Journal of Structural Geology 74 (2015) 81–104

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Analogue modelling of different angle thrust-wrench fault interference in a brittle medium

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ARTICLE INFO

Article history:
Received 24 October 2014
Received in revised form
3 March 2015
Accepted 7 March 2015
Available online 14 March 2015

Keywords:
Analogue modelling
Brittle deformation
Corner zone thrust-wrench tectonics
Fault interference angle

ABSTRACT

Analogue modelling experiments of thrust-wrench fault interference in a brittle medium are presented and discussed. Simultaneous reactivation of confining strike-slip and thrust faults bounding a (corner) zone of interference defined by the angle between the two fault systems is simulated, instead of previously reported discrete (time and space) superposition of alternating thrust and strike-slip events. The influence of different considered interference angles of 60°, 90° and 120° is investigated through comparison between the obtained structural configurations in each case. It is shown that under these conditions a characteristic morpho-structural pattern with a deltoid shape resembling a tie-knot consistently forms in the (corner) zone between the two fault systems. The specific structural configuration of a such tie-knot structure (TKS) varies significantly as a function of the prescribed fault interference angle, which determines the orientation of the displacement vector shear component ($\overrightarrow{ds}$) along the main frontal thrust system, and critically controls the geometry and kinematics of the TKS. Comparison with three natural examples shows remarkable geometric and kinematic similarity, confirming model predictions and suggesting the existence of common underlying dynamic processes governing the specific (TKS) structural configuration of different thrust-wrench fault interference corner-zones in nature.

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1. Introduction

Analogue modelling of both thrust and wrench tectonic systems has been profusely addressed in recent literature, although in the vast majority of the cases through considering either thrusting or wrenching separately, essentially attempting a mechanical characterization of the processes that are in each case responsible for the geometry, kinematics and space-time distribution of the resulting structures in differently considered rheological mediums (e.g. Mandl et al., 1977; Malavieille, 1984; Mulugeta, 1988; Richard and Krantz, 1991; Richard et al., 1991; Lallemand et al., 1994; An and Sammis, 1996; Gutscher et al., 1998a,b; McClay and Bonora, 2001; Schopfer and Steyrer, 2001; Agarwal and Agrawal, 2002; Marques and Cobbold, 2002; Lohrmann et al., 2003; Schellart and Nieuwland, 2003; Ellis et al., 2004; McClay et al., 2004; Le Guerroue and Cobbold, 2006; Bonnet et al., 2007; Zhou et al., 2007; Rosas et al., 2009; Malavieille, 2010; Dooley and Schreurs, 2012; Bose et al., 2014). In contrast, the joint analysis of coeval, or successively superposed deformation, resulting from thrust-wrench fault interference is less common (see below), and generally focused on detailed problems arising from specifically targeted natural examples (e.g. Diraison et al., 2000; Viola et al., 2004; Di Bucci et al., 2006, 2007; Duarte et al., 2011; Rosas et al., 2012).

Contrary to fold superposition, which has long been dealt with in the literature (e.g. Ramsay, 1962; Ghosh et al., 1993; Ramsay and Lisle, 2000; Alsop and Holdsworth, 2002; Grujic et al., 2002), fault interference is recognizably a much less common subject, and the relationship between the mechanics at stake and the possible resulting structural patterns in different interference situations is not yet fully understood. Therefore, in the present paper we present and discuss new results concerning three sets of analogue modelling (sandbox) experiments, simulating thrust-wrench fault interference in a brittle medium as a function of differently considered

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http://dx.doi.org/10.1016/j.jsg.2015.03.005

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interference angles (of 60°, 90° and 120°) defined between the intersecting thrust and strike-slip faults. Our focus is on the type of interference that affects such a fault-bounded corner area to better understand the mechanics involved in this type of interference, and specifically the effect that the considered fault interference angle exerts on the resulting thrust-wrench structural configuration. We further compare the results of the three sets of experiments amongst each other as well as with several different natural examples.

Previous contributions focussing on solving different tectonic puzzles in various settings have tackled through distinct analogue modelling approaches the problem of thrust-wrench fault interference. However, in most cases this subject was not investigated specifically in a systematic way. Diraison et al. (2000) made a series of experiments replicating a lithospheric scale thrust-wrench tectonic scenario complying with the general framework of the major late Cretaceous-Cenozoic structures along the southernmost Andes cordillera. The cited authors reported thrust-wrench transition structures along a continental corner zone, accounting for the structural main elements that characterize such a tectonic scenario. Viola et al. (2004) approached the subject of thrust-wrench tectonic interference in a somehow indirect way, by modelling pure strike-slip and transpressive reactivation of a pre-existing (“old”) reverse fault, to gain insight on the tectonic evolution of the Giudicarie fault system in the Central Eastern Alps (e.g. Viola et al., 2001). Di Bucci et al. (2006, 2007) aimed at evaluating the relevance of thrust-wrench fault interference within the active tectonics setting of the southern Apennines and Adriatic foreland. Their sandbox experimental simulation of such tectonic interference confirmed the hidden importance of the foreland dextral strike-slip faults in the interpretation of the southern Apennines seismogenic setting. Duarte et al. (2011) tested the chronological sequence of thrust-wrench interference between major active strike-slips faults and an imbricated thrust wedge in the Gulf of Cadiz region (offshore SW Iberia and NW Morocco). Their experimental results highlighted the key role of a linear basement structural grain, corresponding to the fault trace of inactive inherited but non-reactivated structures (simply behaving as linear weak anisotropies), in determining the geometric and kinematic structural pattern of the superposed tectonic thrusting. More recently, Rosas et al. (2012) used coupled analogue and numerical modelling to simulate active thrust-wrench fault interference in the NE Atlantic (offshore SW Iberian margin), trying to understand the formation of a conspicuous morphotectonic pattern recognized in the interference zone between a major dextral strike-slip fault and a thrust faults.

In the present work we carried out a series of analogue modelling experiments designed to study thrust-wrench structural interference in a brittle medium (e.g. upper crust). Building on the sandbox analogue modelling of Rosas et al. (2012), our experiments simulate the simultaneous reactivation of a strike-slip and a thrust fault, both bounding a confined (corner) zone of interference defined by the angle between the two. This is different from what was done by Duarte et al. (2011), in which the “simultaneous” character of thrust-wrench fault interference always implied a discrete successive superposition of alternating thrust and strike-slip events active at different time intervals. Conversely, in the present case we specifically consider fault interference arising from strictly simultaneously thrust and strike-slip fault reactivation, manifesting in the corner zone confined (i.e. bounded) by both these faults systems. The designed simulation of such a fault-bounded corner zone implies that the reactivation of one of the fault systems necessarily leads to the simultaneous reactivation of the other, since such a corner zone area is limited by the angle between the strike-slip fault and the thrust faults. Also, in their experiments Rosas et al. (2012) have only considered a single interference angle (of 120°), whereas in the present case we use their obtained results and additionally investigate the specific influence exerted by two other interference angles (60° and 90°) in the development of the resulting thrust-wrench structural pattern. Furthermore, we systematically compare the obtained results for the three situations corresponding to obtuse, acute and orthogonal fault interference (120°, 60° and 90°, respectively), and compare them with other relevant natural examples.

2. Experimental procedure

2.1. Material properties and scaling

Dry quartz sand was used to account for the mechanical brittle behaviour of upper crustal rocks (see sand properties in Table 1). Sand is classically considered to yield following a Coulomb fracture criterion, and has hence been extensively used to model brittle faulting in the upper crust (e.g. Hubbert, 1937, 1951; Davis et al., 1983). All scaling assumptions in the present work (Appendix A and Table 1) are the same derived for previous similar analogue experiments (e.g. Krantz, 1991; Schellart, 2000; Lohrmann et al., 2003; Rosas et al., 2012) in which dynamic scaling and similarity were achieved through establishing model/prototype ratios for fundamental units according to the scale model theory of Hubbert (1937). As in that work, inertial accelerations in the present case are considered to be negligible when compared to gravity, and hence make the model/prototype cohesion ratio (Σ) ultimately dependent on the product of correspondent density (δ) and length (λ) ratios (see Table 1 and Appendix A).

2.2. Apparatus, initial stage and procedure

All the experiments were carried out in a 100 × 60 cm Perspex deformation rig depicted in Fig. 1A–C. It consists of two basal rigid plates placed side by side (plates A and B in Fig. 1), overlain by a flat thin metal sheet with variable geometry and a negligible thickness of 0.3 mm attached to the base of a fixed back-stop. The basal plates were driven by a stepping motor that can be connected either to both plates at once, conveying equal (kinematically coupled) movement to these, or to one plate at a time, promoting lateral shifting relatively to one another to simulate strike-slip kinematics. In either case basal plate movement always implies sliding beneath the motionless flat thin metal sheet, the edge of which therefore defines a linear convergent limit or velocity discontinuity (VD in Fig. 1). In the experiments of Rosas et al. (2012) the angle between the VD and the strike-slip direction was always of 120° (when measured on top of plate A, see Fig. 1C). In the present work we add to these results two new sets of experiments, in which we analyse the structural pattern resulting from the same interference when it occurs at angles of 60° and 90° (Fig. 1A and B, respectively).

In all the experiments a 3 cm thick sand layered cake was placed (in frictional contact) on top of both the Perspex basal plates and the thin metal sheet, oriented relatively to the *X*, *Y*, *Z* coordinate axis as illustrated in Fig. 2A. A moving elongated funnel with a width matching the one of the deformation rig was used to evenly distribute the sand, hence assuring the flatness of the model layering and surface. Several layers of alternate coloured sand were stacked in this way in each experiment to be used as strain markers along the *Z* direction. Similarly, equally spaced strain marker lines were also placed on the model top surface, orientated parallel to the *Y* direction, to monitor strain in the *XY* plane.

Model deformation always comprised two main steps (Fig. 2B). In the first step both basal plates were moved along the X direction sliding underneath the fixed thin metal sheet (Fig. 2B – 1st step),

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