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Increase in late Neogene denudation of the European Alps confirmed by analysis of a fission-track thermochronology database

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ABSTRACT

A sharp increase in deposited sediment volume since Pliocene times has been observed worldwide and in particular around the European Alps. This phenomenon has been linked to a rise in denudation rates controlled by an increase of either climatic or tectonic forcing. Observation of in-situ cooling histories for orogens is critical to assess the reality of the inferred increase in denudation rates, and to determine whether this phenomenon is widespread or localized at active tectonic structures. We exploit the unique density of fission-track ages in the Western European Alps to reconstruct cooling isoage surfaces and to estimate exhumation rates on the orogen scale between 13.5 and 2.5 Ma. Our novel technique is based on the association of isoage contours with age–elevation relationships. It uses map-view interpolation, enabling a spatio-temporal analysis of exhumation rates over the entire Western Alps. The resulting exhumation histories reconstructed for eight areas of the Western Alps display strong similarities in timing and rates with orogen-wide average denudation rates inferred from sediment volumes. This consistency validates the use of both techniques for the study of an orogen characterized by strong relief and high recent exhumation rates. We conclude that exhumation rates in the Western Alps have increased more than twofold since Late Miocene times. This increase may have been locally modulated by the distinct response of different tectonic units.

1. Introduction

Widespread indications for an increase of global sedimentation rates in the Early Pliocene have been reported from localities around the world (e.g., Zhang et al., 2001; Molnar, 2004). However, the cause of this event, its exact timing and synchronicity remain controversial. Possible causes that have been proposed include global cooling and incipient glaciations (Hinderer, 2001; Ehlers et al., 2006), an increase in the magnitude and frequency of climate oscillations (Zhang et al., 2001; Molnar, 2004), and a recent increase in the uplift rates of major orogens (Raymo and Ruddiman, 1992).

The quantification of sediment volumes in the basins surrounding the European Alps by Kuhlemann et al. (2002) shows a more than twofold increase in erosion rates in both the Western and Eastern Alps around 5 Ma (Fig. 1). An independent study of the exhumation of the Molasse basin (Fig. 2), based on borehole apatite fission-track data, demonstrated approximately 1400 m of basin exhumation since 5 Ma, interpreted as a record of isostatic rebound of the basin driven by accelerated erosional unloading of the Alps (Cederbom et al., 2004).

The estimation of source-area denudation rates from the sediment record suffers, however, from poorly quantified uncertainties in both the volumetric calculations and the dating accuracy (Kuhlemann et al., 2002). Moreover, the impossibility of quantifying the roles of chemical erosion and sediment recycling may lead to an underestimation or overestimation, respectively, of source-area denudation rates through time.

An increase in exhumation at ca. 5 Ma, if real, should be recorded more directly by low-temperature thermochronometers in the bedrock of the mountain belt. Classically, the derivation of exhumation rates from thermochronometry is based on temperature–time paths reconstructed from multiple thermochronometric analyses, age–elevation profiles from altitudinal transects or boreholes, or kinetic modeling of apatite fission-track annealing using track-length distributions (e.g., Hurford, 1991; Gallagher et al., 1998). In different regions of the Western Alps, Neogene-age exhumation rates quantified using these approaches range between 0.1 and 1.5 mm yr^{-1} (e.g., Michalski and Soom, 1990; Leloup et al., 2005; Malusa et al., 2005;

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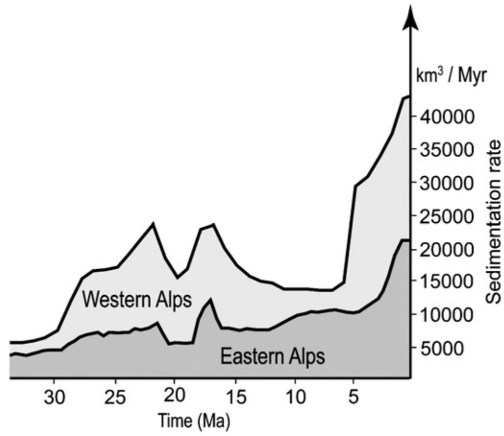

Fig. 1. Evolution of sedimentation rates through time, reconstructed from the preserved volume of sediments originating from the Western and the Eastern Alps, respectively (modified from Kuhlemann et al., 2002).

Tricart et al., 2007). However, most of these studies are local or at best regional in scope and a consistent denudation history at the orogen scale has yet to emerge. Apatite fission-track (AFT) thermochronology appears the most suitable technique to study Mio-Pliocene exhumation rates over a large area such as the Western Alps because of the abundance of ages ready for database compilation, and because the AFT age range (Fig. 3a) comprises the target period of the late Neogene time interval.

The spatial integration of discrete thermochronological data covering large study areas is most easily achieved by interpolating between ages in map view (e.g., Hunziker et al., 1992; Fig. 3a and b). However, this simple technique only presents the integrated result of a possibly complex denudation history and does not allow variations in denudation rate through time to be inferred. Published methods aimed at describing the history of exhumation rates in map view have used either analysis of multiple thermochronometers, or kinetic modeling of fission-track length distributions (e.g., Morris et al., 1998; Gallagher and Brown, 1999; Schlunegger and Willet, 1999; Bistacchi and Massironi, 2000; Stephenson et al., 2006). Despite many years of intensive thermochronological studies in the Alps, samples permitting such analyses are still relatively rare, disallowing such a study at the orogen scale. Techniques based on modeling of fission-track length distributions offer the greatest wealth of interpretation in settings characterized by slow long-term denudation, such as rifted continental margins (e.g. Gallagher and Brown, 1999). In rapidly exhuming orogens, in contrast, track-length distributions are not easily measured (because of generally young AFT ages) and are much less discriminative.

We propose a new method in which we exploit the extensive AFT dataset available for the Western Alps (Figs. 2 and 3) together with the significant relief of the mountain belt to reconstruct three-dimensional surfaces of equal AFT age (referred to here as isoage surfaces). We subsequently use the difference in elevation between these surfaces to estimate the spatial pattern in rates of exhumation back to Middle Miocene times (13.5 Ma), as recorded in the spatial relationship between AFT ages at outcrop today. The aims of this study are to test for the presence of changing exhumation rates during late Neogene times across the Western Alps, and if present, to describe the temporal and spatial variability of this signal. In addition, we present updated maps of interpolated apatite fission-track ages and mean track lengths, as well as zircon fission-track ages. We complete this study by the assessment of evolving trends of exhumation rates using samples with paired zircon and apatite fission-track ages. In the following, we first briefly outline the geological setting and evolution of the Alps and present the thermochronological database we constructed. We then explain the different methods we used to analyze the database. Finally, we present our main results and their implications for the late Neogene denudation history of the Alps as well as its possible tectonic or climatic controls.

2. Geological setting of the Alps

The European Alps (Fig. 2) are located at the boundary between the European and Apulian plates. They are the product of the Early Cretaceous closure of the Piemont–Ligurian ocean, followed by continental subduction resulting in nappe stacking (cf. reviews in Schmid et al., 2004; Rosenbaum and Lister, 2005).

The main tectonic units in the Alps and their structural relationships have been described extensively within the last century (e.g., Trümpy, 1960; Debelmas and Lemoine, 1970; Schmid et al., 2004). They originate from the European continental margin basement (External Crystalline Massifs) and overlying deposits (Helvetic sediments), the Briançonnais micro-continent and its two bordering oceanic units (Piemont–Ligure and Valais oceanic crust and flysh), and finally basement and sedimentary units of the Apulian margin, grouped as the Austroalpine and the South Alpine units (Fig. 2). The North (Molasse) and South (Po) Alpine foreland basins formed by flexure of the lithosphere in response to the weight of the orogenic prism on the European and Apulian plates and are filled with Eocene to Recent flysch, molasse and glacial deposits (e.g., Homewood et al., 1986; Scardia et al., 2006).

One of the most important arc-parallel tectonic boundaries, the Penninic thrust, may have been extensionally reactivated (Seward and Mancktelow, 1994) as part of a series of Neogene extensional features observed throughout the axial region of the Western Alps (e.g., Sue et al., 2007; Tricart et al., 2007 and references therein). Most of these extensional features may be caused by a Neogene dextral transtensive event (Sue et al., 2007) triggered by the anti-clockwise rotation of the Apulian plate. Such rotation can also explain the current strain pattern in the Western Alps (Calais et al., 2002). At present, geodetic and GPS data show limited (≤2 mm yr^{-1}) east–west extension in the Western Alps (Calais et al., 2002; Sue et al., 2007). The lack of present-day convergence in the Western Alps, together with the observation of sediment-sealed thrusts in the western part of the Po basin (Pieri and Groppi, 1981), and the cessation of thin-skinned deformation in the Jura at ca. 4 Ma (Becker, 2000) all suggest very limited current orogenic activity within the chain.

We limit our study area to the Western half of the Alps, as far east as the Silvretta nappe/Engadine window, or approximately the Swiss–Austrian border, which marks the western limit of widespread outcrop of Austroalpine units. The reason for this eastern limit to the study area is that few AFT studies have been published for the Austroalpine units because of the low abundance of apatite in their constitutive lithologies.

3. Data

3.1. Apatite and zircon fission-track databases

During the last thirty-five years, the Western Alps have been extensively sampled for thermochronological analyses, in particular using the apatite and zircon fission-track thermochronometers, characterized by closure temperatures of ca. 120 and 240 °C respectively (e.g., Brandon et al., 1998; Gallagher et al., 1998). We have compiled 740 AFT ages, from data in 37 publications completed by 160 unpublished ages (references are given in the caption of Fig. 3a) from samples located in the European Alps west of 10° 20′ east (an area of ca. 48,000 km^2). We similarly compiled 380 zircon fission-track (ZFT) ages from 24 publications completed by 22 unpublished ages (see Fig. 3b for references).