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Episodic growth of fold-thrust belts: Insights from Finite Element Modelling

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ABSTRACT

The sequential development of a fold-thrust belt was investigated using 2D Finite Element Modelling (FEM). The new model results show that a thrust system is typically composed of three distinct regions: the thrust wedge, pre-wedge, and undeformed region. The thrust wedge involves growth that repeats episodically and cyclically. A cycle of wedge building starts as frontal accretion occurs, which is accompanied by a rapid increase in wedge width reducing the taper angle below critical. In response to this, the wedge interior (tracked here by the 50 m displacement position) rapidly propagates forwards into a region of incipient folding. The taper angle progressively increases until it obtains a constant apparent critical value (~10°). During this period, the wedge experiences significant shortening after a new thrust initiates at the failure front, leading to a decrease in wedge width. Successive widening of the wedge and subsequent shortening and thrusting maintain a reasonably constant taper angle. The fold-thrust belt evolves cyclically, through a combination of rapid advancement of the wedge and subsequent gradual, slow wedge growth. The new model results also highlights that there is clear, although minor, deformation (0–10 m horizontal displacement) in front of the thrust wedge.

1. Introduction

The Coulomb Wedge Model (CWM) has been very successful in describing the mechanics of orogenic and subduction-related thin-skinned fold-thrust belts from around the world (Davis et al., 1983; Dahlen, 1984; Dahlen et al., 1984; Platt, 1986; Zhao et al., 1986; Lallemand and Le Pichon, 1987; Woodward, 1987; Dahlen, 1990; Braathen et al., 1999; Mouthereau et al., 2006; Suppe, 2007; Fagereng, 2011; von Hagke et al., 2014; Sun et al., 2016). According to the model, the thrust belt is analogous to a wedge of soil or snow in front of a moving bulldozer, and the material within the wedge deforms until it develops a critical taper, and basal shear and wedge translation can occur (internal and basal shear stresses are balanced in critical state), after which it grows self-similarly as additional material is accreted at the toe (Davis et al., 1983; Dahlen, 1984, 1990; Dahlen et al., 1984). The theory can be used to understand the effects of internal and basal strength (Mulugeta, 1988; Willett, 1992; Burbidge and Braun, 2002; Lohrmann et al., 2003; Simpson, 2009), dip of detachment (Davis et al., 1983; Koyi and Vendeville, 2003; Smit et al., 2003), surface slope and topography (Marques and Cobbold, 2002, 2006; Sun et al., 2016), lateral friction (Zhou et al., 2016), surface processes, i.e., erosion and sedimentation (Storti and McClay, 1995; Hoth et al., 2006; Simpson, 2006; Stockmal et al., 2007; Cruz et al., 2010; Simpson, 2010a; Wu and McClay, 2011; Fillon et al., 2012), and the rheology of single and multiple detachments (Ruh et al., 2012) on the growth of fold-thrust belts. For a review see Buiter (2012) and Graveleau et al. (2012).

Coulomb Wedge Model only provides a static view of the thrust wedge, assuming constant conditions with the wedge maintained at Coulomb failure throughout (Chapple, 1978; Davis et al., 1983). A simple Coulomb Wedge retains a constant taper as it moves without addition of material being encountered (Fig. 1a, see Supplementary Material). In reality, as a wedge grows, new material is added, most commonly at the toe (Fig. 1b), with the thrust wedge accreting in a piggyback style during its forward advance (Mulugeta and Koyi, 1992). Accommodated by nucleation of new thrusts in front of the wedge, accretion of sediments thickens the

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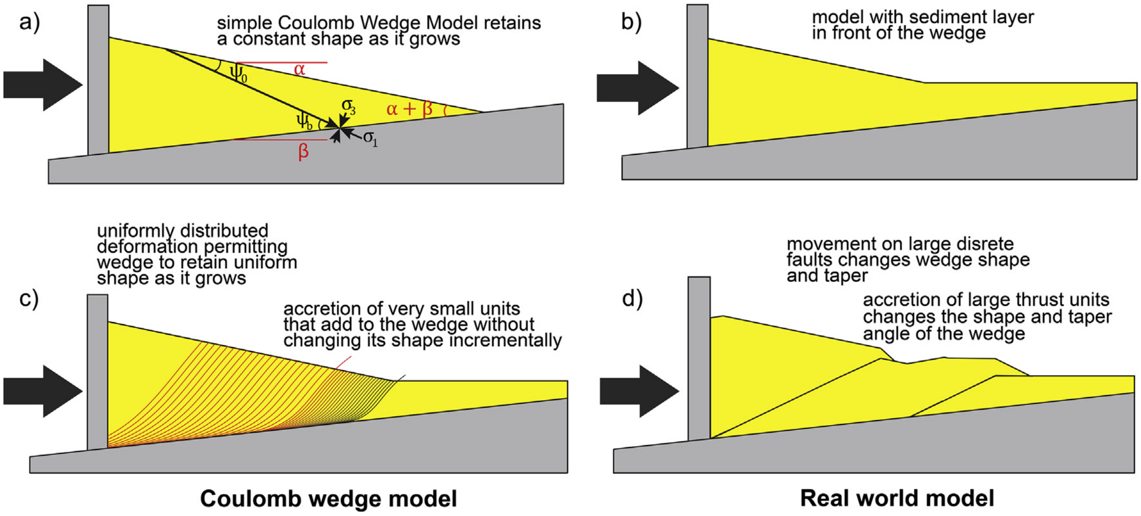

Fig. 1. Conceptual cartoon illustrating the difference between the theoretical Coulomb wedge model and a real world example. (a) Simple Coulomb Wedge Model (CWM), which retains a constant shape as it moves, α and β are topographic slope and detachment dip, respectively,ψ_b and ψ_0 are the angles between the maximum principal compressive stress σ_1 and base and top of the wedge; (b) Model with sediment layer in front of wedge; (c) Simple Coulomb Model without advance of wedge front; (d) Accretion by imbrication on large discrete thrusts that will change the wedge shape and taper with time.

wedge and raises the surface topography (Platt, 1986; Mulugeta and Koyi, 1992; Gutscher et al., 1996; Burbidge and Braun, 2002; McClay et al., 2004; Bigi et al., 2010), rendering the wedge unstable. A stable geometry can be regained by internal deformation, most commonly involving shortening, imbricating and folding (Fig. 1c; Davis et al., 1983; Lallemand and Le Pichon, 1987; Burbidge and Braun, 2002). As real world thrust wedges develop, they do so by the addition of discrete, often large, thrust sheets (Fig. 1d). Evolution of the wedge taper angle occurs by progressive internal deformation and accretion of new units to the wedge front (Fig. 1c). The initiation of discrete faults or zones of deformation produces an episodic development (Fig. 1d), with a change in shape and taper angle as the wedge grows. Accretion of new material into the wedge may not occur at the same time as deformation within the wedge. This behaviour is seen in physical analogues, with the wedge geometry changing as the accretion of imbricate slices builds the wedge forward, thereby lowering the taper to subcritical (Gutscher et al., 1996; Lohrmann et al., 2003). The assumption that thrust wedges constantly exist in a state of critical taper is therefore not sufficient to describe the dynamic evolution of a real thrust wedge.

In natural systems, a number of studies of the growth of fold-thrust belts have been undertaken. Fitz-Diaz et al. (2014) used illite Ar/Ar dating to obtain absolute ages of folds and shear zones, suggesting episodic progression of deformation from west to east in Mexican Fold-Thrust Belt. Through detailed chronostratigraphic study of syn-tectonic sediments, the episodic uplift of mountain ranges (Ji et al., 2008; Lease et al., 2012) and growth of an individual anticline (Masaferro et al., 1999) have been reported. Studies of the deep-sea turbidites and silicic plutonic sequences revealed the episodic growth of the south-west Alaska convergent margin (Byrne and Fisher, 1987). Though these field-based studies reveal the overall growth pattern of mountain belt and accretionary prism, the quantitative spatial and temporal variations in associated geometric parameters are still poorly resolved. For example, what is the behaviour of wedge material when transported forwards? Is deformation constant or episodic? What are the effects of thrust initiation and frontal accretion on wedge geometry? What happens in front of the wedge when developing a critical taper? How do these different elements correlate with each other during the wedge-building process?

Numerical modelling and scaled analogue experiments with digital image correlation technique can provide insights into the dynamic evolution of deforming wedges because these enable us to simulate the development of a realistic thrust system, and to measure the geometry, stress, and strain at every stage in its growth, which cannot be done for natural examples (Beaumont et al., 1992; Ellis et al., 2004; Adam et al., 2005; Buiter et al., 2006; Simpson, 2006; Yamada et al., 2006; Selzer et al., 2007, 2008; Stockmal et al., 2007; Simpson, 2009; Cruz et al., 2010; Simpson, 2010b; Buiter, 2012; Fillon et al., 2012; Ruh et al., 2012, 2013; Adam et al., 2013; Buiter et al., 2016; Dotare et al., 2016).

This study aims to produce a 2D finite element model (FEM), built with Abaqus 6.14, to investigate the dynamic growth of a simple fold-thrust belt that includes frontal accretion at the wedge toe. This model is used to understand:

(1) How the system propagates at the wedge toe and quantify what happens in front of the thrust wedge.
(2) How the critical taper is achieved in response to wedge accretion, testing this against the theoretical predictions from the CWM (Dahlen, 1984). How the spatial and temporal evolution of different variables can be resolved during the critical-subcritical transition period.
(3) How the thrust system evolves over many cycles of wedge building in terms of internal wedge movement, propagation of displacement front and failure front, and variations in wedge height and width.

2. Models

2.1. Brittle rheology and material properties

The wedge is modelled as a mass of homogeneous, cohesive material whose behaviour is visco-elasto-plastic resembling that of dry quartz sand (Table 1). The material deforms elastically until plastic or viscous yield is reached, after which deformation continues on yield (Buiter et al., 2006). It is therefore equivalent to physical analogue (sandbox) models that themselves constitute scaled models of natural systems. The mechanical parameters assigned to the model are density, Young's modulus, Poisson's ratio, internal friction angle and basal friction angle, Poisson's ratio,