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Experimental modelling of tectonics–erosion–sedimentation interactions in compressional, extensional, and strike–slip settings

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ABSTRACT

Tectonically controlled landforms develop morphologic features that provide useful markers to investigate crustal deformation and relief growth dynamics. In this paper, we present results of morphotectonic experiments obtained with an innovative approach combining tectonic and surface processes (erosion, transport, and sedimentation), coupled with accurate model monitoring techniques. This approach allows for a qualitative and quantitative analysis of landscape evolution in response to active deformation in the three end-member geological settings: compression, extension, and strike–slip.

Experimental results outline first that experimental morphologies evolve significantly at a short time scale. Numerous morphologic markers form continuously, but their lifetime is generally short because erosion and sedimentation processes tend to destroy or bury them. For the compressional setting, the formation of terraces above an active thrust appears mainly controlled by narrowing and incision of the main channel through the uplifting hanging-wall and by avulsion of deposits on fan-like bodies. Terrace formation is irregular even under steady tectonic rates and erosional conditions. Terrace deformation analysis allows retrieving the growth history of the structure and the fault slip rate evolution. For the extensional setting, the dynamics of hanging-wall sedimentary filling appears to control the position of the base level, which in turn controls footwall erosion. Two phases of relief evolution can be evidenced: the first is a phase of relief growth, and the second is a phase of upstream propagation of topographic equilibrium that is reached first in the sedimentary basin. During the phase of relief growth, the formation of triangular facets occurs by degradation of the fault scarp, and their geometry (height) becomes stationary during the phase of upstream propagation of the topographic equilibrium. For the strike–slip setting, the complex morphology of the wrench zone, composed of several interacting fault segments, enhances the interactions with the drainage network. Because of the widening of the main fault zone toward the surface, a significant amount of distributed deformation is observed along the wrench zone. Locally, where two terminations of fault segments interact, less than a quarter of the far field displacement can remain measurable using fault offsets, leading to a systematic underestimation of the real fault slip rate.

These different experimental examples illustrate the great potential of the approach coupling deformation mechanisms and erosion–transport–sedimentation processes to investigate qualitatively and quantitatively the morphotectonic evolution of tectonically controlled landscapes.

1. Introduction

Dynamic evolution of topography in tectonically active areas results from complex interactions between deformation and surface processes (erosion, transport, and sedimentation). As a consequence, specific geomorphological, structural, and sedimentary features develop according to the geological context. They are for instance: (i) uplifted or folded terraces, reverse fault or fold scarps, and wind gaps in compressional tectonic settings (e.g., Avouac et al., 1993; Keller et al., 1998; Chen et al., 2007); (ii) triangular facets and wine glass valleys developing along normal faults in extensional settings (Cotton, 1950; Armijo et al., 1986; Gawthorpe and Leeder, 2000); and (iii) offset terraces and channels, beheaded streams, shutter ridges, and sag ponds developing along strike–slip fault zones (Wesson et al., 1975) (Fig. 1). All these depositional or erosional features constitute useful

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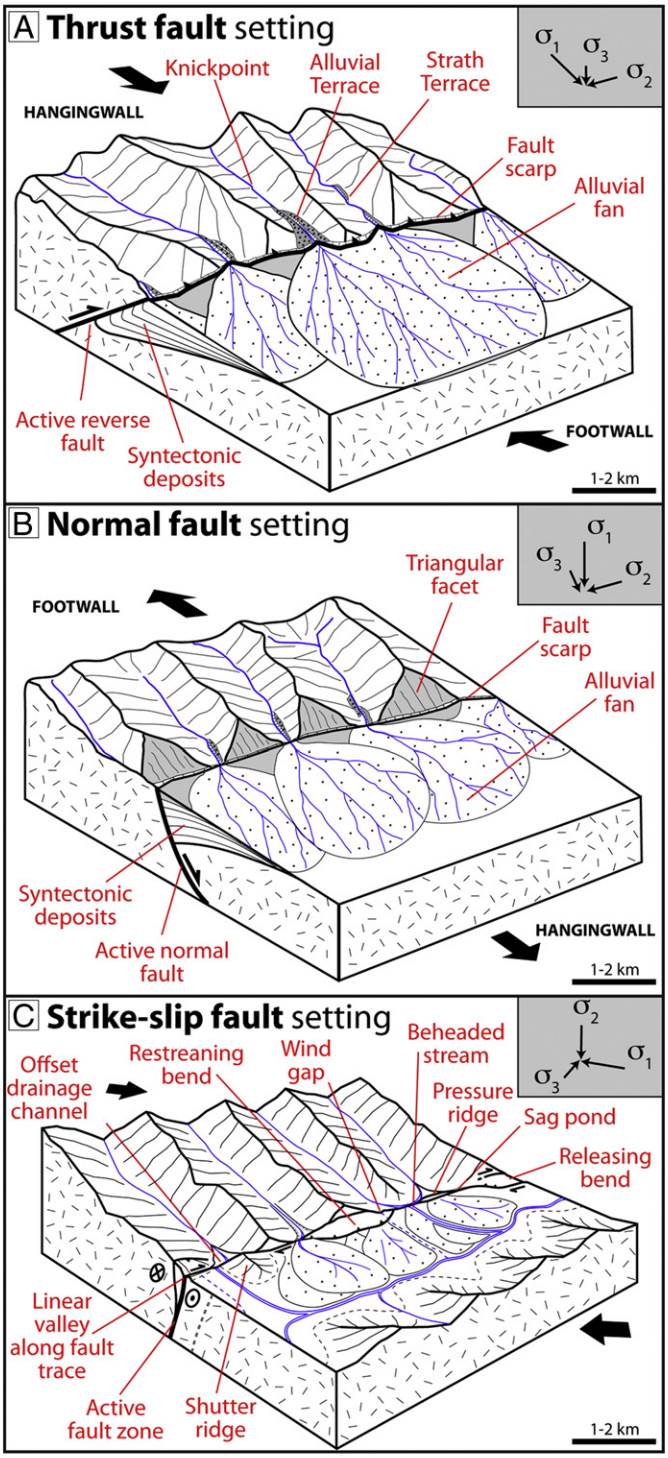

Fig. 1. Tectonic geomorphology with relevant morphotectonic markers in (A) thrust fault setting, (B) normal fault setting, and (C) strike–slip fault setting.

geomorphic markers that provide key information to better constrain recent Earth's surface deformation mechanisms and kinematics (Burbank and Anderson, 2001; Keller and Pinter, 2001).

At the seismic time scale, the study of active faults aims at recovering information on past (i.e., last 10^2–10^4 years) large earthquakes to understand the incremental processes accounting for the growth of topography and to improve seismic risk assessment. The classical approach consists in searching deformed or offset markers (e.g., topography, river beds, alluvial fans, drainage networks, terraces), in measuring their shape, and finally in reconstructing their original geometry. Combined with marker dating, it gives quantitative information on active fault parameters, such as earthquake magnitude, time recurrence, clustering, typical failure lengths and amplitude of coseismic surface displacements (e.g., Van Dissen and Berryman, 1996; Van der Woerd et al., 2001; Armijo et al., 2010; Klinger et al., 2011). However, results strongly depend on the recognition and interpretation of chosen deformed markers, whose initial geometry and morphological evolution following their formation and very first fault disruption are often difficult to determine unambiguously.

Tectonic landforms as observed in most mountain ranges generally rise coseismically (e.g., Stein et al., 1988), following a succession of seismic cycles (Reid, 1910). A topographic signal is generated when deformation reaches the surface in the form of a fault or fold scarp. If the seismic cycle duration is shorter than the time required to totally erode the coseismic scarp, the topographic signal accumulates through time and generates a long-term tectonic landform. Linking the short-term component of Earth surface deformation with the long-term cumulative landforms, as recorded in the morphology, is challenging. It requires that landforms contain a detailed and preserved message of their growth history (e.g., Sieh, 1984; Gaudemer et al., 1995; Keller et al., 1998; Manighetti et al., 2001; Pazzaglia and Brandon, 2001; Carretier et al., 2002; Hubert-Ferrari et al., 2007; Li et al., 2012; Le Béon et al., 2014; Simoes et al., 2014). In that case, insights can be brought for instance on the steadiness (both in amplitude and direction) of the strain rate or the model of fault break (e.g., characteristic earthquake model). However, this approach faces some difficulties related to the sparse spatial distribution of available data (e.g., from seismics, well logging, geodesy, thermochronology, paleomagnetism, geochemistry) and generally reveals little of past relief evolution.

Questions concerning the formation, evolution, and record of deformation of morphologic markers are still difficult to answer. Similarly, understanding the time scales of landscape responses to tectonic deformation and the spatiotemporal variations of surface fluxes (erosion and sedimentation rates) in relation to tectonic fluxes are worth investigating. To tackle those issues, the development of modelling techniques has contributed to improving our understanding of the feedback mechanisms between deformation and surface processes (e.g., Buiter, 2012; Corti, 2012; Dooley and Schreurs, 2012; Graveleau et al., 2012). Particularly, experimental modelling investigated the response of landforms to changes in internal parameters (i.e., rheology) or external forcing (i.e., tectonics, climate) with various apparatus, length, and time scales: either with the erosion box device (Ouchi, 1985, 2004, 2011; Hasbargen and Paola, 2000; Schumm et al., 2000; Bonnet and Crave, 2003; Lague et al., 2003; Babault et al., 2005, 2007; Turowski et al., 2006; Douglass and Schmeeckle, 2007; Malverti et al., 2007; Bonnet, 2009; Rohais et al., 2012) or the sand box device (Barrier et al., 2002, 2013; Nalpas et al., 2003; Gestain et al., 2004; Persson et al., 2004; Konstantinovskaia and Malavieille, 2005; Bonnet et al., 2007, 2008; Pichot and Nalpas, 2009; Malavieille, 2010; Malavieille and Konstantinovskaya, 2010; Konstantinovskaya and Malavieille, 2011; Perrin et al., 2013). Within the community of researchers working on relief dynamics, an original approach has been developed in the Experimental Tectonic Laboratory at Geosciences Montpellier, France. Active deformation of experimental materials (including nucleation, reactivation, and propagation of faults) and active morphogenesis (including channel and hillslope processes, transport, and sedimentation) have been closely combined to address the natural mechanisms of topography growth. Experiments either in compressional (Graveleau, 2008; Graveleau and Dominguez, 2008), extensional (Strak et al., 2011; Strak, 2012), or strike–slip settings (Chatton et al., 2012) have been performed. This experimental approach enables a survey of the formation and evolution of a fault from its immature stages up to several hundred slip events. The spatial and temporal evolution of fault kinematics and topography is continuously recorded thanks to accurate measurement techniques. Therefore, the impact of erosion and sedimentation on the