Journal of Structural Geology 99 (2017) 45–69

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Analogue modelling of thrust systems: Passive vs. active hanging wall strain accommodation and sharp vs. smooth fault-ramp geometries

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ARTICLE INFO

Article history:
Received 26 October 2016
Received in revised form
20 April 2017
Accepted 3 May 2017
Available online 4 May 2017

Keywords:
Analogue modelling
Thrust-systems
Hanging wall passive deformation
Basal velocity discontinuity
Thrust ramp geometry
Thrust-wedge morpho-structural configuration

ABSTRACT

We present new analogue modelling results of crustal thrust-systems in which a deformable (brittle) hanging wall is assumed to endure *passive* internal deformation during thrusting, i.e. exclusively as a consequence of having to adapt its shape to the variable geometry of a rigid footwall. Building on previous experimental contributions, we specifically investigate the role of two so far overlooked critical variables: a) concave-convex (CC) vs. flat-ramp-flat (FRF) thrust ramp geometry; and b) presence vs. absence of a basal velocity discontinuity (VD). Regarding the first variable, we compare new results for considered (CC) smoother ramp types against classical experiments in which (FRF) sharp ramp geometries are always prescribed. Our results show that the considered sharp vs. smooth variation in the thrust-ramp geometry produces important differences in the distribution of the local stress field in the deformable hanging wall above both (lower and upper) fault bends, with corresponding styles of strain accommodation being expressed by marked differences in measured morpho-structural parameters.
Regarding the second variable, we for the first time report analogue modelling results of this type of experiments in which basal VDs are experimentally prescribed to be absent. Our results critically show that true passive hanging wall deformation is only possible to simulate in the absence of any basal VD, since *active* shortening accommodation always necessarily occurs in the hanging wall above such a discontinuity (i.e. above the lower fault bend). In addition, we show that the morpho-structural configuration of model thrust-wedges formed for prescribed VD absence conditions complies well with natural examples of major overthrusts, wherein conditions must occur that approximate a frictionless state along the main basal thrust-plane.

1. Introduction

Thrusts faults are often formed in nature in different tectonic settings to accommodate compressive horizontal stresses in the lithosphere. This process often implies exhumation of older crustal segments of rocks that are gradually transported over a low dipping (≤30°) fault-ramp on top of younger upper-crustal rock sequences. Thrust hanging wall rocks are thus generally subjected to deformation under retrogressive metamorphic conditions undergoing cooling and decompression at upper crustal levels, whereas footwall sequences generally undergo opposite conditions of prograde metamorphism assisted by increase of lithostatic pressure and heating. At crustal-lithospheric depths where the effects of temperature are generally not enough to trigger a prevailing viscous behaviour (i.e. crystal-plastic deformation mechanisms), the implied overall mechanical conditions can in general be well represented by a rigid footwall basement on top of which a brittle deforming hanging wall block is thrust. The study of this type of thrust-system in which a (relatively) softer hanging wall unit is passively deformed as a consequence of adapting to the geometry of a rigid footwall thrust-ramp has been recurrently addressed in the literature since the classic work of Rich (1934), aiming to

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http://dx.doi.org/10.1016/j.jsg.2017.05.002
0191-8141/

understand the fundamentals of the underlying mechanics of such systems (e.g. Serra, 1977; Wiltschko, 1979; Suppe, 1983; Cooper and Trayner, 1986; Eisenstadt and De Paor, 1987; Cello and Nur, 1988; Kilsdonk and Fletcher, 1989; Taboada et al., 1990; Chester et al., 1991; Zoetemeijer and SASSI, 1992; Strayer and Hudleston, 1997; Erickson et al., 2001; Maillot and Leroy, 2003; among others).

Likewise, analogue modelling investigations of upper crustal thrust-systems (in a brittle medium) have been presented profusely in the literature (e.g. Davis et al., 1983; Malavieille, 1984, 2010; Lallemand et al., 1994; Gutscher et al., 1998a,b; Mulugeta, 1988; Storti and Salvini, 2000; Casas et al., 2001; Agarwal and Agrawal, 2002; Lohrmann et al., 2003; Ellis et al., 2004; McClay et al., 2004; Bonini, 2007; Bonnet et al., 2007; Zhou et al., 2007; Duarte et al., 2011; Bose et al., 2014; Rosas et al., 2015; Saha et al., 2016), including for the specific case in which a brittle deformable hanging wall is thrust on top of a rigid (footwall) basement (Merle and Abidi, 1995; Bonini et al., 1999, 2000; Persson, 2001; Persson and Sokoutis, 2002; Mulugeta and Sokoutis, 2003; Maillot and Koyi, 2006; Koyi and Maillot, 2007). Such previous contributions have been mostly focused on the following main variables: a) thrust-ramp dip angle (e.g. Bonini et al., 1999, 2000; Persson, 2001; Persson and Sokoutis, 2002); b) thrust-ramp rheology and basal friction conditions (e.g. Merle and Abidi, 1995; Bonini et al., 2000; Maillot and Koyi, 2006; Koyi and Maillot, 2007); and c) existence and degree of hanging wall erosion/redeposition (Merle and Abidi, 1995; Persson, 2001; Persson and Sokoutis, 2002).

In the present paper, building on this previous (analogue modelling) experimental work, we investigate the effects that two other variables exert on the mechanics and corresponding morpho-structural (geometric/kinematic) configuration of this type of thrust system: a) thrust-ramp geometry (either flat-ramp-flat or concave-convex configuration); and b) presence vs. absence of a basal velocity discontinuity (as originally defined in this context by Beaumont et al., 1994, 1996). Furthermore, we specifically discuss the significance of the obtained results, evaluating the relevance of the newly investigated parameters in the mechanics of the thrust-systems at stake, and in view of their compliance with given natural examples.

1.1. Previous work

To gain insight in the origin and tectonic evolution of this type of thrust system several authors have previously addressed such typical structural-mechanical setting through different analogue modelling techniques, focusing mainly on the deformation processes implied by hanging wall brittle accommodation above a rigid basement footwall (Merle and Abidi, 1995; Bonini et al., 1999, 2000; Persson, 2001; Persson and Sokoutis, 2002; Mulugeta and Sokoutis, 2003; Maillot and Koyi, 2006; Koyi and Maillot, 2007):

Initial analogue modelling experiments of this type carried out by Merle and Abidi (1995) differed from (all) ensuing contributions in the fact that the hanging wall sand-layered cake was pushed against, instead of indented by, a rigid footwall ramp. Such experimental procedure was conceived to account for a thin-skinned tectonic setting, comprising actively induced shortening in the hanging wall, and thus, not exclusively the deformation resulting from the passive accommodation of this (brittle/softer) allochthonous unit to the geometry of a rigid footwall. In their work these authors focused on assessing the influence of basal friction and erosion on the resulting overall structural configuration of the thrust hanging wall units. They specifically considered a (sharp) 30° flat-ramp-flat footwall geometry, and prescribed in some experiments a thin viscous silicone layer at the base of the granular hanging wall (i.e. along the main-thrust basal plane) accounting for low viscosity thrust lubricant rocks that can occur in nature (e.g. evaporites, marble- or quartz-mylonites). Their results showed that, for the modelled specific case of thin-skinned thrusting, the resulting structural configuration of the hanging wall unit is highly dependent on the ratio between tangential displacement rate vs. erosion rate, with a sort of feedback effect expressed by the circumstance that higher displacement rates result in higher reliefs, which thus tend to be more efficiently compensated by higher erosion rates, which again result in basal thrust unloading and consequently higher tangential displacement rates.

Bonini et al. (1999, 2000) focused for the first time on a systematic analogue modelling analysis of two main critical variables controlling the overall structural configuration of this type of thrust system and its underlying mechanics: a) the dip angle of the sharp ramp; and b) the basal ramp frictional vs. viscous slip conditions. They concluded that the overall accommodation of hanging wall deformation depended greatly on both variables, determining the height and width of the allochthonous deformable wedge, the number, geometry, dip and spacing of implied inner wedge backthrusts, and the development of hanging wall normal-fault reactivation of such inner backthrusts as a result of abrupt changes in the local stress field orientation above the sharp ramp-to-flat transition.

Using a similar experimental approach Persson (2001) and Persson and Sokoutis (2002) looked into the influence of syntectonic erosion vs. sedimentation on the development of similar deformable hanging wall wedges. Their results showed that in steep ramps (typically $\geq 45°$) lithostatic unloading due to prescribed local erosion favoured the continuation of thrust-slip along a single backthrust for a longer period of time, hence leading to the formation of a smaller number of this type of inner wedge thrusts, and to a less prominent topography. Redeposition of the eroded material in the margins of the thrust-wedge would further prolong the life of given active internal backthrusts, since the resulting overburden would hinder the formation of new underlying ones.

Mulugeta and Sokoutis (2003) added to a hitherto essentially geometrical-kinematical approach an attempted characterization of the dynamic and rheological constraints governing the same type of thrust system. They studied different hanging wall accommodation styles in sharp 30° flat-ramp-flat thrust centrifuged models, using different ductile and frictional materials and varying the shear strength/gravity stress ratio for the different cases. Their results showed that changes in the material strength strongly influence hanging wall strain accommodation, making kinematic restoration more complex than anticipated by strictly geometric-kinematic models alone. The same results have also shown that matching of natural fault bend folding geometries was better achieved in experiments in which elastic-plastic strain hardening materials were used.

Maillot and Koyi (2006) and Koyi and Maillot (2007) considered the influence of the same two critical variables originally addressed by Bonini et al. (2000), ramp friction and ramp dip, although using a somewhat different modelling setting and procedure simulating steady-state emerging ramps (i.e. without relief build-up, with topographic bulging being recurrently compensated by experimentally prescribed erosion). Additionally, they adopted a systematic variation in the friction coefficients of the used hanging wall granular materials, consisting of a two-layer sand cake separated by a thin layer of glass micro-beads. Focus was specifically on the critical control exerted by these variables on the amount of hanging-wall thickening over the ramp, on inner thrust refraction mechanisms across beds, and on experimental verification of previous theoretical approaches to explain inner wedge structural configuration in this type of thrust system (mean dissipation theory of Maillot and Leroy, 2003). Their experimentally obtained results