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Invited review

The topographic state of fluvially conditioned mountain ranges

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ABSTRACT

The topography of mountain ranges reflects the competition of constructive and destructive processes driven by tectonics and climate, respectively. There is a vital debate whether the topography of individual orogens reflects stages of growth, steady-state or decay that is fueled by the million-year time scales hampering direct observations on landscape evolution, the superposition of various process patterns and the complex interactions among different processes. Hence, there is a demand for sophisticated analysis tools to extract constraints on the long-term evolution of orogens from their topography. We review the field of orogen-scale landscape evolution from a numerical perspective, summarize the most prominent modelling concepts and their implications for the fluvially-driven development of mountain topography, and finally evaluate their applicability for understanding real-world orogens.

Following the concept of equilibrium – a state where uplift rates are balanced by erosion rates and topography remains steady over time – the erosional long term response of rivers and hillslopes can be mathematically formalised by the stream power and mass diffusion equations, respectively. Based on a simple 1-dimensional model consisting of two rivers separated by a watershed we explain the influence of uplift rate and rock erodibility on steady-state channel profiles and show the time-dependent development of the channel - drainage divide system. Dynamic drainage network reorganisation adds additional complexity and its effect on topography is explored on a two-dimensional model. River capture events and drainage divide migrations as expression of the ongoing drainage network reorganisation cause changes in topography until a stable network topology, and hence full topographic steady-state is achieved. The long time spans needed for this drainage network optimization suggest that orogens on Earth may never reach full topographic steady-state.

In real world orogens, we find evidence for premature, mature and decaying topography as well as relief rejuvenation by analysing slope-elevation distributions and trace the expression of crustal strain distorting drainage networks by applying the χ transform. We conclude that modern concepts of landscape evolution allow sophisticated analyses of real-world orogens, but emphasize that unambiguous results are mostly derived from regions dominated by a limited number of interacting processes such as mountain ranges with limited or no glacial imprint. This results in a high demand for techniques to disentangle the complex topography of real-world orogens into the signals resulting from the individual land-shaping processes.

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1. Introduction

Collisional orogens are among the most spectacular morphological expressions of plate tectonics on Earth. Over an orogenic cycle, the horizontal motion of converging plates is transferred into vertical motion of rock (rock uplift) and topography (surface uplift) via shortening, crustal thickening, and isostatic compensation (e.g. England and McKenzie, 1982; England and Houseman, 1986; Houseman and England, 1986; Houseman and England, 1993; Robl and Stüwe, 2005a; Robl and Stüwe, 2005b). Erosional surface processes act along evolving topographic gradients and counteract the formation of topography as erosion rates increase with topographic gradients at hillslopes (e.g. Culling, 1960) and channel slopes at rivers (e.g. Howard, 1994). As a consequence, erosion rates tend to adjust to uplift rates (e.g. Whipple, 2004a) until the orogen approaches a topographic steady-state where surface elevation is constant over time (Kooi and Beaumont, 1996; Montgomery, 2001; Willett and Brandon, 2002). With the cessation of plate convergence erosional surface processes erase existing topography until topographic gradients vanish (Baldwin et al., 2003; Egholm et al., 2013; Tucker and van der Beek, 2013). Hence, mountainous landscapes reveal deep insights into mountain range evolution that is controlled by competing processes building-up and destroying topography and reflect the million years' interplay of climate and tectonics (e.g. Whipple, 2009, Willett, 1999). Processes acting on these spatial and temporal scales and resulting topographic patterns are in the focus of this review.

Given that in tectonically active orogens rates of uplift (e.g. Serpelloni et al., 2013; Liang et al., 2013 and erosion (e.g. Milliman and Syvitski, 1992; Galy and France-Lanord, 2001; Vance et al., 2003; Koppes and Montgomery, 2009; Norton et al., 2010; Herman et al., 2013a) hardly exceed a few millimetres per year, an alpine landscape represents a certain topographic state over a human observation period – a snapshot during the dynamic topographic cycle from low elevations to high alpine terrain back to hilly landscapes and low gradient planes as described by Davis (1899), Penck (1953) and Hack (1975), just to remind of the most famous concepts on landscapes evolution (for a detailed review see Bishop, 2007). Deciphering the topographic record represents a key approach to constrain the evolutionary state of an orogen: Do we observe features of a premature landscape characteristic for an early state of topography where uplift rates exceed erosion rates and mean elevation increases? Does the mean elevation remain constant as equilibrium between uplift rates and erosion rates has already been established or do we even discover a decaying landscape indicating the fading or cessation of tectonic forcing?

While evolution of topography over a human observation period manifests in form of discrete erosive events such as floodings, landslides or debris flows, fundamental concepts on the long-term evolution of topography assume a continuous development (Davis, 1899; Penck, 1953; Hack, 1975; Howard, 1994; Willett et al., 2014). In the light of a rapidly growing number of studies applying morphometric approaches to decipher the latest tectonic and climatic history of orogens (e.g. Kirby and Whipple, 2001; Wobus et al., 2006a; Robl et al., 2008a; Kirby and Whipple, 2012; Legrain et al., 2014b) new theoretical advances in analysing topographic patterns (Hergarten et al., 2010; Royden and Perron, 2013; Perron and Royden, 2013; Willett et al., 2014; Fox et al., 2016) and novel numerical models to describe the time-dependent evolution of alpine landscapes (Robl et al., 2008c; Stüwe et al., 2008; Yang et al., 2015; Garcia-Castellanos and Jiménez–Munt, 2015; Goren et al., 2015) we (a) review the long term evolution of topography in collisional orogens from a numerical perspective and give a detailed overview on the theoretical framework from Hack's pioneering study on longitudinal channel profiles (Hack, 1957) to the χ transform (Perron and Royden, 2013; Royden and Perron, 2013), (b) apply this framework to one- and two-dimensional numerical models and (c) transfer model outcomes to real-world examples.

1.1. Topographic expression of plate tectonics

Topography is the deviation of Earth's surface from the geoid caused by properties of the lithosphere and mechanical work performed by plate tectonics. The two different types of lithosphere, oceanic and continental, are clearly distinguishable by two distinct maxima in the hypsometric curve of the Earth (Fig. 1). One maximum is located at about −4500 m in the oceanic domain and another one slightly above the sea level in the continental domain. Among other arguments, Wegener (1915) based his then controversial continental drift theory on the peculiar hypsometry of Earth's surface.

Although mid-ocean ridges and deep sea trenches cover only a few percent of the ocean floor (large gradients in the hypsometric curve), they host most of the recent geodynamic processes within the oceanic domain (i.e. the creation and the destruction of oceanic lithosphere), while the huge abyssal planes (lower hypsometric maximum) are tectonically calm. Similarly, the largest portion of