



## Deformation, crustal melting and magmatism in the crustal-scale East-Variscan Shear Zone (Aiguilles-Rouges and Mont-Blanc massifs, Western Alps)

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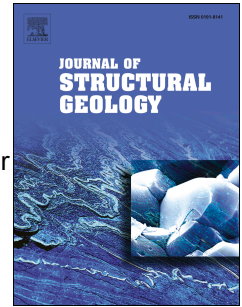
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**Deformation, crustal melting and magmatism in the crustal-scale East-Variscan Shear Zone  
(Aiguilles-Rouges and Mont-Blanc massifs, Western Alps).**

Jonas Vanandois<sup>1\*</sup>, Pierre Trap<sup>2</sup>, Françoise Roger<sup>3</sup>, Jérémie Melleton<sup>4</sup>, Didier Marquer<sup>2</sup>, Jean-Louis Paquette<sup>5</sup>, Philippe Goncalves<sup>2</sup>, Florence Cagnard<sup>4</sup> and Benjamin Le Bayon<sup>4</sup>

vanar030@umn.edu; pierre.trap@univ-fcomte.fr; francoise.roger@umontpellier.fr;

j.melleton@brgm.fr ; didier.marquer@univ-fcomte.fr; j.l.paquette@opgc.univ-

bpclermont.fr; philippe.goncalves@univ-fcomte.fr; f.cagnard@brgm.fr; b.lebayon@brgm.fr

<sup>1</sup>Department of Earth Sciences, University of Minnesota, Minneapolis, MN 55455, USA

<sup>2</sup>UMR 6249 Chrono-environnement, Université de Bourgogne-Franche-Comté, 25030 Besançon, France.

<sup>3</sup>Géosciences Montpellier, Campus Triolet, Université Montpellier, CNRS, 34095 Montpellier Cedex 5, France.

<sup>4</sup>BRGM-French Geological Survey, 3 Avenue Claude Guillemin, 45100, Orléans, France.

<sup>5</sup>Laboratoire Magmas et Volcans (CNRS-UMR 6524), Campus Universitaire des Cézeaux, 63178 Aubière Cedex, France.

\*Corresponding author: vanar030@umn.edu; +33606755562; Present address: 116 Church Street SE, John H. Tate Hall suite 150, Minneapolis, MN 55455.

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21 **Key points:** Variscan Belt, Transpression, Structural analysis, Zircon and monazite LA-ICMPS  
22 U-Th-Pb dating, crustal-scale East Variscan Shear Zone

23

## 24 **Abstract**

25 The Aiguilles-Rouges and Mont-Blanc massif represent a segment of a crustal-scale  
26 transpressional shear zone named the East Variscan Shear Zone (EVSZ) along which two  
27 plutonic pulses occurred during Early and Late Carboniferous times. The aim of this study is to  
28 constrain the relationships between the dynamics of the crustal-scale shear zone, the  
29 mechanisms of pluton emplacement at different structural levels within the crust and the  
30 magma sources. A detailed structural analysis of the whole massif highlights the crustal-scale  
31 anastomosed network of the EVSZ. Microstructural observations and LA-ICPMS U-Th-Pb zircon  
32 ages from large plutons constrain the beginning of the transpression at ca. 340 Ma. From 340  
33 to 305 Ma, the EVSZ broadened and formed a 25 km-wide dextral S-C-C' anastomosed shear  
34 zone network with dilation zones acting as preferential pathways for melt migration and  
35 pluton growths. Moreover, LA-ICPMS U-Th-Pb zircon ages from small magmatic bodies (i.e.  
36 pegmatite, aplite and microgranite) indicate an Ordovician-age inheritance component. Field  
37 evidences and zircon inheritance indicate that Late Carboniferous granitic melts are mainly  
38 derived from water-fluxed melting of Ordovician orthogneiss with the input of mantellic-  
39 source derived magmas. Over time, the growth of the dextral anastomosed network enhanced  
40 water transfer through the shear zones and water-fluxed melting to produce more anatectic  
41 melts.



42

43 **1. Introduction**

44 Continent-scale shear zones are pathways along which ductile and brittle deformation leads  
45 to segregation and transport of melts from deep to shallow crustal levels where syn-kinematic  
46 plutons might be emplaced (e.g. D'Lemos et al., 1992; Tikoff and Teyssier, 1994; Tommasi et  
47 al., 1994; Brown and Solar, 1998; Brown, 2013). Large crustal-scale shearing may last tens of  
48 millions of years (Oriolo et al., 2018; Carosi et al., 2022) but may also be the sum of localized  
49 and transient events (e.g. Fossen and Cavalcante, 2017). The duration and amount of melt  
50 production depends on main parameters such as the rock composition, melting reactions,  
51 mantle and crustal heat flux and the amount of water. Recently, water-fluxed crustal melting  
52 has been increasingly regarded as an important mechanism for initiation of voluminous  
53 melting (Weinberg and Hasalová, 2015) and for production of large batholiths (Collins et al.,  
54 2016) as an alternative to biotite or amphibole dehydration melting. This issue of the  
55 contribution of water-fluxed melting is disputed (Clemens and Stevens, 2015) and remains to  
56 be tackle.

57 The dynamics of granitic pluton emplacement depends on the source of melts and the  
58 geodynamic context (e.g. Jacob et al., 2022). The timing of pluton emplacement depends on  
59 their volume and progressive infilling rates, and large batholiths ( $>10 \text{ km}^3$ ) can grow at rates  
60 of about 1-10 Ma (Brown, 2013; de Saint Blanquat et al., 2011). Pluton emplacements in large-  
61 scale shear zones can induce local stress field and modify the regional strain partitioning (e.g.  
62 Brun and Pons, 1981; Neves et al., 1996). To fully understand the genesis and emplacement  
63 of granitic magmas along crustal-scale shear zones, timing, rates and interplay between

processes like shear deformation, melt production, melt and aqueous fluid transfer, pluton growth and emplacement must be further examined.

In the Western Alps, the Aiguilles-Rouges (AR) and Mont-Blanc (MB) massifs expose sections of middle and upper crust where migmatites and syn-kinematic Carboniferous granitic plutons are spatially and temporally correlated with the continental-scale East-Variscan Shear Zone (EVSZ; Guillot et al., 2009; Simonetti et al., 2020) (Fig. 1A). Previous geochronological studies have documented two distinct magmatic events at ca. 340-330 Ma and ca. 310-300 Ma (von Raumer and Bussy, 2004 and references therein). This twofold Carboniferous plutonism is typical for the Variscan basement of the External Crystalline Massifs (ECMs) of the Alps (Debon and Lemmet, 1999) and other parts of the Variscan belt (Corsica-Sardinia: Paquette et al., 2003; Rossi et al., 2009; Vosges: Tabaud et al., 2014, 2015). In the AR and MB massifs, the Early Carboniferous plutons are small (ca. 1-2 km<sup>2</sup>) and emplaced in the upper crust whereas the Late Carboniferous plutons are large, with an approximate area of ca. 20 to 200 km<sup>2</sup> (Bussy et al., 2000). These large plutons growth and crystallized in the migmatitic middle crust. The source of the granitic melts is thought coming from the deep part of the over thickened continental crust (Bussy, 1990; von Raumer and Bussy, 2004). Synchronous basic intrusions and peraluminous dykes (Bussy et al., 2000) suggest that the source is more complex. Also, the draining structures and melt-present deformation history can be better understood.

We present a multi-scale structural analysis performed to define the strain pattern of the EVSZ and the relationships with syn-kinematic granitic intrusions in the AR and MB massifs. Field work and LA-ICPMS U-Th-Pb zircon and monazite ages provide new insights about the nature of the protolith source, partial melting and emplacement age of magmatic bodies within the metamorphic basement. We propose a model for the production, ascent and emplacement

of granitic magmas within the EVSZ. It emphasizes the importance of water-fluxed crustal melting and the occurrence of kilometre-scale dilation zones controlling melt transfers from the anatectic source to the pluton sink.

## 2. Geological setting

The AR and MB massifs, located in the western Alpine external domain, are two narrow NE-SW trending Variscan massifs bounded by autochthonous and allochthonous Mesozoic sedimentary rocks (Fig. 1B). These two massifs, part of the ECMs, represent an exhumed portion of the Variscan crust deformed between ca. 340 and 300 Ma (e.g. von Raumer and Bussy, 2004; Vanandois et al., 2022) (Fig. 1). Structures in the AR massif suggests dextral transpression (von Raumer and Bussy, 2004) and the Emosson-Bérard Shear Zone (EBSZ) is interpreted as a branch of the EVSZ network (Simonetti et al., 2020). However, the meter to regional scale strain pattern of the whole AR and MB massifs has not been documented yet. Besides, the place of the EVSZ and ECMs within the Variscan belt reconstruction are debated (see Fig. 1A for instance) (e.g. Ballèvre et al., 2018; Simonetti et al., 2020; Martinez-Catalan et al., 2021; Faure and Ferrière, 2022).

The AR and MB massifs are composed of Proterozoic and Cambro-Ordovician amphibolitic facies gneissic basement and two greenschists facies or unmetamorphosed Carboniferous basins (Servoz and Salvan-Dorénaz synclines respectively) (Fig. 1B). The protolith of the gneissic basement consists of an upper Proterozoic to Cambrian sedimentary and volcanoclastic sequence intruded by Ordovician granite laccoliths (Bussy et al., 2011; Paquette et al., 1989; Fig. 1B). Two metamorphic events are distinguished. The first, related to collision

and crustal thickening, consists of a mid- to high-pressure metamorphism recorded as garnet-kyanite bearing assemblage in micaschists and paragneisses, and as omphacite-bearing eclogitic assemblage within tholeiitic meta mafic lenses (von Raumer and Schwander, 1985; von Raumer and Bussy, 2004; Liégeois and Duchesne, 1981; Vanandois et al., 2022). High-pressure conditions have been estimated at 1.6-1.85 GPa and 680-750°C for the Lac Cornu eclogites (Vanandois et al., 2022), and 1.3-1.5 GPa and 650-750°C for the Val Bérard eclogites (Schulz and von Raumer, 1993, 2011) (see Fig. 1B for locations). Recently, LA-ICPMS U-Th-Pb analyses on zircon and rutile from a Lac Cornu eclogite specimen has dated the HP metamorphism at 340-330 Ma and the emplacement age of the protolith at ca. 460 Ma (Vanandois et al., 2022). The AR and MB massifs were subsequently metamorphosed at pressures between 0.2 and 0.6 GPa and temperatures at ~600-750°C (Dobmeier, 1996, 1998; Schulz and von Raumer, 1993, 2011; von Raumer et al., 1996; Chiaradia, 2003; Marshall et al., 1997; Genier et al., 2008).

The development of the main fabric in the AR massif is coeval with the HT-LP metamorphism. It consists of sub-vertical 330 to 030 striking foliations bearing a sub-horizontal mineral lineation. Dextral kinematic indicators are common (Bellière, 1958; von Raumer and Bussy, 2004; Simonetti et al., 2020) within centimeter- to meter-sized mylonites, documented in the whole gneissic basement (von Raumer and Bussy, 2004). Moreover, a hectometer-sized mylonitic zone is described near the Lac Emosson (Joye, 1989; Genier et al., 2008; Simonetti et al., 2020). This shear zone recorded dextral transpression (von Raumer and Bussy, 2004; Joye, 1989; Simonetti et al., 2020). Bellière (1958) proposed a crustal-scale structural model but modern concepts like strain partitioning, heterogeneous or supra/subsolidus deformation fabrics are not considered or documented at the scale of the whole AR and MB massifs. Relics

of earlier planar fabrics are reported in several studies (Bellière, 1958; Joye, 1989; von Raumer, 1984; von Raumer and Bussy, 2004). In the Lac Cornu area (see Fig. 1B for location), Vanardois et al. (2022) interpreted an early sub-horizontal foliation as the result of horizontal flow of the partially molten crust.

Partial melting in the AR and MB massifs started during the HT-HP metamorphism, at near peak pressure conditions at  $\sim 1.3$ - $1.85$  GPa at ca. 340-330 Ma (Vanardois et al., 2022). Ongoing partial melting occurred during decompression and subsequent HT-LP metamorphism (Genier et al., 2008). The metamorphic peak recorded in metapelitic rocks from the Emosson area (see Fig. 1B for location) and the crystallization age of the anatectic melts occurred at  $327 \pm 2$  Ma and  $320 \pm 1$  Ma, respectively (ID-TIMS U-Pb on monazite, Bussy et al., 2000). Cordierite-bearing migmatites in the Fully area (Krummenacher, 1959) (see Fig. 1B for location) yield ID-TIMS zircon ages at ca. 307 Ma (Bussy et al., 2000). In the MB massif, Bussy and von Raumer (1994) dated leucogranitic injections into dextral shear bands at  $317 \pm 2$  Ma (ID-TIMS U-Pb on monazite). It remains unclear if the gneissic basement underwent one protracted partial melting event lasting from ca. 330 to 307 Ma or two distinct episodes at ca. 330-315 Ma and ca. 307 Ma.

In the Servoz area (see Fig. 1B), a Visean sequence is composed of metagreywackes, phyllites and metavolcano-sedimentary rocks overlying fine-grained gneisses ("Pormenaz gneisses" in Fig. 1B) (Dobmeier et al., 1999). It is affected by the transcurrent shearing under greenschist to low amphibolite facies metamorphism (Dobmeier, 1996, 1998; Bellière and Streel, 1980). The uppermost Variscan crust is composed of Late Carboniferous fluvial and volcanic rocks (Pilloud, 1991; Capuzzo and Wetzel, 2004) lying (1) in the upper part of the Servoz syncline and (2) in the Salvan-Dorenaz syncline that are unconformably deposited over the Variscan

metamorphic rocks (Dobmeier and von Raumer, 1995; Lox and Bellière, 1993) (Fig.1B). These rocks were metamorphized by the Alpine deformation at temperatures lower than 350 °C (Boutoux et al., 2016). Dobmeier and von Raumer (1995) considered that these rocks were not affected by Variscan deformation, whereas Lox and Bellière described Variscan open folds with subvertical axial planes oriented N020 but without more details about any tectonic significance.

The syn-kinematic Vallorcine granite emplaced along the EBSZ at  $306.5 \pm 1.5$  Ma during dextral transpression (ID-TIMS U-Pb on zircon and monazite; Bussy et al., 2000). Similar emplacement ages (ID-TIMS U-Pb on zircon) at  $307 \pm 6/-5$  Ma,  $303 \pm 2$  Ma and  $304 \pm 3$  Ma are reported for the Montenvers and the Mont-Blanc granites (Bussy and von Raumer, 1993, 1994) (Fig. 1B). The Mont-Blanc and Montenvers granites are cross-cut by local subsolidus mylonites (Bussy, 1990; Bussy et al., 2000). The Morcles microgranite is meter-sized dykes dated at  $303 \pm 3$  Ma,  $304 \pm 1$  Ma and  $311 \pm 2$  Ma (LA-ICPMS U-Th-Pb on zircon) and are interpreted as a shallow extension of the Vallorcine granite (Bussien et al., 2017) (Fig.1B). Rhyolitic dykes of the MB massif and dacites in the Salvan-Dorenaz syncline have been dated at  $307 \pm 2$  Ma and  $308 \pm 3$  Ma, respectively (ID-TIMS U-Pb on zircon; Capuzzo and Bussy, 2000) (Fig. 1B). The Visean rocks of the Servoz syncline are intruded by the peraluminous Montées-Pélissier monzogranite and the metaluminous Pormenaz monzonite, dated at  $331 \pm 2$  Ma and  $332 \pm 2$  Ma, respectively (ID-TIMS U-Pb on zircon; Bussy et al., 2000) (Fig. 1B). These two granites, represent a first magmatic pulse at ca. 330 Ma. Several authors propose that the Pormenaz and Montées-Pélissier plutons are syn-tectonic granites emplaced along vertical shear zones during bulk dextral shearing (Bussy et al., 2000; Dobmeier, 1996, 1998).

In the basement, Alpine tectonics and metamorphism are limited to the development of shear zones active under greenschist facies conditions (Rolland et al., 2003; Rossi et al., 2005). In the surrounding Mesozoic sedimentary cover, Alpine metamorphism did not exceed 350°C (Boutoux et al., 2016). Alpine tectonics is also responsible for the pinch of the NE-SW elongated Carboniferous Salvan-Dorenaz syncline (Fig. 1B) (Pilloud, 1991). Variscan tectono-metamorphic imprint is widespread in the AR and MB with higher-grade metamorphic conditions easily distinguishable from the lower-grade rocks in the Alpine localized shear zones (e.g. von Raumer and Bussy, 2004; Simonetti et al., 2020).

### **3. Structural data**

#### *3.1. D1 deformation*

D1 deformation is recorded in the gneissic basement by a sub-horizontal S1 foliation that dips gently to the NE with an L1 020-trending mineral lineation plunging at about 15° (Fig. 2B). Although S1 fabric has been transposed by subsequent D2 deformation, it is locally preserved at the outcrop-scale and at the regional-scale in the Pormenaz and Arpille areas (Fig. 2 and 3). In domains where D2 deformation is pervasive, S1 foliation is transposed and folded into open to isoclinal upright folds (Fig. 3 and 4A to D) or remains recognizable only in the hinge zones of F2 folds. Few rootless isoclinal folds (F1) have been recognized in the preserved D1 domains where an older planar fabric, designated Sx, is only locally observed in the hinges of F1 folds. (Fig. 4D and F). In the preserved domains, kinematic indicators such as asymmetrical boudinage, mica-fish and S-C fabrics indicate top-to-the-E and NE kinematics (Fig. 4E to H).

In the Lac Cornu area (see Fig. 1 and 2 for locations), the D1 deformation is defined by an S1 compositional layering in stromatitic orthogneiss migmatites (Fig. 4C), and within the core of boudins of retrogressed eclogite (Vanandois et al., 2022). In the Arpille massif (Fig. 1B), S1 foliation is defined by the shape and preferential alignment of the leucosomes in anatectic metapelites and metagraywackes (Fig. 4A). In the Pormenaz area, the S1 and L1 fabrics are observed in the non-anatectic fine-grained Pormenaz gneiss (Fig. 4H).

### 3.2. D2 deformation

#### 3.2.1. D2 deformation at the outcrop scale

D2 main fabric in the migmatitic basement and in the greenschist facies rocks of the Servoz syncline is an S2 sub-vertical foliation striking 150-170 (Fig. 2C). In D1 preserved domains, S2 is a weak crenulation cleavage that strikes ~ N160 (Fig. 4A to D). A decameter-wide strain gradient from the D1 preserved domains toward the S2 pervasive foliation is observed with the progressive tightening of F2 folds and the reorientation of the S1 sub-horizontal foliation into a sub-vertical position. Steeply-dipping and 160-striking axial planes of F2 folds are sub-parallel to S2 foliation. F2 fold axes plunge shallowly to steeply along the 160-striking axial planes. In pervasive D2 domains, we observed S-C-C' fabrics where vertical C2 shear bands striking 000-020 progressively reorient S2 foliations and become the main planar fabric, before being reoriented by the vertical C'2 shear bands striking 020-040 (Fig. 5A to C).

In the Lac Cornu migmatites, the S2 foliation is defined by mineralogical layering in the stromatic migmatite. Injections of melt in the C2 and C'2 shear bands (Fig. 5A) argue for suprasolidus conditions of shearing in this part of the massif. In the Lac Cornu metamafic lenses, the retrogression of the eclogite facies to amphibolitic facies is associated with D2



(Vanandois et al., 2022). In the Fully area (see Fig. 1 for location), cordierite-bearing migmatites show a gneissic layering and cordierite clots sub-parallel to the orientation of C'2 shear bands. Migmatites are also affected by centimeter-sized ultramylonitic bands sub-parallel to C'2 fabric (Fig. 5D). S2, C2 and C'2 planar fabrics are commonly associated with a shallowly N-plunging (30°) L2 mineral lineation (Fig. 2C). The D2 deformation is conspicuously associated with dextral kinematics highlighted by shear criteria and the S-C-C' fabrics (Fig. 5).

### 3.2.2. D2 architecture at the regional scale

The compilation of all measurements of planar fabrics related to D2 led to a well-defined three-fold subdivision: a first group labelled as S2 (150-170), a second group labelled as C2 (000-020) and a third group labelled as C'2 (020-040) (Fig. 2C). Where one of the three planar fabrics (S2, C2 or C'2) is predominant at the outcrop scale, the corresponding orientation is considered to build the foliations trajectory map of figure 2. One may notice that S2 foliation is predominant in the western and upper structural levels (Servoz-Pormenaz-Brevent areas) whereas the eastern AR massif shows mostly C2 and C'2 planar fabrics (Fig. 2). The S-C-C' regional structure resemble the one observed at all scales from millimetre to decametre. Furthermore, pervasive C2 and C'2-domains form three main kilometre-wide dextral shear zones: the Cornu Shear Zone (CSZ), the Montenvers (MSZ) and Emosson-Bérard shear zones (EBSZ). The orientation of these structures is in good agreement with a massif-scale S-C-C'-like structures.

### 3.3. D3 deformation

D3 structures are only observed in the south-western part of the AR massif, within the Pormenaz gneiss and the Viséan metasedimentary rocks (Fig. 2, 6 and 7). D3 is recorded in

metre- to decametre-sized domains where D2 deformation is folded by open to tight F3 folds with a sub-horizontal S3 cleavage (Fig. 6, 7 and 8). S3 cleavage and F3 fold axial planes are sub-parallel, and are both gently E-dipping (Fig. 6B). F3 folds axes are gently SE-plunging. L3 lineation has been only locally observed (Fig. 6B) and corresponds to an intersection lineation between S2 and S3 fabrics. Due to the lack of mineral or stretching L3 lineation, kinematics of D3 deformation remains unknown. D3 fabrics are defined by typical greenschist facies minerals such as chlorite (Fig. 8B). Few quartz-feldspar bearing leucocratic bodies interpreted as leucosomes are folded by the S3 fabric (Fig. 8C).

#### 4. Description of dated samples

Eleven samples of magmatic rocks have been sampled from different locations of the “plumbing” in the AR and MB massifs, corresponding to five large magmatic bodies: Couteray orthogneiss (AR37), Pormenaz granite (AR801), Montées-Pélissier granite (AR865), Vallorcine granite (AR73), Montenvers granite (MB43), Mont-Blanc granite (MB37); and four smaller bodies: Morcles microgranite (AR1028) and pegmatitic and aplitic dykes (AR833, AR1020, AR1006 and AR916). See Figs. 1, 3, and 7, and Table 1 for sample locations. Mineral assemblages are detailed in Table 1..

##### 4.1. Large magmatic bodies

The Couteray orthogneiss (AR37) is a N-S-trending elongate meta-igneous body located in the Val Bérard near the Vallorcine granite (Fig. 1B and 3A). It shows well-pronounced N-S D2 deformation, corresponding to C2 and C'2 planes based on their orientations, clearly

indicative of dextral shearing (Fig. 9A). Local myrmekite are observed in shear bands passing through large K-feldspar grains (Fig. 9A).

The Pormenaz granite (AR801) emplaced in the gneisses of the eastern limb of the Servoz syncline (Fig. 1B). Field observations in the western part of the pluton, where sample AR801 was collected, indicate that the magmatic fabric is marked by the alignment and preferred orientation of euhedral K-feldspar megacrysts that define a S1 sub-horizontal planar fabric and a mineral lineation L1 O20-trending and plunging 10° (Fig. 9B), similar to D1 deformation observed in the surrounding gneisses (Fig. 6 and 7). The D1 deformation is pervasive along the pluton contacts and is not observed in its core (Fig. 7A). In the eastern part of the pluton, the S1 foliation is deformed and reoriented by O00- to O20-striking D2 vertical structures (Fig. 6 and 7). In this area, K-feldspar megacrysts are deformed as well as the surrounding matrix (Fig. 9C). K-feldspar grains are fractured and no myrmekite was observed. The quartz grains show undulose extinction and recrystallization by bulging grain boundaries.

The sample AR865 comes from the core of the Montées-Pélissier pluton, which is a fine-grained monzogranite that intruded the Visean metasedimentary rocks in the Servoz syncline (Fig. 1 and 7B). In the whole pluton and in our sample, the magmatic assemblage is pervasively deformed by the D2 such that any magmatic fabric that may have existed is not preserved. In thin-section, feldspar crystals are oriented sub-parallel with the C2 shear bands and show common extensive microfractures filled by quartz (Fig. 9D).

The Vallorcine granite (AR37) is a NE-SW-trending elongate pluton located in the north-eastern part of the AR massif in the EBSZ (Fig. 1B and 3). This granite crosscuts the C'2 shear bands near the Lac Emosson (Fig. 9E). The sample commonly possesses a magmatic foliation defined by biotite and feldspar sub-parallel to the C'2 orientation (Joye, 1989; Bussy et al.,

2000). At the microscale, in sample AR73, feldspar is undeformed and quartz is nested with undulose extinction and shows grain boundary migration in quartz (Fig. 9E). Local millimeter shear bands are associated to subgrain rotation recrystallization in quartz.

The Montenvers granite (MB43) intruded paragneiss and orthogneiss migmatites of the MB massif (Fig. 1B and 3A). The Montenvers granite and its host rocks are strongly deformed within an anastomosed network of C2 and C'2 shear zones of the MSZ (Fig. 2, 3A and 9F). In sample MB43, fractures in feldspar are filled by quartz and recrystallized polygonal quartz (Fig. 9G). Locally, the quartz polygons are deformed within C'2 shear bands.

The Mont-Blanc granite (MB37) is a kilometer-large NE-SW-trending elongate pluton and forms the main part of the MB massif (Fig. 1B and 3B). The pluton contacts are deformed in C2 and C'2 structures whereas its core is weakly deformed. The granite shows a magmatic foliation defined by the weak alignment of K-feldspar, biotite crystals and mafic enclaves striking 020-040 (Bussy, 1990), sub-parallel to the C'2 shear planes (Fig. 9H).

#### 4.2. *Smaller magmatic bodies*

Sample AR1028 comes from one of the dykes composing the Morcles microgranite, located in the northern part of the AR massif (Fig 1B and 3C). This microgranite has a main NE-SW-trending orientation and locally crosscuts C2 and C'2 shear zones. There is no apparent preferred mineral orientation. Quartz grains do not show undulose extinction and are locally nested (Fig. 9I). Calcite had partially replaced some feldspar grains and is present in cracks in feldspar (Fig. 9I).

Pegmatites are common in the orthogneiss of the Lac Cornu area (Fig. 1B and 7D). The sample AR833 is from one of these pegmatites, that has a diffuse contact with the orthogneiss

migmatite (Fig. 10A). The feldspars in the pegmatite are preferentially oriented parallel to the C2 shear bands in the surrounding rocks (Fig. 10A). K-feldspar grains are surrounded by myrmekite.

The sample AR1020 corresponds to a pegmatite that crosscuts the C2 planes of an amphibolite lens in the Lac Cornu orthogneiss (Fig. 10B). It does not have an apparent preferred mineral orientation. Quartz has weakly developed undulose extinction and recrystallization by grain boundary migration.

The Lacs Noirs pegmatite is a ten centimeter-large dyke in paragneiss. It is affected by the D2 dextral wrenching and C2 shear bands are recognized (Fig. 1B and 10C). Quartz is strongly deformed and well-developed undulose extinction. Tourmaline is either undeformed and oriented parallel to the foliation or sub-parallel to the foliation, fractured and truncated. K-feldspar is replaced by muscovite in shear bands.

The sample AR916 comes from an aplite dyke that emplaced within a decametric C2 shear zone in metasedimentary rocks (Fig. 1B and 10D). The mineral assemblage does not have an apparent preferred mineral orientation. Some plagioclase and K-feldspar are partially replaced by white mica.

## **5. U-Th-Pb dating of studied samples**

### *5.1. analytic method*

Zircon and monazite U-Th-Pb age determinations of these samples were carried out using Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) at the Laboratoire

Magmas et Volcans, Clermont–Ferrand (France). Separated zircon and monazite grains were mounted in epoxy resin discs that were polished to reveal equatorial cross sections. Cathodoluminescence (CL) and Back-Scattered Electron (BSE) images were used to select points for analysis. The analyses involve the ablation of minerals with a Resonetics Resolution M-50 powered by an ultra-short pulse ATL Atlex Excimer laser system operating at a wavelength of 193 nm (detailed description in Müller et al., 2009). The detailed analytical procedures are described in Paquette and Tiepolo (2007), Hurai et al. (2010), and Paquette et al. (2014) and detailed in the Supplementary material (S1). Data reduction was carried out with the GLITTER<sup>®</sup> software package developed by Macquarie Research Ltd (Jackson et al., 2004). The analytical data are provided in the Supplementary Material 1 (SM1). Ages and diagrams were generated using the Isoplot/Ex v. 2.49 software package by Ludwig (2001). Only the concordant data and the discordant data fitting with the discordia line were taken into account in the age calculation. In the text and figures, all uncertainties in ages are given at  $\pm 2\sigma$  level.

## 5.2. Couteray orthogneiss (AR37)

Zircon grains from the Couteray orthogneiss are transparent and euhedral with a shape that varies from equant to elongate. CL images show either the presence of inherited cores surrounded by rims with concentric oscillatory zones, or uniform grains also with concentric oscillatory zones (Fig. 11A). Twenty-eight analyses were conducted on seventeen zircon crystals (Fig. 12A; Table S1). Analyses of inherited cores with concentric zones and Th/U ratios between 0.18 and 0.99 (Table S1) yield one concordant date at 691 Ma (#12) and a cluster of five data (#8, 10, 18, 20, 25) giving a concordia age of  $587 \pm 10$  Ma ( $\text{MSWD}_{\text{(C+E)}} = 1.16$ ) (Fig. 12A). Nineteen analyses on cores and rims with concentric zones and Th/U ratios

ranging between 0.01 and 0.76 (Table S1) yield a concordia age at  $480 \pm 4$  Ma ( $\text{MSWD}_{(C+E)} = 0.61$ ,  $n = 19$ ) (Fig. 12A).

### 5.3. Early Carboniferous (Visean) granites (ca. 340-330 Ma).

#### 5.3.1. The Pormenaz granite (AR801)

Most of the zircon grains analysed are euhedral, either prismatic with a shape ratio up to 2:1 or stubbier with a shape ratio of 1:1 (Fig. 11B). They are pinkish, transparent to slightly opaque. CL images show strong evidence of concentric or oscillatory igneous growth zones as well as the presence of cores displaying either sector-like or patchy zone textures surrounded by zoned rims (Fig. 11B). Seventy-five analyses were performed on sixty-five zircon crystals (Table S1). In the Tera Wasserburg diagram, excepting from two cores (#10 and 35) concordant around 650 Ma, all data are scattered along the concordia curve between around 340 to 190 Ma with thirty-two data yielding a concordia age of  $338 \pm 2$  Ma ( $\text{MSWD}_{(C+E)} = 1.4$ ) (Fig. 12B). These data are mainly obtained on zoned cores (24 cores and 8 rims). The analysed grains have a range of Pb (8.5-69 ppm), Th (most 55-281 ppm) and U (150-1526 ppm) contents and Th/U ratios (most 0.15-0.51) (Table S1). Other discordant data (dotted ellipses) mainly composed of rims (34 rims and 7 cores) are characterized by similar Pb, Th and U contents (17-75 ppm, 64-458 ppm and 351-2027 ppm) and Th/U ratios (most 0.14-0.66) (Table S1). These data are not taken into consideration for the age calculation because they are discordant. These discordances are probably due to radiogenic Pb losses and common Pb contaminations.

#### 5.3.2. The Montées-Pélissier granite (AR865)

Zircon crystals from sample AR865 are pinkish, transparent, euhedral and elongate but commonly broken. CL images show strong evidence of concentric or oscillatory igneous growth zones (Fig. 11C). Forty-three analyses are obtained on rims or cores of 43 crystals and present Th/U ratios ranging between 0.04 and 1.02 (most 0.16-0.67) with homogeneous Pb content (most 21-64 ppm) and variable U (most 555–1450 ppm) and Th (most 90–347 ppm) contents (Table S1). In the Tera Wasserburg, the data are scattered along the concordia curve between around 350 to 210 Ma (Fig. 12C). The eight oldest data (#2, 6, 7, 8, 12, 13, 22 and 34) form a cluster around 340-335 Ma that yields a concordia age of  $340 \pm 5$  Ma ( $\text{MSWD}_{(\text{C+E})} = 2.2$ ). Other data (dotted ellipses), often discordant, show younger  $^{206}\text{Pb}/^{238}\text{U}$  dates (Table S1; Fig. 12C). These data are not considered because they were probably affected by radiogenic Pb losses as well as common Pb contaminations.

#### 5.4. Late Carboniferous granite (ca. 305 Ma)

##### 5.4.1. Vallorcine granite (AR73)

The zircon crystals from the Vallorcine granite (AR73) are transparent, pinkish and euhedral. Zircon ranges in shape from equant to elongate. The latter are commonly fractured. CL images show complex internal textures such as the presence of apparently inherited cores and concentric oscillatory and patchy zones textures (Fig. 11D). Twenty-nine analyses were carried out on twenty-two zircon crystals (Fig. 12D). Two data from two cores (#4 and 25) are sub-concordant and yield an upper intercept at  $2071 \pm 75$  Ma in the concordia diagram. These zircon cores have similar Pb (64-67 ppm), Th (31-59 ppm) and U (181-184 ppm) contents with Th/U ratios of 0.17 and 0.32 (Table S1). Three data obtained on cores show Th/U ratios of ca.



0.3 and are sub-concordant around 650 Ma (#15 and 20) and 840 Ma (#2) (Table S1). The other twenty-four data are scattered along the concordia curve between ca. 840 to 220 Ma in two main distinct clusters: one very wide between 485 and 450 Ma (group 1) and the other more restricted between 310 to 300 Ma (group 2). Group 1 dates (#3, 5, 6, 10, 12, 18, 22) were determined from 5 cores and 2 rims. These seven analyses are characterized by variable Pb and Th contents ranging from 19 to 52 ppm and 11 to 183 ppm, respectively and by Th/U ratios from 0.04 to 0.54 (most 0.13-0.54) (Table S1). The linear regression on these seven data yields a lower intercept of  $468 \pm 13$  Ma (MSWD = 2). Amongst these data, six give a concordia age of  $469 \pm 12$  Ma (MSWD<sub>(C+E)</sub> = 2.6). Group 2 dates (#7, 8, 11, 16, 19, 21, 23, 26, 27, 29) are obtained from 2 cores and 8 rims. Pb and Th contents ranging from 12-72 ppm and 11-201 ppm, respectively, and with Th/U ratios from 0.01 to 0.31 (most 0.1-0.31). These ten data yield a concordia age of  $306 \pm 5$  Ma (MSWD<sub>(C+E)</sub> = 1.8). Five data (white ellipses) between these two clusters may correspond to a mixed age. The two youngest data (dotted ellipses) may be the result of radiogenic Pb loss.

#### 5.4.2. Montenvers granite (MB43)

Zircon crystals from sample MB43 are pinkish and transparent. They are either equant with a shape ratio up to 2:1 or in the form of prismatic or elongate grains. CL images show concentric or oscillatory igneous growth zones as well as the presence of cores displaying either sector-like or patchy zones textures surrounded by zoned rims with locally a thinner and CL-dark over-rim (Fig. 11E). Forty-five analyses are obtained on rims or cores of 40 crystals and present Th/U ratios ranging between <0.01 and 1.30 (most 0.01-0.82) with variable Pb (3.3-404 ppm), U (most 98–5721 ppm) and Th (most 29–869 ppm) compositions (Table S1). In the Tera Wasserburg diagram, excepting datum #4 (not plotted) measured on the inherited core of the

zircon Z9 with a Th/U ratio of 1.30 and a discordant position around 1.8 Ga, all other data are scattered along the concordia curve between ~620 to 220 Ma in a cluster around 310-220 Ma and two others more restricted around 600 Ma and 450 Ma (Fig. 12E). The cores of zircons Z10 (#9) and Z19 (#19) have a Th/U ratio of 0.32 and 0.79 and give concordant data at  $615 \pm 16$  Ma and  $592 \pm 16$  Ma, respectively. The cluster at 450 Ma consisting of the analyses obtained on three tips (#1, 35, 43; Th/U = 0.01-0.26) and two cores (#29, 37; Th/U = 0.15-0.38) yields a concordia age of  $447 \pm 10$  Ma ( $\text{MSWD}_{(C+E)} = 1.6$ ,  $n = 4$ ). Among the thirty-eight youngest data, nineteen data from 10 cores and 9 rims yield a concordia age of  $306 \pm 3$  Ma ( $\text{MSWD}_{(C+E)} = 1.6$ ) (Fig. 12E). In the diagram, the dotted ellipses are obtained mainly on the metamict CL-dark rim and are characterized by very high U contents (1315-9763 ppm).

#### 5.4.3. Mont-Blanc granite (MB37)

The zircon crystals from the Mont Blanc granite (MB37) are transparent, pinkish and euhedral with an elongate shape with a shape ratio up to 3:1. CL images show oscillatory igneous growth zones as well as the presence of few cores displaying either sector-like zones surrounded by CL-dark zoned rims (Fig. 11F). Forty-three analyses were carried out from forty-two zircons (Fig. 12F; Table S1). Among them, two are (#15 and 34) composed by cores characterized by concentric zones and a Th/U ratio of 0.34, and are concordant at ca. 485 Ma and ca. 558 Ma. There are two more data (#1 and 10) obtained on a core and a rim with a Th/U around 0.3-0.4, that are concordant at ca. 335 Ma. Otherwise, thirty-five data plot as a cluster characterized by Th/U ratios ranging between 0.2 and 0.86 and yield a concordia age of  $305 \pm 2$  Ma ( $\text{MSWD}_{(C+E)} = 1.5$ ,  $n = 35$ ). Two discordant data (dotted ellipses) (#37 and 42) obtained on CL-dark rims show youngest  $^{206}\text{Pb}/^{238}\text{U}$  dates, which may be the result of radiogenic Pb loss as well as common Pb contamination.

## 5.5. Smaller granitic bodies (e.g. microgranite, aplite and pegmatite dykes)

### 5.5.1. Morcles microgranite (AR1028)

Zircon crystals from sample AR1028 are colourless to slightly pink and transparent. They are either prismatic with an shape ratio up to 3:1, or ovoid, but also sometimes as fragment-like. CL images show complex internal features such as the presence of cores and concentric oscillatory and patchy zones textures (Fig. 13A). Some crystals have metamict rims, which could not be analysed because they are too rich in common Pb. Monazite crystals were found in this sample. They are light yellow, transparent and euhedral. EBS images exhibit concentric oscillatory or patchy zones (Fig. 13A).

Twenty analyses on seventeen zircon crystals yield Th/U ratios ranging between 0.08 and 0.62 (most 0.1-0.44) with variable Pb (3.9-118 ppm), U (40–2298 ppm) and Th (16–731 ppm) contents (Table S1). In the Tera Wasserburg diagram, excepting data 5 and 8, the concordant to sub-concordant data are scattered between ca. 800 and ca. 450 Ma (Fig. 14A). The linear regression on ten data (#1, 4, 6, 9, 10, 11, 14, 16, 17, 18) obtained on 5 cores and 5 rims yields a lower intercept of  $463 \pm 10$  Ma (MSWD = 2.9 Ma). Sixteen analyses were also performed on nine monazite crystals (Table S1). Excepting the analysis #11, data form a cluster with a concordia age of  $313 \pm 2$  Ma ( $\text{MSWD}_{(\text{C+E})} = 0.49$ ,  $n = 15$ ) (Fig. 14B). Spot #11, that has a discordant position around ca. 360 Ma may correspond to an analytical mixture.

### 5.5.2. Lac Cornu pegmatites (AR833 and AR1020)

Zircon crystals from sample AR833 are euhedral, colourless and transparent. Their shapes are either elongate or rounded. CL images highlight various cores surrounded by rims with concentric and oscillatory zones (Fig. 14B). Sixty-three analyses on forty-three zircon grains

are distributed into four clusters (Fig. 14C). Three data (#15, 20, 46) from cores with Th/U ratios between 0.16 and 0.23 yield a mean  $^{238}\text{U}/^{206}\text{Pb}$  date at  $724 \pm 28$  Ma (MSWD = 1.3). Four data (#2, 4, 22, 34) also from cores with similar Th/U ratios (0.19-0.28) return a concordia age at  $552 \pm 12$  Ma (MSWD<sub>(C+E)</sub> = 2.4). The main cluster is composed of fifty-one analyses from cores and rims with concentric and oscillatory zones and lower Th/U ratios (mostly 0.04-0.15) from ca. 465 Ma to 420 Ma. Among them, twenty-eight data yield a concordia age at  $462 \pm 3$  Ma (MSWD<sub>(C+E)</sub> = 1.08). In addition, two sub-concordant data (#45, 48) from rims with oscillatory and concentric zones and low Th/U ratios (0.00-0.01) yield a mean  $^{238}\text{U}/^{206}\text{Pb}$  date at  $317 \pm 6$  Ma (MSWD = 1.04). One datum (#16) from a zircon core is concordant at 2.0 Ga (Table S1).

Zircon crystals from the pegmatite AR1020 are not common, often metamict and pinkish, or transparent to milky. Their shapes vary from elongate to rounded. CL images reveal complex textures such as the presence of cores surrounded by rims, concentric oscillatory and patchy zones textures (Fig. 14C). Nineteen analyses were performed on eleven grains (Table S1). Despite the various and complex zones of these zircon grains and their scattered Th/U ratios (0.05-1.03), all the data are between ca. 465 and 375 Ma and thirteen yield a concordia age at  $456 \pm 4$  Ma (MSWD<sub>(C+E)</sub> = 0.5) (Fig. 14D). Other analyses might reflect Pb loss or common Pb contamination.

### 5.5.3. Lacs Noirs pegmatite (AR1006)

Zircon crystals from the pegmatite specimen are colourless and transparent fragments. CL images show that most of the grains have resorption structures affecting cores and rims with oscillatory and concentric zones (Fig. 13D). Thirty-three analyses were performed on thirty-two zircon grains (Fig. 14E). Twenty-two data with Th/U ratios ranging between 0.04 and 0.70

align and form a lower intercept at  $455 \pm 3$  Ma (MSWD = 0.48). Among them, seventeen data yield a concordia age at  $456 \pm 3$  Ma (MSWD<sub>(C+E)</sub> = 0.89). Other analyses, except one (#14), are concordant or sub-concordant and spread from 535 to 997 Ma.

#### 5.5.4. Chéserys aplite (AR916)

Zircon crystals from aplite are not common and are mainly transparent and colourless grains with elongate to ovoid shapes. CL images show mainly simple internal structures with concentric and oscillatory zones (Fig. 13E). A few grains show a core surrounded by a rim with oscillatory zones. Some grains also display a metamorphic rim. Thirty-three analyses on thirty-two zircon grains (Fig. 14F) yield a cluster between 460 and 420 Ma. Among them, eighteen analyses on cores and rims with Th/U ratios between 0.04 and 0.95 yield a concordia age at  $458 \pm 3$  Ma (MSWD<sub>(C+E)</sub> = 1.3). One analysis (#22) on a core is sub-concordant at 839 Ma. Several discordant data show  $^{206}\text{Pb}/^{238}\text{U}$  dates younger than 400 Ma.

## 6. Discussion

### 6.1. Emplacement ages of granites and pegmatites

#### 6.1.1. Ordovician magmatism

Zircon grains from the Couteray orthogneiss (AR37) yield two concordia ages: one Ordovician at  $480 \pm 4$  Ma and the other Precambrian at  $587 \pm 10$  Ma (Fig. 12A). The first one was obtained on zircon cores and rims showing oscillatory and concentric zones (Fig. 11A) typical of magmatic origin (Linnemann et al., 2011; Tiepel et al., 2004); we therefore interpret it as the Ordovician emplacement age of the magmatic protolith of the Couteray orthogneiss. The

Precambrian age was obtained on zircon cores that are locally partially resorbed (Fig. 11A, Zr36). The Precambrian one was obtained on zircon cores that are locally partially resorbed (Fig. 11A, Zr36). The geological significance of this inherited precambrian age remains unknown.- The Ordovician age is slightly older than the magmatic protolith emplacement ages of other orthogneisses from the AR and MB massifs dated between 465 and 455 Ma (Bussy and von Raumer, 1994; Bussy et al., 2011) (Fig. 1B). However, this age remains consistent with the 480-450 Ma age range proposed for the Ordovician magmatic event that is well-documented throughout the Variscan belt (Melleton et al., 2010 and references therein; Lotout et al., 2017; Chelle-Michou et al., 2017).

#### *6.1.2. Early Carboniferous plutonism (ca. 340-330 Ma)*

Most of the zircon grains analysed from the Pormenaz (AR801) and Montées-Pélissier (AR865) granites show magmatic growth zones with Th/U ratios from 0.1 to 1.0 typical of an igneous zircon origin (Tiepel et al., 2004; Linnemann et al., 2011) (Fig. 11B and C; Table S1). The zircon concordia ages of  $338 \pm 2$  Ma and  $340 \pm 5$  Ma obtained on these two plutons match within uncertainties and are interpreted as emplacement ages (Fig. 12B and C). These results agree with the ages at  $332 \pm 2$  Ma and  $331 \pm 2$  Ma documented by Bussy et al. (2000), and therefore confirm the occurrence of an Early Carboniferous (Visean) magmatism in the AR massif (Fig. 1B). Moreover, these two samples yield discordant data, mainly obtained on zircon rims, which are probably affected by radiogenic Pb losses during the successive Variscan and Alpine tectono-metamorphic events.

#### *6.1.3. Late Carboniferous plutonism*

The concordia ages of  $306 \pm 5$  Ma,  $306 \pm 3$  Ma and  $305 \pm 2$  Ma on the Vallorcine (AR73), Montenvers (MB43) and Mont-Blanc granites (MB37), respectively, are from zircon cores and rims showing concentric and oscillatory zones with Th/U ratios mostly higher than 0.1 typical of igneous zircons (Tiepel et al., 2004; Linnemann et al., 2011) (Fig. 11D-F and 12D-F; Table S1). These dates are interpreted as emplacement ages and are consistent with previous published ID-TIMS U-Pb ages on zircon and monazite at ca. 305 Ma for these same plutons (Bussy et al., 2000; Bussy and von Raumer, 1993, 1994) (Fig. 1).

In this study, most of the concordant data obtained on zircon from the felsic dykes (AR1028, AR833, AR1020, AR1006 and AR916) range from ca. 465 to 455 Ma (Fig. 14; cf section 5.2). Field-work shows that these felsic dykes emplaced contemporaneously with dextral shearing during Carboniferous times (Bussy and von Raumer, 1994; von Raumer and Bussy, 2004; Fig. 10). Therefore, the Ordovician record reflects the presence of an inherited component associated with an Ordovician magmatic event at ca. 465-455 Ma.

Zircon and monazite U-Th-Pb dating of the Morcles microgranite (sample AR1028) yielded two distinct concordia ages, one at  $313 \pm 2$  Ma and the other at  $463 \pm 10$  Ma (Fig. 14A and B). The younger one was determined on euhedral monazite grains showing concentric growth zones, and is similar to the zircon LA-ICPMS U-Th-Pb age at ca. 312-309 Ma obtained for one of the magmatic pulses proposed for the Morcles microgranite dykes in Bussien et al. (2017). Therefore, we interpret the monazite concordia age at  $313 \pm 2$  Ma as the emplacement age of the AR1028 microgranite dyke and the zircon concordia age at  $463 \pm 10$  Ma as the age of an inherited Ordovician component, which was identified in Bussien et al. (2017) too.

Moreover, two zircon grains from the Lac Cornu pegmatite AR833 show two sub-concordant analyses at ca. 317 Ma (Fig. 14C). These analyses were obtained on zircon rims with oscillatory

and concentric zones and low Th/U ratios (0.00-0.01; Table S1), which is characteristic of magmatic zircon that may have originated from high-SiO<sub>2</sub> and/or peraluminous granitoids (Lopez-Sanchez et al., 2016). This mean at  $317 \pm 6$  Ma might represent the emplacement age of the pegmatite AR833 and would be consistent with the emplacement age of the Morcles microgranite at  $312 \pm 2$  Ma and the  $317 \pm 3$  Ma age proposed for the anatectic leucogranitic dykes of the Mont-Blanc massif (Bussy and von Raumer, 1994). However, given the small number of data ( $n = 2$ ), we cannot exclude that these two analyses are be the result of a mixture between an Ordovician component and a younger component either Late Carboniferous ( $\sim 305$  Ma), Permo-Triassic or even Tertiary in age.

## 6.2. Zircon inheritance and source of Carboniferous magmas

Most of magmatic bodies we studied (i.e., microgranitic, pegmatitic and aplitic dykes) show zircon grains that do not record their age of emplacement (Carboniferous). Our results from zircon crystals from the Morcles microgranitic dyke show a well-marked Ordovician inheritance at  $463 \pm 10$  Ma (Caledonian event) and minor Ediacaran contributions (Pan-African event) (Fig. 14A) as already suggested in Bussien et al. (2017). The zircon U-Th-Pb ages from the Lac Cornu (AR833 and AR1020) and Lacs Noirs (AR1006) pegmatites and the Chéserys aplite (AR920) also yielded similar Ordovician ages at  $462 \pm 3$  Ma,  $456 \pm 4$  Ma,  $455 \pm 3$  and  $458 \pm 3$  Ma, respectively. This ca. 460-450 Ma inheritance was obtained on zircon grains characterized by concentric growth zones and high Th/U ratios typical of an igneous origin (Tiepel et al., 2004; Lineman et al., 2011) (Fig. 13; Table S1).



In granitic magmas, inherited zircon crystals originate from the melted sources (Bea et al., 2021). Thus, the important Ordovician inheritance recorded by the zircon crystals of the smaller magmatic bodies argues for a genetic link between these intrusions and the partially molten Ordovician orthogneisses. Such hypothesis of orthogneisses as being the main source for silicic melts is consistent with our field-observations of, for instance, pegmatite AR833 that formed in-situ within orthogneiss migmatite (Fig. 10A) or the pervasive leucocratic vein and dykes complex into the partially molten orthogneiss that surrounds the Mont Blanc granite (Vitel, 1965; Bussy and von Raumer, 1994). All the smaller magmatic bodies dated in this study may thus represent anatectic melt that originated from orthogneiss migmatite and that crystallized during ascent (Brown, 2013 and references therein) between ca. 320-310 Ma.

Growth of zircon in an anatectic melt is considered to result solely from the dissolution of pre-existing zircon grains and (re)precipitation of overgrowths or neograins directly from the melt (Watson, 1996; Yakymchuk and Brown, 2014; Bea et al., 2006; Kelsey et al., 2008; Mintrone et al., 2020). The solubility of zircon in silicate melts depends on melt temperature composition (Watson and Harrison, 1983; Boehnke et al., 2013). It also depends on heating and cooling rates (Bea et al., 2007), that are controlled by the shape and size of the magmatic body (de Saint-Blanquat et al., 2011). In the AR and MB massifs, the range of metamorphic peak temperatures estimated in the partially molten gneissic basement is about 650-750°C (Schulz and von Raumer, 1993, 2011; Chiaradia, 2003; Genier et al., 2008) and rises 750-800°C in the lower crust (Vanandois et al., 2022). In the middle crust, at temperatures between 650-700 °C, biotite and amphibole dehydration melting is limited (e.g. Wienberg and Hasalova, 2015). The absence of peritectic minerals in migmatite leucosome, their low muscovite and sillimanite contents and the high leucosome fraction observed in the AR and MB migmatites

(von Raumer and Bussy, 2004) attest for melt production through water-present melting reactions (White et al., 2005; Sawyer, 2010), as previously proposed in Genier et al. (2008) for migmatite of the Ecosson area. Couzinié et al. (2021) highlighted water-fluxed melting of quartzo-feldspathic orthogneisses in the eastern French Massif Central. The conclusions of Couzinié et al. (2021) are that low melting temperature involve limited zircon solubility in the melt phase. In addition, zircon grains armoured as inclusions in non-reacting biotite prevents the crystallization of newly formed zircon from the anatectic melt (Bea, 1996; Yakymchuk and Brown, 2014). We propose that most of the pegmatite, aplite and microgranite in the AR and MB massifs, that are characterized by important Ordovician inheritance without Carboniferous zircon recrystallization, originated from water-fluxed melting of Ordovician orthogneisses. Although less pronounced, the Ordovician inheritance was also recorded in magmatic zircon cores in the Montanvers (MB43), Vallorcine (AR73) and Mont-Blanc (MB37) granites (Fig. 12D-F). These late Carboniferous granites (~305 Ma) have peraluminous chemical compositions and a continental crust origin (von Raumer and Bussy, 2004). They are also spatially associated to the orthogneiss migmatite (Fig. 1B; Vitel, 1965). Similarly, we propose that the main melt production process at the origin of the Vallorcine, Montanvers and Mont-Blanc granites is water-fluxed melting of Ordovician orthogneisses. The discrete presence of Ordovician inheritance in the Montanvers, Vallorcine and Mont-Blanc granites can be attributed to the kinetics of heat transfer in felsic magmas that impacted zircon dissolution. Because of a greater volume, plutons have lower cooling rates than dykes (de Saint-Blanquat et al., 2011), and have higher temperature conditions that enhance the dissolution of zircon grains (Bea et al., 2007). Zircon grains of Early Carboniferous plutons (AR801, AR865) show almost no inheritance (Fig. 12B and C). This could also be the result of

an efficient zircon dissolution process due to the metaluminous composition of magmas (Bea et al., 2006) and/or higher temperature conditions (Kelsey et al., 2008).

The importance of Lower Paleozoic igneous rock contributions, particularly Ordovician intrusions, has been widely proposed for the sources of the Late Carboniferous Variscan granites in the French Central Massif (Downes and Duthou, 1988; Pin and Duthou, 1990; Turpin et al., 1990; Downes et al., 1997), in the Armorican massif (Ballouard et al., 2017, 2018) and in Iberia (Neiva et al., 2012; Villaseca et al., 2012; Rodriguez et al., 2022). The strong contribution of meta-igneous rocks as melt sources for Late Carboniferous magmatism suggests that an important part of the melt fraction produced during the Variscan orogeny was generated by water-fluxed melting reactions rather than water-absent dehydration melting. This interpretation is consistent with recent studies highlighting that water-fluxed partial melting reactions are common phenomena in orogenic crust and are often at the origin of crustal-derived magmas (i.e. peraluminous magmas) (e.g. Wienberg and Hasalova, 2015; Sawyer et al., 2011). The water supply may originate from different sources such as water coming from the dehydration of nearby metapelitic rocks (Sawyer, 2010; White et al., 2005; Weinberg and Hasalová, 2015) or from the lower crust (Braga and Massone, 2012).

Mafic enclaves are found in the Mont-Blanc pluton (Bussy, 1990) and several ca. 307 Ma old mafic intrusions have also been documented in the Fully area (Bussy et al., 2000) arguing for a contribution of a mantle source in the Late Carboniferous magmatism. Similarly, based on their geochemical signatures, von Raumer and Bussy (2004) suggested that the Montées-Pélissier and Pormenaz plutons probably originated from partial melting of the overthickened lower crust and interpreted enclaves of durbachites and lamprophyres as evidence of a mantle source. Early Carboniferous plutons also described in other ECMs (e.g. Schaltegger and Corfu,

1992; Debon et al., 1994, 1998; Guerrot and Debon, 2000; Rubatto et al., 2001) show similar geochemical compositions and are also interpreted as a mixing between crustal and mantle sources (Debon and Lemmet, 1999 and reference therein). Granite emplacement with a major mantle component and dated between 340-330 Ma is also known in other Variscan massifs (e.g., Vosges: Guillot et al., 2020; Tabaud et al., 2015; Corsica: Paquette et al., 2003; Li et al., 2014). These similarities suggest that a mantle thermal anomaly may have affected a large part of the Variscan belt and may have contributed into the bulk heat budget of the continental crust. The significance of the two successive thermal anomalies (i.e. Early and Late Carboniferous) associated with the two magmatic pulses in the AR and MB massifs and others ECMs remains elusive. Several orogenic-scale geodynamic events have been proposed, such as delamination of the lithospheric mantle (e.g. Laurent et al., 2017; Vanderhaeghe et al., 2020), mantle plume (Franke, 2014) or sub-lithospheric relamination and magmatic flow as recently invoked in the Bohemian massif (Maierova et al., 2018, 2021).

### *6.3. Melt drainage during crustal-scale shear zone evolution*

Based on structural and geochronological data, we propose a temporal evolution of the tectono-magmatic system during Carboniferous transpression. This conceptual model emphasizes the role of anastomosed shear zone network growth and water-fluxed melting of orthogneisses (Fig. 15). In the AR and MB massifs, the Variscan magmatism started around 340-330 Ma with the emplacement of the Pormenaz and Montées-Pélissier granites (Fig. 12B and C; Bussy et al., 2000). This magmatic pulse occurred in an overthickened crust as documented by the pressure conditions at ca. 1.75 GPa recorded in the eclogites and dated at 340-330 Ma (Vanandois et al., 2022). These two Early Carboniferous granites were emplaced

664 at upper crustal levels. The root zone of plutons is not exposed and the feeder structures are  
665 unknown. Our observations argue for a subsolidus deformation with the development of S2  
666 and C2 structures. In addition, microstructures show fractured K-feldspar grains without  
667 myrmekite formation and bulging recrystallization in quartz (Fig. 9C and D), suggesting a  
668 subsolidus deformation (Passchier and Trouw, 2005). The magmatic foliation and lineation in  
669 the western side of the Pormenaz granite show sub-parallel orientation to the D1 deformation  
670 in the surrounding rocks and can be interpreted as syn-D1. Alternatively, the Montées-  
671 Pélissier granite displays microfractures in plagioclase healed by quartz (Fig. 9D), which is  
672 typical of submagmatic deformation (Bouchez et al., 1992; Pawley and Collins, 2002), and  
673 plagioclase porphyroblasts are oriented sub-parallel to the S2 and C2 structures. These  
674 features may indicate an emplacement through vertical shear zones during the D2  
675 transpression (Fig. 15A) and a subsolidus deformation during the ongoing D2 transpression.  
676 Therefore, we propose that the vertical dextral shear zones may have initiated at 340-330 Ma  
677 with limited upward transfer of fluids and melts from the lower crust to upper crustal levels  
678 (Fig. 15A). Similar ages for the beginning of the dextral transpression are documented in the  
679 Argentera massif (Simonetti et al., 2018, 2021). Vanandois et al. (2022) proposed that D1  
680 initiated after the peak of pressure at ca. 340-330 Ma and interpreted D1 as a record of  
681 longitudinal flow of the partially molten lower crust. Based on the similar ages of the  
682 Pormenaz and Montées-Pélissier granites interpreted as syn-D1 and syn-D2 plutons,  
683 respectively, our results suggest that the initiation of D2 transpression is coeval with this D1  
684 longitudinal flow. The similar stretching direction (330-040) recorded by L1 and L2 lineations  
685 are consistent with the concomitant D1 deformation longitudinal flow and the onset of D2  
686 transpression. Similar partitioning of the deformation between horizontal and vertical fabrics

during longitudinal flow has been described in the Variscan belt (e.g. Cochelin et al., 2021) and in others hot orogens (e.g. Gapais et al., 2005; Yin and Taylor, 2011; Xu et al., 2015).

Ongoing dextral transpression is responsible for the development of a regional-scale anastomosed shear zone network with a S-C-C'-like structure. Numerous felsic dykes and pegmatites located in the C2 shear zones show evidences of syn-kinematic emplacements as exemplified by diffuse contact with the C2 migmatite layers (Lac Cornu pegmatite; Fig. 10A) or typical S-C structures (Lacs Noirs pegmatite; Berthé et al., 1979) (Fig. 10C). These dykes are dated between 310-320 Ma (Fig. 14B and C), similar to the  $317 \pm 2$  Ma age of leucogranitic injections in dextral shear bands documented in the MB massif (Bussy and von Raumer, 1994). These ages are also consistent with the dextral shearing constrained at ca. 320 Ma in the EBSZ (Simonetti et al., 2020). We propose that the formation and broadening of these shear zones enhanced aqueous fluid drainage in the orthogneisses and, thus, increased the water-fluxed melting reaction (Fig. 15B). The anatectic melts were collected in the C2 shear zones and formed the syn-kinematics dykes (Fig. 10 and 15B).

The Vallorcine granite crosscuts C'2 shear bands (Fig. 9E). The granite also shows magmatic planar fabrics sub-parallel to the C'2 structures (Bussy et al., 2000) and a weakly developed subvertical foliation in surrounding granitic dykes (Simonetti et al., 2020). Therefore, the emplacement of this granite is syn-C'2. A similar magmatic fabric in the core of the Mont-Blanc granite also indicates a syn-C'2 emplacement. The Montenvers granite has recorded quartz-polygonal recrystallization typical of high-temperature deformation (Passchier and Trouw, 2005) and fracture in plagioclase healed by quartz indicating submagmatic deformation (Bouchez et al., 1992; Pawley and Collins, 2002) (Fig. 9G), whereas deformation of quartz in shear bands emphasizes lower-temperature deformation (Fig. 9G). Our structural and

microstructural analyses indicate that the emplacements of the Vallorcine, Montenvers and Mont-Blanc granites took place inside crustal dextral C'2 shear zones (Fig. 2 and 9E to H) and no compressive structures are observed in their country rocks. Therefore, we interpret the C'2-dominant domains (i.e. the EBSZ and MSZ) as large-scale dilation shear structures that enhanced the emplacement of large volumes of melts within the continental crust at ca. 305 Ma (Fig. 15C). The C'2 shear zones represent the last structures of the dextral transpressional system. This interpretation is also consistent with the occurrence of cordierite-bearing migmatites in the Fully area showing cordierite clots parallel to C'2 plans (Fig. 5D) indicating a syn-C'2 partial melting dated at ca. 307 Ma (Bussy et al., 2000). We speculate that local D3 deformation observed in the upper structural levels in the Servoz syncline may represent a limited vertical thinning due to these dilation structures or to the upward movements and emplacements of plutons. This deformation phase is not shown in figure 15.

These structural and geochronological results document a progressive growth of an anastomosed shear zone network at the scale of the AR and MB massifs during the same large-scale transpressional deformation. The formation of this anastomosed network started with the progressive nucleation of the S2 foliation and C2-dominant shear zones at ca. 340-330 Ma. The development and broadening of the anastomosed shear zone network occurred between ca. 330-310 Ma. The formation of two large-scale dilation C'2 zones occurred at the end of the transpression at ca. 305 Ma.

## 7. Conclusion

Our bulk structural analysis on the Variscan crust at the scale of the Aiguilles-Rouges and Mont-Blanc massifs highlights a crustal scale S-C-C' anastomosed network formed during dextral transpression along the EVSZ closely associated to plutons ascent and emplacement. Zircon and monazite LA-ICPMS U-Th-Pb dating of syn-tectonic dykes and large plutons constrain this bulk continental dextral deformation between ca. 340 and 305 Ma. During this time span, the transcurrent EVSZ network broadened and formed a regional-scale anastomosed system enhancing vertical flow and where C'-type shear zones acted as dilation structures that guided the ascent and the preferential growth of plutons. Zircon inheritance indicates that Late Carboniferous granitic melts are mainly derived from water-fluxed melting of Ordovician orthogneiss with the input of mantle-source derived magmas. Over time, the growth of the dextral anastomosed network enhanced water transfer through the shear zones and water-fluxed melting to produce more anatectic melts.

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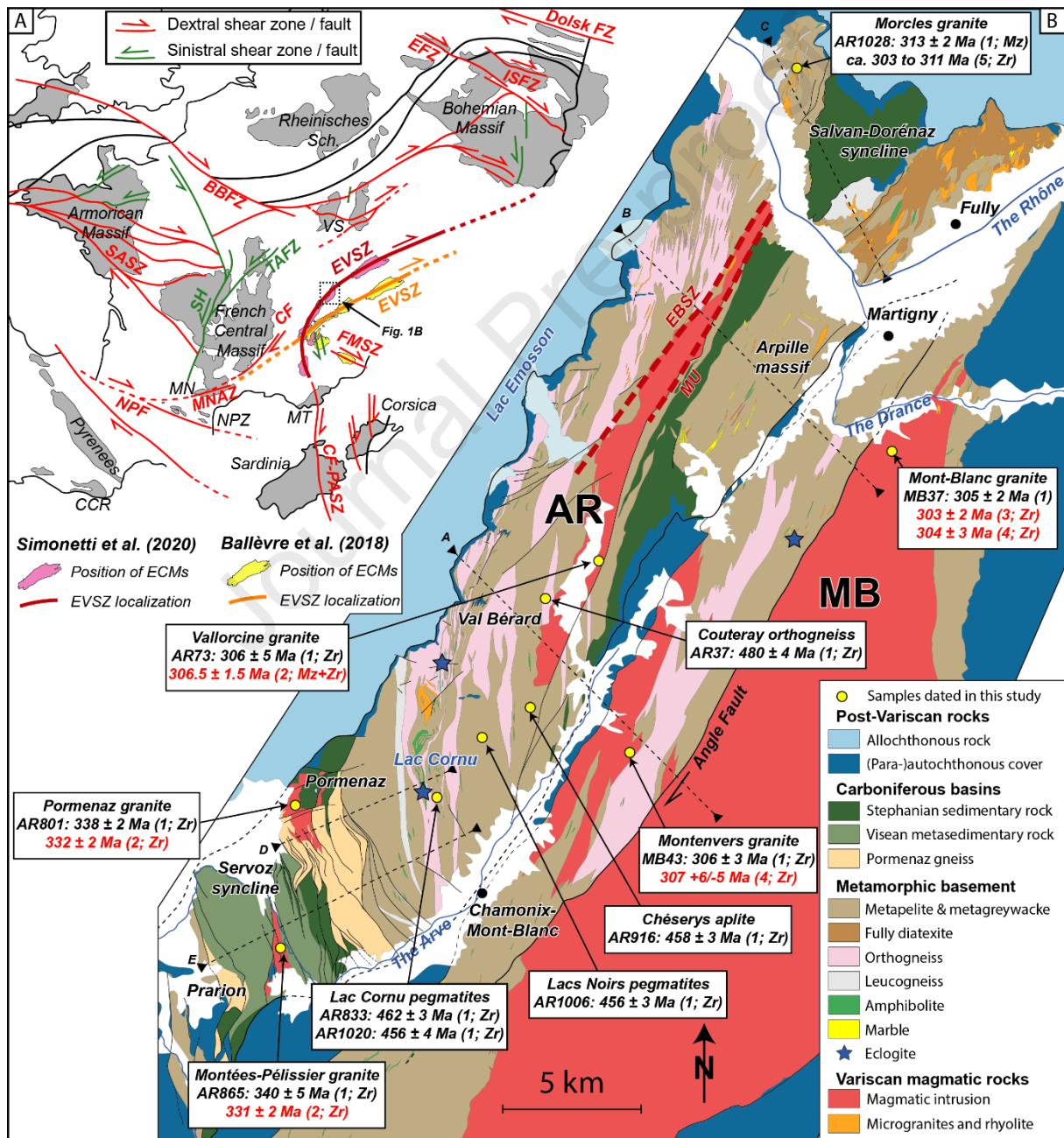


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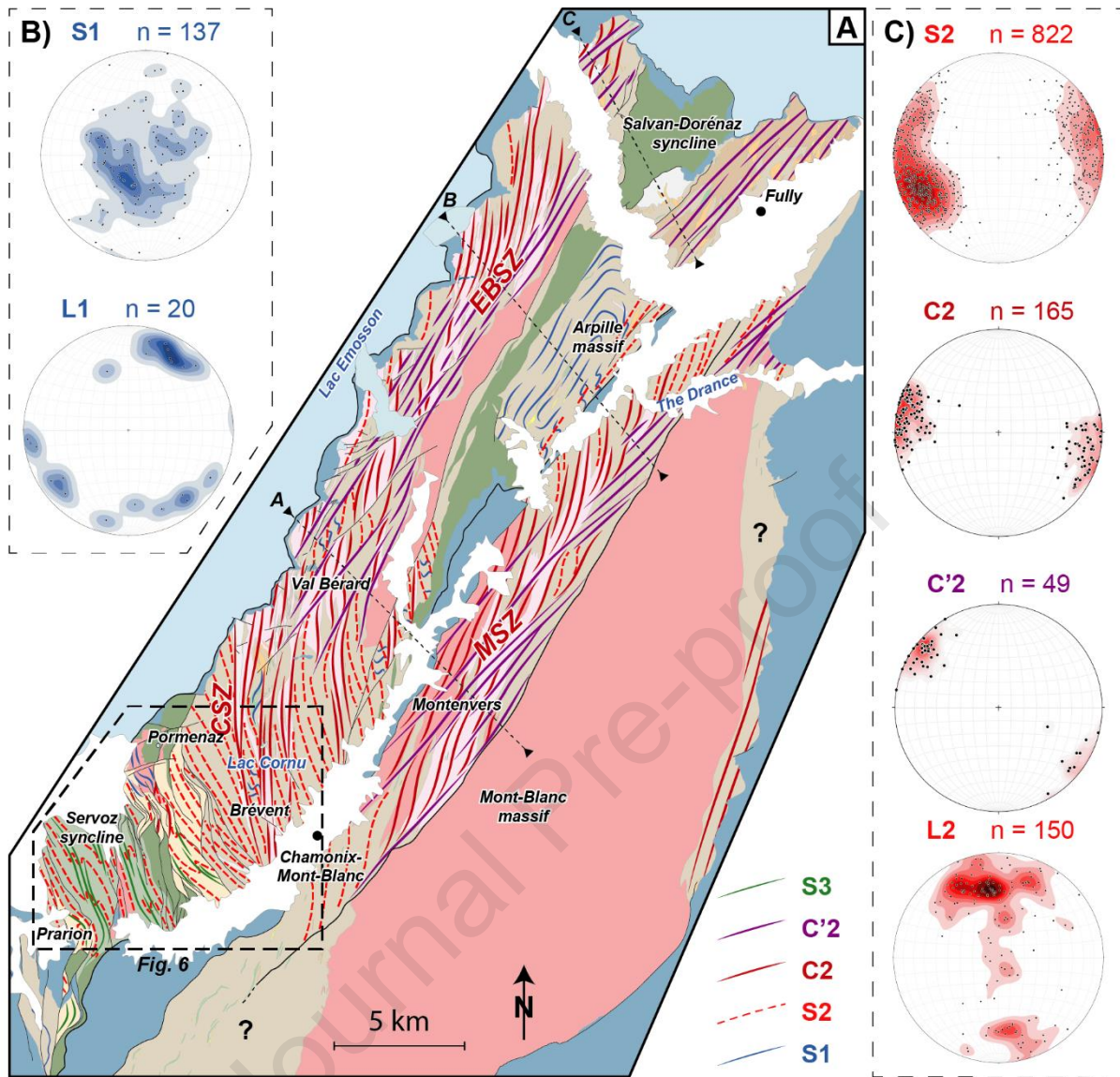
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# Figure captions



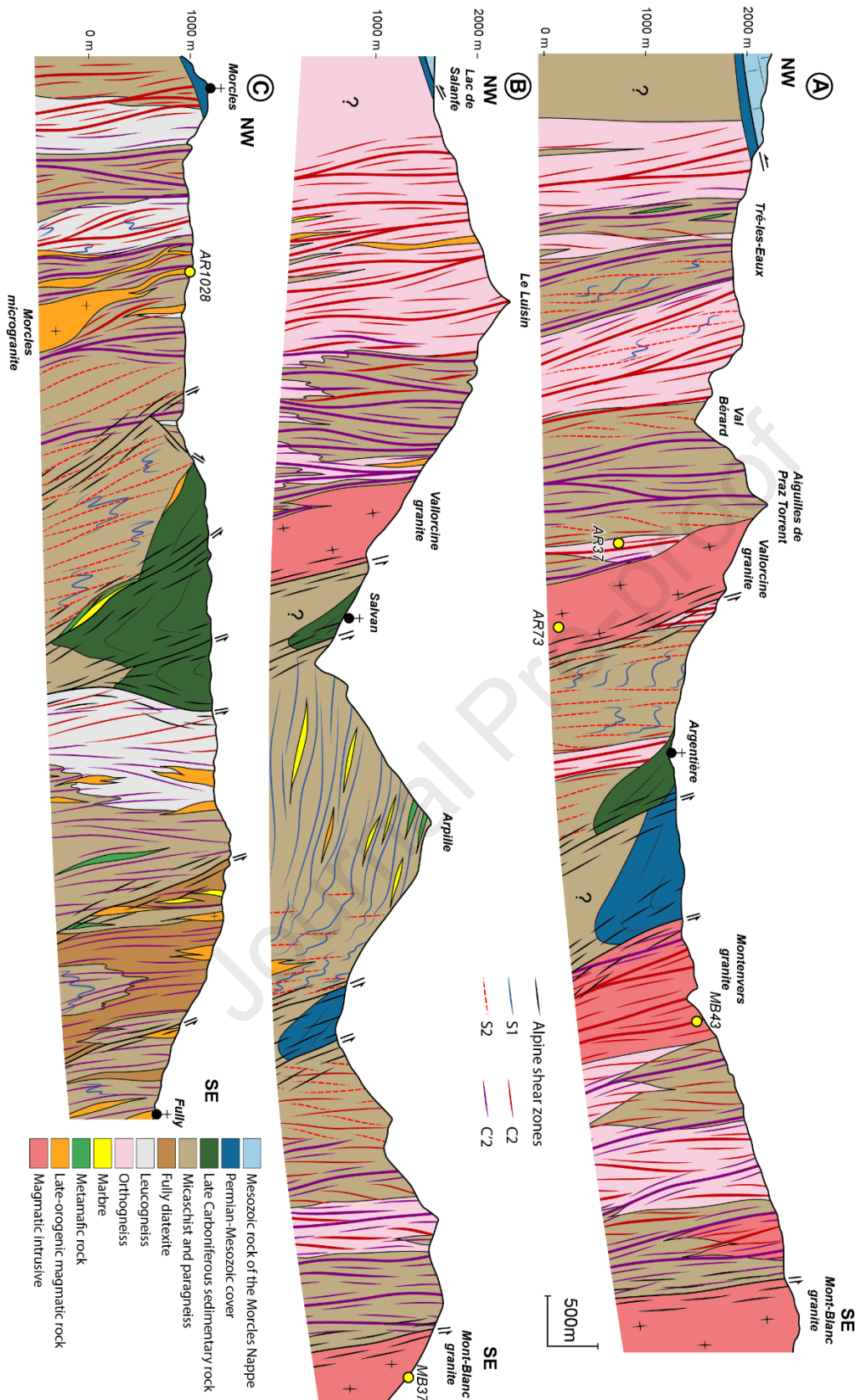
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**Fig. 1:** (A) Paleogeographic reconstitution of the European Variscan Belt at the end of the Variscan orogeny modified from Franke et al. (2017). Sardinia and Corsica have the same position as the one used in Simonetti et al. (2020). Models of the EVSZ are after Simonetti et al. (2020) and Ballèvre et al. (2018). The position of ECMs is after Bellahsen et al. (2014) in the Ballèvre et al. (2018) model. *BBFZ*: Bristol Bray Fault Zone; *CCR*: Catalan Coastal Ranges; *CF*: Cévennes Fault; *EFZ*: Elbe Fault Zone; *EVSZ*: East Variscan Shear Zone; *FMSZ*: Ferrière-Mollière Shear Zone; *CF-PASZ*: Cavalaire Fault - Posada-Asinara Shear Zone; *ISFZ*: Intra-Sudetic Fault Zone; *MN*: Montagne Noire; *MNAZ*: Montagne Noire Axial Zone; *NPF*: North Pyrenean Fault; *NPZ*: North Pyrenean Zone; *SASZ*: South Armorican Shear Zone; *SH*: Sillon Houiller fault; *TAFZ*: Taure-Aigueperse Fault Zone; *VS*: Vosges-Schwarzwald. (B) Geological map of the Aiguilles-Rouges (AR) and the Mont-Blanc (MB) Massifs with geochronological results and sample locations. *EBSZ*: Emosson-Bérard shear zone; *MU*: Miéville ultramylonite. Synthesis of Variscan ages obtained by ID-TIMS (red) and LA-ICPMS (black) U-Th-Pb method on zircon (Zr) and monazite (Mz) after (1) this study, (2) Bussy et al. (2000), (3) Bussy and von Raumer (1993), (4) Bussy and von Raumer (1994), (5) Bussien et al. (2017). Structure sections A, B, C, D and E are to those in Figures 3 and 7.



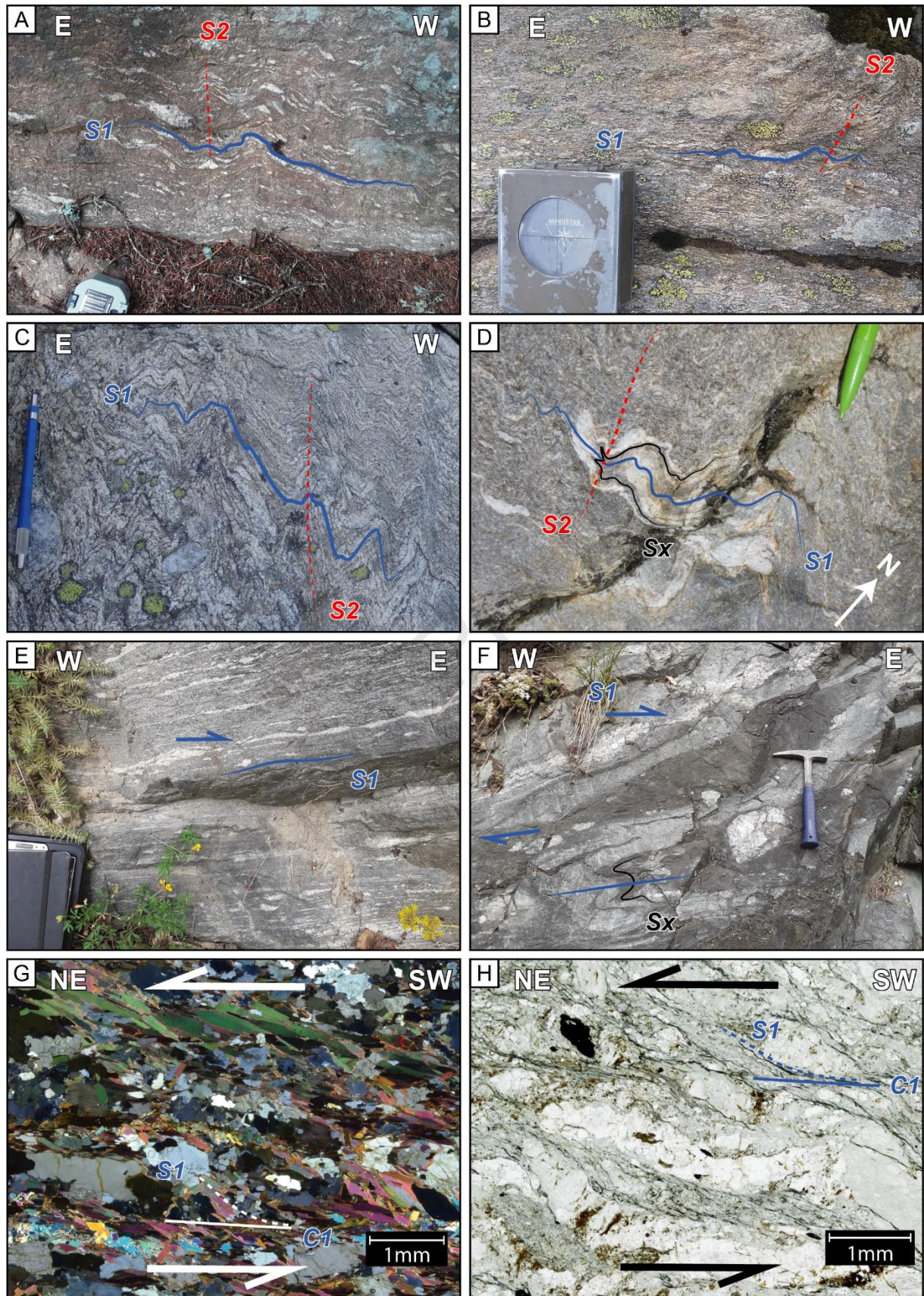
**Fig. 2:** (A) Synthetic map showing the simplified foliation trajectories of D1, D2 and D3 deformation. Lithological legend is the same as in Figure 1B. The area corresponding to Figure 6 is indicated. CSZ: Cornu Shear Zone; EBSZ: Emosson-Bérard Shear Zone; MSZ: Montenvers Shear Zone. (B and C) Stereograms of poles to planar fabrics and mineral lineation for D1 and D2 deformation are Wulff lower-hemisphere projections.





**Fig. 3:** E-W Structure sections through the Aiguilles-Rouges and the Mont-Blanc Massifs (see location of sections on Figures 1 and 2). Same structures symbols as in Figure 2.

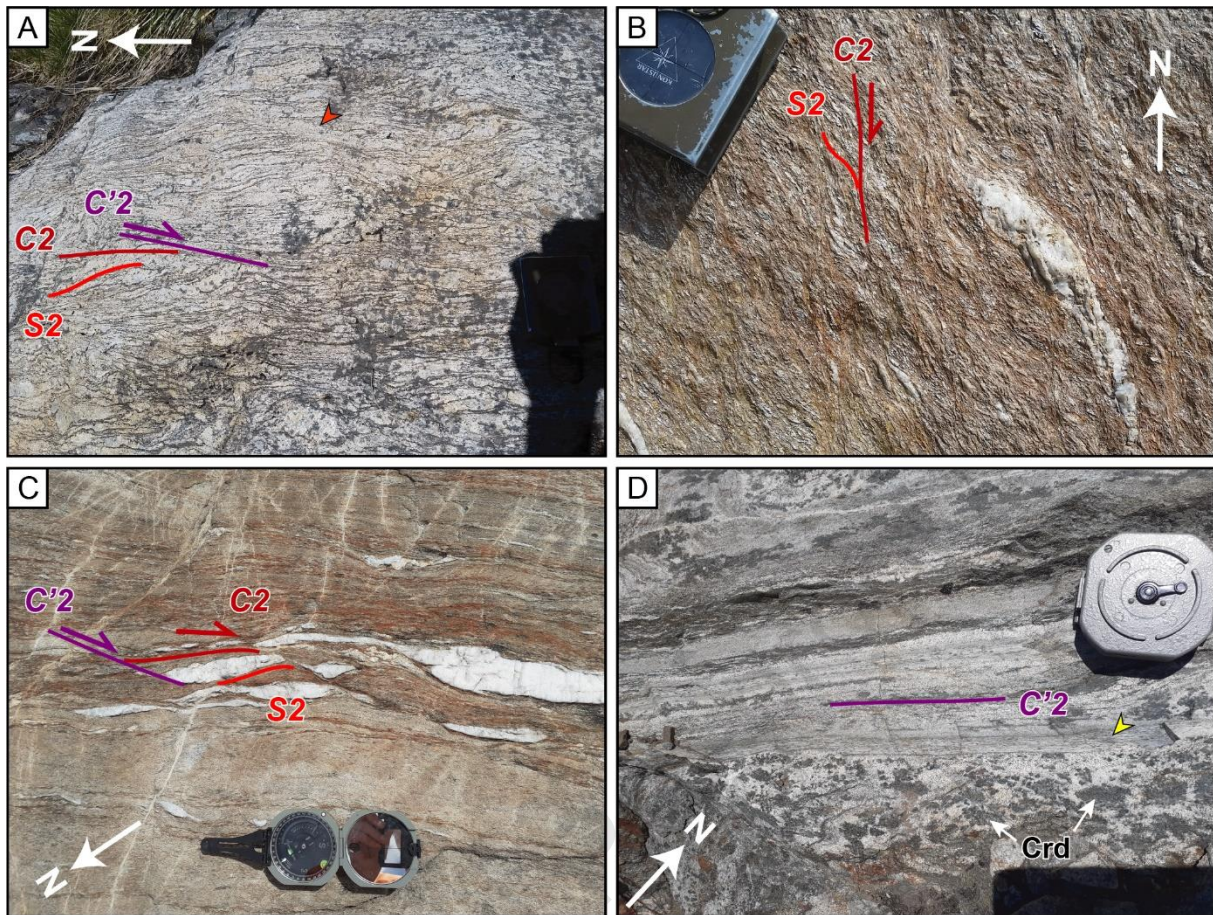






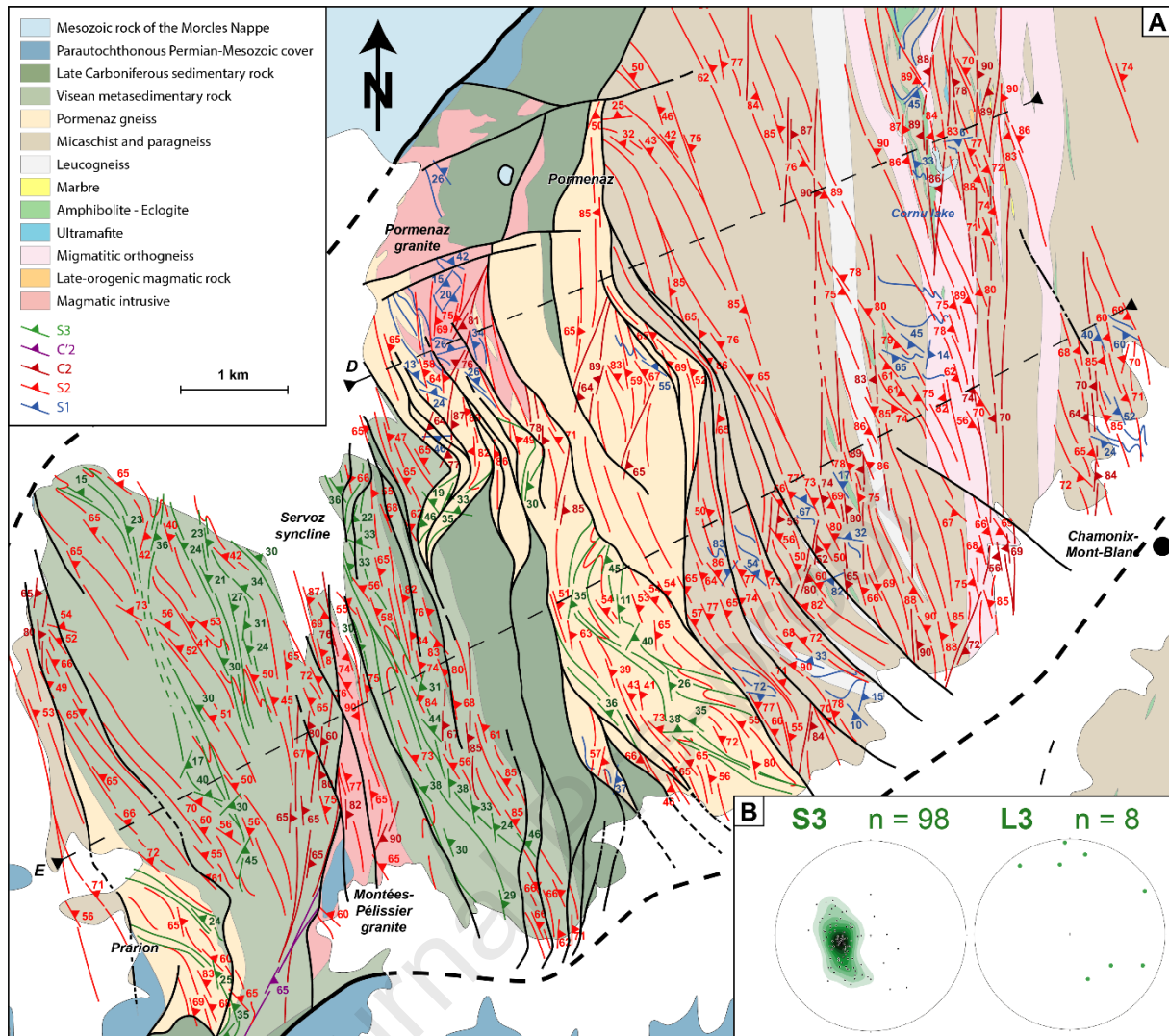
1144 **Fig. 4:** D1 deformation and D1/D2 relationships. S1 foliation and weak S2 schistosity in the  
1145 Arpille massif (A; N46.110779; E7.039935), near the Brévent location (B; N45.941226;  
1146 E6.842971) and in the Lac Cornu area (C; N45.956048; E6.853897). (D) D1/D2 fold  
1147 interference: an F1 fold deforming an Sx foliation, the S1 foliation is subsequently deformed  
1148 by F2 folds with an associated S2 schistosity, Val Bérard area (N46.004630; E6.872713). (E and  
1149 F) Top-to-the-NE kinematics indicated by asymmetric boudinage/structures in Prarion  
1150 metabasites (N45.865415; E6.734047). (G) Top-to-the-NE kinematics indicated by sheared  
1151 biotite mica-fish, Arpille massif (N46.110362; E7.040006). (H) Top-to-the-NE C-S structures in  
1152 a low-grade Pormenaz gneiss (N45.941793; E6.782782).

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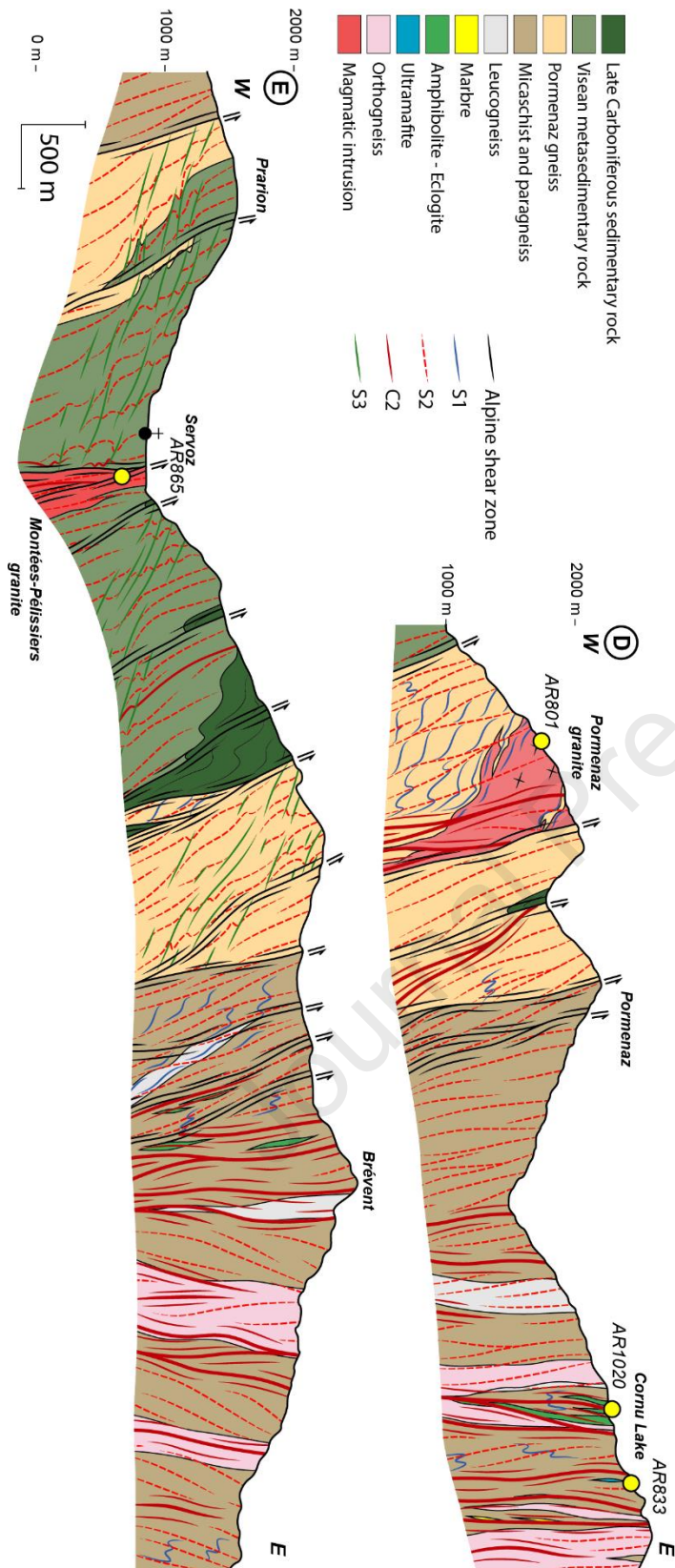


**Fig. 5:** D2 deformation. S2-C2-C'2 structures in the Lac Cornu area (A) (N46.066231; E6.916211) and near Chamonix-Mont-Blanc (B) (N45.927587; E6.825600). Red arrow indicates melt injection in a C'2 shear band. (C) S2-C2-C'2 structures in the Lac Emosson area (N46.067197; E6.923349). (D) Cordierite-bearing migmatite with cordierite clots (Crd) oriented parallel with C'2 planes and centimeter-sized ultramylonitic C'2 shear bands (yellow arrow) (N46.123427; E7.078374).





**Fig. 6:** (A) Detailed map of the D1-D2-D3 foliations and their trajectories in the southwestern part of the Aiguilles-Rouges Massif. (B) Stereograms of poles of planar fabrics and lineations of D3 deformation are Wulff lower-hemisphere projections. Location of structure sections D and E is indicated.

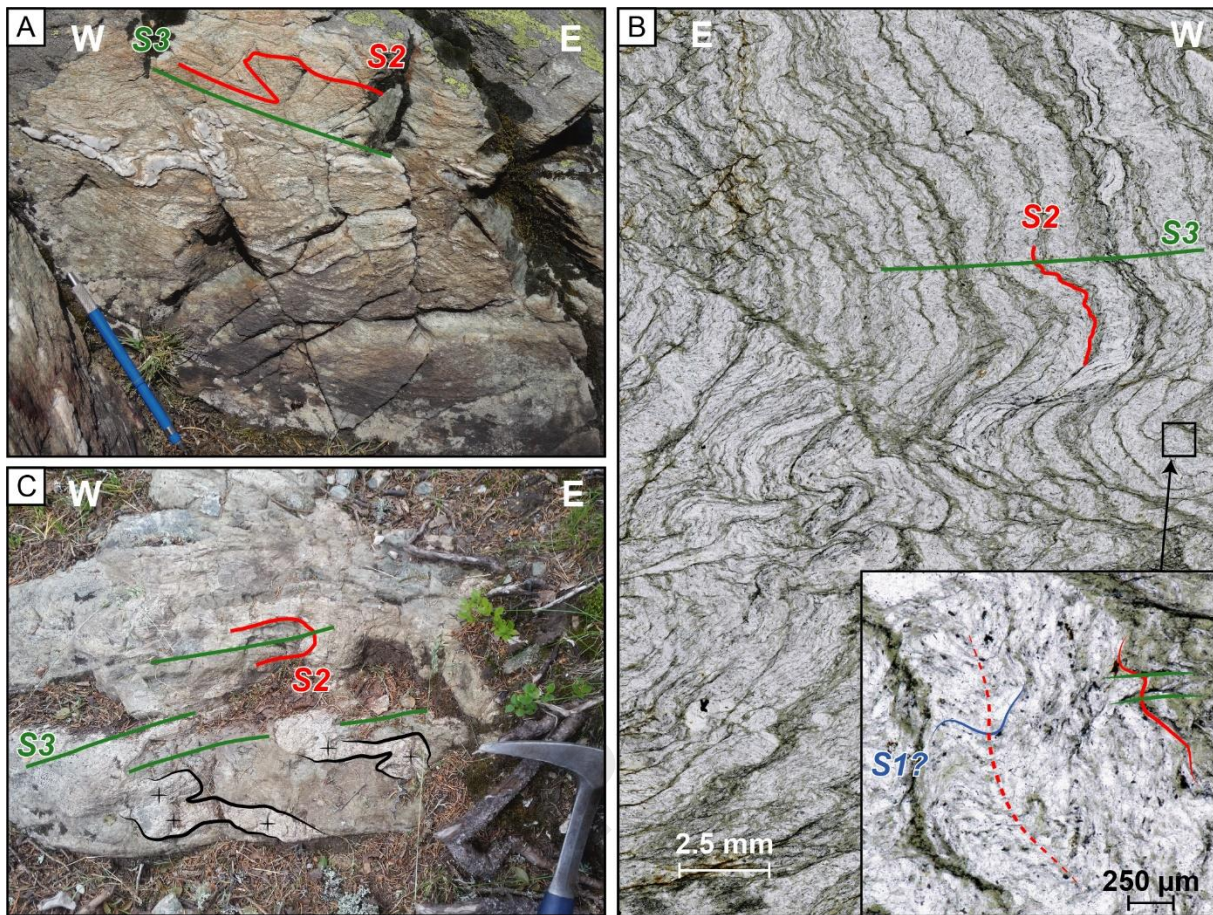


**Fig. 7:** E-W structure sections at the southwestern extremity of the Aiguilles-Rouges Massif.

(D) In the Pormenaz area and (E) through the Servoz syncline. Location on Figure 6.



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1171 **Fig. 8:** D3 deformation. (A) F3 folds from the western limb of the Servoz syncline, Prarion area  
 1172 (N45.894366; E6.750432). (B) Photomicrograph in plane-polarized light showing the  
 1173 relationships between S1-S2-S3 planar fabrics in Visean metasedimentary rocks (N45.906481;  
 1174 E6.778808). (C) Weakly deformed trondhjemitic melts (highlighted in black) affected by F3  
 1175 folds (N45.887808; E6.753523).



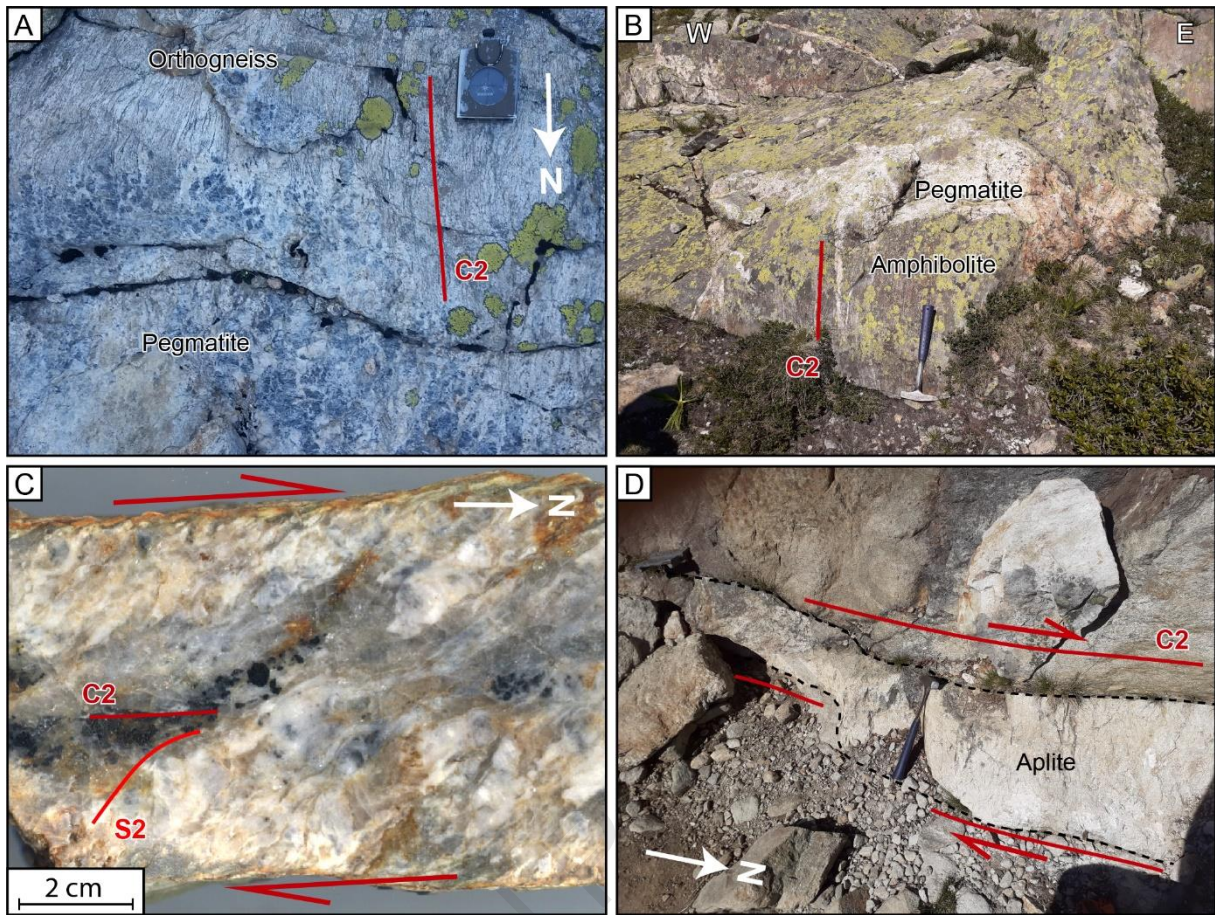


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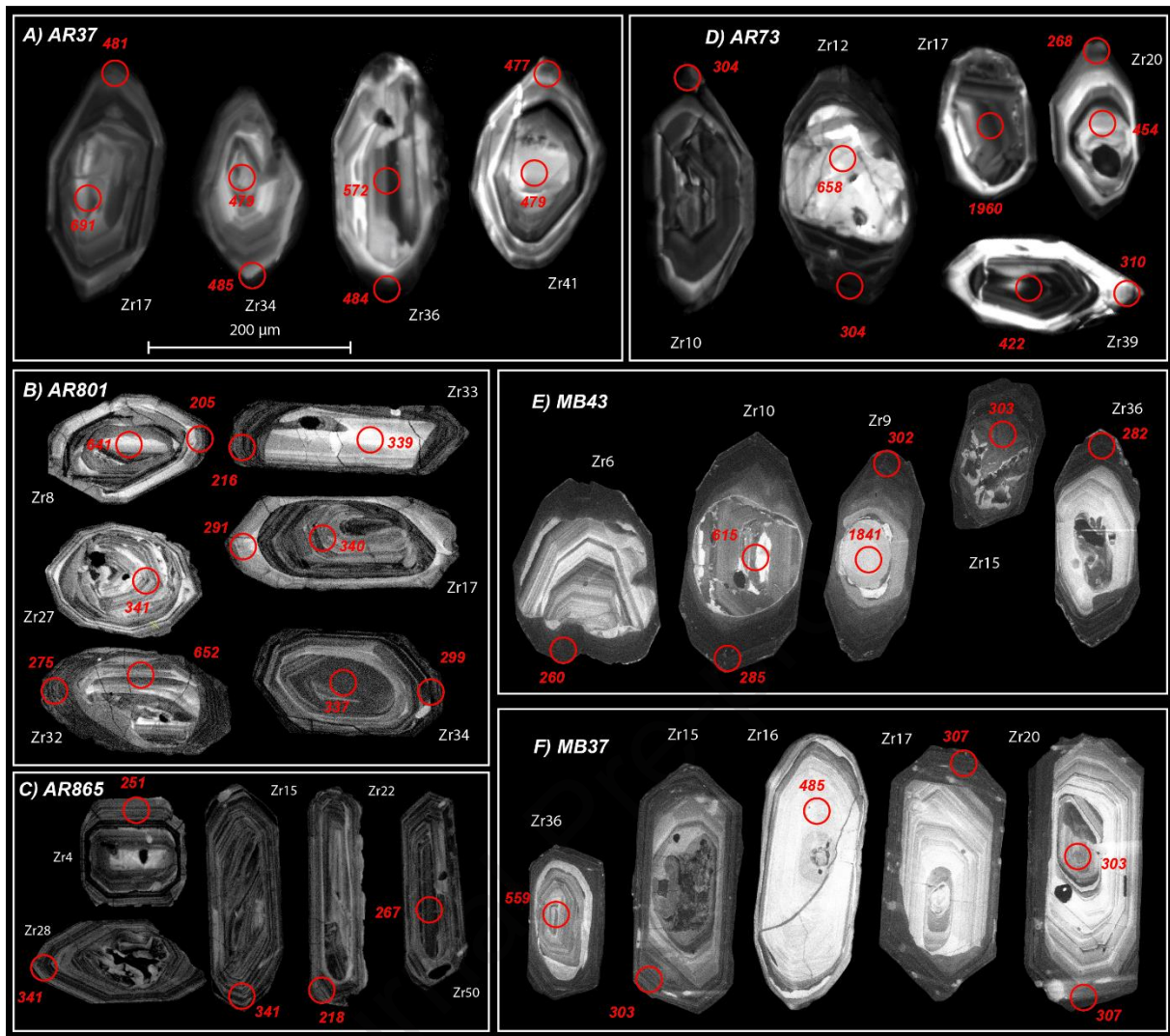
1177 **Fig. 9:** Deformation features in the magmatic rocks of the AR and the MB Massifs. Sample  
 1178 locations are shown in Fig.1B. (A) Couteray orthogneiss with C2-C'2 shear bands highlighted  
 1179 and local preserved leucosomes are visible (orange arrow). (B) L1 mineral lineation indicated



1180 by euhedral K-feldspar from the western part of the Pormenaz granite (AR801). (C) Pormenaz  
1181 granite deformed in D2 in the eastern part of the pluton. (D) Photomicrograph in cross-  
1182 polarized light of the Montées-Pélessier granite (AR865) with feldspar oriented parallel with  
1183 the C2 planes. Orange arrows indicate microfractures in feldspar infilled by quartz  
1184 emphasizing the presence of melt during deformation. (E) Vallorcine granite (AR73) cross-  
1185 cutting the C'2 planar fabrics of the EBSZ and cross-polarized light microphotograph showing  
1186 grain boundary migration recrystallization in quartz aggregates. (F) Montenvers granite  
1187 deformed during D2. (G) Photomicrograph in cross-polarized light of the Montenvers granite  
1188 (MB43). Orange and yellow arrows indicate microfractures in feldspar infilled by quartz and  
1189 polygonal quartz suggesting high temperature deformation. Blue arrows indicate polygonal  
1190 quartz deformed at lower temperature. (H) Mont-Blanc granite (MB37) with a magmatic  
1191 foliation inferred by the alignment of K-feldspar sub-parallel to C'2. (I) Photomicrograph in  
1192 cross-polarized light of the Morcles microgranite (AR1028) without preferred mineral  
1193 orientation.

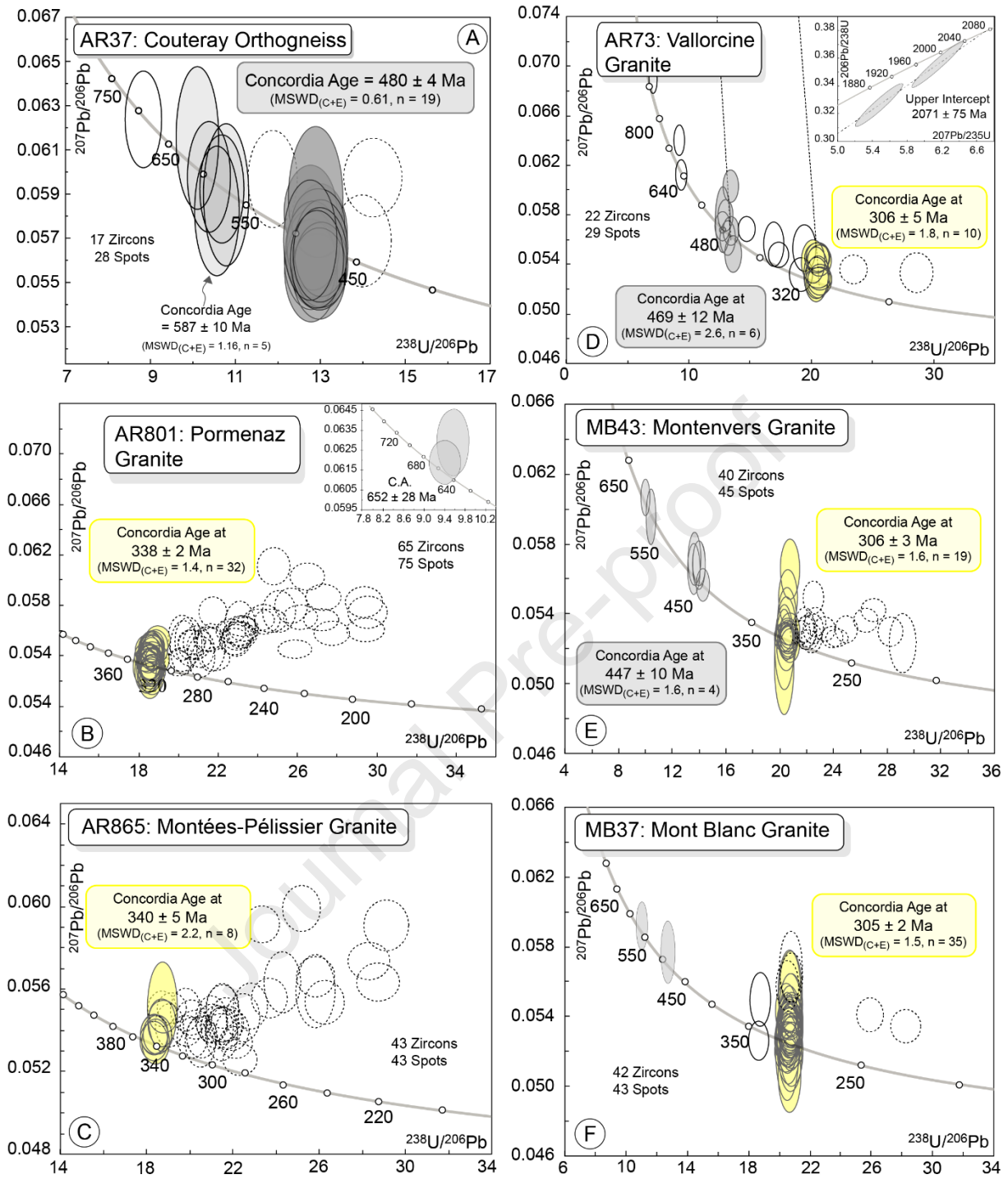


**Fig. 10:** Pegmatitic and aplitic samples. (A) Pegmatite AR833 from the Lac Cornu area embedded in a orthogneiss migmatite with diffusive contacts. (B) Pegmatite AR1020 crosscutting the C2 planes of an amphibolite boudin in the Lac Cornu area. (C) Section of the Lacs Noirs pegmatite (AR1006) showing C-S structures. (D) Chéserys aplite (AR916) emplaced in a C2 shear zone.



**Fig. 11:** Cathodoluminescence images of zircon grains from: (A) the Couteray orthogneiss; (B) the Pormenaz granite (sample AR 801); (C) the Montées Pélissier granite (AR865); (D) the Vallorcine granite (AR73); (E) the Montenvers granite (MB43); (F) the Mont Blanc granite (MB37). Red circles indicate the analytical spot locations with the  $^{206}\text{Pb}/^{238}\text{U}$  age without errors associated. Zr number corresponds to the zircon grain numbers reported in Table S1. The bar scale indicated in A is used for all pictures (B to F).





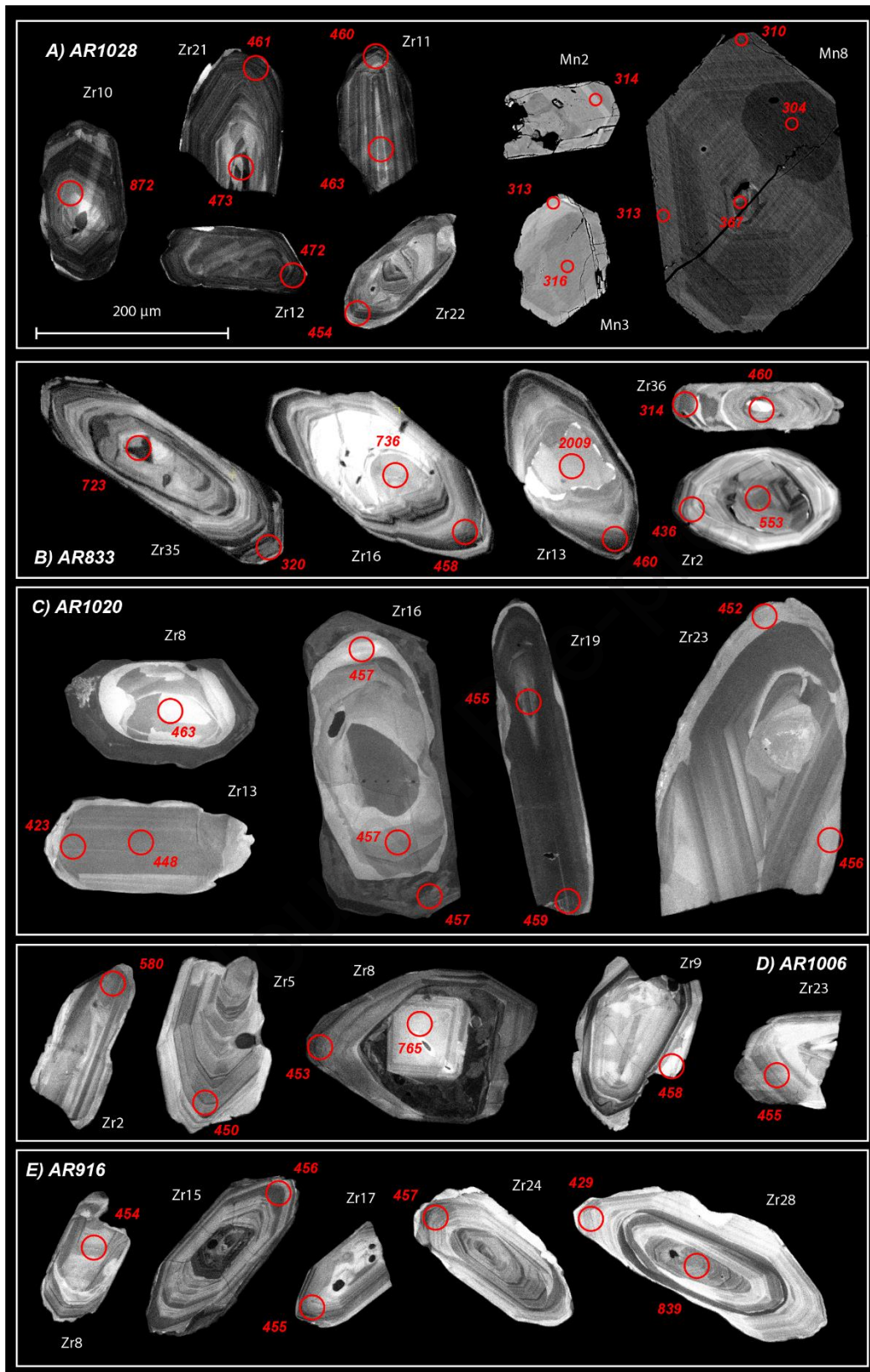
**Fig. 12:** Zircon U-Pb Tera Wasserburg diagrams obtained by LA-ICPMS from (A) the Couteray orthogneiss, (B) the Pormenaz granite (AR801), (C) the Montées Pélissier granite (AR865), (D) the Vallorcine granite (AR73), (E) the Montenvers granite (MB43), (F) the Mont Blanc granite (MB37). Error ellipses and uncertainties in ages are  $\pm 2\sigma$  level. The discordance of dotted



1213 ellipses is due to radiogenic Pb losses and common Pb contaminations. Dotted and white

1214 ellipses are not considered for the age calculation.

1215

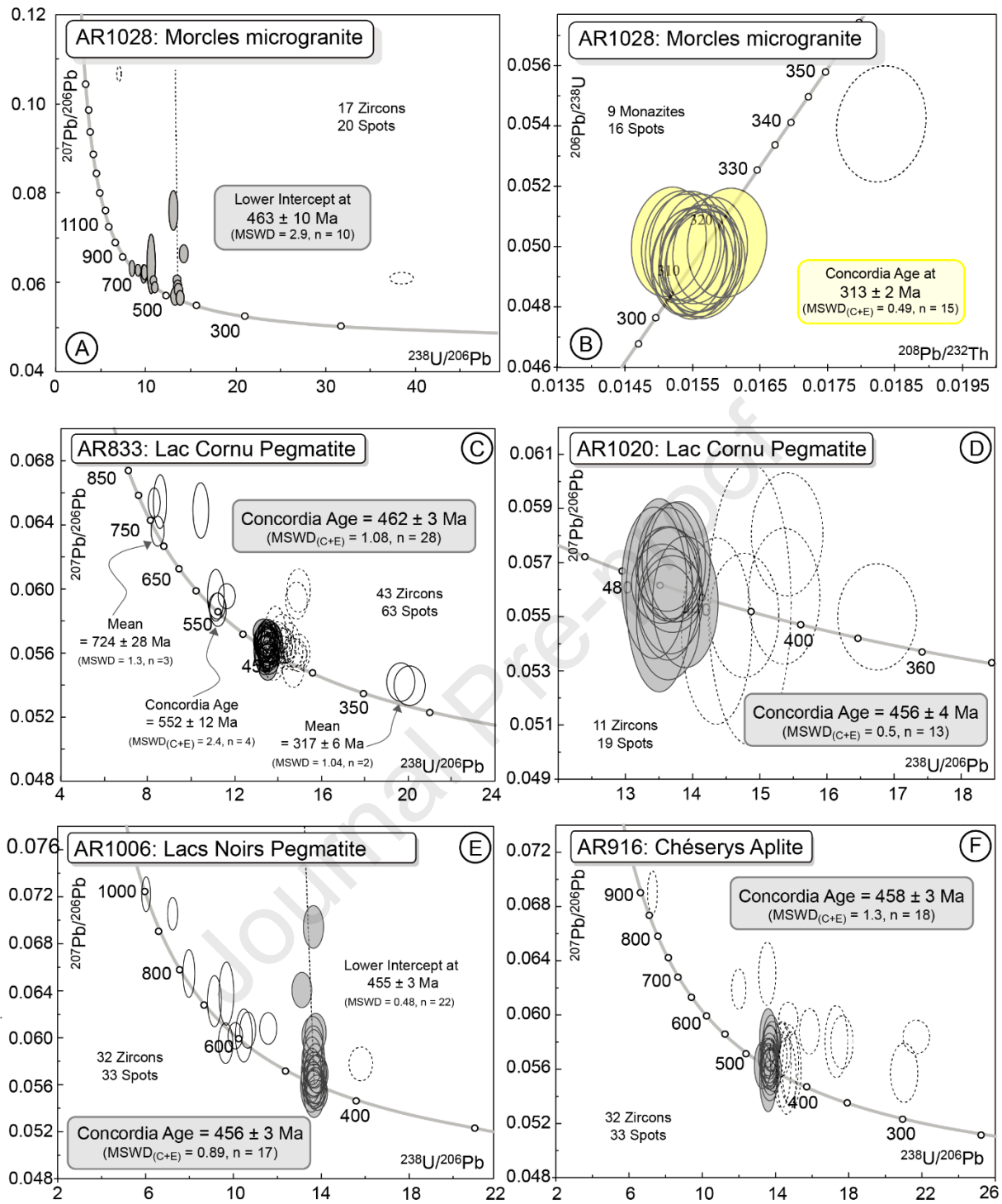


1216

1217 **Fig. 13:** Cathodoluminescence and back-scattered electron images of zircon (Zr) and monazite

1218 (Mn) grains from: (A) the Morcles microgranite (AR1028); (B) a Lac Cornu pegmatite (AR833);

1219 (C) a Lac Cornu pegmatite (AR1020); (D) the Lacs Noirs pegmatite (AR1006); (E) the Chéserys  
1220 aplite (AR916). Red circles indicate the analytical spot locations with the  $^{206}\text{Pb}/^{238}\text{U}$  or  
1221  $^{208}\text{Pb}/^{232}\text{Th}$  ages measured without the error associated for the zircon and the monazite grains  
1222 analysed, respectively. Zr (or Mn) number corresponds to the zircon (or monazite) grain  
1223 numbers reported in Table S1. The bar scale indicated in A is used for all pictures (B to E).



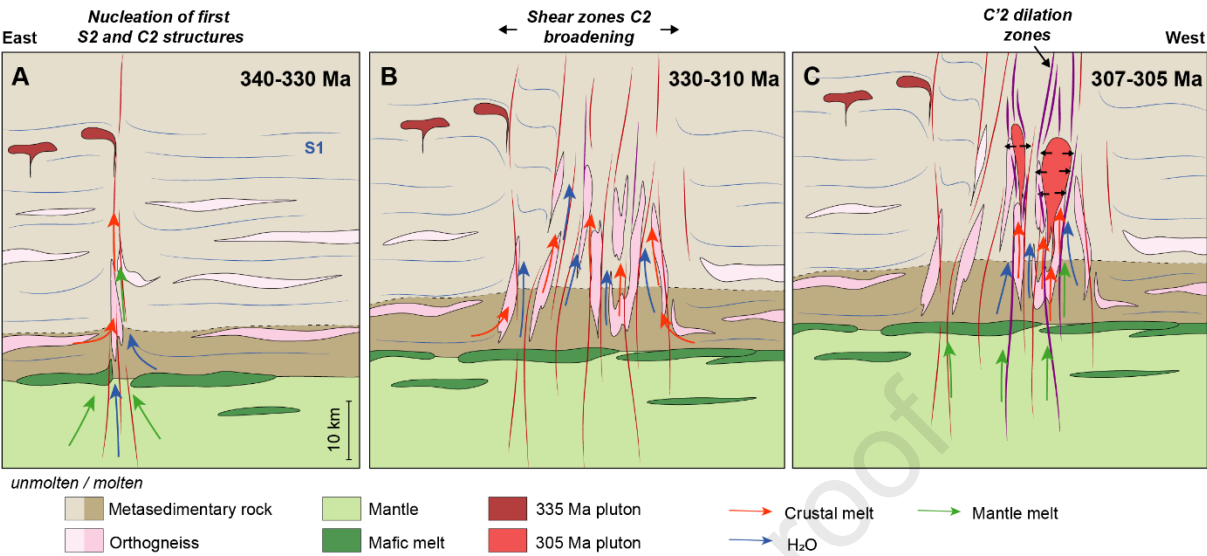
**Fig. 14:** Zircon U-Pb Tera Wasserburg diagrams (A, C, E, F, D) and monazite U-Th-Pb concordia diagram (B) obtained by LA-ICPMS: (A and B) on the Morcles microgranite (AR1028), (C and D) on the Lac Cornu pegmatites (AR833 and AR1020), (E) on the Lacs Noirs pegmatite (AR1006), (F) on the Chéserys aplite (AR916). Error ellipses and uncertainties in ages are  $\pm 2\sigma$  level. The

1229 discordance of dotted ellipses is due to radiogenic Pb losses and common Pb contaminations.

1230 Dotted and white ellipses are not considered for the age calculation (see text for detail).

1231

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**Fig. 15:** Tectono-magmatic evolution of the AR and MB massifs. (A) Initiation of the dextral shearing after the nappe stacking. The fluids, anatectic lower crustal melts and mantle mafic melts are drained upward and form small plutons in the upper crust. (B) Broadening of the C2 shear zones drains more fluids that increase the partial melting of meta-igneous rocks forming the numerous aplitic and pegmatitic dykes. (C) C'2 shear zones, acting as dilation zones, collect anatectic melts and the small mantle supply to form large plutons.

1241 **Table 1:** Sample descriptions and locations

| Sample | Rock type                 | GPS location             | Mineral assemblage                    | Mineral dated      | U-Th-Pb age               |
|--------|---------------------------|--------------------------|---------------------------------------|--------------------|---------------------------|
| AR37   | Courtenay orthogneiss     | N46.019559<br>E06.907883 | Qtz + Kfs + Pl<br>+ Ms + Bt           | Zircon             | 587 ± 10 Ma<br>480 ± 4 Ma |
| AR801  | Pormenaz granite          | N45.949951<br>E06.789104 | Qtz + Kfs + Pl<br>+ Bt(Chl)           | Zircon             | 338 ± 2 Ma                |
| AR865  | Montées-Pélessier granite | N45.917067<br>E06.77147  | Qtz + Kfs + Pl<br>± Ms ±<br>Bt(Chl)   | Zircon             | 340 ± 5 Ma                |
| AR73   | Vallorcine granite        | N46.032901<br>E06.936665 | Qtz + Kfs + Pl<br>+ Bt                | Zircon             | 306 ± 5 Ma                |
| MB43   | Montenvers granite        | N45.96768<br>E06.949665  | Qtz + Kfs + Pl<br>+ Ms + Bt ±<br>Grt  | Zircon             | 306 ± 3 Ma                |
| MB37   | Mont-Blanc granite        | N46.063859<br>E07.08007  | Qtz + Kfs + Pl<br>+ Bt                | Zircon             | 305 ± 2 Ma                |
| AR1028 | Morcles microgranite      | N46.193943<br>E07.043689 | Qtz + Kfs + Pl<br>± Ms ±<br>Bt(Chl)   | Zircon<br>Monazite | 463 ± 10 Ma<br>313 ± 2 Ma |
| AR833  | Lac Cornu Pegmatite       | N45.956094<br>E06.853814 | Qtz + Kfs + Pl<br>± Ms                | Zircon             | 462 ± 3 Ma<br>317 ± 6 Ma  |
| AR1020 | Lac Cornu Pegmatite       | N45.958210<br>E06.846594 | Qtz + Kfs + Pl                        | Zircon             | 456 ± 4 Ma                |
| AR1006 | Lac Noirs Pegmatite       | N45.966231<br>E06.871656 | Qtz + Kfs +<br>Tur + Ms               | Zircon             | 456 ± 3 Ma                |
| AR916  | Chéserys Pegmatite        | N45.982963<br>E06.908710 | Qtz + Kfs + Pl<br>+ Ms ± Tur ±<br>Grt | Zircon             | 458 ± 3 Ma                |

## Highlights

- The strain pattern of a portion of the crustal East-Variscan Shear Zone is given.
- The main shear direction is not NE-SW but N-S directed.
- The S-C-C' - like strain pattern controls the transfer and emplacement of magmas.
- Late-orogenic magmas come from H<sub>2</sub>O-saturated melting of meta-igneous protoliths.



Author statement

Jonas Vanardois: Conceptualization, Investigation, Writing - Original Draft, Project administration, Funding acquisition

Pierre Trap: Conceptualization, Investigation, Writing - Original Draft, Supervision, Project administration, Funding acquisition

Françoise Roger: Conceptualization, Validation, Investigation, Writing - Review & Editing

Jérémie Melleton: Conceptualization, Writing - Review & Editing

Didier Marquer: Writing - Review & Editing, Supervision, Funding acquisition

Jean-Louis Paquette: Validation, Investigation, Writing - Review & Editing

Philippe Goncalves: Writing - Review & Editing

Florence Cagnard: Investigation, Writing - Review & Editing

Benjamin Le Bayon: Investigation, Writing - Review & Editing

### **Declaration of interests**

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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