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A new experimental material for modeling relief dynamics and interactions between tectonics and surface processes

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ABSTRACT

We developed a new granular material (MatIV) to study experimentally landscape evolution in active mountain belt piedmonts. Its composition and related physical properties have been determined using empirical criteria derived from the scaling of deformation, erosion-transport and sedimentation natural processes. MatIV is a water-saturated composite material made up with 4 granular components (silica powder, glass microbeads, plastic powder and graphite) whose physical, mechanical and erosion-related properties were measured with different laboratory tests. Mechanical measurements were made on a modified Hubbert-type direct shear apparatus. Erosion-related properties were determined using an experimental set-up that allows quantifying the erosion/sedimentation budget from tilted relaxation topographies. For MatIV, we also investigated the evolution of mean erosion rates and stream power erosion law exponents in 1D as a function of slope.

Our results indicate that MatIV satisfies most of the defined criteria. It deforms brittlely according to the linear Mohr-Coulomb failure criterion and localizes deformation along discrete faults. Its erosion pattern is characterized by realistic hillslope and channelized processes (slope diffusion, mass wasting, channel incision). During transport, eroded particles are sorted depending on their density and shape, which results in stratified alluvial deposits displaying lateral facies variations. To evaluate the degree of similitude between model and nature, we used a new experimental device that combines accretionary wedge deformation mechanisms and surface runoff erosion processes. Results indicate that MatIV succeeded in producing detailed morphological and sedimentological features (drainage basin, channel network, terrace, syntectonic alluvial fan). Geometric, kinematic and dynamic similarity criteria have been investigated to compare precisely model to nature. Although scaling is incomplete, it yields particularly informative orders of magnitude. With all these characteristics, MatIV appears as a very promising material to investigate experimentally a wide range of scientific questions dealing with relief dynamics and interactions between tectonics, erosion and sedimentation processes.

1. Introduction

Understanding the dynamic interactions between tectonics, erosion and sedimentation in mountain belts is a difficult challenge because field morphological and structural observations correspond to a “snapshot” in the long geological history of the topography. In addition, they usually deliver sparse datasets in both time and space that are difficult to integrate into comprehensive 4D evolution models. To access to relief dynamics, experimental modeling can be used as a good complement to fieldwork investigations. Up to now, two types of approaches can be distinguished. First, the “tectonic” approach, commonly called “sandbox modeling”, has been intensively used for a long time to study accretionary wedge and fold-and-thrust belt dynamics (Fig. 1a) (Cadell, 1888; Davis et al., 1983; Hubbert, 1951; Malavieille, 1984). Erosion and sedimentation are mainly modeled in 2 dimensions by respectively removing material from high topographies (Konstantinovskaia and Malavieille, 2005, 2011; Mulugeta and Koyi, 1987) and by sifting fresh material in basins (Fig. 1a) (Bonnet et al., 2007; Cobbold et al., 1993; Larroque et al., 1995; Malavieille, 2010; Malavieille and Konstantinovskaya, 2010). Second, the “geomorphic” approach is focused mainly on landscape dynamics in response to changes in tectonic, climatic or initial boundary conditions (Babault et al., 2005; Bonnet and Crave, 2003; Hasbargen and Paola, 2000; Lague et al., 2003; Pelletier, 2003; Rohais et al., 2011). Erosion and sedimentation are triggered by sprinkling water micro-droplets on the model surface whereas tectonics consists essentially in pure uplift. Model uplift is performed mechanically by lowering channel outlet to decrease the river base-level or by elevating a central column of material (Fig. 1b).

Model materials in both set-ups are generally granular media (such as sands, beads or powders) because their mechanical properties are suitable to simulate deformation and erosion of rocks in the upper continental crust (Hubbert, 1951; Lohrmann et al., 2003;

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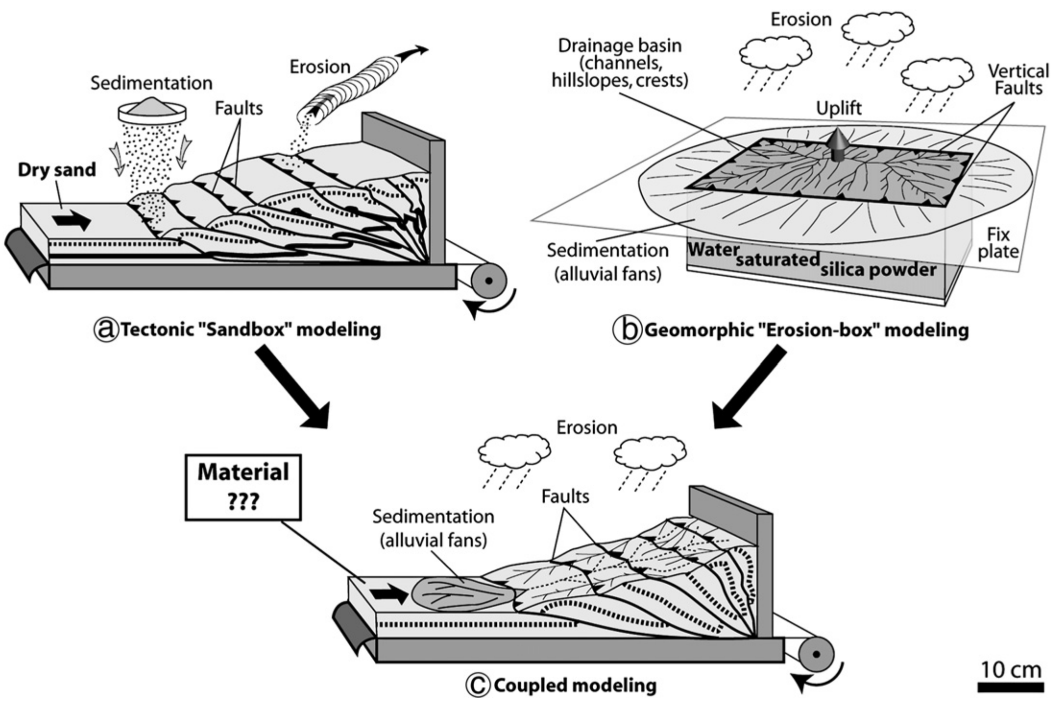

Fig. 1. Analog modeling of interactions between tectonics, erosion and sedimentation. (a) Typical tectonic "sandbox" set-up used for studying fold-and-thrust belts and orogenic wedge dynamics (Davis et al., 1983). It uses dry granular materials (typically, sand). Erosion is simulated by scrapping off material from relief whereas sedimentation is obtained by sifting fresh particles in basins (Konstantinovskaia and Malavieille, 2005). (b) Typical geomorphic "erosion box" set-up used for studying the dynamics of topography (Babault et al., 2005; Lague et al., 2003). A block of moistened powder (loess or silica powder) is uplifted vertically and eroded by sprinkling water micro-droplets over surface model. Sedimentation occurs over a surrounding plateau at the base of the topography. (c) Experimental set-up used in this paper to study interactions between tectonic and surface processes in an active foreland (Graveleau and Dominguez, 2008). It combines orogenic wedge deformation from set-up "a" and surface processes modeling by water runoff from set-up "b".

Ramberg, 1981). In tectonic modeling, materials are mainly dry quartz sand or silts (Cobbold and Castro, 1999), but other components are also used to weaken or strengthen the sand pack and improve monitoring techniques. Among these materials are garnet sand (Wilkerson et al., 1992), silica powders (Bonnet et al., 2007; Galland et al., 2006), glass microbeads (Bonnet et al., 2008; Hoth et al., 2007), glass or aluminum microspheres (Rossi and Storti, 2003), mica flakes (Storti et al., 2000), Pyrex grains (Baby et al., 1995) or walnut shells (Cruz et al., 2008). In geomorphic experiments, granular materials are generally sandy particles or fine powders systematically dampened with water. There are natural sands (Schumm et al., 1987; Wittmann et al., 1991), sand/silt/clay mixtures (Bryan et al., 1998; Flint, 1973; Gabbard et al., 1998; Koss et al., 1994; Pelletier, 2003; Phillips and Schumm, 1987; Schumm and Parker, 1973), loess (Lague et al., 2003; Rieke-Zapp and Nearing, 2005), artificial fly ashes (Hancock and Willgoose, 2001) or silica powders (Babault et al., 2005; Bonnet, 2009; Bonnet and Crave, 2003; Crave et al., 2000; Rohais et al., 2011; Turowski et al., 2006). Graphite powders are also used to model coastal stratigraphy (Heller et al., 2001; Paola et al., 2001) whereas plastic powders are used to study the evolution of submarine canyon morphology (Lancien et al., 2005; Métivier et al., 2005).

In a previous work, we presented a new experimental device and protocol based on both "tectonic" and "geomorphic" set-ups (Fig. 1c) (Graveleau and Dominguez, 2008). Objectives were to study the morphological evolution of an active piedmont controlled by the interactions between accretionary wedge deformation mechanisms and coeval erosion–transport–sedimentation processes. In the present paper, we focus on the characteristics of the specific material developed to model simultaneously orogenic wedge deformation mechanisms (faulting, folding) and realistic surface processes (incision, hillslope processes). First, we detail and discuss the specifications and required physical properties. Second, we describe the four granular media that compose the selected material. Then, we analyze the typical morphologic, tectonic and sedimentary features obtained with this material. Finally we discuss deformation and erosion–transport processes and model scaling.

2. Specifications and required physical properties of model materials

2.1. Deformation and surface processes in models

Deformation of rocks in the upper continental crust is brittle and responds to the Mohr–Coulomb failure criterion (Byerlee, 1978). In mountain belt piedmont, the deformation is essentially localized along imbricated thrusts that dip toward the hinterland and branch on deep crustal décollements (Molnar and Lyon-Caen, 1988; Suppe, 1981). It generates wedge-shape geometry and indicates the forward propagation of deformation toward the undeformed foreland (Chapple, 1978; Davis et al., 1983). In "sandbox" experiments, such deformation mechanisms, style and sequence are well reproduced with dry granular materials (Fig. 1a) (Davis et al., 1983; Malavieille, 1984; Mandl et al., 1977). In our model, we expect such an accretionary wedge deformation style and such sequences of thrust nucleation and propagation.

Mountain belt topography is shaped by a variety of surface processes that are mainly controlled by topographic slopes (Montgomery and Brandon, 2002). Generally, high slopes are observed at elevated topography and are shaped by specific hillslope processes (rockfall, landslides, debris flows, slumping) whereas low slopes lay at low elevation and are dominated by fluvial processes. Sedimentation occurs essentially in foreland flexural basins (Jordan, 1981) and piggy-back basins (Ori and Friend, 1984) where the decrease in river transport capacity brings sediment load to deposit. In "morphologic" experiments, erosion and transport processes are usually triggered by sprinkling water droplets over the model (Fig. 1b). Overland flow