Journal of Structural Geology 93 (2016) 131–148

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Main Frontal thrust deformation and topographic growth of the Mohand Range, northwest Himalaya

Vinee Srivastava [a], Malay Mukul [a,*], Jason B. Barnes [b]

[a] Continental Deformation Laboratory, Department of Earth Sciences, Indian Institute of Technology-Bombay, Powai, Mumbai 400076, India
[b] Landscape Analytics LLC, Seattle, WA 98115, USA

ARTICLE INFO

Article history:
Received 31 December 2015
Received in revised form
24 October 2016
Accepted 26 October 2016
Available online 27 October 2016

Keywords:
Himalayan Main Frontal thrust
Fault propagation folding
Fault damage zone
Frontal fold topography
Real Time Kinematic GNSS
Boundary Element Method
Dislocation modelling

ABSTRACT

The Main Frontal thrust (MFT) uplifts the Himalayan topographic front. Deciphering MFT deformation kinematics is crucial for understanding how the orogen accommodates continuing continental collision and assessing associated hazards. Here, we (a) detail newly discovered fault-zone exposures along the MFT at the Mohand Range front in northwestern India and (b) apply contemporary fault zone theory to show that the MFT is an emergent fault with a well-developed fault zone overlain by uplifted Quaternary gravels over a horizontal length of ~700 m. Northward from the front, the fault zone grades from a central, gouge-dominated core to a hanging-wall, rock-dominated damage zone. We observed incohesive, non-foliated breccia, fault gouge, and brittle deformation microstructures within the fractured country rocks (Middle Siwaliks) and outcrop scale, non-plunging folds in the proximal hanging wall. We interpret these observations to suggest that (1) elastico-frictional (brittle) deformation processes operated in the fault zone at near surface (~1–5 km depth) conditions and (2) the folds formed first at the propagating MFT fault tip, then were subsequently dismembered by the fault itself. Thus, we interpret the Mohand Range as a fault-propagation fold driven by an emergent MFT in contrast to the consensus view that it is a fault-bend fold. A fault-propagation fold model is more consistent with these new observations, the modern range-scale topography, and existing erosion estimates. To further evaluate our proposed structural model, we used a Boundary Element Method-based dislocation model to simulate topographic growth from excess slip at a propagating fault tip. Results show that the frontal topography could have evolved by slip along a (a) near-surface fault plane consistent with the present-day MFT location, or (b) blind MFT at ~3 km depth farther north near the drainage divide. Comparing modelled vs. measured high resolution (~16 cm) topographic profiles for each case provides permissible end-member scenarios of an either dynamically-evolving, high erosion, northward-migrating frontal scarp or a static, low, and symmetric, MHT-related fold, respectively. Our integrated approach is expected to deliver an improved understanding of coupled fault-generated deformation and topographic growth that may be applied more broadly across the entire Himalayan front.

1. Introduction

The India-Eurasia plate margin is one of the world's most active collision zones. It has created the Himalayan mountains for the last ~65 Ma (e.g. Molnar and Tapponnier, 1975; Hodges, 2000; Yin, 2006). The Main Frontal thrust (MFT) defines the orogen's southernmost margin across an entire ~2500 km-long arc between two syntaxes (Schelling and Arita, 1991; Srivastava and Mitra, 1994; DeCelles et al., 1998). The MFT generates and maintains the active, modern Himalayan deformation and topographic front (Nakata, 1989; Yeats and Lillie, 1991; Valdiya, 1992; Wesnousky et al., 1999; Lave and Avouac, 2000; Mukul et al., 2007; Kumar et al., 2010; Burgess et al., 2012) and is thought to be the near-surface expression of the main basal decollément called the Main Himalayan thrust (MHT) (Zhao et al., 1993; Lavé and Avouac, 2000; Bilham et al., 2001). Thus, the MFT-MHT deformation boundary is the contemporary plate interface between India and Eurasia (Bilham et al., 2001; Yeats and Thakur, 2008; Thakur, 2013). Continuing Indo-Asian collision causes strain accumulation along this boundary that is periodically released during great (M > 8) earthquakes (Bilham et al., 2001). It is postulated that the MFT is

* Corresponding author.
E-mail address: malaymukul@iitb.ac.in (M. Mukul).

http://dx.doi.org/10.1016/j.jsg.2016.10.009

fully locked along its frontal, 100 km across-strike width over its entire strike-parallel length (Stevens and Avouac, 2015). During great earthquakes, the MFT can unlock and transfer strain along the MHT to the MFT (Lavé and Avouac, 2000). Over centuries, MFT motion has caused frequent, large earthquakes that demonstrate how vital the MFT-MHT deformation zone is for Himalayan tectonics, seismicity, and the associated natural hazards (Powers et al., 1998; Wesnousky et al., 1999; Kumar et al., 2001, 2006, 2010; Malik and Nakata, 2003; Lave et al., 2005; Malik et al., 2010; Burgess et al., 2012; Sapkota et al., 2013). Large magnitude slip events and earthquakes remain a principal hazard because the Himalayan orogenic wedge thrust belt continues to cycle through various deformation states in an attempt to maintain equilibrium in response to plate motion stresses (e.g. DeCelles and Mitra, 1995; Mukul et al., 2007).

Existing MFT fault zone deformation studies have been restricted to trench excavations that typically access a small fraction of the fault zone or only minor splays off of it (Kumar et al., 2001, 2006, 2010; Malik and Nakata, 2003; Lave et al., 2005; Malik et al., 2010; Mugnier et al., 2013; Sapkota et al., 2013; Vassallo et al., 2015). Although these studies provide important insights for paleo-earthquake behavior, they are of limited use for understanding how the geometry and kinematics of the MFT has evolved throughout the Quaternary. Fortunately, a complimentary framework exists to describe and understand major fault zones that can address this deficiency. In general, major fault zones are meters to kilometers in thickness and characterized by different components with distinctive geometries and textures (e.g. Shipton and Cowie, 2003; Gudmundsson, 2011). They commonly contain a highly deformed core (or slip zone) with maximum grain-size reduction that is flanked on both sides by damage zones in which deformation decreases and grain size increases outward until reaching intact rock that remains unaffected (Fig. 1) (Flinn, 1977; Aydin, 1978; Scholz, 1987; Evans, 1990; Cowie and Scholz, 1992; Chester et al., 1993; Newman and Mitra, 1993; Caine et al., 1996; Sibson, 2003; Wibberley and Shimamoto, 2003; Kim et al., 2004; Shipton et al., 2006; Mitchell and Faulkner, 2009; Gudmundsson, 2011). Fault damage zone rocks are classified by their matrix content, grain size, cohesion, and degree of foliation (Sibson, 1977; Marshak and Mitra, 1988; Shipton and Cowie, 2003). Development of different structures within these damage zones provide valuable information about fault development (Perry, 1978; Aydin, 1988; McGrath and Davison, 1995; Vermilye and Scholz, 1998, 1999; Kim et al., 2001a, b; Nicol et al., 2002), associated fluid flow (Sibson, 1996; Martel and Boger, 1998), and even earthquake initiation and termination (Sibson, 1985; King, 1986; Aki, 1989; Thatcher and Bonilla, 1989; Kim et al., 2004). Furthermore, the physical dimensions of a fault zone are important because they scale and vary along strike with displacement (e.g. Torabi and Berg, 2011) and hence provide additional insight into fault growth (Walsh and Watterson, 1988; Peacock and Sanderson, 1991; Cowie and Scholz, 1992; Gudmundsson, 1992; Cartwright et al., 1995; Dawers and Anders, 1995; Cladouhos and Marrett, 1996; Walsh et al., 2002; Kim and Sanderson, 2005; Soliva and Schultz, 2008) and the topographic response to it (Allen et al., 2013; Ellis and Barnes, 2015). To date, the MFT has not been studied within this conceptual framework, perhaps in part, because it remains difficult to observe at the surface as a commonly documented blind fault (Stein and Yeats, 1989; Valdiya, 1992; Yeats et al., 1992).

Quaternary MFT motion has produced range-scale topography and folding (e.g. Karunakaran and Ranga Rao, 1979; Raiverman et al., 1994; Powers et al., 1998; Wesnousky et al., 1999; Lave and Auovac, 2000; Lave et al., 2005; Delcaillau et al., 2006; Malik et al., 2010; Burgess et al., 2012; Thakur, 2013). Unfortunately, a wide range of structural models have been proposed to explain the evolution of the MFT and its associated folds because the fault has not been observed at the surface in any of these studies. For example, the MFT is described as blind (Mukhopadhyay and Mishra, 2004), emergent (Raiverman et al., 1994; Powers et al., 1998), blind, but very close to the surface and recognizable in seismic sections and boreholes (Wesnousky et al., 1999; Mishra and Mukhopadhyay, 2002), or simply a zone of intense brittle deformation (Srivastava and John, 1999). These discrepancies lead to nontrivial differences in shortening estimates within the MFT thrust sheet; in the Mohand Range, for example, a blind MFT model estimated ~17% shortening (Mishra and Mukhopadhyay, 2002) compared to an emergent MFT model that estimated ~27% shortening (Powers et al., 1998). Furthermore, such disparities have led to a plethora of interpretations for the associated fold kinematics such as fault-propagation folding (e.g. Lave et al., 2005), fault-bend folding (e.g. Wesnousky et al., 1999; Mishra and Mukhopadhyay, 2002), or just a generic growing anticline (e.g. Powers et al., 1998; Burgess et al., 2012). In some cases, including at Mohand, even the exact same anticline has been interpreted differently (e.g. compare Fig. 2C and D) (cf. Raiverman et al., 1994; Powers et al.,

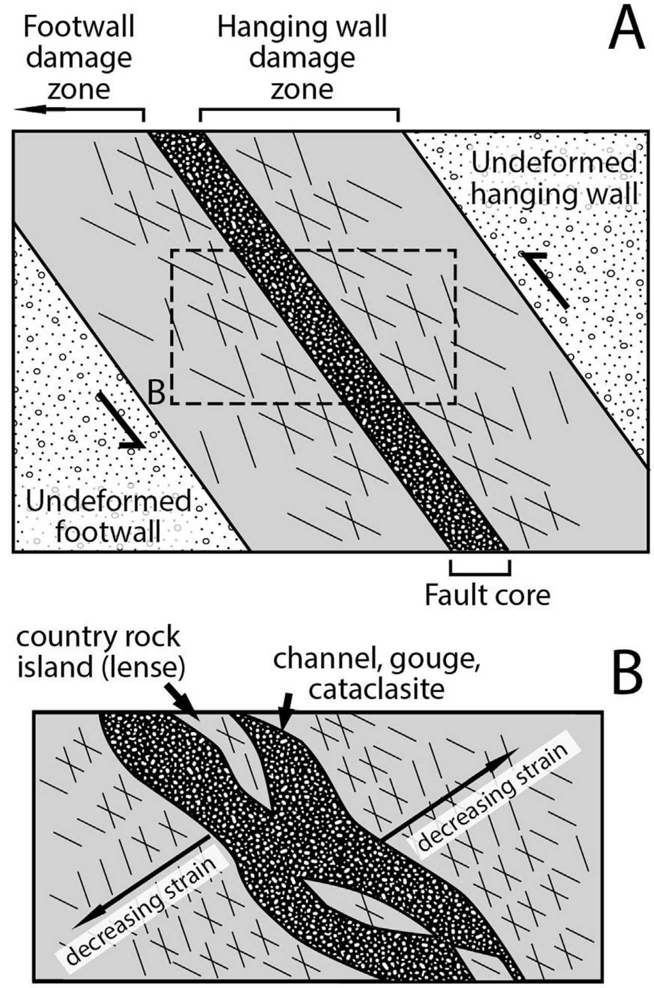

Fig. 1. Schematic thrust fault damage zone in a sedimentary country rock (modified from Shipton and Cowie, 2003; Mitchell and Faulkner, 2009; Gudmundsson et al., 2010). (A) Note the major components: core, damage zone (in the footwall, hanging wall), and the adjacent undeformed country rock. (B) In detail, the fault zone contains a core with channels surrounding islands of more intact, deformed country rock that transition into damage zones characterized by decreasing strain with distance from the core.