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Sandbox modelling of sequential thrusting in a mechanically two-layered system and its implications in fold-and-thrust belts

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ABSTRACT

Many fold-and-thrust belts display multi-storied thrust sequences, characterizing a composite architecture of the thrust wedges. Despite dramatic progress in sandbox modelling over the last three decades, our understanding of such composite thrust-wedge mechanics is limited and demands a re-visit to the problem of sequential thrusting in mechanically layered systems. This study offers a new approach to sandbox modelling, designed with a two-layered sandpack simulating a mechanically weak Coulomb layer, resting coherently upon a stronger Coulomb layer. Our experimental models reproduce strikingly similar styles of the multi-storied frontal thrust sequences observed in natural fold-and- thrust belts. The upper weak horizon undergoes sequential thrusting at a high spatial frequency, forming numerous, closely spaced frontal thrusts, whereas the lower strong horizon produces widely spaced thrusts with progressive horizontal shortening. This contrasting thrust progression behaviour gives rise to composite thrust architecture in the layered sandpack. We show the evolution of such composite thrust sequences as a function of frictional strength (μ_b) at the basal detachment and thickness ratio (T_r) between the weak and strong layers. For any given values of T_r and μ_b, the two thrust sequences progress at different rates; the closely-spaced, upper thrust sequence advances forelandward at a faster rate than the widely-spaced, lower thrust sequence. Basal friction (μ_b) has little effects on the vergence of thrusts in the upper weak layer; they verge always towards foreland, irrespective of T_r values. But, the lower strong layer develops back-vergent thrusts when μ_b is low (~0.36). In our experiments, closely spaced thrusts in the upper sequence experience intense reactivation due to their interaction with widely spaced thrusts in the lower sequence. The interaction eventually affects the wedge topography, leading to two distinct parts: *inner* and *outer* wedges, characterised by steep and gentle surface slopes, respectively.

1. Introduction

Thin-skinned tectonic models have been widely used to explain the process of sequential thrusting in convergent settings. These models generally treat the crustal horizon as a single mechanical layer on a weak basal detachment (Davis et al., 1983; Dahlen, 1984; Mulugeta, 1988; Mulugeta and Koyi, 1987; Huiqi et al., 1992; Koyi, 1995; Schott and Koyi, 2001; Yamada et al., 2006). Davis et al. (1983) and Dahlen (1984) first proposed a thin-skin Coulomb wedge model, analogous to a wedge of snow or soil formed in front of a moving bulldozer. Their model predicts that the wedge at a critical taper is on the verge of failure, and thereby tends to slide over the weak basal detachment. Mechanical incoherence developing at the critical taper is the key factor for initiation of a thrust ramp from the basal detachment (Bose et al., 2014). During the wedge growth, the basal instability and the ramp initiation are two coupled processes synchronously operating in the quasi-stable state of the wedge, and they eventually give rise to a forelandward thrust sequence, splaying from the same detachment surface. Based on this mechanical model, workers have formulated a wide range of geometrical constructions, such as balanced cross sections (Dahlstrom, 1969; Hossack, 1979; Butler, 1983; Mukhopadhyay and Mishra, 2005), to estimate crustal shortening in convergent tectonic belts. However, many orogenic belts display frontal thrust sequences in a multi-storied fashion, consisting of thrust arrays of varying orders (i.e. spatial frequency). For example, the Himalayan wedge has produced a set of continental scale (first order) thrusts, namely Main Crystalline Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT), covering the entire strike length of the mountain belt. Taking a close-view to different sectors in this belt, one can

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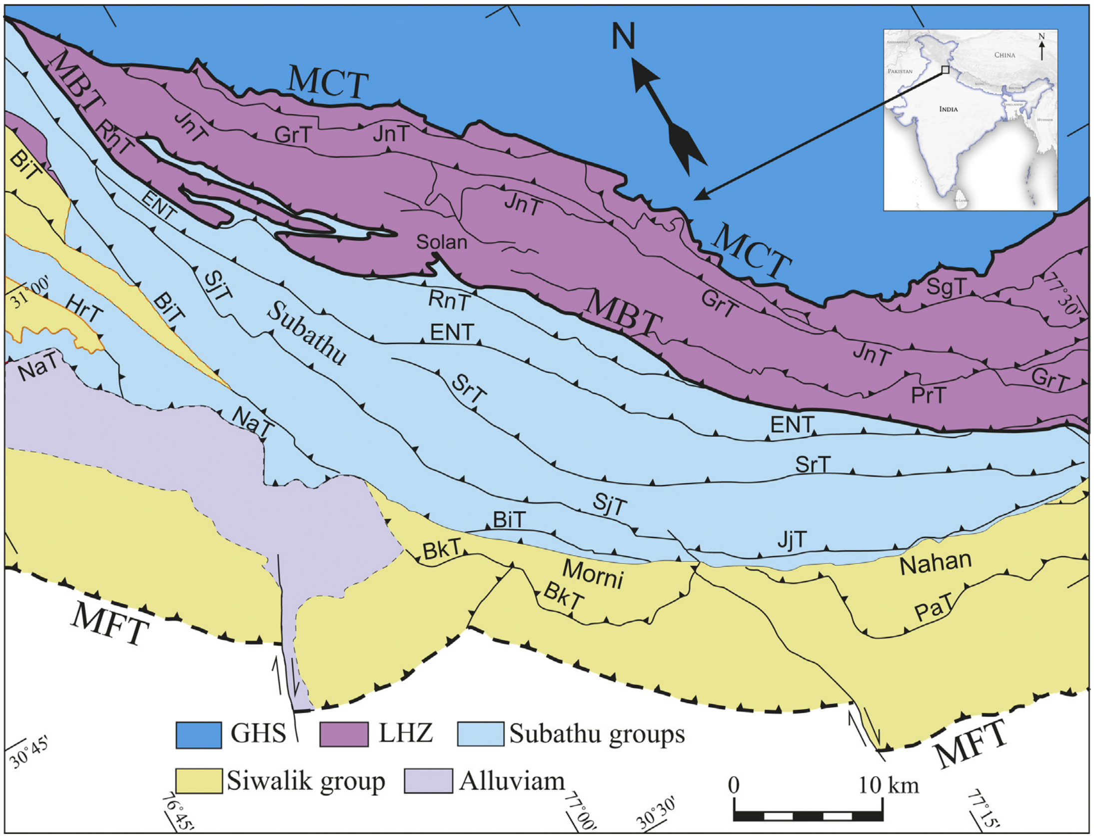

Fig. 1. Structural map showing the imbricate thrust pattern (local names indicated) in the Nahan salient, NW Himalaya (modified after Mishra and Mukhopadhyay, 2012). The thick lines indicate traces of widely-spaced first order thrusts (MCT, MBT and MFT) and thin lines represent closely-spaced, higher order thrusts. Inset shows the location of the study area. JnT—The Jaunsar thrust, SgT—Sangrah thrust, GrT—Giri thrust, PrT—Parana thrust, RnT—Ranon thrust, ENT—East Nahana thrust, SrT—Sarauli thrust, SjT—Surajpur thrust, BiT—Bilaspur thrust, JjT—Jarja thrust, HrT—Haripur thrust, NaT—Nalagarh thrust, BkT—Bisiankanet thrust, PaT—Paonta thrust.

find numerous closely spaced (higher order) thrusts in between any two first order thrusts (Fig. 1). It is thus evident that the Coulomb wedge model discussed above cannot be directly invoked to deal with this type of composite thrust wedges. Our present sandbox modelling study aims to explore the mechanical setting required for such multi-order sequential thrusting in a fold-and-thrust belt.

Earlier sandbox experiments mostly dealt with thrusting in a mechanically homogeneous layer, with an objective to show the role of different mechanical parameters, such as: strength of the wedge materials, basal friction and geometrical parameters including basal slope and layer thickness, in controlling the imbricate thrust architecture on a basal detachment (Davis et al., 1983; Mulugeta, 1988; Huiqi et al., 1992; Mandal et al., 1997). However, the basic premise in these studies is valid for a mechanically homogeneous crustal segment. Recent geological field observations suggest that crustal sections often consist of several mechanical segments separated by multiple decollement horizons, e.g. Zagros Mountain belts and Appalachian Mountains (Hessami et al., 2001). Using numerical simulations, Ruh et al. (2012) have recently demonstrated the effects of multiple decollement on the frontal thrust progression. In their models the horizontal decollements at varied depths interact with one another, and the structural evolution in the sequence depends strongly on their relative mechanical strengths.

All these previous contributions mainly addressed thrust wedge formation in crustal sections, either coherent or segmented by a number of decollements. However, natural fold-and-thrust belts in most cases develop in mechanically segmented crustal structures, e.g. weakly or unmetamorphosed sediment piles of lower strength lying over relatively stronger rocks. Our present work aims to show how such mechanical stratification in the crust can influence the evolution of thrust sequences in fold-and-thrust belts. To address this issue, we carried out sandbox experiments, simulating a mechanically two-layer crustal structure represented by a weak Coulomb layer lying over another Coulomb layer of relatively higher strength. We have not introduced any decollement at the interfaces between the two mechanically distinct layers. Our layered sand models reproduced multi-storied thrust sequences, as extensively reported from natural fold-and-thrust belts. Based on the model results, we show contrasting thrust progression behaviour in the mechanically weak upper and lower strong layers, and their effects on the wedge growth. In addition to the mechanical layering, we also investigate the possible effects of two other parameters: (a) thickness ratio between weak and strong layers and (b) basal frictional strength. This study provides a new basis for understanding the association of major (first order) and minor (higher order) thrusts in convergent tectonic belts.

2. Analogue modelling: methods and materials

Our sandbox models were designed rheologically analogous to upper ~10 km thick crust, covering a horizontal distance in the order of 10^2 km. To model the mechanical layering, two types of granular materials were used: 1. dry natural quartz sand and 2. dry silica powder. These two granular materials had contrasting mechanical strengths; the cohesive strength of silica powder was 150–300 Pa (Krantz, 1991; Galland et al., 2003), whereas that of quartz sand was around 20–60 Pa (Schellart, 2000). Several workers have used silica powder to simulate stronger crustal materials in scaled experiments (Bonnet et al., 2007). The mechanical proper-