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Alpine topography in the light of tectonic uplift and glaciation

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ABSTRACT

In steady-state orogens, topographic gradients are expected to increase with elevation whereas the European Alps feature a transition from increasing to decreasing slopes. This peculiar pattern has been interpreted to reflect either the critical slope stability angle or a premature fluvial landscape but is also consistent with the glacial buzz-saw hypothesis. To disentangle the contributions of each of these principles we split the Alps into contiguous domains of structural units and analyze their slope–elevation distributions emphasizing glaciated and non-glaciated realms. In comparable structural units within the extent of the last glacial maximum (LGM) the transition from increasing to decreasing slopes is located at the equilibrium line altitude (ELA) of the LGM and we interpret this to be evidence for the impact of glacial erosion. Decay rates of glacial landforms towards steady-state slopes depend on lithological properties leading to a landscape characterized by different transient states. Beyond the LGM limits the slope–elevation distributions show local maxima as well, but these are located at varying altitudes implying a tectonic driver. This observation and data from surrounding basins suggests that at least parts of the European Alps experienced a pre-Pleistocene pulse of tectonic uplift. The resulting presence of premature low-gradient terrain above the ELA during the global cooling in Plio–Pleistocene times would have heavily influenced the onset and the extent of an alpine ice cap.

1. Introduction

The topography of the European Alps reflects continental collision, crustal thickening, and buoyancy driven surface uplift overprinted by erosional processes following topographic gradients (e.g. Ratschbacher et al., 1991; Frisch et al., 1998; Robl et al., 2008b; Luth et al., 2013). These processes act on individual spatial and temporal scales and should in principle be identifiable in the resulting landforms. However, superposition, spatially non-uniform rates and different timing of these processes, feedback loops between lithospheric and surface processes, and the state of (non)-equilibrium of landforms still drive the debate on the formation of topography and relief in terms of uplift and erosion in the European Alps (Hergarten et al., 2010; Norton et al., 2010; Wagner et al., 2010; Sternai et al., 2012).

1.1. Formation and destruction of topography in the Alps

The indentation of the Adriatic micro plate with Europe caused spatially and temporally variable uplift as a consequence of a complex deformation field due to contrasting rheological properties of crustal blocks, large scale fault systems, and the Mid-Miocene stress field inversion (e.g. Robl et al., 2008b). Deep-seated mantle processes such as slab breakoff or the delamination of the mantle part of the lithosphere might also be responsible for recent large scale uplift due to increased buoyancy of the European Alps (Lyon-Caen and Molnar, 1989; von Blankenburg and Davis, 1995; Duretz et al., 2011; Valera et al., 2011). This leads to the formation of relief over time which is expressed by increasing topographic gradients and potential energy.

Simultaneously to uplift, gravity-driven erosional surface processes act along the topographic gradients and remove newly formed topography until a morphological steady-state is established where uplift and erosion rates are balanced (Montgomery, 2001). The drainage system represents the backbone of the alpine landscape and is responsible for bed rock erosion and the long range transport of rocks as bed load, suspension or solution downstream towards the foreland basins (e.g. Hinderer et al., 2013). Hillslopes constitute the largest parts of a mountain landscape where the drainage system sets the lower boundary condition for the hillslope evolution over time. Hillslope gradients adjust to river incision by mass wasting towards steady-state hillslope angles (Strahler, 1950; Montgomery, 2001). Gradients in channels and hillslopes are controlled by the erosional resistance of the lithology suggesting that rock properties are a first-order control on the topographic evolution of a mountain range.

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Mass wasting along hillslopes, bed rock incision in drainage systems and glacial scouring are conditioned by the climate (e.g. Norton et al., 2010). A globally recorded cooling trend initiated in Pliocene times (e.g. Zachos et al., 2001) and culminated in the Pleistocene glaciation cycles. During these glacial stages, a predominant part of the European Alps was covered by an ice cap and the landscape was reshaped by glacial erosion (e.g. Penck, 1905). Consequently, glacial landforms like cirques and glacial troughs are abundant throughout the Alps (e.g. van der Beek and Bourbon, 2008) representing transient landscapes during inter- and postglacial periods (Norton et al., 2008; Salcher et al., 2014). As a consequence, the geometry of the drainage system is characterized by a massive glacially-induced disturbance of former (steady-state?) longitudinal channel profiles in mountainous regions in the form of prominent knick points and the so-called “inner gorges” that have been preserved through repeated alpine glaciations (Montgomery and Korup, 2011). In addition, a horizontal shift of the main streams may occur due to both glacial erosion and increased sediment delivery (Robl et al., 2008a; Garzanti et al., 2011; Monegato and Vezzoli, 2011).

Extensive glacial dissection of the alpine landscape happened since around 0.87 Ma (Muttoni et al., 2003; Haeuselmann et al., 2007; Scardia et al., 2012) and resulted in base level lowering of several tens (and possibly hundreds) of meters in the main channels of the Western (Schlunegger and Schneider, 2005; Herman et al., 2011) and Eastern Alps (Preusser et al., 2010; Reitner et al., 2010). In addition, alpine base level changes are also related to spatial and temporal variable uplift rates (Wagner et al., 2010; Meyer et al., 2011; Legrain et al., 2014b) and the desiccation of the Mediterranean during the Messinian salinity crisis (e.g. Willett et al., 2006). Channels transfer the information on base level changes upstream by the migration of knick points that incise into the bed rock (e.g. Whipple et al., 2013), enter tributaries and trigger mass wasting processes at corresponding hillslopes (Schlunegger, 2002; Robl et al., 2008a; Schlunegger et al., 2009). This may cause an orogen-wide reorganization of the drainage system by the migration of divides and river piracy events (Stüwe et al., 2008; Willett et al., 2014). Again, the pace of landscape reorganization towards steady-state strongly depends on lithology (e.g. Hurst et al., 2013).

A feedback between tectonics and climate exists via erosional unloading of the orogen. Hillslopes locally transfer regolith to confining streams or glaciers which in turn transport mass from the mountains to the foreland basins unloading the orogen (e.g. Hinderer et al., 2013). The orogen responds with flexural isostatic uplift driven by erosion leading to the formation of additional relief (Gudmundsson, 1994; Wittmann et al., 2007; Champagnac et al., 2009; Scardia et al., 2012). In contrast to tectonically controlled uplift, peaks are rising but the mean elevation and potential energy of the orogen decrease in sum of erosion and isostatic surface uplift (Wager, 1937; Szekely, 2003; Champagnac et al., 2007).

Kuhlemann et al. (2002) discovered a massive increase of sediment delivery from the European Alps caused by erosion rates approximately doubling since around 5 Ma and posed the question on climatic or tectonic drivers. This observation is consistent with the low temperature thermochronology from the Western and Central Alps indicating a significant increase of exhumation rates within this time slice (Vernon et al., 2008). Whatever drivers (climate or tectonics) may have caused the increased denudation rates and sediment delivery, the alpine landscape is currently in a transient state and patterns of processes that adjust the alpine landscape towards a geomorphic equilibrium are recorded constantly as expression of alpine topography and can therefore be extracted by analyzing digital elevation models.

1.2. The topographic pattern in digital elevation models

Triggered by the pioneering morphometric studies of Frisch et al. (2000) and Szekely (2001) many authors analyzed digital elevation models (DEMs) of the Alps to infer tectonic, climatic and lithological conditioning from topographic gradients and channel slopes (e.g. Robl et al., 2008a).

Kühni and Pfiffner (2001) analyzed the topographic pattern in the Swiss Alps and discovered an increase of topographic gradients with increasing surface elevation up to 1500 m, followed by a constant average slope of about 25° up to 2900 m and a further steepening in the summit regions. They interpreted this pattern as the average limiting slope stability angle for the Swiss Alps that is in good agreement with the average slope of 25° reported by Schmidt and Montgomery (1995). The increase in slope at about 2900 m is interpreted as a combination of permafrost stabilizing the regolith cover of the slopes and the transition from a fluvial to a glacial erosional regime.

Hergarten et al. (2010) analyzed channel slopes at given catchment sizes instead of topographic gradients to avoid complications introduced by the non-linearity of the stream power formulation. They interpreted the increase of channel slopes with increasing surface elevation up to about 1500–2000 m and the decrease of channel slopes above as evidence for the morphological prematurity of the Alps caused by accelerated uplift since around 5 Ma. In fact, a recent large scale uplift event is documented at the periphery of the Alps and in adjacent basins (Wagner et al., 2010; Cederbom et al., 2011; Gusterhuber et al., 2012; Legrain et al., 2014a). This is consistent with the observed transient landscape of the inner Alps where the channel morphology of the lower regions may be interpreted as morphological equilibrium state of the recent pulse of uplift. Domains at high altitudes characterized by reduced channel gradients may represent lower uplift rates that have driven topography formation before this latest pulse of uplift.

Both studies present strong arguments in favor of their hypotheses with a consistent but not unique interpretation of the observed pattern. Alternatively, glacial erosion is thought to cause a similar slope distribution: Several studies describe a maximum in the hypsometric curve at the equilibrium line altitude (ELA) in regions characterized by a strong glacial impact (Brozović et al., 1997; Spotila et al., 2004; Egholm et al., 2009) and the formation of over-deepened valleys and glacial lakes with nearly vertical valley flanks (e.g. van der Beek and Bourbon, 2008). Hence, the shape of the hypsometric curve of the Alps may be caused by a decrease of mean elevation as a consequence of the “glacial buzz-saw” resulting in lower topographic gradients at and above the ELA and in the formation of valley scale relief due to glacial dissection below the ELA (e.g. Sternai et al., 2012).

The slope–elevation distribution of the Alps as observed by Kühni and Pfiffner (2001) and Hergarten et al. (2010) seems also consistent with and could therefore be caused by glacial erosion. The scope of this study is to disentangle the potential influence of prematurity, slope stability and glacial erosion on the peculiar topography of the European Alps.

1.3. Hypothetical slope–elevation effects of prematurity, slope stability and glacial sculpting

Each of the three geomorphological principles described above — morphological prematurity, slope stability and glacial erosion predicts an individual characteristic slope–elevation distribution (Fig. 1). Assuming a simplified mountain range with surface uplift rate linearly increasing towards the main divide (tent-shaped uplift rate), fluvial equilibrium is represented by an increase of average slope with surface elevation (Hergarten et al., 2010).

In case of prematurity, the slope–elevation distribution is characterized by a turning point from increasing to decreasing slope with elevation (Fig. 1a). However, spatial variations in uplift are unlikely for the small scale structural units investigated in this study. Here, we rather expect uniform uplift rates hence constant slopes over the entire elevation range in geomorphological equilibrium as long as the distribution of upstream drainage areas does not change significantly with altitude. Given uniform uplift, prematurity also features a turning point in the slope–elevation distribution separating high topographic gradients at low altitudes from low topographic gradients at high altitudes.