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Glacial impact on short-wavelength topography and long-lasting effects on the denudation of a deglaciated mountain range

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ABSTRACT

Distinct alpine landforms in most high to mid-latitude mountain chains highlight the importance of glacial erosion in shaping mountain topography. The modifications to the initially, fluvially shaped landscape are associated with a massive and sustainable change in the distribution and magnitude of denudation following deglaciation. In this paper we focus on the glacially induced modifications to the short-wavelength topography of the deglaciated European Central Alps in an attempt to characterize the degree of glacial erosion on mountain topography and to explore the potential impact on millennial scale catchment denudation. We propose that short-wavelength topography is characteristically obliterated by glacial action and a measure of this process is provided by drainage density, which can be obtained by measuring the topographic curvature extracted from a DEM. Drainage density is well correlated with catchment-wide denudation rates from cosmogenic nuclides (^{10}Be), but in two separate domains, identified by the degree of glacial conditioning. At lower elevations, where fluvial erosion processes dominate at present, drainage density tends to increase with denudation rate and mean slope. At higher elevations drainage density tends to decrease with increasing denudation rate but is not sensitive to mean slope. The transition between these domains is approximately coincident with the equilibrium line altitude of the last glacial maximum. Our results indicate that the decreasing drainage density in the higher domain reflects the cumulative impact of glacial erosion. We speculate that the commensurate lengthening of hillslopes increases slope instability and mass flux, thereby resulting in higher denudation rates. Rock mass strength seems to have a further significant effect on these relationships.

1. Introduction

The alpine topography of many high- and mid-latitude mountain ranges gives a qualitative impression that glaciers have been highly efficient erosive agents during the Quaternary (e.g. Penck, 1905; Brozović et al., 1997; Mitchell and Montgomery, 2006; Pedersen et al., 2010; Herman et al., 2013; Pedersen and Egholm, 2013). The Plio–Pleistocene climate has driven dozens of cycles of glacial advance and retreat (e.g., Raymo, 1994; Raymo, 1997) and these have shaped landscapes very differently from those in which rivers are the main erosive agent (e.g. Hallet et al., 1996; Meigs and Sauber, 2000; Pedersen and Egholm, 2013). Multiple glaciations form the topography by promoting U-shaped valleys, cirques, isolated horns, narrow ridges and long bare-rock hillslopes (e.g. Whipple et al., 1999; Brocklehurst and Whipple, 2002; Egholm et al., 2009). Styles of erosional mechanisms differ also noticeably from those achieved by rivers after glaciers have receded (e.g. Brocklehurst and Whipple, 2006; Brardinoni et al., 2009; Hobley et al., 2010). Glacial retreat exposes landscapes, leaving slopes in an unstable state and highly susceptible to modification as new geomorphic processes take over. The period of rapid adjustment following glacial retreat (Benn and Evans, 1998), over which "glacially conditioned sediment stores are either exhausted or attain stability" (Ballantyne, 2002a), typically operates over timescales of 10^1 to 10^4 years (e.g. Church and Slaymaker, 1989; Harbor and Warburton, 1993; Hinderer, 2001; Hinderer et al., 2013). The glacially-induced transience of the topography, however, may last considerably longer (e.g. Whipple et al., 1999; Ambrosi and Crosta, 2011). Response times to fully erase the glacial signature of an orogen must exceed an interglacial (Brardinoni and Hassan, 2006; Hobley et al., 2010) and rather is on the order of 10^5 to 10^6 years, depending on climate conditions, rock type and tectonic uplift (e.g. Whipple, 2001). The glacial signature will therefore tend to become more dominant considering multiple cycles of glacial erosion during the Quaternary (e.g. Herman and Braun, 2008; Steer et al., 2012; Pedersen and Egholm, 2013). Given that glacial impact has been proposed to control patterns of modern catchment denudation and uplift (Wittmann et al., 2007; Champagnac et al., 2009; Norton et al., 2010a, 2010b; Glotzbach et al., 2013) clarification of the link between glacial modification and long-term impacts on the erosion of a deglaciated mountain range is clearly needed.

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The degree in glacial modification is commonly expressed by the hypsometric integral (e.g. Brocklehurst and Whipple, 2004; Sternai et al., 2011), with its maximum suggested to show a relation to the long-term position of the equilibrium line altitude (ELA; the suggested site of maximum ice flux and erosion) (Egholm et al., 2009; Pedersen et al., 2010). However, especially on a regional scale it is often not obvious how to interpret the results of such an analysis as the response of hypsometry to tectonic and climatic variability is not unique (Sternai et al., 2011). Similar to other topographic basin parameters in alpine landscapes such as mean slope (e.g. Wittmann et al., 2007; Moon et al., 2011), the hypsometric integral does not help to explain variations in denudation rates on an orogen scale (e.g. Norton et al., 2010a).

It has been suggested that a further major effect of glacial modification is the removal of short-wavelength topography (i.e. decrease in drainage density or increase in hillslope relief; Harbor et al., 1988; Harbor, 1992; Whipple et al., 1999; Brocklehurst and Whipple, 2007; Egholm et al., 2009). Numerical models suggest that the obliteration of small tributary valleys is expressed in a decrease in drainage density with a commensurate lengthening of hillslopes (Harbor et al., 1988; Harbor, 1992). In contrast to the large-wavelength modifications, systematic changes to the short-wavelength topography remain surprisingly unexplored (Brocklehurst and Whipple, 2007). Considering that changes to the hillslope relief (or drainage density) are generally accepted to have a first order impact on the type and magnitude of denudation (e.g. Oguchi, 1997; Talling and Sowter, 1999; DiBiase et al., 2011; Hurst et al., 2012; Schlunegger et al., 2013), the glacial history of a mountain range might be critical in setting a long-term control on denudation rates (e.g. Korup and Schlunegger, 2007; Korup et al., 2010).

The core component of our study was (i) the development of a novel and simple approach to estimate the relative degree in glacial modification from short-wavelength topography in a mountain range affected by multiple glacial cycles and (ii) to investigate how these glacially-induced changes may sustainably affect the denudation of a deglaciated mountain range. We addressed these questions to the European Central Alps, a region which has been multiply glaciated during the Quaternary and is home to exceptional information on crustal and surface geology, catchment-wide denudation rates, past and present glacial extend and the ELA (i.e. snowline) elevation since the LGM (Last Glacial Maximum). We explored changes to the short-wavelength topography by extracting the topographic drainage density in non-glacial and glacial catchments with variable lithology and a variable time-span of glacial impact (i.e. low to high mean elevation). The relations to modern denudation rates have been investigated by compiling existing catchment-wide denudation rates from cosmogenic nuclides (Wittmann et al., 2007; Norton et al., 2008; Kober et al., 2012).

2. Study area

2.1. Tectonics and lithology

The European Central Alps form a doubly-vergent asymmetric orogen with a crystalline core of European upper crust (Schmid et al., 1996) partly overlain by Mesozoic to Early Miocene sedimentary units of the former Helvetic and Penninic Ocean domains. Neogene compression led to a thick-skinned fold-and thrust belt, in which the crystalline basement was exhumed and shortened (Pfiffner et al., 1997). Exhumation occasionally exposed an erosionally resistant crystalline basement, i.e. the external massifs (Aar, Gotthard, Aiguilles Rouges and Mont Blanc) the Lepontine Dome and the Ivrea Zone (Schmid and Kissling, 2000). The soft rocks of the Central Alps are typically represented by the sedimentary deposits of the Helvetic and Penninic cover units (e.g. Bündner Schist) (Kühni and Pfiffner, 2001). The Alps are flanked by foreland basins on either side; the Molasse Basin in the north and the Po-Basin in the south. Basin fill comprise deep to shallow marine sediments with intercalations of fluvial sequences. Since the Late Miocene convergence significantly slowed and is presently about 1 mm/a (Marotta and Sabadini, 2008). GPS data based synthesis suggests that the Central Alps are currently not in a state of active convergence (Weber et al., 2010). Modern uplift is suggested to be dominantly driven by erosional unloading (Champagnac et al., 2007; Wittmann et al., 2007).

2.2. Quaternary glaciations

The European Alps have been repeatedly glaciated during the Quaternary with the exception of its very eastern and southern parts (Penck and Brückner, 1909; Schlüchter, 1986; Ehlers and Gibbard, 2007; Preusser et al., 2011). The imprint of glacial erosion is expressed in an Alpine landscape representing typical features such as horns, arêtes, cirques, U-shaped valleys and oversteepened slopes (e.g. Penck, 1905; Kelly et al., 2004). Alpine Foreland areas might not have been affected by glaciation until the mid-Pleistocene transition (around 900 ka; Lisiecki, 2010). Since that time, glacial activity in the Alps dramatically increased (e.g. Muttoni et al., 2003; Häuselmann et al., 2007; Valla et al., 2011), with a potential increase in net erosion rate (Kuhlemann et al., 2002; Willett, 2010). At least 3 glaciations with similar extent as the LGM (Fig. 1) can be deduced from glacial remnants preserved in the adjacent Bavarian and Austrian Foreland (Penck and Brückner, 1909; Salcher et al., 2010). The mean ELAs of these peak glacial periods, which followed the mid-Pleistocene transition ("major glaciations", Raymo, 1997; Muttoni et al., 2003) can therefore be assumed as similar. Glacial maxima following the mid-Pleistocene transition such as the LGM, covered the entire Central Alps and almost its entire Foreland with the exception of small regions (Fig. 1). The latter are, through their original fluvial shape, morphologically clearly distinguishable from the surrounding glacially eroded areas (e.g. Schlunegger and Hinderer, 2003; Büchi et al., 2014). Sedimentary records of former glaciations have been largely eroded (e.g. Preusser et al., 2010) and are only locally preserved (e.g. Graf, 2009; Dehnert et al., 2012; Starnberger et al., 2013). However, given the appearance of glaciers with similar extent to the LGM during each peak glacial period (e.g. Preusser et al., 2011), information about the period after the LGM might mirror a typical scenario of glacial recession during a glacial/interglacial transition. Glaciers remained at their LGM position for only a short period, not exceeding a couple of thousands of years (between ca. 25–21 ka; Van Husen, 1997; Ivy-Ochs et al., 2008). The Alpine Foreland was already ice-free at 18 k.a B.P. (Ivy-Ochs et al., 2006) and glaciers have receded in the tributary side valleys of the main troughs long before the Holocene (Ivy-Ochs et al., 2008; Starnberger et al., 2013). Data from the Late Glacial indicates several stagnations or short-timed glacial re-advances after the LGM (Ivy-Ochs et al., 2008 and references therein) with the most prominent re-advance occurring during the Younger Dryas ("Egesen Stadial") (Van Husen, 1997; Preusser, 2004; Ivy-Ochs et al., 2007; Ivy-Ochs et al., 2009). During all postglacial re-advances, glaciers stayed within inner Alpine valleys and did not reach the main trough valleys (e.g. of the Rhine, the Rhone or the Ticino).

With respect to the modern ELA, the LGM ELA of the Swiss Alps was lower by about 1300 to 1600 m and during the Younger Dryas by about 550–280 m (Ivy-Ochs et al., 2008; Ohmura, 2010 and references therein). The ELA range reflects the slightly different climate north and south of the divide, which can be assumed to be sustained for much of the Quaternary (Florineth and Schlüchter, 2000; Anders et al., 2010). The modern ELA position in the Swiss Alps is around 3000 m. As the highest parts of the Swiss Central Alps are above this elevation, some massifs are presently glaciated (e.g. Aar Massif, Valais, Bernina) (Fig. 1).

3. Materials and methods

3.1. DEM data, short-wavelength topography and drainage density

The topographic calculations of Central Alpine catchments in Switzerland and Italy were done i) for catchments where averaged denudation rates from cosmogenic nuclides exist (Fig. 1; Tab. A.1 in