Spatial correlation between long-term exhumation rates and present-day forcing parameters in the western European Alps

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ABSTRACT

The relative intensity of tectonic and climatic forcing in the western European Alps has been a matter of debate since the recognition of a significant increase in denudation rates over the past few million years. We address this question by quantitatively correlating the spatial pattern of long-term exhumation rates with those of potential short-term tectonic, climatic, and morphologic variables. We find that present-day rock-uplift rates (as measured by geodesy relative to a specific reference point) and mean elevation are correlated with long-term exhumation rates, whereas relief, present-day precipitation, discharge, stream power, and released seismic energy are not, or are only weakly, correlated. We attribute the lack of correlation between long-term exhumation and precipitation to a strong temporal variability in climate and erosional processes during Pliocene–Pleistocene time. The correlations among present-day rock-uplift rates, present-day elevations, and long-term exhumation rates suggest that rock-uplift rates have been sustained for millions of years, consistent with rock-uplift rates being the isostatic response to crustal unloading. The lack of a correlation of the released seismic energy with either rock uplift or long-term exhumation denies active tectonics supporting evidence.

INTRODUCTION

The topographic and denudation histories of mountain belts result from an interplay between tectonics and erosion. In addressing the relative importance of potential climatic, tectonic, or morphologic controlling parameters, different authors have reached contrasting conclusions (e.g., Burbank et al., 2003; Dadson et al., 2003; Reiners et al., 2003; Wobus et al., 2003). An inherent problem in these kinds of studies is the different time scales addressed: whereas geologically meaningful denudation rates inferred by low-temperature thermochronology are measured on Ma time scales, records of controlling parameters (e.g., precipitation, runoff, released seismic energy, current deformation as measured by global positioning system) rarely exceed a few tens of years.

Recent studies of the western Alps (Fig. 1) yield seemingly paradoxical observations. The predicted outcome of the proposed extensional collapse of the mountain belt from late Miocene time onward (e.g., Selverstone, 2005; Sue et al., 2007b, and references therein) would be a decrease in sediment production; instead the surrounding basins record a dramatic increase in sediment flux from the Alps since ca. 5 Ma ago (Kuhlemann et al., 2002; Willett et al., 2006). The latter finding was corroborated in Vernon et al. (2008), in which a compilation of thermochronological data was used to show that exhumation rates have at least doubled since ca. 5 Ma ago in the western Alps. Similarly, geodetic measurements attest to ongoing rock uplift within most parts of the belt (e.g., Schlatter, 2007). Here we use the term "rock uplift" to mean the upward vertical motion of rock particles with respect to an external reference level, as defined by England and Molnar (1990), and measured on short time scales by geodetic techniques.

Several different mechanisms have been proposed to explain the present-day exhumation and rock-uplift patterns in the western Alps. These include active faulting (Persaud and Pfiffner, 2004) and mantle processes (Kuhlemann, 2007; Lyon-Caen and Molnar, 1989). However, climatically induced mechanisms have also been proposed; in particular, the spatial coincidence of highest rock-uplift rates with areas of most deeply incised valleys has been used to infer that a significant part of the uplift

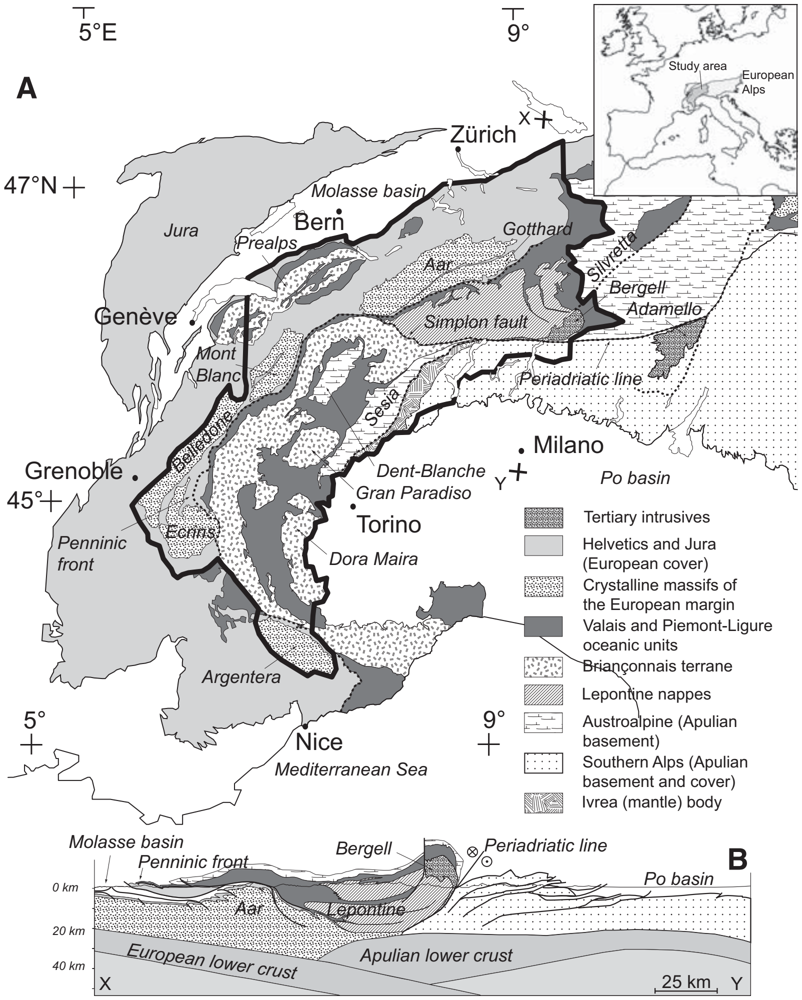

Figure 1. A: Geological map of western Alps (after Schmid et al., 2004). B: Crustal cross section along NFP20-East seismic line (Schmid et al., 2004; X-Y in map). Inset shows location in Europe. Thick black line contours study area. Major tectonic units and cities are indicated.

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signal results from isostatic response to focused erosion of the mountain belt (Champagnac et al., 2007; Schlunegger and Hinderer, 2001).

Here we study the spatial correlation between present-day climatic and tectonic forcing parameters with long-term exhumation rates, as inferred from a fission-track thermochronology database (Vernon et al., 2008). Our aim is to establish what may be driving present-day rock uplift and exhumation in the western Alps. Although we are aware that a spatial correlation does not imply a causal relationship, especially given the contrasting time scales, we are encouraged by recent findings that show a strong spatial correlation between millennial-scale denudation rates recorded by cosmogenic isotope abundances in river sediments, and both long-term relief characteristics and present-day rock-uplift rate (Wittmann et al., 2007).

DATA AND METHODS

We extract parameters characterizing long-term exhumation rates from an apatite fission-track (AFT) database, used to derive a map of interpolated AFT ages as well as the elevation of iso-age surfaces joining points with equal AFT ages (Vernon et al., 2008). We compare the spatial distribution of long-term exhumation rates with those of elevation, relief, seismicity, present-day rock uplift, and present-day precipitation, used here as a surrogate for climate. Morphologic parameters are extracted from the 3 arc-second (~90 m) resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM). Rock-uplift rates are from the Swiss Federal Office of Topography (SwissTopo) geodetic database (Schlatter, 2007) and are tied to a reference point in northern Switzerland, where vertical motion has been arbitrarily set to zero (Egli et al., 2007). We mapped the spatial variation in seismic energy released between 1959 and 2000 using the database compiled by Delacou et al. (2004). Although this database only contains earthquakes for which reliable focal mechanisms are available, causing underrepresentation of events with local magnitude $M_l < 3$, the available record represents >95% of the total seismic energy released during that time interval (Sue et al., 2007a). We quantified the released seismic energy (Se) from the local magnitudes using the classical relationship $\log Se\,[J] = 1.5\,M_l + 4.8$ (Gutenberg and Richter, 1954). Values were cumulated in a sliding 25-km-radius window cropped at 25 km around data points.

Potential precipitation controls were inferred from the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) 1971–1990 database (Frei and Schaer, 1998; Schwarb et al., 2001). Precipitation values were interpolated from rain-gauge measurements by Schwarb et al. (2001) using the model of Daly et al. (1994), which takes into account the orographic control on precipitation. Cumulated flow in streams is estimated by integrating the amount of annual precipitation over the upstream drainage area, assuming that runoff equals upstream precipitation and thus neglecting the effect of evapo-transpiration and local water recycling. Unit stream power (SP) is calculated from the annual cumulated flow (Q) and local slope (S), obtained from the SRTM DEM, using the relationship $SP \sim Q^{0.5}\,S$, based on the assumption that channel width is proportional to $Q^{0.5}$.

All data sets were resampled on a common 3 arc-second grid clipped at a distance of 15–25 km around each data point, to remove unconstrained interpolated values. Therefore, due to the uneven resolution of the original data, the coverage of the study area is not complete for every map. Maps of the most relevant variables are shown in Figure 2; all

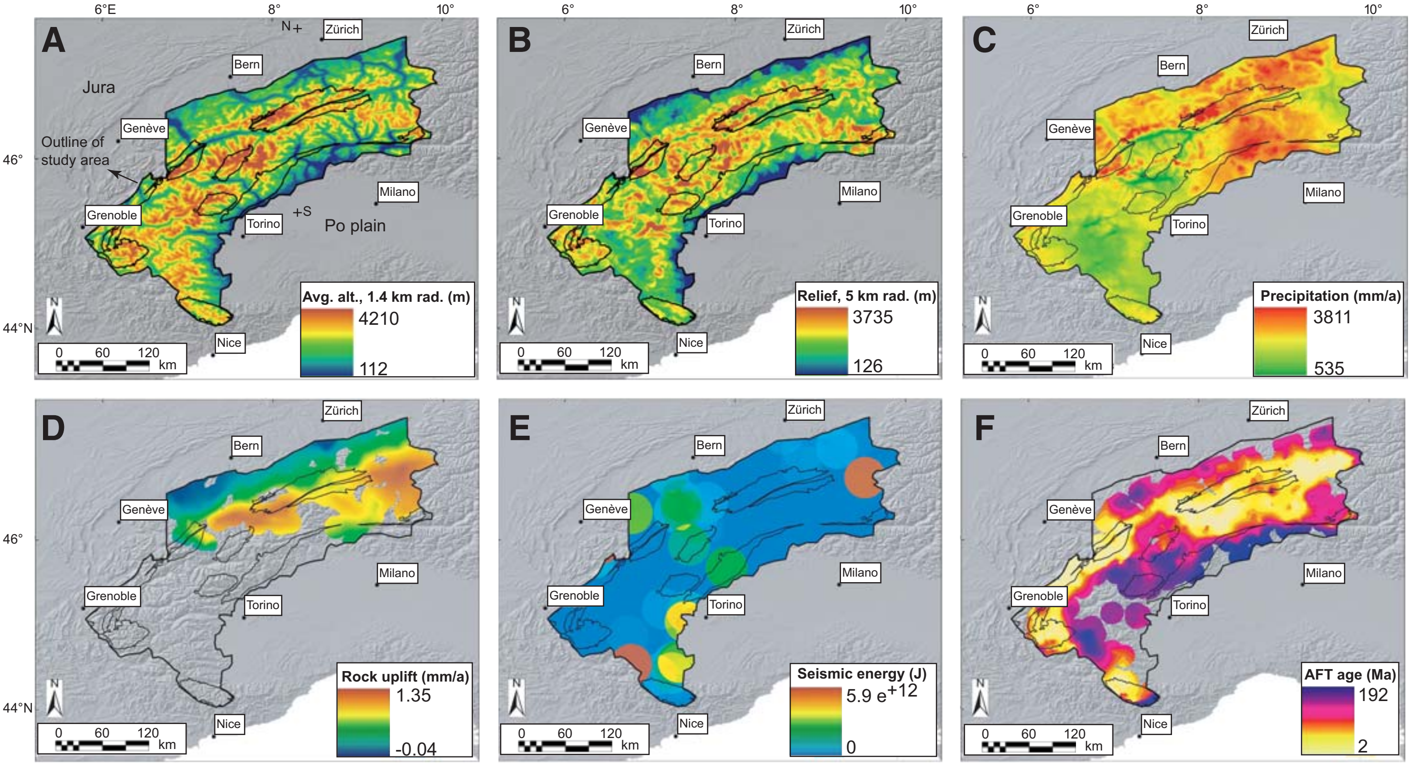

Figure 2. Maps of selected parameters for correlation. A: Average elevation within radius of 1.4 km, calculated using digital elevation model obtained from Consultative Group for International Agricultural Research–Consortium for Spatial Information (CGIAR-CSI) Shuttle Radar Topography Mission (SRTM) 3″ resolution database (http://srtm.csi.cgiar.org). Thin black lines contour major tectonic units detailed in Figure 1. N-S: location of cross section shown in Figure 3. B: Relief (difference between maximum and minimum elevation) in a 5 km radius. C: Annual precipitation (Frei and Schaer, 1998; Schwarb et al., 2001). D: Rock-uplift rate (after Schlatter, 2007). E: Seismic energy released (after Delacou et al., 2004; Sue et al., 2007a). F: Interpolated apatite fission-track (AFT) age (Vernon et al., 2008).

maps are included in Appendix DR1 of the GSA Data Repository[1].

Every grid was sampled at the location of 258,311 pixels forming the fluvial network draining more than 1.5 km^2 for the purpose of spatial correlation analysis. We estimated the strength of relationships between each association of two variables using a Kendall τ-b test. The unknown Gaussian nature of each data field and the presence of outlier points justify the use of this normalized, nonparametric test based on ranks rather than absolute values (Noether, 1981). We also show a north-south cross section across these data sets in Figure 3, in order to better visualize potential (anti) correlations between the different variables.

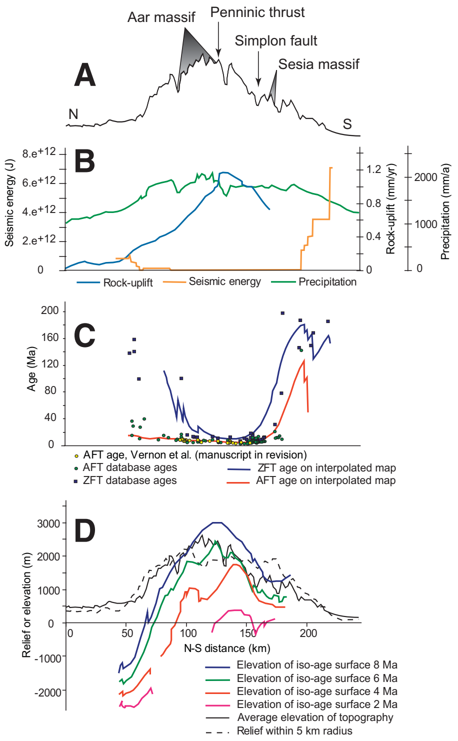

Figure 3. North-south cross section showing value of parameters averaged over 34-km-wide swath centered on profile line shown in Figure 2A. A: Major tectonic units projected over the mean topography. B: Present-day rock uplift, precipitation, and seismic energy released. C: Apatite and zircon fission-track ages (AFT, ZFT) indicating long-term exhumation rates (from database compiled in Vernon et al., 2008, or collected by Vernon et al. (unpublished data). D: Mean topography and relief within 5 km radius, and elevation of four different AFT iso-age surfaces. Maps used to extract information on this transect are provided with references in section A3 of the Data Repository (see footnote 1).

CORRELATION RESULTS

Table 1 reports the Kendall τ-b rank-correlation coefficients for pairs of potential forcing parameters and different measures of long-term exhumation rates. Note that the notion of "forcing" parameters is problematic, as it implies external and independent forcing that is unlikely to occur in a system characterized by feedback effects. Rock uplift, for example, may facilitate erosion, but it also results from erosion because of the isostatic response to removal of mass. Also, some of the calculated parameters are not fully independent: stream power, for example, is tied to both precipitation and topography. Tables DR2 and DR3 (in the Data Repository) report the correlation coefficients between the different control parameters and the different measures of long-term exhumation. Measures of long-term exhumation rates are fairly to very strongly correlated between themselves, suggesting that they are consistent and measure a significant quantity.

Our results show that present-day rock uplift and mean elevation are correlated to long-term exhumation rates (taking τ-b > 0.15 as an arbitrary cutoff). The same parameters appeared to correlate strongly with millennial-scale catchment-wide erosion rates from cosmogenic data (Wittmann et al., 2007); our results thus support these findings and suggest they can be extrapolated toward long-term exhumation rates.

In contrast, precipitation and relief correlate only weakly (τ-b ≤ 0.15) with measures of long-term exhumation, and neither cumulated flow, stream power, nor released seismic energy correlate with any of them (τ-b < 0.10). The lack of correlation between stream power and long-term exhumation results from the transient nature of the postglacial Alpine landscape (Brocard et al., 2003; Schlunegger and Hinderer, 2003), which causes strong short-wavelength spatial variability of the stream-power signal. The weak correlation between relief and long-term exhumation may be explained by the widespread occurrence of threshold hillslopes (Montgomery and Brandon, 2002). The forcing parameters tested here only describe present-day fluvial incision, calculated from the 20 year precipitation record, whereas glacial erosion must have been the dominant mechanism during most of the Quaternary in the Alps. However, Schlunegger and Hinderer (2001) suggested a correlation between glacial and fluvial sediment yield for a given catchment.

The cross section in Figure 3 shows how these variables are distributed across the Alps: whereas present-day rock-uplift and long-term exhumation rates peak in the central, highest, and most dissected part of the belt, precipitation appears more widely distributed and seismic energy is currently mostly released toward the interior edge of the belt, with the exception of an area between the Mont-Blanc and the Aar massifs (Fig. 2).

DISCUSSION AND CONCLUSIONS

The record of seismic energy release spans only 41 years, significantly shorter than the return period of major earthquakes in the Alps. Consequently, the released seismic energy may be locally underestimated. However, the pattern of present-day seismicity appears to be consistent with paleo-stress measurements throughout the western Alpine arc (Sue et al., 2007b, and references therein). The pattern of released seismic energy does not correlate with present-day rock uplift, measured over a comparable time interval. Therefore, it appears that neither present-day rock uplift nor long-term exhumation is coupled to seismicity. These results do not provide support for the notion that exhumation is controlled by active faulting in the short term (e.g., Persaud and Pfiffner, 2004).

The strong spatial correlation between elevation, rock uplift, and long-term exhumation can be interpreted as indicating either long-term steady state between rock uplift and exhumation in an active orogenic wedge, or isostatic response to focused denudation of a postorogenic mountain belt. The lack of correlation between the pattern of long-term exhumation and released seismic energy argues against an active orogenic wedge, as denudation rates appear to be strongly correlated with seismicity in such settings (Dadson et al., 2003), unless aseismic deformation plays a major role. These observations thus corroborate the notion that isostasy has dominated the rock uplift signal on a Pliocene–Quaternary time scale (Cederbom et al., 2004; Champagnac et al., 2007), although

TABLE 1. KENDALL τ-b CORRELATION COEFFICIENTS BETWEEN DIFFERENT POTENTIAL FORCING PARAMETERS AND MEASURES OF LONG-TERM EXHUMATION

	Rock uplift	Precipitation	Cumulated flow	Stream power	Seismic energy	Relief (5 km)	Mean elevation
Apatite fission-track age	–0.424	–0.127	–0.046	–0.093	0.067	–0.143	–0.052
2 Ma iso-age surface elevation	0.389	–0.084	–0.006	0.104	0.025	0.055	0.182
4 Ma iso-age surface elevation	0.412	–0.151	–0.035	0.037	0.033	0.049	0.189
Distance between 4–2 Ma iso-age surfaces	0.179	0.171	–0.023	0.053	–0.131	0.144	0.265

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[1] GSA Data Repository item 2009208, Appendix, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

they cannot rule out the interpretation that maintenance of a tapered thrust wedge by active faulting was the primary driver during late Miocene–early Pliocene time (Willett et al., 2006).

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