample MCE240 is a fine-grained micaschist with an S₁ planar fabric defined by the preferred orientation of platy biotite and muscovite grains (Fig. 9A). The S₁ foliation wrapped around inherited mm- to cm-scale lenses displays a garnet + biotite + muscovite + kyanite + albite + plagioclase + quartz assemblage (Fig. 9A). These lenses are devoid of any clear microstructural elements. Garnet appears as fractured mm-sized porphyroblasts. The garnet’s chemical
composition ranges from ca. Alm$_{65}$; Py$_{06}$; Grs$_{21}$ and Spss$_{09}$ in the core to ca. Alm$_{70}$; Py$_{10}$; Grs$_{19}$ and Spss$_{01}$ in the rim (Table 2). Kyanite grains are mm sized and highly retrogressed, with the development of secondary white mica (Mu2) (Fig. 9A). Plagioclase is homogeneous in composition with Ab$_{78}$-89. Biotite grains exhibit an average X$_{Mg}$ ranging between 0.42 and 0.45 (Table 2).

Garnet-staurolite micaschist (MCE56va)

The MCE56va rock consists of a fine-grained micaschist with a garnet + staurolite + biotite + muscovite + quartz main assemblage (Fig. 9B). The S$_1$ planar fabric is defined by the preferred orientation of micas (Fig. 9B). Garnet and staurolite grains appear as mm-sized porphyroblasts with asymmetric quartz pressure shadows indicating a top-to-the-East shearing along the plane parallel to L$_1$. Garnet porphyroblasts are subhedral, rich in quartz inclusions, and have a homogeneous composition of ca. Alm$_{80}$; Py$_{14}$; Grs$_{6}$ and Spss$_{004}$. Subhedral staurolites reach 0.5 to 1 mm in size and have X$_{Fe}$ contents ranging from 0.87 to 0.89. Biotite has a variable composition with an X$_{Mg}$ ranging between 0.45 and 0.49 (Table 2).

Garnet-bearing metatexite (MCE195a)

Sample MCE195a consists of an assemblage of garnet, biotite, muscovite, plagioclase, quartz (Fig. 9C) and rare sillimanite (<1%). Platy muscovite and biotite grains define the planar fabric (Fig. 9C). Sillimanite grains oblique to the S$_1$ foliation suggest late crystallization (see insert in Fig. 9C). Garnet appears as small µm-sized subhedral grains that nucleate around biotite grains (Fig. 9C). Garnet is homogeneous in composition with ca. Alm$_{75}$; Py$_{10}$; Grs$_{03}$ and Spss$_{10}$. Biotite has an X$_{Mg}$ around 0.46-0.48 (Table 2). The mm-to cm-thick leucocratic layers have a mineral assemblage of quartz, plagioclase, and rod-shaped muscovite grains.

4.2 P-T metamorphic conditions
The P-T metamorphic conditions were obtained from computation of phase diagram sections calculated in the MnO-Na₂O-CaO-K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O (MnNCKFMASH) system for micaschists. Calculations were performed with Perple_X'6.7.1 (Connolly and Pettini, 2002; Connolly, 2005) using bulk rock compositions that were obtained by WD-XRF analysis at the University of Lausanne, Switzerland (Table 3). Thermodynamic data for end-members are from the updated version of the internally consistent thermodynamic dataset of Holland and Powell (1998), revised in Coggon and Powell (2002). Solid-solution models and end-member phases considered in the pseudosection calculations are listed in Table 4.

Results for Sample MCE240 are presented on Figure 10. The amount of water used in the P-T pseudosection modeling is determined by the calculation of a T-XH₂O pseudosection (XH₂O stands for the amount of water in the bulk composition). It appears that H₂O content is the critical parameter influencing the stability of garnet + chlorite vs garnet + kyanite assemblages (Fig. 10A). Considering H₂O as a saturated component, the garnet + chlorite assemblage is stable but kyanite is not predicted. The peak temperature equilibrium assemblage observed in the rock sample, i.e., biotite + plagioclase + muscovite + garnet + kyanite + albite + quartz, is predicted to be stable at undersaturated conditions only (Fig. 10A). To estimate the H₂O content we considered the LOI (2.3wt%, corresponding to 0.0127 mol) to represent XH₂O=1. The T-XH₂O diagram shows that the kyanite-bearing equilibrium is stable for an XH₂O=0.6, for T<660°C and P=0.7 GPa. We then used the corresponding molar content (H₂O=0.083) to calculate the P-T pseudosection shown in Figure 10B. The predicted P-T fields of the observed main paragenesis (biotite + muscovite + plagioclase + albite + garnet + kyanite + quartz) are predicted to be stable for PT conditions from 310 °C to 450°C and 0.3 GPa to 0.78 GPa, respectively (Fig. 10 B). The chemical composition of the garnet rim and isopleth contouring allow us to refine the P-T conditions to 0.68 ± 0.1 GPa and 427 ± 16 °C (Fig. 10B). The garnet core chemical composition provides prograde P-T estimates at 0.33 ± 0.05 GPa and
370 ± 25°C (Fig. 10). A second P-T pseudosection is proposed, to take into account the garnet fractionation during prograde metamorphism, since it has been demonstrated that 2 vol% of garnet can significantly affect garnet isopleth thermobarometry (Lanari and Engi, 2017).

Figure 10C shows the P-T pseudosection calculated from a new bulk composition after 5% of garnet fractionation. A point-counting estimation revealed a maximum of 8-10 vol% of garnet in Sample MCE240. However, for the P-T conditions of the garnet core, thermodynamic computation predicts less than 5vol% of garnet (for instance, 1.8 wt% at 0.3GPa and 360°C with a garnet-core composition). We chose to consider a 5% fractionation. Based on this value we recalculated a bulk rock composition minus the contribution of 5vol% of garnet with a core composition, (in wt%) of: SiO2, 65.82; Al2O3, 14.47; Fe2O3, 5.74; MgO, 1.97; CaO, 0.35; Na2O, 1.79, K2O 3.43; TiO2, 0.81; MnO, 0.0; H2O 2.34. The major typology differences between the two P-T pseudsections (Bulk 1 and Bulk 2 (-5%grt)) are shown in figure 10D. First, the removal of 5vol% of garnet lead to a shift to lower temperature of the kyanite-out boundary. Secondly, the biotite + muscovite + plagioclase + albite + garnet + kyanite + quartz stability field area is reduced, with a change in pressure condition from ca. 0.55±0.2 GPa to 0.475±0.1 GPa. The XCaGrt isopleths are shifted to lower temperatures and pressures. The XMgGrt isopleth typology remains similar (Fig. 10D). Accordingly, we consider that the best estimation for the peak P-T conditions recorded by sample MCE240 is P=0.535±0.045 GPa and T=427.5±17.5 °C.

For Sample MCE56Va, the P-T diagram was computed with H2O as a saturated component. In this condition, the pseudosection of Sample MCE56va (Fig. 11A) shows the stability field of biotite + muscovite + garnet + staurolite + quartz + H2O equilibrium ranging between 0.43 GPa and 0.74 GPa and 575°C and 640°C (Fig. 11A). Isopleth contouring of the chemical compositions of biotite and garnet enable us to refine the P-T conditions to 0.58 ± 0.06 GPa and 608 ± 14 °C (Fig. 11A).
For the migmatite (Sample MCE195a), the water content used in the pseudosection calculation cannot be deciphered solely on the basis of the bulk composition analysis. For high temperature conditions, the amount of water involved was determined via the calculation of a T-X$_{H2O}$ pseudosection, such that the solidus is water-saturated at 0.7 GPa (Figure 11B). Thermodynamic modeling of the migmatitic Sample MCE195a shows a stability field for biotite + muscovite + plagioclase + garnet + quartz + melt ranging between 0.66 GPa and 0.9 GPa and 650°C to 700°C (Fig. 11B). Under these conditions, the volume fraction of melt predicted at the peak conditions by the model is 0.06vol%. Garnet chemical composition constrains the peak P-T conditions to 0.78 ± 0.07 GPa and 680.5 ± 11.5 °C (Fig. 11B).

To sum up, two metamorphic events are documented from these petrological results. The first is characterized by the kyanite-bearing metapelite MCE240, and records a medium pressure – low temperature (MP-LT) metamorphism. The second event corresponds to a medium pressure – high temperature (MP-HT) metamorphism recorded by the staurolite-garnet micaschist MCE56Va and the migmatite MCE195a. The MP-HT conditions are interpreted as those of the D$_1$ nappe stacking event. Such thermodynamic modeling results are consistent with field observation and argue for an eastward increase in temperature up to partial melting (Fig. 5A).

5. Geochronological constraints

In the SE Belledonne area, radiometric data are rare, and some of them were acquired more than 30 years ago. The advances in analytical techniques and the development of in situ and in-context methods allow us to refine the timing of the evolution of this Variscan segment. In this section zircon and monazite age data from several tectonic units are presented and discussed.
Zircon SIMS U-Pb age of the plagioclase-rich leucocratic sills in the Rioupéroux-Livet unit

As mentioned in the previous sections, several plagiogranitic dykes and sills intrude the bimodal volcanoclastic rocks of the Rioupéroux-Livet unit. Sample MCE116, collected near Rioupéroux just below the RT, is one of these plagioclase-rich leucocratic sills, (located at 45° 5'17.99"N; 5°53'50.80"E; Fig. 2). This rock comprises an assemblage of quartz and plagioclase with some late chlorite and epidote, developing along fractures from Ca-rich plagioclase, and secondary calcite probably developed during Cenozoic Alpine events. Plagioclase, up to 2-3 mm in size, exhibits a clear oscillatory zoning (Fig 12B). Zircon grains were carefully handpicked under a binocular microscope, placed on an epoxy mount and polished. Sixty zircon grains were selected for SIMS U-Pb analyses, performed at the Institute of Geology and Geophysics of the Chinese Academy of Sciences, Beijing. The Plešovice zircon (Sláma et al., 2008) standard was measured to monitor the accuracy and yielded a concordia age of 335.3 ± 2.5 Ma (N=14, MSWD=0.43), which is in good agreement with the reported ID-TIMS age of 337.1 ± 0.4 Ma (Sláma et al., 2008). The methodology employed is described in Li et al. (2009) and Do Couto et al. (2015). The zircon grains exhibit a well-developed magmatic oscillatory zoning, typical of a magmatic origin (Corfu et al., 2003) (Table 5; Fig. 12C). U and Pb contents range between 70-685 ppm and 4-40 ppm respectively. These zircon grains yield a concordant age of 352 ±1 Ma (N=60; MSWD=0.66) (Fig. 12A). This age is interpreted as the age of magmatic emplacement of the plagioclase-rich sills’ protolith.

Detrital zircon ages from the Série Satinée turbidite

Ninety-nine detrital zircon grains extracted from a sandstone of the Série Satinée turbidite (MC5) sampled near the Lac Mort, near Laffrey (45° 2'8.73"N, 5°47'29.48"E, Fig. 2)
were analyzed by LA-ICP-MS at the Institute of Geology and Geophysics of the Chinese Academy of Sciences, Beijing, following the protocol described by Wang et al. (2010).

These zircon grains were carefully handpicked under a binocular microscope, placed on an epoxy mount and polished. The zircons were selected to represent the full variation in shape, color and size of the zircons in the rock sample. In this study, we excluded zircon age analyses with discordances higher than ±10%. The majority of analyses (98 grains) exhibit a main Neoproterozoic peak at ca. 600-645 Ma, along with subordinate peaks at 800, 900, 2100, and 2800 Ma (Fig. 13). The absence of Mesoproterozoic ages is typical of North Gondwana derived materials (Melleton, 2008 and reference therein). The youngest zircon grain yields an age of ca. 463 Ma, providing a maximum estimate for the deposition age of this sandstone in Ordovician times (Table 6; Fig 13).

*Detrital zircon ages from the Taillefer conglomerate*

One hundred and twelve detrital zircon grains extracted from a conglomerate of the Taillefer unit sampled in the Southern part of Taillefer massif (44°54′35.13″N, 5°56′50.69″E; Figure 1) were analyzed by LA-ICP-MS at the Université Rennes 1 using a ESI NWR193UC Excimer laser system coupled to an Agilent 7700x quadrupole ICP-MS. The analytical protocol may be found in Manzotti et al. (2016) and the analytical conditions in Supplementary Table 1. Along with the unknowns, the Plešovice zircon (Sláma et al., 2008) standard was measured to monitor accuracy and yielded a $^{206}\text{Pb}/^{238}\text{U}$ concordia age of 336.3 ± 3.3 Ma (N=6, MSWD=0.54), which is in good agreement with the reported ID-TIMS age of 337.1 ± 0.4 Ma (Sláma et al., 2008). In this study, we excluded zircon analyses with a discordance greater than ±10%.

The main population (104 grains) defines an Ordovician peak at ca. 450 Ma and a second major upper Cambrian peak in the 500-550 Ma range. Subordinate peaks at 600-800 Ma, 2100, 2600
and 2900 Ma are also observed (Figure 14). Some Mesoproterozoic ages are also seen. The youngest concordant zircon provides a Devonian age of ca. 395 Ma, implying a post late early Devonian deposit (Table 7, Figure 14).

LA-ICP-MS U-Pb dating of monazite from micaschist in the Rioupéroux-Livet unit

LA-ICP-MS U-Pb analyses on seven monazite grains from a biotite-garnet-staurolite micaschist (MCE56Va; 45° 6’38.81”N, 5°56’3.63”E, Fig. 2), were carried out at the Université de Montpellier II following the procedure described in Bruguièr et al. (2009). Analyses were conducted on a polished thin section (Supplementary Table 2), thereby preserving the textural context of the dated grains. The dated monazite grains are elongated in the metamorphic foliation (S₁) of the micaschist, and they show no chemical zoning (Fig 15 A, 15B). Two slightly concordant analyses and 5 discordant analyses, with common lead content, are spread along a discordia curve line representing a mixing between radiogenic and common with theoretical common Pb values. In a Tera-Wasserburg concordia diagram, a regression through the data points yields an intercept age of 337 ± 7 Ma (MSWD=0.17).

The textural relationships, as well as grain contacts between monazite, biotite, staurolite and the development of monazite grains along pressure shadows, indicate that the crystallization of monazite took place during amphibolite facies metamorphism (Fitzsimons et al., 2005). We therefore consider that the age of 337 ± 7 Ma obtained corresponds to the D₁ tectonometamorphic event (Table 8; Fig. 15C).

6. Discussion

6.1 Tectonometamorphic evolution
Two metamorphic stages are evident from our thermobarometrical work. MP-LT metamorphism (Mx) is recorded in a lens of kyanite-bearing micaschist from the Rioupéroux-Livet unit. The P-T estimates indicate a prograde evolution from $0.33 \pm 0.05$ Gpa and $370 \pm 25^\circ C$ up to $0.535 \pm 0.045$ Gpa and $427.5 \pm 17.5^\circ C$ (Fig. 16). The strain fabric associated with the Mx kyanite-bearing assemblage remains unknown owing to the intense D$_1$ and D$_2$ overprint. Nevertheless, an early MP-LT Dx/Mx tectonometamorphic event has already been described by Guillot and Ménat (1999). We suggest that the Dx/Mx event documented here may correspond to the thrusting at the mid-crustal level of the Chamrousse ophiolite upon the Rioupéroux-Livet unit, from west to wast.

The second metamorphic event (M$_1$) is recorded in the staurolite-bearing micaschist from the Rioupéroux-Livet unit, with peak conditions of $0.58 \pm 0.06$ GPa and $608 \pm 14^\circ C$. In agreement with Guillot and Ménat (1999), M$_1$ is interpreted as coeval with the top-to-the-E nappe stacking event responsible for the penetrative D$_1$ fabric ($S_1$, $L_1$, $F_1$) observed in the Chamrousse ophiolitic complex, the Rioupéroux-Livet unit and the Allemont migmatitic unit. It is worth noting that the Série Satinée unit recorded a pre-D$_2$ event, which could correspond to the D$_1$ event (Simeon, 1979). Absence of the D$_1$ deformation in the Taillefer unit is in agreement with its post-D$_1$ (Visean) deposition age, as proposed by Gibergy (1968). In our interpretation, the D$_1$/M$_1$ event is the main tectonometamorphic phase experienced by the SE part of the Belledonne Internal Domain, whereas it was previously considered to be a back-thrusting event (Guillot and Ménat, 1999). Previous works (Fernandez et al., 2002; Guillot et al., 2009; Guillot and Ménat, 2009) proposed a top-to-the-NW shearing event responsible for the nappe stacking in the Chamrousse ophiolite, followed by a back thrusting of this realm. However, recent studies show that during the Alpine orogeny the deformation was partially accommodated in the Variscan basement along shortening structures characterized by east-dipping Alpine shear zones with top-to-the-NW kinematics (Bellahsen et al., 2014; Bellanger...
et al., 2014, 2015). Accordingly, we argue that the top-to-the-W shear bands are related to the Alpine events and that an early NW-directed nappe stacking event is unlikely.

The M₁ event recorded in the Rioupéroux-Livet unit corresponds to the partial melting of the Allemont unit micaschist, under the P-T conditions of 0.78 ± 0.07 GPa and 680.5 ± 11.5°C obtained from a metatexite (Fig. 16). On the basis of the apparent top-to-the-W shear bands in the Allemont and Rioupéroux-Livet units, a southwesterly extensional event has been invoked to accommodate the exhumation of the Allemont migmatitic unit (Fernandez et al., 2002; Guillot et al., 2009; Guillot and Ménot, 2009, 1999). Based on our structural analysis, we suggest that the top-to-the-W shear bands are instead the result of the D₂ shortening event developed in the west-dipping limbs of the F₂ folds. We also documented the D₂ as a pervasive event corresponding to a bulk NE-SW shortening observed in the Série Satinée unit of the western Belledonne, the Chamrousse ophiolitic complex, and the Rioupéroux-Livet, Allemont migmatitic and Taillefer units. D₂ is also responsible for the partial reorientation of the E-W trending L₁ lineation into a N30-trending direction.

In previous studies, the D₂ tectonometamorphic event was poorly documented and more commonly associated with the nappe stacking event, with the L₂ crenulation lineation interpreted as the result of interference between D₁ and an earlier west-directed deformation phase (Fernandez et al., 2002; Guillot et al., 2009). The N30-trending stretching lineation corresponding to the reoriented L₁, was previously interpreted as related to late dextral strike slip shearing along the East Variscan Shear Zone (Guillot et al., 2009). Moreover, the petrologic analysis, as well as the age of the equivalent unit in the Pelvoux massif (330 ± 3 Ma, (Fréville, 2016)) shows that the migmatization that occurred at the end of the prograde M₁ metamorphism, was contemporaneous with the syn-D₁ crustal thickening event. We therefore prefer to interpret the migmatization in the Allemont migmatitic unit as the result of syn-collisional prograde
metamorphism rather than as the expression of a late Carboniferous extensional event 
(Fernandez et al., 2002; Guillot et al., 2009; Guillot and Ménot, 1999, 2009).

In agreement with previous petrological studies that documented the presence of 
sillimanite in the Allemont unit (Guillot and Ménot, 1999), our results support an eastward 
temperature increase, reaching its climax at the base of the nappe pile. Although not observed 
during our study, cordierite has been reported in the Allemont migmatitic unit and interpreted 
as coeval with the deformation responsible for the shear band development (Guillot and Ménot, 
1999). However, the crystallization of cordierite, unambiguously coeval with a late increment 
of the D2 event, took place during the exhumation of the migmatite, but this might also have 
ocurred during bulk shortening.

6.2 Timing of the tectonic, magmatic and metamorphic events

The absolute timing of the tectonometamorphic events is poorly documented, in 
particular for the early MP-LT event. Nevertheless, the Dx event might be bracketed between 
approximately 500 Ma and 355 Ma, corresponding to the age of the Chamrousse ophiolitic 
complex and the age of the bi-modal magmatism of the Rioupéroux-Livet unit respectively. 
Based on hornblende 40Ar/39Ar dating from amphibolite at the base of the ophiolitic nappe, 
Guillot et al. (2009) proposed an age of ca. 376 ± 7 Ma for the Dx event.

The absolute ages of the D1 and D2 events remain undocumented. Nevertheless, 
considering the K-Ar dating on amphibolite (Ménot et al., 1987) and the granite emplacement 
age (Debon et al., 1998) that postdate the D1 phases, Guillot et al. (2009) considered that the 
nappe stacking event occurred between 341 ± 13 Ma and 324 ± 13 Ma. In our study, the 
monazite age from the staurolite-bearing micaschist defines the age of prograde metamorphism 
(M1) at 337 ± 7 Ma, coeval with the nappe stacking event (D1).
The deposition location, the deposition age and the deformation age of the Taillefer unit within the nappe pile remain uncertain. As shown above, this unit was assumed to be Visean in age, and was interpreted as being unconformably deposited upon the ophiolitic complex and the Rioupéroux-Livet unit (Carme, 1965a, 1965b; Gibergy, 1968). The Taillefer’s sedimentary rocks may have been deposited during a Visean extensional phase (Guillot et al., 2009). However, no Visean extensional features have been recognized in the SW Belledonne area. Furthermore, the absence of detrital Carboniferous zircon in the Taillefer conglomerates (Fig. 14) is not in agreement with the development of any rift-related basin since volcanic zircon clasts would be expected there. Moreover, a recent study in the Pelvoux area showed that the Taillefer unit is intruded by a Carboniferous granitoid emplaced at 336 ± 5 Ma (U/Pb, zircon, Fréville, 2016). These new data imply that the Taillefer unit was already emplaced on the top of the nappe pile during the D1 event, before this granitoid intrusion. We therefore propose that the Taillefer unit may correspond to a thrust sheet emplaced during the late stage of the D1 event. Finally, the D2 event occurred during the late Carboniferous (i.e., 330-300 Ma), which is in agreement with the ages of 330 Ma and 325 Ma already proposed by Guillot et al. (2009) and Guillot and Ménot (2009).

It was previously proposed that the nappe stacking event was followed by the tectonic juxtaposition of the Série Satinée unit and the Eastern Domain along the SMF between 305 and 270 Ma, in response to large displacements accommodated by the East Variscan Shear Zone (Guillot et al., 2009; Guillot and Ménot, 2009). Nevertheless, if the upright folding experienced by the Série Satinée is the same as the D2 deformation in the Internal Domain, the Série Satinée unit must have reached its present location before the onset of the D2 event (Late Carboniferous). Assuming that the Série Satinée unit experienced the D1 event implies that this unit was already in its present position before the D1 event, which occurred at ca. 340 Ma, and it should therefore have recorded the MP-LT Mx metamorphism. If the Série Satinée unit was
already in its present location before the Visean, then the Late Carboniferous EVSZ cannot account for the position of this part of the Variscan basement as previously proposed (Corsini and Rolland, 2009; Guillot et al., 2009; Guillot and Ménat, 2009; Padovano et al., 2012).

An interpretative tectonic scenario is proposed in Figure 17, which presents the succession of deformation events and related P-T paths from 400 to 300 Ma:

(1) From ca. 400 Ma to 380 Ma, the westward subduction of the Chamrousse oceanic domain was responsible for the eclogite that crops out in the NE Belledonne (Fig. 17A).

(2) Between ca. 380 Ma and ca. 360 Ma a slice of the oceanic domain was overthrust towards the east, forming the Chamrousse ophiolitic nappe. This corresponds to the Dx tectonic event, which is responsible of the MP-LT metamorphism recorded in the Rioupéroux-Livet unit (Fig. 17B).

(3) From ca. 360 Ma to ca. 350 Ma, the Rioupéroux-Livet magmatic rocks were emplaced as sill intrusions into the thinning crust during rifting. We have as yet no reliable evidence allowing us to identify the cause of rifting. The age of the Rioupéroux-Livet unit was previously considered to be 367-362 Ma based on K/Ar dating on amphibole and 367 ± 17 Ma and 352 ± 55 Ma by the U/Pb method on zircon (Ménat, 1986; Ménot et al., 1985, 1987, 1988). In agreement with Ménot (1986), the zircon ages obtained in this study suggest that the Rioupéroux-Livet bimodal magmatism took place during the Tournaisian at 352 ± 1 Ma. In this interpretation we suggest that the Taillefer volcanic-elastic sedimentary rocks were deposited at that time (Fig. 17C).

(4) From ca. 350 to ca. 330 Ma, the D1 event was responsible for nappe stacking and crustal thickening that lead to MP-HT metamorphism. Partial melting of the deep crust proceeded from late prograde metamorphic evolution (Fig. 17D). As argued above, the thrusting of the Taillefer unit toward the east may have occurred during the late-D1 period.
(5) From 330 to 310 Ma, the D₁ tectonic pile was folded by the D₂ horizontal NW-SE shortening (Fig. 17E). The D₂ deformation may have occurred during peak temperature and retrograde evolution. One may consider that the transition from D₁ to D₂ results from progressive deformation causing overlap between late-D₁ and early-D₂ structures.

6.3 Comparison with some neighboring Variscan domains.

The major portion of the ECMs consists of magmatic rocks and granitoids especially in the easternmost domain (Fig. 1). Early Paleozoic ophiolites, such as the Chamrousse examples, are not recognized in other parts of the ECMs, thus, a direct comparison between the SW part of the Belledonne Massif and the Eastern domain is not straightforward. Nevertheless, the SW part of the Aiguilles Rouges Massif displays some lithological and structural features similar to those described here in the Belledonne Massif. Three units are recognized in the SW section of the Aiguilles Rouges Massif (Dobmeier, 1998), These are: (i) a Visean unit made up of metagraywackes and metavolcanites that can be compared to the Taillefer unit; (ii) greenschist and amphibolite facies metamorphic units composed of micaschists and epidote-amphibolites, comparable to the Rioupéroux-Livet unit; and (iii) a gneissic unit with incipient traces of partial melting. These units reveal a tectonometamorphic evolution similar to that of the SW Belledonne Massif with an east-directed thrusting event that emplaced the greenschist and amphibolite facies metamorphic units upon the migmatitic gneissic unit. As for the Rioupéroux-Livet unit, this nappe stacking event is coeval with similar metamorphic PT conditions (0.65 GPa and 600 °C) dated at ca. 331-337 Ma (Dobmeier, 1998; Von Raumer et al., 1999). This event would probably correspond to the D₁ event recorded in the SW part of the Belledonne Massif. After the thrusting of the Visean metagraywacke and metavolcanite unit (similar to the Taillefer unit), an E-W bulk shortening event is reported (Von Raumer et al., 1999) that might correspond to the D₂ event recorded in the Belledonne Massif.
To the south, in the Argentera Massif (Fig. 1), in spite of the recognition of HP metamorphic rocks and migmatites (Compagnoni et al., 2010; Paquette et al., 1989; Rubatto et al., 2010), the Variscan deformation sequence is not clearly identified, owing to a strong Alpine overprint. Nonetheless, recent U-Pb geochronological studies argue for a Carboniferous HP metamorphism recorded by zircons dated at 340.7 ± 4.2 Ma and 336.3 ± 4.1 Ma, within HP granulites that recorded peak PT conditions of ca. 1.4 GPa and 735 ± 15 °C (Ferrando et al., 2008; Rubatto et al., 2010). These Carboniferous ages in the Argentera Massif are in agreement with the D₁/M₁ event reported in the Belledonne Massif and can be related to the same crustal thickening.

In the Maures Massif, a polyphase synmetamorphic deformation was documented in the mid-1960s (e.g. Arthaud et al., 1966; Oliot et al., 2015 and enclosed references). It comprises a first top-to-the-W shearing that appears to be the main tectonic event, followed by a back-folding event. Although the same tectonic succession is reported with nappe stacking followed by folding, the lithological and structural correlation between the Belledonne and Maures massifs cannot be unambiguously confirmed.

Farther south, in Variscan Corsica, a northern domain (in current geographic coordinates) characterized by gneisses and amphibolites (partly retrogressed from eclogitic metagabbros) experienced a top-to-the-NE ductile shearing coeval with an MP-MT metamorphism (Faure et al., 2014). This tectonic event could be related to the D₁ nappe stacking event described in the SW Belledonne Massif.

At a larger scale, on the basis of a recent review (Lardeaux et al., 2014), a tentative first-order comparison of the tectonometamorphic evolution of the Belledonne Massif and other Variscan massifs, such as the French Massif Central, Vosges, and Bohemian Massifs could be suggested. The Carboniferous evolution of the Belledonne Massif described in this review may exhibit certain similarities with the tectonometamorphic history recognized in the Moldanubian zone.
of the Variscan belt, for instance: i) the formation of a bimodal magmatism similar to that of the Rioupéroux-Livet unit; ii) a collisional phase coeval with an MP-HT metamorphism M₀; and iii) the Visean unconformity of the volcanosedimentary unit similar to that of the Taillefer unit. However, several lines of evidence argue against simple correlations. In particular, the bimodal magmatism of the Rioupéroux Livet unit, dated at 355 ± 1 Ma, is younger than other bimodal magmatic domains, such as the Brévenne unit in the French Massif Central, which is dated at 366 ± 5 Ma (Pin and Paquette, 1997). Also, the Brévenne unit is interpreted as a back-arc basin (Faure et al., 1997, 2009) while the geodynamic setting of the Rioupéroux-Livet unit is not yet settled. Moreover, on the basis of similar P-T conditions, the reported age of ca. 337 Ma in the Belledonne Massif, which corresponds to the D₁ nappe stacking event, might be compared to the D₂ event in the French Massif Central (Faure et al., 2005, 2009). However, the D₂ event in the French Massif Central occurred during late Devonian to early Carboniferous time, i.e., 20 Ma before the main D₁ tectonometamorphic event in the Belledonne Massif.

Based on similar lithology and age, a parallel can be made between the Taillefer unit of the Belledonne Massif and the Visean “Tufs Antracifères” series that crops out in the NE part of the French Massif Central and in the southern Vosges Massif. However, because of the lack of geochemical data on the Taillefer’s sedimentary rocks, an unambiguous correlation of this unit with the Tufs Antracifères series remains tentative for now. Concerning the possible relationships between the Belledonne Massif and the Vosges and Bohemian Massifs, further investigations are needed.

7. Conclusion

The SW part of the Variscan Belledonne Massif recorded three tectonometamorphic events, identified as Dx, D₁ and D₂ (Table. 1). The Dx event corresponds to the eastward thrusting of
the Chamrousse ophiolitic complex onto the Rioupéroux-Livet unit, causing an LT-MP metamorphism at 0.535 ± 0.045 GPa and 427.5 ± 17.5 °C (Mx). The Dx event may have occurred before 360 Ma. The bimodal magmatism of the Rioupéroux-Livet unit, occurred at 352 ± 1 Ma. The main synmetamorphic deformation event D1 occurred at 337 ± 7 Ma with peak metamorphic conditions of 0.58 ± 0.06 GPa and 608 ± 14 °C. D1 corresponds to an eastward nappe stacking event that transported the Chamrousse ophiolitic complex onto the Rioupéroux-Livet unit. The partial melting at the base of the nappe pile gave rise to the Allemont migmatite, developed at 0.78 ± 0.07 GPa and 680.5 ± 11.5 °C. During the late Visean (330-325 Ma), volcanites, sandstone and conglomerate of the Taillefer unit were thrust onto the previously deformed units (Table 1). Subsequently, the D2, NW-SE bulk shortening event, characterized by folding of the S1 foliation, and development of the NE-SW L2 crenulation, affected all units, including the Cambro-Ordovician flysch unit (the Série Satinée).

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FIGURE CAPTIONS

Figure 1. A: Location of External Crystalline Massifs (ECMs) within the Variscan belt, modified after (Faure et al., 2005, 2014; Tabaud, 2012; Talbot et al., 2005; Von Raumer, 1998). B: Geological map of ECMs, modified after (Debon and Lemmet, 1999; Guillot et al., 2009). Dashed box shows the position of Figure 2.

Figure 2. Geological map of the Southwestern part of the Belledonne Massif. The cross-sections on Figures 6A and 6B are shown by lines A and B respectively. Stars indicate samples used for thermobarometry (see Figs. 10, and 11. Squares indicate the dated samples of Figures 12, 13 and 15.

Figure 3. Outcrop photographs of structures related to D₁. A: contact between serpentinite and microgabbro in the Chamrousse ophiolitic complex showing top-to-the-NE sense of shear. B: F₁ drag fold of S₀₁ foliation showing a top-to-the-NE sense of shear in the Rioupéroux-Livet unit near Séchilienne. Note the development of axial planar foliation. C: asymmetric sigmoidal quartz-feldspar aggregates indicating a top-to-the-E-NE sense of shear. D: transposition of S₀ bedding by S₁ cleavage during top-to-the-NE motion in the Rioupéroux-Livet unit. E: mylonitic metapelite near Allemont in the Rioupéroux-Livet unit. Note the west-to-east deformation increase in the Rioupéroux-Livet unit between outcrop photographs B to E. F: Initially E-W-striking mineral lineation reoriented in the NE-SW direction close to NE-SW crenulation lineation during the D₂ folding.

Figure 4. Outcrop photographs of structures related to D₂. A: folding of S₀₁ foliation during the D₂ event in the metavolcanic rocks of the Rioupéroux-Livet unit. Note the absence of penetrative S₂ foliation. B: NE-SW-striking F₂ fold in metapelite near Allemont. Note i) the top-to-the-NW sense of shear on the NW flank and top-to-the-SE shearing on SE flank, and ii) the presence of melt pockets on each flank of the fold showing that melting is earlier than the
D$_2$ deformation. Black boxes indicate detail photographs E and F. C: S$_2$ foliation developed parallel to axial plane of F$_2$ fold in metapelite in the Rioupéroux-Livet unit. D: NE-SW striking crenulation lineation in weakly-metamorphosed schist in the Taillefer unit. E: Top-to-the-NW sheared melt pocket on the NW flank of the D$_2$ fold shown in picture B. F, Top-to-the-SE-sense of shear in the SE flank of the D$_2$ fold shown in picture B.

Figure 5. A: SW-NE cross-section through the Belledonne Massif. Stars indicate the locations of samples used for thermobarometry (See Figs. 10 and 11, B): W-E cross-section through the Taillefer unit. The two cross-sections are located on Figure 2. SMF: Synclinal Median Fault; ASZ: Allemont Shear Zone; RBE: Rivier Belle Etoile fault; RT: Rioupéroux Thrust.

Figure 6. Stereographic plots of poles of foliation planes, lineations and fold axes plotted on the lower hemisphere in equal-area projection; n represents the number of measurement. Contour interval = 10% probability of measurement values.

Figure 7. Representative photomicrographs of microstructures and mineral phases. The thin sections are parallel to the stretching lineation and perpendicular to foliation. A: sigmoidal garnet indicating a top-to-the-NE sense of shear in the Rioupéroux-Livet unit. B: conjugate shear bands developed on each flank of a D$_2$ fold in volcanoclastic facies of the Rioupéroux-Livet unit. C: sigmoidal garnet indicating a top-to-the-ENE sense of shear. D: sigmoidal kyanite indicating a top-to-the-ENE shearing related to the Dx deformation.

Figure 8. Field sketches of D$_1$-D$_2$ relationships. Quartz-feldspar-rich beds are shown in gray.
A: Folding of the S$_{0-1}$ foliation by D$_2$ folds responsible for local development of S$_2$ in metapelitic layers. B: Reorientation of L$_1$ mineral lineation by D$_2$ event. C: Tight D$_2$ folding responsible
for shortening of \( S_{0-1} \), development of \( S_2 \) foliation, and \( L_1 \) reorientation. D: Relationships between the conjugate post-folial shear bands developed on both limbs of \( D_2 \) folds, and refolding of \( L_1 \) stretching lineation. The N070E plane is parallel to the reoriented \( L_1 \) lineation.

Figure 9. Photomicrographs of mineralogical assemblages. A: Kyanite (Ky), plagioclase (Pl), garnet (Gt), muscovite (Mu), biotite (Bi), quartz (q) mineralogical assemblage observed in migmatitic metapelite of the Allemont migmatitic unit (sample MCE240). B: Garnet, biotite, muscovite, staurolite (Std), quartz mineralogical assemblage in metapelite of the Rioupéroux-Livet unit (Sample MCE-56va). C: Garnet, biotite, muscovite, plagioclase, quartz mineralogical assemblage in metapelite (Sample MCE-195a). Note the garnet overgrowth around biotite. Insert: Sillimanite grain cutting the \( S_1 \) foliation.

Figure 10: Isochemical phase diagrams of metapelite Sample MCE240 calculated for MnNCKFMASH system. See Figures 2 and, 5 for location. A. \( T\times X(H_2O) \) of Sample MCE240 at 0.7 GPa. B. Isochemical phase diagram with the original bulk (Bulk1). The predicted \( Bi + Pl + Ab + Mu + Gt + ky + q \) peak assemblage observed in thin section (Figure 9A) gives P-T conditions of \( 0.68 \pm 0.1 \) Gpa and \( 427 \pm 16 \) °C. Prograde P-T conditions are estimated at \( 0.33 \pm 0.05 \) Gpa and \( 370 \pm 25 \) °C. Dotted line represents garnet compositional isopleths for rim and core. C. Isochemical phase diagram taking into account 5% of garnet fractionation (Bulk 2). The predicted \( Bi + Pl + Ab + Mu + Gt + ky + q \) peak assemblage observed in thin section (Figure 9A) gives P-T conditions of \( 0.535 \pm 0.045 \) Gpa and \( 427.5 \pm 17.5 \) °C. Dotted line represents garnet compositional isopleths for rim. D. P-T diagram showing the major typology difference between Bulk 1 and Bulk 2. Mineral abbreviations used are: Bi, Biotite; Mu, muscovite; Chl, Chlorite; Crd, Cordierite; St, Staurolite; San, K-feldspar; Pl, Plagioclase; Ab,
Albite; mic, Microcline; gl, Glaucophane; Gt, Garnet; and, Andalusite, ky, Kyanite; sill, Sillimanite; Opx, Orthopyroxene; q, Quartz; melt, silicate liquid.

Figure 11. A: Isochemical phase diagrams calculated for MnNCKFMASH system for metapelite Sample MCE-56va. See Figures 2, 5 for location. The predicted Bi+St+Mu+Gt+q assemblage observed in thin section (Figure 9B) gives P-T conditions of $0.58 \pm 0.06$ Gpa and $608 \pm 14^\circ$C. Biotite, muscovite and pyrope compositional isopleths. B. T-X($H_2O$) of Sample MCE195a. C: Pseudosection diagrams calculated for MnNCKFMASH system for migmatitic metapelite Sample MCE-195a. See Figures 2, 5 for location. The predicted Bi+Pl+Mu+Gt+q+melt assemblage observed in thin section (Figure 9C) gives P-T conditions of $0.78 \pm 0.07$ Gpa and $680.5 \pm 11.5^\circ$C. Garnet compositional isopleths. Mineral abbreviations are the same as for Figure 10.

Figure 12. Zircon SIMS U-Pb geochronological data for plagioclase-rich sills (Sample MCE116), see Figure 2 for location. A: Concordia diagram showing a $352.4 \pm 1.4$ Ma age. B: photomicrograph showing the texture of the dated plagioclase-rich sills. C: CL image of representative dated zircon.

Figure 13. Relative probability diagram of zircon LA-ICP-MS U-Pb ages of for detrital zircon from sandstone Sample MC5 from the Série Satinée of Western Belledonne, see Figure 2 for location. Age peaks are Neoproterozoic, since no zircon younger than 463 Ma was found, an Ordovician maximum age of deposition is assumed.
Figure 14. Relative probability age diagram of zircon LA-ICP-MS U-Pb ages of detrital zircons from a conglomerate sample from the Taillefer unit. Age peaks are Cambrian, with no zircon younger than 396 Ma. Location in Fig. 1

Figure 15. Monazite LA ICP-MS U-Pb ages of metapelite (Sample MCE-56va), see Figure 2 for location. A: Location of one representative monazite grain in the S1 foliation plane. B: SEM-BSE image of representative dated monazite. C: Concordia diagram giving a lower intercept age of 337 ± 7 Ma.

Figure 16. Summary of the metamorphic conditions recorded in the southwestern part of the Belledonne Massif. The black squares are P-T data from (Guillot and Ménut, 1999). Black and gray (dashed) arrows represent inferred P-T path corresponding to the observed structures. Dx, D1, and D2 indicate the deformation phases described in this paper, including the literature data.

Figure 17. Conceptual model of the geodynamic evolution of the SW Belledonne Massif shown as schematic cross-sections through the orogen. A: Westward subduction of the Chamrousse oceanic domain at ca. 400-380 Ma. B: At ca. 380-360 Ma a slice of the Chamrousse oceanic domain is thrust eastwards, triggering an MP-LT metamorphism that defines the Dx/Mx tecto-metamorphic event. C: At ca. 360-350 Ma the bimodal magmatism of the Rioupéroux-Livet unit takes place and the Taillefer volcanosedimentary rocks are deposited; D: During the Early Carboniferous, between ca 350 Ma and 330 Ma, the D1/M1 tectonometamorphic event is responsible for eastward nappe stacking coeval with an MP-HT prograde metamorphism. E: After 330 Ma, the orogenic crust recorded the D2 event in response to a NW-SE bulk shortening.
Table 1. Summary of tectonic and metamorphic events recorded in this study for the Southwestern part of the Belledonne Massif. The two geochronological data shown [1] and [2] for the Dx event are from Ménot et al. (1988) and Pin and Carme (1987), respectively.

Table 2. Bulk rock composition in weight percent oxides for Samples MCE240, MCE56-Va, and MCE195a.

Table 3. Representative chemical compositions of minerals used for themobarometric calculation.

Table 4. List of solid solutions used in the themobarometric modeling.

Table 5. Zircon U-Pb analyses of plagioclase-rich sill MCE116.

Table 6. Detrital zircon U-Pb analyses of sandstone MC5.

Table 7. Detrital zircon U-Pb analyses of conglomerate from Taillefer unit.

Table 8. Monazite U-Pb analyses of micaschist MCE56-Va.
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Age

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Table 8

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Highlights

- A detailed petrostructural evolution of the Belledonne massif is proposed.
- New geochronological and thermo-barometrical constrains allow to refine the history of this area.
- Two main events are responsible of the variscan structuration of the Belledonne massif.
Figure 1

A

Variscan Massifs
Suture Zone
Main Fault
Alpine thrust

B

Aar
Gotthard

Aiguilles Rouges
Mont Blanc

Mesozoic cover & Quaternary deposits
Carboniferous & Permian deposits

Western domain
Micaschists

Central domain
Chamrousse Ophiolitic complex
Metavolcanites and metaconglomerates
Migmatitic volcanoclastic & volcanoclastic units

Eastern domain
(Ortho)Gneiss
Metavolcanosedimentary and metapelitic rocks
Granitoids 330-345 Ma
Granitoids 290-315 Ma
(Supposed) Migmatites
Undifferenced metamorphic rocks

Pelvoux
Argentera

20 km

Figure 2

Samples of Taillefer conglomerate Figure 14
Figure 2

Synclinal Médian Fault

Outer branch
South Western inner branch

Allemon shear zone
6° 00E

5° 50E

Places:
V: Vizille
S: Séchilienne
R: Riouperoux
L: Livet
A: Allemont
BO: Le bourg d'Oisans

Foliation:
from Bartfety et al., 1972: from this study:
0-30° 30-70° 70-90°
0-30° 30-70° 70-90°

Structure:
Variscan Thrust
Early Jurassic Fault
D, Km-scale folds axis

Samples location for:
Petrological analysis
Geochronological analysis

Lineations:
from this study:
D, Strecching lineation
D, Mineral lineation
D, Crenulation

Alluvium & glacier deposits
Mesoozoic sedimentary rocks
Migmatitic ©Allemont unit©
Metavolcanites and metaconglomerates ©Taillefer©
Volcanosedimentary rocks with metapelitic layers ©Rioupéroux Livet unit©

Chamrousse ophiolitic complex
Micaschists ©Série Satinée©
Granite
Migmatitic amphibolites

«Cortical Pelvoux»
Figure 10
Figure 11
Figure 12

Concordia Age = 352 ±1 Ma
(2σ, decay-const. errs included)
MSWD = 0.66, n=60
Probability = 0.998
Detrital Zircon of Série Satinée sandstone

Figure 13
Figure 14

Detrital Zircon of Taillefer Conglomerate

ICP-MS U/Pb$_{zr}$

Number

Age (Ma)

Relative probability

No age data

Neo-proterozoic
Figure 15

Sample MCE56-Va
Intercept at
337 ± 7 Ma
MSWD = 0.17

data-point error ellipses are 2σ

207\text{Pb}/206\text{Pb}

238\text{U}/206\text{Pb}
Figure 16

Inferred P-T path:

Dx

D1 and D2 (dotted line)
Figure 17

A  400-380 Ma
Deposition of the Série-satinée turbidic rocks
Chamrousse ophiolite

B  380-360 Ma
Dx Thrusting

C  360-350 Ma
Deposition of the Taillefer volcano-sedimentary rocks
Emplacement of magmatic rocks of the Riouperoux-Livet Unit

D  350-330 Ma
D1 Thrusting

E  330-310 Ma
D2 Shortening

Figure 17