Tectonophysics 664 (2015) 109–124

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Drainage network evolution and patterns of sedimentation in an experimental wedge

Marc Viaplana-Muzas [a], Julien Babault [a], Stéphane Dominguez [b], Jean Van Den Driessche [c], Xavier Legrand [d]

[a] Departament de Geologia, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain
[b] Géosciences Montpellier, Université Montpellier II, F-34095, France
[c] Géosciences Rennes, Université de Rennes 1, Campus de Beaulieu, Rennes, France
[d] Petronas CariGali, Twin Tower KLCC, 50088, Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 13 February 2015
Received in revised form 2 September 2015
Accepted 3 September 2015
Available online 24 September 2015

Keywords:
Experimental modeling
Accretionary wedge
Drainage network organization
River diversion
Sedimentation patterns
Source-to-sink

ABSTRACT

In fold and thrust belts drainage organization and patterns of sedimentation depend conceptually on the ability or not for preexisting reaches to incise uplifting thrust sheets. In this study we investigate experimentally the dynamics of drainage network in a wedge submitted to shortening and erosion. It allows us to reproduce and to monitor the interactions between tectonics, erosion and sedimentation during the development of up to five successive thrust sheets. In the experiments channels adjust to uplift rate by both increasing their slope and narrowing their channels as it is observed in nature. The series of experiments shows that the proportion of persistent preexisting transverse channels increases with the ratio of rainfall over shortening rates. The experiments confirm the view that the competition between discharge and tectonic uplift controls along-strike variations in sediment flux in sedimentary basins by controlling the drainage organization. If the transverse channels draining a wedge are not diverted, a line-source dispersal system develops in front of the active structure. If channels are diverted in the backlimb of the frontal structure it results in point-sourced depositional systems separated by areas fed only by small channels developing in the front of the wedge. Fans accumulated in front of the active structures reveal two stages of sedimentation, one of progradation, while the frontal structure is active and a second one of valley backfilling and thrust sealing during internal deformation of the wedge. The experiments also suggest that spatial variations in rock uplift rate along a thrust front may be evidenced by minimum-discharge variations of persistent transverse channels.

1. Introduction

The drainage network at the Earth's surface exerts a first order control on the relief dynamics and the erosion of mountain belts. Beyond its role in shaping the topography, the drainage network is a main controlling factor of the coupling between surface processes and deep crustal deformation, as well as of the relations between tectonics and climate variations, and the sedimentary record in basins. During mountain building, the drainage network development involves river diversions and captures at different scales (e.g. Babault et al., 2012; Castelltort et al., 2012; Giletycz et al., 2015) resulting in rapid changes in sediment routing and spatial distribution of erosion. Indeed, in response to folding or thrusting, transverse rivers are commonly diverted into longitudinal reaches, parallel to the structures, that gather into greater rivers, which maintain gorges through growing structures (e.g. Burbank et al., 1999; Burbank and Vergés, 1994; Jackson et al., 1996; Jolley et al., 1990; Oberlander, 1985; Talling et al., 1995). By controlling the spacing between outlets, drainage diversion may eventually control the loci of sediment supply and the stratigraphic architecture in foreland basins (Gupta, 1997; Horton and DeCelles, 2001; Tucker and Slingerland, 1996). Conceptually, the ability or not for preexisting reaches to incise uplifting structures controls the number of diversions, and by extension drainage organization, a view confirmed by numerical models (Champel et al., 2002; Humphrey and Konrad, 2000; Koons, 1994, 1995; Sobel et al., 2003; Tomkin and Braun, 1999; van der Beek et al., 2002). In particular, numerical models, where deformation is reduced to uplift and advection over a thrust, show that the proportion of persistent preexisting transverse channels scales with the ratio of precipitation over shortening rate (Champel et al., 2002; Tomkin and Braun, 1999). Alternatively, it has been proposed that aggradation in the backlimb of emergent thrusts also helps transverse rivers to balance uplift rates allowing them to maintain their course instead of being diverted (Humphrey and Konrad, 2000), or that axial slopes, controlled by the dip of the décollement layer where the thrusts are rooted, may divert preexisting transverse channels before they reach the uplifts (Champel et al., 2002; van der Beek et al., 2002).

E-mail addresses: marc.via.mu@gmail.com (M. Viaplana-Muzas), julien.babault@uab.es (J. Babault), dominguez@gm.univ-montp2.fr (S. Dominguez), jean.van-den-driessche@univ-rennes1.fr (J. Van Den Driessche), legrand.xavier@petronas.com.my (X. Legrand).

http://dx.doi.org/10.1016/j.tecto.2015.09.007
0040-1951/

In this study we investigate experimentally how the interaction between drainage network and deformation controls along-strike variations in sediment flux in wedges submitted to shortening and erosion. We first investigate the similarities of behavior (geometries and kinematics) between experimental and natural channels evolving under uplifting conditions. We examine the differences in both the drainage organization and along-strike variations in sediment accumulations as a function of the ratio of rainfall rate over shortening rate. We determine the factors that control (1) the capacity for channels to incise uplifting structures and (2) the patterns of sedimentation that resulted from the drainage organization.

2. Method

2.1. Setup

The experimental setup used in this study is adapted from the setup used by Graveleau and Dominguez (2008) and Graveleau et al. (2011). The deformation device dimensions are 80 × 150 cm and are constituted by a basal film pulled beneath a static buttress. The film is overlaid by the analogue material that models the upper part of the crust. Shortening induces material deformation and generates an accretionary wedge composed of imbricated thrusts. The rainfall system is composed by sprinklers that deliver water micro-droplets over the model. Sprinklers deliver water micro-droplets in sequences of 10 s with rain and 3 s without rain in order to improve channel incision processes. During the 3 s without rain, slope erosion processes are mostly inhibited whereas in the river network, water, collected by the channel catchments during the 10 s rain phase, continues to flow for a while (a few seconds up to tens of seconds depending on the length of the considered channel). During the dry time period, channel incision is then enhanced generating a more incised topography and favoring fluvial and alluvial terrace formation. This protocol was implemented to limit channel widening induced by the high river flow dynamics. Droplet size is small enough (diameter ≤100 μm) to reduce rain-splash effect and potential surface craterization. Rainfall in the experiment allows water runoff to generate both diffusive erosion processes on hillslopes and incision/lateral erosion in channels but it does not intend to simulate real water droplets (Graveleau et al., 2015). Spatial variation of rainfall rates due to air convection induced by water supply from sprinklers has been measured to be minor (<10% on average).

The analogue material is composed of three different materials: glass microbeads, silica powder and plastic powder (PVC). To obtain experiments with thrusts spaced enough to avoid the burying of thrust backlimbs by fans, we adjust the composition of material mixtures, the thickness of the material and layering of different materials. As mentioned above, aggradation in the backlimb of an uplifting thrust helps transverse rivers to balance uplift rates. Two different analogue material mixtures were derived and deposited in two layers in the sand-box. The upper layer is the material submitted to erosion and it is made up of 46% of glass microbeads, 30% of silica powder and 24% of plastic powder (PVC) plus some graphite (<1%) necessary for photo-correlations (material IV). This mixture is slightly different to the material IV used in Graveleau and Dominguez (2008), Graveleau et al. (2011) and Strak et al. (2011). The lower layer is made of 50% of glass microbeads and 50% of PVC. We performed several tests and we found empirically that a total thickness of 55 mm made by a basal layer of 5 mm of glass microbeads (décollement layer), overlaid by 45 mm of the analog materials plus a thin layer (5 mm) of glass microbeads within the upper mixture results in 14-cm-spaced thrust sheets (Fig. 1). The thin layer of glass microbeads within the upper mixture allows slip to occur within material IV resulting in folding at the surface above the ramps, as in nature. The deformation style reproduces well an accretionary wedge pattern made of individualized in-sequence thrust faults dipping toward the buttress. The material IV submitted to erosion has enough cohesion for valleys and crests to develop but not too high for basal shear stress applied by the fluid on the riverbed to exceed the thresholds for detachment and transport.

Digital Elevation Models (DEM) are acquired by an optical measurement bench composed by high resolution cameras coupled to a laser interferometer. This device acquires digital topographies at a 3D resolution close to 0.2 mm. It requires stops in both shortening and rainfall systems during 30–45 min to dry the uppermost 1–2 mm of the model surface and avoid bright laser points that could affect DEM resolution. Photograph cameras allow us to document the dynamical evolution of the relief by video movies and image correlation analyses (Graveleau and Dominguez, 2008). Finally, the model is cut in serial cross-sections in order to study the 3D geometry of thrusts and syntectonic deposits.

In this work we present eight experiments run under shortening rates ranging from 4 cm/h to 100 cm/h, of which six were submitted to a precipitation rate of 9 mm/h (named A1 to A6) and the other two to a precipitation rate of 18 mm/h (named B1 and B2).

2.2. Analysis of the accretionary wedges

Most of the deformation in the experimental wedges occurs by frontal accretion due to forward propagation of the thrust sequence as observed classically in experiments (e.g. Davis et al., 1983). Two domains can be differentiated in the experimental wedges. The prowedge is located in the frontal part of the wedge, and formed by forethrusts and the retrowedge is located in the rear of the wedge and formed by backthrusts. Prowedge slope is ruled by the Coulomb wedge theory (Davis et al., 1983) and depends on the internal friction of the material, the basal friction and the dip angle of the décollement level (flat in our experiments). The spacing between thrusts and the dip of the thrusts also depends on the basal friction and on the total thickness of the layer but also on the mechanical resistance (cohesion) of the layer. We measured prowedge slopes, spacing between thrusts in the external part of the prowedge, when a new thrust appears, and we measured the dip of the thrusts to check if the rheology of the bulk material was equivalent in all the experiments.

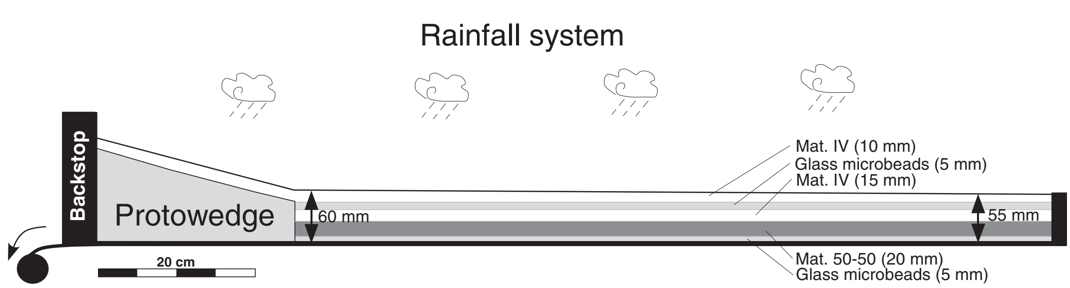

Fig. 1. Scheme of the experimental setup. We imposed a slope of 0.5° at the surface of the models in order to enhance runoff connectivity. The initial thickness of the layered material is 60 mm close to the protowedge and 55 mm in the distal part.