



## **Shortening of the European Dauphinois margin (Oisans Massif, Western Alps): New insights from RSCM maximum temperature estimates and $^{40}\text{Ar}/^{39}\text{Ar}$ in situ dating**

Mathieu Bellanger, Romain Augier, Nicolas Bellahsen, Laurent Jolivet, Patrick Monié, Thierry Baudin, Olivier Beyssac

### **► To cite this version:**

Mathieu Bellanger, Romain Augier, Nicolas Bellahsen, Laurent Jolivet, Patrick Monié, et al.. Shortening of the European Dauphinois margin (Oisans Massif, Western Alps): New insights from RSCM maximum temperature estimates and  $^{40}\text{Ar}/^{39}\text{Ar}$  in situ dating. *Journal of Geodynamics*, 2015, 83, pp.37-64. <10.1016/j.jog.2014.09.004>. <insu-01093878>

**HAL Id: insu-01093878**

**<https://insu.hal.science/insu-01093878v1>**

Submitted on 9 Jan 2015

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

**Shortening of the European Dauphinois margin (Oisans Massif, Western Alps): new insights from RSCM maximum temperature estimates and  $^{40}\text{Ar}/^{39}\text{Ar}$  *in situ* dating.**

M. Bellanger <sup>a, b, c</sup>, R. Augier <sup>a, b, c, \*</sup>, N. Bellahsen <sup>d, e</sup>, L. Jolivet <sup>a, b, c</sup>, P. Monié <sup>f</sup>, T. Baudin <sup>a, b, c</sup>, O. Beyssac <sup>g</sup>,

<sup>a</sup> Univ d'Orléans, ISTO, UMR 7327, 45071, Orléans, France

<sup>b</sup> CNRS/INSU, ISTO, UMR 7327, 45071 Orléans, France

<sup>c</sup> BRGM, ISTO, UMR 7327, BP 36009, 45060 Orléans, France

<sup>d</sup> Sorbonne Universités, UPMC Univ. Paris 06, UMR 7193, ISTeP, F-75005 Paris, France

<sup>e</sup> CNRS, UMR 7193, ISTeP, F-75005 Paris, France

<sup>f</sup> Géosciences Montpellier, CC 60, UMR 5243, Univ. Montpellier 2, Place Eugène Bataillon, 34095 Montpellier cedex 05, France

<sup>g</sup> Univ. Pierre et Marie Curie, UMR 7590 UPMC-CNRS, 4 place Jussieu, 75252 Paris cedex 05, France

\* Corresponding author: romain.augier@univ-orleans.fr

**Abstract**

The Oisans Massif, located in the external zones of the western Alps, experienced significant shortening during the Alpine collision. While a series of major top-to-the west shear zones was recently described, the general low grade of the metamorphism has not attracted much petrological and geochronological studies. This paper provides combined temperature and age constraints on the evolution of the Oisans Massif. Temperature was estimated with the Raman Spectrometry of Carbonaceous Material (RSCM) method and chlorite geothermometry. Maximum temperature reached by the Mesozoic cover (T<sub>max</sub>) from Grenoble to the Galibier pass (E-W) and from Saint Jean de Maurienne to Embrun (N-S) yielded almost constant ca. 330°C temperatures all through the Massif. Temperatures however strongly decrease either westward toward the top of the Vercors sedimentary sequence or eastward toward the Penninic Frontal Thrust. Age constraints were retrieved using  $^{40}\text{Ar}/^{39}\text{Ar}$  *in situ* analyses performed on variously strained samples from Alpine shear zones. Over strain gradients, incipient Alpine recrystallizations progressively develop at the expense of former Variscan parageneses. A combined textural and EPMA approach permitted to identify newly formed chlorite and phengite that unequivocally grew in response to deformation or to low grade metamorphism. Chlorites recorded temperatures from ca. 350 to 150°C during the activity of shear zones. In parallel,  $^{40}\text{Ar}/^{39}\text{Ar}$  *in situ*



experiments enabled dating deformation using both synkinematic phengites crystallized below the closure temperature of white-micas and former Variscan muscovite whose isotopic system have been, at least partially re-opened. Activity of top-to-the-west shear zones responsible for the shortening and thickening of the Oisans massif thus occurred between 34-33 and 25 Ma. Integrating these new age-constraints, Tmax estimates, and published geological data on the Oisans Massif and neighbouring areas allow proposing a new shortening scenario for the external zones. From ca. 34-33 Ma, the Oisans Massif was buried as a rigid block below more internal units and reached temperature of ca. 330°C. Shearing progressively localized along a series of top-to-the-W shear zones in the basement until 25 Ma. Deformation then localised along a major thrust at the base of the ECM massif and propagated along the basement-cover interface below the Vercors massif after 16Ma.

## 1 Introduction

The involvement of basement units in the external zones of collisional orogens is still poorly understood because the associated deformation is not intense and metamorphic conditions not severe enough to erase the effects of earlier deformation episodes, rendering the syn-collision deformation difficult to recognize. The deformation and kinematic history of these continental units thus often remains partly enigmatic and the rheology of the crust in the early stages of collision poorly known.

The Oisans Massif, which belongs to the External Crystalline Massifs (ECM) of the Western Alps is a key-place to understand the first stages of continental collision. Major basement brittle/ductile shear zones reworking the earlier Variscan fabric have been recognized which have accommodated most of the collisional shortening (Wibberley, 1999, 2005; Bellahsen et al., 2012, 2014; Bellanger et al., 2014; Boutoux et al., 2014a), but precise P, T, time data are still lacking to better constrain the sequence of shortening and thickening.

The Oisans Massif also comprises a Mesozoic sedimentary cover, mainly deposited during the Early Jurassic rifting episode, which has not seen the Variscan metamorphic conditions and can thus be used to assess the Alpine history. Bellahsen et al. (2012) and Bellanger et al. (2014) have shown that localised west-verging Alpine shear zones developed in the basement during collision while the cover was strongly folded above without a major décollement in between. The geometry and kinematics of these shear zones is thus now established and it remains to estimate the P-T conditions of their development and to date them.

In this contribution, we first provide a map of the maximum temperature ( $T_{\max}$ ) reached by the cover between Grenoble and the Galibier pass (E-W) and between Saint Jean de Maurienne and Embrun (N-S) (Fig. 1) using the RSCM method (Beyssac et al., 2002). It constrains the thermal history as well as the burial dynamics around the Oisans Massif. Then, we compare these  $T_{\max}$  with temperatures obtained in both basement and cover, using two chlorite geothermometers (Cathelineau and Nieva, 1985; Cathelineau, 1988; Vidal et al., 2001, 2005, 2006). In a second step, we provide EPMA analyses of white micas coupled to detailed microstructural and textural analysis of samples collected from various shear zones, in order to document the nature of these white micas, i.e. inherited vs. synkinematic. Finally, in a third step we performed *in situ* dating of white micas using the  $^{40}\text{Ar}/^{39}\text{Ar}$  method. These results constrain the scenario of collisional shortening in the external zones of the Western Alps.

## 2 Geological setting

### 2.1 The Oisans Massif within the Western Alps

The Belledonne, Grandes Rousses, and Oisans massifs belong to the external zones and more particularly to the Dauphinois zone of the Western Alps (Fig. 1). External zones, which mainly recorded the Liassic rifting stage and the Oligo-Miocene collision event, were affected by a low-grade metamorphism after the end of Eocene. These massifs are parts of the External Crystalline Massifs (noted ECM, thereafter) that correspond to uplifted Variscan basement covered by Mesozoic to Cenozoic sedimentary series. The ECM were underthrust below an orogenic prism made of stacked continental (Briançonnais zone) and oceanic (Piemontais zone) nappes transported along the Penninic Frontal Thrust (PFT). The PFT, also called the Crustal Pennine Thrust or the Embrunais Basal Thrust in Dumont et al. (2011, 2012) was active with top-to-the-(north-)west motion during the Early Oligocene (Ceriani et al., 2001; Tricart et al., 2001, 2006). The internal zones, east of the PFT (Fig. 1), corresponds to the subducted continental margin of Europe and the Ligurian Ocean. They are pervasively affected by high-pressure low-temperature (HP/LT) metamorphism, which occurred between 70 and 35 Ma (Rosenbaum and Lister, 2005; Berger and Bousquet, 2008). During the Palaeozoic, the Oisans Massif experienced a complex tectonometamorphic history (Debon and Lemmet, 1999; Guillot and Menot, 1999; Von Raumer et al., 1999; Guillot et al., 2009). High-grade Carboniferous metamorphism has strongly overprinted previous tectonometamorphic records. The Oisans Massif mainly consists of late Variscan

granites and earlier Devonian-Dinantian plutonic and younger volcano-sedimentary sequences, including Viséan conglomerates, volcano-sedimentary and coal intercalations (Barf  ty and P  cher, 1984). The Belledonne and Rochail massifs were then structured by nappe stacking during the Vis  an and later affected by late Carboniferous to early Permian late-orogenic gravitational collapse (Guillot and Menot, 1999), contemporaneous with partial-melting and plutons emplacement between 330-290 Ma and the formation of extensional Stephano-Westphalian continental basins (i.e. in Grandes Rousses, Belledonne and La Mure massifs) (Barf  ty and P  cher, 1984; Barf  ty et al., 1984, 1988; Guillot et al., 2009). This zone was ultimately eroded during Permian to Triassic times as evidenced by the continental Permo-Triassic deposits (sandstones and conglomerates together with coal intercalations) and middle to late Triassic shallow marine sediments (dolomitic limestone with evaporitic layers). These formations remained attached to the basement during Alpine deformation, and the contact can thus be used as a reference surface to quantify both the extensional strain during the rifting episode and the later compressional deformation during collision (Dumont et al., 2008, 2011; Bellahsen et al., 2012, 2014; Bellanger et al., 2014; Boutoux et al., 2014a).

During early Liassic times, the post-Variscan basement was stretched during the rifting episode (Dumont, 1988; Dumont et al., 1998), as evidenced by basaltic flows ("spilites") (Laurent, 1992) and a series of large-scale fault-bounded tilted blocks, limited by major normal faults that still shape the present-day geometry of the external zones (Barf  ty and Gidon, 1983; Lemoine et al., 1986; Lemoine and De Graciansky, 1988). During the early Liassic, the Meije block (Fig. 3) was a horst, as evidenced by a condensed sedimentary cover and shallow paleobathymetric conditions (Roux et al., 1988; Bouillin et al., 1997; Corna et al., 1997).

After the rifting stage, the Liguro-Piemontais oceanic domain formed between the European and Apulian continental domains from the Bajocian onward, as evidenced by the age of the first sediments deposited above the ocean floor (De Wever and Caby, 1981; De Wever et al., 1987). Subduction of the Ligurian domain, which started during late Cretaceous times was followed by subduction of the leading edge of the European continental margin under the Apulian microplate as evidenced by the HP to UHP metamorphism in the internal zones (e.g., Chopin, 1984; Agard et al., 2001). The more proximal margin was subducted to shallow depths and shortened and the deformation propagated outward.

The "Pyreneo-Proven  al phase", Late Cretaceous to Early Eocene in age, responsible for E-W folds and thrusts especially in the southern part of the external zone, is the first post-

147 Variscan shortening event (Lemoine, 1972; Caby, 1973). Ante-Senonian E-W fold axes  
 148 described in the Dévoluy massif, were recently interpreted as due to submarine sliding  
 149 (Michard et al., 2010). The Nummulitic series are deposited within the foreland flexural  
 150 basin from Lutetian/Bartonian to Priabonian/Rupelian (Sinclair, 1997; Du Fornel et al., 2004  
 151 Mulder et al., 2010). They unconformably overly reverse faults associated to N-S  
 152 shortening, south of the Oisans Massif (Ford, 1996). The timing and the kinematics of other  
 153 thrusts north of the Oisans Massif, such as the Meije or Combeynot thrusts, are debated,  
 154 whether they are pre- (Barbier, 1963; Bravard and Gidon, 1979; Ford, 1996), or syn- to post-  
 155 Nummulitic (Beach, 1981b; Dumont et al., 2011; Bellanger et al., 2014). The only evidence  
 156 of N-S to NW-SE Oligocene shortening within the basement is restricted to a narrow area  
 157 around the PFT (Bellanger et al., 2014).

158 The main Alpine collisional tectonometamorphic event in the external zones was thus due to  
 159 its burial under the internal units immediately after the deposition of a Rupelian olistostrome  
 160 topping the Nummulitic series, the so-called "schistes à blocs" (Kerckhove, 1969; Gidon and  
 161 Pairis, 1980; Sinclair, 1997; Mulder et al., 2010). In the Oisans Massif, E-W shortening was  
 162 responsible for folding in the cover with axial plane cleavage development in the west  
 163 (Gratier and Vialon, 1980; Bellahsen et al., 2012; Bellanger et al., 2014). The metamorphic  
 164 peak reached 300 to 350°C for 1-5 kbar (Waibel, 1990; Jullien and Goffé, 1993; Crouzet et  
 165 al., 1999, 2001; Ceriani et al., 2003), which implies a tectonic overburden of around 10km  
 166 when considering a normal geothermal gradient. The temperature in the Bourg d'Oisans area  
 167 (Crouzet et al., 1999, 2001) reached 330°C after the end of deformation. The metamorphic  
 168 peak was dated with large uncertainties around 26-24 Ma by K-Ar method in fine clay  
 169 fraction from the cover (Nziengui, 1993), zircon fission-tracks ages ranging between 27 Ma  
 170 (alt. 3065m) and 13 Ma (alt. 1310m) (van der Beek et al., 2010). A deformation stage was  
 171 dated between 34 and 27 Ma by  $^{40}\text{Ar}/^{39}\text{Ar}$  phengite ages from strike-slip shear zones related  
 172 to E-W shortening in the eastern part of the Oisans Massif (Simon-Labric et al., 2009).  
 173 Bellahsen et al. (2012) and Bellanger et al. (2014) have further proposed that the E-W  
 174 shortening in the Oisans Massif was mainly accommodated by kilometer-scale top-to-the-  
 175 west reverse shear zones, which are summarized in the next section.

176

## 177 ***2.2 Inherited or newly formed: the Oisans shear zones revisited***

178 Contrary to the internal zones where deformation is too intense to preserve former  
 179 structures, the amount of shortening of the Oisans Massif was less than ca. 30-40% during  
 180 the Alpine collision (Dumont et al., 2008; Bellahsen et al., 2012, 2014; Bellanger et al.,

2014). As a consequence, inherited structures are still preserved, which allows studying relationships between inherited and Alpine newly formed structures. The detailed structural evolution of the Oisans Massif, which is beyond the scope of the present paper, was recently investigated by Bellahsen et al. (2012) and Bellanger et al. (2014) in order to describe the distribution of the deformation in the basement.

The Oisans Massif presents unambiguous evidence of intense shortening either at small (outcrop) scale or at large (kilometric) scale. Maps of shortening axes of small-scale structures together with transport directions over the whole Oisans Massif reveal only one major E-W shortening stage (Fig. 2). Strain localization in the basement leads to the formation of a set of newly-formed, top-to-the-west, reverse shear zones that fold the basement-cover interface to the west and form large basement thrusts near the Penninic Frontal Thrust (Bellanger et al., 2014). Alpine shear zones can be separated from the Variscan deformation by the lower-temperature, more localised character of the deformation that cross-cuts a former high-temperature, pervasive Variscan fabrics. Moreover, an Alpine age is ensured by the deformation with consistent top-to-the-west kinematics within the Triassic-Liassic tegument (Bartoli et al., 1974; Barféty and Pêcher, 1984; Bellahsen et al., 2012; Bellanger et al., 2014).

While similar Alpine shear zones of Argentera or Mont Blanc massifs were recently dated from the Oligo-Miocene (Rolland et al., 2008; Sanchez et al., 2011a; Cenki-Tok et al., 2013), the only recent constraints on the timing of the Alpine deformation were performed on strike-slip shear zones of the eastern Oisans Massif (Simon-Labrie et al., 2009). The most prominent structures accommodating most of the shortening, W-directed reverse shear zones remain therefore undated.

### 3 Aims and methods

To put age-constraints on reverse shear zones developed during collision in the Oisans Massif, deformed rocks of four main shear zones were sampled across the W- E profile. These are, from west to east: the Col de Cluy, Plan du Lac, Col du Lac and Combeynot shear zones (Fig. 2), all sharing a common and consistent E-W to SE-NW stretching lineation and an overall top-to-the-west sense of shear. *In situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  laser ablation method (Maluski and Monié, 1988) was chosen as it allows linking radiochronology to petrology and particularly to textures/structures (Agard et al., 2002; Müller, 2003; Augier et al., 2005; Gerber, 2008). This link is particularly important as

different parameters such as temperature, deformation or fluid circulations may drastically impact the behaviour of the K/Ar system. It is therefore crucial to decipher the respective contribution of these parameters to isolate the signal related to deformation.

To ensure a reliable T record, temperatures were constrained at the scale of the Oisans Massif and the neighbouring areas using the Raman Spectrometry of Carbonaceous Material method (RSCM; Beyssac et al., 2002; Lahfid et al., 2010). These data were supplemented by local temperature estimates using the chemical composition of chlorite in the chlorite-quartz-water equilibrium (Vidal et al., 2001, 2005, 2006) either to control RSCM results or to put direct constraints within the shear zones. In parallel, impact of the deformation was evaluated by a combined textural/petrological study of the dated samples and particularly the behaviour of white-micas. Besides, the potential impact of the fluid percolations was evaluated by a careful study of output isotopic ratios. The next sections are dedicated to a brief description of the methods used in this study.

### 3.1 Raman spectrometry of carbonaceous material (RSCM)

The Raman Spectrometry of Carbonaceous Material method (Beyssac et al., 2002) is based on the quantitative study of the degree of graphitization of carbonaceous material (CM), which is a reliable indicator of metamorphic T. Because of the irreversible character of graphitization, CM structure is not sensitive to the retrograde reactions during exhumation and therefore depends on maximum T (noted T<sub>max</sub>, thereafter) reached during metamorphism (Beyssac et al., 2002). T<sub>max</sub> can be determined in the range 200-650°C by using two empirical geothermometers which link the degree of graphitisation measured from Raman Spectra (RS) to the highest temperature ever experienced by the rock (Beyssac et al., 2002; Lahfid et al., 2010). Lahfid et al. (2010) geothermometer was used when the D4 defect band was present in the RS, for the low-grade rocks. Absolute precisions of ca. 50°C between 650 and 300°C and ca. 25°C between 330 and 200°C are related to uncertainties on petrological data used for the calibration. However, relative uncertainties on T<sub>max</sub> appear however much smaller, probably around 10-15°C and variations of that order of magnitude may be detected (Beyssac et al., 2004, 2007; Gabalda et al., 2009; Vitale-Brovarone et al., 2013).

All Raman spectra were measured and analysed following procedures described in Beyssac et al. (2002, 2004 and 2007) and Lahfid et al. (2010). Raman spectra were obtained using a Renishaw InVIA Reflex microspectrometer (IMPMC, Paris, France) with a 514 nm argon laser. RSCM analyses were conducted on thin sections prepared on CM-rich metasediments

particularly abundant in the cover series in the studied area, cut in the structural X-Z plane (i.e. orthogonal to foliation and parallel to lineation). To avoid defects on the CM related to thin-section preparation, analyses were all performed below the surface of the section by focusing the laser beam beneath a transparent crystal (i.e. dominantly quartz, calcite, albite and occasionally phyllosilicates). Before each session, the spectrometer was calibrated with a silicon standard. 10-20 spectra were routinely recorded for each sample to smooth out the inner structural heterogeneity of CM within samples.

### 3.2 Microprobe and independent temperature estimates

Mineral analyses were performed with a Cameca SX50 electron microprobe (ISTO-BRGM, Orléans). Analytic conditions were 15 kV accelerating voltage and 10 nA beam current using Fe<sub>2</sub>O<sub>3</sub> (Fe), MnTiO<sub>3</sub> (Mn, Ti), diopside (Mg, Si), CaF<sub>2</sub> (F), orthoclase (Al, K), anorthite (Ca), albite (Na) as standards. Elements, which are measured in %weight of oxide, are SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MgO, MnO, CaO, Na<sub>2</sub>O, K<sub>2</sub>O, TiO<sub>2</sub>, F and Cl. Chemical composition of chlorite and the white-micas were particularly studied. Composition of chlorite has been used to retrieve independent T constraints using a thermodynamic approach (Vidal et al., 2001, 2005, 2006). Besides, composition of white-micas was used to distinguish different mineral generations to characterise the dated minerals.

Chlorite, which is abundant in the studied low-grade metamorphic rocks, was used as a geothermometer. Temperatures were estimated by two ways: i) traditional empirical geothermometry based on temperature dependency of the Si, Al and vacancy content of the tetrahedral and octahedral sites within chlorite (Cathelineau and Nieva, 1985; Cathelineau, 1988), and ii) a thermodynamical approach (Vidal et al., 2001, 2005, 2006) that integrates multiple substitutions (FeMg<sub>-1</sub>, Al<sub>IV</sub>Al<sub>VI</sub>Si<sub>-1</sub>Mg<sub>-1</sub>, (Mg, Fe<sup>2+</sup>)<sub>3</sub>□<sub>-1</sub>Al<sub>2</sub> where □ is the vacancy). In the last case, metamorphic temperatures that prevailed during the formation of chlorite were estimated upon 4 equilibria at fixed water activity and pressure ( $a_w=1$  and  $P=4\text{ kbar}$  (Simon-Labric et al., 2009)). Standard deviations are routinely close to  $\pm 10^\circ\text{C}$  (from  $\pm 4^\circ\text{C}$  to  $\pm 32^\circ\text{C}$ ).

### 3.3 In situ <sup>40</sup>Ar/<sup>39</sup>Ar dating

The <sup>40</sup>Ar/<sup>39</sup>Ar *in situ* laser ablation method was first described by Schaeffer et al. (1977) and successively upgraded by York et al. (1981) and Maluski and Monié (1988). Procedure was detailed in Agard et al. (2002), Augier et al. (2005) or Turrillot et al (2011).

282 We recall here the main stages for  $^{40}\text{Ar}/^{39}\text{Ar}$  *in situ* sample preparation and analytical  
283 procedure.

284 Measurements were all performed at Géosciences Montpellier (France) with an analytical  
285 system that consists of: (a) an IR-CO<sub>2</sub> laser of 100 kHz used at 5-15% during 60-80 sec; (b)  
286 a beam shutter for selection of exposure times; (c) a lenses system for beam focusing; (d) a  
287 camera connected to the monitor for beam focusing and selection of ablated zones; (e) a  
288 steel chamber with a copper plate and the four samples on. This chamber is depressurized to  
289  $10^{-8}$  to  $10^{-9}$  bar; (f) an inlet line for purification of gases including two Zr-Al getters; (g) a  
290 Argus VI (Thermo-Fisher) multi-collector mass spectrometer from; (h) a software which  
291 controls the timing of extraction/purification and the data acquisition. Rock sections of 1  
292 mm thick, which had been used to make the petrographic thin-sections, were double  
293 polished to c. 1  $\mu\text{m}$ . Whole section and detailed-area photographs of both the rock section  
294 and corresponding thin section were taken for an accurate selection of suitable areas for  
295 laser experiments. All samples were ultrasonically rinsed in ethanol and distilled water,  
296 wrapped in pure aluminium foils and then irradiated in the Triga Mark II nuclear reactor  
297 (Pavia, Italia) with several aliquots of the Fisch Canyon sanidine standard ( $28.03 \pm 0.08\text{Ma}$ ,  
298 (Jourdan and Renne, 2007) as flux monitors. After irradiation, both the monitors and the  
299 sections were placed on a Cu-holder inside the sample chamber and heated for 48 h at 150–  
300 200 °C.

301 For each experience, argon was released from a 100 x 300  $\mu\text{m}$  mean surface corresponding  
302 very often to aggregates of white micas. Incision of the sample did not exceed 10-20  $\mu\text{m}$   
303 depending on the three-dimensional orientation of the white mica crystals. For each  
304 experiment, ages have been obtained after correction with blanks, mass discrimination,  
305 radioactive decay of  $^{37}\text{Ar}$  and  $^{36}\text{Ar}$  and irradiation-induced mass interferences. They are  
306 reported with  $1\sigma$  uncertainty and were evaluated assuming an atmospheric composition for  
307 the initially trapped argon [i.e.  $(^{40}\text{Ar}/^{36}\text{Ar})_i = 295.5$ ]. The proportion of  $^{38}\text{Ar}$  and  $^{37}\text{Ar}$   
308 isotopes that result from interference with chlorine and calcium during irradiation reveals  
309 the contribution of Cl and Ca-rich minerals or inclusions to the overall argon release and so  
310 to the calculated age. A blank analysis was done every two or three analyses to evaluate the  
311 argon background within the whole analytical system. Isotopic data are computed with the  
312 ArArCalc freeware (Koppers, 2002) based on the algorithms described in (York, 1968;  
313 Faure, 1986; McDougall and Harrison, 1988; Renne et al., 1998; Min et al., 2000).

314 Along with a strong dependency with temperature and deformation, the behaviour of the  
315 K/Ar system in white micas can be partially altered by fluid circulations. As fluid



circulations are hardly detected *a priori*, output isotopic ratios ( $^{36}\text{Ar}/^{39}\text{Ar}$ ,  $^{37}\text{Ar}/^{39}\text{Ar}$  and  $^{38}\text{Ar}/^{39}\text{Ar}$  ratios) were carefully checked.

#### **4 Temperature record within the sedimentary cover**

##### ***4.1 A large-scale RSCM Tmax cover in the sedimentary series***

###### ***First order thermal features***

Our dataset consists of 70 samples collected across the external zones, from Vif to the Penninic Frontal Thrust (E-W transect) and from Saint Jean de Maurienne to Chorges (N-S transect) in various lithologies and all structural units of the studied area except Variscan basement rocks (Table 1, Fig. 4). A more systematic sampling was performed along the E-W transect where the thermal structure is so far poorly documented. Results are all presented in maps of various scales and projected along structure-orthogonal cross-sections. For the sake of comparison, results of previous studies including illite-crystallinity maps (Aprahamian, 1974; Barlier et al., 1974) or RSCM data in bounding areas (e.g. Gabalda et al., 2009) are also shown (Fig. 4).

At first glance, an unexpected major result of this study is the relative homogeneity of the Tmax value at the scale of study area, with an average value of ca. 330°C (329±8 for 27 Tmax values along an E-W cross-section), from the Lower Jurassic series close to Vif, all the way to the Galibier pass, at the eastern edge of the study area (Fig. 4, 5). Conversely, lower Tmax ca. 200-220°C is recorded to the south either in the Mesozoic series or Eocene flysch (north of Saint Michel de Chaillol; Fig. 4). Moreover, Tmax results recorded further south along an E-W section between Chorges and l'Argentière-la-Bessée (Fig. 4) highlight a drastic southward lateral change in the thermal structure. There, Tmax values present an overall upward temperature increase from 253±10°C to more than 330±5°C in the vicinity of the Penninic Frontal Thrust. Besides, additional important temperature variations were recorded either to the west of the study area (Belledonne and La Mure massifs), to the east in the vicinity of the Penninic Frontal Thrust (Fig. 4, 5). These variations are described here in more details.

###### ***Thermal structure of the western bound of the Belledonne and La Mure massifs***

To the west of the Belledonne and La Mure massifs, Tmax values decrease upward the stratigraphic succession from 334±6°C-329±8 in the Liassic, 325±6-286±5°C in

calcareous Dogger and  $227\pm 23$ – $<200^\circ\text{C}$  in upper Jurassic black-shales (Fig. 4, 5) highlighting a ca.  $130^\circ\text{C}$  temperature variation. In details,  $T_{\text{max}}$  values gradually decrease sequence along a ca.  $30^\circ\text{C}/\text{km}$  gradient but also highlight a localised temperature decrease near the top of the calcareous Dogger ( $296\pm 5$ – $286\pm 5^\circ\text{C}$ ) and the base of the upper Jurassic ( $227\pm 23$ – $204\pm 14^\circ\text{C}$ ). This ca.  $80^\circ\text{C}$  temperature gap can be followed 40 km strike, which is consistent with a normal sense west-dipping tectonic contact located within the upper Jurassic black-shales (Oxfordian). However, due to poor local outcrop conditions, this contact has not been observed in the field.

In the same area, the base of thick Jurassic sequences of the Vercors yielded  $T_{\text{max}}$  value close to  $335^\circ\text{C}$  ( $334\pm 6^\circ\text{C}$ ) while the thin Jurassic cover of the Belledonne and La Mure massifs yielded only ca.  $280^\circ\text{C}$  ( $279\pm 9^\circ\text{C}$ ). In this case,  $T_{\text{max}}$  distribution evidenced an east-verging shear zone/thrust consistent with the description of a large-scale backthrust in the field by Butler (1989). The Mesozoic sequence of the Vercors therefore appears i) transported eastward above the La Mure thrust which roots in Triassic or Liassic units, and ii) is partly dismembered by an extensional structure (Fig. 4, 5).

365

#### 366 ***Thermal structure in the vicinity of the Penninic Frontal Thrust***

To the east of the study area, close to the Lautaret and Galibier passes,  $T_{\text{max}}$  values decrease gradually from ca.  $330^\circ\text{C}$  in the easternmost Mesozoic cover of the Oisans Massif to ca.  $260^\circ\text{C}$  in the Helminthoids flysch (Tête Noire area) despite the presence of numerous tectonic contacts including the PFT.  $T_{\text{max}}$  results therefore align well along an apparent  $20$ – $30^\circ\text{C.km}^{-1}$  gradient suggesting either that the  $T_{\text{max}}$  imprint was post-tectonic or that extensional movements are not restricted to the PFT and rather distributed over numerous small-scale, normal-sense structures. In any case, in their current position, Briançonnais units did not experience  $T_{\text{max}}$  higher than ca.  $270^\circ\text{C}$  which fall well below the ca.  $330^\circ\text{C}$  temperatures characterising the internal Dauphinois. Conversely, a ca.  $40^\circ\text{C}$  localized temperature drop is recorded further south, across the PFT (around L'Argentière-la-Bessée, Fig. 4) where the Nummulitic series yielded ca.  $330\pm 5^\circ\text{C}$  while Briançonnais units only experienced  $291\pm 6^\circ\text{C}$ . There, this result is consistent with both field and low-temperature thermochronology evidences of the reactivation of the PFT as an extensional structure (Tricart et al., 2001, 2004, 2006, 2007; Ceriani and Schmid, 2004).

381

#### 382 ***4.2 Independent temperature record using chlorite geothermometry***

Four samples were selected from the sample collection of the sedimentary cover for the RSCM approach (see location on Table 2 and on Fig. 2). The main aim of this approach is to estimate the temperature recorded by the cover series using independent geothermometers based on the chemical composition of chlorites (Cathelineau and Nieva, 1985; Cathelineau, 1988; Vidal et al., 2001, 2005, 2006). Results are all presented on figure 6.

Chlorites present different habits and occur in various textures. They are either dispersed in the matrix (samples A-2-2, A-4-232, see location Fig. 2), crystallized within veins (samples A-1-345(2)) or along the foliation and top-to-the-W shear bands (sample A-1-321). Irrespectively to their structural position and to the potential impact of the protolith bulk chemical composition, the two geothermometers yielded quite consistent results for all samples within both the analytical and calibration errors and the within-sample internal dispersion. However, the thermodynamical approach generally yield more dispersed temperature results between ca. 210 and 350°C than empirical geothermometry that show an unimodal distribution centred on the narrow ca. 270-330°C range (Fig. 6). Temperature ranging from 150 to 350°C was retrieved from sample A.2.2, 150-340°C from sample A-4-232, 230-380°C for sample A-1-321 and 240-390°C for sample A-1-345 (Fig. 6). Interestingly, RSCM T<sub>max</sub> fall systematically within the high temperature value indicating i) the cross-validation of the methods and that ii) chlorites, at variance with the RSCM, do record other discrete metamorphic increments. However, textural observations did not allow distinguishing the relative timing of successive chlorite growth events during the metamorphic evolution (prograde or retrograde (re-)equilibrations).

## **5 Phyllosilicate habits, chemical composition and chlorite temperature (T<sub>Chl</sub>) record for dated samples**

The crystallisation-deformation relationships of chlorite and white-micas that were first recognised in the field were then strengthened by detailed textural observations in thin-section. Mineral chemical compositions were used to constrain i) the chemistry of dated minerals and ii) the physical conditions by chlorite geothermometry. Together with textural observations, these results are of prime importance to gather accurate *a priori* constraints and discussion elements for *in situ* laser-probe investigations.

### 5.1 First order common features: guidelines for the $^{40}\text{Ar}/^{39}\text{Ar}$ in situ approach

At the scale of the outcrop, rocks present routinely large white-mica crystals. Conversely, aggregates of very fine-grained white-micas occur only in deformed zones. At the scale of thin-sections, deformed samples present two contrasted habits of white-micas. Large, up to 2mm variously oriented white-mica flakes appear closely associated with a former high-temperature foliation and high-temperature parageneses (Fig. 7). These crystals coexist with aggregates of fine-grained white-micas growing either at the expense of former large crystals or in cracks of various scales within feldspars. Besides, this population presents a close association with deformation structures and particularly with top-to-the-west shear bands within proto-mylonites, mylonites or phyllonites. This strong correlation has been observed at the scale of strain gradients along which large, well-developed white-mica clasts tend to disappear whereas fine-grained blasts form the frame of the rock (Fig. 7). Interestingly, EPMA analyses reveal the existence of two texturally controlled groups of white-mica of contrasted compositions reminding the results of Lanari et al. (2012) in the Briançonnais domain, further east. The first group, which plots close to the muscovite end-member composition, is mainly represented by the large white-micas clasts population carried by an earlier foliation (Fig. 7). Besides, the Na-content of this population is systematically higher than 0.05 a.p.f.u. (atoms per formula unit) while the Si content is lower than 3.1 a.p.f.u. (Fig. 7). The second group, mostly corresponding to fine-grained aggregates of white-micas, has a phengite chemistry, i.e. between muscovite and celadonite end-member due to Tschermak substitutions. This group presents variable silica-content scattered between 3.2 and 3.6 a.p.f.u. and Na-content systematically lower than 0.05 a.p.f.u. (Fig. 7, 8). However, the small size of crystals and large internal variations of compositions suggest a partial mixing between two end-members.

EPMA analysis of the chemical compositions confirm the presence of two unrelated generations of white-micas recognised on the basis of textural observations and characterized by contrasted chemical compositions. Being conspicuously involved with the greenschist facies partial reequilibration of former high-temperature parageneses and closely associated with a top-to-the-W asymmetry, phengites therefore appear as a synkinematic mineral particularly suitable to put age-constraints on the deformation. Conversely, the habits of pre-kinematic clasts and the muscovite composition of most of the large white-mica population are likely inherited crystals pertaining to Variscan parageneses.

Besides, temperature, which is the most important factor controlling Argon diffusion, must be estimated to make a difference between cooling and deformation (crystallisation) ages. Similarly to temperature estimates performed in the cover series, temperature recorded by basement rocks was estimated using two different chlorite geothermometers. Results are all presented in figure 8.

## 5.2 Textural and chemical characteristics of dated samples

Following this structural and chemical guideline, white-micas present in the dated samples were carefully studied. Besides, chemical composition of chlorite was used to constrain the temperature experienced by the rocks. Results are all presented from west to east on figure 8.

### *Col de Cluy shear zone*

Samples from Col de Cluy are Variscan micaschists and gneisses with greenschist to amphibolite facies associations with quartz, white-micas, feldspar, biotite and/or chlorite. Rocks show generally only an incipient recrystallization. Former biotite and K-feldspar are still preserved and locally abundant. White-micas, which are present in all samples, mostly occur as ca. 1-2mm weakly deformed flakes and locally as clasts involved in shear bands. This population coexists with fine-grained white-micas that occur as rare isolated aggregates. Grain-size is generally less than 10 x 50  $\mu\text{m}$  and white-mica crystals are often closely associated with chlorite. EPMA analyses of the white-micas mostly plot within a rather narrow composition range close to the muscovite end-member. Analyses of fine-grained white-micas plot along continuous pattern from muscovite (Si(3.05); Na(0.09;0.12)) to low-silica content phengite (Si(3.15;3.25); Na(0;0.02)) (Fig. 8). Chlorite occurs as numerous small-scale aggregates. Chlorite shows variable composition with 70 to 85% of clinocllore and XMg values close to 0.45 for variable silica content. Geothermometric results yield quite contrasting results. While the thermodynamic approach yielded dispersed temperature between 150 to 370°C, empirical geothermometry showed quite consistent ca. 230 to 320°C temperature results (Fig. 8). Being devoid of conspicuous Alpine re-equilibrations, these samples appear, at a first glance poorly suitable to allow dating the deformation and were therefore not used for the  $^{40}\text{Ar}/^{39}\text{Ar}$  *in situ* approach.

### 483 *Plan du Lac shear zone*

484

485 Thanks to good outcrop conditions allowing the recognition of the strain distribution,  
 486 the Plan du Lac shear zone was particularly studied. Four samples were selected over the  
 487 strain gradient. Sample A-4-74b is a proto-mylonite sample showing a rather weak Alpine  
 488 deformation by comparison to samples A-4-68 and 68b that are phyllonites. Sample A-4-66b  
 489 was selected from an intermediate position within the strain gradient. All samples show a  
 490 clear top-to-the-west asymmetry except sample A-4-66b picked along a localized top-to-the-  
 491 E shear zone.

492 All samples derive from a quartz, feldspar, biotite and white mica Variscan gneiss.  
 493 Chlorite pervasively replaces biotite either as static pseudomorphs in low strain domains or  
 494 as synkinematic crystallisations in mylonites. In low strain domain, white mica occur as  
 495 large, up to ca. 1-2mm clasts with clear disequilibrium textures while fine-grained white-  
 496 mica are rare and clearly secondary. Conversely, mylonite and phyllonite are almost devoid  
 497 of large clasts and exclusively made of fine-grained white-micas. EPMA composition of  
 498 white-micas reveals two distinct poles with very few intermediate values (Fig. 8). The first  
 499 pole that corresponds to muscovite (Si(3.15); Na(0.06;0.08)) and the second one to a silica-  
 500 rich phengite (Si(3.2;3.4); Na(0;0.02)) (Fig. 8). Interestingly, mineral composition shows a  
 501 conspicuous dependency to deformation. Mylonite and phyllonite samples yield mostly  
 502 phengitic white-micas. Conversely, less-deformed proto-mylonite sample yield texturally-  
 503 controlled chemical compositions with muscovite compositions for the large clasts and  
 504 phengite composition for the fine-grained blasts.

505 Chlorite is locally abundant. It occurs in the matrix, growing at the expense of  
 506 biotite, crystallized in syn-deformation veins or associated with fine-grained white-micas  
 507 along shear planes. Most analyses yield consistent results with 70 to 90% of clinocllore  
 508 content, an XMg close to 0.45 for a variable silica content (Fig. 8). Regardless of strain  
 509 intensity, structural position and habits, most results cluster between 260 to 290°C (Fig. 8).

510

### 511 *Col du Lac shear zone*

512

513 Sample A-1-355 was collected from the core of a top-to-the-W shear band  
 514 characterized by a thin layer of phengite-quartz phyllonites. This sample derives from a  
 515 Variscan high-grade gneiss still preserved a few decimetres apart on the same outcrop. The  
 516 rock is made of quartz, feldspar and biotite partly turned into chlorite. Interestingly, white

mica is absent from the mineralogical composition of the protolith. Small-scale but abundant white-mica aggregates from the phyllonites are therefore newly-crystallized as the result of strain and/or fluid-induced destabilization of the K-feldspar (e.g. Gueydan et al., 2003). Accordingly, EPMA analyses of the white-micas all yielded phengitic compositions with a very low dispersion (Si(3.2;3.4); Na(0;0.02)).

Chlorite occurs as small-scale aggregates and rare dispersed larger crystals that may derive from former biotites. Chlorite shows almost constant composition close to the clinocllore end-member with XMg values around 0.6. Most geothermometric results cluster between 250 and 290°C for both geothermometers (Fig. 8).

### ***Combeynot shear zone***

Sample A-1-345 was selected in the most deformed outcropping ductily-deformed basement rocks of the Combeynot shear zone. Mylonites are scarce and proto-mylonites, derived from orthogneiss, which belongs to a volcano-sedimentary complex (Barbier et al., 1973), are often directly overthrust onto the sedimentary cover. White micas occur generally as large clasts surrounded by very fine-grained blasts. Aggregates of fine-grained white-micas also occur in tension gashes in K-feldspar. Composition of white-micas shows a rather continuous pattern from muscovite (Si(3.05;3.15); Na(0.06;0.08)) to phengite (Si(3.25;3.5); Na(0;0.02)) (Fig. 8). Despite a clear partial re-equilibration within Alpine physico-chemical conditions, Alpine white-micas occur as very fine grained aggregates. Chlorite is rare, small and often closely associated with white-micas. Thus, most chlorites show mixed composition with white-micas (i.e. K-rich chlorite) and were thus discarded. Data are thus only presented in table 2.

Synkinematic fine-grained aggregates of phengite appear particularly adapted to put age-constraints on the activity of the shear zones. Accordingly, samples from Col de Cluy shear zone which may record only a weak Alpine re-equilibration have not been selected from the *in situ*  $^{39}\text{Ar}/^{40}\text{Ar}$  approach. For all other samples, success of the study relies on our ability to effectively analyze newly formed crystals whose typical size is often small (150µm max.).

Temperatures recorded in the shear zones yielded very consistent results close to 250-300°C which falls below RSCM T<sub>max</sub> recorded in the cover series. Chlorite therefore probably recorded retrograde metamorphic increments during exhumation and cooling of the Oisans

Massif. It is noteworthy that temperatures recorded at peak-T conditions also fall below the lower bound of the closure temperature of white-micas (e.g. Dodson, 1973; Cliff et al., 1998; Villa, 1998).

554

## 555 **6 $^{40}\text{Ar}/^{39}\text{Ar}$ age constraints**

556 Our dataset consists of 199 *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  ages performed on 7 samples collected  
557 over three main Alpine shear zones, namely (from west to east), the Plan du Lac, Col du  
558 Lac, and the Combeynot shear zones (Table 3, see location on Fig. 2). To ensure the  
559 coverage of the different strain facies recognized in the field, a more systematic sampling  
560 was performed over the Plan du Lac shear zone. Results of the *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  approach are  
561 all shown and discussed in Fig. 9 as apparent ages for which an initial  $^{40}\text{Ar}/^{39}\text{Ar}$  ratio of  
562 295.5 is assumed for the non-radiogenic argon component. These age results are described  
563 in the light of the textural/structural observations, chemical composition results and the  
564 output isotopic ratios ( $^{36}\text{Ar}/^{39}\text{Ar}$ ,  $^{37}\text{Ar}/^{39}\text{Ar}$  and  $^{38}\text{Ar}/^{39}\text{Ar}$ ) informative of potential  
565 disturbances of the K/Ar system. For small-scale phengite aggregates located in the vicinity  
566 of chlorite, calcium or fluid inclusions-bearing minerals, the release of the  $^{38}\text{Ar}$  and  $^{37}\text{Ar}$   
567 isotopes interfering with chlorine and calcium revealed that argon was extracted from both  
568 phengites and K-poor minerals (Brereton, 1970; McDougall & Harrison, 1988). The quoted  
569 errors represent one sigma deviation and do not include uncertainty on the monitor. Errors  
570 are routinely inferior to ca. 1 Ma while larger error (ca. 2 to 15 Ma) are generally due to both  
571 a weak argon signal and a high atmospheric contribution (Table 3).

572 At a first glance, an important conclusion is that the successive phengite generations  
573 recognized on the basis of textures (e.g. Fig. 7), compositions (Figs 8) effectively yield  
574 successive ages. Fine-grained aggregates of synkinematic phengites yield Alpine ages *sensu*  
575 *lato*. Conversely, white-micas characterized by muscovite chemical compositions and/or  
576 presenting clear pre-kinematic (i.e. inherited) habits yielded pre-alpine ages or even  
577 sometimes Variscan ages. Interestingly, a clear dependency to the intensity of the  
578 deformation may even be detected either at the scale of the sample or at the scale of the  
579 strain gradient within a shear zone (e.g. Fig. 10). Therefore, most ages are tentatively  
580 interpreted either as, at least partially, re-opened Variscan isotopic systems for “old” ages or  
581 as genuine crystallization ages for the “young” ca. 35-25 Ma ages. More locally, results  
582 however show important age variations that may also record fluid percolations.

583

### 584 **6.1 Plan du Lac shear zone**



585 In order to study the potential impact of the finite Alpine deformation, four samples  
 586 were selected over a single strain gradient toward the core of the Plan du Lac shear zone.  
 587 The relative structural position of samples is given on figure 10.

588

589 *A-4-74b (Proto-mylonite)*

590 In this sample, discrete ca. 1mm-thick shear bands partially overprint a high-  
 591 temperature inherited texture composed by large, brittlely fractured feldspar clasts and more  
 592 ductilely stretched quartz and muscovite crystals (Fig. 10). Conversely, this sample contains  
 593 Alpine phyllosilicates including phengite and chlorite either carried along a weak vertical  
 594 foliation, or crystallized along top-to-the-W shear bands. A total of 40 apparent *in situ*  
 595 analyses were performed to cover all situations. Apparent *in situ* ages are scattered between  
 596  $207 \pm 5.2$  Ma and  $24.3 \pm 1.8$  Ma (Fig. 10). 22 analyses corresponding to the oldest ages are  
 597 correlated with high  $^{38}\text{Ar}/^{39}\text{Ar}$  ratio and atmospheric content (Table 3) but ages fall within  
 598 the age range of uncontaminated phengites. Interestingly, the core of the shear bands  
 599 provides ca. 25 Ma consistent ages ( $24.3 \pm 1.8$  Ma and  $26.7 \pm 0.6$  Ma).

600

601 *A-4-66b (Top-to-the-E Mylonite)*

602 This sample is characterized by a schistosed high-grade gneiss traversed by a 3 mm-  
 603 thick top-to-the-E shear band (Fig. 10). While Variscan fabrics are still well developed in  
 604 most of the rock volume, Alpine synkinematic recrystallizations are almost complete within  
 605 shear bands. There, former muscovites and feldspars are absent and a ca. 2mm thick  
 606 phengitized fringe is developed (Fig. 10). 34 *in situ* analyses were performed. No  
 607 relationship between apparent ages and the  $^{37}\text{Ar}/^{39}\text{Ar}$  and  $^{38}\text{Ar}/^{39}\text{Ar}$  variations were detected,  
 608 except for the 3 three apparent ages older than ca. 100Ma, which have high  $^{38}\text{Ar}/^{39}\text{Ar}$  values  
 609 (Table 3). Analyses show a first order textural control of the age. Large muscovites, at least  
 610 partially preserved within the matrix yielded  $301.4 \pm 6.6$  and  $62.3 \pm 1.4$  Ma. Conversely,  
 611 small-scale phengites within the shear band yielded 30 alpine ages ranging between  $40.5 \pm$   
 612  $1.1$  Ma and  $29.5 \pm 0.6$  Ma plus an older age of  $47.6 \pm 1.2$  Ma (Fig. 10). Interestingly, while  
 613 ages depict a clear first order younging toward and within the shear band, older ages occur  
 614 within the core of the shear band over a ca. 1-2mm-thick fringe (Fig. 10). In this case, a late  
 615 gradient of  $^{40}\text{Ar}$  excess seems to overprint an initial age gradient related to deformation.

616

617 *A-4-68 (Phyllonite)*

Sample A-4-68 is a phyllonite sample. 15 *in situ* analyses were performed and yielded ages ranging between  $93.5 \pm 2.0$  and  $22.4 \pm 0.9$  Ma (Table 3). Most of apparent ages cluster between 32 and 22 Ma (Fig. 10). There is no relationship of apparent ages with  $^{37}\text{Ar}/^{39}\text{Ar}$  unlike with  $^{38}\text{Ar}/^{39}\text{Ar}$ , suggesting some interaction with chlorine-rich fluids that may occur as trapped inclusions (Fig. 10).

#### A-4-68b (Phyllonite)

Sample A-4-68b was cut in two distinct rock slabs (section 8 and 5) selected only a few centimeters distant; section 5 being a little less deformed than section 8. Analyses performed on section 5 yielded 21 apparent ages, ranging between  $114.2 \pm 4.3$  and  $25.9 \pm 0.5$  Ma (Fig. 10). Analyses present a strong relationship between apparent ages and  $^{37}\text{Ar}/^{39}\text{Ar}$ ,  $^{38}\text{Ar}/^{39}\text{Ar}$  and atmospheric content. In the absence of Ca-rich and Cl-rich phases in the chip, contamination may be rather related with fluid inclusions trapped in the analysed phengites (Table 3). Despite contamination by Ca-rich and Cl-rich fluids, analyses yielded ages of about 25-27 Ma. Interestingly, analyses performed on section 8 yielded 44 apparent ages, which do not show any evidence of a direct relationship with the  $^{37}\text{Ar}/^{39}\text{Ar}$ ,  $^{38}\text{Ar}/^{39}\text{Ar}$  and atmospheric content. These ages are scattered between  $37.2 \pm 1.0$  Ma and  $23.2 \pm 0.6$  Ma (with two old ages of 46.4 and 47.2 Ma) and define mainly two age groups at 31-33 Ma (7 ages) and 25-27 Ma (18 ages) (Fig. 10).

#### 6.2 Col du Lac shear zone (Sample A-1-355, phyllonites)

Sample A-1-355 was collected from the core of a top-to-the-W shear band characterized by a ca. 1 meter-thick layer of phyllonites. This sample derives from a Variscan high-grade gneiss still preserved a few decimetres apart on the same outcrop and turned into a phengite-quartz rock in the most deformed zone. It contains few chlorites and no remnant of inherited muscovites present in the undeformed protolith. The 30 apparent ages are scattered between  $110 \pm 7$  Ma and  $15 \pm 10$  Ma and 25 of them range between  $42.68 \pm 2.22$  and  $23.88 \pm 1.6$  Ma (Table 3). No correlation between the apparent age and  $^{38}\text{Ar}/^{39}\text{Ar}$  and  $^{37}\text{Ar}/^{39}\text{Ar}$  ratios was observed. However, some analyses, particularly the “old”, up to 50 Ma ages present high  $^{38}\text{Ar}/^{39}\text{Ar}$  values and/or an important atmospheric contribution (Table 3). Interestingly, these old ages were found in micas from C'-type shear bands and therefore argue for a  $^{40}\text{Ar}$  excess. These results are quite similar to those obtained in the most deformed parts of sample A-4-66b. Despite this potential contamination, analyses with low

$^{38}\text{Ar}/^{39}\text{Ar}$  ratio and low atmospheric content yielded 15 internally consistent apparent ages scattered between  $32.9 \pm 0.9$  and  $24.8 \pm 0.6$  Ma (Fig. 10).

### 6.3 Combeynot shear zone (*Sample A-1-345, proto-mylonite*)

Sample A-1-345 was selected in the most deformed outcropping ductilely-deformed basement rocks of the Combeynot shear zone. Mylonites are scarce and protomylonites, derived at the expense of orthogneiss (former leucogranite) are often directly overthrust onto the sedimentary cover. It is the less deformed sample of the data set. None of the 15 *in situ* analyses provide Alpine age (Table 3, Fig. 10). Instead, apparent ages are distributed between  $389 \pm 27$  Ma and  $156 \pm 3$  Ma with no clear textural control. Part of the apparent ages is correlated with the  $^{38}\text{Ar}/^{39}\text{Ar}$  ratio, which suggests a possible contribution of Cl-rich phases or fluid inclusions. High  $^{37}\text{Ar}/^{39}\text{Ar}$  ratios (Table 3) are probably due to the degassing of Variscan epidote or titanite, but again no systematic correlation between the variation of these ratios and the age dispersion was observed.

## 7. Discussion

### 7.1 Reliability, significance of the RSCM *T*<sub>max</sub> mapping

RSCM *T*<sub>max</sub> estimates has proven an efficient mean to put extensive temperature constraints on the thermal structure of coherent units or on the importance of tectonic contacts (Beyssac et al., 2002; Augier et al., 2005; Negro et al., 2006; Gabalda et al., 2009; Angiboust et al., 2011). In the Oisans Massif, RSCM *T*<sub>max</sub> fall in the same temperature range as more punctual results issued from other methods available in literature. The most important result is the uniformity of *T*<sub>max</sub> values at the scale of study area, with an average value of ca. 330°C with a relative error that may not exceed 10-15°C (Beyssac et al., 2004). Thermopaleomagnetic studies indicate that cooling started from 335°C in the north of the Emparis formations and in the Bourg d'Oisans basin, after the main tectonic phase at ca. 25 Ma (Ménard and Rochette, 1992; Crouzet et al., 1999, 2001) (Fig. 11). The stability field of paragenesis observed in the Jurassic cover (quartz-cookeite-margarite-pyrophyllite) that most likely recorded peak-metamorphism conditions in the Emparis basin is restricted from 270 to 340°C and from 1 to 5kbar (Jullien and Goffé, 1993) (Fig. 11). Besides, the overall

684 thermal structure of the Oisans Massif as recorded by the distribution of RSCM  $T_{\max}$  is  
 685 consistent with illite-crystallinity maps (Aprohmanian, 1974; 1988; Barlier et al., 1974) (Fig.  
 686 4).

687 Related to the irreversible character of graphitization, and the insensitivity of the CM  
 688 structure to retrograde reactions (e.g. Beyssac et al., 2002; Lahfid et al., 2010; Aoya et al.,  
 689 2010), RSCM record the highest temperature ever undergone by the rock sample. In  
 690 principle, RSCM  $T_{\max}$  results issued from a continuous section may therefore be  
 691 diachronous and represent the superimposition of distinct thermal events.

692 In the Bourg d'Oisans and Emparis basins, metamorphic peak-T conditions of ca. 335°C  
 693 where reached at ca. 25 Ma (i.e. Crouzet et al., 1999, 2001). As the restored sedimentary  
 694 cover of this area is generally thinner than ca. 2 km (Barf  ty et al., 1972; Barbier et al.,  
 695 1973; Crouzet et al., 2001; Bellahsen et al., 2012), these temperatures are clearly ascribed to  
 696 an Alpine tectonometamorphic event and particularly to the tectonic burial of the  
 697 Dauphinois domain under internal units (Crouzet et al. 2001; Dumont et al., 2008). Besides,  
 698 the progressive temperature decrease toward the top of the overthrusting units close to the  
 699 Galibier pass is consistent with a late to post-tectonic temperature imprint, as suggested by  
 700 thermopaleomagnetic results (Crouzet et al., 1999, 2000). Interestingly, the upward RSCM  
 701  $T_{\max}$  evolution indicates a ca. 20-30°C.km<sup>-1</sup> gradient (Fig. 4C), which is consistent with the  
 702 gradient around 20 to 25°C.km<sup>-1</sup> proposed by Crouzet et al. (1999) but lower than the ca. 40-  
 703 50°C.km<sup>-1</sup> gradient deduced from fluid inclusion data (Gratier et al., 1973; Nziengui, 1993)  
 704 (Fig. 12). However, high geothermal gradients deduced from fluid inclusions may result  
 705 from an underestimated pressure due to reequilibration of fluid inclusion densities during an  
 706 isothermal decompression as proposed by Boullier (1999) or Crouzet et al. (2001).

707 Conversely, in the sedimentary cover west of the Belledonne Massif,  $T_{\max}$  values show  
 708 large temperature variations from 335°C to less than 200°C (Fig. 4, 5). Tilted with the  
 709 bedding, this ca. 130°C  $T_{\max}$  upward sequence decrease may witness a post-metamorphic  
 710 peak westward tilting of the sedimentary succession (Fig. 4, 5). Moreover,  $T_{\max}$  recorded at  
 711 the base of the succession is consistent with the ca. 8 km thickness of the Mesozoic series  
 712 assuming a ca. 40°C.km<sup>-1</sup> geothermal gradient (Philippe et al., 1998). Besides, this result is  
 713 consistent with the 60 to 80 mW.m<sup>-2</sup> basal heat flow estimated in this area (Deville and  
 714 Sassi, 2006) and a bulk thermal conductivity close to 1.5 W.m<sup>-1</sup>.K<sup>-1</sup> (Beardsmore and Cull,  
 715 2001).

716 Minor and local fluid circulations along the basement-cover interface cannot be ruled out  
 717 but an overall thermal imprint related to large-scale fluid circulations is unlikely as available

studies show that the fluid flow operated only at small scale in the studied area (Henry et al., 1996; Kirschner et al., 1999; Boutoux et al., 2014b).

## 7.2 Significance of the $^{40}\text{Ar}/^{39}\text{Ar}$ in situ ages

Geochronological data and particularly  $^{40}\text{Ar}/^{39}\text{Ar}$  data are traditionally interpreted as recording closure of the isotopic system at a specific temperature depending on the isotopic diffusion properties of the mineral (e.g. Dodson, 1973; Cliff et al., 1998; Villa, 1998; Harrison et al., 2009). Accordingly, many studies therefore assume that the closure temperature of the K/Ar system for muscovite argon retention is around 350-450°C depending on cooling-rates, grain-size and other controlling factors such as the geometry of the diffusion domain (e.g. Wijbrans & McDougall, 1986; Hames & Bowring, 1994; Reddy et al., 1996; Villa, 1998). Using recent results of modeling, the closure temperature for muscovite would fall in the range of 400-420°C for a 10-30°C.Ma<sup>-1</sup> cooling-rate and a diffusion radius of 100µm (Harrison et al., 2009). However, closure temperature for phengite is still discussed as it may largely vary as a function of both intrinsic (e.g. grain-size) and extrinsic (cooling-rates, temperature, pressure and deformation or fluid circulations) parameters. Recent studies suggest that phengite is more retentive for argon than muscovite and that phengite ages are interpretable as crystallisation ages to temperature as high as 500-550°C (e.g. Dunlap, 1997; Agard et al., 2002; Müller, 2003; Mulch and Cosca, 2004; Augier et al., 2005; Mulch et al., 2005; Gerber, 2008; Rolland et al., 2008, 2009; Sanchez et al., 2011a). Temperature experienced during the Alpine orogeny by dated samples did not exceeded 330°C ± 30°C since they initially cooled at the end of the Variscan Orogeny. Ages of the fine-grained synkinematic phengites therefore likely represent crystallization ages. Conversely, large, inherited clasts of muscovite may reflect Variscan cooling ages in the absence of additional disturbing factors. Stratigraphic constraints indicate that the flexural basin of the external zones was diachronously filled up from Lutetian to Bartonian (45 to 33Ma) (Du Fornel et al., 2004; Mulder et al., 2010; Salles et al., 2011). Burial of this basin below internal units occurred during Rupelian (34 to 28 Ma; Fry, 1989; Sinclair, 1997; Ford and Lickorish, 2004; Mulder et al., 2010). In Champsaur and Saint-Antonin basins, amphiboles reworked from Oligocene volcanism coeval with deposition yielded ca. 34-31 Ma Priabonian ages by  $^{40}\text{Ar}/^{39}\text{Ar}$  methods (Féraud et al., 1995; Ivaldi et al. 2003), giving a maximum age for the burial of the basins under the

internal nappes. In addition, part of the Oisans Massif formed a 500 m high relief in the Oligocene (Gupta and Allen, 2000) and dated samples, restored in their inferred initial position, were probably less than 2km deep, between ca. 40 and 34 Ma. It therefore appears unlikely that phengites were formed under these P-T conditions and the ca. 34-33 Ma age clearly fixes the upper bound of the possible ages for the deformation of the Oisans Massif. 97 *in situ* experiments yielded ages younger than 34 Ma.

Interestingly, young ages are clearly correlated with the intensity of fine-grained white-micas blastesis particularly important in high-strain zones. It is therefore proposed that ages younger than 34 Ma reflect synkinematic crystallisation ages and thus deformation ages, in a broad sense. In addition, apparent ages show a bimodal distribution with a first age group settled at ca. 33-30 Ma and a second group at ca. 28-25 Ma ages (Fig. 11). These results are consistent with results of a conventional  $^{40}\text{Ar}/^{39}\text{Ar}$  approach performed on wrench shear zones of the same area (Simon-Labric et al., 2009). However, our interpretation differs. Based on age spectra scattered between 32 and 24 Ma, Simon-Labric et al. (2009) proposed the superimposition of two distinctive shearing events (one at ca. 32 and one ca. 24 Ma). In this study, the use of an *in situ* mean over strain gradients allow linking deformation ages and the amount of finite strain experienced by the rocks. Accordingly, proto-mylonite and mylonite samples yielded older, ca. 33-30Ma ages while highly strained samples (phyllonites) yielded younger ca. 28-25 Ma ages, suggesting that the deformation progressively localized along the phyllonite bands thus leaving large rock volumes devoid of further recrystallizations. In any case, intense E-W shortening started with or just after the burial of external zones under the internal nappes around ca. 34-33 Ma and was still active at ca. 25 Ma. Synchronous deformation ages of either top-to-the-W reverse shear zones or wrench shear zones thus confirm the small-scale mutual cross-cutting relationships observed in the field (Bellanger et al., 2014).

102 *in situ* experiments yielded ages mostly clustering between 100 and 40 Ma with ages as old as 380 Ma. Older than ca. 34 Ma and presenting sometimes pre-Alpine or even genuine Variscan ages, these apparent ages clearly do not record alpine collisional deformation. Relying on temperature estimates throughout the studied area, the temperature concept predicts that all white-micas sharing common pre-Alpine textures and inherited muscovite chemical composition should yield the same age corresponding to the time elapsed since initial cooling at the end of the Variscan Orogeny. Yet this is not the case for most analyses. On the contrary, the correlation of *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  ages and finite strain intensity at any scale reveals that ages are texturally-controlled and therefore independent of closure

785 temperature. This deviation to the closure temperature concept could be simply explained in  
 786 terms of presence of  $^{40}\text{Ar}$  excess either due to (1) partial deformation-induced resetting of  
 787 Variscan muscovites (inherited argon), or (2) genuine incorporation of extraneous argon  
 788 related to fluid circulations. Besides, a straightforward yet possible source of geologically  
 789 meaningless ages could be simply explained by mixtures between inherited muscovite and  
 790 synkinematic phengite argon reservoirs during lasering.

791 At first glance, as stated above, an overall correlation with the intensity of the finite strain  
 792 can be drawn between samples. Weakly strained samples (from the Combeynot or the Plan  
 793 du Lac shear zones) yielded rather old, sometime only pre-Alpine ages while phyllonites  
 794 yielded much younger ages that tend to crystallization ages of newly formed crystals. Such  
 795 control by the deformation is also perceptible at the scale of some dated rock samples with  
 796 an overall age decrease toward the core of a shear band from ca. 300 Ma to less than 30 Ma  
 797 in less than 1 centimetre (Fig. 11). It appears therefore tempting to ascribe to deformation  
 798 the ability to facilitate argon diffusion and thus to partially reset (i.e. re-open) inherited  
 799 muscovite isotopic system. Intensity of deformation, whether it occurs by grain-size  
 800 reduction during mylonitization or by presence and distribution of high-diffusivity pathways  
 801 lattice-modifying microstructures would therefore be the main controlling factor explaining  
 802 the age scatter between an inherited cooling ages and the age of a tectonometamorphic event  
 803 (i.e. Scaillet et al., 1990; West and Lux, 1993; Hames & Cheney 1997; Kramar et al. 2001,  
 804 2003; Mulch et al. 2002). As suggested by the linear relationships observed between some  
 805 apparent ages and corresponding  $^{38}\text{Ar}/^{39}\text{Ar}$  ratios arguing for interactions with Cl-rich fluids,  
 806 minor excess argon cannot be simply ruled out. Besides, a limited yet conspicuous input of  
 807 extraneous argon within and in the vicinity of shear bands is clearly detectable for some  
 808 samples (Fig. 10). In this case, results of absolute chronology are markedly inconsistent with  
 809 the relative chronology established independently on the basis of microtextures. For  
 810 example, mylonite sample A-4-66b presents a series of ca. 50-40 Ma old ages occurring  
 811 within the core of the shear band while other analyses show a clear age decrease toward the  
 812 shear band. Excess argon was moreover reported within fluid inclusions from Oisans  
 813 basement quartz veins (Nziengui, 1993). In this study seven K/Ar experiments on white-  
 814 micas from the sedimentary cover yielding initially 48 to 30 Ma ages were corrected to 27-  
 815 23 Ma by removing excess  $^{40}\text{Ar}$  content from fluid inclusions. If excess argon exists, it  
 816 should have a homogeneous composition at the scale of the whole study area, which seems  
 817 particularly unlikely. Excess argon is therefore present but does not explain the first order  
 818 features of the results.

819

820

821

822 **7.3 A new tectonic scenario**

823

824 This study brings primarily T-t-d (Temperature-time-deformation) results that further  
 825 constrain the tectonometamorphic evolution of the external zones of the Western Alps. In  
 826 this section, these results are all integrated into a compilation of published P-T-t-d results  
 827 (Fig. 11 and 12) in order to discuss a new tectonic scenario (see also in Bellahsen et al.,  
 828 2014) (Fig. 13).

829 Among the new results, this study constrains the thermal structure of a large volume of the  
 830 external basement. Results, despite local variations, show a constant  $T_{\text{max}}$  around 330°C.  
 831 This constant temperature along several tens of kilometres suggests that the basement and  
 832 the cover preserved in half-grabens have been first quickly underthrust with rather limited  
 833 internal shortening. Deformation ages from this study and from Simon-Labric et al. (2009)  
 834 are consistent with a burial of the external zones around between 34 and 25 Ma (Fig. 12,  
 835 13). The main shortening seems to have occurred at or around the metamorphic peak (Fig.  
 836 12) as suggested in Boutoux et al. (2014b). The distribution of isotherms obtained with  
 837 thermopaleomagnetic method, which cross-cut the folds, indicates that the main shortening  
 838 had ended before cooling started in the Bourg d'Oisans basin (Crouzet et al., 1999). The  
 839 sampled profile may therefore correspond to an east-dipping isotherm (around 330°C)  
 840 during underthrusting of the Oisans Massif, which would then suggest that the whole area  
 841 behaved as a more or less rigid block below the internal units during part of its burial  
 842 history, before it was ultimately shortened. Similarly, the geothermal gradient observed  
 843 close to the Lautaret and Galibier passes (around 20-30°C.km<sup>-1</sup>) seems to seal the PFT  
 844 activity dated between 32 and 27 Ma (Freeman, 1998). Thus, deformation mainly occurred  
 845 just prior or during metamorphic-peak conditions and seems, in any case, to have ceased  
 846 before the onset of the main cooling event. During this time period, and around the  
 847 metamorphic peak conditions, the external zone crust underwent homogeneous shortening  
 848 until approximately 25 Ma. Shortening was progressively localized into phyllonite bands. At  
 849 25 Ma, the crust was progressively decoupled from the subducting lithosphere and started to  
 850 exhumate. The PFT was then inactivated. These results argue against a progressive westward  
 851 thrust slice development that lead to the exhumation of units after that they have reached



852 diachronously temperatures close to 330°C. However, this would imply that the basement  
 853 top has been heated up uniformly from 50-100°C to 300-350°C uniformly over ca. 70km,  
 854 which in turn suggests a rather slow burial.

855 At the scale of individual shear zones, high-strain samples (phyllonite) are younger  
 856 (28-25Ma) than proto-mylonite and mylonite (33-30Ma). This suggests that deformation  
 857 progressively localized along phyllonite bands. Moreover, ages of deformation (33-25 Ma)  
 858 reveal that the deformation is contemporaneous all along the profile from the PFT to the  
 859 Plan du Lac shear zone, i.e. over more than ca. 30km. This synchronicity of deformation  
 860 shows that shortening in the ECM was distributed in space and time and confirms that the  
 861 crust was relatively weak during shortening as proposed in Bellahsen et al. (2012). This is in  
 862 agreement with the formation of newly formed shear zones rather than normal faults  
 863 reactivation.

864 Later, shortening reached the Vercors fold and thrust belt during Burdigalian to  
 865 Langhian times (Fig. 13). This shortening appears linked to crustal ramps below the  
 866 Belledonne Massif, which suggests that the deformation localized in frontal parts after the  
 867 end of the main shortening phase of the ECM at around 20 Ma (Ménard, 1979; Butler, 1989;  
 868 Philippe et al., 1998). Between 25 and 20 Ma, the Oisans Massif has undergone fast cooling  
 869 at a rate of 33°C.Ma<sup>-1</sup> (Crouzet et al., 2001) and was exhumed at a rate of 0.4 km.Ma<sup>-1</sup> (van  
 870 der Beek et al., 2010). Final cooling, whose age is estimated from fission tracks ages  
 871 (Vernon et al., 2008), occurred after 15 Ma, which corresponds to the age of thrusting within  
 872 the Vercors Massif. During this more external fold and thrust belt shortening, only slight  
 873 deformation occurred in the Oisans Massif (Dumont et al., 2008). The new argon data  
 874 reported here thus complete the scenario of burial and first shortening at ca. 33 Ma,  
 875 progressive localisation of shear zones until 25 Ma, and final exhumation above a crustal  
 876 ramp until after 15-20 Ma.

877 Exhumation of the ECM was also accompanied by extensional reactivation of the PFT since  
 878 the late Oligocene (Tricart et al., 2007) (Fig. 13). Thus, during the late Oligocene and early  
 879 Miocene, the ECM was a crustal unit bordered by a normal fault to the east and a reverse  
 880 fault to the west, transported with low internal deformation, similarly to the models of syn-  
 881 collisional rock exhumation described by Chemenda et al. (1995) (Fig. 14). Moreover,  
 882 numerous veins witnessing for fluids circulation have been documented between 17 to 5Ma  
 883 in the Aar Massif (Mullis et al., 1994; Mullis, 1996; Challandes et al., 2008), in the Mont  
 884 Blanc Massif (Leutwein et al., 1970; Marshall et al., 1998) or in the Belledonne Massif

(Gasquet et al., 2010), indicating that this event was coeval with a fluid-rich process which affected all the orogen.

## 8. Conclusion

Following the description of Alpine shear zones responsible for shortening of the Oisans External Massif of the Western Alps by Bellahsen et al. (2012) and Bellanger et al. (2014), the alpine thermal structure of the massif is established here thanks to the RSCM method and the shear zones were dated. The main outcome is that the interface between the cover and the basement has recorded a maximum temperature of  $\sim 330^{\circ}\text{C}$ , constant across the whole massif and that the shortening was accommodated by top-to-the west shear zones that progressively localized from 34 to 25 Ma, before the ECM were finally exhumed above a crustal ramp after 15-20 Ma, which in turn controlled shortening in the deformed cover further west (Vercors Massif).

## Acknowledgments

This research was funded by the European Research Council (ERC) under the seventh Framework Programme of the European Union (ERC Advanced Grant, grant agreement No 290864, RHEOLITH) and has received funding from the BRGM (contract L10 U 044). We would like to thank M. Sellos and M. Vacelet for constructing discussions and for their help in the field; J.-G. Badin, S. Janiec for thin-section preparation. Y. Rolland and T. Dumont are thanked for constructive comments that greatly improved the quality of a previous manuscript.

## References

- Agard, P., L. Jolivet, and B. Goffe (2001), Tectonometamorphic evolution of the Schistes Lustrés Complex; implications for the exhumation of HP and UHP rocks in the Western Alps, *Bulletin de la Societe Geologique de France*, 172(5), 617–636, doi:10.2113/172.5.617.
- Agard, P., P. Monié, L. Jolivet, and B. Goffé (2002), Exhumation of the Schistes Lustrés complex: in situ laser probe  $^{40}\text{Ar}/^{39}\text{Ar}$  constraints and implications for the Western Alps, *Journal of Metamorphic Geology*, 20(6), 599–618, doi:10.1046/j.1525-1314.2002.00391.x.

- 920 Allen, P. A., and J. R. Allen (2005), Basin analysis: principles and applications, 2nd ed.,  
921 John Wiley & Sons Inc.
- 922 Angiboust, S. (2011). Couplages profonds et comportement de la lithosphère océanique dans  
923 les zones de subduction: approches pétrologiques et thermomécaniques (Doctoral  
924 dissertation, Paris 6).
- 925 Aoya, M., Y. Kouketsu, S. Endo, H. Shimizu, T. Mizukami, D. Nakamura, and S. Wallis  
926 (2010), Extending the applicability of the Raman carbonaceous-material  
927 geothermometer using data from contact metamorphic rocks, *Journal of*  
928 *Metamorphic Geology*, 28(9), 895–914, doi:10.1111/j.1525-1314.2010.00896.x.
- 929 Aprahamian, J. (1974), La cristallinité de l'illite et les minéraux argileux en bordure des  
930 massifs cristallins externes de Belledonne et du Pelvoux (Variations et relations  
931 possibles avec des événements tectoniques et métamorphiques alpins), *Géologie*  
932 *Alpine*, 50, 5–15.
- 933 Aprahamian, J. (1988), Mapping of low to very low-grade metamorphism in the External  
934 Zone of the French Alps by use of illite crystallinity index. *Geodinamica Acta*  
935 (Paris), 2(1), 25–32.
- 936 Augier, R., P. Agard, P. Monié, L. Jolivet, C. Robin, and G. Booth-Rea (2005), Exhumation,  
937 doming and slab retreat in the Betic Cordillera (SE Spain): in situ  $^{40}\text{Ar}/^{39}\text{Ar}$  ages  
938 and P–T–d–t paths for the Nevado-Filabride complex, *Journal of Metamorphic*  
939 *Geology*, 23(5), 357–381, doi:10.1111/j.1525-1314.2005.00581.x.
- 940 Baggio, P., G. Ferrara, and R. Malaroda (1967), Results of some Rb/Sr age determinations  
941 of the rocks of the Mont Blanc tunnel, *Boll. Soc. Geol. Ital.*, 86, 193–212.
- 942 Barbier, R. (1963), La tectonique de la zone ultradauphinoise au NE du Pelvoux, *Géologie*  
943 *Alpine*, 39, 239–246.
- 944 Barbier, R., J.-C. Barféty, P. Bocquet, P. Le Fort, J. Meloux, R. Mouterde, A. Pêcher, and M.  
945 Petiteville (1973), Geological map and explanatory text of the sheet n°798 “la  
946 Grave”, scale: 1:50000, ed. BRGM.
- 947 Barféty, J.-C., P. Bordet, F. Carne, J. Debelmas, M. Meloux, G. Montjuvent, R. Mouterde,  
948 and J. Sarrot-Reynauld (1972), Geological map and explanatory text of the sheet  
949 n°797 “Vizille”, scale: 1:50000, ed. BRGM.
- 950 Barféty, J. C., and A. Pêcher (1984), Geological map and explanatory text of the sheet n°822  
951 “St Christophe en Oisans,” *Carte géologique de la France au 1/50 000*, BRGM,  
952 Orléans, France.
- 953 Barféty, J. C., J. Blaise, J.-C. Fourneaux, and J. Meloux (1984), Geological map and  
954 explanatory text of the sheet n°750 “La Rochette,” *Carte géologique de la France au*  
955 *1/50 000*, BRGM, Orléans, France.
- 956 Barféty, J. C., G. Montjuvent, A. Pêcher, and F. Carne (1988), Geological map and  
957 explanatory text of the sheet n°821 “La Mure,” *Carte géologique de la France au*  
958 *1/50 000*, BRGM, Orléans, France.

- 959 Barféty, J.-C., and M. Gidon (1983), La stratigraphie et la structure de la couverture  
960 dauphinoise au Sud de Bourg d'Oisans. Leurs relations avec les déformations  
961 synsédimentaires jurassiques, *Géologie Alpine*, 59, 5–32.
- 962 Barlier, J., J.-P. Ragot, and J.-C. Touray (1974), L'évolution des Terres noires subalpine  
963 méridionales d'après l'analyse minéralogique des argiles et la réflectométrie des  
964 particules carbonées., *Bulletin du BRGM*, 2(6), 533–548.
- 965 Bartoli, F., A. Pêcher, and P. Vialon (1974), Le chevauchement Meije-Muzelle et la  
966 répartition des domaines structuraux alpins du massif de l'Oisans (partie Nord du  
967 Haut-Dauphiné cristallin), *Géologie Alpine*, 50, 17–26.
- 968 Beach, A. (1981a), Some observations on the development of thrust faults in the  
969 Ultradauphinois Zone, French Alps, *Geological Society, London, Special  
970 Publications*, 9, 329–334, doi:10.1144/GSL.SP.1981.009.01.29.
- 971 Beach, A. (1981b), Thrust tectonics and cover-basement relations on the northern margin of  
972 the Pelvoux massif, French Alps, *Eclogae Geologicae Helvetiae*, 74(2), 471–479.
- 973 Beach, A. (1982), Strain analysis in a cover thrust zone, external French Alps,  
974 *Tectonophysics*, 88(3–4), 333–346, doi:10.1016/0040-1951(82)90245-1.
- 975 Beardsmore, G. R., & Cull, J. P. (2001). *Crustal heat flow: a guide to measurement and  
976 modelling*. Cambridge University Press.
- 977 Van der Beek, P. A., P. G. Valla, F. Herman, J. Braun, C. Persano, K. J. Dobson, and E.  
978 Labrin (2010), Inversion of thermochronological age-elevation profiles to extract  
979 independent estimates of denudation and relief history - II: Application to the French  
980 Western Alps, *Earth and Planetary Science Letters*, 296, 9–22.
- 981 Bellahsen, N., L. Jolivet, O. Lacombe, M. Bellanger, A. Boutoux, S. Garcia, F. Mouthereau,  
982 L. Le Pourhiet, and C. Gumiaux (2012), Mechanisms of margin inversion in the  
983 external Western Alps: Implications for crustal rheology, *Tectonophysics*, 560–  
984 561(0), 62–83, doi:10.1016/j.tecto.2012.06.022.
- 985 Bellahsen, N., F. Mouthereau, A. Boutoux, M. Bellanger, O. Lacombe, L. Jolivet, and Y.  
986 Rolland (2014), Collision kinematics in the western external  
987 Alps, *Tectonics*, 33, 1055–1088, doi:10.1002/2013TC003453.
- 988 Bellanger, M. (2013). *Raccourcissement alpin du massif des Ecrins: cinématique, calendrier  
989 tectonique et conditions pression-température* (Doctoral dissertation, Orléans).
- 990 Bellanger, M., N. Bellahsen, L. Jolivet, T. Baudin, R. Augier, and A.  
991 Boutoux (2014), Basement shear zones development and shortening kinematics in  
992 the Ecrins Massif, Western Alps, *Tectonics*, 33, 84–111,  
993 doi:10.1002/2013TC003294.
- 994 Berger, A., and R. Bousquet (2008), Subduction-related metamorphism in the Alps: review  
995 of isotopic ages based on petrology and their geodynamic consequences, *Geological  
996 Society, London, Special Publications*, 298(1), 117–144, doi:10.1144/SP298.7.

- 997 Bernard, D. (1978), Microthermometrie des inclusions fluides de cristaux syn-cinematiques.  
 998 Application à la couverture sedimentaire du Nord Pelvoux., Univ. Grenoble, France.
- 999 Beucher, R. (2009), Évolution Néogène de l'Arc Alpin sud-occidental. Approches  
 1000 sismotectonique et thermochronologique, Univ. Joseph Fourier, Grenoble, France.
- 1001 Beucher, R., P. van der Beek, J. Braun, and G. E. Batt (2012), Exhumation and relief  
 1002 development in the Pelvoux and Dora-Maira massifs (western Alps) assessed by  
 1003 spectral analysis and inversion of thermochronological age transects, *J. Geophys.*  
 1004 *Res.*, 117(F3), n/a–n/a, doi:10.1029/2011JF002240.
- 1005 Beyssac, O., B. Goffé, C. Chopin, and J. N. Rouzaud (2002), Raman spectra of  
 1006 carbonaceous material in metasediments: a new geothermometer, *Journal of*  
 1007 *Metamorphic Geology*, 20(9), 859–871, doi:10.1046/j.1525-1314.2002.00408.x.
- 1008 Beyssac, O., Bollinger, L., Avouac, J. P., & Goffé, B. (2004). Thermal metamorphism in the  
 1009 lesser Himalaya of Nepal determined from Raman spectroscopy of carbonaceous  
 1010 material. *Earth and Planetary Science Letters*, 225(1), 233–241.
- 1011 Beyssac, O., Simoes, M., Avouac, J. P., Farley, K. A., Chen, Y. G., Chan, Y. C., & Goffé,  
 1012 B. (2007). Late Cenozoic metamorphic evolution and exhumation of  
 1013 Taiwan. *Tectonics*, 26(6).
- 1014 Bigot-Cormier, F., G. Poupeau, and M. Sosson (2000), Dénudations différentielles du massif  
 1015 cristallin externe alpin de l'Argentera (Sud-Est de la France) révélées par  
 1016 thermochronologie traces de fission (apatites, zircons), *Comptes Rendus de*  
 1017 *l'Académie des Sciences - Series IIA - Earth and Planetary Science*, 330(5), 363–  
 1018 370, doi:10.1016/S1251-8050(00)00127-0.
- 1019 Bogdanoff, S., A. Michard, M. Mansour, and G. Poupeau (2000), Apatite fission track  
 1020 analysis in the Argentera massif: evidence of contrasting denudation rates in the  
 1021 External Crystalline Massifs of the Western Alps, *Terra Nova*, 12(3), 117–125,  
 1022 doi:10.1046/j.1365-3121.2000.123281.x.
- 1023 Bouillin, J.P., Pecher, A., Rolland, Y., Carrio, E., Dumont, T. and Tricart, P., (1997). Les  
 1024 filons sédimentaires jurassiques du Pelvoux, enregistreurs des déformations alpines  
 1025 de la bordure orientale du massif cristallin externe de l'Oisans (Alpes occidentales).  
 1026 *C. R. Acad. Sci.Paris*, 324, 409–415.
- 1027 Boullier, A.-M. (1999), Fluid inclusions: tectonic indicators, *Journal of Structural Geology*,  
 1028 21(8–9), 1229–1235, doi:10.1016/S0191-8141(99)00039-5.
- 1029 Boutoux, A., Bellahsen, N., Lacombe, O., Verlaquet, A., & Mouthereau, F. (2014a).  
 1030 Inversion of pre-orogenic extensional basins in the external Western Alps: Structure,  
 1031 microstructures and restoration. *Journal of Structural Geology*, 60, 13–29.
- 1032 Boutoux, A., Verlaquet, A., Bellahsen, N., Lacombe, O., Villemant, B., Caron, B., ... &  
 1033 Cartigny, P. (2014b). Fluid systems above basement shear zones during inversion of  
 1034 pre-orogenic sedimentary basins (External Crystalline Massifs, Western  
 1035 Alps). *Lithos*, accepted. DOI: 10.1016/j.lithos.2014.07.005

- 1036 Bravard, C., and M. Gidon (1979), La structure du revers oriental du Massif du Pelvoux:  
1037 Observations et interprétations nouvelles, *Géologie Alpine*, 55, 23–33. Burgisser, J.,  
1038 and M. Ford (1998), Overthrust shear deformation of a foreland basin; structural  
1039 studies southeast of the Pelvoux massif, SE France, *Journal of Structural Geology*,  
1040 20(11), 1455–1475.
- 1041 Brereton, N. R. (1970). Corrections for interfering isotopes in the  $^{40}\text{Ar}/^{39}\text{Ar}$  dating  
1042 method. *Earth and Planetary Science Letters*, 8(6), 427–433.
- 1043 Butler, R. W. H. (1989), The influence of pre-existing basin structure on thrust system  
1044 evolution in the Western Alps, Geological Society, London, Special Publications,  
1045 44(1), 105–122, doi:10.1144/GSL.SP.1989.044.01.07.
- 1046 Caby, R. (1973), Les plis transversaux dans les Alpes occidentales: implications pour la  
1047 genèse de la chaîne alpine, *Bulletin de la Société géologique de France*, (5-6), 624–  
1048 634.
- 1049 Cathelineau, M. (1988), Cation Site Occupancy in Chlorites and Illites as a Function of  
1050 Temperature, *Clay Minerals*, 23(4), 471–485, doi:10.1180/claymin.1988.023.4.13.
- 1051 Cathelineau, M., and D. Nieva (1985), A chlorite solid solution geothermometer the Los  
1052 Azufres (Mexico) geothermal system, *Contr. Mineral. and Petrol.*, 91(3), 235–244,  
1053 doi:10.1007/BF00413350.
- 1054 Cenki-Tok, B., J. R. Darling, Y. Rolland, B. Dhuime, and C. D. Storey (2013), Direct dating  
1055 of mid-crustal shear zones with synkinematic allanite: new in situ U-Th-Pb  
1056 geochronological approaches applied to the Mont Blanc massif, *Terra Nova*, n/a–n/a,  
1057 doi:10.1111/ter.12066.
- 1058 Ceriani, S., and S. M. Schmid (2004), From n-s collision to WNW-directed post-collisional  
1059 thrusting and folding: Structural study of the Frontal Penninic Units in Savoie  
1060 (Western Alps, France), *Eclogae Geologicae Helvetiae*, 97(3), 347–369.
- 1061 Ceriani, S., B. Fugenschuh, and S. M. Schmid (2001), Multi-stage thrusting at the “Penninic  
1062 Front” in the Western Alps between Mont Blanc and Pelvoux massifs, *International  
1063 Journal of Earth Sciences*, 90(3), 685–702.
- 1064 Ceriani, S., B. Fugenschuh, S. Potel, and S. Schmid (2003), Tectono-metamorphic evolution  
1065 of the Frontal Penninic units of the Western Alps: correlation between low-grade  
1066 metamorphism and tectonic phases, *Swiss Bulletin of Mineralogy and  
1067 Petrology*, 83(2), 111–131.
- 1068 Challandes, N., D. Marquer, and M. Villa (2008), P-T-t modelling, fluid circulation, and  
1069  $^{39}\text{Ar}$ - $^{40}\text{Ar}$  and Rb-Sr mica ages in the Aar Massif shear zones (Swiss Alps), *Swiss  
1070 Journal of Geosciences*, 101(2), 269–288, doi:10.1007/s00015-008-1260-6.
- 1071 Chemenda, A. I., M. Mattauer, J. Malavieille, and A. N. Bokun (1995), A mechanism for  
1072 syn-collisional rock exhumation and associated normal faulting: Results from  
1073 physical modelling, *Earth and Planetary Science Letters*, 132(1–4), 225–232,  
1074 doi:10.1016/0012-821X(95)00042-B.

- 1075 Chopin, C. (1984), Coesite and pure pyrope in high-grade blueschists of the Western Alps: a  
1076 first record and some consequences, *Contr. Mineral. and Petrol.*, 86(2), 107–118,  
1077 doi:10.1007/BF00381838.
- 1078 Chopin, C., and H. Maluski (1980), 40Ar-39Ar dating of high pressure metamorphic micas  
1079 from the Gran Paradiso area (Western Alps): Evidence against the blocking  
1080 temperature concept, *Contr. Mineral. and Petrol.*, 74(2), 109–122,  
1081 doi:10.1007/BF01131997.
- 1082 Clauzon, G. (1990), *Genèse et évolution du piémont néogène subalpin du Bas-Dauphiné.*  
1083 *Livret guide de l'excursion préforum du 3ème forum national de géomorphologie,*  
1084 *Aix en Provence, Unité de recherche associé (URA) n°903 - C.N.R.S.*
- 1085 Cliff, R. A., A. C. Barnicoat, and S. Inger (1998), Early Tertiary eclogite facies  
1086 metamorphism in the Monviso Ophiolite, *Journal of Metamorphic Geology*, 16(3),  
1087 447–455, doi:10.1111/j.1525-1314.1998.00147.x.
- 1088 Corna, M., J.-L. Dommergues, C. Meister & K. Page (1997) - Les faunes d'ammonites du  
1089 Jurassique inférieur (Hettangien, Sinémurien et Pliensbachien) au nord du massif des  
1090 Écrins (Oisans, Alpes occidentales). *Revue de Paléobiologie*, 16 : 321-409.
- 1091 Corsini, M., G. Ruffet, and R. Caby (2004), Alpine and late-hercynian geochronological  
1092 constraints in the Argentera Massif (Western Alps), *Eclogae geol. Helv.*, 97(1), 3–  
1093 15, doi:10.1007/s00015-004-1107-8.
- 1094 Crespo-Blanc, A., H. Masson, Z. Sharp, M. Cosca, and J. Hunziker (1995), A stable and  
1095 40Ar/39Ar isotope study of a major thrust in the Helvetic nappes (Swiss Alps):  
1096 Evidence for fluid flow and constraints on nappe kinematics, *Geological Society of*  
1097 *America Bulletin*, 107(10), 1129–1144, doi:10.1130/0016-  
1098 7606(1995)107<1129:ASAAAI>2.3.CO;2.
- 1099 Crouzet, C., G. Menard, and P. Rochette (1999), High-precision three-dimensional  
1100 paleothermometry derived from paleomagnetic data in an Alpine metamorphic unit,  
1101 *Geology*, 27(6), 503–506.
- 1102 Crouzet, C., P. Rochette, and G. Menard (2001), Experimental evaluation of thermal  
1103 recording of successive polarities during uplift of metasediments, *Geophysical*  
1104 *Journal International*, 145(3), 771–785.
- 1105 Debon, F., and M. Lemmet (1999), Evolution of Mg/Fe Ratios in Late Variscan Plutonic  
1106 Rocks from the External Crystalline Massifs of the Alps (France, Italy, Switzerland),  
1107 *Journal of Petrology*, 40(7), 1151–1185.
- 1108 Depardon, J. P. (1979), *Les déformations de la couverture mésozoïque au Nord de l'Oisans,*  
1109 *Université Claude Bernard - Lyon I.*
- 1110 Deville, E., and W. Sassi (2006), Contrasting thermal evolution of thrust systems: An  
1111 analytical and modeling approach in the front of the western Alps, *AAPG*  
1112 *bulletin*, 90(6), 887–907.
- 1113 Dodson, M. H. (1973). Closure temperature in cooling geochronological and petrological  
1114 systems. *Contributions to Mineralogy and Petrology*, 40(3), 259-274.

- 1115 Duchêne, S., J. Blichert-Toft, B. Luais, P. Telouk, J.-M. Lardeaux, and F. Albarede (1997),  
 1116 The Lu-Hf dating of garnets and the ages of the Alpine high-pressure metamorphism,  
 1117 *Nature*, 387(6633), 586–589, doi:10.1038/42446.
- 1118 Dumont, T. (1988). Late Triassic-early Jurassic evolution of the western Alps and of their  
 1119 European foreland; initiation of the Tethyan rifting. *Bulletin de la Société géologique*  
 1120 *de France*, 4(4), 601–611.
- 1121 Dumont T., 1998, Sea-level changes and early rifting of a European Tethyan margin in the  
 1122 Western Alps and SE France. In : *Mesozoic and Cenozoic sequence stratigraphy of*  
 1123 *European basins*, de Graciansky P.C., Hardenbol J., Jacquin T. & Vail P., Eds. , Soc.  
 1124 *Econ. Petr. Geol Spec. Publ.* 60, p. 623–639
- 1125 Dumont, T., J. D. Champagnac, C. Crouzet, and P. Rochat (2008), Multistage shortening in  
 1126 the Dauphine zone (French Alps): the record of Alpine collision and implications for  
 1127 pre-Alpine restoration, *Swiss Journal of Geosciences*, 101(1), S89–S110.
- 1128 Dumont, T., T. Simon-Labric, C. Authemayou, and T. Heymes (2011), Lateral termination  
 1129 of the north-directed Alpine orogeny and onset of westward escape in the Western  
 1130 Alpine arc: Structural and sedimentary evidence from the external zone, *Tectonics*,  
 1131 30(5), TC5006.
- 1132 Dumont, T., S. Schwartz, S. Guillot, T. Simon-Labric, P. Tricart, and S. Jourdan (2012),  
 1133 Structural and sedimentary records of the Oligocene revolution in the Western  
 1134 Alpine arc, *Journal of Geodynamics*, 56, 18–38.
- 1135 Dunlap, W. J. (1997), Neocrystallization or cooling?  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of white micas from  
 1136 low-grade mylonites, *Chemical Geology*, 143(3–4), 181–203, doi:10.1016/S0009-  
 1137 2541(97)00113-7.
- 1138 Ellenberger, F. (1958), *Etude géologique du pays de Vanoise (Savoie)*, Mémoire servant à la  
 1139 carte géologique de la France, BRGM.
- 1140 Faure, G. (1986), *Principles of Isotope Geology*, John Wiley & Sons.
- 1141 Féraud, G., G. Ruffet, J. Stéphan, H. Lapierre, E. Delgado, and M. Popoff (1995), Nouvelles  
 1142 données géochronologiques sur le volcanisme paléogène des Alpes occidentales:  
 1143 existence d'un événement magmatique bref généralisé, in *Séance Spéciale de la*  
 1144 *Société géologique de France et de l'Association des Géologues du SE*  
 1145 *Magmatismes dans le sud-est de la France*", Nice, pp. 25–26.
- 1146 Ford, M. (1996), Kinematics and geometry of early Alpine, basement-involved folds, SW  
 1147 Pelvoux massif, SE France, *Eclogae Geologicae Helvetiae*, 89(1), 269–295.
- 1148 Ford, M., and W. H. Lickorish (2004), Foreland basin evolution around the western Alpine  
 1149 Arc, edited by P. J. Lomas and S. A. Lomas, pp. 39–63, *Geological Soc Publishing*  
 1150 *House, Bath.* (online) Available from: <Go to ISI>://000223880200004



- 1151 Du Fornel, E., P. Joseph, G. Desaubliaux, R. Eschard, F. Guillocheau, O. Lerat, C. Muller,  
1152 C. Ravenne, and K. Sztràkos (2004), The southern Grès d'Annot outcrops (French  
1153 Alps): an attempt at regional correlation, Geological Society, London, Special  
1154 Publications, 221(1), 137–160, doi:10.1144/GSL.SP.2004.221.01.08.
- 1155 Le Fort, P. (1973) - Geologie du Haut-Dauphiné cristallin (Alpes Française). Etude  
1156 pétrologique et structurale de la partie occidentale. - Sci. de la terre, Nancy. Mem.  
1157 25, 373 p.
- 1158 Freeman, S. R., S. Inger, R. W. H. Butler, and R. A. Cliff (1997), Dating deformation using  
1159 Rb-Sr in white mica: Greenschist facies deformation ages from the Entrelor shear  
1160 zone, Italian Alps, Tectonics, 16(1), 57–76, doi:10.1029/96TC02477.
- 1161 Freeman, S. R., R. W. H. Butler, R. A. Cliff, S. Inger, and A. C. Barnicoat (1998),  
1162 Deformation migration in an orogen-scale shear zone array: an example from the  
1163 Basal Briançonnais Thrust, internal Franco-Italian Alps, Geological  
1164 Magazine, 135(3), 349–367.
- 1165 Fry, N. (1989), Southwestward thrusting and tectonics of the western Alps, Geological  
1166 Society, London, Special Publications, 45(1), 83–109.
- 1167 Fügenschuh, B., and S. M. Schmid (2003), Late stages of deformation and exhumation of an  
1168 orogen constrained by fission-track data: A case study in the Western Alps,  
1169 Geological Society of America Bulletin, 115(11), 1425–1440,  
1170 doi:10.1130/B25092.1.
- 1171 Gabalda, S., O. Beyssac, L. Jolivet, P. Agard, and C. Chopin (2009), Thermal structure of a  
1172 fossil subduction wedge in the Western Alps, Terra Nova, 21(1), 28–34,  
1173 doi:10.1111/j.1365-3121.2008.00849.x.
- 1174 Ganne, J. (2003), Les dômes de socle HP-BT dans le domaine Pennique des Alpes Nord-  
1175 Occidentales: modalité de leur exhumation., Univ. de Savoie, France.
- 1176 Gasquet, D., J.-M. Bertrand, J.-L. Paquette, J. Lehmann, G. Ratzov, R. D. A. Guedes, M.  
1177 Tiepolo, A.-M. Boullier, S. Scaillet, and S. Nomade (2010), Miocene to Messinian  
1178 deformation and hydrothermal activity in a pre-Alpine basement massif of the  
1179 French western Alps: new U-Th-Pb and argon ages from the Lauziere massif,  
1180 Bulletin de la Société Géologique de France, 181(3), 227–241.
- 1181 Gebauer, D., H.-P. Schertl, M. Brix, and W. Schreyer (1997), 35 Ma old ultrahigh-pressure  
1182 metamorphism and evidence for very rapid exhumation in the Dora Maira Massif,  
1183 Western Alps, Lithos, 41(1–3), 5–24, doi:10.1016/S0024-4937(97)82002-6.
- 1184 Gerber, W. (2008), Evolution tectono-métamorphique du Briançonnais interne (Alpes  
1185 Occidentales, massifs de Vanoise Sud et d'Ambin): comportement du socle et de sa  
1186 couverture dans un contexte de subduction continentale profonde, Univ. Pierre et  
1187 Marie Curie, France.
- 1188 Gidon, M., and J.-L. Pairis (1980), Nouvelles données sur la structure des écaïlles de Soleil  
1189 Boeuf (bordure sud du massif du Pelvoux), Bull. Bur. Rech. Geol. Min, 1, 35–41.

- 1190 Gratier, J. P., and P. Vialon (1980), Deformation pattern in a heterogeneous material -  
 1191 folded and cleaved sedimentary cover immediately overlying a crystalline basement  
 1192 (Oisans, French Alps), *Tectonophysics*, 65(1), 151–180.
- 1193 Gratier, J.-P., B. Lejeune, and V. Jean-Louis (1973), Etude des déformations de la  
 1194 couverture et des bordures sédimentaires des massifs cristallins externes de  
 1195 Belledonne, des Grandes Rousses et du Pelvoux (depuis des Aravis jusqu'à le région  
 1196 de Remollon), Université de Grenoble.
- 1197 Gueydan, F., Leroy, Y. M., Jolivet, L., & Agard, P. (2003). Analysis of continental  
 1198 midcrustal strain localization induced by microfracturing and  
 1199 reaction-softening. *Journal of Geophysical Research: Solid Earth* (1978–2012),  
 1200 108(B2).
- 1201 Guillot, S., and R. Menot (1999), Nappe stacking and first evidence of Late Variscan  
 1202 extension in the Belledonne Massif (External Crystalline Massifs, French Alps),  
 1203 *Geodinamica Acta*, 12(2), 97–111.
- 1204 Guillot, S., S. di Paola, R.-P. Ménot, P. Ledru, M. I. Spalla, G. Gosso, and S. Schwartz  
 1205 (2009), Suture zones and importance of strike-slip faulting for Variscan geodynamic  
 1206 reconstructions of the External Crystalline Massifs of the western Alps, *Bulletin de*  
 1207 *la Societe Geologique de France*, 180(6), 483–500, doi:10.2113/gssgfbull.180.6.483.
- 1208 Gupta, S., and P. A. Allen (2000), Implications of foreland paleotopography for stratigraphic  
 1209 development in the Eocene distal Alpine foreland basin, *Geological Society of*  
 1210 *America Bulletin*, 112(4), 515–530.
- 1211 Hames, W. E., & Bowring, S. A. (1994). An empirical evaluation of the argon diffusion  
 1212 geometry in muscovite. *Earth and Planetary Science Letters*, 124(1), 161–169.
- 1213 Hames, W. E., & Cheney, J. T. (1997). On the loss of  $^{40}\text{Ar}^*$  from muscovite during  
 1214 polymetamorphism. *Geochimica et Cosmochimica Acta*, 61(18), 3863–3872.
- 1215 Harrison, T. M., J. Célrier, A. B. Aikman, J. Hermann, and M. T. Heizler (2009), Diffusion  
 1216 of  $^{40}\text{Ar}$  in muscovite, *Geochimica et Cosmochimica Acta*, 73(4), 1039–1051,  
 1217 doi:10.1016/j.gca.2008.09.038.
- 1218 Henry, C., Burkhard, M., & Goffe, B. (1996). Evolution of synmetamorphic veins and their  
 1219 wallrocks through a Western Alps transect: no evidence for large-scale fluid flow.  
 1220 Stable isotope, major-and trace-element systematics. *Chemical Geology*, 127(1), 81–  
 1221 109.
- 1222 Hurford, A. J., and J. C. Hunziker (1989), A revised thermal history for the Gran Paradiso  
 1223 massif, *Schweiz. Mineral. Petro. Mitt.*, 69(3), 319–329.

- 1224 Hurford, A. J., J. C. Hunziker, and B. Stöckhert (1991), Constraints on the late  
1225 thermotectonic evolution of the western Alps: Evidence for episodic rapid uplift,  
1226 *Tectonics*, 10(4), 758–769, doi:10.1029/91TC00167.
- 1227 Ivaldi, J. P., Bellon, H., Guardia, P., Mangan, C., Müller, C., Perez, J. L., & Terramorsi, S.  
1228 (2003). Contexte lithostructural, âges  $^{40}\text{K}/^{40}\text{Ar}$  et géochimie du volcanisme calco-  
1229 alcalin tertiaire de Cap-d'Ail dans le tunnel ferroviaire de Monaco. *Comptes Rendus*  
1230 *Geoscience*, 335(4), 411–421.
- 1231 Jourdan, F., and P. R. Renne (2007), Age calibration of the Fish Canyon sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$   
1232 dating standard using primary K–Ar standards, *Geochimica et Cosmochimica Acta*,  
1233 71(2), 387–402, doi:10.1016/j.gca.2006.09.002.
- 1234 Jullien, M., and B. Goffé (1993), Cookeite and pyrophyllite in the Dauphinois black shales  
1235 (Isères, France): implications for the conditions of metamorphism in the Alpine  
1236 external zones, *Schweiz. Mineral. Petro. Mitt.*, 73, 357–363.
- 1237 Kerckhove, C. (1969), La « zone du Flysch » dans les nappes de l'Embrunais-Ubaye (Alpes  
1238 occidentales), *Géologie Alpine*, 45, 5–204.
- 1239 Kirschner, D. L., M. A. Cosca, H. Masson, and J. C. Hunziker (1996), Staircase  $^{40}\text{Ar}/^{39}\text{Ar}$   
1240 spectra of fine-grained white mica: Timing and duration of deformation and  
1241 empirical constraints on argon diffusion, *Geology*, 24(8), 747–750,  
1242 doi:10.1130/0091-7613(1996)024<0747:SAASOF>2.3.CO;2.
- 1243 Kirschner, D. L., Masson, H., & Sharp, Z. D. (1999). Fluid migration through thrust faults in  
1244 the Helvetic nappes (Western Swiss Alps). *Contributions to Mineralogy and*  
1245 *Petrology*, 136(1–2), 169–183.
- 1246 Koppers, A. A. P. (2002), ArArCALC—software for  $^{40}\text{Ar}/^{39}\text{Ar}$  age calculations,  
1247 *Computers & Geosciences*, 28(5), 605–619, doi:10.1016/S0098-3004(01)00095-4.
- 1248 Kramar, N., M. A. Cosca, and J. C. Hunziker (2001), Heterogeneous  $^{40}\text{Ar}^*$  distributions in  
1249 naturally deformed muscovite: in situ UV-laser ablation evidence for  
1250 microstructurally controlled intragrain diffusion, *Earth and Planetary Science*  
1251 *Letters*, 192(3), 377–388, doi:10.1016/S0012-821X(01)00456-3.
- 1252 Krummenacher, D., and J. F. Evernden (1960), Déterminations d'âge isotopique faites sur  
1253 quelques roches des Alpes par la méthode Potassium-Argon, *Schweiz. Mineral. Petro.*  
1254 *Mitt.*, 40, 267–277.
- 1255 Lahfid, A., O. Beyssac, E. Deville, F. Negro, C. Chopin, and B. Goffé (2010), Evolution of  
1256 the Raman spectrum of carbonaceous material in low-grade metasediments of the  
1257 Glarus Alps (Switzerland), *Terra Nova*, 22(5), 354–360, doi:10.1111/j.1365-  
1258 3121.2010.00956.x.
- 1259 Lanari, P., S. Guillot, S. Schwartz, O. Vidal, P. Tricart, N. Riel, and O. Beyssac (2012),  
1260 Diachronous evolution of the alpine continental subduction wedge: Evidence from  
1261 P–T estimates in the Briançonnais Zone houillère (France – Western Alps), *Journal*  
1262 *of Geodynamics*, 56–57(0), 39–54, doi:10.1016/j.jog.2011.09.006.

- 1263 Laurent, J.-C. (1992), Les épisodes magmatiques filoniens basiques du Massif des Pelvoux-  
1264 Pelvoux entre Carbonifère et Lias, Université Joseph Fourier - Grenoble 1.
- 1265 Leloup, P., N. Arnaud, E. Sobel, and R. Lacassin (2005), Alpine thermal and structural  
1266 evolution of the highest external crystalline massif: The Mont Blanc  
1267 Tectonics, 24(4), TC4002.
- 1268 Lemoine, M. (1972), Rythme et Modalités des Plissements Superposés dans les Chaînes  
1269 Subalpines Méridionales des Alpes Occidentales Française, Geologische  
1270 Rundschau, 61(3), 975–1010.
- 1271 Lemoine, M., and P. De Graciansky (1988), Histoire d'une marge continentale passive: les  
1272 Alpes occidentales au Mésozoïque: introduction, Introduction: Bulletin de la Société  
1273 Géologique de France, (8), t. IV(4), 597–600.
- 1274 Lemoine, M., Bas, T., Arnaud-Vanneau, A., Arnaud, H., Dumont, T., Gidon, M., ... &  
1275 Tricart, P. (1986), The continental margin of the Mesozoic Tethys in the Western  
1276 Alps, Marine and Petroleum Geology, 3(3), 179–199.
- 1277 Leutwein, F., B. Poty, J. Sonet, and J. L. Zimmerman (1970), Age des cavités à cristaux du  
1278 granite du Mont Blanc, CR Acad. Sci. Paris.
- 1279 Malusà, M. G., R. Polino, M. Zattin, G. Bigazzi, S. Martin, and F. Piana (2005), Miocene to  
1280 Present differential exhumation in the Western Alps: Insights from fission track  
1281 thermochronology, Tectonics, 24(3), n/a–n/a, doi:10.1029/2004TC001782.
- 1282 Maluski, H., and P. Monié (1988), 40Ar-39Ar laser probe multi-dating inside single biotites  
1283 of a Variscan orthogneiss (Pinet, Massif Central, France), Chemical Geology:  
1284 Isotope Geoscience section, 73(3), 245–263, doi:10.1016/0168-9622(88)90005-X.
- 1285 Marignac, C., M. Cathelineau, D. Bank, M.-C. Boiron, M. Ayt Ougoudal, Y. Argouarc'h,  
1286 and B. Poty (1997), Alpine fault sealing at the contact between a crystalline  
1287 basement and its sedimentary cover: La Gardette (French Alps). European current  
1288 research on fluid inclusions. Biennial symposium No14, Nancy, FRANCE  
1289 (01/07/1997), 194–195.
- 1290 Marshall, D., N. Meisser, and R. P. Taylor (1998), Fluid inclusion, stable isotope and Ar-Ar  
1291 evidence for the age and origin of gold-bearing quartz veins at Mont Chemin,  
1292 Switzerland, Mineralogy and Petrology, 62(3-4), 147–165,  
1293 doi:10.1007/BF01178027.
- 1294 McDougall, I., and T. M. Harrison (1988), Geochronology and Thermochronology by the  
1295 40Ar/39Ar Method, Oxford University Press.
- 1296 Meffan-Main, S., R. A. Cliff, A. C. Barnicoat, B. Lombardo, and R. Compagnoni (2004), A  
1297 Tertiary age for Alpine high-pressure metamorphism in the Gran Paradiso massif,  
1298 Western Alps: a Rb–Sr microsampling study, Journal of Metamorphic Geology,  
1299 22(4), 267–281, doi:10.1111/j.1525-1314.2004.00512.x.
- 1300 Ménard, G. (1979), Relations entre structures profondes et structures superficielles dans le  
1301 Sud-Est de la France. Essai d'utilisation de données Géophysiques, Université de  
1302 Grenoble.

- 1303 Ménard, G., and P. Rochette (1992), Utilisation de reaimantations postmetamorphiques pour  
1304 une etude de l'évolution tectonique et thermique tardive dans les Alpes occidentales  
1305 (France), *Bulletin de la Societe Geologique de France*, 163(4), 381–392.
- 1306 Michard, A., T. Dumont, L. Andreani, and N. Loget (2010), Cretaceous folding in the  
1307 Dévoluy mountains (Subalpine Chains, France): gravity-driven detachment at the  
1308 European paleomargin versus compressional event, *Bulletin de la Societe  
1309 Geologique de France*, 181(6), 565–581.
- 1310 Min, K., R. Mundil, P. R. Renne, and K. R. Ludwig (2000), A test for systematic errors in  
1311  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology through comparison with U/Pb analysis of a 1.1-Ga  
1312 rhyolite, *Geochimica et Cosmochimica Acta*, 64(1), 73–98, doi:10.1016/S0016-  
1313 7037(99)00204-5.
- 1314 Monié, P., and P. Philippot (1989),  $^{39}\text{Ar}$ – $^{40}\text{Ar}$  evidence for mid-Eocene high-pressure  
1315 metamorphism in the Monviso ophiolitic massif, *Comptes Rendus de l'Académie  
1316 des Sciences - Series 2*, 309(2), 245–251.
- 1317 Mulch, A., and M. A. Cosca (2004), Recrystallization or cooling ages: in situ UV-laser  
1318  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology of muscovite in mylonitic rocks, *Journal of the  
1319 Geological Society*, 161(4), 573–582, doi:10.1144/0016-764903-110.
- 1320 Mulch, A., M. Cosca, and M. Handy (2002), In-situ UV-laser  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology of  
1321 a micaceous mylonite : an example of defect-enhanced argon loss, *Contrib Mineral  
1322 Petrol*, 142(6), 738–752, doi:10.1007/s00410-001-0325-6.
- 1323 Mulch, A., M. A. Cosca, A. Andresen, and J. Fiebig (2005), Time scales of deformation and  
1324 exhumation in extensional detachment systems determined by high-spatial resolution  
1325 in situ UV-laser  $^{40}\text{Ar}/^{39}\text{Ar}$  dating, *Earth and Planetary Science Letters*, 233(3–4),  
1326 375–390, doi:10.1016/j.epsl.2005.01.042.
- 1327 Mulder, T., Callec, Y., Parize, O., Joseph, P., Schneider, J. L., Robin, C., ... & Zaragosi, S.  
1328 (2010). High-resolution analysis of submarine lobes deposits: Seismic-scale outcrops  
1329 of the Lauzanier area (SE Alps, France). *Sedimentary Geology*, 229(3), 160-191.,  
1330 doi:10.1016/j.sedgeo.2009.11.005.
- 1331 Müller, W. (2003), Strengthening the link between geochronology, textures and petrology,  
1332 *Earth and Planetary Science Letters*, 206(3–4), 237–251, doi:10.1016/S0012-  
1333 821X(02)01007-5.
- 1334 Mullis, J. (1996), P-T-t path of quartz formation in extensional veins of the Central Alps,  
1335 *Schweiz. Mineral. Petro. Mitt.*, 76, 159–164.
- 1336 Mullis, J., J. Dubessy, B. Poty, and J. O'Neil (1994), Fluid regimes during late stages of a  
1337 continental collision: Physical, chemical, and stable isotope measurements of fluid  
1338 inclusions in fissure quartz from a geotraverse through the Central Alps, Switzerland,  
1339 *Geochimica et Cosmochimica Acta*, 58(10), 2239–2267, doi:10.1016/0016-  
1340 7037(94)90008-6.
- 1341 Negro, F., Beyssac, O., Goffé, B., Saddiqi, O., & Bouybaouene, M. L. (2006). Thermal  
1342 structure of the Alboran Domain in the Rif (northern Morocco) and the Western

- 1343           Betics (southern Spain). Constraints from Raman spectroscopy of carbonaceous  
1344           material. *Journal of Metamorphic Geology*, 24(4), 309–327.
- 1345   Nziengui, J.-J. (1993), Excès d'argon radiogénique dans les quartz des fissures tectoniques :  
1346           implications pour la datation des séries métamorphiques. L'exemple de la coupe de  
1347           la Romanche, Alpes Occidentales françaises, Univ. Joseph Fourier, Grenoble,  
1348           France.
- 1349   Pfiffner, A. (1992), Alpine orogeny, D. Blundell, R. Freeman and St. Miller (Editors), A  
1350           Continent Revealed: The European Geotraverse. Cambridge University Press,  
1351           Cambridge, 180–190.
- 1352   Philippe, Y., E. Deville, and A. Mascle (1998), Thin-skinned inversion tectonics at oblique  
1353           basin margins: example of the western Vercors and Chartreuse Subalpine massifs  
1354           (SE France), *Geological Society, London, Special Publications*, 134(1), 239–262,  
1355           doi:10.1144/GSL.SP.1998.134.01.11.
- 1356   Plunder, A., P. Agard, B. Dubacq, C. Chopin, and M. Bellanger (2012), How continuous and  
1357           precise is the record of P–T paths? Insights from combined thermobarometry and  
1358           thermodynamic modelling into subduction dynamics (Schistes Lustrés, W. Alps),  
1359           *Journal of Metamorphic Geology*, 30(3), 323–346, doi:10.1111/j.1525-  
1360           1314.2011.00969.x.
- 1361   Von Raumer, J., J. Abrecht, F. Bussy, B. Lombardo, R. Ménot, and U. Schaltegger (1999),  
1362           The Palaeozoic metamorphic evolution of the Alpine external massifs, Schweiz.  
1363           mineral. petrogr. Mitt, 79(1), 5–22.
- 1364   Reddy, S. M., Kelley, S. P., & Wheeler, J. (1996). A  $^{40}\text{Ar}/^{39}\text{Ar}$  laser probe study of micas  
1365           from the Sesia Zone, Italian Alps: implications for metamorphic and deformation  
1366           histories. *Journal of Metamorphic Geology*, 14(4), 493–508.
- 1367   Renne, P. R., C. C. Swisher, A. L. Deino, D. B. Karner, T. L. Owens, and D. J. DePaolo  
1368           (1998), Intercalibration of standards, absolute ages and uncertainties in  $^{40}\text{Ar}/^{39}\text{Ar}$   
1369           dating, *Chemical Geology*, 145(1–2), 117–152, doi:10.1016/S0009-2541(97)00159-  
1370           9.
- 1371   Riche, P., and P. Trémolières (1987), Tectonique synsédimentaire sur la bordure orientale du  
1372           bassin tertiaire de Valreas, *Géologie Alpine, Mémoire H.S.*, 13, 409–416.
- 1373   Rolland, Y., M. Rossi, S. F. Cox, M. Corsini, N. Mancktelow, G. Pennacchioni, M. Fornari,  
1374           and A. M. Boullier (2008),  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of synkinematic white mica: insights  
1375           from fluid-rock reaction in low-grade shear zones (Mont Blanc Massif) and  
1376           constraints on timing of deformation in the NW external Alps, *Geological Society,*  
1377           *London, Special Publications*, 299(1), 293–315, doi:10.1144/SP299.18.
- 1378   Rolland, Y., S. F. Cox, and M. Corsini (2009), Constraining deformation stages in brittle-  
1379           ductile shear zones from combined field mapping and Ar-40/Ar-39 dating: The  
1380           structural evolution of the Grimsel Pass area (Aar Massif, Swiss Alps), *Journal of*  
1381           *Structural Geology*, 31, 1377–1394.

- 1382 Rosenbaum, G., and G. S. Lister (2005), The Western Alps from the Jurassic to Oligocene:  
1383 spatio-temporal constraints and evolutionary reconstructions, *Earth-Science*  
1384 *Reviews*, 69(3–4), 281–306, doi:10.1016/j.earscirev.2004.10.001.
- 1385 Roux, M., J.-P. Bourseau, T. Bas, T. Dumont, P.-C. de Graciansky, M. Lemoine, and J.-L.  
1386 Rudkiewicz (1988), Bathymetric evolution of the Tethyan margin in the western  
1387 Alps (data from stalked crinoids): a reappraisal of eustatism problems during the  
1388 Jurassic, *Bulletin de la Société géologique de France*, 4(4), 633–641.
- 1389 Rubatto, D., and J. Hermann (2001), Exhumation as fast as subduction?, *Geology*, 29(1), 3–  
1390 6, doi:10.1130/0091-7613(2001)029<0003:EAFAS>2.0.CO;2.
- 1391 Rubatto, D., and J. Hermann (2003), Zircon formation during fluid circulation in eclogites  
1392 (Monviso, Western Alps): implications for Zr and Hf budget in subduction zones,  
1393 *Geochimica et Cosmochimica Acta*, 67(12), 2173–2187, doi:10.1016/S0016-  
1394 7037(02)01321-2.
- 1395 Ruffini, R., R. Polino, E. Callegari, J. Hunziker, and H. Pfeifer (1997), Volcanic clast-rich  
1396 turbidites of the Tavayanne sandstones from the Thone syncline (Savoie, France):  
1397 records for a tertiary postcollisional volcanism, *Schweiz. Miner. Petrogr. Mitt*, 77,  
1398 161–174.
- 1399 Sabil, N. (1995), La datation par traces de fission: aspects méthodologiques et applications  
1400 thermochronologique en contexte Alpin et de Marge Continentale., Univ. Joseph  
1401 Fourier, Grenoble, France.
- 1402 Salles, L., M. Ford, P. Joseph, C. Le Carlier De Veslud, and A. Le Solleuz (2011), Migration  
1403 of a synclinal depocentre from turbidite growth strata: the Annot syncline, SE  
1404 France, *Bulletin de la Société Géologique de France*, 182(3), 199–220.
- 1405 Saliot, P. (1973). Les principales zones de métamorphisme dans les Alpes françaises.  
1406 Répartition et signification. *CR Acad. Sci. Paris*, 276, 3081–3084.
- 1407 Sanchez, G., Y. Rolland, J. Schneider, M. Corsini, E. Oliot, P. Goncalves, C. Verati, J.-M.  
1408 Lardeaux, and D. Marquer (2011a), Dating low-temperature deformation by  
1409  $^{40}\text{Ar}/^{39}\text{Ar}$  on white mica, insights from the Argentera-Mercantour Massif (SW  
1410 Alps), *Lithos*, 125(1), 521–536.
- 1411 Sanchez, G., Y. Rolland, M. Jolivet, S. Bricchau, M. Corsini, and A. Carter (2011b),  
1412 Exhumation controlled by transcurrent tectonics: the Argentera-Mercantour massif  
1413 (SW Alps), *Terra Nova*, 23(2), 116–126.
- 1414 Scaillet, S., G. Féraud, Y. Lagabriele, M. Ballèvre, and G. Ruffet (1990),  $^{40}\text{Ar}/^{39}\text{Ar}$  laser-  
1415 probe dating by step heating and spot fusion of phengites from the Dora Maira nappe  
1416 of the western Alps, Italy, *Geology*, 18(8), 741–744, doi:10.1130/0091-  
1417 7613(1990)018<0741:AALPDB>2.3.CO;2.
- 1418 Scaillet, S., G. Féraud, M. Ballèvre, and M. Amouric (1992), MgFe and ((Mg,Fe)Si-Al<sub>2</sub>)  
1419 compositional control on argon behaviour in high-pressure white micas: A  $^{40}\text{Ar}/^{39}\text{Ar}$   
1420 continuous laser-probe study from the Dora-Maira nappe of the internal western  
1421 Alps, Italy, *Geochimica et Cosmochimica Acta*, 56(7), 2851–2872,  
1422 doi:10.1016/0016-7037(92)90364-O.

- 1423 Schaeffer, O., H. W. Mueller, and T. L. Grove (1977), Laser Ar-39-Ar-40 study of Apollo  
1424 17 basalts, vol. Proceedings. Volume 2. (A78-41551 18-91), New York, Pergamon,  
1425 Houston.
- 1426 Schwartz, S., J. M. Lardeaux, P. Tricart, S. Guillot, and E. Labrin (2007), Diachronous  
1427 exhumation of HP-LT metamorphic rocks from south-western Alps: evidence from  
1428 fission-track analysis, *Terra Nova*, 19(2), 133–140.
- 1429 Seward, D., and N. S. Mancktelow (1994), Neogene kinematics of the central and western  
1430 Alps: Evidence from fission-track dating, *Geology*, 22(9), 803–806,  
1431 doi:10.1130/0091-7613(1994)022<0803:NKOTCA>2.3.CO;2.
- 1432 Simon-Labric, T., Y. Rolland, T. Dumont, T. Heymes, C. Authemayou, M. Corsini, and M.  
1433 Fornari (2009), Ar-40/Ar-39 dating of Penninic Front tectonic displacement (W  
1434 Alps) during the Lower Oligocene (31-34 Ma), *Terra Nova*, 21(2), 127–136.
- 1435 Sinclair, H. D. (1997), Tectonostratigraphic model for underfilled peripheral foreland  
1436 basins: An Alpine perspective, *Geological Society of America Bulletin*, 109(3), 324–  
1437 346, doi:10.1130/0016-7606(1997)109<0324:TMFUPF>2.3.CO;2.
- 1438 Strzermyski, P., S. Guillot, P. H. Leloup, N. Arnaud, O. Vidal, P. Ledru, G. Courrioux, and  
1439 X. Darmendrail (2012), Tectono-metamorphic evolution of the Briançonnais zone  
1440 (Modane-Aussois and Southern Vanoise units, Lyon Turin transect, Western Alps),  
1441 *Journal of Geodynamics*, 56–57(0), 55–75, doi:10.1016/j.jog.2011.11.010.
- 1442 Tilton, G. R., W. Schreyer, and H.-P. Schertl (1991), Pb–Sr–Nd isotopic behavior of deeply  
1443 subducted crustal rocks from the Dora Maira Massif, Western Alps, Italy-II: what is  
1444 the age of the ultrahigh-pressure metamorphism?, *Contr. Mineral. and Petrol.*, 108(1-  
1445 2), 22–33, doi:10.1007/BF00307323.
- 1446 Tricart, P., S. Schwartz, C. Sue, G. Poupeau, and J.-M. Lardeaux (2001), La denudation  
1447 tectonique de la zone ultradauphinoise et l’inversion du front briançonnais au sud-est  
1448 du Pelvoux (Alpes occidentales); une dynamique miocene a actuelle, *Bulletin de la*  
1449 *Societe Geologique de France*, 172(1), 49–58, doi:10.2113/172.1.49.
- 1450 Tricart, P., S. Schwartz, C. Sue, and J.-M. Lardeaux (2004), Evidence of synextension tilting  
1451 and doming during final exhumation from analysis of multistage faults (Queyras  
1452 Schistes lustrés, Western Alps), *Journal of Structural Geology*, 26(9), 1633–1645,  
1453 doi:10.1016/j.jsg.2004.02.002.
- 1454 Tricart, P., J.-M. Lardeaux, S. Schwartz, and C. Sue (2006), The late extension in the inner  
1455 western Alps: a synthesis along the south-Pelvoux transect, *Bulletin de la Societe*  
1456 *Geologique de France*, 177(6), 299–310, doi:10.2113/gssgfbull.177.6.299.
- 1457 Tricart, P., P. Van der Beek, S. Schwartz, and E. Labrin (2007), Diachronous late-stage  
1458 exhumation across the western Alpine arc: constraints from apatite fission-track  
1459 thermochronology between the Pelvoux and Dora-Maira Massifs, *Journal of the*  
1460 *Geological Society*, 164(1), 163–174.



- 1461 Turrillot, P., Augier, R., Monié, P., & Faure, M. (2011). Late orogenic exhumation of the  
1462 Variscan high-grade units (South Armorican Domain, western France), combined  
1463 structural and  $^{40}\text{Ar}/^{39}\text{Ar}$  constraints. *Tectonics*, 30(5).
- 1464 Vernon, A. J., Van Der Beek, P. A., Sinclair, H. D., & Rahn, M. K. (2008). Increase in late  
1465 Neogene denudation of the European Alps confirmed by analysis of a fission-track  
1466 thermochronology database. *Earth and Planetary Science Letters*, 270(3), 316-329.
- 1467 Vidal, O., T. Parra, and F. Trotet (2001), A Thermodynamic Model for Fe-Mg Aluminous  
1468 Chlorite Using Data from Phase Equilibrium Experiments and Natural Pelitic  
1469 Assemblages in the 100° to 600°C, 1 to 25 kb Range, *American Journal of Science*,  
1470 301(6), 557–592, doi:10.2475/ajs.301.6.557.
- 1471 Vidal, O., T. Parra, and P. Vieillard (2005), Thermodynamic properties of the Tschermak  
1472 solid solution in Fe-chlorite: Application to natural examples and possible role of  
1473 oxidation, *American Mineralogist*, 90(2-3), 347–358, doi:10.2138/am.2005.1554.
- 1474 Vidal, O., V. De Andrade, E. Lewin, M. Munoz, T. Parra, and S. Pascarelli (2006), P–T-  
1475 deformation-Fe<sup>3+</sup>/Fe<sup>2+</sup> mapping at the thin section scale and comparison with  
1476 XANES mapping: application to a garnet-bearing metapelite from the Sambagawa  
1477 metamorphic belt (Japan), *Journal of Metamorphic Geology*, 24(7), 669–683,  
1478 doi:10.1111/j.1525-1314.2006.00661.x.
- 1479 Villa, I. M. (1998). Isotopic closure. *Terra Nova-Oxford*, 10(1), 42-47.
- 1480 Vitale Brovarone, A., Beyssac, O., Malavieille, J., Molli, G., Beltrando, M., & Compagnoni,  
1481 R. (2013). Stacking and metamorphism of continuous segments of subducted  
1482 lithosphere in a high-pressure wedge: the example of Alpine Corsica (France). *Earth-*  
1483 *Science Reviews*, 116, 35-56.
- 1484 Waibel, A. F. (1990), Sedimentology, petrographic variability and very-low-grade  
1485 metamorphism of the Champsaur sandstone (Paleogene, Hautes-Alpes, France).  
1486 Evolution of Volcaniclastic Foreland Turbidites in the External Western Alps., Univ.  
1487 Genève, Switzerland.
- 1488 West, D. P., and D. R. Lux (1993), Dating mylonitic deformation by the  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  method:  
1489 An example from the Norumbega Fault Zone, Maine, *Earth and Planetary Science*  
1490 *Letters*, 120(3–4), 221–237, doi:10.1016/0012-821X(93)90241-Z.
- 1491 De Wever, P., and R. Caby (1981), Datation de la base des schistes lustrés  
1492 postophiolitiques par des radiolaires (Oxfordien supérieur? Kimmeridgien moyen)  
1493 dans les Alpes Cottiennes (Saint Vêran, France), *Comptes Rendus de l'Académie des*  
1494 *Sciences*, 292, 467–472.
- 1495 De Wever, P., T. Danelian, M. Durand-Delga, F. Cordey, and N. Kito (1987), Datations des  
1496 radiolarites post-ophiolitiques de Corse alpine à l'aide des Radiolaires, *CR Acad.*  
1497 *Sci. Paris*, 305, 893–900.

- 1498 Wibberley, C. (1999), Are feldspar-to-mica reactions necessarily reaction-softening  
1499 processes in fault zones?, *Journal of Structural Geology*, 21(8), 1219–1227.
- 1500 Wibberley, C. A. . (2005), Initiation of basement thrust detachments by fault-zone reaction  
1501 weakening, *Geological Society, London, Special Publications*, 245, 347–372.
- 1502 Wijbrans, J. R., & McDougall, I. (1986).  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of white micas from an Alpine  
1503 high-pressure metamorphic belt on Naxos (Greece): the resetting of the argon  
1504 isotopic system. *Contributions to Mineralogy and Petrology*, 93(2), 187–194.
- 1505 York, D. (1968), Least squares fitting of a straight line with correlated errors, *Earth and*  
1506 *Planetary Science Letters*, 5(0), 320–324, doi:10.1016/S0012-821X(68)80059-7.
- 1507 York, D., C. M. Hall, Y. Yanase, J. A. Hanes, and W. J. Kenyon (1981),  $^{40}\text{Ar}/^{39}\text{Ar}$  dating  
1508 of terrestrial minerals with a continuous laser, *Geophys. Res. Lett.*, 8(11), 1136–  
1509 1138, doi:10.1029/GL008i011p01136.

1510

# 1511 **Figure captions**

1512

1513 Figure 1: (a) Large-scale tectonic map of the Western Alps. Indicated is the location of the  
1514 figure 2 that embraces the whole studied area. (b) Geological cross-section across the  
1515 studied area close to the 45th parallel modified from Bellanger et al. (2014).

1516

1517 Figure 2: Simplified structural map of the studied area modified from Bellanger et al.  
1518 (2014). Indicated is the location of the studied samples either from the Mesozoic cover for  
1519 RSCM and chlorite geothermometry or from the basement shear zones for chlorite  
1520 geothermometry and for the  $^{40}\text{Ar}/^{39}\text{Ar}$  *in situ* approach. See tables for precise locations of  
1521 samples.

1522

1523 Figure 3: Deformation features of the Oisans Massif at decreasing scales. (a) kilometer-scale  
1524 view as illustrated by a geological cross-section from the Penninic Frontal Thrust (PFT) to  
1525 La Mure Massif. Note the distribution of the Alpine shear zones and the overall eastward  
1526 increasing of the finite strain intensity; (b) landscape-scale view as illustrated by a picture of  
1527 a part of the Plan du Lac shear zone in the Vénéon Valley. Note the anastomosed  
1528 relationships of the shear planes, the folded shape of the basement-cover interface and the  
1529 pinched part of Mesozoic cover. Field-sketch diagrams represent macroscopic features of

the deformation from mylonite to phyllonite at outcrop-scale. (c) Thin-section pictures showing small-scale deformation features of from proto-mylonite to phyllonite strain-stage. Note the clear increase of the phengite fraction with strain increasing.

Figure 4: First-order results from the Raman Spectrometry of Carbonaceous Material approach. (a) RSCM Map showing mapping of the  $T_{\max}$  results and inferred isotherms. The isotherm shape was drawn from interpolated map and from the distribution of the Illite crystallinity; (b) Illite crystallinity map modified from Aprahamian (1974) and Barlier et al. (1974). (c) Projection of the RSCM  $T_{\max}$  over a classical E-W cross-section from the west of the Belledonne Massif to the Penninic Frontal Thrust. (d and e) RSCM  $T_{\max}$  results vs. longitude and elevation along the cross-section (c). Data represented with smaller symbols to the east of the Penninic Frontal Thrust come from Beyssac et al. (2002); Gabalda et al. (2009); Lanari et al. (2012) and Plunder et al. (2012). Detailed results are given in table 1.

Figure 5: Local-scale features of results from the Raman Spectrometry of Carbonaceous Material approach. (a) Distribution of the  $T_{\max}$  to the west of the Belledonne Massif from RSCM (circle) and vitrinite reflectance results (star; data from Deville and Sassi (2006) transformed into temperatures using the equation proposed in Allen and Allen (2005). The distribution of the  $T_{\max}$  in the sedimentary pile is aligned along a ca.  $30\text{-}50^{\circ}\text{C.km}^{-1}$  gradient. Besides, temperature gaps across narrow zones highlight localized tectonic contacts. (b) Distribution of the RSCM  $T_{\max}$  results close to the Lautaret and Galibier passes. The structural data come from Depardon (1979), Beach (1981a, 1982), Ceriani et al. (2001), and Bellanger (2013). Note that the distribution of the  $T_{\max}$  within the tectonic pile is consistent with a ca.  $20\text{-}30^{\circ}\text{C.km}^{-1}$  post-tectonic field gradient. Detailed results are given in table 1.

Figure 6: Chlorite composition and results from chlorite geothermometry the Mesozoic cover. (a) XMg vs. Silica content diagram. (b) Clinocllore/Amesite/Sudoite ternary plot. Note that chlorite composition is first controlled by the bulk composition of the protolith. (c) Internal consistency of the geothermometric results. Chlorite geothermometry results using

both thermodynamic and empirical approaches (Cathelineau and Nieva, 1985, Vidal et al., 2005, 2006) are compared to RSCM data. Chlorite probably records a part of the cooling (retrograde) evolution. Detailed results are given in table 2.

Figure 7: Example of microstructural and composition of sample A.4.64 used as a guideline for dated samples. (a) Contrasted habits of white-micas as seen on several close-up views from the same thin-section. (b) White-mica chemical composition in ternary plots and XMg vs. Silica content diagram. Fine-grained, often syn-kinematic white-micas present in C-type and S-type foliation have phengite compositions. Well-developed white-mica clasts have a muscovite composition.

Figure 8: White-micas composition and chlorite geothermometry from dated samples (basement shear zones). For each of the dated shear zone, presented is the composition of white-micas as a function to their textural position in Si vs. Na content diagram and Muscovite/Celadonite/Pyrophyllite ternary plot together with results of chlorite geothermometry using both thermodynamic and empirical approaches (Cathelineau and Nieva, 1985, Vidal et al., 2001, 2005, 2006). Detailed results are given in table 2. (a) corresponds to results for the Col de Cluy shear zone while (b), (c) and (d) correspond to Plan du Lac, Col du Lac and Combeynot shear zones, respectively. Due to a very poor dataset, results for the Combeynot shear zone are not shown.

Figure 9: Time-chart showing all results of the *in situ*  $^{40}\text{Ar}/^{39}\text{Ar}$  approach. Detailed results are given in table 3. Stratigraphic age for the Nummulitic flysch deposit is from Mulder et al. (2010); zircon and apatite fission-tracks results from Van der Beek et al. (2010).

Figure 10: Pictures showing the distribution of *in situ* laser ablation of the  $^{40}\text{Ar}/^{39}\text{Ar}$  approach. Note the overall dependency of the K/Ar system to the finite strain intensity. Detailed results are given in table 3.

Figure 11: Pressure-Temperature-deformation-time evolution of the Oisans Massif. (a) Pressure-Temperature (P-T) constraints for the Oisans Massif. The P-T data come from (Gratier et al., 1973; Bernard, 1978) and references therein (Thermobarometry from fluids inclusions and paragenesis from cover and basement veins), (Jullien and Goffé, 1993) (conventional metamorphic petrology from the Emparis basin Mesozoic cover, (Crouzet et al., 1999) (thermopaleomagnetism from the Bourg d'Oisans basin), (Ceriani et al., 2003) (Zircon fission track and Kübler index and b-cell dimension of white mica from the Nummulitic cover of the Cheval noir unit), this study (RSCM from Mesozoic and Nummulitic cover). Temperature-deformation-time (T-d-t) constraints for the Oisans Massif. The T-d-t data come from (1) (Nziengui, 1993); (2) (Jullien and Goffé, 1993); (3) this study; (4) (Crouzet et al., 1999); (5) (Ménard and Rochette, 1992); (6) (Crouzet et al., 2001); (7) (van der Beek et al., 2010); (8) (Sabil, 1995; van der Beek et al., 2010; Beucher et al., 2012).

Figure 12: Large-scale compilation of existing time-constraints for the External zone and for the Western Alps close to the 45th parallel. (1) (Riche and Trémolières, 1987) (2) (Clauzon, 1990) (3) (Philippe et al., 1998) (4) (Du Fornel et al., 2004) (5) (Mulder et al., 2010) (6) (Féraud et al., 1995) (7) (Marignac et al., 1997) (8) (Gasquet et al., 2010) (9) (Simon-Labric et al., 2009) (a: Combeynot sinistral strike-slip shear zone; b: Pelvoux dextral strike-slip shear zone; c: Ailefroide dextral strike-slip shear zone); (10) this study; (11) (Nziengui, 1993) (12) (Crouzet et al., 1999, 2001) (13) (van der Beek et al., 2010) (14) (Sabil, 1995; van der Beek et al., 2010; Beucher et al., 2012) (15-16) (Fügenschuh and Schmid, 2003) (17) (Ceriani and Schmid, 2004) (18) (Ceriani et al., 2003; Fügenschuh and Schmid, 2003) (19) (Fügenschuh and Schmid, 2003) (20) (Féraud et al., 1995) (21) (Corsini et al., 2004) (22) (Sanchez et al., 2011a) (23) (Bigot-Cormier et al., 2000) (24) (Bigot-Cormier et al., 2000; Bogdanoff et al., 2000; Sanchez et al., 2011b) (25) (Pfiffner, 1992) (26) (Ruffini et al., 1997) (27-29) (Leutwein et al., 1970) (30) (Marshall et al., 1998) (31) (Crespo-Blanc et al., 1995) (32) (Kirschner et al., 1996) (33-34) (Rolland et al., 2008) (35) (Krummenacher and Evernden, 1960) (36) (Leutwein et al., 1970) (37-40) (Leloup et al., 2005) (41) (Baggio et al., 1967) (42-43) (Seward and Mancktelow, 1994; Leloup et al., 2005) (44-45) (Fügenschuh and Schmid, 2003) (46) (Freeman et al., 1998) (47) (Beucher, 2009) (48-49) (Fügenschuh and Schmid, 2003; Tricart et al., 2007) (50) (Ellenberger, 1958) (51) (Ganne, 2003) (52) (Gerber, 2008) (53) (Malusà et al., 2005) (54-56) (Ganne, 2003) (57-61) (Gerber, 2008) (62)

(Strzeczynski et al., 2012) (63) (Freeman et al., 1997) (64) (Agard et al., 2002) (65) (Duchêne et al., 1997) (66) (Rubatto and Hermann, 2003) (67) (Monié and Philippot, 1989) (68-69) (Cliff et al., 1998) (70-71) (Schwartz et al., 2007; Tricart et al., 2007; Beucher, 2009) (72) (Agard et al., 2002) (73) (Duchêne et al., 1997) (74) (Gebauer et al., 1997) (75) (Rubatto and Hermann, 2001) (76 et 78) (Tilton et al., 1991) (77) (Scaillet et al., 1992) (79) (Gebauer et al., 1997) (80) (Beucher et al., 2012) (81 et 83) (Chopin and Maluski, 1980) (82) (Ganne, 2003) (84) (Meffan-Main et al., 2004) (85-86) (Hurford and Hunziker, 1989; Hurford et al., 1991).

Figure 13: Lithospheric reconstructions of the Alps along a cross-section close to the 45th parallel. See text for explanations.

# **Table captions**

Table 1: Detailed results from the RSCM approach. Given are the GPS position (latitude (Lat.) and longitude (Long.) in decimal degrees (WGS84) and the elevation in meter), the tectonic unit, the stratigraphic age, the lithology, the number of Raman spectra (Sp.), the R2 or the RA1 ratio, the RSCM temperature (mean and standard deviation). R2 ratio, in regular font (Beyssac et al., 2002) or the RA1 ratio, in italic font (Lahfid et al. 2010) was preferred depending on the shape of the spectra and the presence of the D4 peak (Lahfid et al., 2010).

Table 2: Detailed results from the chlorite geothermometry approach. Given are the GPS position (latitude (Lat.) and longitude (Long.) in decimal degrees (WGS84) and results of thermodynamic and empirical approaches (Cathelineau and Nieva, 1985, Vidal et al., 2005, 2006). Results are presented separately for the Mesozoic cover and the basement (Alpine shear zones).

Table 3: Detailed results from the  $^{40}\text{Ar}/^{39}\text{Ar}$  approach. Given are the GPS position (latitude (Lat.) and longitude (Long.) in decimal degrees (WGS84) in decimal degrees (WGS84) and different output isotopic ratio.



	317	159.84	± 9.51	34.09	1.06	42.598	100.620	81.736	41	
	318	83.59	± 2.05	17.45	0.22	19.188	33.359	10.534	14	
	319	116.28	± 2.50	24.50	0.27	19.849	18.212	8.634	9	
	320	89.33	± 2.20	18.68	0.24	19.482	126.785	6.793	9	40
A-4-66b	19	37.78	± 3.17	7.79	0.33	21.743	41.626	26.734	47	
Plan du Lac	20	37.63	± 2.03	7.76	0.21	19.494	7.915	16.086	35	
Gneiss	26	38.95	± 1.54	8.03	0.16	15.253	0.760	11.468	27	
Lat.: 44.982410°	27	36.87	± 2.03	7.60	0.21	17.892	2.116	16.419	36	
Lon.: 6.147040°	29	301.42	± 6.56	66.91	0.79	35.325	0.000	34.137	13	
	30	62.29	± 1.41	12.93	0.15	16.109	16.173	6.088	11	
	33	129.05	± 3.03	27.29	0.33	27.668	8.263	15.628	14	
	34	36.00	± 0.98	7.42	0.10	12.959	0.000	5.512	16	
	37	35.72	± 1.89	7.36	0.20	22.241	35.724	14.517	34	
	39	32.67	± 1.63	6.73	0.17	17.296	12.892	12.831	33	
	40	32.08	± 1.10	6.60	0.11	14.308	7.733	7.737	23	
	42	30.72	± 1.09	6.32	0.11	14.967	0.000	7.800	24	
	43	32.87	± 1.14	6.77	0.12	13.521	3.686	8.014	23	
	45	33.49	± 0.77	6.90	0.08	13.770	2.480	3.254	11	
	46	33.55	± 0.82	6.91	0.09	13.321	3.816	4.022	13	
	48	29.17	± 0.68	6.00	0.07	14.767	13.296	2.745	10	
	49	29.58	± 0.67	6.08	0.07	15.319	13.327	2.398	9	
	51	31.49	± 0.65	6.48	0.07	13.435	4.182	1.473	5	
	52	31.98	± 0.70	6.58	0.07	14.403	2.899	2.587	9	
	54	33.12	± 0.79	6.82	0.08	14.390	5.062	3.737	12	
	55	39.81	± 0.89	8.21	0.09	14.321	2.465	3.589	10	
	57	37.33	± 2.48	7.70	0.26	18.621	8.016	20.685	41	
	58	31.65	± 2.39	6.51	0.25	19.490	4.940	20.049	44	
	60	35.03	± 1.33	7.22	0.14	18.049	2.470	9.941	26	
	61	34.70	± 1.35	7.15	0.14	18.266	3.038	10.078	27	
	63	37.84	± 0.96	7.80	0.10	15.423	5.192	5.144	15	
	64	40.50	± 1.06	8.35	0.11	18.151	4.933	6.022	16	
	66	36.59	± 1.26	7.54	0.13	18.187	8.598	8.838	23	
	67	38.66	± 1.45	7.97	0.15	18.954	7.837	10.731	26	
	69	47.58	± 1.20	9.83	0.13	16.492	6.142	6.583	15	
	70	125.56	± 3.47	26.52	0.38	36.088	10.440	22.749	20	
	72	31.89	± 0.88	6.56	0.09	16.576	0.000	4.987	16	
	73	30.51	± 0.74	6.28	0.08	14.076	2.988	3.610	13	
	74	30.90	± 0.72	6.36	0.07	14.087	5.008	3.139	11	34
A-4-68	245	61.32	± 2.22	12.72	0.23	19.501	25.355	16.475	26	
Plan du Lac	246	40.61	± 2.03	8.38	0.21	21.339	32.150	16.278	34	
Gneiss	247	31.80	± 0.80	6.55	0.08	15.058	19.614	4.127	14	
Lat.: 44.984950°	249	28.77	± 1.17	5.92	0.12	16.462	21.462	8.823	27	
Lon.: 6.143560°	250	93.51	± 2.10	19.58	0.23	24.615	5.839	9.355	12	
	251	74.73	± 1.81	15.56	0.19	24.938	42.041	9.522	14	
	253	24.28	± 1.26	4.99	0.13	15.279	87.896	9.612	32	
	254	25.98	± 1.67	5.34	0.17	16.846	9.266	13.651	39	
	255	49.36	± 2.18	10.21	0.23	26.893	34.100	17.096	31	
	257	32.08	± 1.17	6.60	0.12	21.853	29.097	8.412	25	
	258	24.47	± 0.77	5.03	0.08	16.339	36.424	4.936	19	
	259	32.06	± 1.34	6.60	0.14	24.525	32.552	10.214	28	
	264	25.79	± 0.79	5.30	0.08	16.313	21.900	5.101	19	
	265	22.35	± 0.90	4.59	0.09	15.449	29.685	6.636	26	
	266	36.85	± 0.87	7.60	0.09	16.856	28.362	4.120	12	15
A-4-68b (Ech8)	144	24.88	± 0.54	5.14	0.06	12.752	3.706	0.478	2	
Plan du Lac	145	27.16	± 1.41	5.62	0.15	17.908	0.000	0.000	0	
Gneiss	146	26.65	± 0.55	5.51	0.06	13.920	0.000	0.507	2	
Lat.: 44.984950°	148	25.74	± 0.56	5.32	0.06	14.891	0.000	0.727	3	
Lon.: 6.143560°	149	25.16	± 0.55	5.20	0.06	14.784	0.000	0.583	3	
	150	25.95	± 0.55	5.37	0.06	14.536	12.917	0.570	3	
	152	26.58	± 0.69	5.50	0.07	12.124	5.811	0.701	3	
	153	25.66	± 2.89	5.30	0.30	12.211	0.000	0.066	0	
	154	25.75	± 3.15	5.32	0.33	12.126	271.884	0.184	0	
	156	32.57	± 3.85	6.75	0.40	10.353	108.067	1.046	4	
	157	47.23	± 1.41	9.82	0.15	11.567	168.834	3.893	9	
	158	46.40	± 1.90	9.65	0.20	17.515	18.150	14.508	29	
	160	201.82	± 12.76	43.83	1.46	46.660	2794.213	115.611	42	
	161	25.34	± 0.63	5.24	0.07	14.586	8.934	0.558	3	
	162	28.20	± 0.64	5.83	0.07	15.229	181.960	2.092	8	
	164	25.22	± 0.59	5.21	0.06	14.405	2.375	2.040	9	
	165	28.43	± 1.02	5.88	0.11	14.576	75.735	7.377	24	
	166	27.73	± 1.10	5.74	0.12	14.654	0.432	8.144	26	
	168	25.92	± 0.58	5.36	0.06	10.834	14.811	0.693	3	
	169	25.30	± 0.53	5.23	0.05	12.533	13.464	0.821	4	
	170	32.25	± 0.74	6.68	0.08	14.533	15.877	2.877	10	
	172	31.89	± 0.86	6.61	0.09	14.772	25.511	4.845	16	
	173	26.67	± 0.61	5.52	0.06	13.389	0.000	2.188	9	
	174	32.11	± 0.84	6.65	0.09	14.983	227.616	4.170	13	
	176	26.71	± 0.62	5.52	0.07	10.443	40.681	2.076	9	
	177	28.76	± 0.68	5.95	0.07	14.683	11.784	2.458	9	
	178	30.74	± 0.66	6.36	0.07	12.792	56.401	1.576	6	
	180	31.38	± 2.22	6.50	0.23	15.375	6.264	18.517	42	
	181	26.39	± 0.57	5.46	0.06	13.365	44.315	1.762	7	
	182	26.68	± 0.86	5.52	0.09	16.617	31.735	5.459	20	



Sample	An.	Age (+2s)	40%/39(k)	Is	38Ar/39Ar (*1000)	37Ar/39Ar (*1000)	36Ar/39Ar (*1000)	% Atm	n
<i>A-1-345</i>	110	389.51 ± 27.17	89.23	3.46	109.716	5.672	280.279	48	
Combeynot	111	315.64 ± 11.36	70.80	1.39	62.828	8.248	100.136	29	
Porphyroid	113	199.95 ± 5.88	43.40	0.67	34.056	22.486	42.774	22	
Lat.: 45.026510°	114	330.96 ± 7.53	74.56	0.93	42.462	3.763	44.245	15	
Lon.: 6.404380°	116	294.73 ± 6.91	65.72	0.83	40.937	5.032	43.083	16	
	117	290.84 ± 6.72	64.78	0.81	36.516	0.000	40.250	15	
	119	231.14 ± 6.59	50.62	0.77	38.998	4.310	48.412	22	
	120	276.63 ± 9.00	61.37	1.08	50.417	8.596	74.129	26	
	122	231.91 ± 5.81	50.80	0.68	38.043	4.734	37.637	18	
	123	221.72 ± 6.55	48.43	0.76	40.747	2.831	49.034	23	
	125	169.08 ± 3.29	36.39	0.37	13.650	11.799	3.969	3	
	126	272.85 ± 5.81	60.46	0.69	29.630	24.865	17.269	8	
	128	252.54 ± 4.98	55.64	0.59	16.655	37.405	7.473	4	
	129	156.32 ± 3.22	33.52	0.36	21.734	4.032	7.403	6	
	130	206.61 ± 4.42	44.93	0.51	33.808	22.324	11.769	7	15
<i>A-1-355</i>	205	30.82 ± 1.00	6.38	0.10	18.330	67.910	5.718	18	
Col du Lac	206	38.08 ± 3.64	7.90	0.38	58.001	138.816	11.462	27	
Gneiss	207	32.87 ± 0.88	6.81	0.09	15.744	85.272	2.104	7	
Lat.: 45.017860°	209	27.30 ± 0.80	5.65	0.08	16.684	40.285	4.607	17	
Lon.: 6.273540°	210	27.06 ± 0.99	5.60	0.10	16.173	83.580	5.847	20	
	211	24.80 ± 0.76	5.13	0.08	15.227	32.113	3.441	14	
	213	24.80 ± 0.57	5.13	0.06	13.758	26.275	2.476	11	
	214	26.58 ± 1.41	5.50	0.15	30.685	83.420	4.539	17	
	215	26.02 ± 0.65	5.38	0.07	16.349	154.835	2.906	11	
	217	32.34 ± 1.05	6.70	0.11	16.960	124.361	7.162	21	
	218	27.13 ± 0.91	5.61	0.09	17.432	244.419	5.225	18	
	219	27.77 ± 1.05	5.74	0.11	19.465	251.880	6.967	23	
	221	26.22 ± 0.66	5.42	0.07	15.212	51.173	2.493	10	
	222	88.86 ± 8.58	18.70	0.93	22.432	121.326	71.317	52	
	223	58.72 ± 2.12	12.25	0.22	22.361	24.720	14.784	25	
	225	27.22 ± 0.88	5.63	0.09	15.473	93.917	5.594	20	
	226	31.72 ± 1.11	6.57	0.12	19.244	109.244	6.726	20	
	227	26.44 ± 2.01	5.47	0.21	18.452	89.430	16.213	42	
	229	41.30 ± 1.63	8.58	0.17	15.750	79.334	11.810	27	
	230	30.61 ± 1.13	6.34	0.12	19.183	111.046	5.922	19	
	231	23.88 ± 1.64	4.93	0.17	16.507	58.995	13.359	40	
	233	27.55 ± 1.44	5.70	0.15	10.904	120.782	9.622	29	
	234	26.44 ± 4.85	5.47	0.50	16.482	272.598	41.140	64	
	235	21.09 ± 4.19	4.36	0.44	23.129	37.242	36.304	67	
	237	14.54 ± 9.58	3.00	0.99	31.718	0.581	83.039	86	
	238	33.41 ± 2.36	6.92	0.25	22.418	113.398	18.933	41	
	239	42.68 ± 2.22	8.87	0.23	15.109	82.208	16.743	33	
	241	36.11 ± 2.27	7.49	0.24	19.655	164.103	18.251	38	
	242	109.75 ± 7.11	23.23	0.78	27.052	135.090	49.364	38	
	243	37.65 ± 2.33	7.81	0.24	24.920	87.031	18.521	38	30
<i>A-4-74b</i>	268	169.77 ± 3.55	36.31	0.40	27.306	43.850	13.453	10	
Plan du Lac	269	52.47 ± 1.07	10.86	0.11	16.745	55.616	2.240	5	
Gneiss	270	74.94 ± 2.66	15.61	0.28	19.667	1412.051	14.647	19	
Lat.: 44.984930°	272	26.69 ± 0.60	5.48	0.06	12.978	52.107	1.561	7	
Lon.: 6.125820°	273	24.76 ± 0.68	5.09	0.07	13.439	3.485	3.354	14	
	274	24.29 ± 1.75	4.99	0.18	16.268	13.714	14.242	41	
	277	105.95 ± 2.91	22.26	0.32	31.313	74.487	7.328	9	
	278	186.61 ± 4.40	40.10	0.50	26.968	0.000	22.227	14	
	279	158.63 ± 4.59	33.82	0.51	28.448	79.390	30.843	21	
	281	207.10 ± 5.24	44.76	0.60	34.788	41.001	32.855	18	
	282	132.95 ± 4.52	28.14	0.50	31.099	26.803	32.926	25	
	283	76.73 ± 3.65	15.99	0.39	12.256	154.469	25.925	31	
	285	126.70 ± 3.73	26.77	0.41	22.875	33.883	24.493	21	
	286	43.97 ± 5.66	9.08	0.59	22.167	48.539	48.845	59	
	287	57.14 ± 1.27	11.84	0.13	16.889	58.258	4.372	9	
	289	105.53 ± 2.37	22.17	0.26	21.393	37.534	6.227	7	
	290	131.78 ± 3.12	27.89	0.34	26.144	18.864	14.691	13	
	291	111.61 ± 6.66	23.49	0.72	37.316	48.608	54.146	40	
	293	40.96 ± 0.98	8.45	0.10	18.950	68.986	1.636	5	
	294	36.84 ± 0.82	7.59	0.09	16.349	5.038	2.719	9	
	295	54.01 ± 1.35	11.18	0.14	20.151	2.290	6.796	14	
	297	32.65 ± 0.93	6.72	0.10	16.406	321.626	4.222	13	
	298	36.43 ± 0.87	7.51	0.09	14.979	25.149	1.999	6	
	299	32.17 ± 0.80	6.62	0.08	15.178	20.601	3.209	11	
	301	40.05 ± 0.91	8.26	0.09	13.792	14.734	2.443	7	
	302	32.71 ± 0.81	6.73	0.08	13.812	102.166	1.986	7	
	303	38.28 ± 1.00	7.89	0.10	15.011	2.251	5.515	16	
	305	46.66 ± 1.09	9.64	0.11	17.635	42.403	4.734	12	
	306	47.53 ± 1.15	9.83	0.12	17.989	25.982	5.711	13	
	307	59.65 ± 1.67	12.37	0.18	19.478	125.491	9.956	18	
	309	25.22 ± 1.08	5.18	0.11	15.696	103.169	8.232	28	
	310	43.87 ± 1.14	9.06	0.12	16.736	4.395	6.180	15	
	311	86.77 ± 3.01	18.13	0.32	26.519	11.467	22.305	26	
	313	45.26 ± 1.45	9.35	0.15	20.073	12.845	9.898	22	
	314	34.80 ± 1.04	7.17	0.11	16.355	471.527	6.146	17	
	315	73.72 ± 3.24	15.35	0.34	28.247	13.271	25.751	32	

	Sample	Lat. (°)	Lon. (°)	Shear zone (or area)	Lithology	n	T $\sigma$		T $\sigma$		XFe <sub>3</sub> $\sigma$		RSCM $\sigma$	
							Cathelineau and Nieva [1985]		Vidal et al. [2005, 2006]		Beyssac et al. [2002]			
Cover	A-2-2	45.16481	5.851862	Uriage	Limestone	25	294	17	252	61	6	5	306	13
	A-1-321	45.223812	6.138562	Bourg d'Oisans	Shale	11	296	9	313	55	6	6	345	9
	A-1-345(2)	45.00973	6.26403	Col du Lac	Limestone	24	297	12	294	45	7	5	335	5
	A-4-232	44.55958	6.47881	Embrun	Black shale	13	288	13	269	51	5	5	308	5
Basement	A-4-114	45.08019	6.11031	Col de Cluy	Chloritoschist	4	259	15	187	61	34	9		
						7	275	17	255	43	30	10		
	A-4-64	44.97745	6.15251	Plan du Lac	Gneiss	8	267	8	255	26	29	4		
						3	256	16	267	11	34	3		
						4	261	7	250	32	31	7		
						5	262	16	250	8	32	4		
	A-4-28a	45.0173	6.270507	Col du Lac	Gneiss	7	268	7	258	15	32	4		
						10	266	6	262	11	30	4		
	A-4-222c	45.01764	6.28244		Gneiss	2	265	4	271	10	42	3		
						2	262	2	263	9	46	0		
						4	269	1	283	4	38	1		
						1	266		268	-	40	-		
	A-1-355	45.01786	6.27354		Gneiss	17	255	8	267	13	56	5		
						5	239	18	263	9	62	3		
	A-1-345	45.02651	6.40438	Combeynot	Orthogneiss	2	263	1	244	1	31	0		

Table 2

Sample	Lat.	Lon.	Elev.	Tectonic unit	Stratigraphic age	Lithology	n	R2/RA/ ratio	Tmax (°C)	sd (°C)
	(°)	(°)	(m)							
A-1-001	45.004578	5.70136	560	Dauphinois	Upper Lias	Slate	14	0.70	329	8
A-1-004	44.87225	5.86169	948	Dauphinois	Upper Lias	Slate	25	0.58	258	7
A-1-007	45.069906	6.000484	806	Dauphinois	Lower Lias	Limestone	12	0.72	321	6
A-1-009	45.08103	6.04491	1513	Dauphinois	Lower Lias	Limestone	13	0.71	327	3
A-1-016	45.03812	6.131952	1257	Dauphinois	Lower Dogger	Slate	12	0.63	321	12
A-1-025	45.14811	6.31462	1516	Dauphinois	Upper Lias	Slate	12	0.69	335	6
A-1-029	45.032105	6.381495	1952	Dauphinois	Middle Dogger	Limestone	12	0.69	335	2
A-1-030	45.038448	6.398698	2128	Dauphinois	Lower Lias	Limestone	11	0.69	333	4
A-1-32	45.042092	6.388473	2215	Dauphinois	Priabonian	Flysch	15	0.61	298	4
A-1-37	45.291423	6.324367	1485	Dauphinois	Upper Lias	Slate	12	0.69	333	2
A-1-171	45.226435	6.190374	2119	Dauphinois	Lower Lias	Limestone	12	0.71	327	5
A-1-208	45.062326	6.126121	1761	Dauphinois	Lower Lias	Limestone	11	0.63	319	8
A-1-224	45.049632	6.102744	1166	Dauphinois	Lower Lias	Limestone	11	0.70	330	5
A-1-225	45.037	5.97841	1120	Dauphinois	Lower Lias	Limestone	10	0.70	331	3
A-1-318	44.984199	6.123207	982	Dauphinois	Upper Lias	Slate	14	0.69	333	9
A-1-320	45.127996	6.045468	801	Dauphinois	Upper Lias	Slate	12	0.69	336	9
A-1-321	45.223812	6.138562	1770	Dauphinois	Upper Lias	Slate	11	0.67	345	9
A-1-322b	45.21556	6.213118	1794	Dauphinois	Upper Lias	Slate	12	0.70	329	3
A-1-323	45.215115	6.252217	1461	Dauphinois	Upper Lias	Slate	12	0.69	336	8
A-1-324	45.192802	6.290928	1271	Dauphinois	Lower Lias	Limestone	12	0.69	332	3
A-1-326	45.200339	6.336937	1502	Dauphinois	Lower Dogger	Slate	11	0.63	322	10
A-1-327	45.218918	6.305905	1290	Dauphinois	Upper Lias	Slate	11	0.66	347	4
A-1-328	45.227265	6.303567	1240	Dauphinois	Lower Lias	Limestone	11	0.69	336	5
A-1-329	45.249661	6.28425	1286	Dauphinois	Lower Dogger	Slate	8	0.69	334	5
A-1-330	45.2608	6.367982	776	Dauphinois	Lower Dogger	Slate	12	0.66	347	6
A-1-331	45.291702	6.23121	1107	Dauphinois	Upper Lias	Slate	12	0.69	332	12
A-1-332	45.045302	6.313245	1464	Dauphinois	Upper Lias	Slate	12	0.69	332	8
A-1-333	45.040348	6.30609	1592	Dauphinois	Lower Dogger	Slate	12	0.71	326	4
A-1-334	45.039006	6.304639	1587	Dauphinois	Lower Dogger	Slate	11	0.70	328	4
A-1-337	45.052165	6.288855	1806	Dauphinois	Lower Dogger	Slate	13	0.70	330	4
A-1-342	45.076795	6.338908	2119	Dauphinois	Middle Dogger	Limestone	11	0.64	326	4
A-1-345(2)	45.00973	6.26403	3193	Dauphinois	Upper Lias	Slate	12	0.69	335	5
A-2-002	45.16481	5.851862	813	Dauphinois	Lower Dogger	Slate	12	0.62	306	13
A-2-003	45.162054	5.81894	393	Dauphinois	Middle Dogger	Limestone	10	0.62	306	6
A-3-019	44.526656	6.726225	1690	Embrunais-Ubaye	Cretaceous	Helm. Flysch	12	0.59	262	6
A-4-005	45.052408	6.390277	2355	Dauphinois	Priabonian	Flysch	12	0.61	296	9
A-4-006	45.05279	6.40051	2379	Dauphinois	Priabonian	Flysch	12	0.61	288	6
A-4-010	45.06035	6.4223	2758	Tête Noire	Cretaceous	Helm. Flysch	12	0.59	265	8
A-4-011	45.06062	6.42282	2772	Tête Noire	Cretaceous	Helm. Flysch	11	0.58	261	9
A-4-014	45.063536	6.412644	2670	Subbriançonnais	Eocene	Flysch	12	0.59	267	6
A-4-039c1	45.04773	6.13796	1072	Grandes Rousses	Carboniferous	Sandstone	15	0.63	319	7
A-4-042	45.044332	6.15657	1064	Dauphinois	Lower Dogger	Slate	15	0.69	335	14
A-4-044	45.042854	6.168657	1462	Dauphinois	Lower Dogger	Slate	12	0.70	329	5
A-4-055	45.0421	6.35506	1770	Dauphinois	Lower Dogger	Slate	12	0.69	335	3
A-4-057	45.016852	6.039292	1509	Dauphinois	Lower Lias	Limestone	12	0.69	334	2
A-4-121	44.95072	5.96606	978	Dauphinois	Lower Lias	Limestone	10	0.64	326	7
A-4-122	44.89179	5.8778	695	Dauphinois	Lower Lias	Limestone	12	0.61	298	10
A-4-123	44.87871	5.7535	793	Dauphinois	Lower Dogger	Slate	12	0.60	279	9
A-4-124	44.87459	5.71011	667	Dauphinois	Lower Lias	Limestone	14	0.64	334	6
A-4-126	44.96182	5.81198	1181	Dauphinois	Upper Lias	Slate	11	0.63	314	8
A-4-140	45.33314	6.33442	1137	Dauphinois	Upper Lias	Slate	11	0.70	331	3
A-4-196	44.789297	6.45698	1671	Dauphinois	Priabonian	Flysch	11	0.64	330	5
A-4-197	45.03796	5.7054	403	Dauphinois	Upper Lias	Slate	12	0.69	334	4
A-4-198	45.04444	5.69423	309	Dauphinois	Middle Dogger	Limestone	11	0.64	325	6
A-4-199	45.04834	5.68057	340	Dauphinois	Middle Dogger	Limestone	12	0.61	296	5
A-4-200	45.01018	5.63507	499	Subalpine chain	Lower Malm	Marls	12	0.54	208	9
A-4-201	45.00197	5.62223	741	Subalpine chain	Lower Malm	Marls	14		< 200	
A-4-223	45.013605	6.283496	2509	Dauphinois	Lower Lias	Limestone	11	0.68	338	4
A-4-231	44.63593	6.56532	912	Subbriançonnais	Eocene	Flysch	16	0.62	302	10
A-4-232	44.55958	6.47881	883	Vocontian domain	Dogger/Malm	Black Shale	13	0.62	308	5
A-4-233	44.58166	6.39937	1211	Vocontian domain	Dogger/Malm	Black Shale	11	0.59	271	11
A-4-235	44.5549	6.34229	1246	Vocontian domain	Dogger/Malm	Black Shale	11	0.58	253	10
A-4-236	44.714333	6.156877	1667	Dauphinois	Upper Lias	Slate	11	0.56	228	8
A-4-238	44.713257	6.167974	1960	Dauphinois	Upper Lias	Slate	12	0.54	202	4
A-4-239b	44.714389	6.168411	1982	Dauphinois	Priabonian	Flysch	13		< 200	
A-4-242	45.027604	6.312056	2228	Dauphinois	Lower Lias	Limestone	10	0.64	333	8
A-4-244	44.83378	5.93966	1002	Dauphinois	Upper Lias	Slate	11	0.57	237	7
A-4-247	44.844446	6.127314	2055	Dauphinois	Lower Lias	Limestone	12	0.69	334	2
A-5-1	44.867686	5.61239	847	Subalpine chain	Lower Malm	Marls	13	0.54	204	14
A-5-2	44.92326	5.63483	829	Dauphinois	Middle Dogger	Limestone	11	0.61	288	7
A-5-3	44.95121	5.60154	788	Subalpine chain	Upper Dogger	Marls	11		< 200	
A-5-4	44.9613	5.58629	701	Subalpine chain	Lower Malm	Marls	12		< 200	
A-5-5	44.92913	5.63472	819	Dauphinois	Middle Dogger	Limestone	11	0.60	286	5
A-5-6	44.9058	5.6258	902	Subalpine chain	Upper Dogger	Marls	15	0.56	227	23
A-4-154	45.25002	6.78357	1438	Subbriançonnais	Lias	Limestone	12	0.51	412	5
A-4-228	44.814212	6.567413	1147	Dent Parraché	Malm	Limestone	12	0.61	291	6

Table 1

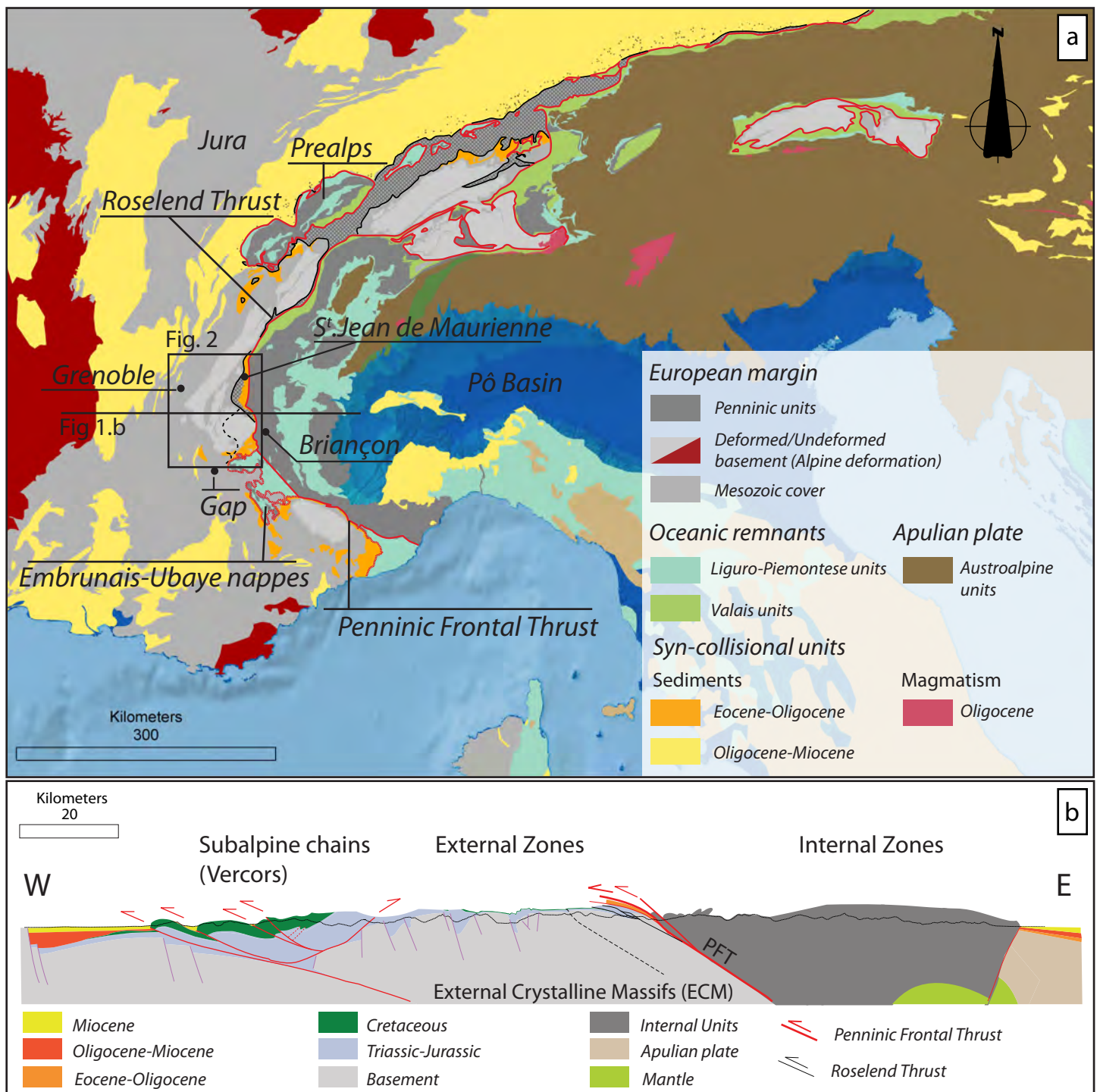


Figure 1

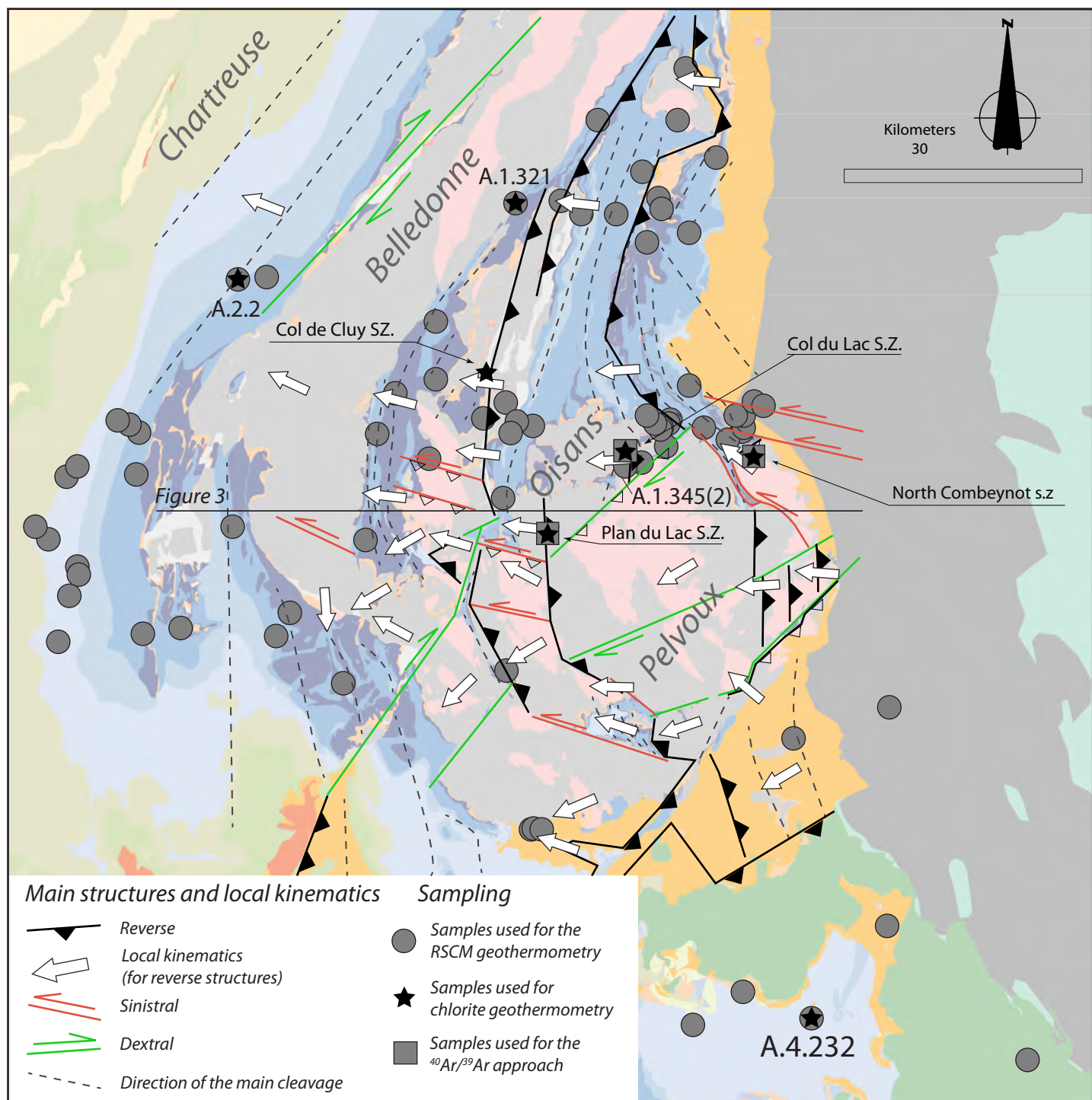


Figure 2



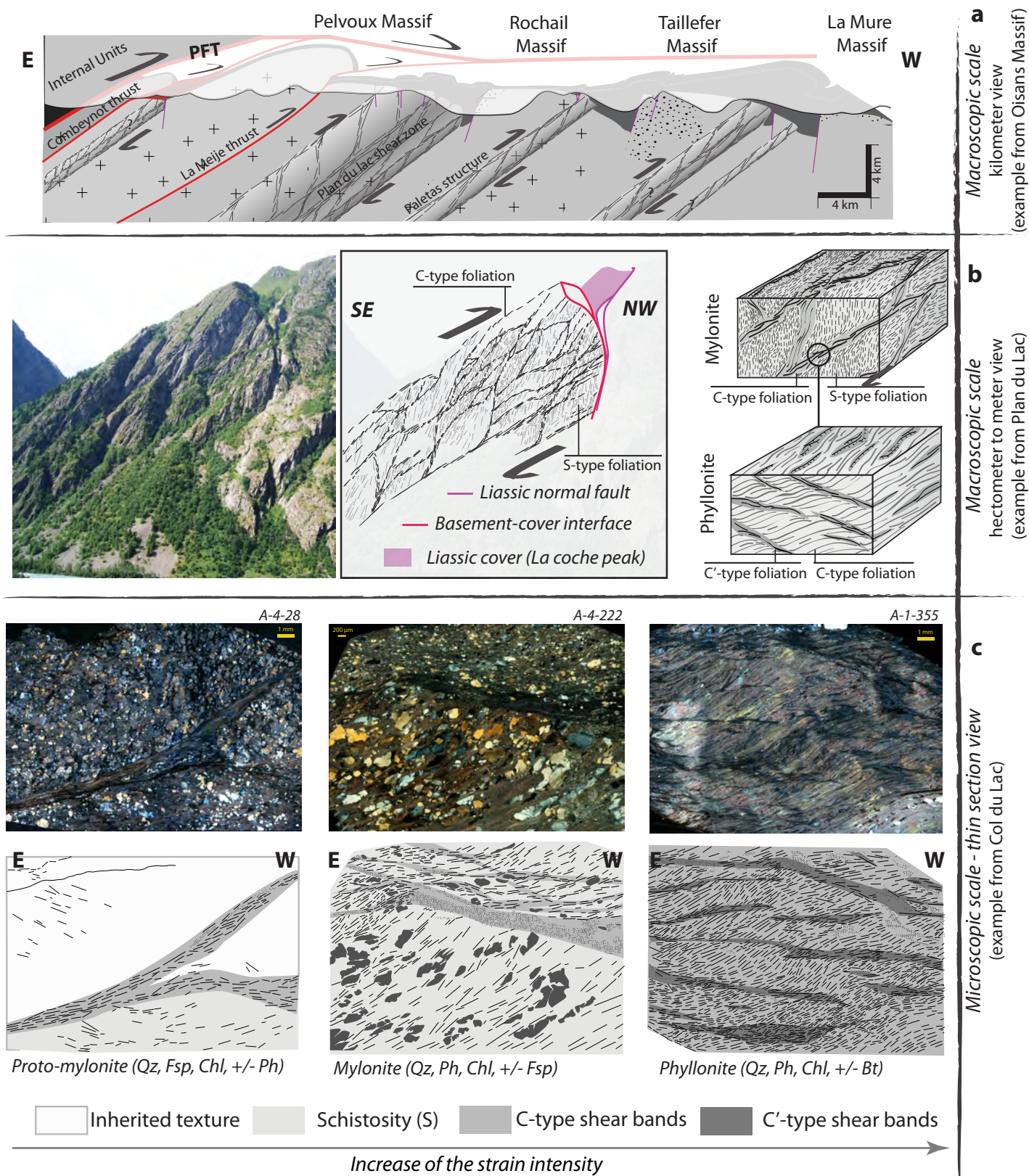


Figure 3

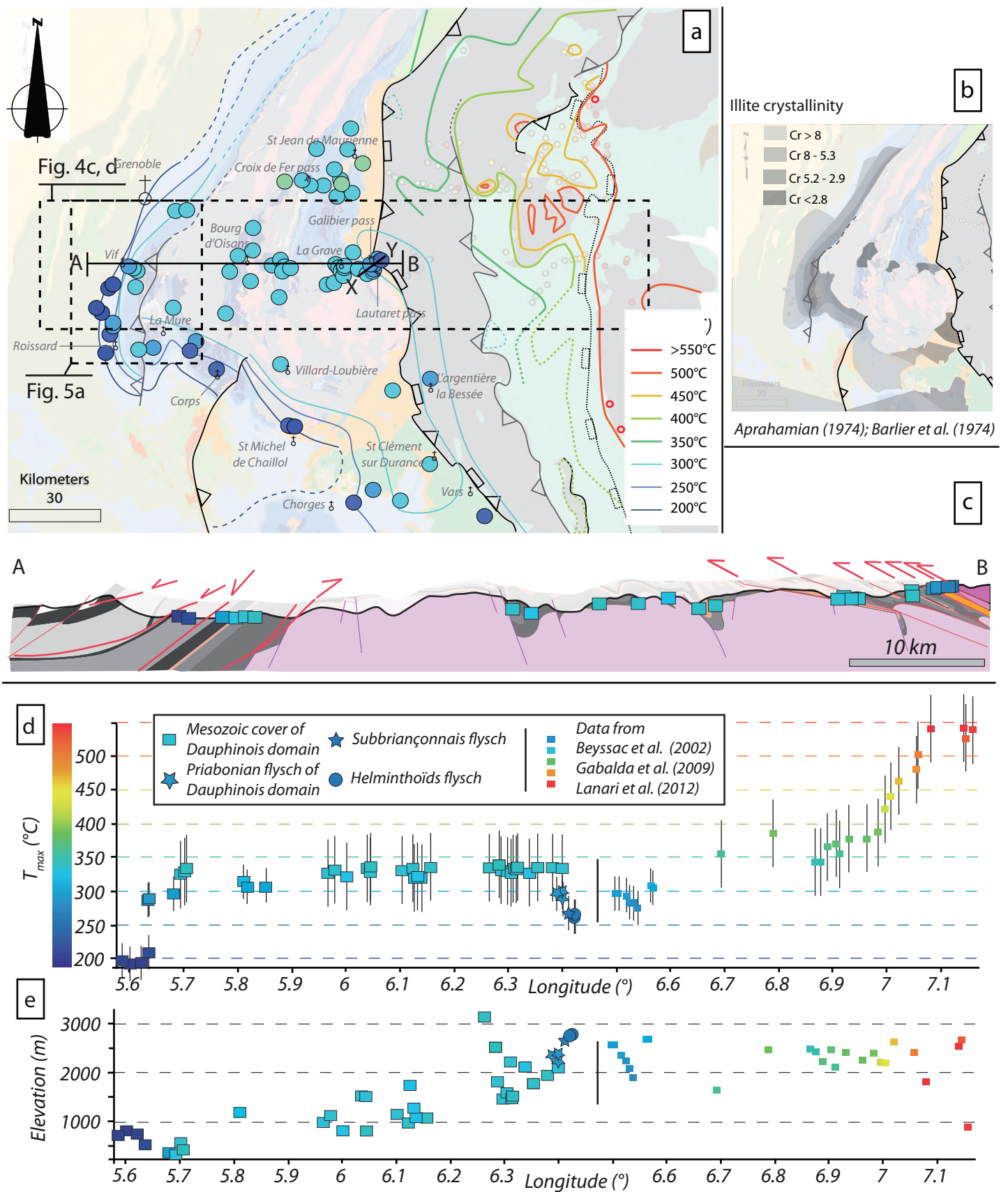


Figure 4

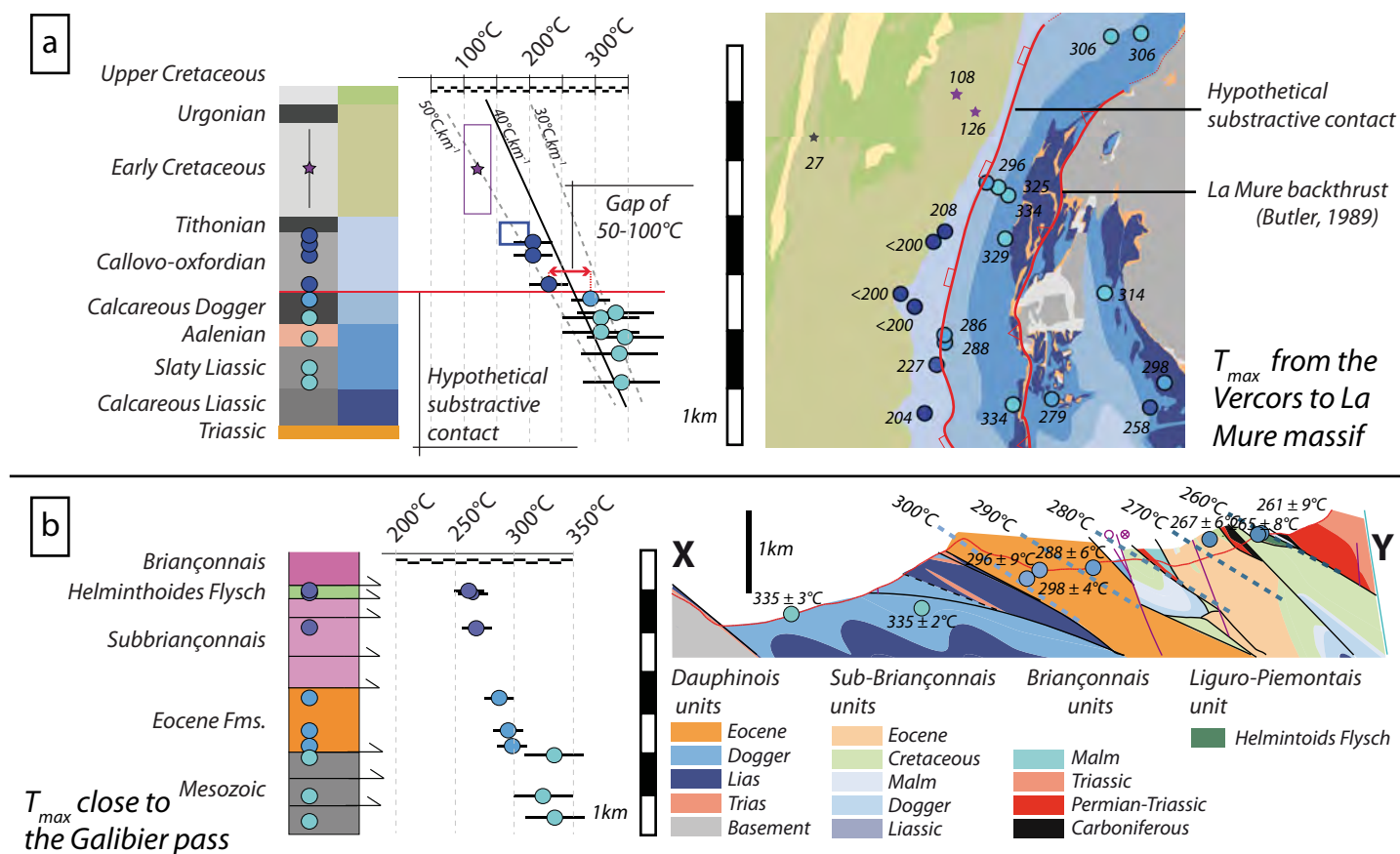


Figure 5



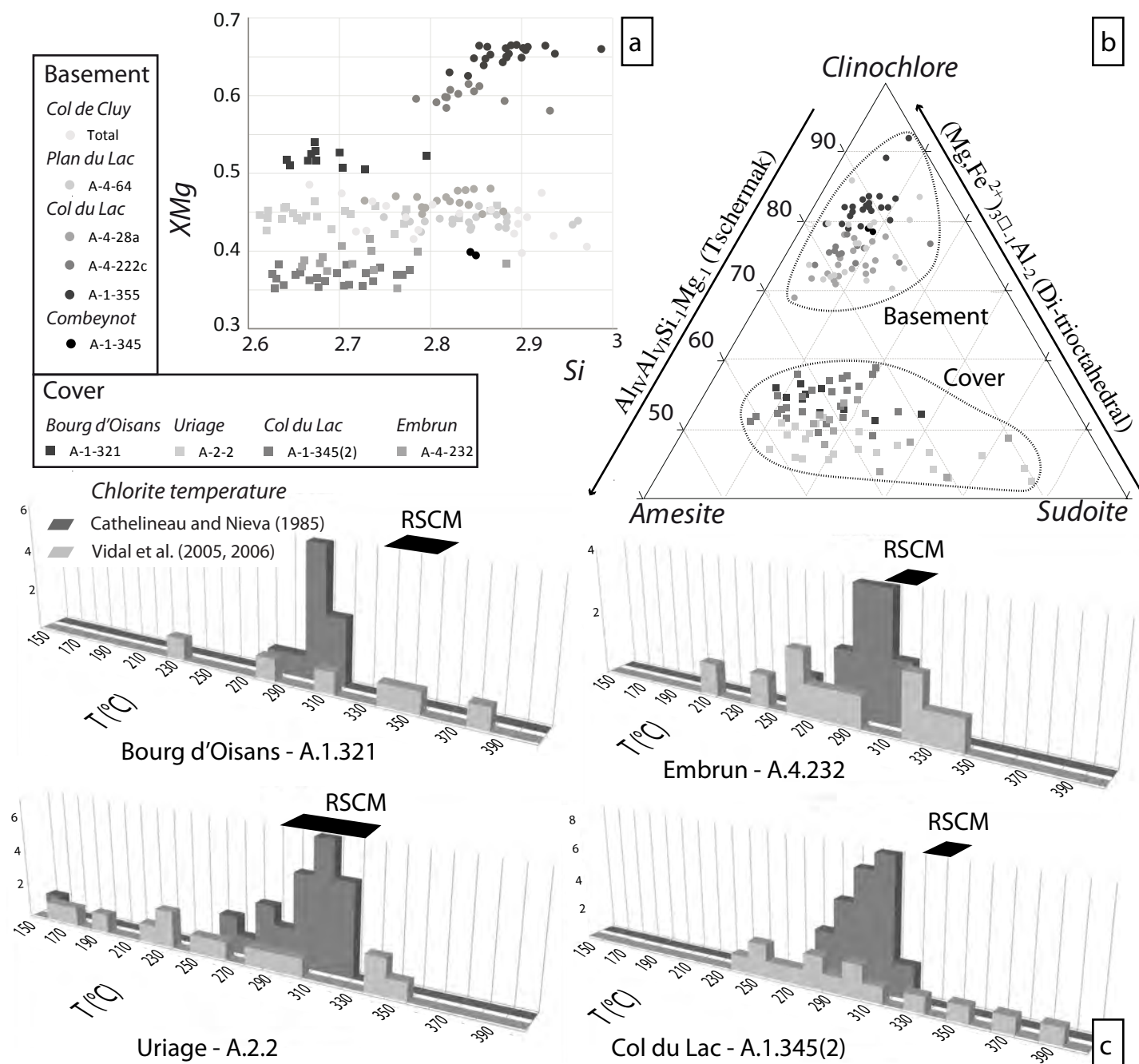


Figure 6

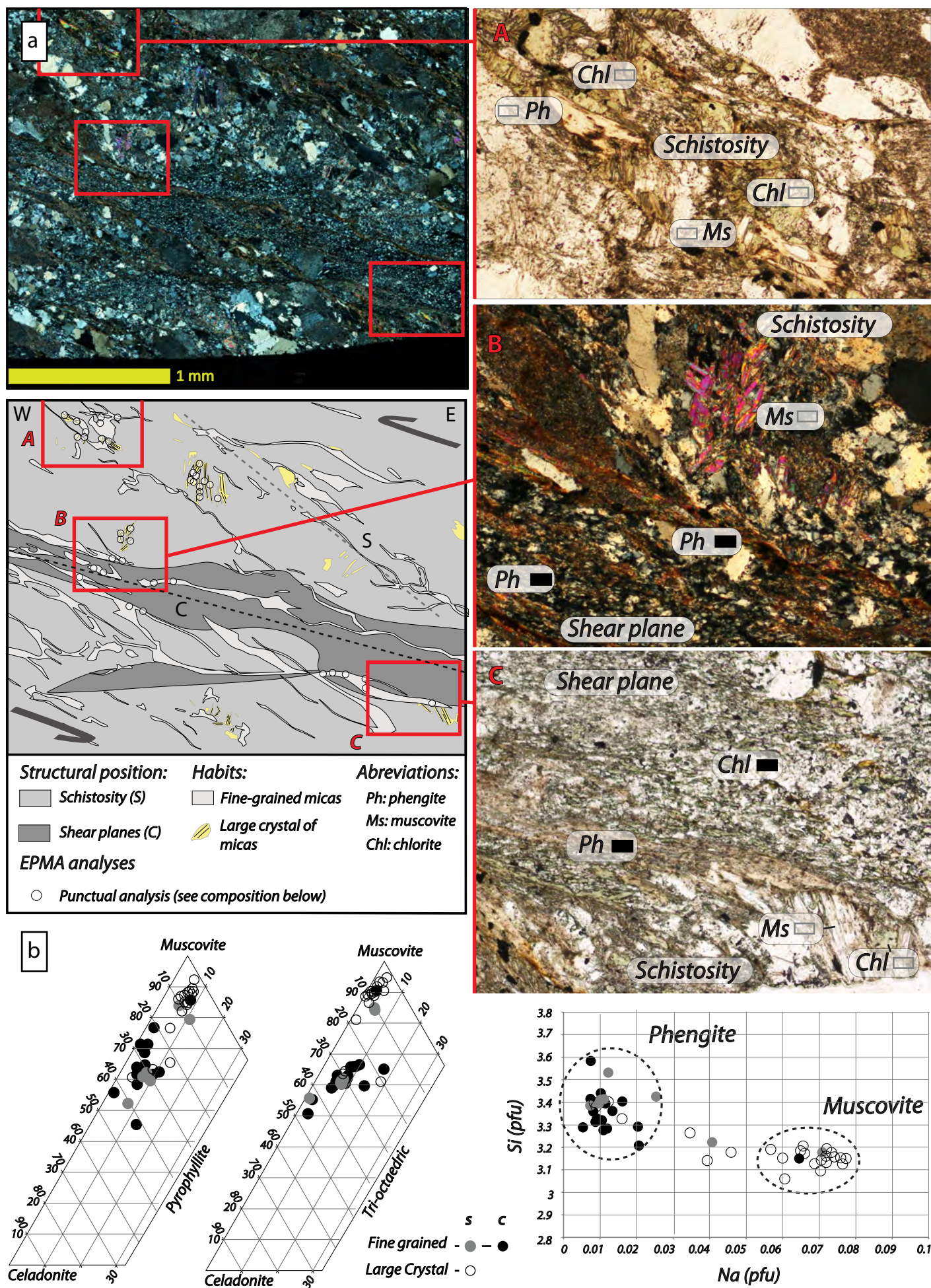


Figure 7



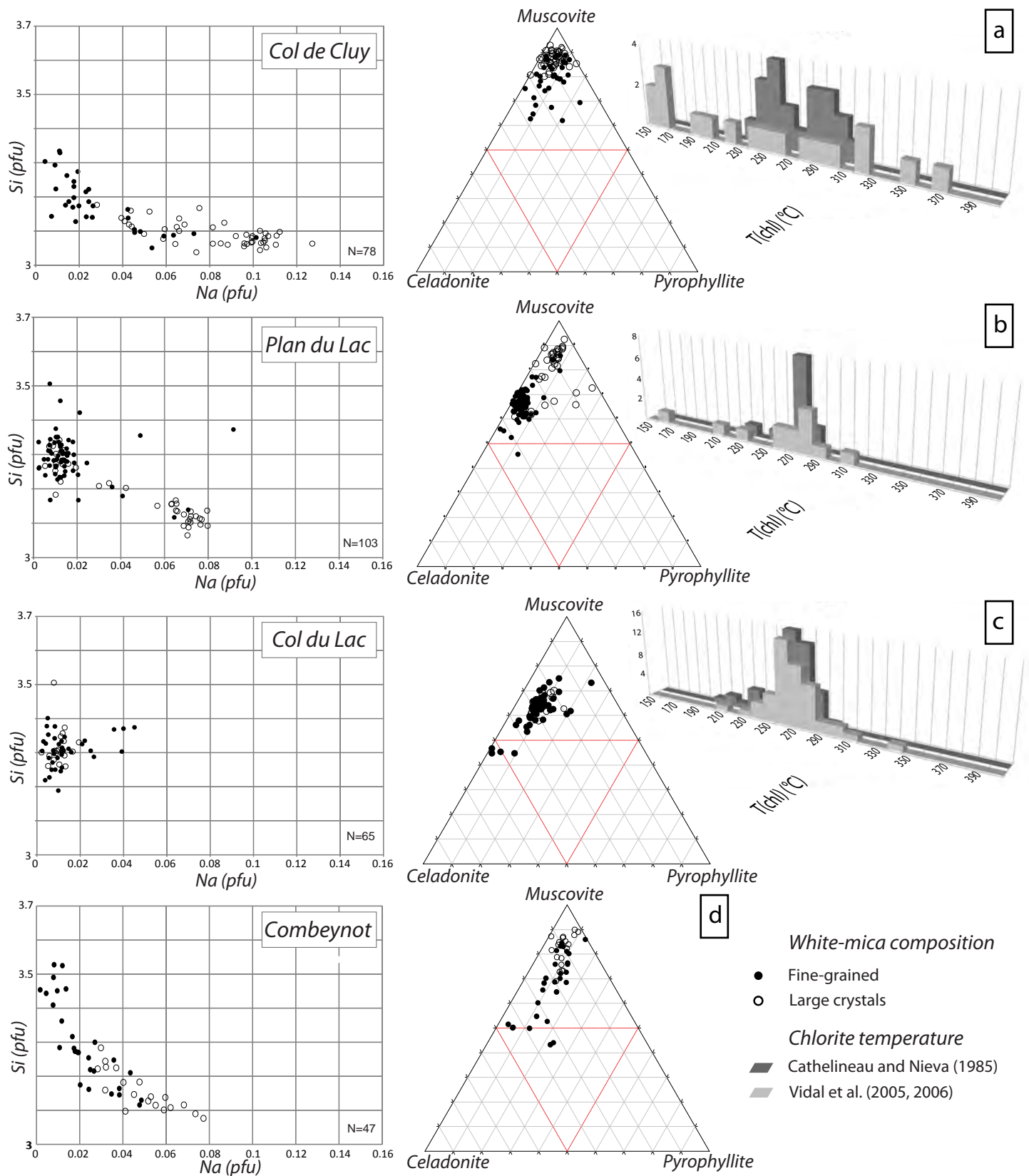


Figure 8

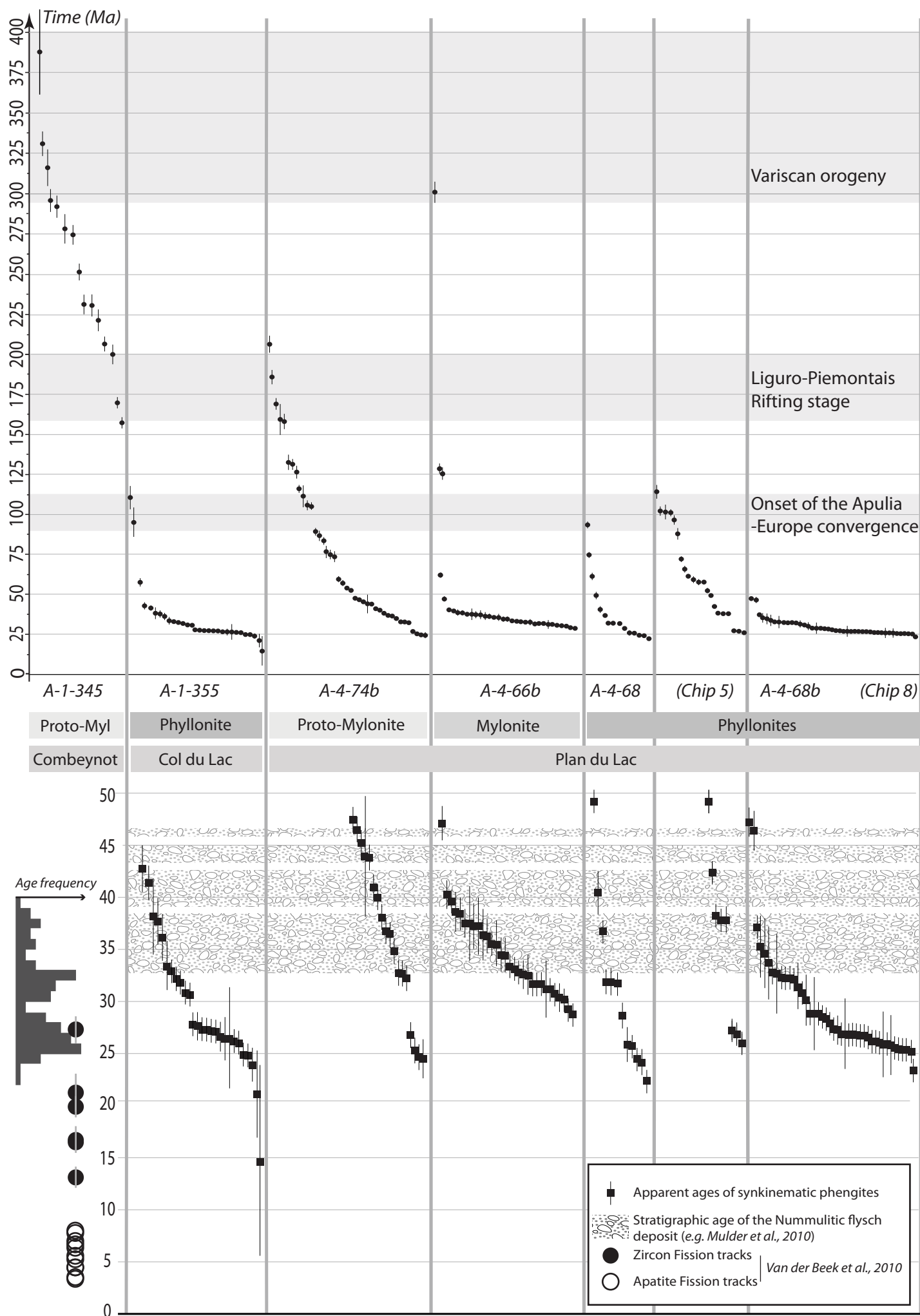


Figure 9

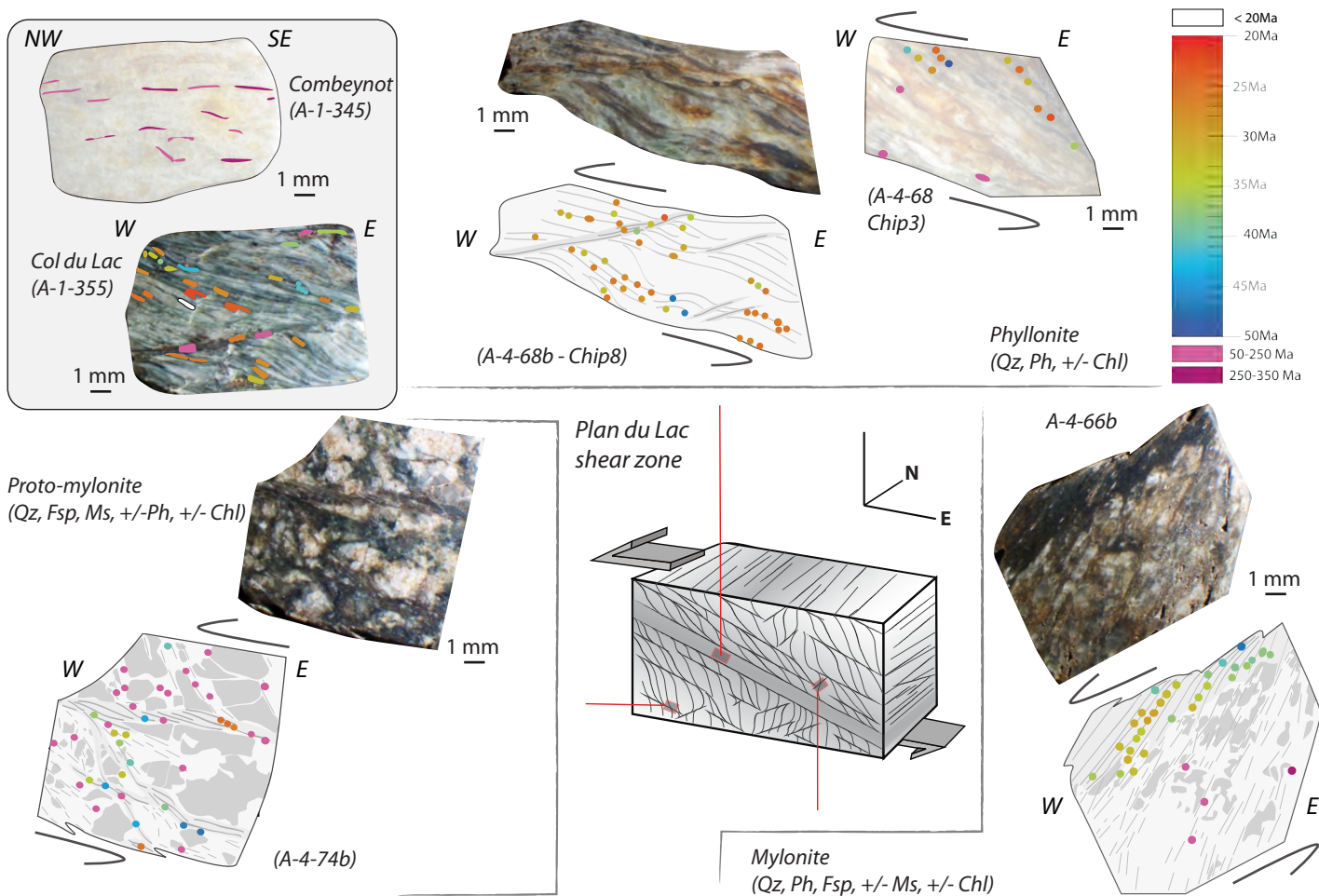


Figure 10

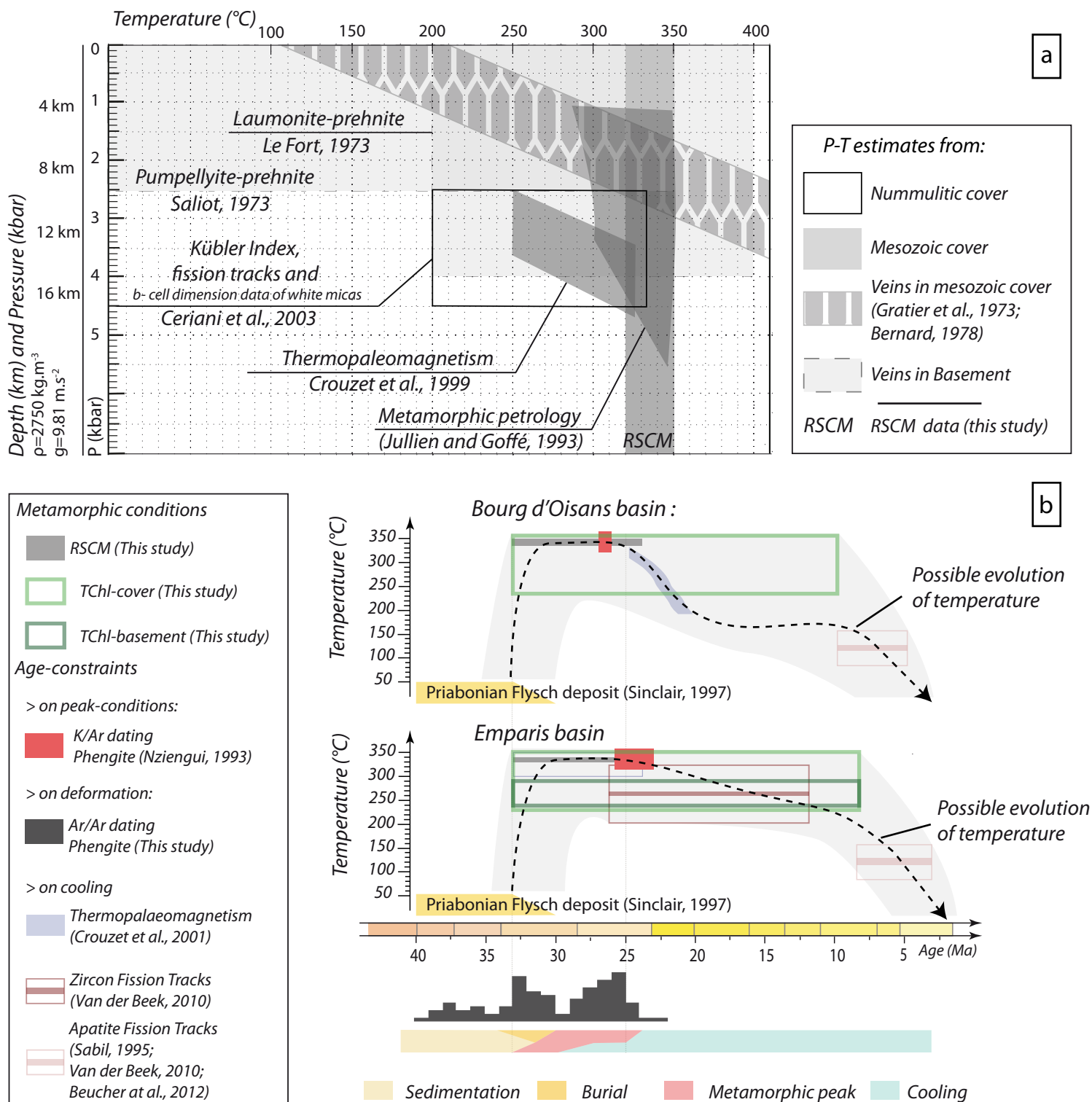


Figure 11

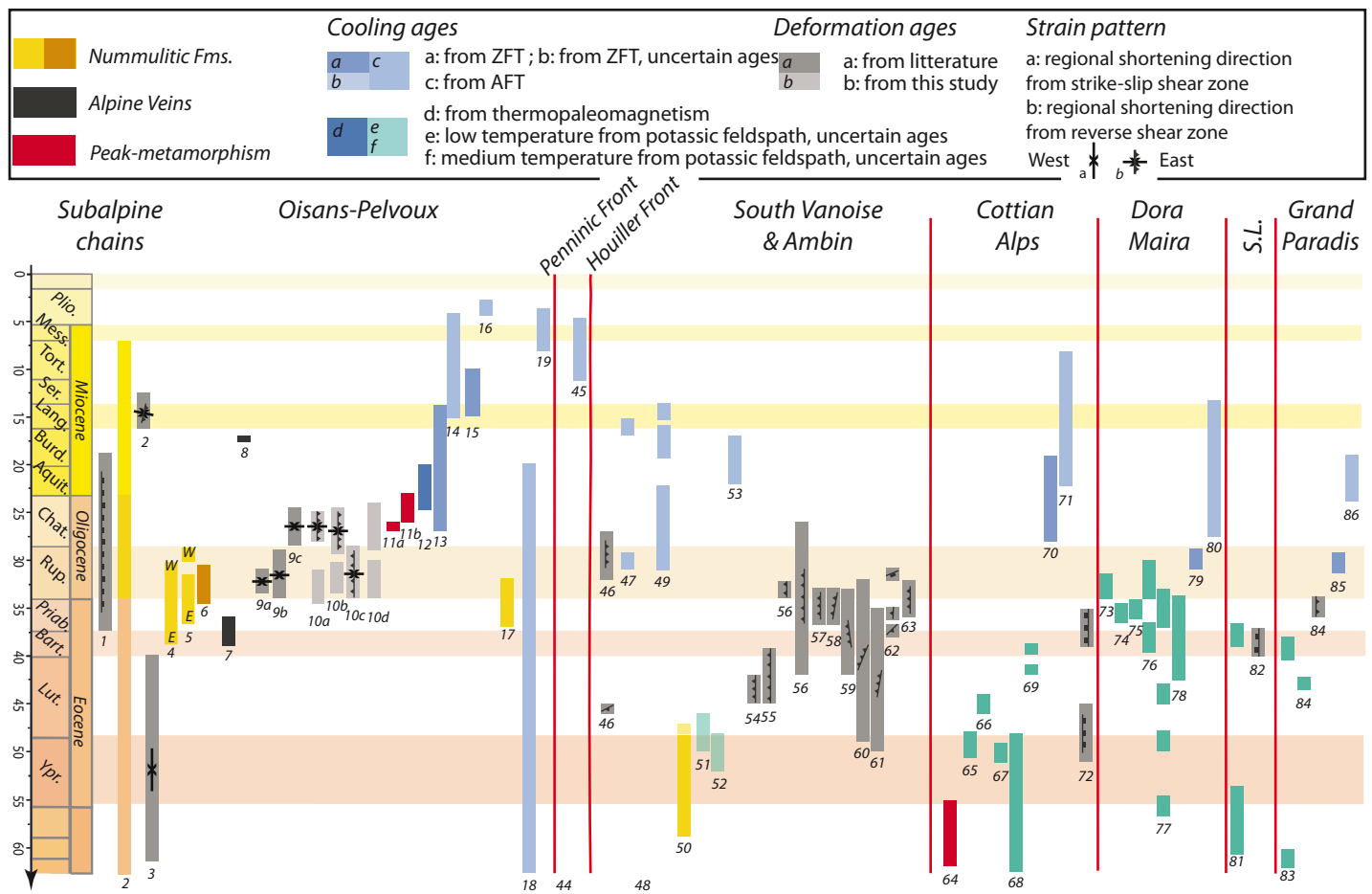
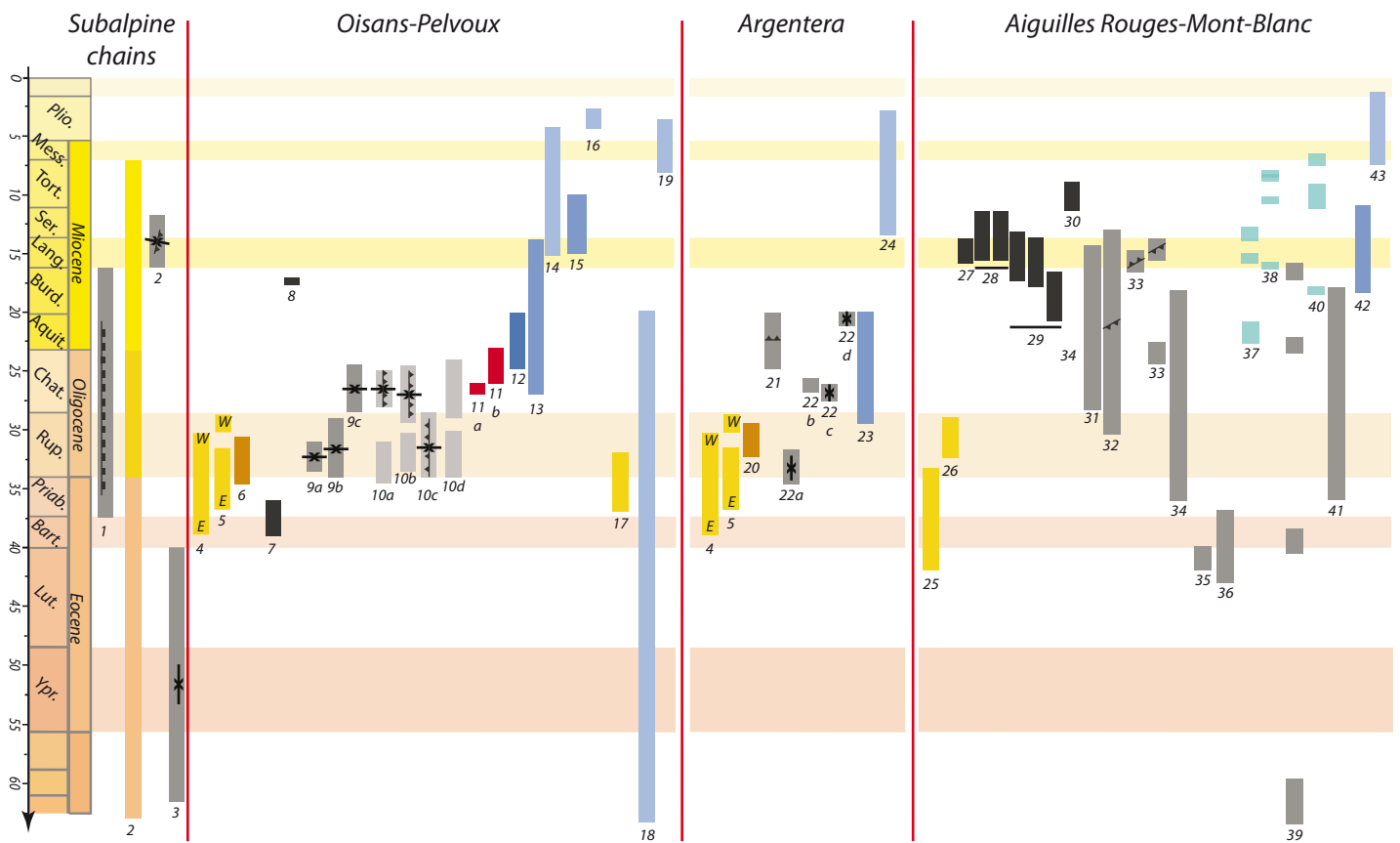
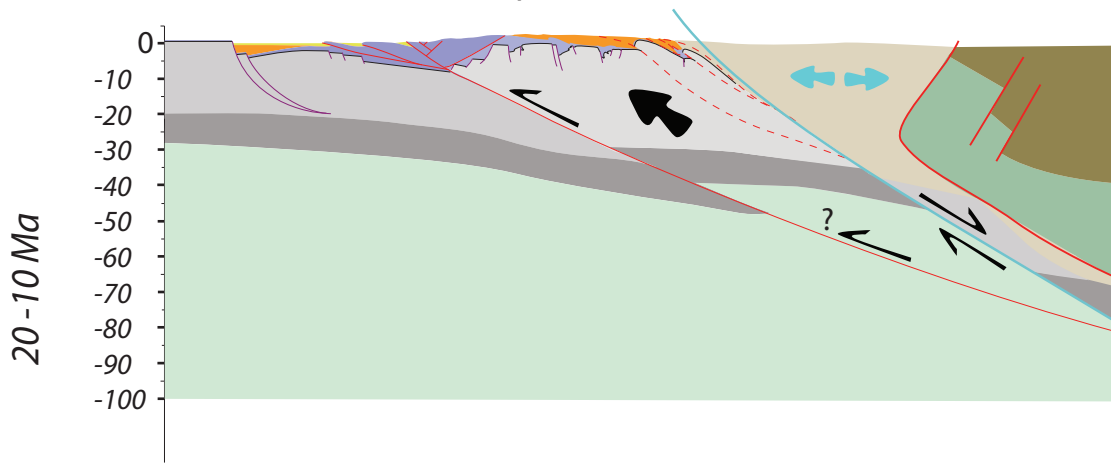
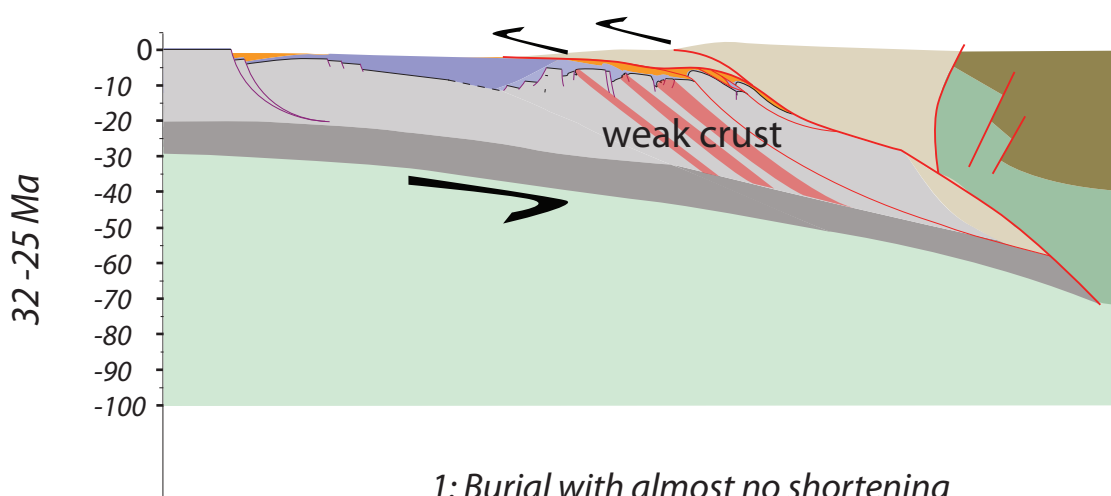


Figure 12

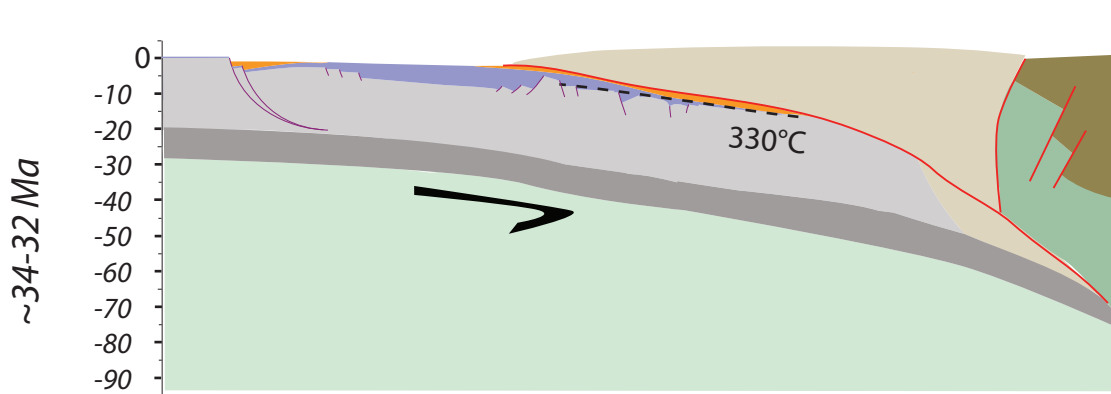
### 3: Crustal ramp and exhumation of the ECM



### 2: Internal shortening and progressive strain localisation



### 1: Burial with almost no shortening



European plate :

- Tertiary cover
- Mesozoic cover
- Upper crust

- Lower crust
- Mantle
- Penninic units

Apulian plate :

- Crust
- Mantle

Figure 13