Geophysical Research Abstracts,
Vol. 10, EGU2008-A-12420, 2008
SRef-ID: 1607-7962/gra/EGU2008-A-12420
EGU General Assembly 2008

Late Neogene Exhumation and Relief Development of the European Alps: a Review of the Evidence and possible controlling Mechanisms

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The Neogene sedimentary record provides strong indications for a sharp increase in global sediment fluxes during the Pliocene. In Europe, sediment flux from the Alps has been inferred to have at least doubled since ~5 Ma, and numerous studies have hinted at accelerating denudation rates in other orogens (e.g., Betics, Apennines, southern Carpathians, Caucasus) around this time. Although tectonic mechanisms have been invoked to explain such increases in each individual setting, the roughly synchronous nature of a continent-wide and even global increase in denudation rates suggests that it may be climatically driven. Possible climatic mechanisms for increasing Pliocene denudation rates include a global increase in climatic variability, onset of Northern Hemisphere glaciations and, for Europe, increasing precipitation due to the onset of North Atlantic Gulf Stream circulation.

We review the evidence for, and possible controlling mechanisms on, increased Pliocene denudation rates in the European Alps. We have recently exploited the unique density of fission-track thermochronology data in the Western European Alps to estimate exhumation rates on the orogen scale between 13.5 and 2.5 Ma. This analysis corroborates both the timing and magnitude of the increase in denudation rates inferred from the sedimentary record, but also suggests some spatial variability in the signal. An independent analysis of the exhumation of the Molasse foreland basin in-

dicates relatively uniform, km-scale denudation of the basin since early-mid Pliocene times, which can be explained at least in part as recording flexural isostatic rebound of the orogen-basin system in response to erosional unloading of the orogen core. Such flexural rebound is also recorded by tilting of late Pliocene foreland basin remnants in south-eastern France. The timing of increased denudation post-dates orogenic wedge growth in the Alps and cannot be readily linked to a particular tectonic event. It is consistent with regional climatic change driven by the onset of Gulf Stream circulation, but both the exact nature of this change (amount of increase in precipitation) and its impact on denudation rates remain insufficiently quantified at this time.

Two major questions remain to be solved in the Alpine context. One is the relationship between increased exhumation and relief development. The present-day morphology of the Alps is clearly in a transient state and has been strongly impacted by Quaternary glaciations, which have significantly widened and overdeepened all major Alpine valleys. A morphologic analysis has shown that the volume of material excavated from these valleys is consistent with the increase in sediment flux recorded in surrounding basins. The modelled flexural isostatic rebound in response to valley carving can explain at least half of both the present-day rock uplift signal and the long-term tilting of foreland basin remnants. In contrast, the thermochronology data show spatial variations in exhumation on length scales smaller than the flexural wavelength, suggesting some tectonic modulation of the signal. This leads to the second open question of whether tectonics played an active or passive role in accommodating the forcing of increased Pliocene exhumation within a context of minimal present-day convergence rates in the Alps.