Pattern, rate, and timing of surface rupturing earthquakes acorss the northwest Himalaya

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An elegant model sensibly links interseismic strain accumulation, historic and paleoseismic earthquakes, and intermediate- to long-term shortening in the central Himalaya. Records of historic and paleoseismic earthquake include more frequent, blind earthquakes ($<M_w$ 8.4) and less frequent, emergent earthquakes ($>M_w$ 8.5) on the Himalayan Frontal thrust (HFT). These earthquakes relieve the majority of the interseismic strain accumulation and faults within the central Himalayan accommodate little strain [Bettinelli et al., 2006; Kumar et al., 2006; Larson et al., 1999; Lavé et al., 2005]. Active deformation of the northwestern Himalaya reveals a different story. An asymmetric anticline marks the deformation front in Kashmir and the HFT is inferred to be blind. The Salt Range thrust system (SRT) defines the thrust front in Pakistan to the west, which includes active folds in the footwall of the SRT proper [Yeats and Thakur, 2008]. Within the orogenic wedge to the north of the deformation front, active shortening occurs along a system of surface-rupturing reverse faults, extending from the Balakot-Bagh fault, source of the Mw 7.6 Kashmir earthquake of 2005 in Pakistan Kashmir, to the Reasi fault in Indian Kashmir to the southeast [Gavillot, 2010; Hebeler, 2010; Hussain et al., 2009]. Farther north, faults in the Kashmir Valley cut Quaternary deposits [Madden, 2010; Nakata, 1989]. Active deformation thus occurs on faults distributed more than 120 km across the orogen from the deformation front in the foreland into the northwest Himalayan orogen.

Northwest Himalayan thrust front

Gee [1989] summarizing his earlier work in a series of maps along the Salt Ranges demonstrated that the SRT deforms young surficial deposits and is an active fault. New mapping and preliminary OSL dates from deformed Holocene sediments exposed along the westernmost SRT reveal that the last surface rupture on this fault occurred with the last several thousand years. Our observations of 1000's years between surface rupturing events is with consistent with the low SRT shortening rates (4 to 13 mm/yr).

It is simply unknown whether the HFT ruptures to the surface in the Kashmir Himalaya, Tilted fluvial strath terraces across the frontal structure imply that a fold defines the deformation front.

However, ~20 m-high escarpments oriented perpendicular to rivers suggest that unrecognized thrust fault(s) reach the surface locally. Contacts relations within the Siwalik sediments on the limb of the frontal anticline implies fold growth between 0.78 Ma and 1.5 Ma [Ranga Rao et al., 1988; Raynolds, 1980]. Folded river terraces and dip data suggest that the thrust at depth is a southwest-dipping backthrust rather than a north- or northeast-dipping forethrust as is seen along strike along the SRT and in India to the southeast.

Active faults at intermediate distances from the thrust front

A seismically active emergent thrust fault system extends stepwise from the Balakot-Bagh fault (BB; source of the Mw 7.6, 2005 Kashmir earthquake [Kaneda, 2008; Kumahara and Nakata, 2006]) southeast more than 200 km to the Reasi fault (RF) [Hussain et al., 2009]. Both the BB and RF are reverse faults; the BB locally cuts the 17 – 12 Ma Kamlial Formation. A balanced cross-section indicates a minimum of 20 km fault displacement on the BB, yielding a minimum 1.2-1.7 mm/yr long-term slip rate, lower than the 1.4 -4.1 mm/yr slip rate inferred from faulted Quaternary fluvial terraces [Kaneda, 2008]. The penultimate earthquake occurred between 500 and 2200 y.r. B.P. [Kondo et al., 2008].

The RF is a ~70 km-long, ~50° northeast-dipping reverse fault system, which lies ~40 km north of the deformation front in the Kashmir Himalaya [Gavillot et al, 2010]. Two strands define the Reasi fault. The northern strand, Main Reasi fault (MRF), places Precambrian Sirban Limestone on folded unconsolidated conglomerates. Younger alluvial deposits cover the MRF. A preliminary OSL age of 80 ± 6 ka from a 350 m-high Bidda terrace in the upper plate of the MRF, yields a minimum long-term uplift rate of 4.4 ± 0.3 mm/yr, a slip rate of 5.7 ± 0.4 mm/yr, and a shortening rate of 3.7 ± 0.3 mm/yr for the RF. To the south, the Reasi (Riasi) frontal fault (RFF) includes a fault scarp that offsets Holocene deposits. Trenches excavated across the RFF reveal a distinct angular unconformity, steeply dipping strata cut by low-angle thrusts, and an unconformity below relatively undeformed strata [Hebeler et al., 2010]. Trench relations can be explained by surface rupture of the RF ~4,500 yrs ago. The age of this unconformity is constrained to be ~4,500 yrs old based on calibrated calendar C-14 ages from detrital charcoal. These results and those from the BB [Kondo et al., 2008] imply recurrence intervals of $\geq$ 2,000 yrs).

Active faults in the hinterland

Active faulting also occurs within the Kashmir Valley (KV) [Maddenet al., 2010], an intermontane basin ~100 km north of the deformation front. Three northeast-dipping reverse faults cut Quaternary terraces on the southwest side of the KV. Deformed terraces along the Rambira River exhibit ~13 m of vertical separation across one of the faults (the 40-km-long Balapora fault (BF)). Weakly developed soils and the lack of loess suggest deposition after the last glacial maximum (22-17 ka), possibly as young as 10-6 ka. Given the 60° fault dip, we estimate a preliminary BF shortening rate of 0.3 to 1.3 mm/yr. Fault and stratal relations in trenches suggest at least 2 surface rupturing events in the latest Quaternary.

Given a ~34 mm/yr India-Asia convergence rate in the NW Himalaya [Bettinelli et al., 2006], active structures within the NW Himalaya absorb roughly 15 to 50% of that convergence. In contrast to the central Himalaya where deformation is focused at the HFT, up to ~20% of the shortening occurs on structures north of the HFF, within the NW Himalayan orogenic belt. Recognition of internal surface-rupturing reverse faults indicates probabilistic models for seismic hazards in the NW Himalaya ought to account for great earthquakes on the Main Himalayan thrust (the basal décollement), moderate earthquakes on upper plate faults, and potentially events in the down-going Indian plate.

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