Quaternary erosion-induced isostatic rebound in the western Alps

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ABSTRACT

The high elevation and deep incision of the Alps have traditionally been used as an argument for recent tectonic activity that has elevated the belt and increased erosion rates. Normal faulting and horizontal extension, however, dominate current tectonic activity, and isostatic compensation of thinning crust should lead not to increased but to decreased mean elevations. Here we test the idea that enhanced Quaternary erosion of the Alps and isostatic compensation of the mass removed can account for the distribution of present-day geodetically measured rates of vertical movement in the western Alps. Using geophysical relief and Kuhlemann's estimated average erosion rate for the Alps, we quantify the spatial distribution of erosion and the volume of eroded rock, respectively. From these, we obtain a map of rock eroded within a given time span. The calculated isostatic response of the Alpine lithosphere to erosional unloading for a variety of values of the flexural rigidity of the Alpine lithosphere reaches a maximum of ~500 m since 1 Ma in the inner Swiss Alps, and vertical movement extends across the entire belt, including peri-Alpine basins. Assuming a steady erosion rate since 1 Ma, this rebound accounts for half of the measured vertical motion of 1.1 mm/yr in the southern Valais. Thus, a significant fraction (~50%) of the present-day vertical movement results from the isostatic response to enhanced erosion during Plio-Quaternary time.

Keywords: western Alps, Pliocene erosion rate, geophysical relief, isostatic rebound.

INTRODUCTION

The classic question of the relative roles of tectonics and erosion in shaping mountain ranges remains open. The answer probably lies somewhere between two end-member ideas: On the one hand, tectonics, via horizontal shortening, thickens the buoyant crust and elevates Earth's surface, and on the other, erosion produces relief, which through the isostatic response of the removed mass, elevates peaks above the surroundings (e.g., Wager, 1937; Holmes, 1965). In the same way, where crust extends horizontally and thins, isostatic compensation of that thinned crust should reduce mean elevations. In the European Alps, abundant geological, geodetic, and seismological evidence demonstrates active extension, whereas geodetic measurements attest to ongoing upward movement of benchmarks. The core of this belt has undergone extension since the Miocene epoch (Sue et al., 1999; Sue and Tricart, 2003; Delacou et al., 2004; Selverstone, 2005; Champagnac et al., 2006). What dynamics drive this vertical movement? Although several geodynamic processes have been proposed to explain this vertical component of movement (postglacial rebound, slab breakoff, crustal overcompensation, …), we examine the simple hypothesis that the isostatic response to erosion dominates the observed vertical motion. Erosion of a mountain range removes rock from the inner parts and modifies the mass balance, the stress field, and the force equilibrium in the edifice. Isostatic response to erosion induces rock uplift (relative to sea level) at up to 80% of the erosion rate, and peaks should rise where erosion is focused in adjacent valleys, as demonstrated in several places around the world (Wager, 1937; Holmes, 1965; Guillaume and Guillaume, 1982; Montgomery, 1994; Small and Anderson, 1998; Stern et al., 2005).

Despite a long history of study of Alpine geology, the relationship between erosion and isostatic response has seldom been taken into account in the Alps. Thus, one might wonder if the contribution of erosion to current Alpine kinematics and geomorphology is significant. Both a compilation of sediment accumulation surrounding the western Alps (Kuhlemann, 2000; Kuhlemann et al., 2006) and recent analyses of fission tracks from rocks in the Molasse Basin north of the belt (Cederbom et al., 2004) and from high terrain (e.g., Bogdanoff et al., 2000; Vernon et al., 2006) demonstrate rapid Plio-Quaternary erosion, a factor of three higher than earlier (Fig. 1). The close correlation with climate changes that include increased glaciation associated with global cooling (Molnar and England, 1990), greater variability of climate (Zhang et al., 2001; Molnar, 2004), and changes in ocean and atmospheric circulation (Haug and Tiedemann, 1998; Cederbom et al., 2004) suggests that some combination of these has been responsible for the accelerated erosion of the western Alps. Our aim is to determine the isostatic response to this increase in erosion rates and its contribution to the present-day topography of the western Alps.

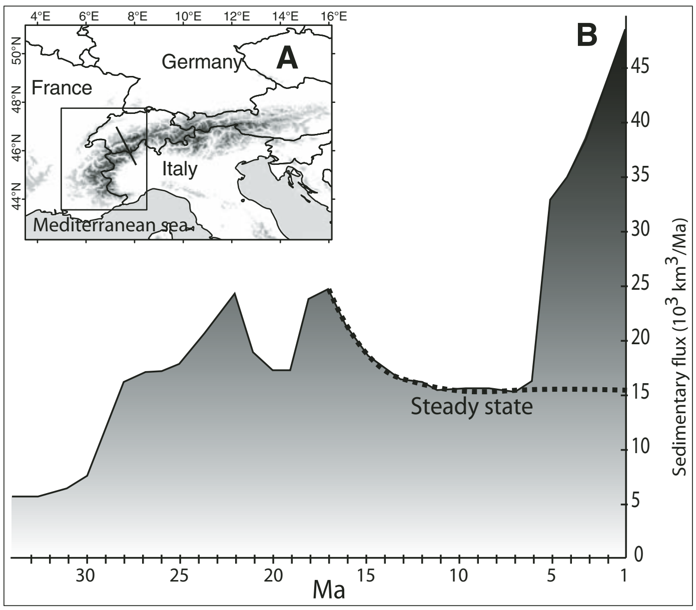

Figure 1. A: Relief map of area studied and location of cross section in Figure 2A. B: Average sediment discharge from western Alps into the surrounding basins in Cenozoic time (from Kuhlemann et al., 2002). This curve is used to estimate average erosion rate in the western Alps. Note the constant sediment discharge from 12 Ma to 5 Ma, which we assume to be the signature of a steady state of the erosion before the dramatic increase ca. 5 Ma, and use as a background erosion rate for the Pliocene (dotted line). Errors in the volumes are ±10% before 5 Ma and ±25% since 5 Ma (J. Kuhlemann, 2006, personal commun.).

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MEAN EROSION RATE IN THE WESTERN ALPS

Kuhlemann (2000) used volumes of sediment accumulation in regions surrounding the Alps to estimate an Oligocene to Quaternary history of mean erosion rates for the western Alps. The most striking feature is a dramatic increase of the erosion rate at ca. 5 Ma (Fig. 1); for the western Alps (area = 10^5 km^2) the average rate of 150 m/m.y. before 5 Ma rises to 480 m/m.y. since 1 Ma. Assuming that the upper Miocene erosion rate reflects a landscape in steady state (Burbank, 2002; Willett and Brandon, 2002; Bonnet and Crave, 2003), as Kuhlemann et al. (2006) proposed, one can split the Pliocene sediment budget into two parts: (1) an upper Miocene background average rate of 150 m/m.y. and (2) an enhanced rate since 5 Ma (by 330 m/m.y. for the last 1 m.y.). Before ca. 5 Ma, we may assume that the peaks erode at the same rate as the valleys (pale gray in Fig. 2C). For times of enhanced erosion, especially in Plio-Quaternary time in which glacial erosion dominated, we assume that the rate of erosion in the valleys exceeded that on the peaks (dark gray in Fig. 2C). Thus, for the last 1 m.y., we assume that erosion included a background rate (150 m/m.y.) *plus* a "non-steady-state part" (at an average of 330 m/m.y.).

SPATIAL DISTRIBUTION OF EROSION AND ITS GEOPHYSICAL RESPONSE

For a given cross section of the Alps, if one assumes that erosion is spatially distributed as a Gaussian function with a width (two standard deviations) of 160 km, the expected maximum erosion rate, using Kuhlemann's (2000) sediment budget, is 0.9 mm/yr averaged over the last 1 m.y. Assuming local isostatic response (Airy), the remaining uneroded rock would rise at 0.7 mm/yr. Relaxing this local compensation assumption to allow finite flexural rigidity, and using an effective elastic thickness of 10 km for the Alpine lithosphere, the maximum isostatic response reduced somewhat to 0.6 mm/yr. This simple calculation shows that a significant part of the 1.1 mm/yr geodetically measured present-day vertical movement could have been induced by the enhanced erosion, as previously suggested (Schlunegger and Hinderer, 2001, 2003; Kuhlemann et al., 2002; Cederbom et al., 2004). Therefore, the important change in erosion rates at the beginning of the Pliocene undoubtedly influenced the late history of vertical motion of the Alps and correlatively the recent tectonics of the belt.

Because of the arcuate shape of the belt, the high spatial variability in (paleo)climate, and strong lithological variations, we estimate the spatial distribution of erosion in order to calculate a realistic isostatic response. We used the topography given by the GTOPO30 digital elevation model (DEM), ~1 km resolution) to generate several surfaces from which we calculated a spatial distribution of eroded mass. Within a circular sliding window of a specified radius, which we varied from 1 to 50 km, the highest point within each circle was recorded. We then interpolated a surface connecting these highest points. The larger the circle, the higher the surface that connects them. The distance between this bounding surface and the present-day topography is called the "geophysical relief" by Small and Anderson (1998). Its distribution provides an estimate of the missing mass for the given radius of the sliding circle (Fig. 2A). Because the resulting map of geophysical relief does not include the unknown amount of erosion of peaks and ridge crests, we treat it as an estimate of only the "non-steady-state part" of the erosion.

We then compare the volume of eroded rocks derived from the map of geophysical relief with a realistic estimate of erosional volume from Kuhlemann's (2000) sediment budget. As illustrated in Figure 2B, a large calculation circle implies a large volume of eroded rock, and thus a large geophysical relief. If we match the non-steady-state part of Kuhlemann's (2000) sediment budget to the volume of eroded rock, we obtain an estimate for the appropriate size of the sliding circle. For the last 1 m.y., the volume of the geophysical relief in the western Alps calculated using a radius of 3 km (circle with an area of 28 km^2) matches the non-steady-state part of the sediment budget curve for that period (Fig. 2B). To estimate the total erosion for the last 1 m.y., we add the steady-state background rate (150 m/m.y.) to that derived from the geophysical relief over the 1 m.y. timescale (pale gray + dark gray in Fig. 2C). The map of geophysical relief (Fig. 3) provides an estimate of the distribution of the erosion during the last 1 m.y. and takes into account the total volume of eroded rock from the Alpine Arc during the same time span. We use this map to calculate the isostatic response of the Alpine lithosphere to this recent erosion.

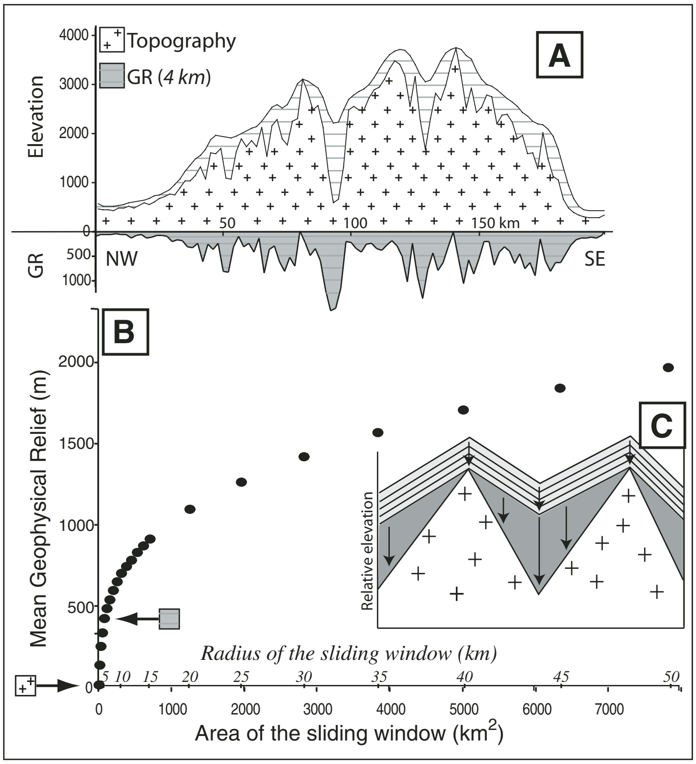

Figure 2. A: NW-SE cross section (see location on Fig. 1) with the topography (white surface) and the geophysical relief (GR) calculated with a sliding circle of 4 km radius (horizontal lines above the topography, and gray with horizontal lines below the 0 m line). B: Relationship between the area (*and the radius*) of the circular sliding window and the mean geophysical relief. Note that the geophysical relief increases dramatically from a radius of 1–10 km, and then more slowly. Arrow indicates geophysical relief that matches the non-steady-state part of the sediment budget of Kuhlemann et al. (2002). C: Cartoon of the split of the erosion rate into two parts. Upper part (pale gray with lines) corresponds to the steady-state part of the erosion. Lower part (gray) corresponds to the enhanced erosion, deepening of the valleys, and our calculated geophysical relief.

CALCULATION OF THE ISOSTATIC RESPONSE

Using the erosion map, we then calculated the flexural isostatic response to removal of this material, using a two-dimensional flexural model. We express results as an average rate of rock uplift for the last 1 m.y. (Fig. 4). We explored a range of effective elastic thicknesses (T_e) of 7–25 km for the Alpine lithosphere (Stewart and Watts, 1997), in all cases assuming that the flexural rigidity of the lithosphere is uniform. To avoid edge effects, we padded the calculation space by 200 km in all directions. The maximum response depends on the effective elastic thickness; for $T_e \leq 15$ km the predicted rock uplift rate exceeds 500 m/m.y. in the northern Val d'Aosta and southern Valais. Most of the western Alpine area exhibits a response >400 m/m.y. In the Molasse Basin north of the Swiss Alps, our calculations suggest between 200 m and 300 m of vertical movement

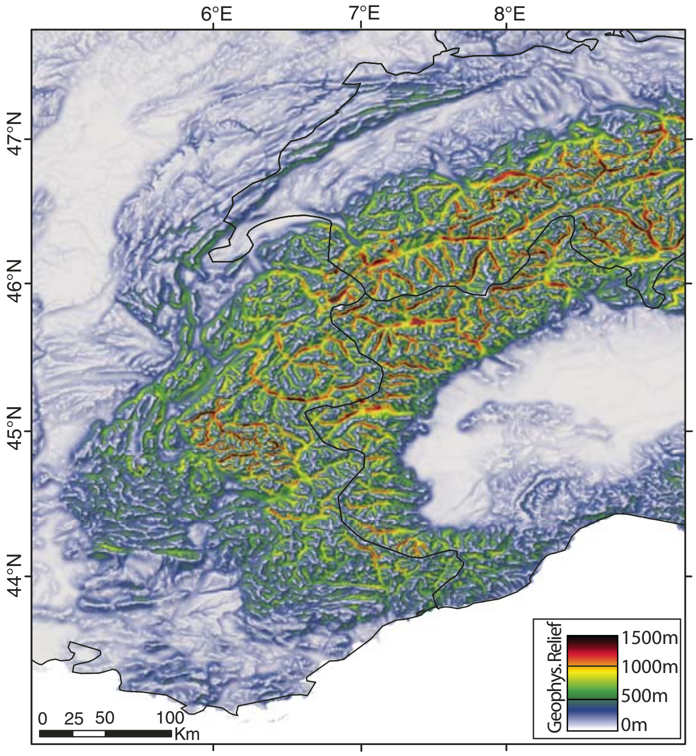

Figure 3. Map of geophysical relief of the western Alps, calculated with a radius of 3 km for the circular sliding window. Highest values (up to 1500 m) are located in the wide valleys of the northwest Alps, which were highly glaciated during the Last Glacial Maximum. Volume of the missing mass is consistent with the non-steady-state part of the sediment budget for the last 1 m.y. (33 × 10^6 km^3 for the western Alps; Kuhlemann et al., 2002). Black lines represent the borders between France, Italy, Switzerland, and Germany.

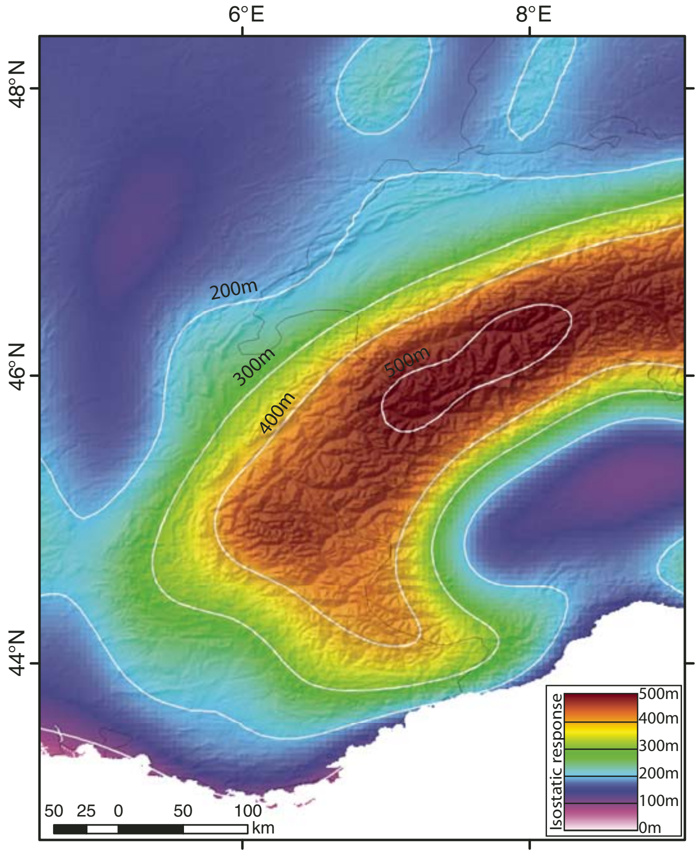

Figure 4. Map of isostatic rebound to erosion, calculated using a two-dimensional elastic plate with point loads. Calculation used the missing mass in Figure 3 (plus background erosion rate of 150 m/m.y.) and is smoothed to a 5 km pixel size in the calculation. Maximum vertical response, located between Valais and Val d'Aosta, approaches 500 m since 1 Ma (average of 0.5 mm/yr). Most of the western Alps undergoes vertical motion faster than 0.4 mm/yr. Variables used here are the following: T_e (effective elastic thickness of the lithosphere) = 10 km; μ (Poisson's ratio) = 0.25; ρ_c (density of the crust) = 2700 kg/m^3; ρ_m (density of the mantle) = 3300 kg/m^3.

since 1 Ma, which is qualitatively consistent with its eroded morphology. The Po plain south of the Alps exhibits 100 m of rock uplift, which also is consistent with recent data (Scardia et al., 2006).

DISCUSSION AND CONCLUSIONS

The separation of Kuhlemann's (2000) mean erosion rate into two parts (background rate + non-steady-state enhancement since 5 Ma) allows us to use the geophysical relief as an estimator of the distribution of the erosion. This assumption is valid if we consider that the enhanced Plio-Quaternary erosion has focused erosion in the valleys and deepened them, most likely by accelerated glacial erosion, and is reasonable for the Quaternary history of the Alps (Kuhlemann et al., 2002; Schlunegger and Hinderer, 2001, 2003). The simple one-dimensional calculation of the isostatic response to Plio-Quaternary erosion, using the average erosion rate deduced from the sediment budget, yields results of the same range of values obtained using the more realistic two-dimensional estimation of the spatial distribution. These results may be compared to the vertical component of movement obtained by precise remeasurement of leveling lines in Switzerland (Gubler et al., 1981; Kahle et al., 1997). Fast vertical motion occurs in the NE part of this area, in the Valais (up to 1.1 mm/yr). Assuming a steady rate of erosion for the last 1 m.y., the vertical component of motion that we calculated accounts for roughly half of this rate.

Kahle et al. (1997) showed that present-day vertical motion in the Molasse Basin (with respect to a point located at the NE edge of the basin) ranges from 0 (to the NW, close to the Jura fold-and-thrust belt) to 0.4 mm/yr (to the SW, close to the Alpine front); this is consistent with the rates we have calculated. The gradient of geodetically measured vertical motion is higher than our calculated gradient, which could be due to our use of effective elastic thickness (T_e) that is too large, but values of T_e from 7 km to 25 km give rates that differ little, both in magnitude and in distribution. Small values of T_e, however, yield steeper gradients in vertical movement from the foreland to the hinterland, as well as slightly higher values for the core of the range.

The spatial distribution of calculated erosion rates and the related isostatic response show that a significant part (50%) of the current vertical motion can be attributed to the enhanced erosion rate during the last 1 m.y. Furthermore, the erosion rate for the late Last Glacial Maximum appears to be higher than the average since 1 Ma: Erosion rates during the maximum were up to 0.6 mm/yr, and that during the last deglaciation was yet higher (up to 1.7 mm/yr) (Hinderer, 2001). Thus, Holocene vertical motion related to erosion could be higher than our estimate based on 1 Ma average rates. Since the largest isostatic response is in the northwest Alps (for both geodetic data and our calculations), one cannot exclude the possibility that combined high erosion rate during the Quaternary (and especially during the last deglaciation) and melting of the Alpine ice cap could account for all of the observed geodetic motion, especially because large uncertainties remain about the time span for the Alpine lithosphere to reach an equilibrium after the Last Glacial Maximum (Gudmundsson, 1994). Moreover, the ongoing shrinkage of Alpine glaciers may account for ~50% of the present-day vertical motion (Barletta et al., 2006). Although we cannot exclude other processes related to deep dynamics (slab breakoff, crustal delamination, etc.), the combination of these studies and ours suggests that virtually all of present-day Alpine vertical motion results from climatic change manifested in part by melting ice and in part by enhanced erosion rates in Plio-Quaternary time. The present-day heights of Alpine peaks owe their existence to glacial erosion of the valleys in the Plio-Quaternary. Erosion not only produced the high local relief but may have added several hundred meters to the peaks themselves. As such an increase of the erosion rate is observed not only in the Alps but worldwide (Zhang et al., 2001), one must further consider a global (i.e., climatic) mechanism (Molnar and England, 1990; Cederbom et al., 2004).

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