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River loads and modern denudation of the Alps — A review

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ABSTRACT

This paper presents the first comprehensive analysis of sediment and dissolved load across an entire mountain range. We investigate patterns and rates of modern denudation of the European Alps based on a compilation of data about river loads and reservoir sedimentation from 202 drainage basins that are between ca. 1 to 10,000 km^2 large. The study basins cover about 50% of the total area of the Alps. Modern glaciated basins have the highest sediment yields of up to 7000 t km^{-2} a^{-1}, which are on average 5 to 10 times higher than in non-glaciated basins. Likewise sediment yield and glacial cover are positively correlated. Instead, relief is a relatively weak predictor of sediment yield. The strong glacial impact in the correlations is due to glacier recession since the 19th century as well as due to glacial conditioning during repeated Quaternary glaciations which have produced the strong transient state of the Alpine landscape. We suggest that this is the major cause for ca. 3 fold enhanced denudation of the western compared to the eastern Alps. Chemical denudation rates are highest in the external Alps dominated by carbonate sedimentary rocks, where they make up about one third of total denudation. The high rates cannot be explained without anhydrite dissolution. We estimated that only 45% of the sediments mobilized in headwaters are exported out off the Alps, most sediments being trapped in artificial reservoirs. The total amount of sediment annually trapped within the Alps equates to 43 Mt. When corrected for sediment storage, we obtain an area-weighted mean total denudation rate for the Alps of about 0.32 mm a^{-1}. The pre-dam rate might be as high as 0.42 mm a^{-1}. In total, ca. 35 plus 23 Mt of mass are exported each year out of the Alps as solids and solutes, respectively. These rates are not enough to out pace modern rock uplift. Nevertheless, pattern of sediment yield across the Alps coincides roughly with the intensity of glacial conditioning and modern rock uplift, supporting the hypothesis of an erosion-driven uplift of the Alps.

Contents

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1. Introduction

Rivers are the most important agents of continental erosion and sediment delivery to the world oceans (e.g. Milliman and Meade, 1983; Hay, 1998). The majority of this sediment originates from uplifting mountain ranges and small mountainous rivers (Pinet and Souriau, 1988; Milliman and Syvitski, 1992), and authors agree that relief is a primary control on global riverine sediment yield (e.g. Ahnert, 1970; Summerfield and Hulton, 1994; Harrison, 2000). In addition, it was demonstrated that physical weathering is closely coupled with chemical weathering (Riebe et al., 2004; von Blanckenburg, 2005) leading to the hypothesis that mountain uplift since the Late Cenozoic has accelerated global cooling by CO_2 withdrawal from the atmosphere via silicate weathering (Raymo and Ruddiman, 1992). For these reasons denudation of mountain ranges is of particular importance with respect to global cycles of weathering, erosion and sediment supply to lowlands and oceans. Despite this importance no systematic study on river load data of an entire mountain range has been undertaken so far. This paper aims to fill this gap by exploring a large data base of solid and dissolved river loads and reservoir sedimentation in the Alps. This includes (i) a statistical analysis of potential controlling parameters, (ii) an extrapolation to the entire Alps and calculation of modern total mass export, (iii) a comparison with erosion rates at longer timescales (cosmogenic nuclides, sediment budgets), (iv) a comparison with modern rock uplift rates, and (v) a comparison with other mountain ranges. In particular, we will contribute to hotly debated issues such as the role of glacial conditioning and paraglacial sediment recycling and erosional unloading. A general outcome of this study will be a refined assessment of the role of mountain rivers in global sediment fluxes (Milliman and Syvitski, 1992) and a discussion of what can be learned from the Alps where the best data base exists.

Erosional denudation shows a close linkage to measured rock uplift in the Swiss Alps and has proposed to be the driving force in generating its present relief (Schlunegger and Hinderer, 2001; Champagnac et al., 2009; Norton et al., 2010; Willett, 2010; Norton et al., 2011). Patterns of denudation as calculated by Wittmann et al. (2007) from ^{10}Be in riverine quartz together with post-glacial denudation rates derived from sediment budgets of major Alpine valleys (Schlunegger and Hinderer, 2001) positively correlate with uplift rates, both increasing from the Swiss Plateau to the core of the Alps. Highest denudation rates of about 1 to 1.6 mm/a are located in regions with highest rock uplift rates of about 1 to 1.4 mm/a in the central Swiss Alps (Schlatter et al., 2005). This linkage is less evident in the southeastern Alps, where ^{10}Be derived erosion rates can better explained by active shortening (Norton et al., 2011). Furthermore, it is still unclear whether modern geodetically measured rock uplift rates are overprinted by effects of glacial isostasy after the Last Glacial Maximum or even the Little Ice Age (Gudmundsson, 1994; Barletta et al., 2006; Champagnac et al., 2007). Likewise, the post-glacial storage of Alpine-derived detritus in cirum-Alpine lakes, explains some of the currently measured rock uplift patterns, as discussed in detail by Champagnac et al. (2009).

Modern river loads represent a snapshot of highly fluctuating Pliocene to Quaternary sediment fluxes in the Alps. Sediment budgets and low-temperature thermochronometric data both demonstrate a 3-fold acceleration of erosion and sediment yield of the Alps between the Pliocene to the Quaternary (Bartolini et al., 1996; Bartolini, 1999; Kuhlemann et al., 2002; Vernon et al., 2008). Similar observations are made world-wide which led Molnar and England (1990) to their hypothesis of climate-driven mountain building in the Late Neogene. Recently, Willenbring and von Blanckenburg (2010) questioned the world-wide increase of sediment fluxes based on constant ^{10}Be/^{9}Be ratios of Late Miocene-modern offshore deposits, suggesting a constant erosional mass flux. They argue that rising sedimentation rates and sediment volumes are biased by selective sediment preservation and declare the conclusions drawn by Kuhlemann et al. (2002) from their sediment budget of the Alps to be largely an artifact. Schlunegger and Mosar (2011) qualified this statement and showed that the increase in sedimentation since the Pliocene may be real, but not as pronounced as considered by previous authors. They concluded that a large contribution of the Pliocene increase in Alpine sediment discharge might reflect the recycling of foreland deposits with an additional component derived from Pleistocene glacial erosion, a point that was already noted by Kuhlemann et al. (2002).

Recently, the role of glaciers in steepening the relief of mountain ranges by valley carving was pointed out by several authors who referred to the related topographic response as buzz saw effects (Brozovic et al., 1997; Tomkin and Braun, 2002; Egholm et al., 2009). For the Alps this concept has been confirmed by Szekely (2001), van der Beek and Bourbon (2008), Anders et al. (2010), and Pignalosa et al. (2011) all showing strong glacial imprint on present-day relief in steepening of valley flanks, which then were subject to enhanced erosion in deeply dissected inner gorges. Van den Berg et al. (2012) confirmed these conclusions based on a detailed ^{10}Be erosional budget where a 2–4 fold acceleration of erosion was measured in an inner gorge at the Alpine border. Norton et al. (2010) proposed that the glacial overprint of the Alpine landscape was the major driving mechanism for Holocene erosion and related erosional unloading. Haeuselmann et al. (2007) found evidence for major glacial erosion in the Alps starting between 1 and 0.8 Ma by