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Review Article

Late-Cenozoic relief evolution under evolving climate: A review[☆]

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ABSTRACT

The present review paper is an attempt to summarize quantitative evidence of Late Cenozoic changes in topographic relief. Different meanings of the word "relief", as it is commonly used, and detail the metrics used to quantify it. We then specify methodological tools used to quantify relief change (primarily low-temperature thermochronometry and terrestrial cosmogenic nuclides), and analyze published evidence for different regions.

Our review first shows that relief changes and rates of changes are more important at mid-, than high- or low-latitudes, and appear to be insensitive to mean precipitation rates. It also show that relief change is positive (relief increases) in most of the reported cases (~80%). We subsequently define two functional relationships between relief and erosion, depending on the chosen definition of relief, and propose a conceptual model of landscape memory. We conclude, following others, that erosion rates depend non-linearly on relief evolution, itself being a function of the spatial distribution and rates of erosion. The relief increases documented in this review may be to erosion rate increases during the same timescales. Lastly, we discuss the importance of glacial and periglacial processes on Late Cenozoic relief and erosion rate changes, and stress the importance of frost shattering and glacial erosion at mid- and high-latitudes.

Contents

[☆] *"It is recognized […] that erosional energy changes in space as well as time, and that topographic forms evolve as energy changes."* (Hack, 1960).

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1. Introduction

Relief is one of the metrics that quantifies the shape of the Earth's surface. It results from erosion which is a product of the complex interactions between tectonics and climate, and, potentially, of human activity, whose contribution is sometimes underestimated (Fig. 1). Relief is defined, in geomorphology, as the difference between topographic elevations at two specific spatial locations, but is a ubiquitous word that can have different meanings (see Section 2). Obviously, relief can increase, decrease, or remain constant regardless of absolute erosion rates. Indeed, relief evolution through time directly reflects the spatial distribution of the balance between rock uplift and erosion (Molnar, 2009; Willett and Brandon, 2002). Understanding how, when, and why relief has changed in the past is of prime importance in quantifying the causal relationships between tectonics, climate, and landscape dynamics (e.g. Champagnac et al., 2012; Molnar and England, 1990; Raymo and Ruddiman, 1993), as well as the interactions and feedbacks between climate and erosion (e.g. DiBiase and Whipple, 2011; Herman et al., 2013; Molnar, 2004b; Roe et al., 2008; Schlunegger et al., 2001; Willett, 2010). Since Ahnert (1984), the nature of the endogenic vs. exogenic process(es) that limit(s) topography (i.e. setting an upper limit to relief development) has been widely disputed, and the physical links between climate change, onset of continental glaciations, and relief evolution are only partly solved (e.g. Brozović et al., 1997; Champagnac et al., 2012; Egholm et al., 2009; Schmidt and Montgomery, 1995; Ward et al., 2012). One of the key questions still debated is whether Late-Cenozoic climate change has led to an increase or decrease in mountain range relief, and how global sediment fluxes have evolved accordingly (Herman et al., 2013; Molnar, 2004b; Willenbring and von Blanckenburg, 2010; Zhang et al., 2001).

Relief change can be addressed in three different methodological ways, or combinations thereof: (1) quantification of spatial differences in erosion by either absolute or relative surface dating (e.g. Small and Anderson, 1995) or direct estimation of erosion rates using terrestrial cosmogenic nuclides (e.g. Bierman, 1994), (2) quantification of spatial differences in exhumation histories using thermochronology (Braun, 2002b; e.g. Reiners and Brandon, 2006; e.g. Tucker and Hancock, 2010; van der Beek and Braun, 1998), and (3) numerical modeling of landscape evolution (e.g. Tucker and Hancock, 2010; van der Beek and Braun, 1998). These three methods yield major scientific breakthroughs that allowed "*the field of long-term landscape evolution* [*to*] *blossom* […] *again*" since the 1990s (Bishop, 2007).

The present review is based on published quantitative estimates of relief change; a large number of studies that qualitatively describe

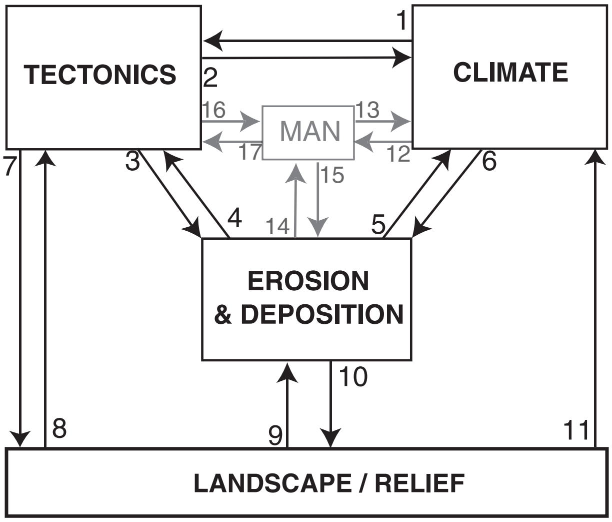

Fig. 1. Schematic sketch of the complex system that links between the Solid Earth and the Atmosphere displaying the relationship between tectonics, climate, erosion and the landscape. Many authors have explored these links (Avouac and Burov, 1996; Beaumont et al., 1992; Bonnet et al., 2007; Grujic et al., 2006; Molnar and England, 1990; Montgomery and Brandon, 2002; Roe et al., 2008; Whipple and Meade, 2006; Willett et al., 1993). Hereafter are listed the major processes of the system and some studies that have quantified or examined these causal relationships in details.
1. Climate can affect tectonics by either loading or unloading the lithosphere, mostly by water or ice (Bettinelli et al., 2008; Bollinger et al., 2010; Doser and Rodriguez, 2011; Hampel et al., 2007; Mann et al., 1998; Stuiver et al., 1995), hence modifying the state of stress and possibly inducing seismicity.
2. The direct tectonic effects on the climate are few, but volcanism can expulse large amount of gas and particle in the atmosphere that can modify both the long-term and the short term climate, locally and/or globally (Lucht et al., 2002; Mann et al., 1998; Meronen et al., 2012; Stuiver et al., 1995; Zielinski, 2000).
3. Tectonics directly affects erosion by rock fracturing (Clarke and Burbank, 2010, 2011; Dühnforth et al., 2010; Molnar et al., 2007), as well as by promoting earthquake-triggered landslides (Dadson et al., 2003; Parker et al., 2011).
4. Erosion modifies the deformation pattern by modifying the mass redistribution within (and outside of) an orogen, hence directly affecting the stress field (Beaumont et al., 2001; Calais et al., 2010; Dahlen and Suppe, 1988; Herman et al., 2010a; Konstantinovskaia and Malavieille, 2005; Koons et al., 2003; Willett et al., 1993). Erosion also affects the thermal structure of the crust (Batt and Braun, 1997; Grasemann and Mancktelow, 1993; Stüwe et al., 1994; Zeitler et al., 2001), hence its rheological properties, as well as possibly the dynamics of subduction (Lamb and Davis, 2003).
5. Erosion and sedimentation affect global climate through chemical weathering and carbon burial (Hagedorn and Cartwright, 2009; Hay, 1996; Ludwig et al., 1996; Volk, 1987).
6. Climate impact on erosion is multifaceted, and encompasses many processes: Frost shattering (Delunel et al., 2010; Foster et al., 2008; Hales and Roering, 2007; Matsuoka, 2008), fluvial erosion (Baldwin et al., 2003; Bridgland and Westaway, 2008; Howard et al., 1994; Huang and Montgomery, 2012; Seidl and Dietrich, 1992; Whipple and Tucker, 2002), landsliding (Arsenault and Meigs, 2005; Korup, 2005b; Korup, 2012; Larsen and Montgomery, 2012; Ouimet et al., 2007) and weathering (Dixon et al., 2009; Wan et al., 2009; White and Blum, 1995), as well as glacial erosion: The idea that glacial and periglacial conditions are able to modify the distribution of the surface elevation and limit the topography of a mountain range is as old as Penck (1905), who stated that "*if* [*a crest line*] *disappear under the attack of the glaciers*, *then a flat surface will be formed* […]. *This surface will*, *however*, *not reach below the snow limit*". Later on, the idea has been formalized by many authors (Brocklehurst and Whipple, 2004; Broecker and Denton, 1989; Brozović et al., 1997; Montgomery et al., 2001; Porter, 1977, 1989), and named the "glacial buzzsaw" by B. L. Isacks in 1992 (e.g. Egholm et al., 2009; Mitchell and Montgomery, 2006b; Spotila et al., 2004).
7. In isostatic equilibrium, and under tectonic crustal stacking, the crust thickness dictates the maximum elevation of mountain ranges (Abbott et al., 1997; Bishop and Brown, 1992; Champagnac et al., 2007; Holmes, 1965; Molnar and England, 1990; Montgomery, 1994; Small and Anderson, 1995; Stern et al., 2005; Wager, 1937; Whipple et al., 1999).
8. The topography at valley scale directly modifies the nearby stress field, hence the fracture of rock (Miller and Dunne, 1996; Molnar, 2004a). At orogen scale, the distribution of topography (hence the distribution and gradient of potential energy) modify the overall stress field and modify development of mountain ranges (Delacou et al., 2005; Gemmer and Houseman, 2007; Jiménez-Munt et al., 2005; Rey et al., 2001).
9. The most direct effect of landscape on erosion is the slope/erosion relationship (e.g. Ahnert, 1970, 1984; Burbank et al., 1996; Dietrich et al., 2003; Montgomery and Brandon, 2002; Portenga and Bierman, 2011; Roering et al., 2007). The steeper the slope, the easier/higher the erosion (see Section 4.1 for a discussion).
10. The effect of erosion on the landscape is maybe the most prominent feature of this sketch. It directly relates the erosion (the removal of one's particle from somewhere) to the topographic shape change associated with this particle removal. It is also related to the still popular belief that the "age" of one mountain range can be simply addressed by looking at its "shape" derived from Davis' geographical cycle (1899).
11. The topography affects the climate by modifying the atmospheric circulation (Hoskins and Karoly, 1981; Kasahara et al., 1973), orographic precipitation (Roe, 2005), and global climate (e.g. Seager et al., 2002).
The six following links are about the relations between "man" and "nature" (erosion and climate). They have been added to this sketch for the sake of completeness. The links #12, #14 and #16 represent the effects at all timescales of the environment on the human activities (civilization building and collapse, migrations, wars and revolutions), and are not detailed in this study (see e.g. Issar and Zohar (2004).
13. The impact of humankind on the climate recently became the new paradigm during the last decades. A vast amount of literature has been produced regarding this crucial relation (e.g. Bond et al., 2013; Charlson et al., 1992; Cox et al., 2000; IPCC, 2007, 2012; Mitchell et al., 1995).
15. The role of agriculture, deforestation, and more generally human land use broadly affected the erosion rate since the beginning of human spreading (e.g. Descroix and Gautier, 2002; Jacob et al., 2009; Montgomery, 2007; Schmidt et al., 2002; von Blanckenburg, 2005).
17. The effects of human activity on tectonic activity (actually, on earthquake occurrence) are best illustrated in the case of pore pressure modification at depth related to water extraction or injection (Cesca et al., 2012; Deichmann and Ernst, 2009; Gonzalez et al., 2012; Terakawa et al., 2012).