TEMPORAL AND SPATIAL ORGANISATION OF FAULTING IN FRICTIONAL WEDGES

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Summary The spatial and temporal organization of thrusting in accretionary wedges and in fold-and-thrust belts results from the coupling between tectonics, erosion and the degradation of the rock strength. A quantitative assessment of this coupling is presented and based on a simple approach which combines geometrical construction of developing thrust-related folds and optimization techniques based on limit analysis. The simple prototype of a triangular wedge resting on a basal layer and a straight decollement is proposed for that purpose. It is shown how the relief builds-up from a sequence of folds which is mainly forwards although interrupted by the activation of out-of-sequences. The recurrence time of this activation is function of the distance to the front and also to the thickness of the basal layer. Damage along activated thrusts, reflected by a drop in the friction angle, eliminates this periodicity both in time and space. Erosion controls the direction of the major thrusts as well as the potential exhumation of rocks.

MOTIVATION, PROTOTYPE AND METHOD

Three fundamental questions regarding the mechanics of accretionary wedges and fold-and-thrust belts are considered. First, there is no estimation for the recurrence time for the activation of out-of-sequence thrusts or of splay faults such as in the Kumano transect of Nankai (Moore et al., 2007). Second, the exhumation of metamorphic rock has been reproduced experimentally (Malavieille, 2010) and deserves now some mechanical analyses. Third, the reasons for the anomalous vergence of the thrust-related folds such as in Cascadia subduction zone (Gutscher et al. 2001) are still debated.

The complex geometry of thrust-related folds and the non-linear material response of the deforming rocks are indicative of the need to apply numerical modeling, such as the finite-element method, to respond to these open questions. This trend is certainly followed (e.g. Stockmal et al., 2007) despite the fundamental difficulties to account for the onset of shear banding and for the accumulation of finite displacement over thrusts. These two technical difficulties are fundamental to capture the basic deformation mechanism of a frictional wedge which is the thrust-related fold. A rather different approach is considered here (Cubas et al., 2008) taking advantage of the simple geometrical constructions of folds proposed since the seminal work of Suppe (1983).

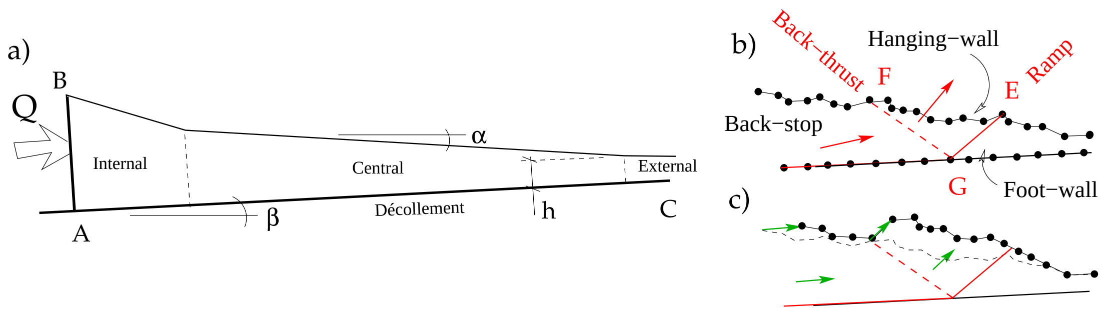

Figure 1. (a) The initial geometry of the prototype. (b) The collapse mechanism for the kinematic approach of limit analysis. (c) The topography is modified by the development of the thrust-related fold.

The prototype presented in Figure 1a is composed of three-regions resting on a weak interface, the décollement, line AC. The central region consists of a triangular wedge of slope α, resting on the basal layer of thickness h set on the décollement dipping at β. The compression results from the application of the tectonic force on the back-wall AB. The materials composing the prototype as well as the décollement are frictional (Coulomb criterion).

Each increment of shortening is decomposed into two steps. The first step consists in finding the optimum collapse mechanism according to the kinematic approach of limit analysis (e.g., Salençon, 2002). The collapse mechanism is illustrated in Figure 1b and consists of the rigid-body motions of the back-stop and of the hanging wall with dissipation along the activated part of the décollement, the ramp (GE) and the back-trust (GF). This optimization is facilitated by the discretization of the topography and of the décollement and any collapse mechanism is defined by the set of three points E,F and G. The second step of the increment in shortening consists in modifying the topography to accommodate the development of the thrust-related fold. The geometrical construction consists in displacing points in the back-stop and in the hanging-wall parallel to the décollement and to the ramp, respectively. The section of the hanging wall over hanging the foot-wall is redistributed to ensure that the local slope of the topography is based on the material angle of repose and such that mass is conserved (Mary et al., 2012). This amendment of the construction of Cubas et al. (2008) is inspired by the observation of the thrust fronts in analogue materials and is fundamental to capture large shortenings. Rock damage (softening) can be accounted for by reducing the friction angle of any active ramp. The erosion law (Malavieille, 2010)

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consists in removing the material in the central region which is found above the line of slope α_e passing by the most forward point of the topography affected by thrusting.

RESULTS

Our understanding of frictional wedges is based on the critical taper theory of Dahlen (1984) and the introduction of the critical topographic slope α_c function of β and of the material frictional properties. If the average topographic slope α is less than α_c, thrusting occurs at the back of the sub-critical wedge and a forward sequence of folds produces the relief responsible for the increase in the average topographic slope. The deformation is transferred to the front as the average slope increases until the whole wedge slips on the décollement, without further internal deformation, for critical slope conditions. This trend is exactly captured by our numerical scheme revealing a forward sequence of thrusts with three features. First, the forward propagation results most often by the displacement of the optimum point G by a short distance compared to the ramp length resulting in a rather diffuse deformation despite the discrete nature of our basic thrusting mechanism. Second, there are discrete jumps in the position of point G such that the point F of the next thrust is close to the point E of the previous thrust. Third, these two forward mechanisms are interrupted by the activation of out-of-sequence thrusts which are contributing to the modification of the average topographic slope.

The basal layer below the triangular wedge becomes important once the deformation is at the external region (Figure 1) since the frontal deformation leads to the accretion of incoming sediments to the wedge. It is shown that the increase in frontal relief because of accretion controls the periodic triggering of out-of-sequences which are positioned where the folds developed during the forward sequence. The recurrence time of this activation is function of the distance to the front and also to the thickness of the basal layer. The thicker is the basal layer, the shorter is the recurrence time. The further away is the out-of-sequence thrust from the front, the longer is the recurrence time of its activation.

Figure 2. Final geometry of the shortened prototype accounting for erosion and softening. Coloured lines and regions are passive markers illustrating the internal wedge deformation.

The introduction of damage along activated thrusts changes completely this spatial and temporal organization during accretion. Out-of-sequence thrusts are still activated but there is no periodicity neither in time nor space. The thickness of the basal layer still has the same influence on the average frequency of the out-of-sequences activation.

Erosion has a profound effect on the internal deformation style of the wedge. A continuous erosion results in a major thrust-related fold with an hinterland ramp (backward thrusting). This vergence is foreland otherwise (forward thrusting). Increasing the increment between two erosion steps leads to exhumation within the central region and foreland verging thrusts at the wedge front, Figure 2. This internal deformation style compares favorably with the experimental results of Malavieille (2010).

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