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Deformation of an experimental drainage network in oblique collision

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ABSTRACT

In oblique collision settings, parallel and perpendicular components of the relative plate motion can be partitioned into different structures of deformation and may be localized close to the plate boundary, or distributed on a wider region. In the Southern Alps of New Zealand, it has been proposed that one-third of the regional convergence is distributed in a broad area along the Southern Alps orogenic wedge. To better document and understand the regional dynamics of such systems, reliable markers of the horizontal tectonic motion over geological time scales are needed. River networks are able to record a large amount of distributed strain and they can thus be used to reconstruct the mode and rate of distribution away from major active structures. To explore the controls on river resilience to deformation, we develop an experimental model to investigate river pattern evolution over a doubly-vergent orogenic wedge growing in a context of oblique convergence. We use a rainfall system to activate erosion, sediment transport and river development on the model surface. At the end of the experiment, the drainage network is statistically rotated clockwise, confirming that rivers can record the distribution of motion along the wedge. Image analysis of channel time-space evolution shows how the fault-parallel and fault-perpendicular components of motion decrease toward the fault and impose rotation to the main trunk valleys. However, rivers do not record the whole imposed rotation rate, which suggest that the natural lateral channel dynamics can alter the capacity of rivers to act as passive markers of deformation.

1. Introduction

Fault-offset rivers have been widely used as passive markers to quantify horizontal tectonic motions displacements on large-scale intracontinental strike-slip faults (Allen, 1965; Replumaz et al., 2001; Walker and Jackson, 2002; Hubert-Ferrari et al., 2002, 2009; Hollingsworth et al., 2008; Klinger et al., 2011; Li et al., 2012). However, the use of active rivers and river networks to quantify the amount of deformation distributed away from localized tectonic structures is not straightforward. In fact, active geomorphic processes such as lateral erosion and river captures (Bishop, 1995; Brookfield, 1998; Hallet and Molnar, 2001; Clark et al., 2004) demonstrate clearly that drainage networks are dynamic entities organizing and reorganizing themselves when submitted to external forcings such as tectonic deformation (Brocard et al., 2003, 2012; Clark et al., 2004; Babault et al., 2012; Willett et al., 2014; Lavé, 2015; Ferrater et al., 2015) and climate change (Tucker and Slingerland, 1997; Roe et al., 2003; Bonnet, 2009; Attal, 2009; Giachetta et al., 2014; Yang et al., 2016). Recently, several studies have proposed that river networks may in some cases act as faithful markers of large-scale surface horizontal displacements. (Hallet and Molnar, 2001) document for instance the distortion of several major rivers in the eastern Himalayan syntaxis in response to the indentation of India into Asia, thus suggesting that these rivers have acted as passive markers of the large scale distributed deformation in this area. Similarly, Ramsey et al. (2007) in Taiwan and Castelltort et al. (2012) in the Southern Alps of New Zealand (Fig. 1) observe that rivers draining the orogen are deviated in a systematic pattern from the normal perpendicular drainage orientation classically observed in linear mountain ranges (Hovius, 1996; Castelltort and Simpson, 2006; Perron et al., 2008; Castelltort et al., 2012) propose that this orientation results from progressive shearing of initially transverse rivers that are thus suggested to act as passive markers of the deformation field. Yet, these authors remark that interfluves and a significant area of the drainage network of the Southern Alps encompass some degree of river capture and reorganization. Such dynamic behavior of drainage networks in response to tectonic deformation is illustrated by (Yang et al., 2015). These authors used the χ metric and numerical experiments to demonstrate that the drainage pattern studied by (Hallet and Molnar, 2001) has been disrupted to some extent, leaving the major streams actively incising in the landscape and acting like passive markers of deformation, while interfluves are left as isolated remnants starved of drainage area, unable to balance tectonic uplift. Recently, (Goren et al., 2015) document another example of large-scale distributed crustal deformation that is recorded in the arrangement of transverse rivers draining Mount Lebanon.

The fundamental problem outlined by these studies is the extent to which a drainage network is able to deform under a given tectonic strain

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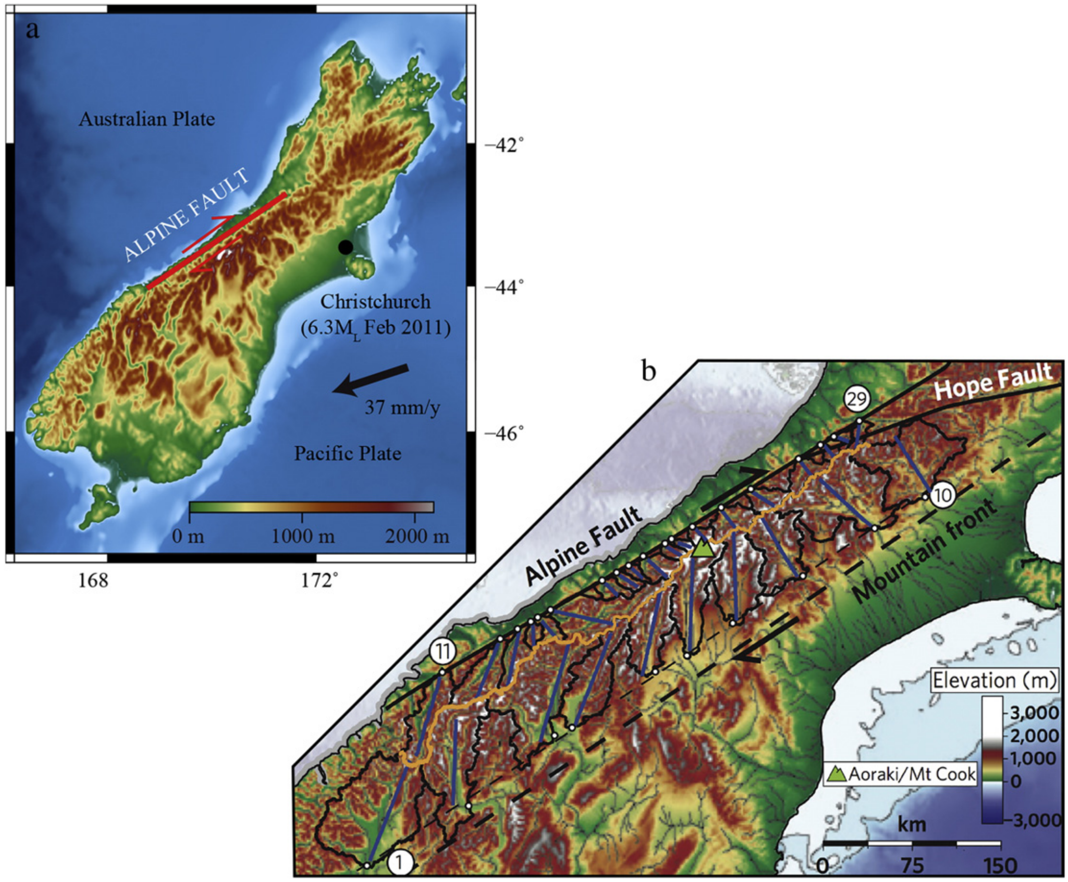

Fig. 1. a) Simplified geodynamic context of the South Island of New Zealand. b) Topography of the South Island with major river basins (black), main river orientation (blue) and the main divide (orange) (modified from (Castelltort et al., 2012)).

field, and to retain a record of that deformation until it yields and loses memory (Kirby, 2012). This problem is crucial because it determines our ability to use river patterns to understand the partitioning of deformation at the Earth's surface between narrow zones of localized deformation and broad areas of distributed strain (Molnar et al., 1999; Hallet and Molnar, 2001; Ramsey et al., 2007; Castelltort et al., 2012). To complement the field observations and the numerical approaches undertaken in the studies cited above, we developed laboratory geomorphic experiments including tectonic and surface processes (erosion, sedimentation) couplings to describe and understand the response of a drainage network to a large scale horizontal deformation. We chose an oblique collisional context in which deformation is expected to be partitioned (Braun and Beaumont, 1995; Burbidge and Braun, 1998; Martinez et al., 2002; Upton et al., 2003; Leever et al., 2011) and that can be discussed with reference to the deformed drainage network of the Southern Alps of New Zealand. This paper documents the development of the experimental orogenic wedge, with a particular focus on the deformation of the drainage network on its surface.

2. Experimental approach

2.1. General boundary conditions inspired by the Southern Alps of New Zealand

Our objective is to perform analogue experiments in oblique setting with strain partitioning as observed in the Southern Alps of New Zealand, in order to study the plausibility of river deformation in such context. Therefore, the experimental model geometry, rheology and kinematic boundary conditions were inspired by the Southern Alps of New Zealand, but the regional specificities of the range are not considered.

Orogenic wedge morphology corresponds to an asymmetric doubly-vergent wedge, with a short and steep retroside and a longer proside with a lower slope (Fig. 2a) (Willett et al., 1993; Koons, 1994). The Alpine Fault, separating the upper Australian plate to the North-West from the lower Pacific plate to the South-East, is the main tectonic structure of the range (Fig. 1a). This major oblique strike-slip fault has accommodated about 400 km of lateral offset since the Cenozoic, and slip presently at about 40 mm/y with a convergence angle of 11° (Molnar et al., 1999; Wallace et al., 2007; Cox and Sutherland, 2007; Castelltort et al., 2012; Norris and Toy, 2014). The strike-parallel motion is of 35–40 mm/y and the strike-perpendicular component amounts to 7–8 mm/y (Walcott, 1998; Sutherland, 1999; Castelltort et al., 2012; Norris and Toy, 2014). Several observations suggest that the current relative plate motion is not entirely accommodated by slip along the Alpine Fault. (Molnar et al., 1999) first pointed out the discrepancy between paleogeography reconstructions and the actual offset of remarkable terranes, which suggests that part of the total strain has been distributed away from the main plate boundary. In addition, (Norris and Cooper, 2001) showed that the offsets of quaternary geomorphic markers on the Alpine Fault do not match with the expected offsets deduced from the current plate motion. Finally, (Castelltort et al., 2012) showed that the large-scale long-term and short-term discrepancies are compatible with the deformation of transverse rivers on the Eastern flank of the range. These studies suggest that only two-third of the motion is actually localized on the Alpine Fault itself while the remaining motion is distributed across the Southern Alps (Norris and Cooper, 2001; Castelltort et al., 2012; Norris and Toy, 2014).

At crustal scale, the range consists of a 15-km-thick layer of greywackes overlying about 15 km of schists (Fig. 2a) (Cox and Sutherland, 2007; Herman et al., 2009). These materials, in particular the top layer of sandstones and greywackes, are affected by reverse