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Seismic imaging of the Main Frontal Thrust in Nepal reveals a shallow décollement and blind thrusting

Rafael V. Almeida [a,*], Judith Hubbard [a,b], Lee Liberty [c], Anna Foster [a,d], Soma Nath Sapkota [e]

[a] Earth Observatory of Singapore, Nanyang Technological University, Singapore
[b] Asian School of the Environment, Nanyang Technological University, Singapore
[c] Department of Geosciences, Boise State University, ID, USA
[d] Département des sciences de la Terre et de l'atmosphère, Université du Québec à Montréal, Canada
[e] Department of Mines and Geology, Kathmandu 44600, Nepal

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ABSTRACT

Because great earthquakes in the Himalaya have an average recurrence interval exceeding 500 yr, most of what we know about past earthquakes comes from paleoseismology and tectonic geomorphology studies of the youngest fault system there, the Main Frontal Thrust (MFT). However, these data are sparse relative to fault segmentation and length, and interpretations are often hard to validate in the absence of information about fault geometry. Here, we image the upper two km of strata in the vicinity of the fault tip of the MFT in central Nepal (around the town of Bardibas) applying a pre-stack migration approach to two new seismic reflection profiles that we interpret using quantitative fault-bend folding theory. Our results provide direct evidence that a shallow décollement produces both emergent (Patu thrust) and blind (Bardibas thrust) fault strands. We show that the décollement lies about 2 km below the land surface near the fault tip, and steps down to a regional 5 km deep décollement level to the north. This implies that there is significant variation in the depth of the décollement. We demonstrate that some active faults do not reach the surface, and therefore paleoseismic trenching alone cannot characterize the earthquake history at these locations. Although blind, these faults have associated growth strata that allow us to infer their most recent displacement history. We present the first direct evidence of fault dip on two fault strands of the MFT at depth that can allow terrace uplift measurements to be more accurately converted to fault slip. We identify a beveled erosional surface buried beneath Quaternary sediments, indicating that strath surface formation is modulated by both climate-related base level changes and tectonics. Together, these results indicate that subsurface imaging, in conjunction with traditional paleoseismological tools, can best characterize the history of fault slip in the Himalaya and other similar thrust fault systems.

1. Introduction: great earthquakes in the Himalaya

The Himalaya (Fig. 1) represents one of the few regions on Earth where great, surface-rupturing thrust earthquakes occur on land. This, combined with the vulnerability of the densely populated Gangetic Plain south of the Himalaya, produces high seismic risk in this region (Bilham, 2014). The Main Frontal Thrust (MFT) in Nepal is the youngest and southernmost structure in the Himalayan Fold and Thrust belt (Fig. 1; Gansser, 1964). This thrust roots into a regional décollement, or bed-parallel fault, known as the Main Himalayan Thrust (MHT) that underlies the entire Himalaya and represents the contact between the Indian and Asian plates (Fig. 1A; Seeber and Armbruster, 1981; Zhao et al., 1993).

Since the identification of the MFT and MHT, questions have been raised about how this fault system slips in earthquakes, and whether this slip is surface emergent. Seeber and Armbruster (1981) proposed that the MHT extends past the MFT underneath the Gangetic Plain, and that coseismic slip during great earthquakes remains blind. Schelling and Arita (1991) and Delcaillau (1992) were among the first to depict the MFT as the frontal ramp of the MHT, raising the possibility that coseismic slip could reach the surface. Wesnousky et al. (1999) and Lave and Avouac (2000) studied uplifted river terraces and concluded that the Holocene convergence rate on the MFT is similar to the geodetically deter-

* Corresponding author.
E-mail address: ralmeida@ntu.edu.sg (R.V. Almeida).

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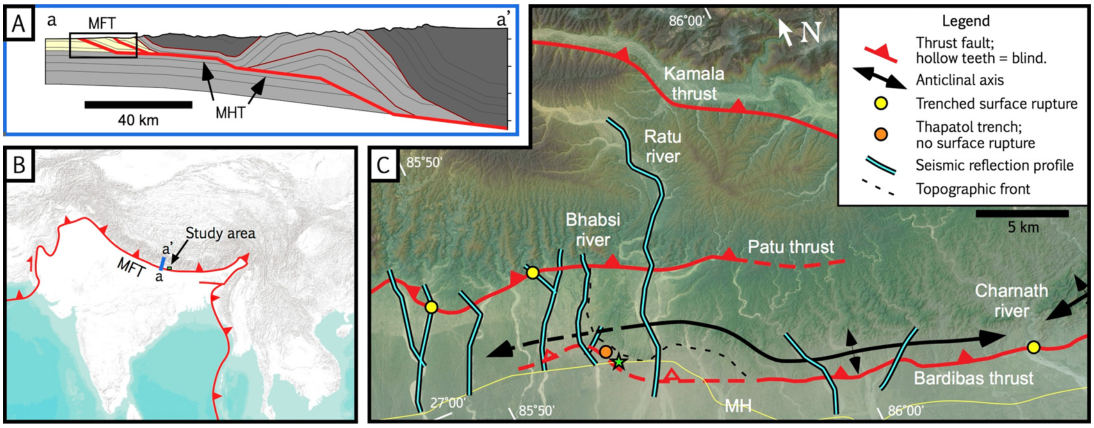

Fig. 1. (A) General cross-section a–a′ across the Himalaya, after Hubbard et al. (2016). Bold red line indicates active faults and thin red lines represent inactive faults; MFT, Main Frontal Thrust; MHT, Main Himalayan Thrust. (B) Location map, showing the kinematic boundary between the Indian and Asian plates (red line with teeth), cross-section a–a′ (blue line), and study area. (C) Study area, showing locations of seismic profiles. Star represents town of Bardibas. MH, Mahendra Highway. Basemaps for (B) and (C) from ESRI, USGS, NOAA SRTM data (Jarvis et al., 2008).

mined convergence rate between India and southern Tibet. This implies that elastic strain is released during great earthquakes on the MFT. Over the past 20 years, trenching studies have reported surface ruptures in the Himalaya, finding evidence of the 1255 (e.g. Nakata et al., 1998; Lave et al., 2005; Wesnousky et al., 2017) and 1934 (Sapkota et al., 2013; Bollinger et al., 2014) earthquakes in Nepal, as well as other ruptures (e.g. Kumar et al., 2006). This has led to a new paradigm: that great earthquakes in the Himalaya commonly breach the surface along the trace of the MFT.

2. Local structure and stratigraphy

Our study area is located in the Himalayan foreland fold and thrust belt, around the town of Bardibas in central Nepal (Fig. 1). The study region encompasses a right-step of the Himalayan range front, with two overlapping northwest–southeast trending fault strands: the northern Patu thrust, and the southern Bardibas thrust. Analyses of trenches and river cuts across the Patu thrust demonstrate that it ruptured in both 1255 and 1934 (Sapkota et al., 2013; Bollinger et al., 2014). However, a trench of the Bardibas thrust near the town of Bardibas did not find a surface rupture, but rather a fold scarp (Fig. 1; Bollinger et al., 2014). The faults in this area deform the Siwalik Group, a ~5 km thick package of mid-Miocene to Pliocene fluvial strata with 2–20 m alternating siltstone and sandstone layers (Delcaillau, 1992). This stratigraphic group is generally divided into Lower, Middle and Upper Siwalik (Gansser, 1964; Delcaillau, 1992). The Lower Siwalik consists of alternating gray fine sandstones and siltstones. The beds attain thicknesses of a few meters and are strongly lithified. The Middle Siwalik consists of massive tan sandstone layers (up to 10s of m in thickness) which occasionally have a characteristic "salt and pepper" texture caused by mica grains. There are occasional lenses of conglomerates. The Upper Siwalik consists of conglomeratic channel deposits and boulder beds. The contact between the latter two units is often transitional, as the proportion of sand to gravel beds changes. However, the Middle to Upper Siwalik transition spans ~100 m on the Ratu River. Further description of the stratigraphy of this area can be found in Delcaillau (1992) and Dhital (2015).

3. Seismic data from central Nepal

We used a vibroseis source to acquire ten high resolution seismic profiles across the MFT during 2014 and 2015 (Fig. 1). The seismic lines follow seasonal riverbeds that are generally orthogonal to the range front. The resulting pre-stack depth migrated seismic reflection profiles image to ~2 km below the surface and provide a robust interval seismic velocity estimate for the upper 500 m. Here, we present two profiles: one along the Ratu River that cuts across both the Patu and Bardibas thrusts, and one along the Bhabsi River to the west of Bardibas (Fig. 1). In the following sections, we discuss the fault location and orientation, faulting style, growth strata and axial surfaces associated with the deformation for each thrust, and estimate the amount of shortening. We highlight our findings that have implications for regional tectonic studies, and then discuss our results in the context of seismic hazard studies. Information on data acquisition and processing can be found in the supplementary materials.

4. Interpretation of seismic data

We use the seismic reflection lines for the Ratu River and Bhabsi River to study the geometry of the fault systems, the amount of shortening that has occurred on these faults, and to infer the development of the shallow stratigraphy. For the structural aspect of this study, we combine the data with surface observations and use classic methods of seismic interpretation, as well as fault-bend fold, shear fault-bend fold, or fault-propagation fold theory as appropriate for each locality.

4.1. The Patu thrust and related deformation, Ratu River profile

Along the Ratu River profile (Fig. 2), the north-dipping Patu thrust is exposed on the river banks at common-depth point (CDP) ~4000. Folded strata, observed both in seismic and at the surface, form a small anticline approximately 0.25 km north of the main thrust (CDP ~3900), and then a larger anticline 1.5 km to the north (CDP ~3300). The region directly below the crest of the larger anticline is not imaged due to a sharp bend in the river that restricted source points in that area. Otherwise, the Ratu River profile reflections are well defined, showing dip magnitudes and directions consistent with surface measurements, and occasional fault-plane reflections.

In particular, the well imaged northern axial surface of the anticline at CDP ~2400 (northernmost dashed green line in Fig. 2), separates flat-lying beds to the north from north-dipping beds to the south. This abrupt transition in reflector or bed dip is also observed in outcrop. Across the axial surface, continuous reflectors can be traced through the fold to a depth of ~1500 m below sea level (bsl; ~2000 m below land surface). We observe that the axial surface bisects the fold, and infer that the folding is accommodated by flexural slip (i.e., slip along bedding planes) as the hanging wall rocks slide through the axial surface and up the fault ramp. We