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Episodic exhumation and relief growth in the Mont Blanc massif, Western Alps from numerical modelling of thermochronology data

C. Glotzbach [a,b,*], P.A. van der Beek [a], C. Spiegel [c]

[a] Institut des Sciences de la Terre (ISTerre), Université Joseph Fourier, CNRS, BP 53, 38041 Grenoble cedex 9, France
[b] Institute of Geology, University of Hannover, Callinstr. 30, 30167 Hannover, Germany
[c] Department 5 Geosciences, University of Bremen, P.O. Box 330440, 28334 Bremen, Germany

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ABSTRACT

The Pliocene–Quaternary exhumational and topographic evolution of the European Alps and its potential climatic and tectonic controls remain a subject of controversy. Here, we apply inverse numerical thermal–kinematic modelling to a spatially dense thermochronological dataset (apatite fission-track and (U–Th)/He) of both tunnel and surface samples across the Mont Blanc massif in the Western Alps, complemented by new zircon fission-track data, in order to better quantify its Neogene exhumation and relief history. Age–elevation relationships and modelling results show that an episodic exhumation scenario best fits the data. Initiation of exhumation in the Mont Blanc massif at 22 ± 2 Ma with a rate of 0.8 ± 0.15 km/Myr is probably related to NW-directed thrusting during nappe emplacement. Exhumation rates decrease at 6 ± 2 Ma to values of 0.15 ± 0.65 km/Myr, which we interpret to be the result of a general decrease in convergence rates and/or extensive exposure of less erodible crystalline basement rocks from below more easily erodible Mesozoic sediments. Finally, local exhumation rates increase up to 2.0 ± 0.6 km/Myr at 1.7 ± 0.8 Ma. Modelling shows that this recent increase in local exhumation can be explained by valley incision and the associated increase in relief at 0.9 ± 0.8 Ma, leading to erosional unloading, isostatic rebound and additional rock uplift and exhumation. Given the lack of tectonic activity as evidenced by constant thermochronological ages along the tunnel transect, we suggest that the final increase in exhumation and relief in the Mont Blanc massif is the result of climate change, with the initiation of mid-Pleistocene glaciations leading to rapid valley incision and related local exhumation.

1. Introduction

Global temperatures have decreased irregularly but steadily during the Cenozoic, at least partly as a response to tectonic processes that formed major mountain belts (*e.g.*, the Himalaya) and led to important changes in ocean circulation through opening/closure of seaways (*e.g.*, closure of the Panama Isthmus) (*e.g.*, Haug and Tiedeman, 1998; Raymo and Ruddiman, 1992; Zachos et al., 2001). Both overall decreasing temperatures and changes in ocean circulation enabled ice-caps and mountain glaciers to form; the latter locally increased long-term erosion rates as recorded by low-temperature thermochronology data (*e.g.*, Ehlers et al., 2006; Shuster et al., 2005; Spotila et al., 2004). The global erosional response to climate cooling remains controversial, however: whereas weathering proxies are consistent with steady-state weathering since at least 12 Ma (Willenbring and von Blanckenburg, 2010), the global sediment budget suggests dramatically increased erosion rates for the last 5 Ma (Hay et al., 1988; Zhang et al., 2001). Such increases may, however, also be explained by observational bias because of better preservation of younger sediments (*e.g.*, Sadler, 1981; Schumer and Jerolmack, 2009).

Similar controversy exists on the orogen scale, such as in the European Alps (*e.g.*, Bernet et al., 2001, 2009; Cederbom et al., 2004; Willett et al., 2006). Detrital thermochronological data from basins surrounding the Alps imply long-term steady-state exhumation of the Western and Central Alps (*e.g.*, Bernet et al., 2001, 2009; Glotzbach et al., 2011) and contrast with a dramatic apparent increase in sediment flux from the Alps since ~5 Ma (Kuhlemann, 2000). *In-situ* thermochronological studies reveal variable exhumation histories including monotonic, decreasing, increasing or episodic exhumation trends for different parts of the western and central Alps (*e.g.*, Campani et al., 2010; Glotzbach et al., 2008, 2010; Reinecker et al., 2008; Vernon et al., 2008, 2009).

The challenge remains to find a tectonic–climate–erosion model capable of explaining these spatially and temporally variable exhumation histories. The European Alps experienced several tectonic

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* Corresponding author at: Institute of Geology, University of Hannover, Callinstr. 30, 30167 Hannover, Germany. Tel.: +49 511 7622289; fax: +49 511 7622172.
E-mail addresses: glotzbach@geowi.uni-hannover.de (C. Glotzbach), pvdbeek@ujf-grenoble.fr (P.A. van der Beek), cornelia.spiegel@uni-bremen.de (C. Spiegel).

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and climatic changes during the last few million years, which potentially drove, or at least noticeably modified, their exhumation and relief history. In general, tectonic convergence declined since Eocene–Miocene nappe stacking and related crustal thickening from ~1.3 cm/y at 65–50 Ma to 0.3 cm/y since 19 Ma (Schmid et al., 1996). Thrusting propagated from internal to more external locations during Miocene times, resulting in exhumation of the external crystalline massifs (ECM) (*e.g.*, Schaer et al., 1975; Wagner et al., 1977). At the same time, orogen-parallel extension in the internal Alps resulted in localised tectonic exhumation along major fault zones, *e.g.* the Rhône–Simplon fault (*e.g.*, Grasemann and Mancktelow, 1993; Fig. 1). Pliocene orogen-perpendicular extension (*e.g.*, Sue et al., 2007) is interpreted to have resulted in localised rapid exhumation in the footwall of orogen-parallel faults such as the Rhône–Simplon fault (Reinecker et al., 2008) or the extensionally inverted Penninic Frontal Thrust (Tricart et al., 2007; Fig. 1). Whereas the Eastern Alps currently accommodate up to ~2 mm/y of convergence (*e.g.*, Nocquet and Calais, 2004), the Western Alps are characterised by widespread gravitationally driven extension in their highly elevated core and more local compression in marginal areas, the net result being close to zero convergence (Sue et al., 2007). Thus, with the overall decrease in convergence, the importance of tectonic exhumation along extensional features increases in the Western and Central Alps, which should result in a decrease in erosional flux. The opposite is implied by the observed sediment budget (Kuhlemann, 2000), which has, however, been questioned due to possible observational bias (Schumer and Jerolmack, 2009; Willenbring and von Blanckenburg, 2010). Several authors have suggested that erosion of the Alps has outstripped crustal thickening over the last few million years, leading to isostatic rock uplift (Cederbom et al., 2004; Champagnac et al., 2007; Kahle et al., 1997; Wittmann et al., 2007).

The currently most popular tectonic–climate–erosion model assumes that increased erosion since ~5 Ma is a response to Late Miocene–Pliocene climate change (Cederbom et al., 2004; Whipple, 2009; Willett et al., 2006) and led to retreat of the active deformation front toward the core of the orogen, enhanced erosion and resulting isostatic rebound. Subsequent initiation of Northern Hemisphere glaciations at ~2.8 Ma (*e.g.*, Raymo, 1994) led to major Alpine glaciations, glacial valley deepening and associated local exhumation since ~0.9 Ma (Champagnac et al., 2007; Glotzbach et al., 2008; Haeuselmann et al., 2007; van der Beek and Bourbon, 2008).

In this study we investigate the potential of a dense thermochronological dataset to accurately estimate time-varying exhumation rates and paleo-relief using age–elevation relationships and numerical thermal–kinematic modelling (Braun, 2003), with particular consideration of the model complexity (*e.g.* the number of exhumation phases). We use new zircon fission-track (ZFT) data and published apatite fission-track (AFT) and apatite (U–Th)/He (AHe) data (Glotzbach et al., 2008) from a transect along the ~12 km long Mont Blanc tunnel and an age–elevation profile in the Mont Blanc massif (France, Italy), which includes the highest summit (4810 m) of the Alps. Obtained results provide new insight in the complex relation between tectonics, climate and erosion in the European Alps. The modelling approach builds on a recently proposed methodology (Herman et al., 2007, 2009; Valla et al., 2010; van der Beek et al., 2010) but improves upon this by (i) explicitly addressing uncertainties in the thermal gradient and (ii) using a log-likelihood function to assess model performance, allowing quantitative assessment of the model complexity that is resolvable from the data.

2. Geological setting

The European Alps formed during Tertiary collision of the European and the African continental margins (corresponding to the Helvetic and Austroalpine domains, respectively), with continental and oceanic crustal fragments of the Penninic domain squeezed in between (*e.g.*, Steck and Hunziker, 1994). Thrusting of the Penninic and Austroalpine units towards the European continent

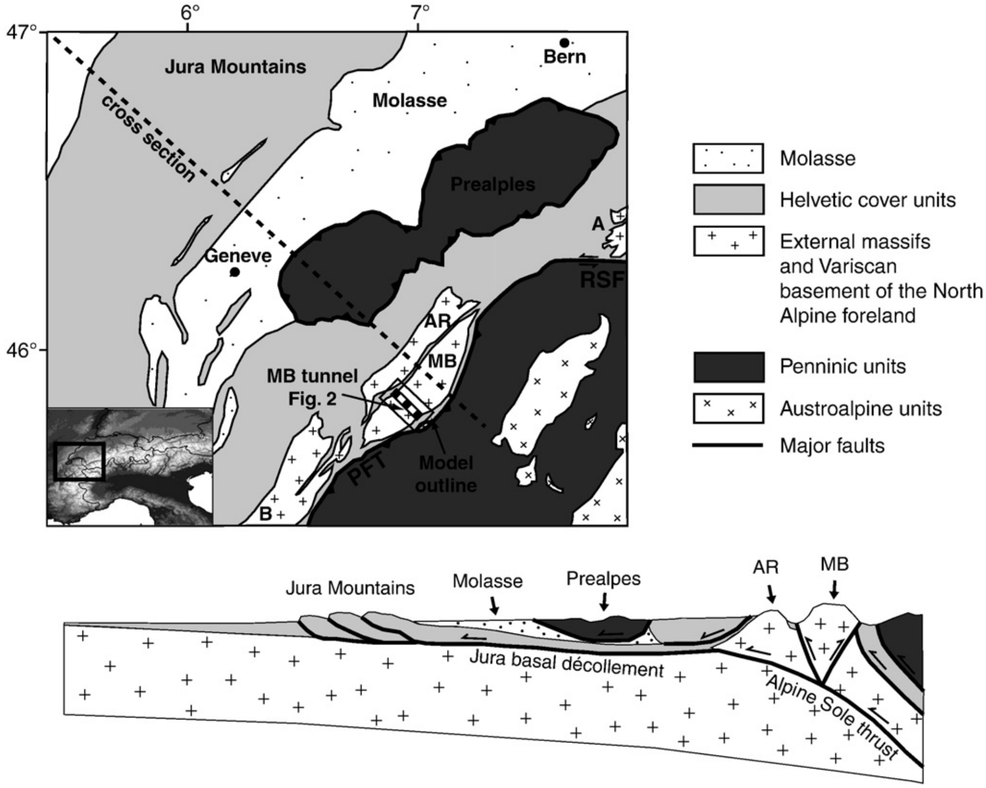

Fig. 1. Simplified geological map and crustal cross section of the NW Alps (after Affolter et al., 2008; Leloup et al., 2005; Schmid et al., 2004). A: Aar Massif; AR: Aiguilles-Rouges; MB: Mont Blanc; B: Belledonne; PFT: Penninic Frontal Thrust; RSF: Rhône–Simplon Fault.