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► **To cite this version:**

Philippe Hervé Leloup, Antoine Mercier, Chenglong Ge. Combining Thermochronology and Geochronology to Constrains Orogenic Processes in the Alps and Tibet. DEEP-2024, Oct 2024, Beijing (China), China. pp.41-43, 10.1111/1755-6724.15235 . hal-04930170

HAL Id: hal-04930170

<https://hal.science/hal-04930170v1>

Submitted on 5 Feb 2025

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Combining thermochronology and geochronology to constrain orogenic processes in the Alps and Tibet.

Philippe, Hervé, LELOUP¹, Antoine, MERCIER¹, Chenglong, GE^{1,2}

1 Laboratoire de Géologie de Lyon : Terre, Planètes et Environnement, CNRS, Université Claude Bernard Lyon 1, ENSL, UJM, 2 rue Raphaël Dubois, 69622 Villeurbanne, France.

2 Key Laboratory of Deep-Earth Dynamics of Ministry of Natural Resources, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China.

Corresponding author. E-mail: herve.leloup@univ-lyon1.fr

Deciphering the kinematics of deformation is key to understand the crustal evolution. In the last decades several techniques have been developed to help constraining the timing of deformation. On one side geochronology techniques allow the dating of a wider range of minerals with higher spatial resolution. On the other side thermochronology, with the help of numerical simulations (Pecube, QTQt ...), help to constrain the rock exhumation history that is often linked to the vertical component of deformation. In both cases the deformation timing can accurately be discussed only together with a serious structural analysis. In only few examples both geochronology and thermochronology have been used simultaneously to test whether they lead to comparable results. Here we present two such cases where structural geology, geochronology and thermochronology concur to constrain the structural evolution and help to decipher between contrasted geodynamic models.

In the external part of the occidental Alps the Mont-Blanc crystalline range is often interpreted as a large basement fold that would correspond to a phase of limited shortening after large-scale thrusting above the internal Penninic thrust and prior to thrusting on the more external Alpine basal thrust. To decipher the structural evolution of the western Alps we apply two distinct geochronological methods to the Mont-Blanc and Aiguilles Rouges crystalline massifs.

On one hand we invert new and published thermochronological data to quantify the differential exhumation between the two massifs by using a thermal-kinematic simulation (Pecube) with Bayesian inference. Prior inversion of data generated from known forward models allow to assess the ability of the data and of the simulations to quantify each parameter including relief and fault slip rate evolution. The inversion allows to reconstruct the evolution of the exhumation rate of the Mont-Blanc and Aiguilles Rouges through time (Fig. 1a), and the differential exhumation between the two ranges (Fig. 1b).

On another hand, three mylonites from the Mont-Blanc shear zone (MBSz) in between the two ranges, and two from the Helvetic basal thrust system (HBT) above them are dated using in situ ⁴⁰Ar/³⁹Ar on white micas. Deformation thermo-barometric conditions are estimated from petro-geochemical quantification and lattice preferred orientation of quartz to be below 500°C and between 0.47 and 0.74 GPa. The samples from the MBSz range in age from 14.9 to 17.3 Ma (Fig. 1c) compatible with previous age determinations (Egli et al., 2017; Rolland et al., 2003; 2008; Leloup et al., 2005). The samples from the HBT on the eastern and western sides of the Mont-Blanc yield ages of 13.7 and 16.3 Ma, respectively.

The results of the two methods are consistent and imply four deformation phases. (i) From 23 Ma to 14 Ma, the Mont-Blanc is exhumed in a duplex of the Helvetic Thrust system. This corresponds both to the geochronologic ages within the Mont-Blanc shear zone and the maximum of exhumation of the Mont-Blanc with respect to the Aiguilles Rouges (Fig. 1 – orange zone). (ii) Between 14 Ma and ~11 Ma, the MBSz central part becomes a breach thrust that crosscuts the HBT. (iii) At 6Ma the Aiguilles Rouges begin to exhume above a back thrust. At that time, thick-skin deformation in the Mont-Blanc is coeval with thin-skin deformation in the Jura. (iv) The two massifs experience a common recent phase of high exhumation since ~1 Ma, coeval with relief building and most likely related to glacial valley incision. The results imply that the Mont-Blanc is not a fold and that three major thrust systems, not two, have propagated in sequence in the western alps: the Penninic, the Helvetic, and the Alpine Sole Thrusts (Fig. 2).

The NE striking Longmen Shan (LMS) mountains are located at the eastern margin of the Tibetan plateau, and tower nearly 5000m above the Sichuan basin, the greatest relief than anywhere else around

the plateau. From west to east, three major sub-parallel faults straddle the Longmen Shan: Wenchuan-Maoxian fault (WMF), Yingxiu-Beichuan fault and Guanxian-Anxian fault. Several models have been proposed to explain the Cenozoic uplift of the Longmen Shan. The major two models are lower crustal channel flow and upper crustal shortening, which imply different shear sense on the Wenchuan-Maoxian fault. The former suggests that the LMS were uplifted above a lower crustal flow expelled from below the Tibetan plateau and would require a normal sense movement on the MWF. The latter implies that a series of upper crustal thrusts controlled the uplift of the LMS, and the WMF should have a reverse sense. Here we present the latest structural geology and geochronology data.

$^{40}\text{Ar}/^{39}\text{Ar}$ ages on white mica grown syn-kinematically show that normal / right lateral ductile deformation occurred at 28.0 ± 0.9 Ma, and top-to-the-east reverse deformation at 15.4 ± 0.2 Ma. K-Ar ages of authigenic illite from two fault gouges show that brittle right-lateral / reverse deformation occurred at 6.9 ± 2.9 Ma (Fig. 3).

These geochronologic ages are coherent with the relative vertical motions across the fault zone deduced from thermochronology data (Fig. 3). Three deformation phases are thus defined: right-lateral / normal in the Middle Oligocene (~30 - 25 Ma), reverse in the Middle Miocene (25-15 Ma), and right-lateral / reverse since the Upper Miocene (since ~6 Ma).

The WMF never experienced pure normal motion, and only shortening since the Oligocene, in contrast to predictions of lower crustal channel-flow models, thus favouring a crustal accretionary prism model for the Cenozoic Longmen Shan building.

These works emphasize the benefits of coupling thermochronology with geochronology and structural geology to decipher the crust structural evolution and discuss the geodynamic models.

Key words: Timing of crustal deformation, Geochronology, Thermochronology, Alpine external crystalline range, Mont-Blanc, Aiguilles Rouges,

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About the first/corresponding author

Philippe, Hervé LELOUP, male, PhD graduated from Paris 6 / IGP university in 1991; now Director of Research from the Centre National de la Recherche Scientifique at the Laboratoire de Géologie de Lyon. He is a specialist of crustal deformation and orogenic processes in the western Alps and in the Himalaya / Tibet area.

Figures and Captions

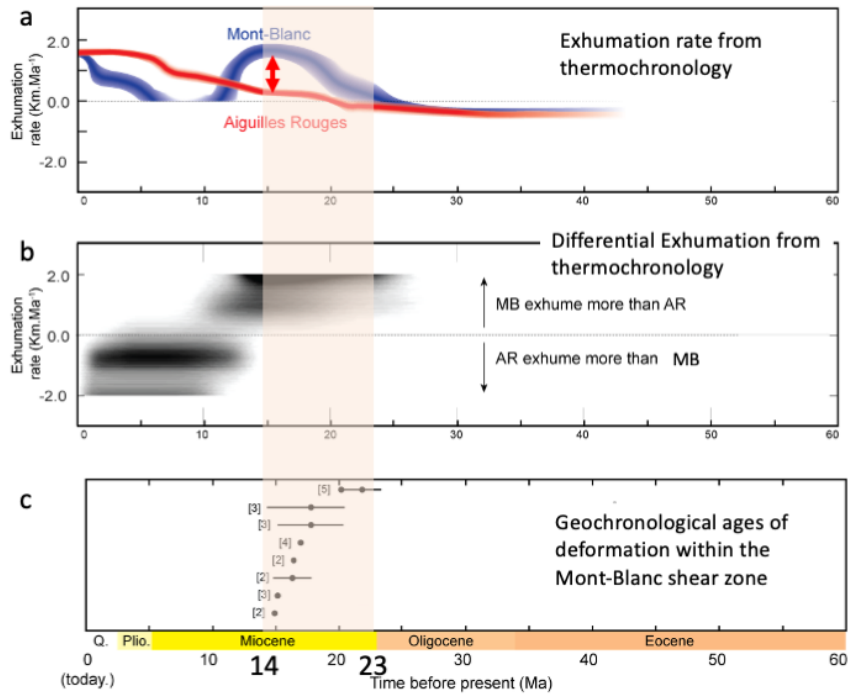


Fig.1 Timing of deformation in the Mont-Blanc and Aiguilles Rouges. Adapted from Mercier 2023, and Mercier et al. (in prep.)

a) Exhumation rate of the Mont-Blanc (blue) and the Aiguilles rouges (red) from inversion of thermochronology data. **b)** Differential exhumation between the Mont-Blanc and the Aiguilles rouges from inversion of thermochronology data. Positive value corresponds to more exhumation of the Mont-Blanc than the Aiguilles Rouges. Mont-Blanc exhumed ~6.5 km more than the Aiguilles Rouges at a rate of 1.5 mm/yr between 22 and 14 Ma. **c)** ⁴⁰Ar/³⁹Ar ages of deformation within the Mont-Blanc shear zone along which the Mont-Blanc is thrust above the Aiguilles Rouges. data along the Mont-Blanc shear zone. References are: [2]: Mercier, 2023; [3]: Egli et al. (2017); Rolland et al. (2008); [4]: Leloup et al. (2005); [5]: Rolland et al. (2003)

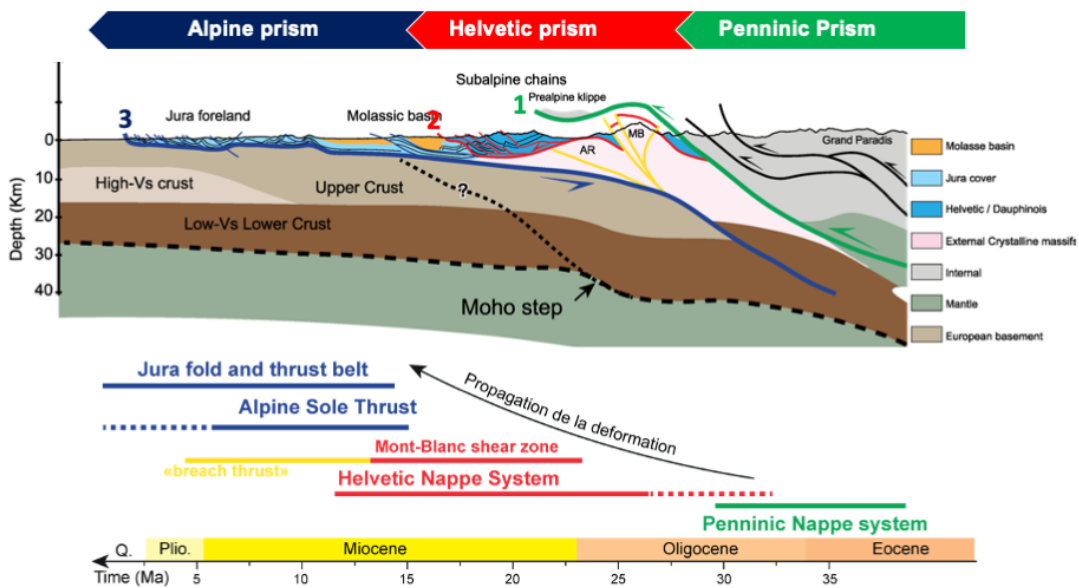


Fig.2 The three main alpine thrusting systems. Adapted from Mercier 2023, and Mercier et al. (in prep.)

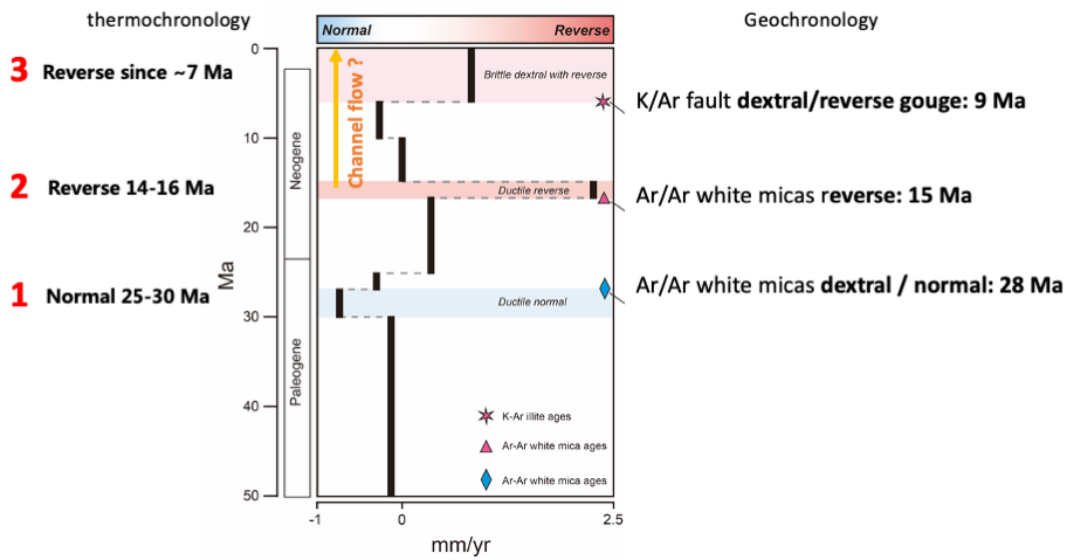


Fig.3 Deformation phases along the Wenchuan-Maowen Fault. Adapted from Ge et al., (2023). Evolution of the vertical relative motion between the two blocks on both side of the fault (black) is compatible with direct dating of the deformation structures (coloured symbols).