Reply to « Comment on the dating of Alpine deformation by Ar-Ar on synkinematic mica in mid-crustal shear zones of the Mont Blanc Massif (paper by Leloup et al.) »

P.H. Leloup, N. Arnaud, R. Lacassin and E.R. Sobel.

P.H. Leloup, Laboratoire des Sciences de la terre, UMR CNRS 5570, Université Claude Bernard, 2 rue Raphaël Dubois, 69622 Villeurbanne Cedex, France. herve.Leloup@univ-lyon1.fr
N. Arnaud, Laboratoire de Dynamique de la Lithosphère (LDL), UMR CNRS 5573, ISTEEM - USTL, Place Eugène Bataillon, 34095 Montpellier Cedex 5, France.
R. Lacassin, Laboratoire de Tectonique, Mécanique de la Lithosphère, UMR CNRS 7578, Institut de Physique du Globe de Paris, 4 place Jussieu, 75252 Paris CEDEX 05, France.
E. R. Sobel, Institut für Geowissenschaften, Universität Potsdam, Postfach 60 15 53, 14415 Potsdam, Germany

The paper we published in Tectonics (Leloup et al. 2005) intended to discuss 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 where: 1) Alpine exhumation of the Aiguilles Rouges was limited to the thickness of the overlying nappes (~10 km), while rocks now outcropping in the Mont Blanc have been exhumed 15 to 20 km. 2) Uplift of the two massifs started ~22 Myr ago; while at 12 Ma, the Mont Blanc shear zone (MBsz), a reverse fault with a slight rigth-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.

Whilst acknowledging that our paper is “a good step forward in the tectonic comprehension of the Mont Blanc and provides a good synthesis of pre-existing data”, Rolland et al. (2006) claim that the timing we propose for the thrust and back-trust events is not in agreement with new $^{40}Ar/^{39}Ar$ data that they publish in their comment. In fact they raise up two main disagreements with our observations / interpretations: 1) Alpine deformations are penetrative within the Mont blanc granite and are 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, Fig.1), but by “numerous anastomosed shear zones in the way described by Choukroune and Gapais (1983) and Gourlay (1986)”. All these deformations 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”. 2) 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 16Ma for the initiation of top to the SE motions on the SE side of the Mont Blanc (backthrust) based on five phengites $^{40}Ar/^{39}Ar$ ages from three shear zones (their Fig. 3).

We will take the opportunity of this reply to address these two points and further discuss possible deformation models of the Mont Blanc range.

1) Alpine structures in the Mont Blanc Range.

1-1 Are all structures of the Mont Blanc granite due to alpine deformations?

Some authors ascribe most deformations 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 **(Fig. 1a)** (e.g., Belliere, 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. (2006) go even further, stating that all foliations within the Mont Blanc granite result from Alpine flattening. The tricky point is that there are indeed variscan deformations in the Mont Blanc range that have to be distinguished from the alpine ones. For instance, migmatitic gneisses are cross-cut by the Mont Blanc granite and by aplitic veins, prior to be affected by green-schist alpine deformation. The geometry of the variscan deformation is clear in the Aiguille Rouge where alpine metamorphism and deformation have been milder, 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 lineation dips relatively shallowly (Figure 4b of Leloup et al., 2005). Variscan (S1) and alpine (S2) foliations cannot be distinguished simply on the base of their strikes because they are close from each other and both vary a lot around a mean value (compare Fig. 4a and 4d of Leloup et al., 2005). We ascribed an alpine age to all green-schist foliations bearing a down-dip lineation and a variscan age to higher temperature foliations without, or with shallow dipping lineation. Aplitic dykes systematically cut the variscan foliations, but are affected by the alpine ones (see Fig. 3b and 3h of Leloup et al., 2005). Within the Mont Blanc granite, a high temperature foliation (S1) that we termed "magmatic foliation", is defined by the alignement of Feldspar porphyroclasts and the flattening of restitic enclaves **(Fig. 2)**. S1 strikes N-S to NE-SW and is cross-cut by undeformed aplitic dykes **(Fig. 2)**. In the absence of radiometric data on the dykes we assumed that, like in many places in the External Crystalline Massifs they are related with late stages of the granite emplacement. This implies that, even in the Mont Blanc granite, S1 is late-Variscan, probably upper Stephanian as it is the case in the Pelvoux External Crystalline Massif (e.g., Strzerzynski et al., 2005).

1-2 Geometry of the alpine shear zones within the Mont Blanc granite: one or several deformation phases?

Rolland et al. (2006) 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 reflect a single phase of NW-SE shortening. Despite several studies (Belliere, 1956; 1988; Bertini et al., 1985; Gourlay, 1986; Rolland et al., 2003; Rossi, 2005) the detailed geometry of the deformations affecting the Mont Blanc granite is still unclear, partly because of access difficulties in the highest part of the range, partly because structures ranging from mylonites to small brittle faults have been mixed together and analyzed with the same tools when they should not have. For example Bertini et al. (1985) present an analysis of "striated fault planes" that obviously include numerous ductile shear zones, while Rossi (2005; Fig. II-3) mixes faults and shear zones to calculate stress directions with Angelier's method (Angelier, 1990) that should be restricted to micro-faults with minor offsets. In the same way, Roland et al. (2006) identifies the stretching lineation to the $\sigma 3$ stress axis, an assumption which is clearly incorrect in shear zones (e.g., Ramsay and Hubert, 1983).

What is clear however is that the main alpine shear zones are steep, show reverse senses 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 (Fig. 1a). At the scale of the range, the shear zones have a fan-like geometry on NW-SE cross-sections **(Fig. 1b)** (also see Fig. 3 of Bertini et al., 1985; and Fig. II-4 of Rossi, 2005). Near the MBsz, less deformed lenses indeed occur between alpine shear zones but all these zones dip SE, implying a top to the NW thrusting of the Mont Blanc (Gourlay, 1986; Leloup, 2005). Symmetrically, most of shear zones dip to the NW near the back thrust (e.g. Guermanini and Pennacchioni, 1998). Such 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).

What is important for the structural history of the Mont Blanc range is to determine if all shear zones and faults are coeval and results 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 (**Fig. 1**). In the absence of unambiguous relative or absolute timing for the shear zones, several evidences lead us to infer that the Back-thrust was (or is still) active more recently than the MBsz: 1) the backthrust borders the highest summits of the range (**Fig. 1**) suggesting that it has a strong influence on the topography; 2) 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 backthrust. We took this as an evidence for very recent uplift on the back-thrust; 3) in the north of the range, where there is no backthrust, the Triassic unconformity, still visible on the top of the Mont Blanc granite (**Fig. 1**), dips ~65° to the east as the overlying series. This passive tilting of the eastern flank of the Mont Blanc range, indicates that, in the northern part 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 backthrust. We thus assumed a late activation of the backthrust with respect to the MBsz on our sequential history depicted in Fig. 12. However, if the age of ~16Ma for the initiation of motion on the Back thrust is retained, as proposed by Rolland et al. (2006), this will not change much our interpretation: a back-thrust will be activated few Myr. after the start of exhumation of the Mont-Blanc absorbing a part of the NW-SE shortening above the basal décollement.

2) Timing of deformations: thermochronology versus ^{39}Ar/^{40}Ar dating of white micas

From a compilation of geochronological ages we proposed a global thermochronological history with an onset of significant cooling around 22Ma (Fig. 8 of Leloup et al., 2005) 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 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 strong fluid circulations. Rolland et al. (2006) 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 has to be cautious prior to reach definite conclusions. 1) dated white micas are claimed to have crystallized in pressure shadows of Kf porphyroclasts. This is obviously not the case on the picture provided by Rolland et al. (2005, Fig. 2), where white micas follow the foliation. This does not prove that these micas did not crystallised during top to the East shearing, but makes possible that they could have formed during a previous deformation stage and have been re-oriented, thus giving the age of another deformation event. 2) The work on aggregates after crushing, although careful selection has been carried out, 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 ~5Ma 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 ~12Ma old micas with older preserved ones would probably produce the same shape of spectra. 3) Finally cooling ages and dating of synkinematic mineral should not be opposed but discussed together. Indeed Rolland et al. (2006) agree that the ages of their micas will be a minimum for the age of deformation and possibly record cooling rather than deformation, 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.

In order to validate their ages, Rolland et al (2006) stress out that they are close to those obtained on white micas within shear zones of the Mont-Blanc sedimentary cover (Crespo-Blanc et al., 1995 and Krischner 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 **(Fig. 1)**. That thrust has a different strike and 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 Morcles and Doldenhorm Helvetic nappes **(Fig. 1)**. This has no direct connections with the age of initiation of motion along the Mont-Blanc back-Thrust.

3) Alpine deformations of the Mont Blanc range: push-up within a dextral strike-slip shear zone or culmination above an alpine basal thrust?

Finally the last issue evoked by Rolland et al. (2006) is to state that the new ages they propose imply that the Mont Blanc is a Push-up along a major dextral shear zone, dismissing our interpretation as 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 backthrust 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 on its sides are inexistent or very weak. In not any case is there any new argument in the work of Rolland et al. (2006) 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°, advocates for a maximum of 2 kilometres of dextral motion to compare with the ~26 km of NW-SE shortening absorbed in the Jura arc in that time interval. 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.

References

Angelier, J., 1990. Inversion of field data in fault tectonics to obtain the regional stress. III: a new rapid inversion method by analytical means. Geophysical Journal International, 103, 363-376.

Bellière, J., Caractère de la déformation Alpine dans les schistes cristallins du massif du Mont-Blanc, Bulletin de la Société Geologique de France, VI, 691-698, 1956.

Bellière, J., On the age of mylonites within the Mont-Blanc massif, Geodinamica Acta, 2, 13-16, 1988

Bertini, G., M. Marcucci, R. Nevini, P. Passerini, and G. Sguazzoni, Patterns of faulting in the Mt Blanc granite, Tectonophysics, 11, 65-106, 1985.

Choukroune, P., and D. Gapais, strain pattern in the Aar granite (central Alps) : orthogneiss developed by bulk inhomogeneous flattening, Journal of Structural Geology, 5, 1-10, 1983.

Gourlay, P., La déformation du socle et des couvertures delphino-helvétiques dans la région du Mont-Blanc (Alpes occidentales), Bulletin de la Société Geologique de France, (8) II, 159-169, 1986.

Guermani, A., and G. Pennacchioni, Brittle precursors of plastic deformation in a granite: an exemple from the Mont-Blanc massif (Helvetic, western Alps), Journal of Structural Geology, 20, 135 – 148, 1998.

Lacassin R., plate-scale kinematics and compatibility of crustal shear zones in the Alps, Alpine tectonics, Coward, M.P., M. P., Dietrich, D. and Park, R. G. eds, Geol. soc. sp. pub., n°45, 339-352, 1986.

Leloup, P. H., N. Arnaud, E. R. Sobel, and R. Lacassin, Alpine thermal and structural evolution of the highest external crystalline massif: the Mont Blanc, Tectonics, 24, TC4002, doi:10.1029/2004TC001676, 2005.

Marshall, D., H.R. Pfeifer, J.C. Hunziker, and D. Kirschner, A pressure-temperature-time path for the NE Mont-Blanc massif: fluid-inclusion, isotopic and thermobarometric evidence, European journal of mineralogy, 10, 1227-1240, 1998.

Masson, F., F. Gal, and P.H. Leloup, Une carte gravimétrique haute résolution du massif du Mont-Blanc: implications structurales, Comptes rendus Geosciences, 334, 1011-1019, 2002.

Poty, B., H.A. Stalder, and A.M. Weisbrod, Fluid inclusions studies in quartz from fissures of western and central Alps, Schweizerishe Mineralogische und petrographische Mitteilungen, 54, 717-752, 1974.

Ramsay J. G. and M. I. Huber, the Techniques of Modern Structural Geology-Strain Analyses, Academic Press, IBSN 0-12-576921-0, 307 p., 1983

Rolland, Y., S.F. Cox, A.M. Boullier, G. Pennacchioni, and N. Mancktelow, Rare Earth and trace element mobility and fractionation in mid-crustal shear zones: insights from the Mont-Blanc Massif (Western Alps), Earth and Planetary Science Letters, 214, 203-219, 2003.

Rolland Y., M. Corsini, M. Rossi, S.F. Cox, G. Pennacchioni, N. Mancktelow, A.M. Boullier (2006), Comment on the dating of Alpine deformation by Ar-Ar on syn-kinematic mica in mid-crustal shear zones of the Mont Blanc Massif (paper by Leloup et al.) », Tectonics.

Rossi, M., Déformation, transferts de matière et de fluide dans la croûte continentale : application aux massifs cristallins externes des Alpes. Ph.D. thesis, University of Grenoble, 388p., 2005.

Strzerzynski, P., S. Guillot, G. Courrioux, P. Ledru, Modélisation géomètrique 3D des granites stéphaniens du massif du Pelvoux (Alpes, France), C. R. Geoscience, 337, p. 1284-1292, 2005.

Figures captions

Figure 1:

Structure of the Mont-Blanc massif. Modified from Fig. 2 of Leloup et al. (2005). **a)** Structural map of the Mont-Blanc massif. The black frame corresponds to the Fig. 1 of Rolland et al. (2006). Black stars are samples from Rolland et al. (2006), 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 grey filling are argon samples from Leloup et al. (2005). **b)** Synthetic cross-section of the Mont-Blanc massif. HBD is the Helvetic basal décollement. 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)** Scketch of an aplitic dyke (A) cross-cutting the Mont-Blanc granite “magmatic” foliation S1. S1 and the dyke are cross-cut by two alpine shear zones (S2). Eperon des géographes above the Leshaux glacier. Horizontal plane, view from above. Hammer gives scale

b) Undeformed aplitic dyke cutting across a flattened (S1) enclave of the Mont Blanc granite. N bank of the Leshaux glacier under the Talèfre glacier. View toward the East of two perpendicular planes: N20 vertical and N110 30S.

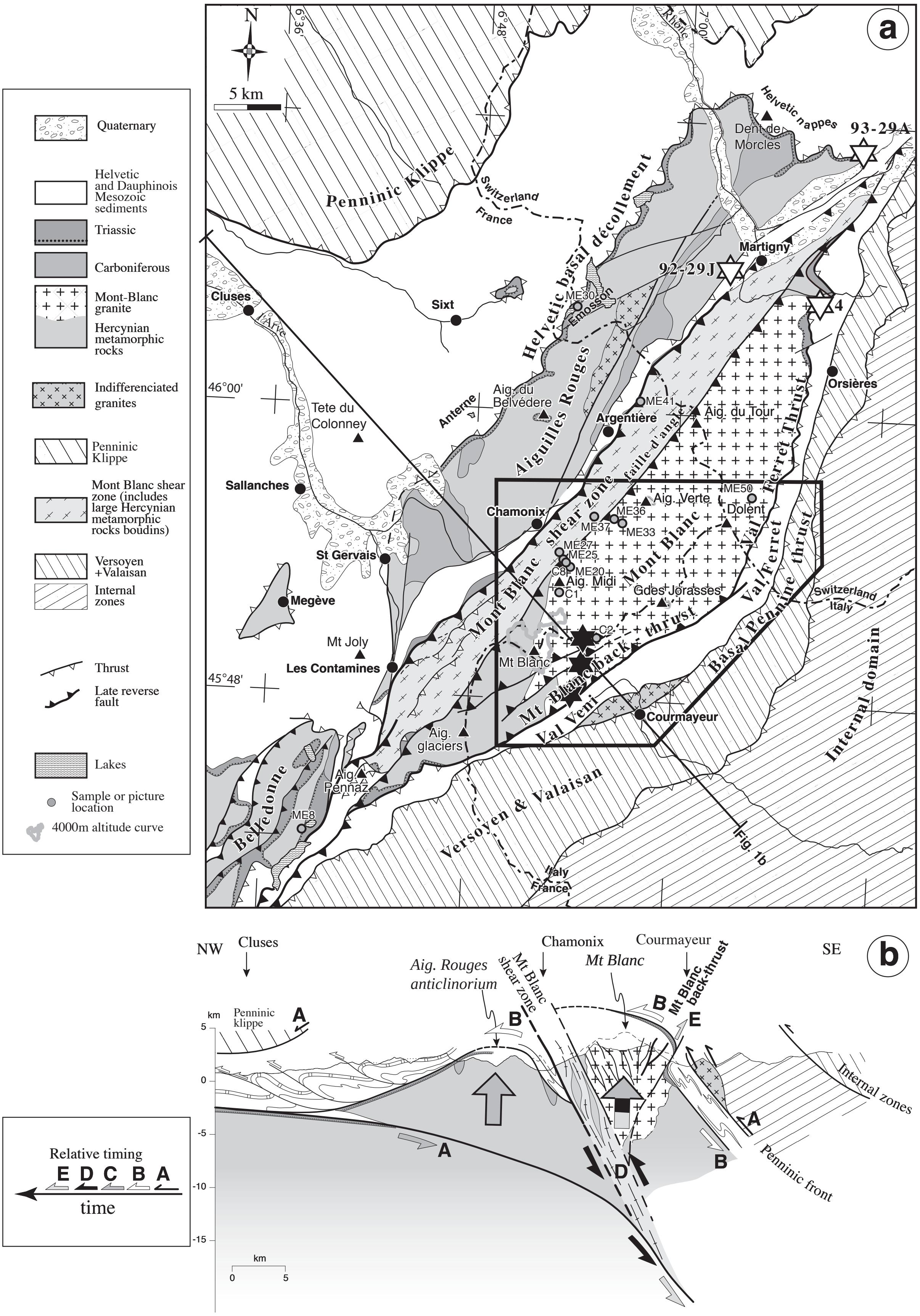
a
N
5 km
6°36'
6°48'
7°00'
Rhône
46°00'
45°48'
Penninic Klippe
Switzerland
France
Helvetic nappes
Dent de Morcles
93-29A
92-29J
4
Martigny
Orsières
Helvetic basal décollement
Sixt
Cluses
L'Arve
ME30
Emosson
Aiguilles Rouges
Aig. du Belvédere
Anterne
Tete du Colonney
Sallanches
St Gervais
Megève
Mt Joly
Les Contamines
Argentière
ME41
Aig. du Tour
faille d'angle
Val Ferret Thrust
Chamonix
Mont Blanc shear zone
ME36
ME37
ME33
Aig. Verte
ME50
Dolent
ME27
ME25
C8
ME20
Aig. Midi
C1
Mont Blanc
Gdes Jorasses
Val Ferret
Basal Pennine thrust
Switzerland
Italy
C2
Mt Blanc
Mt Blanc back-thrust
Val Veni
Courmayeur
Internal domain
Aig. glaciers
Aig. Pennaz
Belledonne
ME8
Versoyen & Valaisan
Italy
France
Fig. 1b
Quaternary
Helvetic and Dauphinois Mesozoic sediments
Triassic
Carboniferous
Mont-Blanc granite
Hercynian metamorphic rocks
Indifferenciated 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
b
NW
Cluses
Chamonix
Courmayeur
SE
Aig. Rouges anticlinorium
Mt Blanc shear zone
Mt Blanc
Mt Blanc back-thrust
km
5
0
-5
-10
-15
Penninic klippe
A
B
B
E
A
A
D
B
Internal zones
Penninic front
km
0
5
Relative timing
E D C B A
time

Figure 1

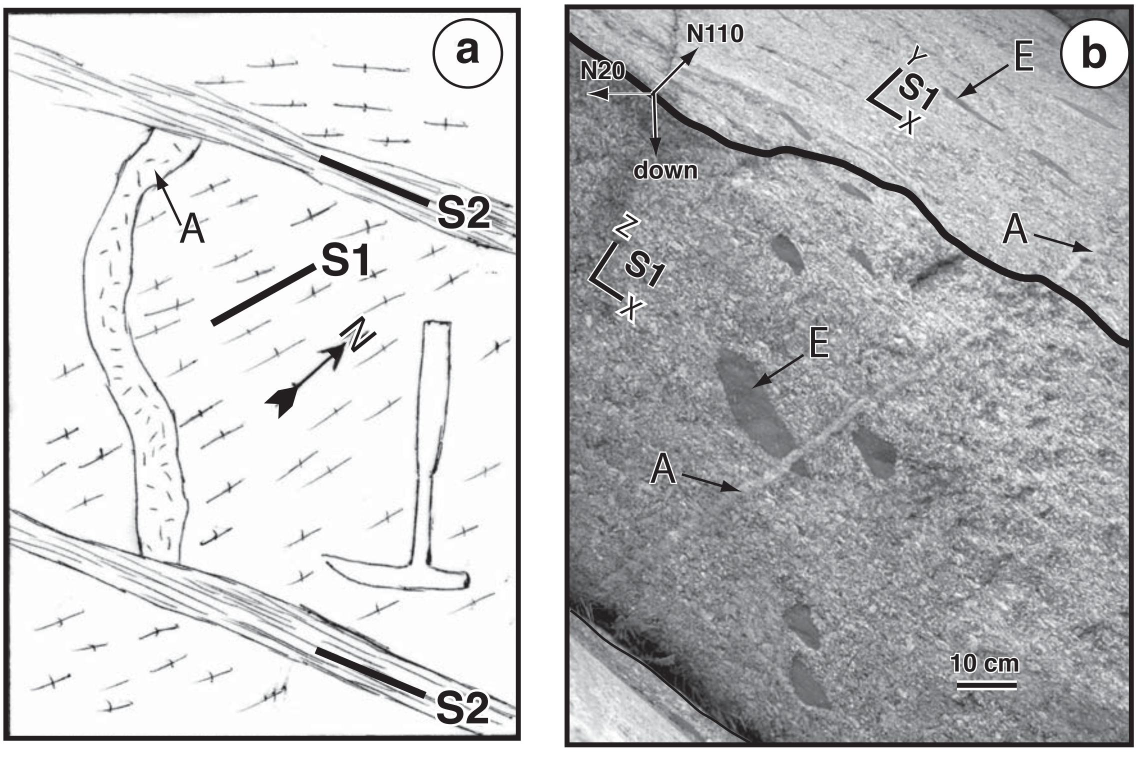

Figure 2