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Comment on "Alpine thermal and structural evolution of the highest external crystalline massif: The Mont Blanc" by P. H. Leloup, N. Arnaud, E. R. Sobel, and R. Lacassin

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1. Introduction

[1] In this comment we discuss the approach used and the significance of Ar-Ar dating of synkinematic phengite within low-grade Alpine shear zones, and we comment the geodynamic models that can be derived from this method. The paper by *Leloup et al.* [2005] is a good step forward in the tectonic comprehension of the Mont Blanc area and provides a good synthesis of preexisting data. *Leloup et al.* [2005] have proposed a polyphase Alpine history for the Mont Blanc Massif (west Alps) based on a multidisciplinary approach: Ar-Ar on biotite for the higher pressure-temperature events of the Mont Blanc, and Ar-Ar on K-feldspar, fission tracks (FT) on zircon and apatite for its later exhumation stages. However, at this point of our knowledge of Alpine deformation in the Mont Blanc Range, the polyphased tectonic evolution, in particular the timing of thrust and back thrust events are not in agreement with recently obtained Ar-Ar data.

2. Structure

[2] The tectonic and kinematic part of the paper by *Leloup et al.* [2005] is constrained by structural and microtectonic analysis. An evolution balanced crustal-scale section is proposed, featuring the massif's evolution through time, which takes good account of available tectonic and structural data. However, analysis of deformation within the Mont Blanc Range shows that there is no evidence for a two-phase thrust/back thrust evolution. Deformation within the Mont Blanc is not restricted mainly to two shear zones but is also accommodated by numerous anastomosing shear zones in the way described by *Choukroune and Gapais* [1983] and *Gourlay* [1986], as is shown on Figure 1. Some major shear zones also occur in the central part of the massif, therefore it is difficult to tell which of the shear zones could be the major shear zone defined as the Mont Blanc shear zone (MBsz) by *Leloup et al.* [2005]. However, we agree that it should be on the west side of the massif. A great part of the deformation is also accommodated by flattening of the granite during the greenschist facies metamorphism. The foliation of the Mont Blanc granite is thus not a magmatic one.

3. P-T-t Data

[3] Although the P-T path proposed is a good synthesis of previously published data, the deformation history does not coincide with the Ar-Ar data that we have obtained [*Rolland et al.*, 2005; *Rossi*, 2005]. *Leloup et al.* [2005] have obtained Ar-Ar data on biotites from the so-called "undeformed granite" on the west and east sides of the massif, and Ar-Ar data on K-feldspar from "undeformed" and mylonitised granite. No Ar-Ar ages were undertaken on synkinematic minerals such as phengite. The results obtained on K-feldspar are extremely difficult to interpret as the authors agreed, even though they have succeeded to show some important feldspar reset during the Cenozoic thermal event. However, it remains difficult to date the timing of Alpine events due to excess Ar. The results on biotite have provided five plateau ages between 63.7 and 20.0 Ma. The discrepancy among biotite ages suggest that they have not been totally reset during the Alpine event, and so they do not reflect cooling ages because in such case relatively similar ages would be obtained across the massif. As shown by *Rossi et al.* [2005], the Alpine deformation is penetrative and affects the granite in a heterogeneous way. Preexisting Variscan minerals have increasingly recrystallized during the Alpine event from the relatively undeformed granite toward the center of shear zones. So it can be expected that they retain some of the original argon, which features either discordant Ar-Ar spectra (feldspar) or unexpectedly old ages (biotite). Consequently, the subsequent activation of the Mont Blanc sole thrust at 15 Ma, followed by the west MBsz at 9 Ma followed by activation of the east Mont Blanc back thrust after 5 Ma is not well supported by the

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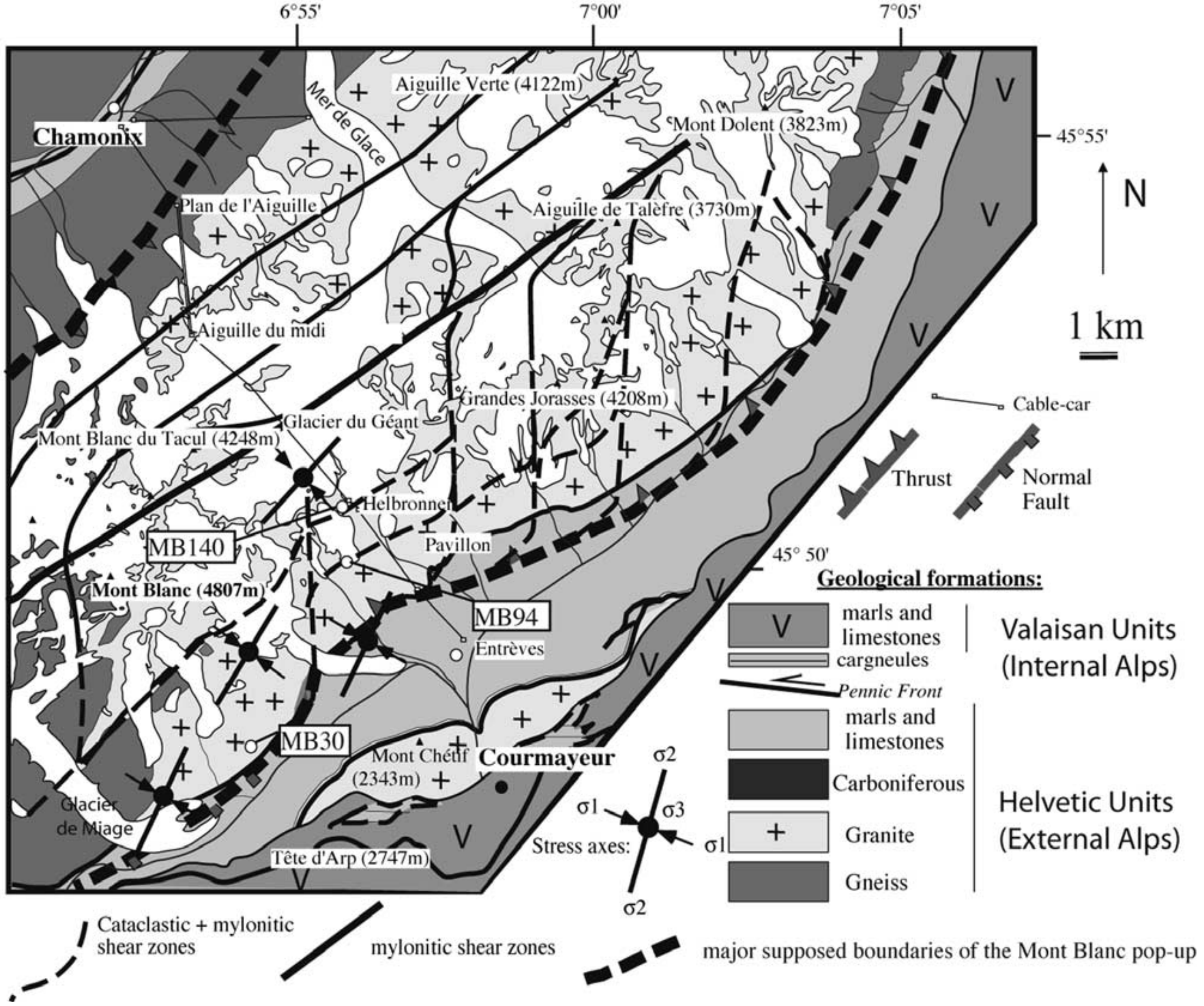

Figure 1. Sketch of geologic and structural map of the Mont Blanc Massif. The location of samples dated by Ar-Ar on phengite is indicated.

data. Constraining the ductile deformation/metamorphic age in the Mont Blanc thus necessitates dating minerals that crystallized during deformation. Precise P-T-t-deformation events must be constrained by thermobarometry performed on the same assemblages that can be dated by Ar-Ar and have crystallized as kinematic indicators. Such data are thus difficult to obtain in low-grade environments such as the Mont Blanc. In the following we show that we obtained such key data on the east side of the Mont Blanc ("back thrust"), which constrain east vergent motions since 16 Ma and not <5 Ma. These data allow us to complement the work of Leloup et al. and lead us to propose a one-phase continuous model of extrusion of the Mont Blanc massif within a transpressive pop-up system.

4. Methodology

[4] Mineral compositions of synkinematic micas, formed in pressure shadows around feldspar porphyroclasts (Figure 2) were determined by electron probe microanalysis (EPMA) to make comparisons of Ca/K ratios of synkinematic phengite with Ca/K ratios obtained by Ar-Ar dating [*Villa et al.*, 1997]. The analyses were carried out at 15 kV and 1 nA using a JEOL 6400 scanning electron microscope (SEM) equipped with an Oxford Instrument light electron diffusion spectrometer (EDS) detector and Link ISIS SEM-quant software, at the Australian National University Electron Microscopy Unit. Natural samples were used as standards.

[5] Geochronology was undertaken by laser ^{40}Ar/^{39}Ar dating. After having checked by EPMA that white mica was chemically homogeneous from core to rim, selected samples were crushed, and grains less than 1mm were separated by careful hand-picking under a binocular microscope. To prevent the presence of altered grains, only perfectly transparent aggregates were selected. The samples were irradiated in the nuclear reactor at McMaster University in Hamilton (Canada), in position 5c. ^{40}Ar/^{39}Ar analysis was

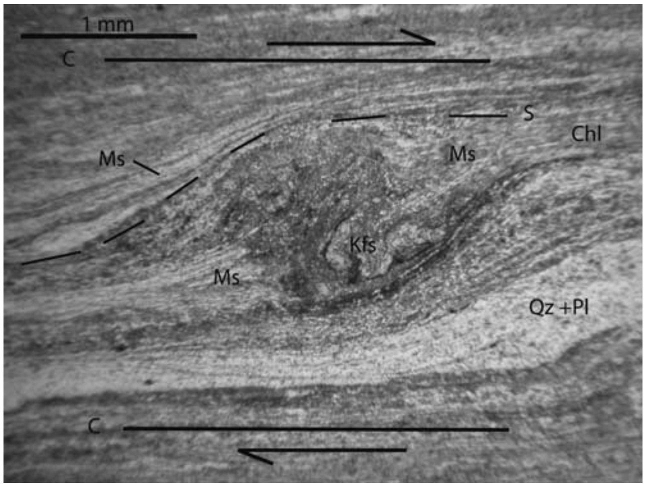

Figure 2. Photomicrograph of a mylonitic Helbronner shear zone (MB140). S-C relationships indicate top-to-SE sense of shear. The orientation of the section is NW–SE, vertical. Note the formation of phengite (Ms) at the expense of K-feldspar (Kfs) clasts. Chl, chlorite; Pl, plagioclase; Qz, quartz.

carried out by single-grain analysis with a 50 W SYNRAD CO_2 continuous laser. Isotopic ratios were measured using a VG3600 mass spectrometer, working with a Daly detector system, in the University of Nice (Géosciences Azur, France). The typical blank values for extraction and purification of the laser system are in the range 4.2–8.75, 1.2–3.9 cm^3 STP for masses 40 and 39, respectively. Decay constants are those of *Steiger and Jäger* [1977]. Uncertainties on apparent ages are given at the 1σ level and do not include the error on the $^{40}Ar^{*}/^{39}Ar_k$ ratio of the monitor. Uncertainties on plateau and miniplateau ages are given at the 2σ level and do not include the error on the age of the monitor.

5. Examples of Results

[6] The so-called "Mont Blanc back thrust" is a complex SE verging shear zone network that outcrops from the Hellbronner cable-car station to the SE crystalline/sedimentary cover contact. We have sampled three points of this large shear zone complex (Figure 1), on its NW rim, the Hellbronner site (sample MB140), in the Toula area (sample MB94, zone described by *Guermani and Pennacchioni* [1998]), and more to the SW, under the Boccalate Hut (sample MB30). In the three zones, white mica is formed at the expense of feldspars (Figure 2) by the following reactions:

$$3\ \mathrm{NaAlSi_3O_8} + \mathrm{K^+} + 2\ \mathrm{H^+} = \mathrm{KAl_3Si_3O_{10}(OH)_2} + 6\ \mathrm{SiO_2} + 3\ \mathrm{Na^+}$$

$$\text{albite} + \text{K–bearing acid fluid} = \text{muscovite} + \text{quartz}$$

$$+\ \text{Na–bearing basic fluid}$$

$$3\ \mathrm{KAlSi_3O_8} + 2\ \mathrm{H^+} = \mathrm{KAl_3Si_3O_{10}(OH)_2} + 6\ \mathrm{SiO_2} + 2\ \mathrm{K^+}$$

$$\text{orthoclase} + \text{acid fluid} = \text{muscovite} + \text{quartz}$$

[7] Phengite crystallizes synkinematically in pressure shadows on the sides of feldspars porphyroclasts, in the $\sigma 3$ direction (Figure 2) [see also *Guermani and Pennacchioni*, 1998]. This $\sigma 3$ direction corresponds to that of a steep mineral lineation measured in the field (W70° on a N45°E – 70 N foliation plane). Kinematic indicators are thus in agreement with a top-to-SE sense of shear, with a slight dextral component in the SW–NE direction.

[8] Ar-Ar ages obtained on phengite pressure shadow aggregates were similar in different grains of individual shear zones (duplicated results of samples MB94 and MB140, Figure 3), and in different shear zones on the eastern side of the massif (MB30, MB94 and MB140. The 2σ plateaus and small plateaus ages obtained for the four Ar-Ar spectra, are similar at 15.8–16 ± 0.2 Ma. Ca/K ratios were globally similar during the analyses (of the order of 10^{-3}), and similar to EPMA Ca/K ratios.

[9] In addition, as shown by our own data presented here, even in the case of pure aggregates, the lower temperature part of the spectra shows a staircase shape. These younger step ages are likely to reflect ^{39}Ar loss due to later reactivations, or to fluid percolation through in shear zones after deformation. Large fluid fluxes in shear zones are indicated by geochemical change during deformation [*Rolland et al.*, 2003]. Current fluid fluxes of several $m^3\ s^{-1}$ were measured in the continuity of MB140 and MB94 shear zones, when the Mont Blanc tunnel was dug [*Maréchal and Perrochet*, 2001].

6. Discussion of the Age of Deformation in the Mont Blanc Massif

[10] Deformation in the Mont Blanc back thrust system is clearly top-to-the-SE reverse sense of shear, with a slight dextral component (lineations plunge 60–90° [*Rossi et al.*, 2005]). P-T calculations made previously in the same shear zones (MB140 [*Rolland et al.*, 2003]) indicate 5 ± 0.5 kbar and 400 ± 25°C, which are maximal PT conditions obtained for the Mont Blanc. Therefore, as phengite growth occurred in pressure shadows on K-feldspar prorphyroclasts (Figure 2) at a temperature close to its closure temperature, it is expected that Ar-Ar dating of phengite will provide a close estimate (or at least a minimum age) of deformation. Therefore it is clear that top-to-the-SE motions on the SE side of the Mont Blanc initiated at least at 15.8–16.0 ± 0.2 Ma. This result is in agreement with the previous datings of vein minerals by K-Ar [*Leutwein et al.*, 1970], yielding 15.2–18.3 Ma (Adularia), 13.4–15.2 Ma (Muscovite), ages for mineral growth in large veins being expected to be slightly younger than in shear zones. It is also similar to Ar-Ar ages of white mica within shear zones of the Mont Blanc sedimentary cover (14.6–18.5 Ma [*Crespo-Blanc et al.*, 1995; *Kirschner et al.*, 1996]). On the basis of the similarity of metamorphic assemblages and age conditions to the east and west of the Mont Blanc, we propose that deformation was synchronous on the two sides of the massif. Ductile deformation dated by both shear zones and veins is in the range 14–18 Ma. The simultaneity of deformations on both sides of the massif is thus in agreement with the interpretation of a pop-up

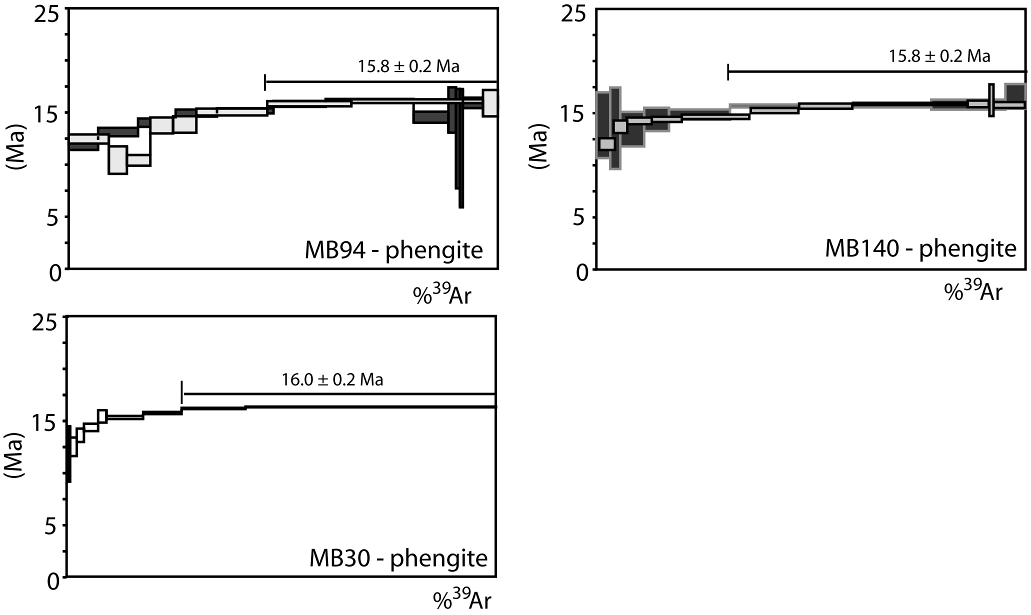

Figure 3. The ^{40}Ar-^{39}Ar spectra of synkinematic pressure shadow phengites of various locations of the SE Mont Blanc slope (see Figure 1 for location).

structure for the Mont Blanc massif as proposed earlier by *Von Raumer* [1974] and *Bertini et al.* [1985] and excludes the two-stage thrust and back-thrust scheme proposed by Leloup et al. On Figure 12 of their paper, there is no reason to activate the west MBsz after 15 Ma nor the east back thrust after 5 Ma. In other words, the tectonic style drawn on Figure 12g should be set since 15 Ma (Figure 12d). On the basis of the P-T-t data, it appears that the massif was exhumed at a continuous rate of $\sim$1 mm yr^{-1} since 16 Ma, which is the rate obtained using both Ar-Ar data and FT data [*Seward and Mancktelow*, 1994; *Leloup et al.*, 2005]. On the basis of these new data, and also on the fact that there is no jump in FT ages across the Mont Blanc Range, we propose that the tectonic context of the Mont Blanc Massif did not change significantly since 16 Ma. The transpressive pop-up structure reflects the deformation on the rim of a large transpressive fault that runs from the Rhone dextral fault system, where the dextral motion is partly transferred to west verging thrusting [e.g., *Hubbard and Mancktelow*, 1992]. As in Figures 12d–12f of *Leloup et al.* [2005], we assume that most of the west verging tectonic transport is accommodated by the thrust system on the west side of the massif.

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