Reply to comment by Y. Rolland et al. on "Alpine thermal and structural evolution of the highest external crystalline massif: The Mont Blanc"

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1. Introduction

[1] *Leloup et al.* [2005] discussed the Cenozoic structural evolution of the Mont Blanc and Aiguilles Rouges ranges by combining new structural, ^{40}Ar/^{39}Ar, and fission track data with published P-T estimates and geochronological data. Our main conclusions were (1) Alpine exhumation of the Aiguilles Rouges was limited to the thickness of the overlying nappes ($\sim$10 km), while rocks now outcropping in the Mont Blanc have been exhumed 15 to 20 km. (2) Uplift of the two massifs started $\sim$22 Myr ago; while at 12 Ma, the Mont Blanc shear zone (MBsz), a reverse fault with a slight right-lateral component, initiated bringing the Mont Blanc above the Chamonix synclinorium and the Aiguilles Rouges; total vertical throw on the MBsz is between 4 and 8 km. (3) Fission track data suggest that relative motion between the Aiguilles Rouges and the Mont Blanc stopped 4 Myr ago. Since that time, uplift of the Mont Blanc has mostly taken place along the Mont Blanc back thrust, a steep north dipping fault zone bounding the southern flank of the range. (4) The highest summits are located where the back thrust intersects the MBsz. (5) Exhumation of the Mont Blanc and Aiguilles Rouges occurred toward the end of motion on the Helvetic basal décollement (HBD) at the base of the Helvetic nappes. Uplift is linked with a deeper, more external thrust that induced the formation of the Jura arc.

[2] While acknowledging that our paper is "a good step forward in the tectonic comprehension of the Mont Blanc area and provides a good synthesis of preexisting data," *Rolland et al.* [2007] claim that the timing we propose for the thrust and back thrust events is not in agreement with new ^{40}Ar/^{39}Ar data that they publish in their comment. In fact, they raise two main arguments with our observations/interpretations:

[3] 1. Alpine deformation is penetrative within the Mont blanc granite and is not accommodated by the two localized shear zones we describe (the SE dipping Mont Blanc shear zone, or MBsz, in the north and the NW dipping back thrust in the south, Figure 1), but by numerous anastomosed shear zones in the way described by *Choukroune and Gapais* [1983] in the Aar massif and *Gourlay* [1986] in the Mont Blanc. All deformations within the Mont Blanc are thus coeval and the Mont Blanc is a transpressive pop-up structure at the rim of a large transpressive fault that runs from the Rhone dextral fault system.

[4] 2. The timing of deformation cannot be obtained through ^{40}Ar/^{39}Ar thermochronology due to excess argon and intense fluid circulation. They instead provide a minimum age of 16 Ma for the initiation of top to the SE motions on the SE side of the Mont Blanc (back thrust) based on five phengites ^{40}Ar/^{39}Ar ages from three shear zones (their Figure 3).

[5] We will take the opportunity of this reply to address these two points and, in a third point, we briefly discuss possible deformation models of the Mont Blanc range.

2. Alpine Structures in the Mont Blanc Range

2.1. Are All Structures of the Mont Blanc Granite due to Alpine Deformation?

[6] Some authors ascribe most deformation of the Mont Blanc range to the Variscan orogeny and restrict Alpine deformation to small-scale brittle faults and the Faille d'Angle fault bounding the Mont Blanc granite to the NE (Figure 1a) [e.g., *Bellière*, 1988]. One important point of our work was to emphasize the importance of alpine deformation and shear zones within and at the margins of the range. *Rolland et al.* [2007] go even further, stating that all foliations within the Mont Blanc granite result from Alpine flattening. However, there are indeed Variscan deformation in the Mont Blanc range that must be distinguished from Alpine deformation, the tricky point being that both schistosities have nearly the same directions.

[7] On the NW flank of the Mont Blanc, migmatitic gneisses are crosscut by the Mont Blanc granite and by

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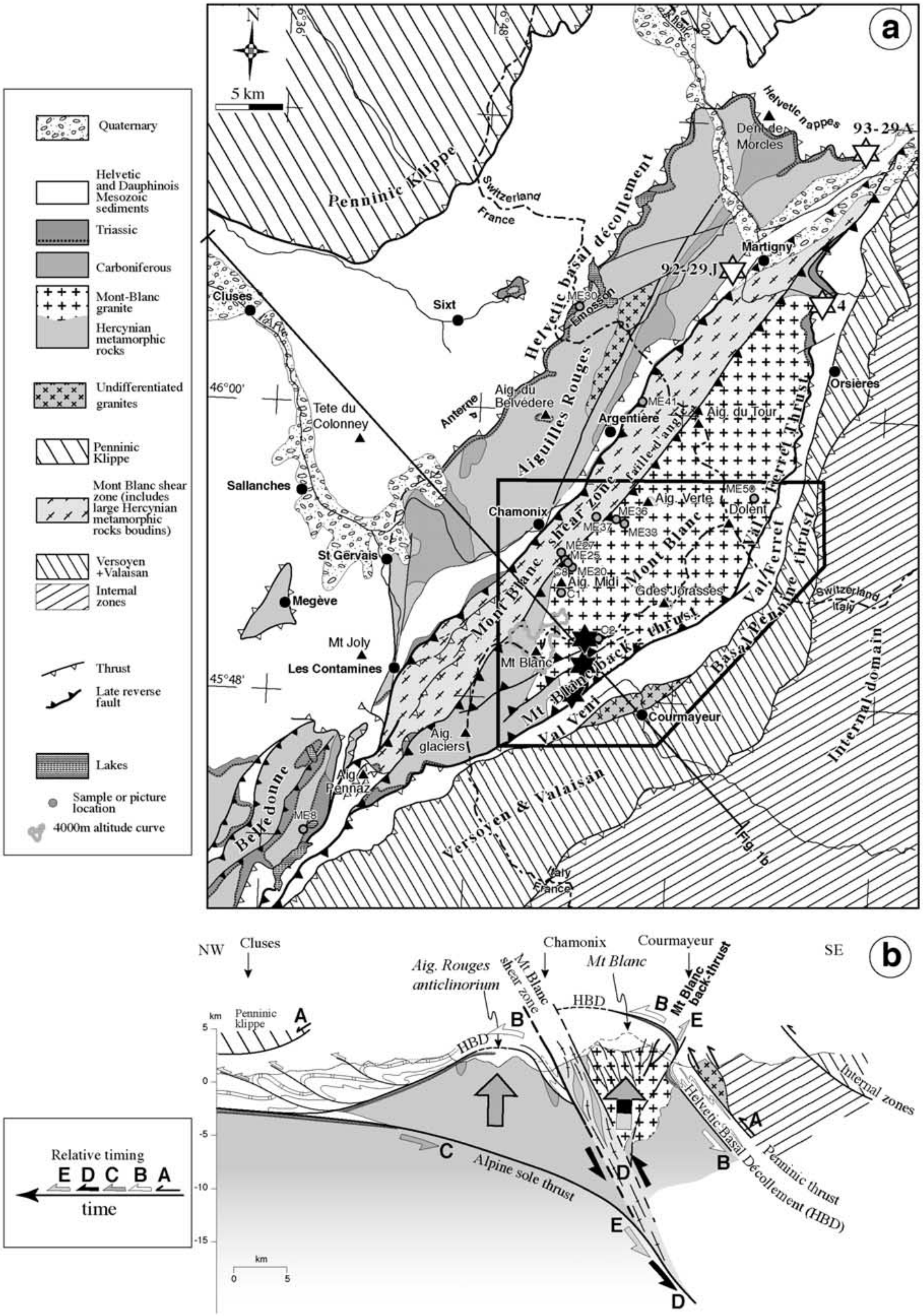
a
5 km
Quaternary
Helvetic and Dauphinois Mesozoic sediments
Triassic
Carboniferous
Mont-Blanc granite
Hercynian metamorphic rocks
Undifferentiated granites
Penninic Klippe
Mont Blanc shear zone (includes large Hercynian metamorphic rocks boudins)
Versoyen +Valaisan
Internal zones
Thrust
Late reverse fault
Lakes
Sample or picture location
4000m altitude curve
Penninic Klippe
Switzerland
France
Helvetic basal décollement
Helvetic nappes
Dent de Morcles
93-29A
92-29J
Martigny
Cluses
Sixt
Emosson
ME30
Aiguilles Rouges
Aig. du Belvédere
Anterne
Tete du Colonney
46°00'
ME41
Argentière
Aig. du Tour
Orsières
Sallanches
Chamonix
Aig. Verte
Dolent
ME36
ME37
ME33
Mont Blanc shear zone
Mont Blanc
Val Ferret thrust
St Gervais
Megève
Aig. Midi
Gdes Jorasses
Switzerland
Italy
Mt Joly
Les Contamines
Mt Blanc
Mt Blanc back thrust
Basal Pennine thrust
45°48'
Val Veni
Courmayeur
Aig. glaciers
Aig. Pennaz
Belledonne
ME8
Versoyen & Valaisan
Internal domain
Fig. 1b
Italy
France
b
NW
Cluses
Chamonix
Courmayeur
SE
Aig. Rouges anticlinorium
Mt Blanc shear zone
Mt Blanc
Mt Blanc back-thrust
Penninic klippe
HBD
Internal zones
Helvetic Basal Décollement (HBD)
Penninic thrust
Alpine sole thrust
km
Relative timing
E D C B A
time

Figure 1

aplitic veins, prior to having been affected by greenschist Alpine deformation [see *Leloup et al.*, 2005, Figures 3b and 3h]. In the absence of radiometric data from the dikes, we assumed that as in many places in the External Crystalline Massifs, they are related with late stages of the granite emplacement and probably have an upper Stephanian age as it is the case in the Pelvoux [e.g., *Strzerzynski et al.*, 2005]. This implies that the migmatitic gneisses are Variscan in age. The geometry of the Variscan deformation is clear in the Aiguilles Rouges, where alpine metamorphism and deformation were mild, and in large boudins preserved from alpine deformation within the MBsz. In these zones, foliations (S1) are steep, strike N335 to N55 (N20 on average) and when present, the stretching lineation plunges relatively shallowly [*Leloup et al.*, 2005, Figure 4b]. Variscan (S1) and alpine (S2) foliations cannot be distinguished simply by their strikes because they are close to each other and both vary significantly around a mean value (compare Figures 4a and 4d of *Leloup et al.* [2005]). We ascribed an alpine age to all greenschist foliations bearing a downdip lineation and a Variscan age to higher temperature foliations without, or with shallowly plunging lineation. Aplitic dikes systematically cut the Variscan foliations, but are affected by the alpine ones.

[8] Within the Mont Blanc granite, a high-temperature foliation (S1) that we termed "magmatic foliation" is defined by the alignment of feldspar porphyroclasts and the flattening of restitic enclaves (Figure 2). S1 strikes N-S to NE-SW, does not bear any lineation and is crosscut by undeformed aplitic dikes (Figure 2). This implies that the penetrative deformation of the Mont Blanc granite (S1) is late Variscan. However, both the granite and the aplitic veins are affected by numerous greenschist shear zones and faults that postdate the magmatic foliation and that most probably corresponds to Alpine deformation.

2.2. Geometry of the Alpine Shear Zones Within the Mont Blanc Granite: One or Several Deformation Phases?

[9] *Rolland et al.* [2007] argue that the geometry of the alpine shear zones in the Mont Blanc is analogous to that of the Aar range described by *Choukroune and Gapais* [1983] and reflects a single phase of NW-SE shortening. Despite several studies [*Bellière*, 1956, 1988; *Bertini et al.*, 1985; *Gourlay*, 1986; *Rolland et al.*, 2003; *Rossi*, 2005], the detailed geometry and the amount of shortening of the deformations affecting the core of Mont Blanc granite is still unclear. This is partly due to access difficulties in the highest part of the range, and partly because structures ranging from mylonites to small brittle faults have been mixed together and inappropriately analyzed with the same tools. For example, *Bertini et al.* [1985] present an analysis of "striated fault planes" that obviously include numerous ductile shear zones, while *Rossi* [2005, Figure II-3] mixes faults and shear zones to calculate stress directions using *Angelier*'s [1990] method, although this should be restricted to microfaults with minor offsets. In the same way, *Rolland et al.* [2007] identify the stretching lineation as the $\sigma3$ stress axis, an assumption that is clearly incorrect in shear zones [e.g., *Ramsay and Huber*, 1983].

[10] What is clear, however, is that the main alpine shear zones are steep, show reverse sense and roughly parallel the main boundaries of the Mont Blanc range: the ~N35°E, SE dipping MBsz to the NW and the ~N50°E NW dipping back thrust to the SE (Figure 1a). At the scale of the range, the shear zones have an upward diverging fan-like geometry on NW-SE cross sections (Figure 1b) [also see *Bertini et al.*, 1985, Figure 3; *Rossi*, 2005, Figure II-4]. Near the MBsz, all alpine shear zones dip SE, implying a top to the NW thrusting of the Mont Blanc [*Gourlay*, 1986; *Leloup et al.*, 2005]. Symmetrically, most shear zones dip to the NW near the back thrust [e.g., *Guermani and Pennacchioni*, 1998]. Such a geometry is fundamentally different to that of the core of the Aar range, where shear zones are anastomosed at the scale of few tens of meters, with conjugate shear zones of opposite dips merging around less deformed lenses [*Choukroune and Gapais*, 1983].

[11] What is important for evaluating the structural history of the Mont Blanc range is to determine whether all shear zones and faults are coeval and result from a single deformation episode. This hypothesis appears to be sustained by the large-scale geometry, with the MBsz and the back thrust resembling conjugate faults. However, these faults are not strictly parallel and, cartographically, the back thrust is much shorter than the MBsz (Figure 1). In the absence of unambiguous relative or absolute timing for the shear zones, several lines of evidence lead us to infer that the back thrust was (or is still) active more recently than the MBsz: (1) the back thrust borders the highest summits of the range (Figure 1), suggesting that it has a strong influence on the topography; (2) the main back thrust contact of the Mont Blanc granite on top of the sedimentary series is brittle, exhibiting cataclasitic granite [see *Leloup et al.*, 2005, Figure 3e], thus suggesting that deformation occurred late in the uplift history of the range; (3) at a given altitude (i.e., along the Mont Blanc tunnel) fission track ages get younger toward the SE and reach 2.8 ± 0.5 Ma near the back thrust [see *Leloup et al.*, 2005, Figure 11b]; we took this as evidence for very recent uplift on the back thrust; and (4) in the north of the range, where there is no back thrust, the Triassic unconformity, still visible on the top of the Mont Blanc granite (Figure 1), dips ~65° to the east as does the overlying series. This passive tilting of the eastern flank of the Mont Blanc range indicates that, in the northern part

Figure 1. Structure of the Mont Blanc massif. Modified from Figure 2 of *Leloup et al.* [2005]. (a) Structural map of the Mont Blanc massif. The black frame corresponds to Figure 1 of *Rolland et al.* [2007]. Black stars are samples from *Rolland et al.* [2007], MB140, MB94, and MB30 from north to south. White stars are samples from *Kirschner et al.* [1996] 93-29A and 93-29J, and *Crespo-Blanc et al.* [1995], 4. Black circles with gray filling are argon samples from *Leloup et al.* [2005]. (b) Synthetic cross section of the Mont Blanc massif. Note that this section is compatible with recent gravity data of the area [*Masson et al.*, 2002]. The geometry of the shear zones within the granite is crudely depicted.

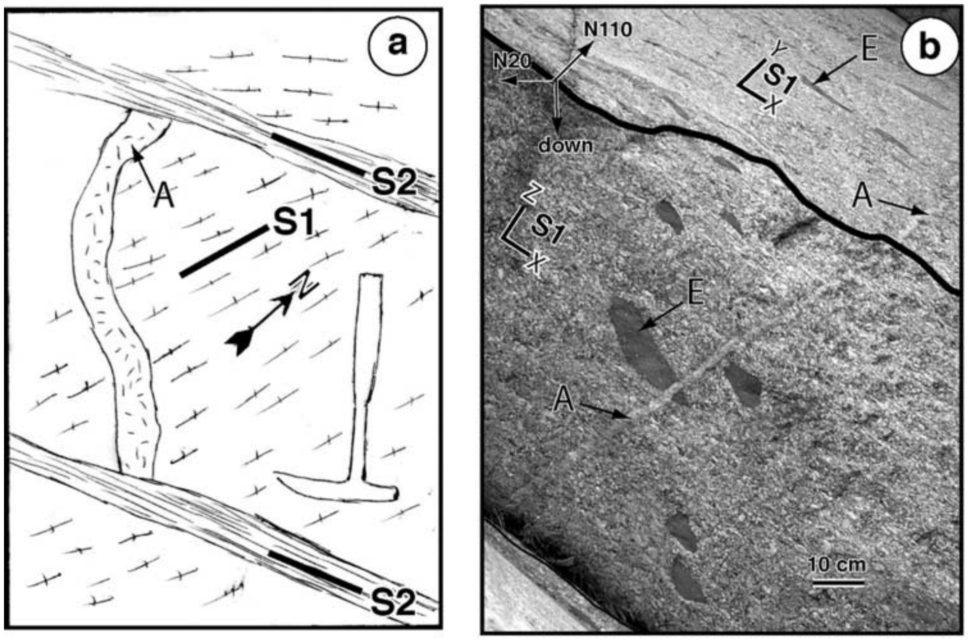

Figure 2. Late Variscan high-temperature foliation in the Mont Blanc granite. (a) Sketch of an aplitic dike (A) crosscutting the Mont Blanc granite "magmatic" foliation S1. S1 and the dike are crosscut by two alpine shear zones (S2). Eperon des géographes above the Leshaux glacier. Horizontal plane, view from above. Hammer gives scale. (b) Undeformed aplitic dike cutting across a flattened (S1) enclave of the Mont Blanc granite. North bank of the Leshaux glacier under the Talèfre glacier. View toward the east of two perpendicular planes: N20 vertical and N110 30S.

of the range, thrusting that drove vertical movement only occurred along the MBsz. Our assertion was that, more to the south, the geometry was similar prior to the initiation of the back thrust. We thus assumed a late activation of the back thrust with respect to the MBsz on our sequential history, depicted in Figure 12 of *Leloup et al.* [2005] However, from structural arguments, it cannot be definitively excluded that the MBsz and the Back thrust initiated coevally and that the back thrust remained active until more recently.

3. Timing of Deformations: Thermochronology Versus ^{39}Ar/^{40}Ar Dating of White Micas

[12] From a compilation of geochronological ages we proposed a global thermochronological history with an onset of significant cooling around 22 Ma [*Leloup et al.*, 2005, Figure 8] that we interpret as the onset of exhumation of the Mont Blanc and Aiguilles Rouges. In the same way, we interpret the high number of LT Kf ages around 12 Ma as representing the timing of initiation of the MBsz. It is true that low-temperature geochronology is difficult in the Mont Blanc because of the strong Variscan inheritance, the relatively mild alpine metamorphism (~400°C) [*Poty et al.*, 1974; *Marshall et al.*, 1998; *Rolland et al.*, 2003], and the fluid circulation overprint. *Rolland et al.* [2007] propose to date the top to the SE deformation by using ^{39}Ar/^{40}Ar dating of synkinematic white micas. The great advantage of that method is to associate an age with a given structure, not with a cooling history. However, each approach has its own pitfalls and one must be cautious prior to reaching definite conclusions.

[13] 1. Dated white micas are claimed to have crystallized in pressure shadows of Kf porphyroclasts. This is obviously not the case in the picture provided by *Rolland et al.* [2005, Figure 2], where white micas follow the foliation. This does not prove that these micas did not crystallize during top to the east shearing but suggests that they could have formed during a previous deformation stage and were later reoriented, thus giving the age of another deformation event.

[14] 2. Analyzing aggregates after crushing, despite careful selection, leaves open the possibility of sampling parts of older micas, as it is the case when working on populations. Only direct dating on thin section could avoid this problem. A simple calculation shows that contamination from only 3% of Variscan (~300 Ma) white mica with similar K content to the alpine ones will shift a ~5 Ma age to ~15 Ma. We note that no real plateau was achieved from the phengites and that all samples yield low-temperature ages around 12 Ma, which is attributed to possible Ar loss during later deformation or fluid percolation. However, an intimate mix of ~12 Ma old micas with older preserved ones would probably produce the same shape of spectra.

[15] 3. Finally, cooling ages and dating of synkinematic minerals need not be in opposition but should be discussed in concert. Indeed, *Rolland et al.* [2007] agree that the ages of their micas provide a minimum constraint on the age of deformation and possibly record cooling rather than defor-

mation, and their ages (~16 Ma) fall at the time we infer for major cooling linked to exhumation. It is possible, therefore, that dated white micas formed during an earlier deformation event, and recorded cooling at ~15 Ma associated with a major phase of Mont Blanc exhumation.

[16] In order to validate their ages, *Rolland et al.* [2007] stress that these are close to those obtained on white micas within shear zones of the Mont Blanc sedimentary cover [*Crespo-Blanc et al.*, 1995; *Kirschner et al.*, 1996]. However, the age of 15.5 Ma of *Crespo-Blanc et al.* [1995] corresponds to the end of west verging thrusting of Helvetic sediments on top of the Mont Blanc along the Val Ferret thrust (Figure 1). That thrust has a different strike and an opposite vergence than the Mont Blanc back thrust. In the same way, *Kirschner et al.* [1996] date the end of motion at the base of the NW verging Morcles and Doldenhorm Helvetic nappes (Figure 1). This has no direct connection with the age of initiation of motion along the SE verging Mont Blanc back thrust.

[17] The ~16 Ma ages of *Rolland et al.* [2007] could correspond to cooling below 390 ± 45°C during the initial stage of the alpine Mont Blanc uplift rather than the activation of the Mont Blanc back thrust. Alternatively, considering an initiation of motion on the back thrust at ~16 Ma would only imply that exhumation on top of the basal décollement has been accommodated in part by the back thrust since the beginning, not postponed until ~4 Ma, as we originally proposed.

4. Alpine Deformations of the Mont Blanc Range: Push-up Within a Dextral Strike-Slip Shear Zone or Culmination Above an Alpine Basal Thrust?

[18] Finally, the last issue invoked by *Rolland et al.* [2007] is to state, without much discussion, that the new ages they present imply that the Mont Blanc is a push-up along a major dextral shear zone, dismissing our interpretation of a culmination above a basal thrust. Note first that the northern half of the range and its southern extremity do not have a symmetrical shape. It is only where the back thrust is present that the Mont Blanc range forms a crustal-scale pop-up (Figure 1). Furthermore, evidence for significant long-lasting (>16 Myr) strike-slip shear in the Mont Blanc range and along its sides are very weak. In any case, there are no new arguments in the work of *Rolland et al.* [2007] to support major NE-SW dextral strike-slip motion absorbed within the Mont Blanc. Kinematics of the MBsz, with pitches of lineations larger that 70°, suggests a maximum of 2 km of dextral motion compared with the ~26 km of NW-SE shortening absorbed in the Jura arc during that time interval [*Leloup et al.*, 2005, and references therein]. Similarly, structural evidence for major right-lateral shear in the SE part of the range is weak. There, the lack of stretching lineations render the precise direction of shearing difficult to constrain, but most shear zones display shear criteria suggesting top to the SE (dip slip) thrusting [*Guermani and Pennacchioni*, 1998]. The brittle faults that affect the granite are mostly parallel to the Mont Blanc back thrust and often show dip slip motions; only a few brittle faults that reactivate schistosity planes in the Val Veni sedimentary series show dextral motion [see *Leloup et al.*, 2005, Figure 6].

[19] The idea of major continuous dextral motion in the Mont Blanc since the middle Miocene still await convincing structural evidences, although a complex connection of the Mont Blanc thrusts with the Rhône-Valais strike-slip zone and with the Simplon normal fault in a way comparable to that described by *Lacassin* [1986] probably exists.

5. Conclusion

[20] To answer to the main points raised by *Rolland et al.* [2007], we make the following conclusions:

[21] 1. Some of the foliations observed in the Mont Blanc granites are pre-Alpine and cannot be used as evidence for alpine penetrative deformation.

[22] 2. NW and SE dipping shear zones in the Mont Blanc granite may be, but are not necessarily, synchronous. They could as well reflect several stages of deformation that may have overlapped in time.

[23] 3. The new $^{39}Ar/^{40}Ar$ ages of ~16 Ma obtained on white micas are compatible with the global thermal history that we proposed for the Mont Blanc. They might date initiation of the south verging shear zones but would require a more complete geochronologic and structural analysis in order to be fully validated.

[24] 4. The new data do not bring any new arguments in favor of a right-lateral transpression context for the Mont Blanc range since the middle Miocene.

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