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Water versus ice: The competing roles of modern climate and Pleistocene glacial erosion in the Central Alps of Switzerland

Fritz Schlunegger [a,*], Kevin P. Norton [b]

[a] Institute of Geology, University of Berne, CH-3012 Berne, Switzerland
[b] School of Geography, Environment and Earth Science, Victoria University of Wellington, NZ-6140 Wellington, New Zealand

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ABSTRACT

Recent studies have identified relationships between landscape form, erosion and climate in regions of landscape rejuvenation, associated with increased denudation. Most of these landscapes are located in non-glaciated mountain ranges and are characterized by transient geomorphic features. The landscapes of the Swiss Alps are likewise in a transient geomorphic state as seen by multiple knickzones. In this mountain belt, the transient state has been related to erosional effects during the Late Glacial Maximum (LGM). Here, we focus on the catchment scale and categorize hillslopes based on erosional mechanisms, landscape form and landcover. We then explore relationships of these variables to precipitation and extent of LGM glaciers to disentangle modern versus palaeo controls on the modern shape of the Alpine landscape. We find that in grasslands, the downslope flux of material mainly involves unconsolidated material through hillslope creep, testifying a transport-limited erosional regime. Alternatively, strength-limited hillslopes, where erosion is driven by bedrock failure, are covered by forests and/or expose bedrock, and they display oversteepened hillslopes and channels. There, hillslope gradients and relief are more closely correlated with LGM ice occurrence than with precipitation or the erodibility of the underlying bedrock. We relate the spatial occurrence of the transport- and strength-limited process domains to the erosive effects of LGM glaciers. In particular, strength-limited, rock dominated basins are situated above the equilibrium line altitude (ELA) of the LGM, reflecting the ability of glaciers to scour the landscape beyond threshold slope conditions. In contrast, transport-limited, soil-mantled landscapes are common below the ELA. Hillslopes covered by forests occupy the elevations around the ELA and are constrained by the tree line. We conclude that the current erosional forces at work in the Central Alps are still responding to LGM glaciation, and that the modern climate has not yet impacted on the modern landscape.

1. Introduction

There has been a substantial interest in exploring potential controls on erosional mechanisms and related landscape form in mountainous landscapes (e.g., Ahnert, 1984; Champagnac et al., 2012; Flint, 1974; Herman et al., 2011; Moon et al., 2011; Safran et al., 2005; Wittmann et al., 2007). For time scales spanning thousands to tens of thousands of years, relationships between rates of crustal deformation, erosional processes, landscape metrics, and climate variables have been established for a variety of regions through the combined application of cosmogenic nuclides, topographic analyses and geodetic surveys (e.g., Bookhagen and Strecker, 2008; Ouimet et al., 2009; Riebe et al., 2001; Safran et al., 2005; Wittmann et al., 2007, 2009). These results have culminated in the recognition of a strong coupling between landscape form, erosion and precipitation in regions of landscape rejuvenation, associated with increased denudation (Abbühl et al., 2011; von Blanckenburg, 2005; von Blanckenburg et al., 2004). In these landscapes, streams have longitudinal profiles with concave segments separated by knickzones (Bishop, 2007), indicative of long-term transience (Whipple, 2009). The landscape in the Bolivian Yungas, a tropical to subtropical broadleaf forest of central Bolivia and eastern Peru, is a classical example where precipitation and rock uplift controls on surface erosion and hillslope form have been successfully identified (e.g., Bookhagen and Strecker, 2008; Masek et al., 1994; Safran et al., 2005). Contrariwise, also for the Bolivian Andes, Insel et al. (2010) found no correlations between ^{10}Be-based erosion rates and landscape metrics. However, causal relationships between these variables have been illustrated for the dry western side of this mountain range (Abbühl et al., 2011; Montgomery et al., 2001). The eastern and western margins of the central Andes share the same conditions as both flanks are characterized by a distinct transience in the landscape development, which has been related to either a tectonic pulse some My ago on the western Pacific side (Schildgen et al., 2007), or to orographically controlled precipitation on the eastern Amazonian flank which has persisted for at least 10 My (Masek et al., 1994). Accordingly, the climate and tectonic forcing have imprinted on the Andean landscape for time scales spanning some millions of years.

* Corresponding author. Tel.: +41 31 631 8767.
E-mail address: schlunegger@geo.unibe.ch (F. Schlunegger).

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The Central European Alps (Fig. 1A) provide a comparable setting in the sense that the transient character of the Alpine landscape is readily seen by knickzones on longitudinal stream profiles (Norton et al., 2010a), and particularly by distinct topographic steps at the confluence between trunk and tributary valleys (e.g., Valla et al., 2010; Van den Berg et al., 2012). In contrast to the Central Andes, however, the transient state of the Alpine landscape has been related to the effects of glacial erosion during the Late Glacial Maximum (LGM) and possibly earlier glaciations (e.g., Sternai et al., 2011; Van der Beek and Bourbon, 2008), which comprise relatively short time scales of <100 Ky. Because of the strong glacial impact, it is not clear whether the modern precipitation pattern has already impacted on the present-day Alpine landscape (Moon et al., 2011). Here, we use relationships between precipitation rates, landscape form, erosional mechanisms and erosional potentials of LGM glaciers to identify the most important controls on the modern shape of the Alpine landscape. We start with a focus on the catchment scale, and then expand our discussion to the scale of drainage basins, and finally

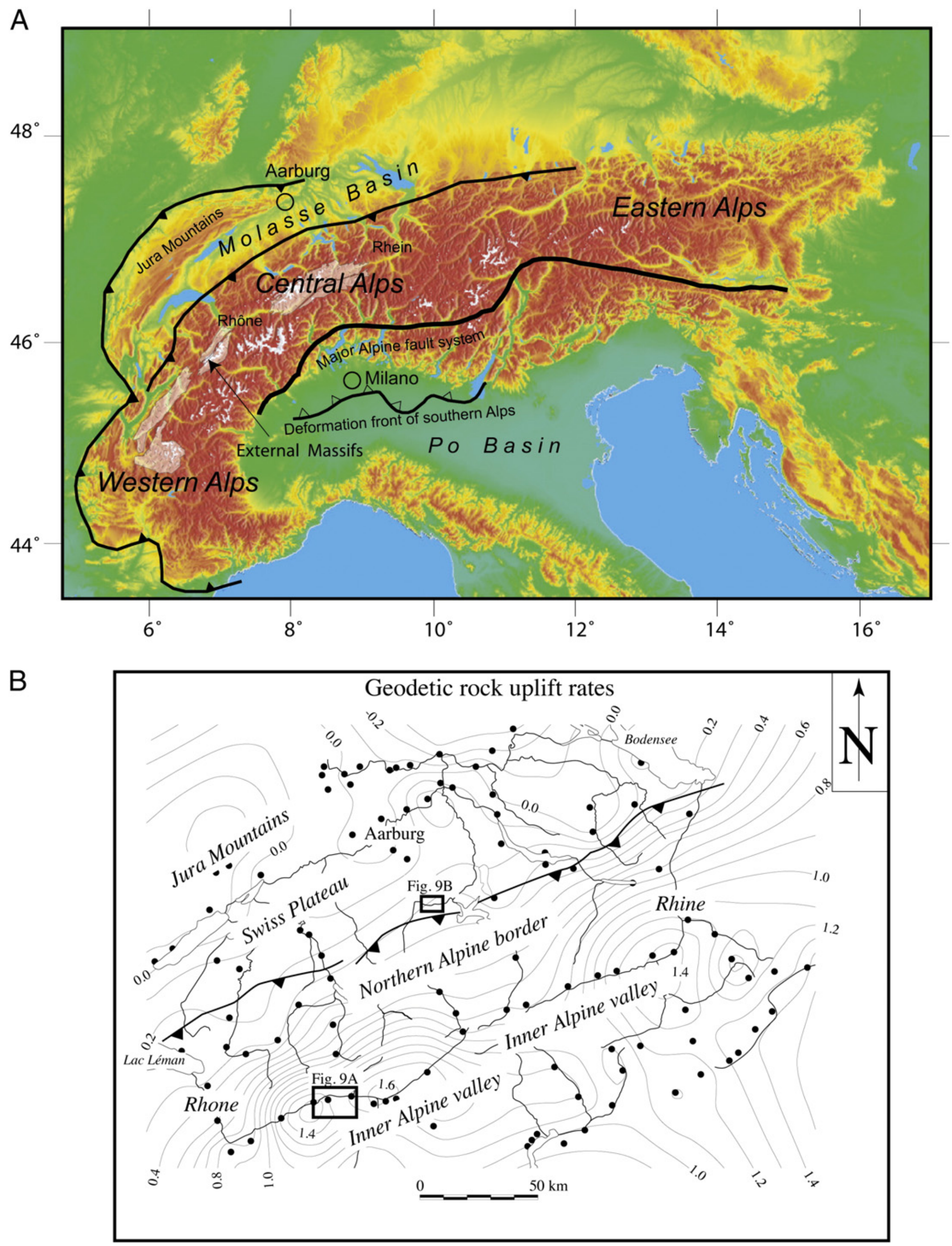

Fig. 1. A) Digital elevation model illustrating the Alps and their large-scale tectonic architecture. The pole of rotation of the Adriatic plate in the south relative to the European plate in the north is located in the vicinity of Milano, with the result of non-measurable shorting across the Central Alps. Aarburg is the reference site for the geodetic rock uplift pattern in the Central Alps. B) Illustrates the contour lines of geodetic rock uplift rates in mm/yr. The black dots are sites where elevations have been repeatedly measured (modified from Kahle et al., 1997).