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A paleoseismic age model for large-magnitude earthquakes on fault segments of the Himalayan Frontal Thrust in the Central Seismic Gap of northern India

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ABSTRACT

Crustal collision between Eurasia and the Indian subcontinent has produced a thrust fault system that accommodates a share of the strain associated with convergence. The foremost of these faults is the Himalayan Frontal Thrust (HFT), also referred to as the Main Frontal Thrust (MFT). Discrete segments of the HFT have produced numerous, large-magnitude earthquakes throughout the last two centuries that are constrained through instrumental and historical records. Paleoseismic studies have established comparable constraint for pre-instrumental ruptures of the fault. The segment of the fault known as the Central Seismic Gap (CSG), which extends from North-Central India into Western Nepal, is of particular interest due to an apparent long-term quiescence that suggests the potential for impending large-scale rupture. Here we compile recent, paleoseismological findings from seven published trench sites into a coherent OxCal age model for large-magnitude ruptures along the CSG. Our results indicate that the western half of the CSG likely ruptured in the event corresponding to historical accounts of an earthquake in 1344 CE.

1. Introduction

The Himalayan thrust fault system lies at the active, tectonic boundary between Eurasia and the Indian subcontinent, and accommodates approximately half of the strain associated with convergence and the concomitant uplift of the Himalayan Mountain Range (Ader et al., 2012), which began in the middle to late Paleogene. The foremost in this series of in-sequence thrust faults, which connect across a common decollement (Fig. 1) and are oriented transverse to convergence, is the Himalayan Frontal Thrust (HFT), also referred to as the Main Frontal Thrust (MFT). The southward-verging HFT dips to the north at ~20–45°, displacing Tertiary and Quaternary (Siwalik Group) sedimentary units from an earlier foreland basin over the Quaternary sediments of the Indo-Gangetic plain. Numerous large-magnitude earthquakes have ruptured discrete segments of this active boundary in the last two centuries, as referenced in earthquake catalogues (e.g. Khattri, 1987; Iyengar et al., 1999; Ambraseys, 2000; Pant, 2002; Ambraseys and Douglas, 2004).

Incomplete historical records and inferred rupture locations lead to uncertainties surrounding the timing and nature of earlier events, which can be addressed through paleoseismic investigation. The need for additional paleoseismological data is particularly critical along segments of the HFT that lack a large-scale 20th century rupture, such as the Central Seismic Gap (CSG), which lies between the areas affected by the 1905 CE Kangra (Himachal Pradesh, India) and 1934 CE Nepal-Bihar earthquakes (Khattri, 1987). Establishing the timing of past earthquakes along the CSG is critical in assessing regional seismic hazards for areas proximal to the HFT that have both large populations and inadequate infrastructures. While several paleoseismic studies have been conducted across the HFT, along and adjacent to the CSG (Kumar et al., 2001, 2006; Malik et al., 2010; Kumahara and Jayangondaperumal, 2013; Rajendran et al., 2015); a comprehensive analysis of the events interpreted in these studies has not previously been completed. In order to better constrain the timing of paleoearthquakes on the west-central, India section of the HFT, we have evaluated trench data and compiled recent radiocarbon age results from previously

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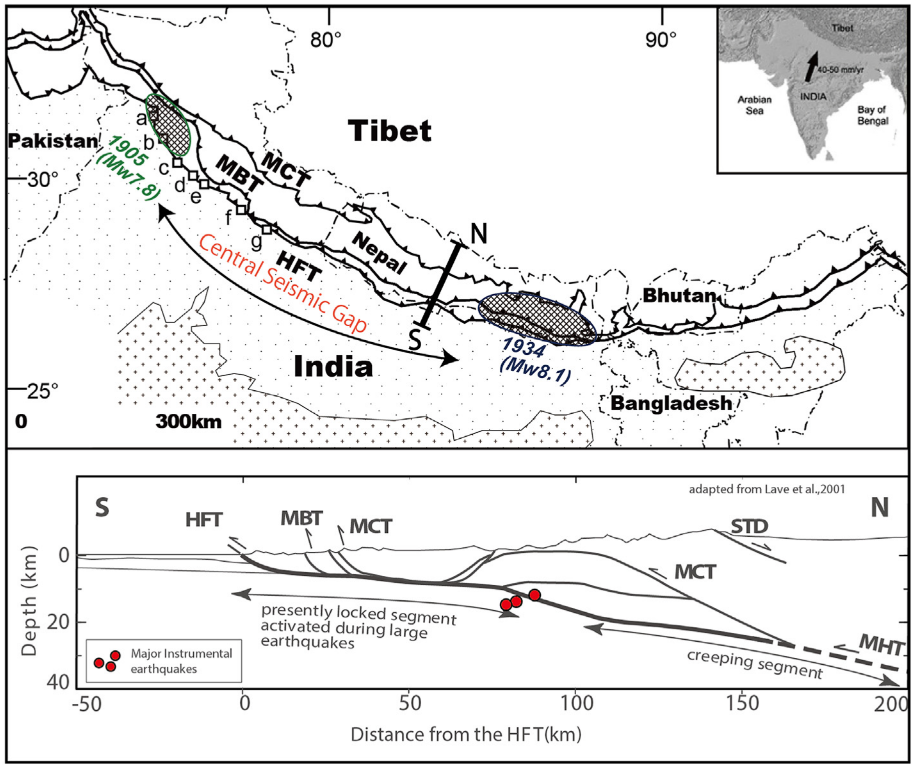

Fig. 1. Map showing the major zones of Himalayan convergence—MCT: Main Central Thrust; MBT: Main Boundary Thrust; and HFT: Himalayan Frontal Thrust. Trench site locations are labeled as in Fig. 2: a) Hajipur, b) Bhatpur, c) Chandigarh, d) Kala Amb, e) Rampur Ganda, f) Lal Dhang, g) Ramnagar. Schematic cross-section through central Nepal showing the main structures and instrumental thrust earthquake foci. STD: Southern Tibet Detachment; MHT: Main Himalayan Thrust; (after Lavé et al., 2005).

published studies for seven sites, including (from northwest to southeast): Hajipur, Bhatpur, Chandigarh, Kala Amb, Rampur Ganda, Lal Dhang, and Ramnagar (Fig. 1) (Kumar et al., 2001, 2006; Malik et al., 2010; Kumahara and Jayangondaperumal, 2013; Rajendran et al., 2015). Review articles by Mugnier et al. (2013) and Bollinger et al. (2016) provided a synopsis of earthquakes along the central Himalaya and Nepal sections of the HFT, respectively. An age model was developed for each of the seven trench sites based on published radiocarbon results, with consideration given to the stratigraphic context of each trench, using the OxCal software program (Bronk Ramsey, 2009a) and the IntCal13 atmospheric calibration curve (Reimer et al., 2013).

2. Methods

Paleoseismic investigations of the HFT incorporate geomorphological analyses of fault scarps, calculation of local uplift rates, examination of faulting exposed in river cutbanks, excavation of paleoseismic trenches across fault scarps, etc. Trench sites are chosen based on several factors, such as: fault scarp geometry, orientation of fault scarps with relation to the direction of regional convergence and accessibility of the sites. The purpose of these excavations is to expose and document geological evidence of past ruptures of the fault, and to collect samples from strategic stratigraphic locations that will allow for dating of those ruptures.

The collection of charcoal samples for radiocarbon analysis is a common technique employed in paleoseismic studies to constrain the timing of past earthquakes, especially where these samples are abundant. However, dating and calibrating individual charcoal samples often results in "… probability distributions, which are often irregular and multimodal …" (Lienkaemper and Bronk Ramsey, 2009). Additionally, constraining the minimum age of paleoseismic events on thrust faults using radiocarbon data can be problematic due to the potential for post-event erosion of fault scarps and associated reworking of charcoal from older units into colluvial deposits. This may result in erroneously old depositional ages for the stratigraphic units that directly overlie the faulted sediments. Modeling these data using a Bayesian statistical program (Bayes, 1763) such as OxCal, that incorporates stratigraphic relationships, can tighten the probability distributions of individual sample ages based on the constraint that samples from overlying layers are younger (Lienkaemper and Bronk Ramsey, 2009), and can increase the accuracy of results through the identification of outliers.

Here we use the OxCal "sequence" command to introduce a depositional chronology for the stratigraphic units, and the "phase" command to include all radiocarbon ages (BP) for an individual stratigraphic unit without consideration for chronological order within that unit. Resultant models are developed through an iterative process, which narrows the probability distribution functions (PDFs) for the ages of each of the calibrated samples and event horizons, and identifies outliers through assignment of an Agreement Index (AI). Here we follow the standard convention of including all radiocarbon age results with an AI $\geq$ 60% and removing all others as outliers (Bronk Ramsey, 2009b). Outliers are best identified when there are a sufficient number of additional data points, highlighting the importance of analyzing an ample number of C-14 samples in each OxCal model.

Employing a secondary dating technique such as Optically Stimulated Luminescence (OSL) can be beneficial for the verification of radiocarbon age results, and for mitigation of factors such as inherited ages of charcoal samples that may lead to overestimation of depositional age. While OSL samples were collected for one of the trench sites in this study, this data is not included in the model

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