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### ► To cite this version:

Kévin Fréville, Pierre Trap, Michel Faure, Jérémie Melleton, Xian-Hua Li, et al.. Structural, metamorphic and geochronological insights on the Variscan evolution of the Alpine basement in the Belledonne Massif (France). *Tectonophysics*, 2018, 726, pp.14-42. 10.1016/j.tecto.2018.01.017 . insu-01698809

**HAL Id: insu-01698809**

**<https://insu.hal.science/insu-01698809v1>**

Submitted on 1 Feb 2018

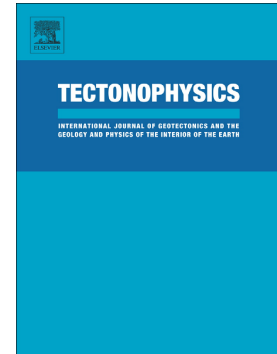
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## Accepted Manuscript

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PII: S0040-1951(18)30029-5  
DOI: <https://doi.org/10.1016/j.tecto.2018.01.017>  
Reference: TECTO 127755  
To appear in: *Tectonophysics*  
Received date: 11 April 2017  
Revised date: 12 January 2018  
Accepted date: 16 January 2018

Please cite this article as: Kévin Fréville, Pierre Trap, Michel Faure, Jérémie Melleton, Xian-Hua Li, Wei Lin, Olivier Blein, Olivier Bruguier, Marc Poujol , Structural, metamorphic and geochronological insights on the Variscan evolution of the Alpine basement in the Belledonne Massif (France). The address for the corresponding author was captured as affiliation for all authors. Please check if appropriate. Tecto(2017), <https://doi.org/10.1016/j.tecto.2018.01.017>

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

Kévin Fréville<sup>a,c,\*</sup>, Pierre Trap<sup>b</sup>, Michel Faure<sup>a</sup>, Jérémie Melleton<sup>c</sup>, Xian-Hua Li<sup>d</sup>, Wei Lin<sup>d</sup>, Olivier Blein<sup>c</sup>, Olivier Bruguier<sup>e</sup>, Marc Poujol<sup>f</sup>

\* Corresponding author: kevin.freville@univ-orleans.fr

<sup>a</sup> UMR 7327, Institut des Sciences de la Terre d'Orléans, Université d'Orléans, CNRS, 45071 ORLEANS Cedex 2, France.

<sup>b</sup> UMR 6249 Chrono-environnement, Université de Franche-Comté, 16 route de Gray, 25030 Besançon Cedex, France

<sup>c</sup> BRGM, Georesources Division, Mineral deposit studies and development unit, 3, avenue Claude-Guillemin, BP 36009 - 45060 Orléans cedex 2 – France

<sup>d</sup> State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China.

<sup>e</sup> Géosciences Montpellier, Université de Montpellier II, Place Eugene Bataillon, 34095 Montpellier Cedex 5, France

<sup>f</sup> Géosciences Rennes, UMR CNRS 6118, OSUR, Université Rennes 1, 35042 Rennes Cedex, France

**Abstract:**

A structural and petrochronological study was carried out in the southern part of the Belledonne crystalline massif. A first tectonometamorphic event, D<sub>x</sub>, 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 D<sub>1</sub> deformation is defined by a penetrative S<sub>1</sub> foliation that mostly dips towards the west and displays an E-W- to NE-SW-trending mineral and stretching lineation L<sub>1</sub>. D<sub>1</sub> 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 ( $0.58$  GPa  $\pm$   $0.06$ ;  $608 \pm 14$  °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 D<sub>1</sub> to  $337 \pm 7$  Ma. The D<sub>2</sub> tectono-metamorphic event is characterized by NE-SW trending, upright to NE-verging synfolial folding. Folding associated with D<sub>2</sub> is pervasively developed in all lithotectonic units with the development of a steeply-dipping S<sub>2</sub> foliation. In particular, D<sub>2</sub> 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 Viséan. A zircon SIMS U-Pb age of  $352 \pm 1$  Ma from a plagioclase-rich leucocratic sill of the Rioupéroux-Livet unit is interpreted as the age of magmatic emplacement. Our results suggest that the D<sub>2</sub> 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. Geological 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 Viséan 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  $395\pm 2$ Ma, 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 serpentized 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 trondhjemitites have been dated at 367-362 Ma by K/Ar on amphibole (Ménot et al., 1985, 1987; Ménot, 1986), and at  $367\pm 17$  Ma and  $352\pm 55$  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  $0.8\pm 0.2$  Gpa and  $590\pm 60$  °C (Fernandez et al., 2002; Guillot and Ménot, 1999).



A near isothermal decompression evolution down to P-T conditions of  $0.7\pm 0.2$  Gpa and  $590\pm 60^\circ\text{C}$  before a late retrogression under greenschist 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  $341 \pm 13$  Ma and  $324 \pm 13$  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 Viséan in age (ca. 330 Ma) (Gibergy, 1968). However, a U/Pb zircon age of  $336\pm 5$  Ma was recently obtained for a granitoid intrusion within the Taillefer unit in the Pelvoux massif (Fréville, 2016). The Taillefer unit experienced a greenschist facies metamorphism coeval with ductile deformation (Barfety et al., 1972). The Taillefer unit rocks unconformably overlie the Rioupéroux-Livet unit (Carne, 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  $D_1$  and  $D_2$ . 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 $D_1$ deformation: Nappe stacking***

The main planar fabric of the *Chamrousse ophiolitic complex* is defined as a metamorphic foliation  $S_1$ , which mostly parallels the primary bedding, which may correspond to magmatic layering.  $S_1$  strikes N-S to NE-SW and dips mainly toward the west, but E- or SE-vergent post-folial folds may disturb the  $S_1$  dip (Figs. 2, 5, 6).  $S_1$  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 ( $30^\circ - 50^\circ$ ) and a decimeter to several meters thick, exhibit a pervasive E-W trending, stretching lineation ( $L_1$ ), 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  $D_1$  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  $D_1$  nappe stacking event.

Within the Allemont migmatitic unit the early  $D_1$  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  $S_1$ . In what follows, this planar structure is also considered to be coeval with the  $S_1$  observed in the Rioupéroux-Livet unit.

An early deformation attributed to  $S_1$ , 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  $D_1$  event described here in several units is not observed in the Taillefer unit (Table 1).

### ***3.2 NW-SE $D_2$ shortening***

In the southwestern part of the Belledonne Massif, in both the inner and outer branches,  $N000^\circ E$  to  $N030^\circ E$  striking, upright or slightly eastward overturned, km-scale  $F_2$  folds are observed (Fig. 2). These structures belong to the  $D_2$  deformation as  $S_1$  is folded along a broad  $N030^\circ E$  trending sub-horizontal axis with sub-vertical or steeply westward dipping axial planes (Figs. 2, 4A, 4B, 4C, 6). Commonly, the  $F_2$  long limbs are moderately ( $20^\circ$  to  $40^\circ$ ) west dipping,

and the short limbs are sub-vertical (Fig. 5). At the centimeter- to decimeter-scale  $F_2$  folds tend to be more upright (Fig. 4A). The  $D_2$  deformation is responsible for a refolding of  $L_1$  in which the initial  $D_1$  E-W trend becomes parallel to a NE-SW direction (Figs. 3F, 8B, 8C). The  $D_2$  linear fabric is dominated by a NE-SW trending, weakly SW plunging  $L_2$  crenulation lineation that parallels the meter-scale  $F_2$  fold axes (Figs. 4D, 6). The  $L_2$  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).

$D_2$  shearing with opposite kinematics, attested by mm- to cm-scale shear bands is recognized along  $F_2$  flanks (Figs. 4B, 4E, 4F, 7B and 8D). These opposite senses of shear, coeval with  $F_2$  folding, can also be seen at the microscopic scale (Fig. 7B). Owing to the geometry of  $F_2$  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  $L_2$  crenulation lineation (Fig. 8D). The Allemont migmatitic unit is also deformed by the  $D_2$  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,  $S_2$  is subvertical and strikes NE-SW (Figs. 4C, 6). The  $S_2$  foliation is mostly observed near the hinge of  $F_2$ .  $S_2$  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  $D_2$  shortening gradient is marked by the tightening of upright folds (Figs. 4A, 5B), and by the development of meter-scale  $S_2$  corridors along which the  $S_{0-1}$  foliation is transposed (Fig. 8C).

Within the Taillefer unit, an  $S_2$  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  $L_2$  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  $D_2$  structures recognized in the Rioupéroux-Livet unit, they are attributed to the  $D_2$  event (Table 1).

In summary, two main phases of penetrative deformation are easily recognized along the Romanche valley, namely an earlier  $D_1$  deformation event corresponding to an eastward nappe stacking, and a subsequent  $D_2$  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  $S_1$  planar fabric defined by the preferred orientation of platy biotite and muscovite grains (Fig. 9A). The  $S_1$  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<sub>65</sub>; Py<sub>06</sub>; Grs<sub>21</sub> and Spss<sub>09</sub> in the core to *ca.* Alm<sub>70</sub>; Py<sub>10</sub>; Grs<sub>19</sub> and Spss<sub>01</sub> in the rim (Table 2). Kyanite grains are mm sized and highly retrogressed, with the development of secondary white mica (Mu<sub>2</sub>) (Fig. 9A). Plagioclase is homogeneous in composition with Ab<sub>78-89</sub>. Biotite grains exhibit an average X<sub>Mg</sub> 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<sub>1</sub> 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<sub>1</sub>. Garnet porphyroblasts are subhedral, rich in quartz inclusions, and have a homogeneous composition of *ca.* Alm<sub>80</sub>; Py<sub>14</sub>; Grs<sub>6</sub> and Spss<sub>004</sub>. Subhedral staurolites reach 0.5 to 1 mm in size and have X<sub>Fe</sub> contents ranging from 0.87 to 0.89. Biotite has a variable composition with an X<sub>Mg</sub> 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<sub>1</sub> 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<sub>75</sub>; Py<sub>10</sub>; Grs<sub>03</sub> and Spss<sub>10</sub>. Biotite has an X<sub>Mg</sub> 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-Na<sub>2</sub>O-CaO-K<sub>2</sub>O-FeO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O (MnNCKFMASH) system for micaschists. Calculations were performed with Perple\_X'6.7.1 (Connolly and Pettrini, 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-X<sub>H<sub>2</sub>O</sub> pseudosection (X<sub>H<sub>2</sub>O</sub> stands for the amount of water in the bulk composition). It appears that H<sub>2</sub>O content is the critical parameter influencing the stability of garnet + chlorite *vs* garnet + kyanite assemblages (Fig. 10A). Considering H<sub>2</sub>O 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 H<sub>2</sub>O content we considered the LOI (2.3wt%, corresponding to 0.0127 mol) to represent X<sub>H<sub>2</sub>O</sub>=1. The T-X<sub>H<sub>2</sub>O</sub> diagram shows that the kyanite-bearing equilibrium is stable for an X<sub>H<sub>2</sub>O</sub>=0.6, for T<660°C and P=0.7 GPa. We then used the corresponding molar content (H<sub>2</sub>O=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



$370 \pm 25^\circ\text{C}$  (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  $360^\circ\text{C}$  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: SiO<sub>2</sub>, 65.82; Al<sub>2</sub>O<sub>3</sub>, 14.47; Fe<sub>2</sub>O<sub>3</sub>, 5.74; MgO, 1.97; CaO, 0.35; Na<sub>2</sub>O, 1.79, K<sub>2</sub>O 3.43; TiO<sub>2</sub>, 0.81; MnO, 0.0; H<sub>2</sub>O 2.34. The major typology differences between the two P-T pseudosections (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.  $0.55 \pm 0.2$  GPa to  $0.475 \pm 0.1$  GPa. The X<sub>Ca</sub><sup>Grt</sup> isopleths are shifted to lower temperatures and pressures. The X<sub>Mg</sub><sup>Grt</sup> isopleth typology remains similar (Fig; 10D). Accordingly, we consider that the best estimation for the peak P-T conditions recorded by sample MCE240 is  $P=0.535 \pm 0.045$  GPa and  $T=427.5 \pm 17.5$  °C.

For Sample MCE56Va, the P-T diagram was computed with H<sub>2</sub>O as a saturated component. In this condition, the pseudosection of Sample MCE56va (Fig. 11A) shows the stability field of biotite + muscovite + garnet + staurolite + quartz + H<sub>2</sub>O equilibrium ranging between 0.43 GPa and 0.74 GPa and  $575^\circ\text{C}$  and  $640^\circ\text{C}$  (Fig. 11A). Isopleth contouring of the chemical compositions of biotite and garnet enable us to refine the P-T conditions to  $0.58 \pm 0.06$  GPa and  $608 \pm 14$  °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- $X_{\text{H}_2\text{O}}$  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  $0.78 \pm 0.07$  GPa and  $680.5 \pm 11.5$  °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<sub>1</sub> 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  $335.3 \pm 2.5$  Ma (N=14, MSWD=0.43), which is in good agreement with the reported ID-TIMS age of  $337.1 \pm 0.4$  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  $352 \pm 1$  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  $\pm 10\%$ . 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  $336.3 \pm 3.3$  Ma (N=6, MSWD=0.54), which is in good agreement with the reported ID-TIMS age of  $337.1 \pm 0.4$  Ma (Sláma et al., 2008). In this study, we excluded zircon analyses with a discordance greater than  $\pm 10\%$ .

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 Bruguier 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 ( $S_1$ ) 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  $337 \pm 7$  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  $337 \pm 7$  Ma obtained corresponds to the  $D_1$  tectonometamorphic event (Table 8; Fig. 15C).

## **6. Discussion**

### *6.1 Tectonometamorphic evolution*

Two metamorphic stages are evident from our thermobarometrical work. MP-LT metamorphism (M<sub>x</sub>) 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  $370 \pm 25^\circ\text{C}$  up to  $0.535 \pm 0.045$  Gpa and  $427.5 \pm 17.5^\circ\text{C}$  (Fig. 16). The strain fabric associated with the M<sub>x</sub> kyanite-bearing assemblage remains unknown owing to the intense D<sub>1</sub> and D<sub>2</sub> overprint. Nevertheless, an early MP-LT D<sub>x</sub>/M<sub>x</sub> tectonometamorphic event has already been described by Guillot and Ménot (1999). We suggest that the D<sub>x</sub>/M<sub>x</sub> 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 east.

The second metamorphic event (M<sub>1</sub>) is recorded in the staurolite-bearing micaschist from the Rioupéroux-Livet unit, with peak conditions of  $0.58 \pm 0.06$  GPa and  $608 \pm 14^\circ\text{C}$ . In agreement with Guillot and Ménot (1999), M<sub>1</sub> is interpreted as coeval with the top-to-the-E nappe stacking event responsible for the penetrative D<sub>1</sub> fabric (S<sub>1</sub>, L<sub>1</sub>, F<sub>1</sub>) 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<sub>2</sub> event, which could correspond to the D<sub>1</sub> event (Simeon, 1979). Absence of the D<sub>1</sub> deformation in the Taillefer unit is in agreement with its post-D<sub>1</sub> (Visean) deposition age, as proposed by Gibergy (1968). In our interpretation, the D<sub>1</sub>/M<sub>1</sub> 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 Ménot, 1999). Previous works (Fernandez et al., 2002; Guillot et al., 2009; Guillot and Ménot, 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  $M_1$  event recorded in the Rioupéroux-Livet unit corresponds to the partial melting of the Allemont unit micaschist, under the P-T conditions of  $0.78 \pm 0.07$  GPa and  $680.5 \pm 11.5^\circ\text{C}$  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 southwestward 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  $D_2$  shortening event developed in the west-dipping limbs of the  $F_2$  folds. We also documented the  $D_2$  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.  $D_2$  is also responsible for the partial reorientation of the E-W trending  $L_1$  lineation into a N30-trending direction.

In previous studies, the  $D_2$  tectonometamorphic event was poorly documented and more commonly associated with the nappe stacking event, with the  $L_2$  crenulation lineation interpreted as the result of interference between  $D_1$  and an earlier west-directed deformation phase (Fernandez et al., 2002; Guillot et al., 2009). The N30-trending stretching lineation corresponding to the reoriented  $L_1$ , 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 ( $330 \pm 3$  Ma, (Fréville, 2016)) shows that the migmatization that occurred at the end of the prograde  $M_1$  metamorphism, was contemporaneous with the syn- $D_1$  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 D<sub>2</sub> event, took place during the exhumation of the migmatite, but this might also have occurred 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 <sup>40</sup>Ar/<sup>39</sup>Ar 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 D<sub>1</sub> and D<sub>2</sub> 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 D<sub>1</sub> 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 (M<sub>1</sub>) at 337 ± 7 Ma, coeval with the nappe stacking event (D<sub>1</sub>).



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 Viséan 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 Viséan extensional phase (Guillot et al., 2009). However, no Viséan 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  $336 \pm 5$  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 D<sub>1</sub> 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 D<sub>1</sub> event. Finally, the D<sub>2</sub> 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 D<sub>2</sub> deformation in the Internal Domain, the Série Satinée unit must have reached its present location before the onset of the D<sub>2</sub> event (Late Carboniferous). Assuming that the Série Satinée unit experienced the D<sub>1</sub> event implies that this unit was already in its present position before the D<sub>1</sub> event, which occurred at *ca.* 340 Ma, and it should therefore have recorded the MP-LT M<sub>x</sub> metamorphism. If the Série Satinée unit was

already in its present location before the Viséan, 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 Ménot, 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 D<sub>x</sub> 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  $367 \pm 17$  Ma and  $352 \pm 55$  Ma by the U/Pb method on zircon (Ménot, 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  $352 \pm 1$  Ma. In this interpretation we suggest that the Taillefer volcano-clastic sedimentary rocks were deposited at that time (Fig. 17C).

(4) From *ca.* 350 to *ca.* 330 Ma, the D<sub>1</sub> 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-D<sub>1</sub> period.

(5) From 330 to 310 Ma, the D<sub>1</sub> tectonic pile was folded by the D<sub>2</sub> horizontal NW-SE shortening (Fig. 17E). The D<sub>2</sub> deformation may have occurred during peak temperature and retrograde evolution. One may consider that the transition from D<sub>1</sub> to D<sub>2</sub> results from progressive deformation causing overlap between late-D<sub>1</sub> and early-D<sub>2</sub> 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 Viséan 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 D<sub>1</sub> event recorded in the SW part of the Belledonne Massif. After the thrusting of the Viséan 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 D<sub>2</sub> 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  $340.7 \pm 4.2$  Ma and  $336.3 \pm 4.1$  Ma, within HP granulites that recorded peak PT conditions of *ca.* 1.4 GPa and  $735 \pm 15$  °C (Ferrando et al., 2008; Rubatto et al., 2010). These Carboniferous ages in the Argentera Massif are in agreement with the D<sub>1</sub>/M<sub>1</sub> 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 D<sub>1</sub> 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  $M_1$ ; and iii) the Viséan 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  $355 \pm 1$  Ma, is younger than other bimodal magmatic domains, such as the Brévenne unit in the French Massif Central, which is dated at  $366 \pm 5$  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  $D_1$  nappe stacking event, might be compared to the  $D_2$  event in the French Massif Central (Faure et al., 2005, 2009). However, the  $D_2$  event in the French Massif Central occurred during late Devonian to early Carboniferous time, i.e., 20 Ma before the main  $D_1$  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 Viséan "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 Anthracifères 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  $D_x$ ,  $D_1$  and  $D_2$  (Table. 1). The  $D_x$  event corresponds to the eastward thrusting of

the Chamrousse ophiolitic complex onto the Rioupéroux-Livet unit, causing an LT-MP metamorphism at  $0.535 \pm 0.045$  GPa and  $427.5 \pm 17.5$  °C (Mx). The Dx event may have occurred before 360 Ma. The bimodal magmatism of the Rioupéroux-Livet unit, occurred at  $352 \pm 1$  Ma. The main synmetamorphic deformation event D<sub>1</sub> occurred at  $337 \pm 7$  Ma with peak metamorphic conditions of  $0.58 \pm 0.06$  GPa and  $608 \pm 14$  °C. D<sub>1</sub> 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  $0.78 \pm 0.07$  GPa and  $680.5 \pm 11.5$  °C. During the late Viséan (330-325 Ma), volcanites, sandstone and conglomerate of the Taillefer unit were thrust onto the previously deformed units (Table 1). Subsequently, the D<sub>2</sub>, NW-SE bulk shortening event, characterized by folding of the S<sub>1</sub> foliation, and development of the NE-SW L<sub>2</sub> crenulation, affected all units, including the Cambro-Ordovician flysch unit (the Série Satinée).

## 8. Acknowledgments

The authors thank ISTO, BRGM, the Laboratoire Chrono-Environnement, and the Observatoire des Sciences de l'Univers en Région Centre for their financial support. We also gratefully acknowledge Pierre Lanarie and anonymous reviewers for their constructive suggestions. We strongly appreciate the English review of this contribution from J.V. Guy-Bray.

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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  $D_1$ . A: contact between serpentinite and microgabbro in the Chamrousse ophiolitic complex showing top-to-the-NE sense of shear. B:  $F_1$  drag fold of  $S_{0-1}$  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  $S_0$  bedding by  $S_1$  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  $D_2$  folding.

Figure 4. Outcrop photographs of structures related to  $D_2$ . A: folding of  $S_{0-1}$  foliation during the  $D_2$  event in the metavolcanic rocks of the Rioupéroux-Livet unit. Note the absence of penetrative  $S_2$  foliation. B: NE-SW-striking  $F_2$  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<sub>2</sub> deformation. Black boxes indicate detail photographs E and F. C: S<sub>2</sub> foliation developed parallel to axial plane of F<sub>2</sub> 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<sub>2</sub> fold shown in picture B. F, Top-to-the-SE-sense of shear in the SE flank of the D<sub>2</sub> 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<sub>2</sub> 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 D<sub>x</sub> deformation.

Figure 8. Field sketches of D<sub>1</sub>-D<sub>2</sub> relationships. Quartz-feldspar-rich beds are shown in gray. A: Folding of the S<sub>0-1</sub> foliation by D<sub>2</sub> folds responsible for local development of S<sub>2</sub> in metapelitic layers. B: Reorientation of L<sub>1</sub> mineral lineation by D<sub>2</sub> event. C: Tight D<sub>2</sub> 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- $X_{(H_2O)}$  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  $608 \pm 14^\circ\text{C}$ . Biotite, muscovite and pyrope compositional isopleths. B. T-X<sub>(H<sub>2</sub>O)</sub> 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  $680.5 \pm 11.5^\circ\text{C}$ . 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  $S_1$  foliation plane. B: SEM-BSE image of representative dated monazite. C: Concordia diagram giving a lower intercept age of  $337 \pm 7$  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 Ménot, 1999). Black and gray (dashed) arrows represent inferred P-T path corresponding to the observed structures.  $D_x$ ,  $D_1$ , and  $D_2$  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  $D_x/M_x$  tectonometamorphic 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  $D_1/M_1$  tectonometamorphic event is responsible for eastward nappe stacking coeval with an MP-HT prograde metamorphism. E: After 330 Ma, the orogenic crust recorded the  $D_2$  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.

Table 1

EVEN TS		SMF				
		Outer branch	SW Inner branch			
			RT			
		Série- Satinée	Chamrouss e ophiolitic unit	Rioupéroux- Livet unit	ASZ Allemont migmatitic unit	Taillefer unit
D <sub>2</sub>	Structure	<ul style="list-style-type: none"> <li>• upright folds</li> <li>• high angle S<sub>2</sub></li> <li>• NE-SW L<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>• buckled folds</li> <li>SE vergent</li> <li>• NE-SW L<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>• buckled folds</li> <li>SE vergent</li> <li>• upright folds</li> <li>• high angle S<sub>2</sub></li> <li>• NE-SW L<sub>2</sub> crenualtion</li> </ul>	<ul style="list-style-type: none"> <li>• buckled folds</li> <li>SE vergent</li> <li>• upright folds</li> <li>• high angle S<sub>2</sub></li> <li>• NE-SW L<sub>2</sub> crenualtion</li> </ul>	<ul style="list-style-type: none"> <li>• upright folds</li> <li>NE-SW axis</li> <li>• NE-SW L<sub>2</sub> crenualtion</li> <li>• L<sub>2</sub> streching lineation</li> </ul>
	Metamorph hism	Greenschist facies	Retrograde Greenschist facies ?	Retrograde Greenschist facies ?	Retrograde amphibolite facies ? Sill - melt	Greenschist facies
	Age					Viséan ca. 340Ma
Late D1 thrusting of the Taillefer unit						
D <sub>1</sub>	Structure	Low angle S <sub>1</sub> ?	<ul style="list-style-type: none"> <li>• Low angle S<sub>1</sub></li> <li>• E-W L<sub>1</sub></li> </ul>	<ul style="list-style-type: none"> <li>• Low angle S<sub>1</sub></li> <li>• Recumbent folds</li> <li>E vergent</li> <li>• E-W L<sub>1</sub></li> </ul>	<ul style="list-style-type: none"> <li>• Low angle S<sub>1</sub></li> <li>• Recumbent folds</li> <li>E vergent</li> <li>• E-W L<sub>1</sub></li> </ul>	
	Kinematics		• top to the E-NE	• top to the E- NE	• top to the E- NE	
	Metamorph hism	Greenschist facies?	Amphibolite Facies P ? T ?	Amphibolite Facies Gt-Bt-melt ca. 0.6 Gpa; 600°C	Amphibolite Facies Gt-Bt-melt ca. 0.8 GPa; 630°C	
	Age		339 ± 5 Ma (U-PbMnz)	339 ± 5 Ma (U-PbMnz)	339 ± 5 Ma (U-PbMnz)	

				Bi-modal magmatism @ 352 ± 1 Ma (U-PbZr). • S <sub>0</sub> bedding	
D <sub>x</sub>	Kinematics		not documented • Eastward thrusting ?	• Eastward thrusting	
	Metamorphism			•Gt-Ky-Ab metapelite ca. 0.3 GPa; 370°C up to ca. 0.5 GPa; 430°C	
	Age			ca. 380 Ma?	
<i>Pre orogenic</i>		turbidite passive margin	Oceanic metamorphism 0.3-0.4 GPa; 500- 600°C	terrigenous passive margin	
		Cambro-ordovician	[1] 496 ± 6 Ma (U-PbZr ) [2] 497 ± 24 Ma (Sm-Ndwr)		

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Table 2

Sample	GARNET			BIOTITE			MUSCOVITE			PLAGIOCLASE	STAUROLITE		
	MCE240 Rim	MCE56-Va Core	MCE195a	MCE240	MCE56-Va	MCE195a	MCE240	MCE56-Va	MCE195a	MCE240	MCE56-Va		
Wt%	37.87	37.20	36.45	34.61	35.96	35.30	46.61	45.99	49.34	70.08	64.21	27.72	
SiO <sub>2</sub>	20.37	20.06	20.84	17.78	18.90	19.03	34.34	36.82	36.10	19.08	19.58	55.91	
Al <sub>2</sub> O <sub>3</sub>	0.12	0.04	0.00	2.12	1.60	2.97	0.78	0.27	0.55	0.00	0.00	0.54	
TiO <sub>2</sub>	0.47	0.49	32.66	20.14	19.72	17.20	1.11	1.07	1.01	0.11	0.10	10.71	
FeO	2.02	1.31	3.28	2.64	8.91	9.76	8.67	0.56	0.66	0.75	0.00	0.70	
MgO	0.96	0.54	0.17	4.59	0.12	-0.02	0.08	0.08	-0.01	0.00		0.19	
MnO	6.75	5.58	2.27	0.96	0.00	-0.01	0.00	0.00	-0.02	0.01	0.23	0.02	
CaO					0.09	0.22	0.22	1.04	1.78	0.25	11.51	9.31	0.07
Na <sub>2</sub> O					8.61	9.21	9.57	9.62	9.20	7.58	0.14	0.15	0.24
K <sub>2</sub> O	99.55	98.08	99.09	98.12	92.38	93.02	94.15	95.76	95.59	101.14	99.56	96.09	
Total													
Mol cations													
Si	3.05	3.08	3.03	3.00	5.62	5.61	5.65	6.29	6.04	6.61	12.09	11.42	7.70
Al	1.93	1.91	1.94	2.02	3.00	3.08	3.15	4.93	5.20	4.99	3.88	4.51	18.32
Ti	0.01	0.00	0.01	0.00	0.23	0.19	0.31	0.07	0.03	0.06	0.00	0.00	0.11
Fe	2.12	1.93	2.42	2.25	2.73	2.57	2.30	0.13	0.12	0.10	0.02	0.01	2.49
Mg	0.24	0.16	0.40	0.32	2.16	2.27	2.07	0.11	0.13	0.15	0.00	0.00	0.29
Mn	0.07	0.04	0.01	0.32	0.01	0.00	0.01	0.01	0.00	0.00			0.04
Ca	0.58	0.66	0.20	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.76	0.01

Na					0.03	0.07	0.07	0.27	0.45	0.07	3.8	3.	
											5	20	0.04
K					1.57	1.62	1.72	1.50	1.41	1.14	0.0	0.	
											3	03	0.08
Fe#													
Mg#					0.44	0.47	0.48						
End													
members %													0.89
												80	
Ab											98.	.0	
											13	8	
												19	
An											1.0	.0	
											6	9	
Orth											0.8	0.	
											1	83	
Prp	8.	5.	13.10	10.8									
	04	29		7									
	70	64											
Alm	.4	.5	80.00	75.5									
	2	8		4									
	19	22											
Grs	.3	.0	6.52	2.84									
	6	1											
Sps	2.	8.	0.38	10.7									
	18	12		4									

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Table 3

Wt%	Samples		
	MCE240	MCE56- Va	MCE195a
SiO <sub>2</sub>	67.13	66.97	58.56
Al <sub>2</sub> O <sub>3</sub>	15.52	17.1	18.60
Fe <sub>2</sub> O <sub>3</sub>	5.64	5.8	7.52
MgO	2.02	1.51	2.68
CaO	0.83	0.33	1.24
Na <sub>2</sub> O	1.76	0.71	3.28
K <sub>2</sub> O	3.37	3.53	4.52
TiO <sub>2</sub>	0.80	0.8	1.02
MnO	0.09	0.07	0.06
P <sub>2</sub> O <sub>5</sub>	0.12	0.11	0.19
Cr <sub>2</sub> O <sub>3</sub>	0.01	0.04	0.01
NiO	0.00	0.01	0.00
H <sub>2</sub> O	2.30	2.29	1.69
Sum	99.59	99.27	99.37

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Table 4

Mineral	Abbr ev.	Solution model	Reference	End-Member
Biotite	Bi	Bio(TCC)	Tajcmanova et al., 2009	mts, sdph, east, mnbi, ann, phl, obi
Muscovite	Mu	Mica(CH A)	Coggon and Holland, 2002 - Auzanneau et al., 2010	mu, pa, ma, cel, fcel
Garnet	Gt	Gt(WPH)	White et al., 2000	spss, alm, py, gr
Cordierite	Crd	hCrd	Baumgartner, 2003	mncrd, fcrd, crd, hmncrd, hfcrd, hcrd
Plagioclase	Pl	Pl(h)	Newton et al., 1981	an, abh
K-Feldspar	San	San	Waldbaum and Thomson, 1968	san, abh
Staurolite	St	St(HP)		mnst, fst, mst
Melt	melt	melt(HP)	White et al., 2001	h2oL, fo8L, fa8L, abl, sil8L, anL, kspL, q8L
Chl	Chl	Chl(HP)	Holland et al. 1998	mame, mafchl, mnchl, fames, fafchl, daph, ames, afchl, clin
Epidote	Ep	Ep(HP)		cz, fep

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Table 5

Samp le/spo t #	[U] (pp m)	[Th] (pp m)	[Pb] (pp m)	T h/ U	f <sub>206</sub> %	Radiogenic isotopic ratios						Age (Ma)					
						<sup>207</sup> Pb ±σ (%)	<sup>207</sup> Pb ±σ (%)	<sup>206</sup> Pb ±σ (%)	<sup>7</sup> Pb/ <sup>20</sup> Pb ±σ (%)	<sup>7</sup> Pb/ <sup>23</sup> Pb ±σ (%)	<sup>6</sup> Pb/ <sup>23</sup> Pb ±σ (%)	<sup>20</sup> Pb/ <sup>20</sup> Pb ±σ (%)	<sup>20</sup> Pb/ <sup>23</sup> Pb ±σ (%)	<sup>20</sup> Pb/ <sup>23</sup> Pb ±σ (%)	<sup>20</sup> Pb/ <sup>23</sup> Pb ±σ (%)		
						206 Pb	235 U	238 U	6P b	5 U	8 U	3 b	3 U	3 U	3 U		
MC11 6@02	364	136	24	0.375	{0.11}	0.054	1.12	0.408	1.97	0.055	1.52	3.4	28.0	3.4	6.6	4.9	5.5
MC11 6@03	116	29	7	0.247	{0.44}	0.056	1.91	0.402	4.07	0.055	1.64	3.1	83.9	4.3	12.7	4.7	6.6
MC11 6@04	627	196	40	0.312	{0.15}	0.053	0.83	0.411	1.72	0.055	1.50	3.4	19.7	5.0	5.0	5.0	5.5
MC11 6@05	332	101	21	0.305	{0.05}	0.053	1.68	0.406	2.31	0.055	1.51	3.5	39.4	4.7	7.4	4.5	5.5
MC11 6@07	229	59	14	0.257	{0.60}	0.057	1.64	0.401	3.18	0.055	1.50	3.0	63.3	4.9	9.4	4.9	5.5
MC11 6@08	357	103	23	0.290	{0.24}	0.054	1.10	0.416	1.86	0.055	1.50	3.7	24.6	5.6	6.5	5.0	5.5
MC11 6@09	301	90	19	0.300	{0.25}	0.054	1.21	0.402	2.22	0.055	1.51	3.1	37.2	4.6	6.4	4.8	5.5
MC11 6@1	451	153	29	0.340	{0.10}	0.053	0.98	0.410	1.80	0.055	1.51	3.6	22.1	4.5	5.4	4.8	5.5
MC11 6@10	311	80	19	0.250	{0.07}	0.054	1.55	0.406	2.26	0.055	1.51	3.4	38.1	4.7	7.4	4.7	5.5
MC11 6@11	163	55	11	0.340	{0.34}	0.053	1.63	0.412	2.22	0.055	1.52	3.3	36.7	5.7	7.5	5.3	5.5
MC11 6@12	481	147	31	0.300	{0.06}	0.052	0.96	0.409	1.78	0.055	1.51	3.2	22.5	4.5	5.5	5.2	5.5
MC11 6@13	167	42	11	0.250	{0.27}	0.054	1.60	0.422	2.21	0.055	1.51	3.9	36.3	5.7	7.5	5.3	5.5
MC11 6@14	366	73	23	0.199	{0.14}	0.054	1.58	0.414	2.29	0.055	1.50	3.7	39.2	5.7	7.4	5.4	5.5
MC11 6@15	177	74	12	0.419	{0.29}	0.054	1.62	0.405	2.87	0.055	1.50	3.2	55.5	4.8	8.4	4.8	5.5
MC11 6@16	170	42	11	0.249	{0.27}	0.054	1.60	0.421	2.24	0.055	1.56	3.8	36.8	5.7	7.3	5.3	5.5
MC11 6@17	391	168	26	0.430	{0.10}	0.054	1.06	0.417	1.94	0.055	1.54	3.4	26.7	5.6	6.5	5.5	5.5

MC11 6@18	84	26	5	0. 30 6	{0 .5 4}	0.0 53 74	2. 29	0.4 17 80	2. 76	0. 05 64	1. 54	3 6 0	3 51 4	3 5 4	8 5 4	5 5 4
MC11 6@21	70	15	4	0. 21 1	{0 .8 7}	0.0 52 86	2. 61	0.4 05 14	3. 03	0. 05 56	1. 54	3 2 3	3 58 5	3 4 3	9 4 9	4 4 5
MC11 6@22	281	122	19	0. 43 5	{0 .1 9}	0.0 54 35	1. 22	0.4 23 79	1. 94	0. 05 66	1. 51	3 8 6	3 27 9	3 5 5	6 6 5	5 5 5
MC11 6@23	383	177	26	0. 46 4	{0 .1 9}	0.0 54 58	1. 06	0.4 20 28	2. 03	0. 05 74	1. 52	3 3 2	3 30 6	3 5 6	6 6 0	5 5 0
MC11 6@24	199	84	13	0. 42 3	{0 .1 4}	0.0 54 69	1. 49	0.4 07 50	2. 32	0. 05 51	1. 50	3 5 5	3 39 7	3 4 7	7 4 6	4 4 5
MC11 6@25	332	102	22	0. 30 6	{0 .1 0}	0.0 54 05	1. 14	0.4 24 55	1. 91	0. 05 70	1. 53	3 7 3	3 25 9	3 5 9	6 6 7	5 5 7
MC11 6@26	151	36	10	0. 24 0	{0 .3 0}	0.0 54 53	1. 71	0.4 30 03	2. 28	0. 05 72	1. 52	3 9 3	3 38 3	3 6 3	7 7 9	5 5 5
MC11 6@27	370	103	24	0. 27 8	{0 .1 1}	0.0 53 57	1. 52	0.4 13 08	2. 18	0. 05 59	1. 56	3 5 3	3 34 1	3 5 6	6 5 1	5 5 5
MC11 6@28	159	39	10	0. 24 4	{0 .2 4}	0.0 52 64	1. 64	0.4 10 93	2. 28	0. 05 66	1. 58	3 1 3	3 37 0	3 5 7	7 5 5	5 5 5
MC11 6@29	170	72	11	0. 42 4	{0 .3 1}	0.0 55 06	1. 62	0.4 09 88	3. 26	0. 05 65	1. 56	3 1 3	3 64 9	3 4 9	10 4 4	5 5 4
MC11 6@30	151	52	10	0. 34 6	{0 .0 7}	0.0 55 79	1. 74	0.4 21 21	2. 44	0. 05 53	1. 52	4 2 1	3 42 7	3 5 7	7 4 7	4 5 7
MC11 6@31	526	121	34	0. 22 9	{0 .0 4}	0.0 54 34	1. 00	0.4 21 17	1. 84	0. 05 66	1. 50	3 7 1	3 24 7	3 5 6	6 5 5	5 5 5
MC11 6@32	355	150	24	0. 42 3	{0 .1 0}	0.0 54 29	1. 13	0.4 17 99	1. 99	0. 05 66	1. 51	3 5 1	3 29 5	3 5 6	6 5 5	5 5 5
MC11 6@33	236	81	15	0. 34 4	{0 .2 8}	0.0 55 24	1. 33	0.4 13 08	2. 44	0. 05 65	1. 53	3 3 0	3 42 1	3 5 7	7 5 4	5 5 4
MC11 6@34	122	39	8	0. 32 1	{0 .2 6}	0.0 55 14	1. 83	0.4 19 67	2. 91	0. 05 73	1. 55	3 3 3	3 55 6	3 5 9	9 5 9	5 5 5
MC11 6@35	685	182	45	0. 26 6	{0 .1 2}	0.0 54 12	0. 77	0.4 28 15	1. 69	0. 05 74	1. 51	3 7 6	3 17 2	3 6 5	5 6 0	6 5 0
MC11 6@36	302	129	20	0. 42 9	{0 .1 1}	0.0 53 71	1. 23	0.4 18 82	1. 95	0. 05 66	1. 52	3 5 9	3 27 5	3 5 5	6 6 5	5 5 5
MC11 6@37	108	39	7	0. 35 8	{0 .2 8}	0.0 52 60	2. 16	0.4 06 95	2. 66	0. 05 61	1. 54	3 1 1	3 49 7	3 4 7	8 8 2	5 5 2
MC11 6@38	219	54	14	0. 24 7	{0 .1 2}	0.0 53 70	1. 40	0.4 21 59	2. 06	0. 05 69	1. 51	3 5 8	3 31 7	3 5 6	6 6 5	5 5 7
MC11 6@39	300	122	20	0. 40 6	{0 .1 1}	0.0 55 13	1. 17	0.4 24 56	2. 02	0. 05 67	1. 51	3 8 3	3 30 9	3 5 6	6 6 5	5 5 6

MC11 6@40	235	106	16	0. 45 2	{0 .1 1}	0.0 54 15	1. 32	0.4 12 53	2. 13	0. 05 61	1. 50	3 4 2	3 34 5	3 5 6	3 5 5	5
MC11 6@41	502	193	32	0. 38 5	{0 .5 7}	0.0 57 46	1. 09	0.4 01 73	2. 26	0. 05 49	1. 51	3 3 0	3 38 4	3 4 3	3 4 5	5
MC11 6@42	144	36	9	0. 25 0	{0 .1 3}	0.0 53 54	1. 74	0.4 24 62	2. 31	0. 05 75	1. 52	3 5 2	3 39 9	3 5 7	3 6 1	5
MC11 6@43	272	95	18	0. 35 1	{0 .0 4}	0.0 52 51	1. 38	0.4 09 06	2. 04	0. 05 65	1. 51	3 0 7	3 31 4	3 6 8	3 5 4	5
MC11 6@44	144	76	10	0. 53 2	{0 .2 2}	0.0 53 36	2. 51	0.4 14 24	2. 93	0. 05 63	1. 52	3 4 4	3 56 2	3 5 9	3 5 5	5
MC11 6@45	197	85	13	0. 43 4	{0 .1 1}	0.0 55 62	1. 45	0.4 12 67	2. 26	0. 05 47	1. 53	3 0 2	3 37 5	3 7 4	3 4 3	5
MC11 6@47	598	250	39	0. 41 8	{0 .0 5}	0.0 53 84	1. 01	0.4 08 13	1. 85	0. 05 54	1. 51	3 4 7	3 24 4	3 5 8	3 4 8	5
MC11 6@48	146	60	9	0. 41 1	{0 .1 5}	0.0 55 21	2. 93	0.4 10 80	3. 57	0. 05 51	1. 55	3 7 3	3 71 4	3 11 4	3 6 4	5
MC11 6@49	229	79	15	0. 34 4	{0 .1 9}	0.0 53 66	1. 57	0.4 22 52	2. 18	0. 05 71	1. 51	3 5 7	3 35 8	3 7 8	3 5 8	5
MC11 6@50	142	35	9	0. 24 7	{0 .3 3}	0.0 54 43	1. 78	0.4 18 70	2. 34	0. 05 58	1. 51	3 8 9	3 40 5	3 7 5	3 0 0	5
MC11 6@51	326	126	21	0. 38 7	{0 .0 6}	0.0 52 91	1. 23	0.4 07 13	1. 94	0. 05 58	1. 50	3 2 5	3 28 4	3 6 5	3 5 0	5
MC11 6@52	434	105	27	0. 24 2	{0 .1 0}	0.0 54 29	0. 97	0.4 08 92	1. 87	0. 05 54	1. 50	3 5 1	3 25 8	3 6 4	3 4 8	5
MC11 6@53	326	88	21	0. 26 8	{0 .1 0}	0.0 52 24	1. 57	0.4 03 40	2. 17	0. 05 60	1. 50	2 9 6	3 35 4	3 6 4	3 5 1	5
MC11 6@54	263	85	17	0. 32 4	{0 .2 1}	0.0 53 61	1. 71	0.4 16 16	2. 33	0. 05 63	1. 58	3 5 5	3 38 3	3 7 5	3 5 3	5
MC11 6@55	254	80	16	0. 31 5	{0 .2 7}	0.0 55 06	1. 31	0.4 05 49	2. 84	0. 05 56	1. 51	3 2 5	3 54 6	3 8 9	3 4 9	5
MC11 6@56	620	246	42	0. 39 7	{0 .0 9}	0.0 53 52	0. 83	0.4 20 73	1. 72	0. 05 70	1. 51	3 5 1	3 19 7	3 5 5	3 5 7	5
MC11 6@57	145	38	9	0. 26 3	{0 .0 8}	0.0 54 46	1. 86	0.4 15 31	2. 53	0. 05 60	1. 50	3 6 3	3 45 3	3 8 1	3 5 3	5
MC11 6@59	274	119	19	0. 43 4	{0 .1 0}	0.0 53 26	1. 25	0.4 20 18	1. 99	0. 05 72	1. 54	3 4 0	3 28 6	3 6 9	3 5 9	5
MC11 6@60	383	167	26	0. 43 6	{0 .0 9}	0.0 52 41	1. 08	0.4 13 29	1. 85	0. 05 72	1. 50	3 0 3	3 24 5	3 6 6	3 5 9	5
MC11 6@61	107	24	7	0. 22 6	{0 .3 7}	0.0 52 84	2. 03	0.4 18 06	2. 58	0. 05 74	1. 59	3 2 2	3 45 5	3 8 8	3 6 0	6

MC11 6@62	251	62	16	0. 24 8	{0 4}	0.0 54 78	1. 45	0.4 12 37	2. 46	0. 05 65	1. 51	3 2 4	43	3 5 1	7	3 5 5	5
MC11 6@63	215	61	14	0. 28 6	{0 0}	0.0 54 68	1. 44	0.4 19 41	2. 37	0. 05 73	1. 51	3 3 3	41	3 5 6	7	3 5 9	5
MC11 6@64	86	20	6	0. 23 1	{0 2}	0.0 53 85	2. 29	0.4 24 05	2. 77	0. 05 71	1. 56	3 5 3	51	6 5 9	8	3 5 8	5
MC11 6@65	282	102	19	0. 36 3	{0 6}	0.0 53 75	1. 58	0.4 18 60	2. 18	0. 05 65	1. 51	3 5 1	35	6 3 5	7	3 5 5	5

ACCEPTED MANUSCRIPT



Table 6

Spot No.	Th (ppm)	U (ppm)	Th / U	Ratios				Ages (Ma)				Disconcordance (%)	Best Ages	$\pm 1\sigma$		
				$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$				$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$
M	89	17	.	0.00	0.00	0.00	0.00	0.60	0.00					5.6	46	7
C5	4	75	5	60	06	74	12	18	54	61	2	46		48	3	
-37			0	19	0	48	5	10	8	0	1	3	7	9	3	
M	17	12	.	0.00	0.00	0.00	0.00	0.60	0.00					2.3	51	8
C5	6	44	1	59	05	82	13	80	59	57	4	51		52	4	
-35			4	50	9	99	9	91	7	7	2	4	8	6	4	
M	85	15	.	0.00	0.00	0.00	0.00	0.60	0.00					2.7	52	8
C5	5	25	5	59	06	84	14	96	63	59	2	52		53	3	
-58			6	77	1	53	3	56	4	5	1	3	8	7	4	
M	33	94	.	0.00	0.00	0.00	0.00	0.70	0.00					3.4	52	8
C5	1	0	3	61	06	84	14	22	66	61	4	52		54	4	
-41			5	71	4	87	3	15	3	8	5	4	8	2	5	
M	21	56	.	0.00	0.00	0.00	0.00	0.60	0.00					2.3	52	8
C5	4	3	3	59	06	84	14	99	64	59	2	52		53	6	
-39			8	72	2	94	3	41	6	3	1	6	8	8	4	
M	76	66	.	0.00	0.00	0.00	0.00	0.70	0.00					3.4	52	9
C5	2	3	1	60	07	85	14	13	83	62	1	52		54	9	
-67			5	55	9	50	9	83	8	3	9	9	9	7	5	
M	71	89	.	0.00	0.00	0.00	0.00	0.70	0.00					4.7	53	9
C5	5	4	8	61	07	85	14	26	79	65	1	53		55	0	
-59			0	46	5	77	8	75	0	5	9	0	9	5	5	
M	12	11	.	0.00	0.00	0.00	0.00	0.70	0.00					5.8	53	9
C5	8	7	1	62	07	86	14	43	79	68	1	53		56	4	
-18			0	42	5	42	7	74	7	9	9	4	9	5	5	
M	13	19	.	0.00	0.00	0.00	0.00	0.70	0.00					0.4	54	9
C5	30	89	6	60	06	87	14	26	65	54	5	54		54	0	
-64			7	15	1	57	8	22	0	9	1	0	9	2	7	
M	53	11	.	0.00	0.00	0.00	0.00	0.70	0.00					2.0	54	9
C5	9	69	4	59	06	87	15	26	71	60	2	54		55	3	
-60			6	89	6	94	0	09	6	0	0	3	9	4	4	

M	53	67	.	0.0	00	0.0	00	0.7	00							2.5	55	9
C5	5	2	8	60	07	89	15	42	78	62	2	55		56		%	0	
-54			0	49	2	02	3	38	6	1	0	0	9	4	5			
			0		0.		0.		0.									
M	35	83	.	0.0	00	0.0	00	0.7	00							-	55	9
C5	3	5	4	59	06	89	15	42	71	52	4	55		54		1.3	3	
-32			2	99	5	80	2	76	7	0	9	3	9	6	6	%		
			0		0.		0.		0.									
M	32	64	.	0.0	00	0.0	00	0.7	00							2.2	55	9
C5	5	0	5	60	06	89	15	45	69	61	2	55		56		%	4	
-44			1	24	3	75	2	46	8	2	1	4	9	6	4			
			0		0.		0.		0.									
M	86	27	.	0.0	00	0.0	00	0.7	00							0.5	56	9
C5	8	3	59	06	90	15	40	73	57	2	56		56		%	0		
-36			1	25	6	69	4	87	8	6	0	0	9	3	4			
			0		0.		0.		0.									
M	27	88	.	0.0	00	0.0	00	0.7	00							2.9	56	9
C5	3	9	3	61	06	90	15	69	71	63	4	56		57		%	0	
-43			1	42	4	88	4	67	2	9	5	0	9	6	5			
			0		0.		0.		0.									
M	79	81	.	0.0	00	0.0	00	0.7	00							1.6	56	9
C5	0	9	9	60	06	91	15	60	73	61	2	56		57		%	5	
-31			6	18	6	68	5	70	7	0	0	5	9	4	4			
			0		0.		0.		0.									
M	39	59	.	0.0	00	0.0	00	0.7	00							1.8	56	9
C5	6	0	6	60	06	91	15	65	70	61	2	56		57		%	7	
-48			7	43	3	88	5	54	7	9	1	7	9	7	4			
			1		0.		0.		0.									
M	17	17	.	0.0	00	0.0	00	0.8	00							5.6	57	9
C5	8	1	0	63	07	92	15	10	80	72	2	57		60		%	1	
-05			4	39	1	70	6	24	0	1	0	1	9	3	4			
			1		0.		0.		0.									
M	86	69	.	0.0	00	0.0	00	0.7	00							2.8	57	9
C5	0	0	2	61	06	93	15	89	69	65	2	57		59		%	5	
-06			5	35	2	34	6	64	8	2	1	5	9	1	4			
			0		0.		0.		0.									
M	17	41	.	0.0	00	0.0	00	0.7	00							1.9	57	9
C5	9	7	4	60	06	93	15	83	71	63	2	57		58		%	6	
-07			3	76	3	52	7	49	1	1	1	6	9	7	4			
			1		0.		0.		0.									
M	40	21	.	0.0	00	0.0	00	0.7	00							-	57	9
C5	3	5	8	58	06	93	15	49	73	53	2	57		56		1.4	6	
-23			8	08	4	53	8	09	5	3	0	6	9	8	4	%		
			0		0.		0.		0.									
M	20	59	.	0.0	00	0.0	00	0.7	00							-	58	9
C5	1	6	3	59	05	94	15	65	67	56	2	58		57		0.5	0	
-20			4	00	9	08	8	39	3	7	2	0	9	7	4	%		











M	13	87	.	0.0	00	0.1	00	1.9	01							1.5	11	2
C5	57	6	5	76	08	83	31	31	80	11	2	10	1	10		%	03	0
-86			5	30	0	59	4	15	5	03	0	87	7	92	6			
			1		0.		0.		0.									
M	17	16	.	0.1	00	0.3	00	6.0	05							2.0	20	1
C5	9	7	0	23	12	56	60	50	47	20	1	19	2	19		%	03	8
-52			7	22	5	17	6	59	4	03	8	64	9	83	8			
			0		0.		0.		0.									
M	12	12	.	0.1	00	0.3	00	6.0	05							4.1	20	4
C5	3	6	9	25	13	49	59	51	68	20	4	19	2	19	1	%	06	0
-33			7	60	3	42	7	39	8	06	0	27	9	65	2			
			0		0.		0.		0.									
M	17	41	.	0.1	00	0.3	00	6.4	05							1.7	20	1
C5	17	5	0	27	12	68	62	67	57	20	1	20	2	20		%	59	8
-42			4	18	4	81	2	11	2	59	8	24	9	41	8			
			1		0.		0.		0.									
M	73	55	.	0.1	00	0.3	00	7.1	06							-	21	1
C5	9	3	3	31	12	92	66	03	10	21	1	21	3	21		1.0	14	8
-65			4	19	7	74	5	30	8	14	8	36	1	24	8	%		
			0		0.		0.		0.									
M	25	28	.	0.1	00	0.4	00	7.4	06							-	21	1
C5	18	21	8	31	12	10	70	58	49	21	1	22	3	21		4.2	23	8
-96			9	89	8	17	0	09	7	23	8	16	2	68	8	%		
			0		0.		0.		0.									
M	11	29	.	0.1	00	0.4	00	9.1	08							0.6	23	1
C5	0	9	3	51	15	39	75	88	45	23	1	23	3	23		%	64	7
-53			7	58	6	64	3	13	7	64	7	49	4	57	8			
			0		0.		0.	10.	0.									
M	11	25	.	0.1	00	0.4	00	7.2	09							1.7	25	1
C5	7	9	4	66	15	68	78	67	05	25	1	24	3	25		%	19	7
-25			5	09	9	40	5	2	9	19	7	77	4	00	8			
			1		0.		0.	13.	0.									
M	30	18	.	0.1	00	0.5	00	4.4	12							4.6	27	1
C5	8	9	6	92	19	06	86	30	05	27	1	26	3	27		%	64	7
-71			4	49	2	55	8	6	8	64	7	42	7	11	8			
			0		0.		0.	14.	0.									
M	97	25	.	0.1	00	0.5	00	5.7	12							-	27	1
C5	4	19	3	92	18	48	93	06	53	27	1	28	3	27		1.9	65	7
-99			9	71	5	43	5	7	7	65	7	19	9	88	8	%		
			0		0.		0.	15.	0.									
M	76	10	.	0.2	00	0.5	00	8.5	13							-	28	1
C5	76	3	7	02	19	68	95	08	52	28	1	29	3	28		1.9	45	6
-01			4	36	6	04	1	3	4	45	6	00	9	68	8	%		
			0		0.		0.	14.	0.									
M	37	38	.	0.2	00	0.5	00	4.9	13							6.1	28	1
C5	4	0	9	03	20	17	88	78	08	28	1	26	3	27		%	52	6
-61			9	24	4	41	7	7	1	52	6	88	8	83	9			













	1					5	1		8							8
	6					1	9		8							7
						2.	1.		1.							0.
	3					5	1		1							9
T	2					3	1		2	0	0		0	2		
a	0					5	8	0.	0	.	.	7	.	5		
il	2					5	1	1	9	3	0	.	0	0		
1	0					6	8	4	0	9	0	7	9	7	2	2
-	6				0	1	2	1	2	4	4	1	3	0	2	2
2	1	9	9	2	4	2	5	8	3	3	4	2	2	2	5	1
2	6	8	4	5	2	5	1	5	6	9	1	9	3	4	0	9
						6.	1.		1.							0.
	3					5	1		2							8
T	3					5	2		0	0	0	1	0	7		
a	0					0	0	0.	5	.	.	.	.	0		
il	2					0	0	0	5	1	0	4	0	1		
1	0					7	6	6	1	5	0	6	1	1		
-	6				0	5	2	9	0	2	1	6	8	9	9	9
2	1	2	6	7	3	3	8	6	9	6	7	6	8	1	1	2
3	6	8	0	7	4	3	8	8	1	7	1	9	8	9	9	5
						1	1.		1.							0.
	3					0.	1		1							9
T	4					5	1		5	0	0	0	0	0		
a	0					9	2	0.	8	.	.	.	.	0		
il	2					8	8	0	8	0	0	7	0	3		
1	0					8	7	6	0	9	0	9	0	6		
-	6				0	3	7	1	5	4	1	6	9	8	6	5
2	1	9	0	3	8	4	5	2	2	3	0	9	8	8	4	2
4	6	3	7	6	5	1	8	7	9	5	5	1	5	1	9	5
						1	1.		1.							0.
	3					1.	1		3							7
T	8					1	2		7	0	0	0	0	8		
a	0					3	5	0.	6	.	.	.	.	9		
il	2					9	0	0	6	0	0	7	0	0		
1	0					5	9	6	7	8	0	4	1	6		
-	6				0	7	7	0	9	9	1	6	0	9	6	5
2	1	1	4	6	2	8	4	2	3	7	0	2	6	7	1	2
5	6	5	0	5	4	9	7	9	8	7	1	2	4	7	4	9
						1	1.		1.							0.
	3					1.	1		1.							8
T	9					9	1		1	0	0	0	0	9		
a	0					4	0	0.	6	.	.	.	.	7		
il	2					0	4	0	9	0	0	6	0	0		
1	0					2	4	5	8	8	0	8	0	6		
-	6				1	9	7	8	8	3	0	1	8	5	5	5
2	1	1	3	1	1	8	7	9	8	7	9	0	4	2	6	2
6	6	5	5	4	6	5	6	8	1	5	3	1	3	8	6	5
T	4					1	1.		1.	0	0	0	0	0.		
a	0					1.	1	0.	5	.	.	.	.	0		7
il	0				0	9	3	0	1	0	0	6	.	3	5	5
1	2	1	0	2	8	4	5	5	9	8	0	7	0	0	5	3
-	0	3	8	8	4	8	1	8	2	3	0	5	1	7	2	3













1	2				6	0	9	1	1	9	0	1	3	3	4	5	8		4
-	0				4	8	8	7	1	6	2	3	2	9	0	6	5		0
5	6					7	1	5	9	4	1	7	1	3					
6	1					2	0		2	3	8	3	6	6					
	6					0	1		6					5					
						7	1		6					5					
						1	1.		1.					0.					
						0.	0		1					8					
T	5					8	9		9	0	0	0	0	7					
a	0					0	0	0.	9	.	.	.	.	2					
il	2					0	8	0	0	0	0	7	0	1					
1	0				0	3	3	6	8	9	0	7	0	3					
-	6				2	0	0	0	0	2	1	7	9	6	6	5	5		2. 5
5	1	2	7	2	5	2	5	8	1	5	0	1	7	9	3	2	7		3 7
7	6	3	3	2	9	4	4	8	6	9	1	3	2	8	5	5	1	6	4 6
						8.	1.		1.					0.					% 1 6
						4	0		1					8					
T	6					5	9		9	0	0	1	0	6					
a	0					1	0	0.	3	.	.	.	.	8					
il	2					6	2	0	8	1	0	0	0	1					
1	0				0	5	6	6	4	1	0	3	1	8					
-	6				1	6	3	3	2	8	1	8	3	9	7	7	7		0. 7
5	1	2	6	7	3	5	6	6	2	3	2	3	0	3	3	2	2		3 2
8	6	2	8	8	8	2	9	6	9	2	9	9	4	5	0	5	1	7	3 7
						1	1.		1.					0.					% 1 7
						0.	1		9					5					
T	7					7	5		8	0	0	0	0	8					
a	0					1	6	0.	4	.	.	.	.	2					
il	2					0	6	0	7	0	0	7	0	2					
1	0				0	0	8	6	0	9	0	9	1	1					
-	6				0	7	8	1	7	3	1	1	5	4	6	5	5		2. 5
5	1	1	3	6	8	8	4	4	9	3	0	2	7	5	5	4	7		8 7
9	6	3	9	1	0	2	4	7	9	7	8	6	2	7	6	2	6	6	2 9
						1.	1.		1.					0.					% 6 6
						1.	0		0			1		9					
T	8					9	8		4	0	0	2	0	6					
a	0					6	3	0.	6	.	.	.	.	7					
il	2					2	5	1	4	5	0	9	1	6					
1	0				0	9	4	8	1	0	0	5	4	9	2	2	2		2
-	6				0	3	2	4	0	9	5	4	5	0	6	6	6		1. 6
6	1	4	9	0	9	9	7	4	7	4	5	1	0	6	9	1	5	2	7 1
0	6	6	5	3	4	7	1	4	6	4	2	3	5	7	3	7	4	4	6 1
						2.	1.		1.					0.					% 3 7
						7	0		1.					9					
T	9					6	8		0	0	0	6	0	5					
a	0					2	5	0.	6	.	.	.	.	6					
il	2					5	6	1	5	3	0	3	0	2					
1	0				0	0	6	2	6	6	0	2	7	0	2	1	2		2
-	6				0	7	5	6	7	1	3	2	1	6	0	9	0		3. 0
6	1	1	3	6	9	2	3	6	7	9	9	0	7	7	5	1	9	1	2 1
1	6	5	7	3	0	5	5	8	3	9	3	7	8	9	2	9	2	9	2 0
																			% 2 9







1	2				4	0	5	9	4	9	0	1	4	6	4	7	1		4
-	0				8	0	3	5	9	0	5	3	3	4	9	1	5		9
7	6					6	1	7	0	1	3	4	7	4					
9	1					6	5		9	8	2	9	1	5					
	6					9	6		5			4		6					
						1			1										
						1	1.		1.					0.					
	3					2.	0		2					8					
T	4					6	8		6	0	0	0		3					
a	0					4	7	0.	4	.	.	.	0	3					
il	2					5	5	0	7	0	0	6	.	3					
1	0					4	0	5	1	7	0	2	0	1					-
-	6				0	2	6	6	1	9	0	0	0	1	4	4	4		0.
8	1	2	8	2	.	2	3	9	0	0	8	6	8	7	8	2	9		4
0	6	2	0	1	8	4	2	3	5	8	6	7	1	9	8	8	1	5	0
						2.	1.		1.										5
	3					3	0		1			1		0.					
T	8					0	7		2	0	0	0	0	9					
a	0					2	9	0.	4	.	.	.	.	1					
il	2					6	9	1	0	4	0	3	1	3					
1	0					6	4	7	4	3	0	8	2	1	2	2	2		1
-	6				0	1	8	3	8	4	4	6	2	1	5	3	4		2
8	1	3	2	8	.	8	4	4	8	2	6	3	8	3	9	1	2	2	7
1	6	6	5	1	4	8	2	8	8	8	9	2	4	8	2	9	5	1	0
						3.			1.										1
	3					4	1.		1					8					
T	9					4	0		8	0	0		0	8					
a	0					1	8	0.	2	.	.	4	.	0					
il	2					7	7	1	7	2	0	.	0	8					
1	0					4	5	0	8	9	0	4	5	1	1	1	1		1
-	6				0	8	9	9	5	0	3	0	4	7	7	6	7		9.
8	1	3	8	1	7	4	2	9	9	5	1	2	3	8	9	2	4	1	1
2	6	8	6	1	8	1	5	1	2	5	6	5	6	7	8	1	4	6	3
						2.	1.		1.										0.
	4					8	0		2					8					
T	0					8	9		0	0	0	6	0	7					
a	0					5	3	0.	8	.	.	.	.	0					
il	2					5	6	1	8	3	0	2	0	7					
1	0					0	0	2	0	4	0	0	7	9	2	1	2		2
-	6				0	3	5	9	8	6	3	5	7	6	0	9	0		9.
8	1	2	3	5	6	2	7	8	1	5	7	2	9	7	9	2	1	1	0
3	6	3	8	8	5	3	2	8	3	6	9	7	3	1	6	1	8	8	5
						3.	1.		1.										0.
	4					4	0		2					8					
T	1					1	9		3	0		4	0	5					
a	0					4	2	0.	6	.	0	.	.	2					
il	2					2	5	1	5	2	.	2	0	5					
1	0					5	6	0	7	9	0	1	5	9	1	1	1		1
-	6				1	1	0	4	9	2	0	2	3	9	7	6	6		2.
8	1	6	1	6	3	0	3	3	7	8	3	4	9	8	0	2	5	1	7
4	6	3	4	5	0	8	5	2	5	9	2	3	8	5	2	3	6	6	6
																			1
																			8
																			0
																			2
																			3





	1					5	5		0										8						
	6					6	2		3										8						
						1	1.		1.										0.						
	1					3.	0		2										8						
	1					2	8		1	0	0	0	0	0	0	0	0	0	6						
T	0					6	7	0.	3	.	.	.	.	.	.	.	.	.	5						
a	2					7	9	0	5	0	0	5	0	1				1							
i	0					8	6	5	0	7	0	9	0	1				1							
l	2				0	7	6	6	6	5	0	0	7	6				6							
-	1				3	8	0	8	8	3	8	8	4	0	4	4	4	0.	4						
7	6	8	4	1	1	5	3	6	6	7	2	1	3	3	5	7	8	5	1	5	6	6	%	8	5
						1	1.		1.										0.						
	1					3.	0		1										9						
	2					2	7		3	0	0	0	0	0	0	0	0	0	0						
T	0					6	4		2	.	.	.	.	.	.	.	.	.	5						
a	2					4	4	0.	4	0	0	5	0	4				4							
i	0					3	1	0	0	7	0	9	0	2				2							
l	2				1	5	3	5	4	5	0	6	7	0	5	4	4	1.	4						
-	1	1	5	1	1	8	0	7	1	3	8	6	0	6	0	2	6	7	4	6					
8	6	8	2	0	3	7	5	4	8	9	1	4	8	3	7	5	9	5	5	5	%	9	5		
						1	1.		1.										0.						
	1					3.	0		2										8						
	6					1	9		7	0	0		0	2				2							
T	0					7	3	0.	1	.	.	0	.	9				9							
a	2					8	8	0	3	0	0	.	0	6				6							
i	0					7	3	5	3	7	0	6	0	2				2							
l	2				0	0	2	7	4	5	0	0	7	7	5	4	4	1.	4						
-	1	1	3	6	1	3	3	4	0	8	8	0	9	6	0	2	7	7	3	7					
9	6	9	4	5	3	2	7	2	3	8	3	7	2	6	7	8	2	5	8	5	%	2	5		
						1	1.		1.										0.						
	1					0.	0		1										8						
T	7					5	8		8	0	0	0	0	8				8							
a	0					7	9	0.	2	.	.	.	.	2				2							
i	2					8	6	0	3	0	0	7	0	7				7							
l	2				0	6	0	6	4	9	0	8	0	1				1							
-	6				0	5	1	0	8	4	1	2	9	2	6	5	5	0.	5						
1	1	3	5	6	4	2	1	0	0	5	0	5	6	3	0	2	8	8	8	8					
0	6	6	3	9	1	3	8	5	4	3	3	8	6	1	5	5	2	6	7	6	%	2	6		
						1	1.		1.										0.						
	1					4.	0		1										9						
T	8					0	8		3	0	0	0	0	0				0							
a	0					3	1	0.	3	.	.	.	.	4				4							
i	2					9	0	0	1	0	0	5	0	3				3							
l	2				0	0	0	5	4	7	0	5	0	1				1							
-	6				1	2	5	6	4	1	0	4	6	0	4	4	4	1.	4						
1	1	6	1	0	0	8	1	4	4	2	7	6	6	5	7	2	4	4	0	4					
1	6	8	7	6	4	5	9	8	8	3	7	3	3	7	0	5	4	5	8	4	%	4	5		
T	1					1	1.		1.	0	0	0	0	0.					0.						
a	9					1.	0	0.	1	.	.	.	.	9					9						
i	0				1	1	8	0	1	0	0	7	0	2	5	5	5	0.	5						
l	2				0	9	5	5	2	8	0	3	0	3	7	2	5	5	9	5					
-	0	2	1	9	7	0	4	9	6	9	0	0	8	4	9	4	2	6	7	5	%	2	6		



2	2				1	4	2	5	3	9	0	1	7	9	9	6	6	8	9					
-	0				6	0	8	5	7	4	3	1	1	7	4	5	3	%	4					
1	6					8	9	3	8	6	2	2	0	8										
8	1					7	6		6	3	2	6	1	6										
	6					5	1		8					4										
						7			5					3										
						1	1.		1.					0.										
	2					3.	0		2					8										
T	9					1	8		2	0	0	0	0	5										
a	0					2	9		6	.	.	.	.	1										
il	2					6	5	0.	2	0	0	6	0	6										
2	0				0	8	2	0	5	7	0	0	0	3										
-	6					0	4	5	2	6	0	8	7	5	5	4	4	1.	4					
1	1	5	2	7	.	4	8	7	1	1	8	1	7	8	2	2	7	8	9	7				
9	6	9	0	4	3	8	9	1	9	6	8	3	3	8	9	6	7	3	5	2	5	%	3	5
						1	1.		1.					0.										
	3					1.	1		4					7										
T	0					5	1		7	0	0	0	0	3										
a	0					7	0	0.	6	.	.	.	.	4										
il	2					1	8	0	5	0	0	7	0	9										
2	0				0	3	5	5	7	8	0	0	1	6										
-	6					9	3	8	8	6	0	1	0	4	5	5	5	1.	5					
2	1	1	4	0	.	5	9	9	4	4	9	9	6	4	6	3	3	4	1	3				
0	6	0	3	8	0	5	7	2	1	2	6	8	1	4	4	1	4	6	0	6	%	4	6	
						1	1.		1.					0.										
	3					3.	1		2					8										
T	1					1	0		1	0	0	0	0	8										
a	0					0	1	0.	3	.	.	.	.	5										
il	2					9	2	0	5	0	0	5	0	9										
2	0				0	5	0	5	0	7	0	9	0	6										
-	6					9	6	6	6	6	0	7	7	3	4	4	4	0.	4					
2	1	3	5	4	1	6	0	8	8	2	8	9	6	0	8	2	7	7	4	7				
1	6	8	2	0	0	2	8	6	6	8	4	6	6	8	6	7	4	5	6	5	%	4	5	
						1	1.		1.					0.										
	3					1.	0		1					8										
T	2					2	8		4	0	0	0	0	9										
a	0					2	8	0.	5	.	.	.	.	4										
il	2					5	9	0	4	0	0	7	0	9										
2	0				0	8	0	6	7	8	0	5	0	9										
-	6					6	8	1	5	9	0	0	9	2	6	5	5	3.	5					
2	1	0	3	5	2	4	8	1	3	0	9	4	1	4	4	2	5	6	3	5				
2	6	5	2	5	3	4	5	1	7	8	7	1	3	3	3	5	0	6	9	5	%	0	6	
						3.	1.		1.					0.										
	3					9	1		2					8										
T	3					9	0		4		0	3	0	5										
a	0					8	7	0.	5	0	.	.	.	2										
il	2					4	5	1	7	.	0	7	0	0										
2	0				0	0	5	0	9	2	0	9	4	4	1	1	1	2	1					
-	6					0	6	9	4	5	2	1	9	3	7	4	5	5	5.	7				
2	1	2	4	9	5	6	9	9	3	0	7	8	2	6	9	2	3	1	9	1	0	9	2	
3	6	5	8	2	2	4	8	7	1	1	7	8	9	5	9	2	9	4	1	0	%	9	2	



Table 8

Th (ppm)	U (ppm)	Radiogenic isotopic ratios								Apparent ages (Ma)				Err R8 %	Err 7/6 %	Con c. (%)
		T h / U	20 8P b/ 20 6P b	20 7P b/ 20 6P b	$\pm$ 1 $\sigma$	20 7P b/ 23 5U	$\pm$ 1 $\sigma$	20 6P b/ 23 8U	$\pm$ 1 $\sigma$	20 6P b/ 23 8U	$\pm$ 1 $\sigma$	20 7P b/ 20 6P b	$\pm$ 1 $\sigma$			
142 31	207 6	6. 8 6	2.1 3	0.0 68 7	0.0 01 2	0.5 18 8	0.0 11 0	0.0 54 8	0.0 006	34 4	4	88 8	3 7	1.1	1.8	38.7
481 8	135 0	3. 5 7	1.1 7	0.1 11 0	0.0 02 6	0.8 64 5	0.0 24 1	0.0 56 5	0.0 008	35 4	5	18 16	4 2	1.5	2.4	19.5
201 81	294 0	6. 8 6	2.1 7	0.0 54 6	0.0 01 3	0.4 10 7	0.0 10 8	0.0 54 5	0.0 007	34 2	4	39 7	5 1	1.3	2.3	86.3
150 72	268 0	5. 6 2	1.7 6	0.0 55 5	0.0 01 3	0.4 08 9	0.0 10 6	0.0 53 4	0.0 007	33 5	4	43 4	4 9	1.3	2.3	77.3
117 44	282 9	4. 1 5	1.9 0	0.1 22 0	0.0 02 7	0.9 71 1	0.0 25 3	0.0 57 7	0.0 008	36 2	5	19 86	3 9	1.4	2.2	18.2
102 00	170 2	5. 9 9	1.8 4	0.0 97 4	0.0 02 4	0.7 72 5	0.0 21 9	0.0 57 5	0.0 008	36 1	5	15 75	4 5	1.4	2.4	22.9
139 30	191 2	7. 2 9	2.2 4	0.0 72 0	0.0 01 6	0.5 43 9	0.0 14 1	0.0 54 8	0.0 007	34 4	4	98 6	4 5	1.3	2.2	34.9

## 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.

ACCEPTED MANUSCRIPT





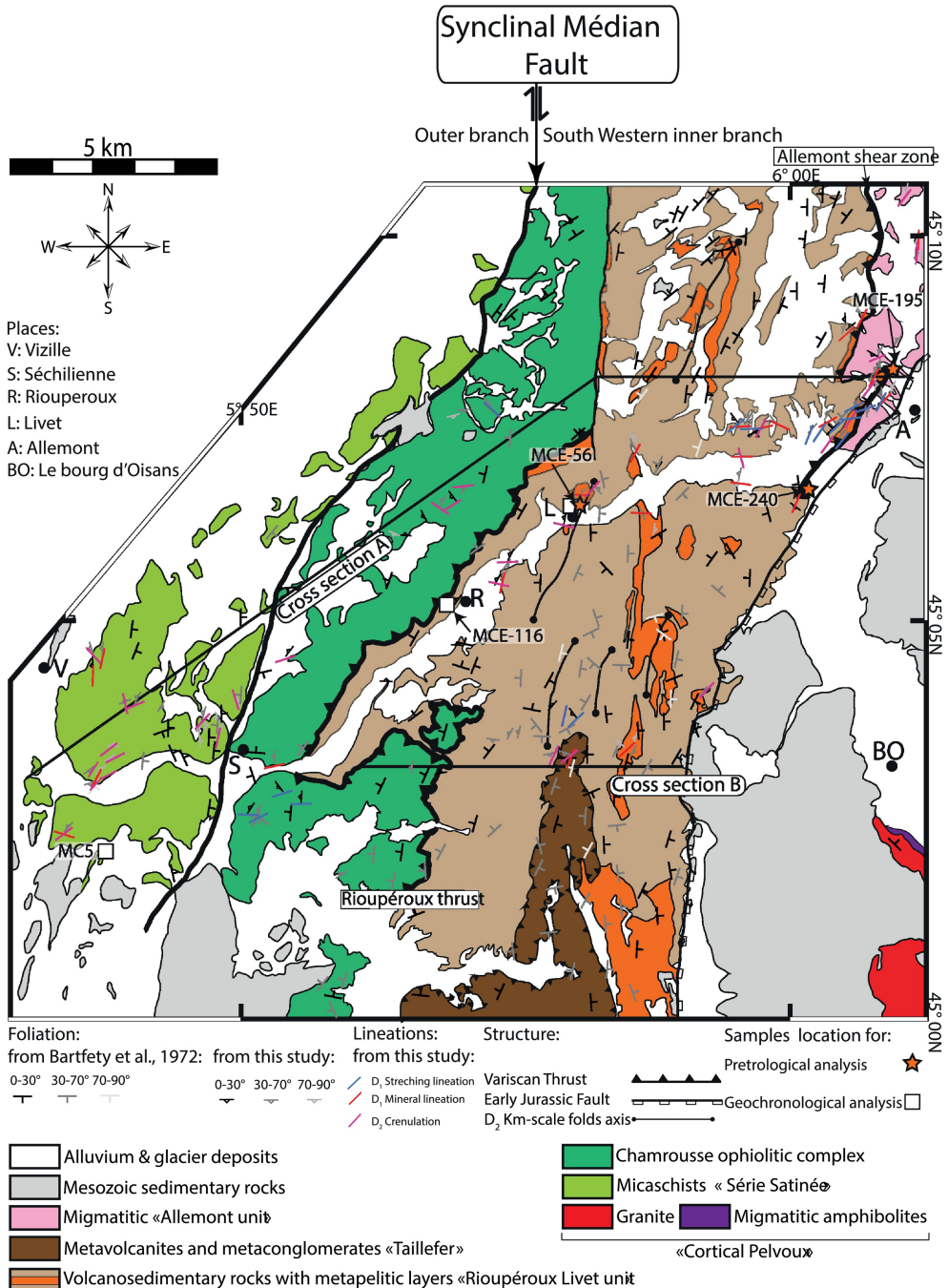


Figure 2

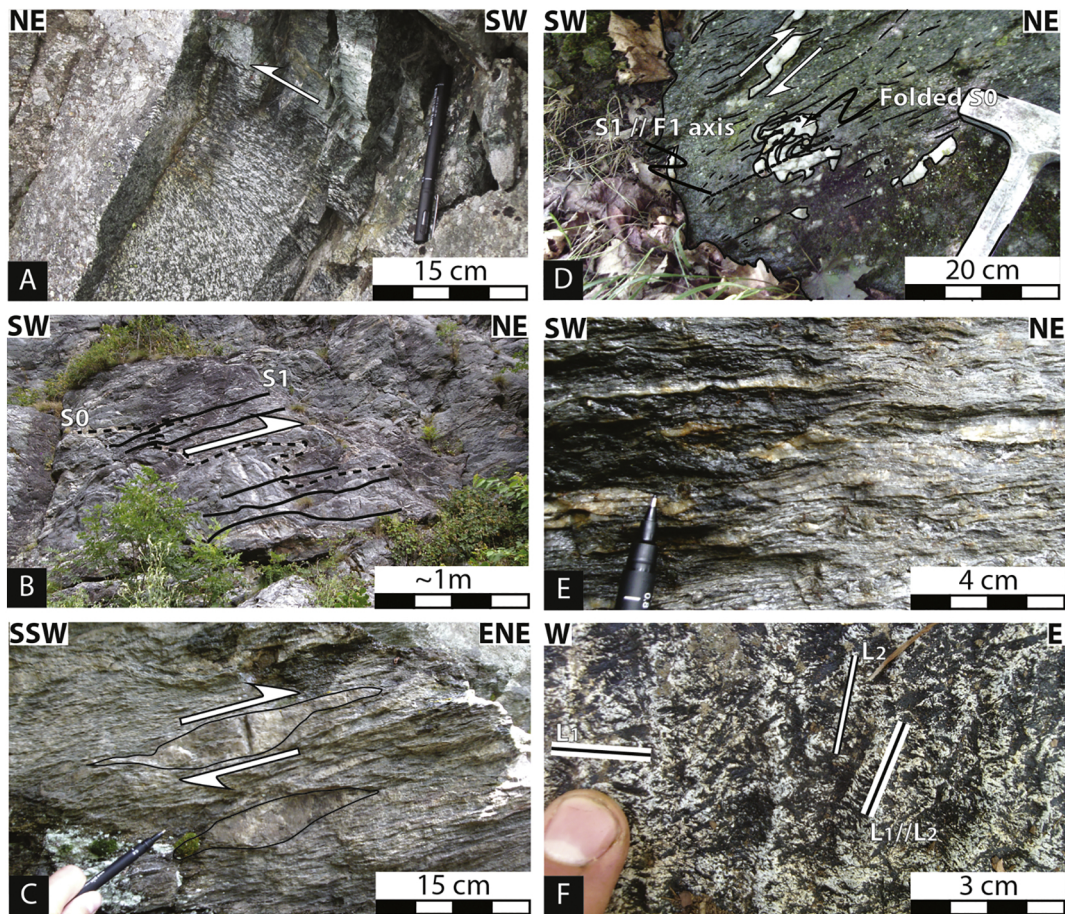


Figure 3

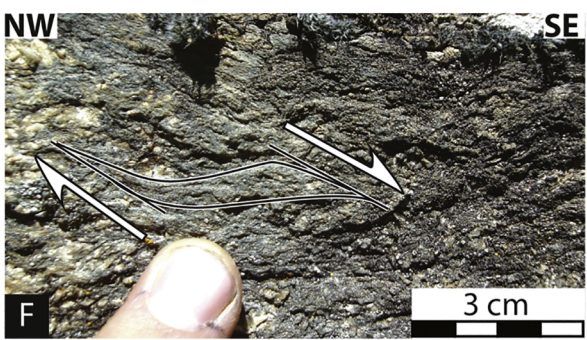
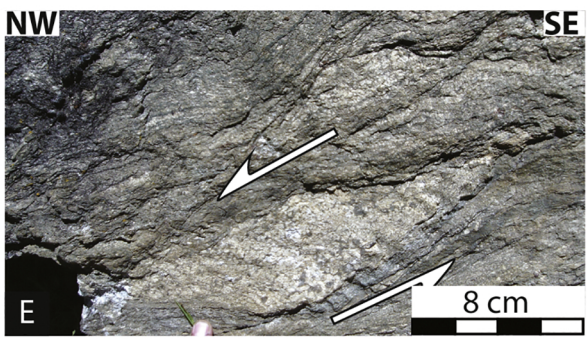
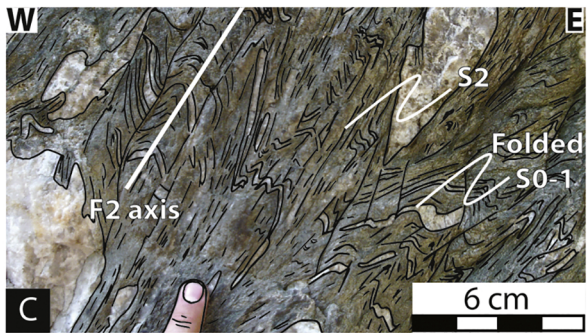


Figure 4

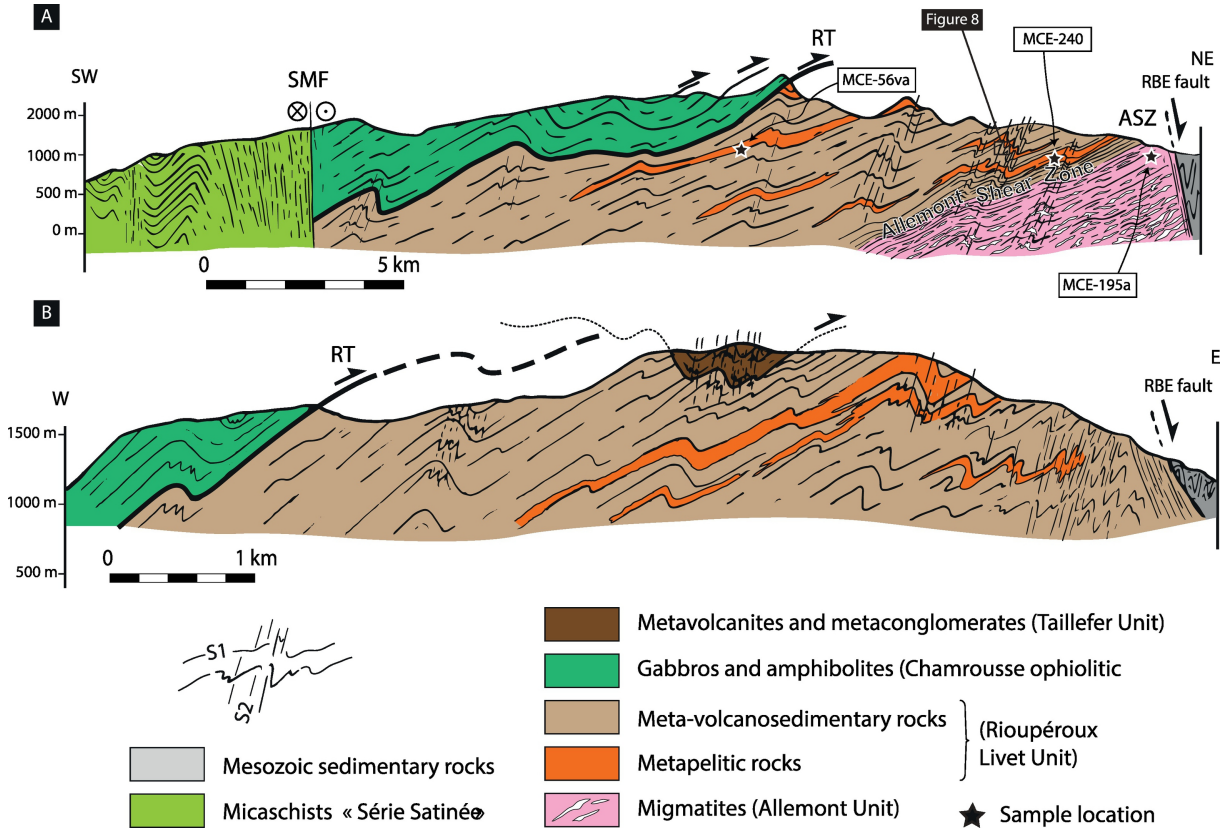
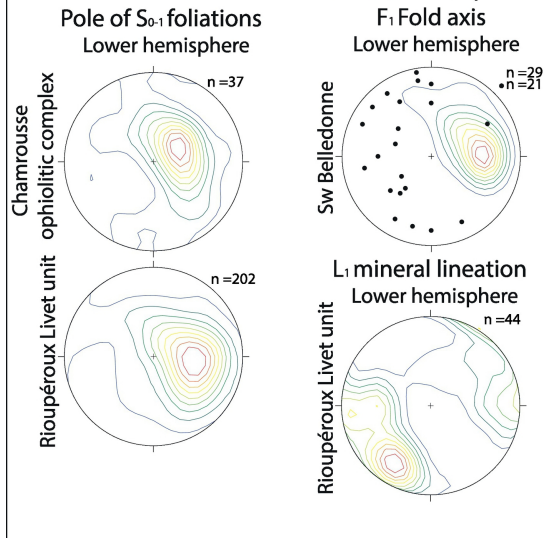


Figure 5

## D<sub>1</sub> Deformation



## D<sub>2</sub> Deformation

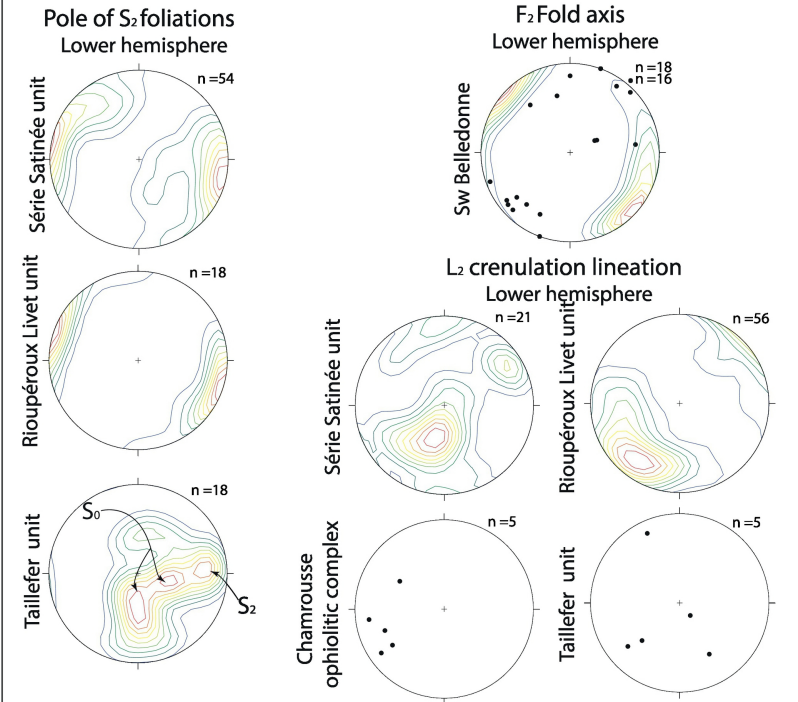


Figure 6

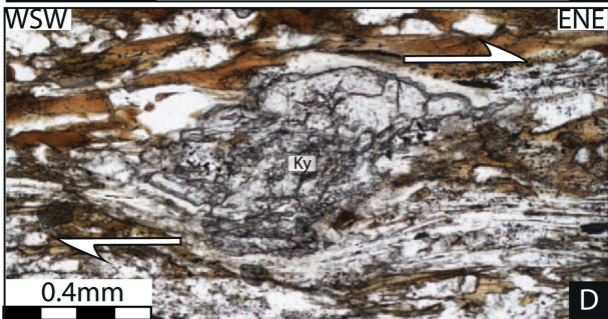
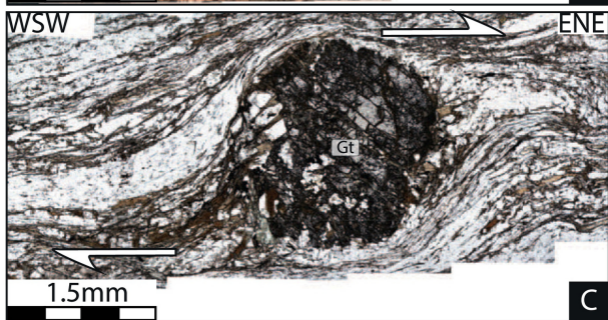
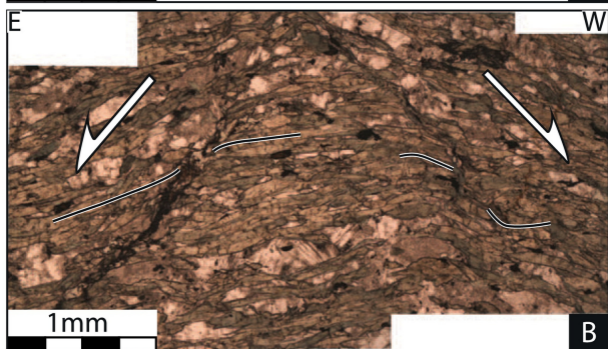
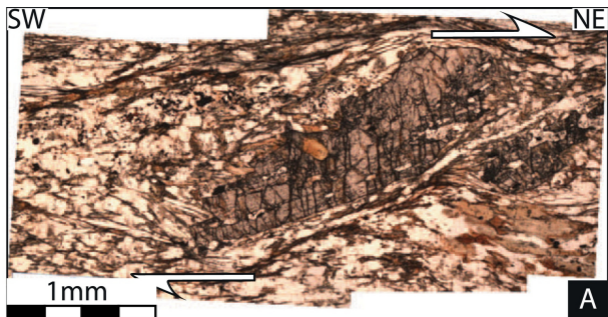


Figure 7

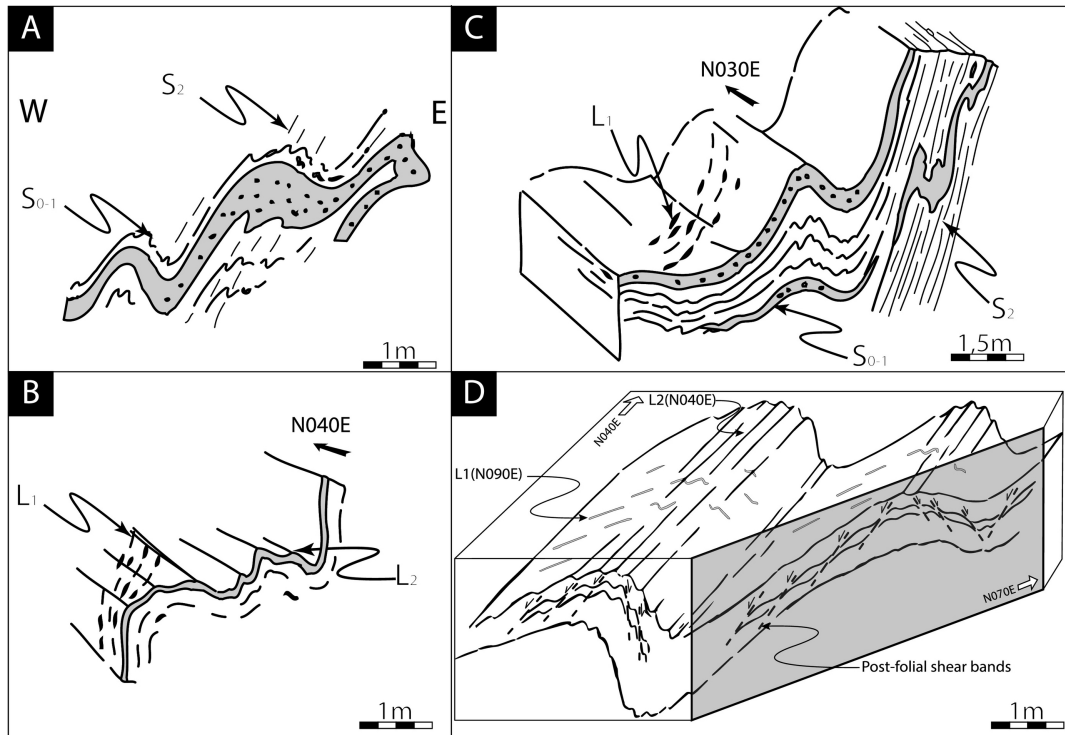


Figure 8

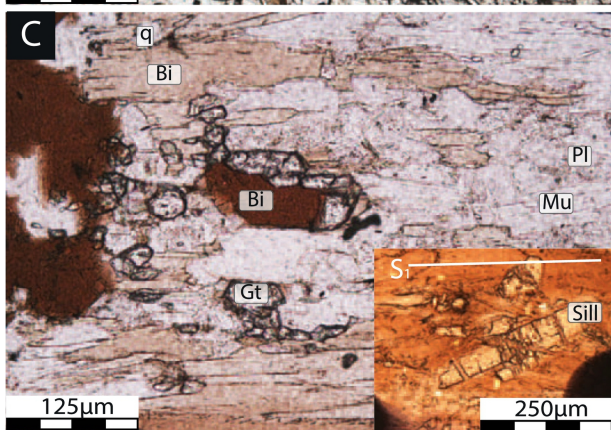
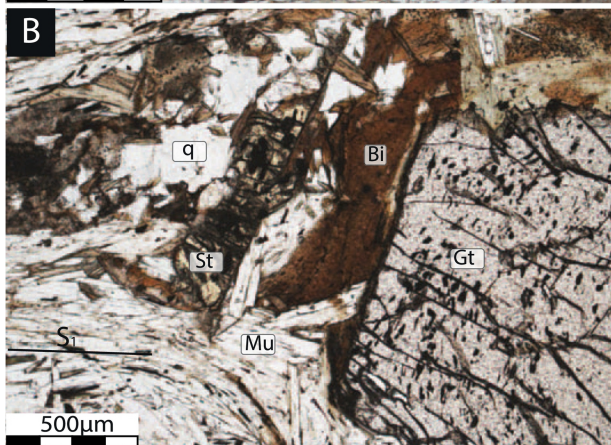
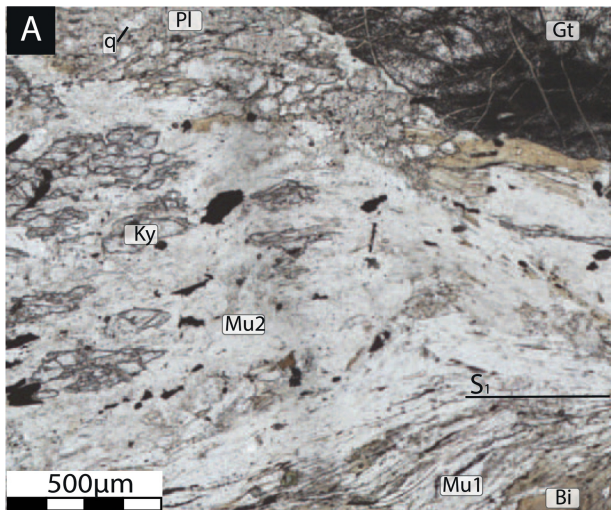


Figure 9



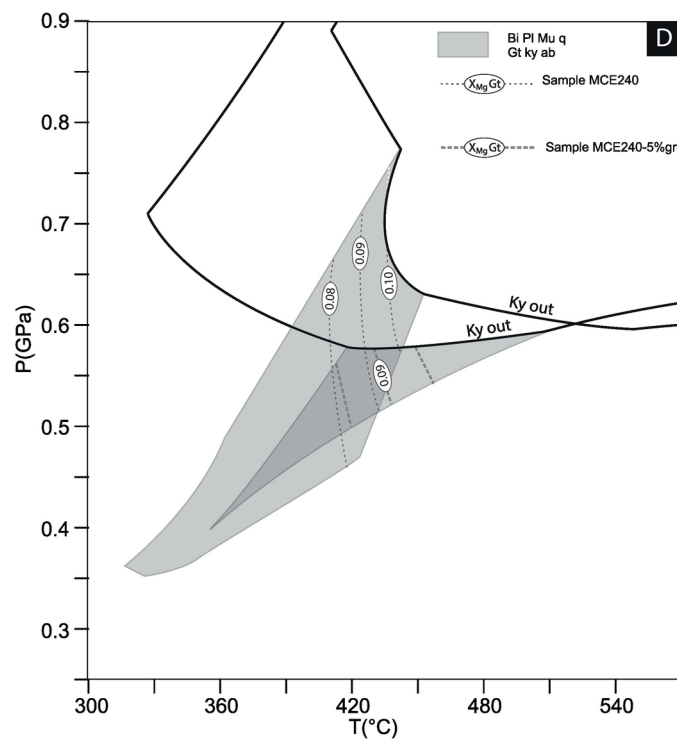
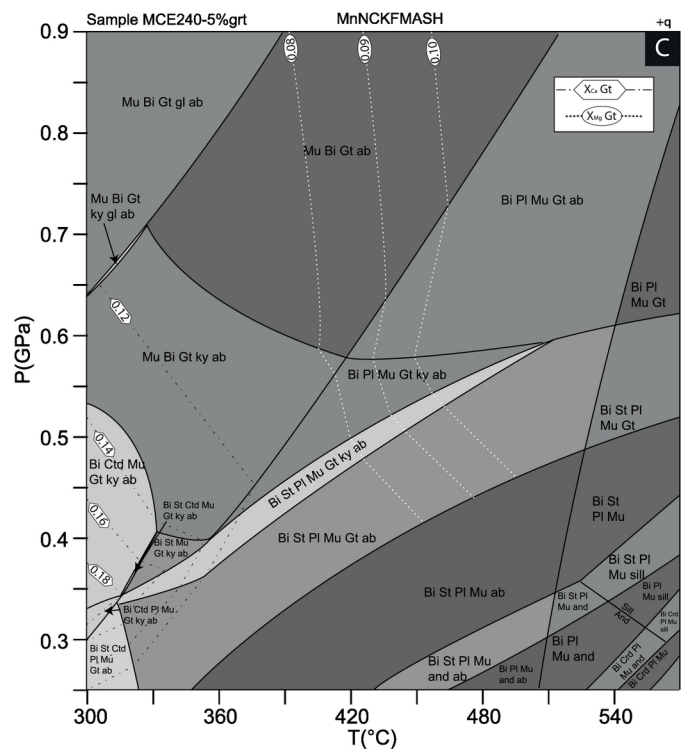
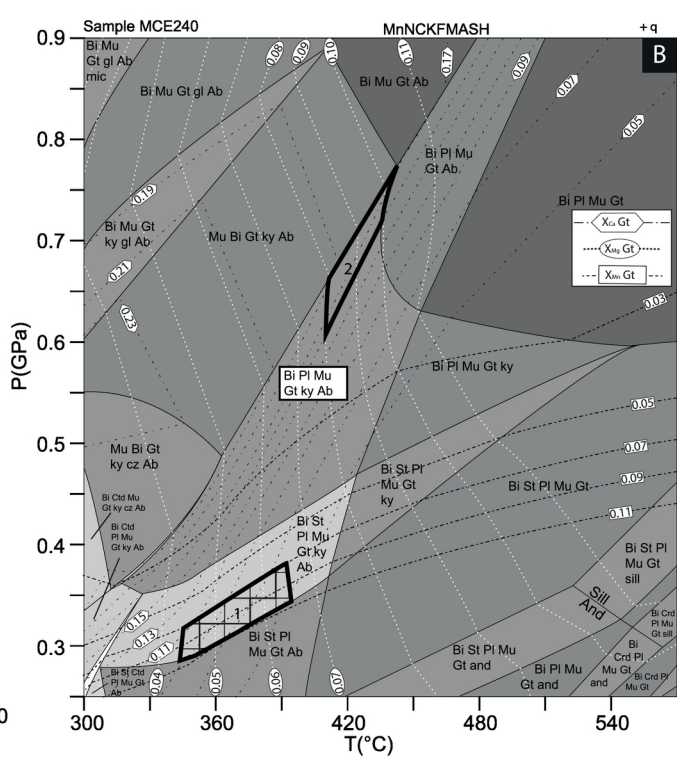
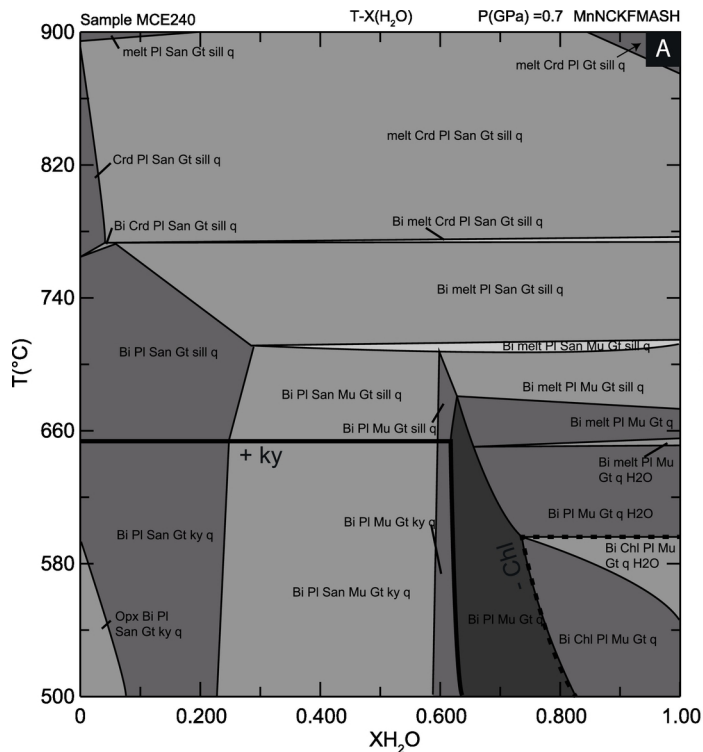


Figure 10

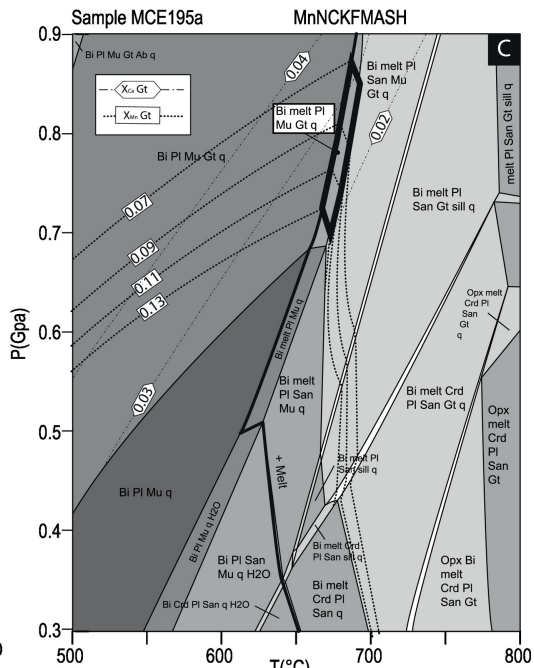
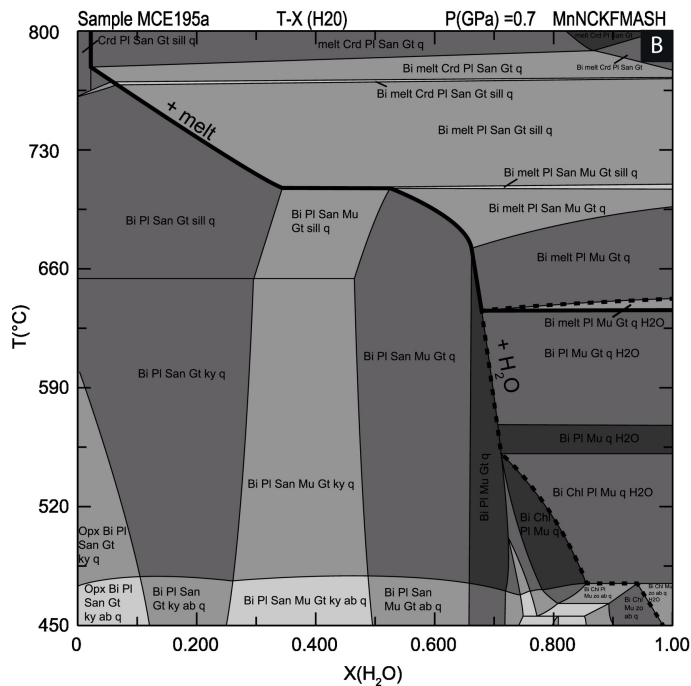
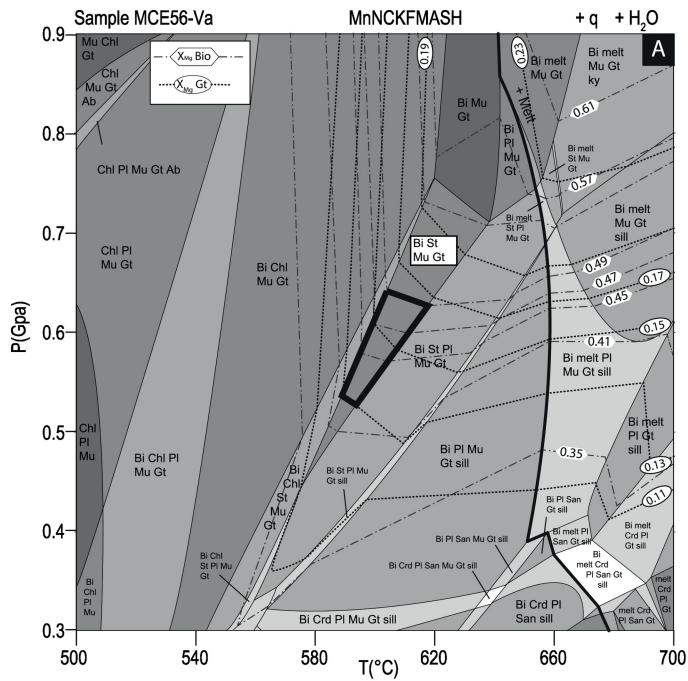


Figure 11

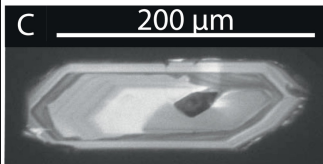
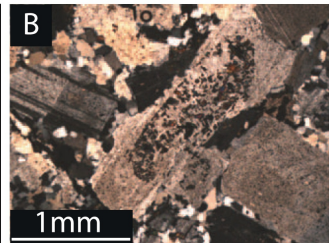
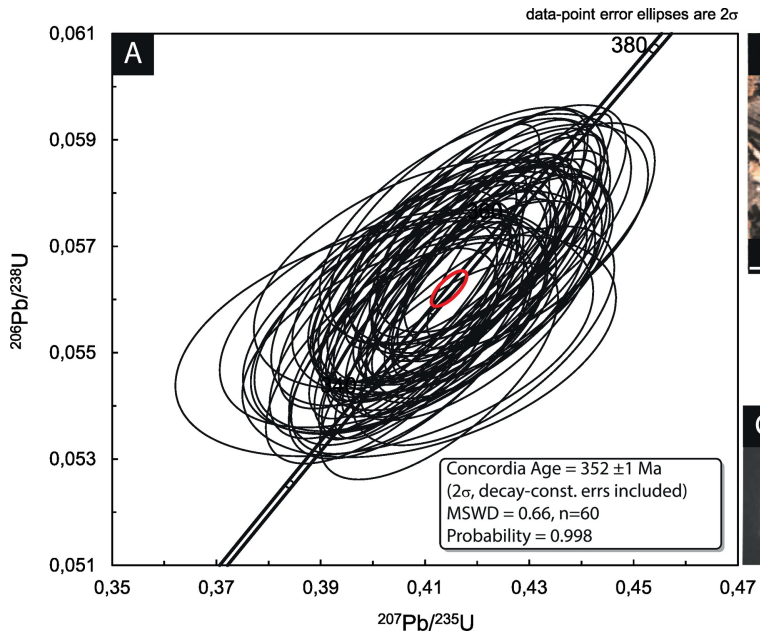


Figure 12

# Detrital Zircon of Série Satinée sandstone

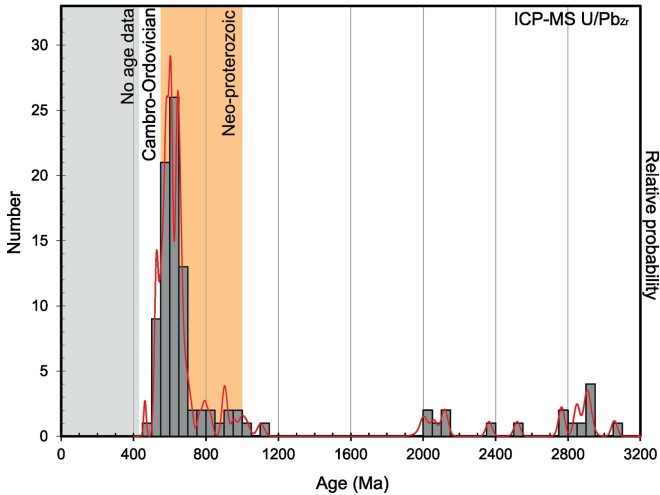


Figure 13

# Detrital Zircon of Taillefer Conglomerate

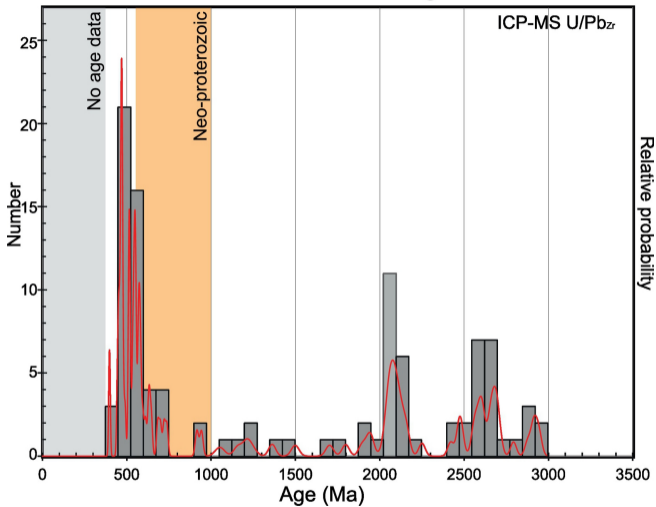


Figure 14

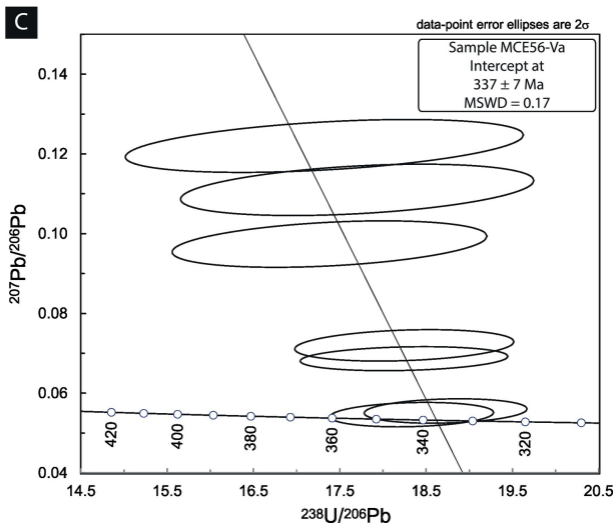
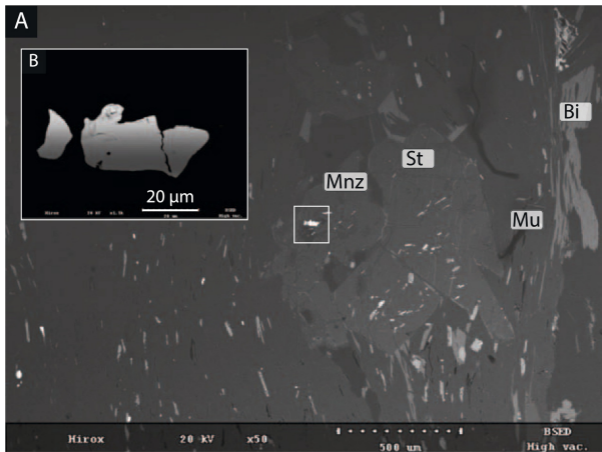


Figure 15

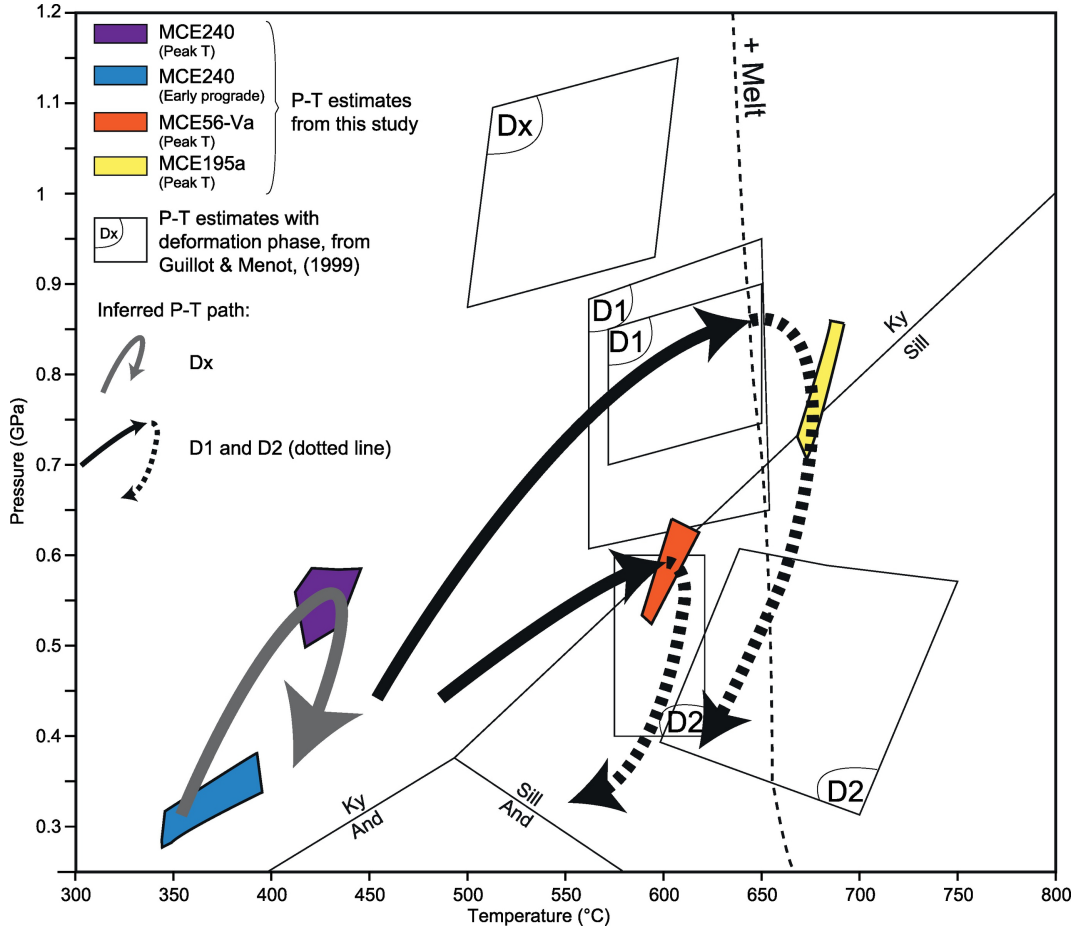
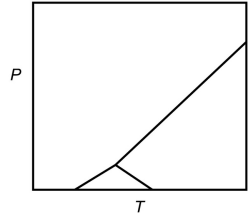
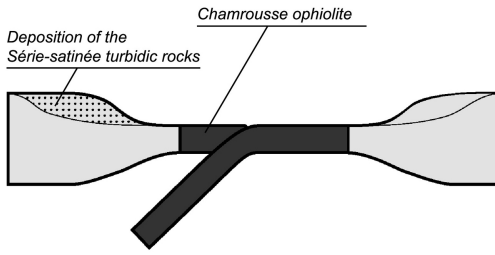


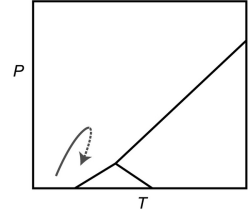
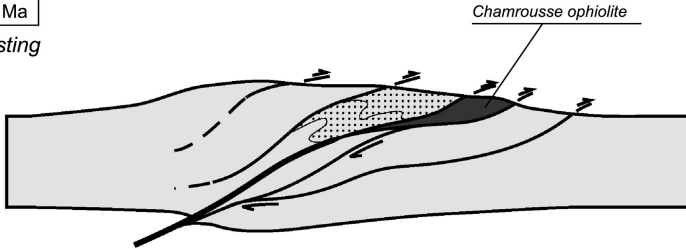
Figure 16

**A** 400-380 Ma



**B** 380-360 Ma

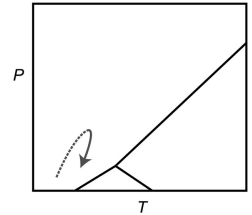
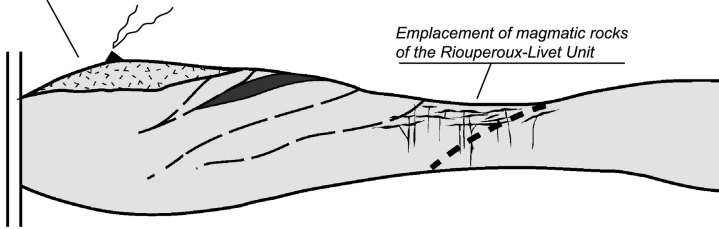
*Dx Thrusting*



**C** 360-350 Ma

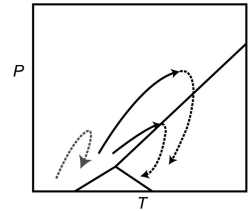
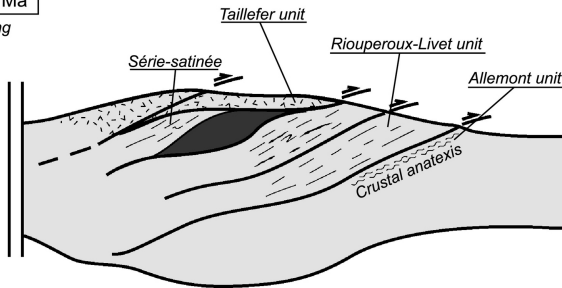
Deposition of the Taillefer volcano-sedimentary rocks

Emplacement of magmatic rocks of the Riouperoux-Livet Unit



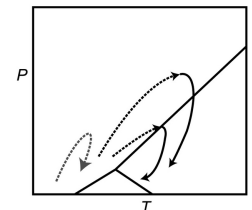
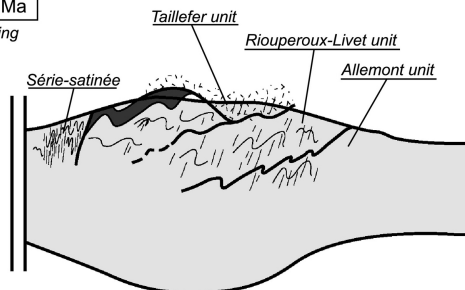
**D** 350-330 Ma

*D1 Thrusting*



**E** 330-310 Ma

*D2 Shortening*



Thrusting of the Taillefer unit

Figure 17