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Do along-strike tectonic variations in the Nepal Himalaya reflect different stages in the accretion cycle? Insights from numerical modeling

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ABSTRACT

Whereas the large-scale morphology and dynamics of orogenic wedges are well explained by critical-taper theory, many questions remain unanswered regarding the details of how deformation is accommodated internally. Here, we investigate the dynamics of a collisional orogenic wedge bounded by an over-thickened continental plateau, using two-dimensional thermo-mechanical numerical models. These models, applied to the Himalayan orogen and compared with reference cross-sections, lead us to propose a new hypothesis to explain along-strike variations in tectonic style, topography and exhumation patterns observed along the Himalayan range by a combination of two mechanisms. First, numerical models produce a cycle of crustal ramp formation and advection toward the rear of the wedge. The asynchronous evolution of this cycle along different segments of the range may account for the well-documented lateral variations in the geometry of the Main Himalayan Thrust (MHT) and for the existence of a well-defined topographic transition in some segments of the range. Second, the models suggest that the formation of duplexes leading to the isolation of klippen along the range front may be controlled by rheological contrasts between the Tibetan plateau and/or the Greater Himalayan Sequence and the colliding Indian plate.

1. Introduction

The dynamics of orogenic systems are frequently described using critical-wedge theory (Chapple, 1978; Dahlen, 1990) under the assumption that, during continental convergence, deformation is pervasive and the entire orogenic system is in a state of stress close to failure, governed by the frictional Mohr–Coulomb criterion. Although very useful, this approximation can only reproduce the first-order characteristics of an orogenic system, such as its long-wavelength slope (Dahlen, 1990) or its response to varying convergence or erosion rates (Whipple and Meade, 2006). It cannot, however, reproduce the details of the complex internal deformation field observed in nature. For this reason, more complex models based on analogue modeling (Konstantinovskaia and Malavieille, 2005), thermochronology and cross-section balancing (Webb, 2013; McQuarrie et al., 2014) or thermo-mechanical numerical modeling (Beaumont et al., 1996; Stockmal et al., 2007; Simpson, 2011; Jamieson and Beaumont, 2013) have been proposed. Among many features of convergent orogenic systems, these models have been able to define the conditions under which thrust sheets form, are accreted into the orogenic wedge and exhumed by uplift and erosion (e.g. Jamieson and Beaumont, 2013). A primary control on thrust-sheet formation is the presence (and depth) of low-viscosity decollements in one or both of the colliding continents (Boyer and Elliott, 1982). The stacking process and associated uplift appears to be controlled, in turn, by the geometry of upper crustal structures and, in particular, the presence of ramps in the main plate interface, which may also exert a primary control on the distribution of rock uplift and exhumation (Herman et al., 2010; Robert et al., 2011 and references therein). In recent years, debate has also focused on the importance of erosion (and potentially climate, which may be controlling erosional efficiency) on determining the spatial distribution of exhumation. Through the resulting redistribution of mass, erosion may also perturb the crustal stress field and, potentially, exert a feedback on the way the crust deforms internally (Willett, 1999; Beaumont et al., 2001).

As we will show later, most, especially large, orogens display along-strike variations in the pattern of present-day and past uplift and erosion rate, which are often related to variations in the geometry of crustal ramps, the process of nappe formation and stacking,

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and/or river-focused erosion (Montgomery and Stolar, 2006; Robert et al., 2011; Webb, 2013). This variability is, in turn, commonly attributed to variability in the depth of the decollement, the rheology of the incoming crust or to pre-existing structures in the underthrusting plate (Mouthereau et al., 2002; Upton et al., 2009; Godin and Harris, 2014).

Here we propose that at least part of the observed along-strike variability could in fact reflect a natural response of orogenic systems that can be attributed to the cyclic temporal evolution of thrust wedges (Hoth et al., 2007; Naylor and Sinclair, 2007). We do this by using a thermo-mechanical model of a mature collision between two continents, i.e. assuming that the collision has been on-going for sufficient time to create a plateau with anomalously thick crust on one side of the collision, similar to the present-day situation in the Tibetan–Himalayan system. In this lithospheric thermo-mecanical model, the presence of a low-viscosity mid-crustal decollement in the incoming continent controls the formation of thrust sheets. The model shows how such a physical system with a visco-plastic rheology naturally tends to favor frontal accretion with a cyclic behavior that explains the geometry of ramps and, in turn, governs the distribution and temporal evolution of surface uplift and exhumation patterns. Our results can potentially be used to explain much of the along-strike variations observed in orogenic systems, but we will focus the interpretation of our results by comparing them with observations from the Tibetan–Himalayan system, for which a variety of conceptual (Hodges, 2000), kinematic (DeCelles et al., 2001; Bollinger et al., 2006; Herman et al., 2010; Long et al., 2012; Webb, 2013) and mechanical (Beaumont et al., 2001) models have been proposed in recent years.

2. Along-strike variations in the Himalaya

The Himalayan mountain belt is a 2,500 km long region of elevated topography that is almost perfectly aligned with a small circle at the Earth's surface (Bendick and Bilham, 2001). Despite this apparent cylindricity, many authors (Duncan et al., 2003; Yin, 2006; Bookhagen and Burbank, 2006) have pointed out important lateral variations in the across-strike topographic profile of the Himalaya, from a quasi-linear shape in Bhutan or western Nepal to a concave-upward shape in central and eastern Nepal. Areas such as the Pakistan Himalaya, the Kumaun Himalaya or parts of central Nepal are also characterized by a very sharp change in topographic gradient (Wobus et al., 2003) along the Main Central Thrust (MCT), a major geological discontinuity separating the crystalline rocks of the Greater Himalayan Sequence (GHS) from a lesser metamorphosed sequence, the Lesser Himalaya, while elsewhere this topographic discontinuity is not so pronounced.

Important along-strike variations in the geology of the range are also noticeable (Yin, 2006). In map view, large klippen composed of crystalline and high-grade metamorphic rocks of Greater Himalayan origin are commonly found along the range but they are laterally discontinuous. Significant changes in the width of major outcropping formations such as the Greater and Lesser Himalayas are also very obvious from geological maps of the Himalaya proposed by Yin (2006) and McQuarrie et al. (2008) (Fig. 1(A)), and indicate that the deeper parts of the belt are also characterized by significant lateral variability. Theses differences are also found among reconstructed crustal-scale cross-sections (Fig. 1). Some sections comprise a limited number of relatively thick thrust sheets (Fig. 1(D), (C), (E)) while others present numerous thin thrust sheets and very sharp edge and kink folds (Fig. 1(B)). These differences may be partly based on the preferred structural style of the authors, but they are also likely to result from important lateral tectonic variations.

Berger et al. (2004) and Jouanne et al. (2004) used microseismicity, historic earthquakes and geodetic data to study the variability in present-day deformation along the Nepal Himalaya. Berger et al. (2004) interpreted these variations as resulting from the existence of three separate segments in this part of the belt, characterized by changes in the geometry of the Main Himalayan Thrust (MHT), the main crustal detachment separating the belt from the underthrusting Indian continent. These segments differ by the dip of the MHT, the presence or absence of a ramp-flat-ramp structure, and the location of the ramp. The segments are assumed to be connected by lateral ramps. Robert et al. (2011) proposed that the existence of a ramp and its location correlate with the existence and location of the strong topographic gradient and regions of high exhumation. They proposed that in Western Nepal and in Buthan/Sikkim, there is no ramp and the MHT dips northward at an angle of, respectively, 8° and 5–6°. Based on exhumation and incision patterns, van der Beek et al. (2016) showed that in western Nepal, the main detachment is characterized by the absence of a major ramp, although the presence of two minor ramps is possible. These areas also present a progressive increase in topography without a sharp topographic transition near the MCT (Fig. 1(B) and (E)). Coutand et al. (2014) proposed that the MHT in Bhutan is characterized by a flat segment bounded by two ramps: a deep one, 150 km North of the surface expression of the MBT, and a shallow one, directly beneath the MBT. For Central Nepal, Robert et al. (2011) proposed that the MHT dips northward at an angle of 5.5°, and that a major ramp exists 75 km North of the MFT. In these areas, a sharp and significant topographic transition is observed. In addition, this transition appears to be closer to the MFT in Central than in Eastern Nepal.

Present-day precipitation patterns also show important lateral variations along the Himalayan arc, which may result in lateral variability in present-day erosion rates. Precipitation rate varies from approximatively 2 m/yr in the western parts of the range up to more than 4 m/yr in the eastern parts (Bookhagen and Burbank, 2006). Strong rainfall variations are also seen across the range. In Central Nepal, precipitation patterns are characterized by two parallel bands of enhanced rainfall, one along the front hills and a second one along the topographic transition (Fig. 1(C) and (D)). In Buthan, (Fig. 1(E)) a single band of precipitation is concentrated on the front hills. In other areas, precipitation is almost homogeneously distributed across the Himalayan topographic front (Fig. 1(B)). In general, variations in precipitation patterns appear to be correlated with variations in topography, potentially reflecting a strong orographic control on precipitation.

These lateral variations in topography, tectonics and precipitation potentially exert a strong control on present-day exhumation patterns, as evidenced by low-temperature thermochronology data. A compilation of such data has recently been published by Thiede and Ehlers (2013), and show strong spatial and temporal variability in exhumation rates over the last 10 My. However, the origin of these variations is debated. Some authors suggest that this variability is controlled by variability in erosion efficiency, potentially related to rainfall variability (Wobus et al., 2003; Thiede et al., 2005), while others suggest a tectonic control that results in locally enhanced uplift rate, topography and orographic precipitation (Herman et al., 2010; Robert et al., 2011; van der Beek et al., 2016).

In this study, we hypothesize that the lateral variations in morphology and structure along the Himalaya are controlled by tectonics rather than climate and attempt to relate these variations to the cyclic development of thrust sheets that are responsible for the formation and advection of ramp-flat-ramp structures across the belt. We also investigate how the shape of these structures, their progressive exhumation, and the potential formation of klippen may be controlled by the rheology of the crust and, in particular, the rheological contrast that might exist between different units