Long recurrence interval of faulting beyond the 2005 Kashmir earthquake around the northwestern margin of the Indo-Asian collision zone

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ABSTRACT

The 2005 Kashmir earthquake in Pakistan occurred on a previously mapped active fault around the northwest margin of the Indo-Asian collision zone. To address the quantitative contribution of the earthquake to plate convergence, we performed paleoseismological trench excavations at Nisar Camp site near Muzaffarabad across the middle section of the 2005 surface rupture. The fault strands exposed in the trench cut late Holocene fluvial deposits and record evidence of both the 2005 and a penultimate event, supported by the presence of colluvial deposits and a downdip increase in displacement along the fault strands. The 2005 event produced a net slip of 5.4 m, and the penultimate earthquake exhibits a similar amount of slip. Radiocarbon ages and historical accounts loosely constrain the timing of the penultimate event between 500 and 2200 yr B.P.; however, the exposed section encompasses ~4 k.y. of stratigraphy, suggesting an average interevent interval of ~2 k.y. for the 2005 type events. We thus conclude that the 2005 event did not occur on the plate boundary megathrusts, but on intraplate active faults within the Sub-Himalaya. Consequently, the accumulated elastic strain around the complex northwestern margin of the Indo-Asian collision zone has not been significantly released by the 2005 earthquake.

Keywords: active fault, paleoseismology, 2005 Kashmir earthquake, Indo-Asian collision zone.

INTRODUCTION

The 2005 Kashmir earthquake in northeastern Pakistan occurred along the northwestern margin of the Indo-Asian collision zone. The fault responsible for the 2005 earthquake (Kumahara and Nakata, 2006; Kaneda et al., 2008) and nearby active faults were mapped in part prior to the earthquake by Nakata et al. (1991). We present here the results of the first successful paleoseismic trenching survey in Pakistan to reveal the timing, recurrence interval, and net slips associated with the 2005 and previous events. The observations are the basis to discuss the role of the 2005 earthquake in the context of the complex northwestern margin of the Indo-Asian collision zone.

The epicenter of the Kashmir earthquake was located within the western transpressional margin of the Indo-Asian collision zone (Fig. 1). This portion of the margin, the Hazara-Kashmir syntaxis, is structurally more complex than to the east, where the margin is marked by a simple arcuate curve that extends for more than 2000 km across India and Nepal. Geodetic surveys using global positioning system measurements by Bilham et al. (2001) and Bilham and Ambraseys (2004) indicate that the equivalent of ~40–50 mm/yr of convergence is currently accumulating as strain across the India-Eurasia plate boundary, with ~10–20 mm/yr of that budget distributed directly along the Himalayan Frontal fault (Nakata et al., 1991). Recent detailed paleoseismic and historical investigations (e.g., Bilham and Ambraseys, 2004; Kumar et al., 2001, 2006) demonstrate the past occurrence of great earthquakes to the east of Pakistan along the Himalayan Frontal fault of India and Nepal. Recent studies postulate that >6 m of slip and the potential for an Mw 8 earthquake have accumulated along the section of Himalayan Frontal fault to the east since the last earthquake there in A.D. 1555 (Bilham and Wallace, 2005). The question thus arises as to what extent the 2005 event (Mw 7.6) has reduced the slip deficit along the more structurally complex section of the Indian-Eurasian plate boundary in which the 2005 earthquake occurred.

NISAR CAMP TRENCH SITE

The Nisar Camp trench site is located at the foot of a fault scarp cutting fluvial terraces northeast of Muzaffarabad in the middle section of the Balakot-Bagh fault, which extends for ~66 km (Fig. 2; see also Fig. DR1 in the GSA Data Repository[1]). While the Balakot-Bagh fault generally extends NW-NNW, the fault at the trench site is located at a fault bend and lateral ramp and strikes almost E-W. Near the site, well-developed and uplifted terrace surfaces along the Neelum River are classified into M1, M2, L1, L2, and L3 surfaces in descending order, based on their relative height. The E-W–trending fault produces a 20-m-high scarp on the L1 surface. The surface rupture associated with the 2005 earthquake produced a 2-m-high monoclinal scarp at the foot of this larger scarp, and horizontal shortening of 4.6 m and left-lateral offset of 0.6 m were also measured near the trench site, based on a row of fence posts (Kaneda et al., 2008). Similar space-geodetic estimates by Avouac et al. (2006) are also reported nearby the site.

First, we excavated an 11-m-long and 4-m-deep trench across the 2-m-high scarp in March 2006. In March 2007, we re-excavated another 20-m-long and 8-m-deep trench just east of the 2006 trench in order to observe deeper sections. We present our results for the western wall of the 2007 trench in Figure 3. The upper and lower sections of the trench wall are separated by a step. Results for the walls of the 2006 trench are provided in Figure DR2).

FAULT STRUCTURE AND PENULTIMATE EVENT

The strata exposed on the trench walls are mainly fluvial deposits, partly colluvium and artificial deposits near the surface (Fig. 3; Fig. DR2 and Table DR1). We divided the strata into 15 units based on lithology and relationship to faulting events. All strata are cut by low-angle

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[1] GSA Data Repository item 2008183, supporting data and references, including Figures DR1–DR2 and Tables DR1–DR3, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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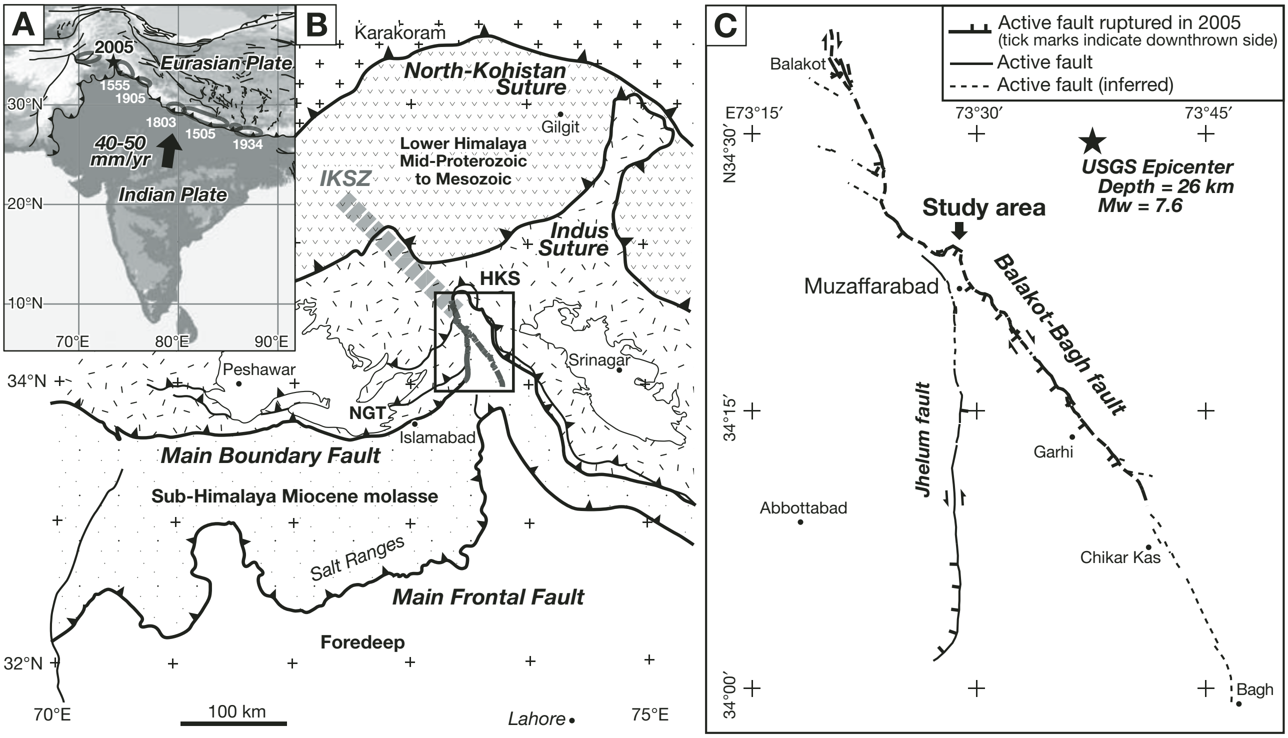

Figure 1. A: Indo-Asian collision zone, plate convergence rate, and major historical earthquakes. B: Tectonic map around northwest margin of Indo-Asian collision zone (modified from Burg et al., 2005). HKS—Hazara-Kashmir syntaxis; NGT—Nathia Gali thrust; IKSZ—Indo-Kohistan seismic zone (after Armbruster et al., 1978). C: Active fault map around epicenter area of the 2005 earthquake and location of the trench excavated. Active fault traces are modified from Kumahara and Nakata (2006).

fault strands that dip ~0º–20ºN and are subjected to monoclinal folding. The detailed lithological characteristics are summarized in Table DR1. The fault structure and deformation related to faulting events are described in the following.

The fault strands exposed on the trench walls cut all units, including artificial deposits. The fault strands dip ~20º to the north from the trench bottom to the level of the footwall surface, where they merge into a subhorizontal single fault (Fig. 3 and Fig. DR2). On the west walls of both the 2006 and 2007 trenches, the artificial deposits (unit 10) consist of road pavement at the surface of the footwall that is clearly thrust into unit 30, indicating shortening of several meters during the 2005 event. Granules and pebbles are reoriented due to shear along the fault plane. From unit 60 to unit 10, each unit has approximately the same thickness on both hanging wall and footwall, except artificial deposits and dragged areas close to the fault planes. Judging from lithological characteristics and the constant thickness, they were originally deposited subhorizontally (Fig. 3; Table DR1).

Units 100 and 90 are overturned and almost vertical within the main fault zone on the trench walls, and their deformation patterns indicate one event prior to the 2005 earthquake. The upper terminations of several fault strands are covered with unit 80, including colluvium with patches of unit 90 derived from the top of the scarp. Unit 78, a sand and granule layer with weak soil horizonation, appears mostly on the footwall. Overlying unit 78, unit 70 on the footwall side is thicker than that on the hanging wall and the unit gradually becomes thinner toward the upthrown side. This indicates that unit 70 was deposited as growth strata filling the paleoscarp after the penultimate event, which occurred after the deposition of unit 90 (Fig. 3).

Units 120 through 90 show larger vertical offset than overlying units and are more highly deformed than the younger layers in units 60–10 (Fig. 3). The cumulative vertical offset of unit 90, almost twice that of the 2005 earthquake, is strong evidence for the penultimate event. The observations thus indicate that the penultimate thrusting event occurred following the deposition of unit 90 and prior to the deposition of unit 80. In addition, the same pattern of faulting and folding is identifiable from the top of unit 120 through unit 90, implying that no other faulting occurred during those deposits.

Based on the strata exposed in the trenches, our best measurement of the net slip is summarized as 5.4 m for the 2005 earthquake (Fig. 4; Table DR3; see also detailed explanations in the GSA Data Repository). Furthermore, a vertical separation of the penultimate event

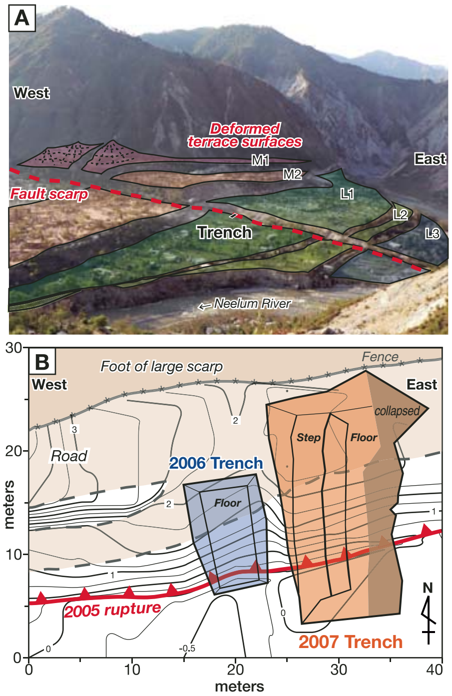

Figure 2. A: Photograph of east-west fault scarp in Muzaffarabad along central section of 2005 surface rupture and location of trench site. Fault scarp is clearly expressed with back-tilting terrace surfaces toward upstream side and flexural deformation at surface. The 2005 surface rupture appears at foot of the preexisting fault scarp in perspective. B: Plan-view map of detailed surface ruptures around the trench site. Contour lines denote elevation at 0.25 m intervals.

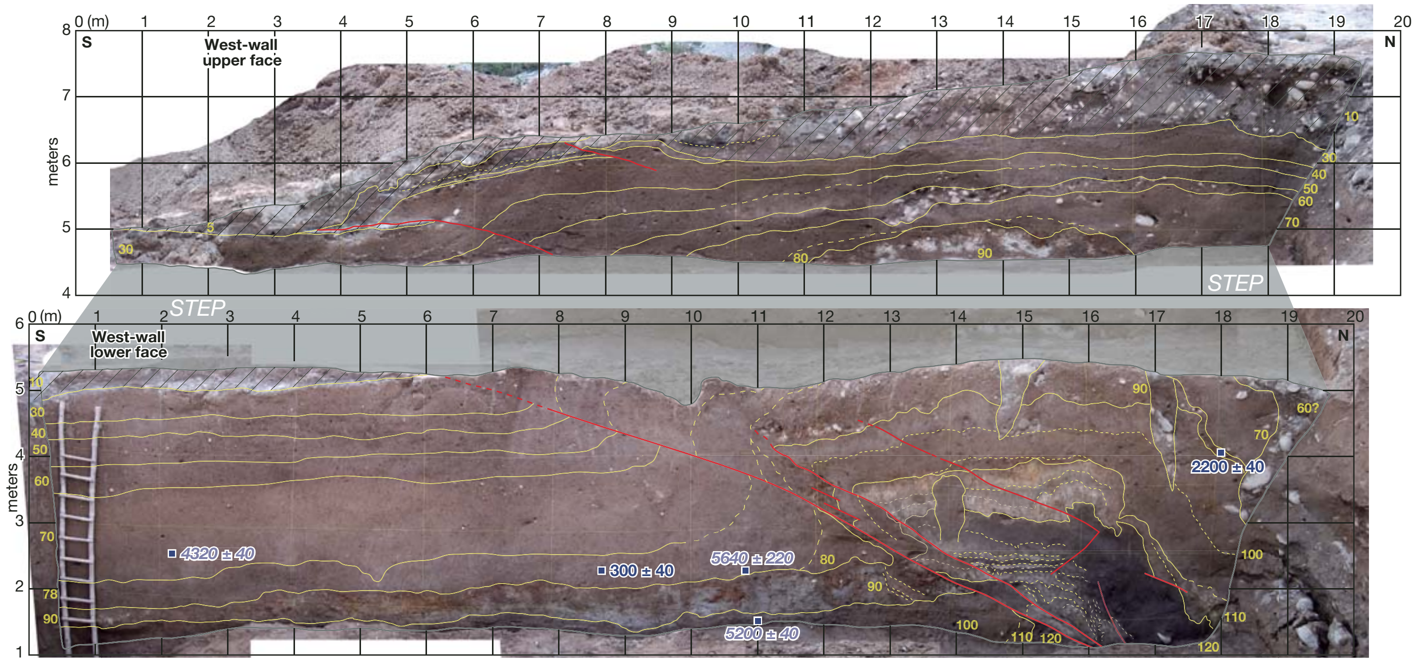

Figure 3. Photomosaics and logs of the 20007 trench walls. Grid interval is 2 m. Red lines indicate faults and numerals denote stratigraphic units. Radiocarbon dates are also shown (without yr B.P.) and stratigraphically contradicting dates are in italics. Note that low-angle fault strands exposed on trench walls cut fluvial and artificial deposits (unit 10: hachured). Two faulting events, including the 2005 Kashmir earthquake, are identifiable. Penultimate event specified between unit 90 and unit 80 forms cumulative vertical offset and monoclinal deformation of strata below unit 90, colluvial deposits of unit 80, and thickening of unit 70 as growth strata.

subtracted from cumulative vertical separation of unit 90 yields a net slip of 5.0 m, assuming the fault dips at 20°.

DISCUSSION AND CONCLUSIONS

Radiocarbon ages show that the 2005 and penultimate earthquakes occurred during the past ~4 k.y. (Fig. 5; Table DR2). The age of the penultimate event on the Balakot-Bagh fault is only weakly constrained by the radiocarbon ages between ca. 300 and 2200 yr B.P. (Fig. 5; Table DR2: samples W2 8.44–2.52 in unit 78 and W2 18.00–4.02 in unit 90). In addition, historical accounts indicate that the 500-yr-old fort in Muzaffarabad has not previously sustained earthquake damage, constraining the penultimate age range between 500 and 2200 yr B.P. If the actual age of the penultimate event is near the younger end of the range, it allows the possibility of aperiodicity or clustering in the repeated occurrence of earthquake displacements at the site with intervals longer than 2 k.y. (e.g., Weldon et al., 2004). If the age for the penultimate event is actually nearer the older end of the range, the data would be consistent with an average recurrence or renewal interval of ~2 k.y. at the site (see also detailed explanations in the GSA Data Repository).

In either case of the age constraint on the penultimate event, the average interevent interval for the recent earthquakes is thus estimated as ~2 k.y. The recurrence interval is significantly longer than the interval of 500–900 yr that has been estimated for large earthquakes with the potential to break the ground surface along the Himalayan Frontal fault (Bilham and Wallace, 2005). Kumar et al. (2006) reported paleoseismic evidence for ~1500 yr return times between great earthquakes on the Indian Himalayan Frontal fault, but the displacements of paleoseismic events in that study are generally two to three times greater than we observe at Nisar Camp. Both the 2005 and penultimate

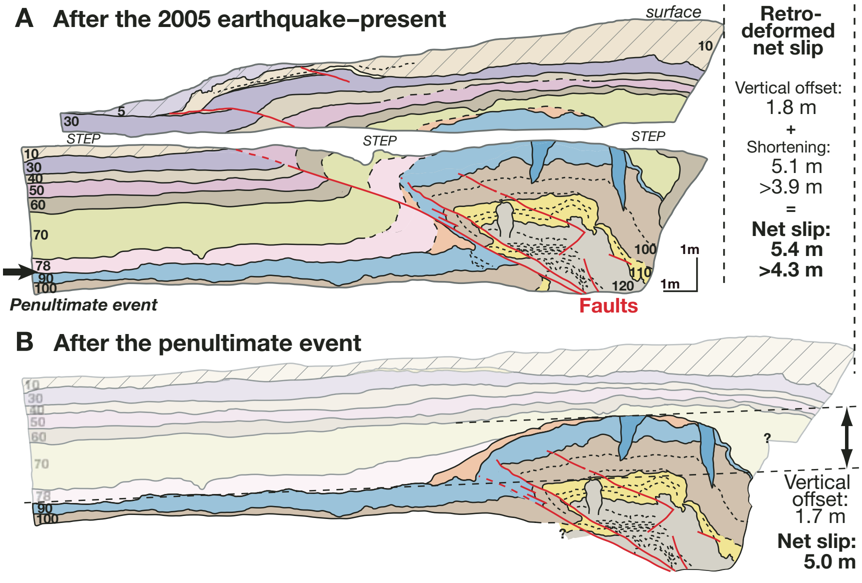

Figure 4. Identification of events and retrodeformation. A: Logs of present fault structure exposed on the 2007 trench walls. Slip information was retrodeformed by subtracting and balancing the logs from B (see Table DR3 and description in GSA Data Repository). Measurement method is same as that of Tsutsumi et al. (2005). B: Schematic diagram after retrodeformation of the 2005 earthquake. Transparent units above unit 90 represent depositional units after the penultimate event. Penultimate faulting event occurred between units 90 and 80. Note that the deformation patterns through unit 120 to unit 90 are similar, implying that only 2005 earthquake and penultimate event produced surface faulting during deposition of those units.

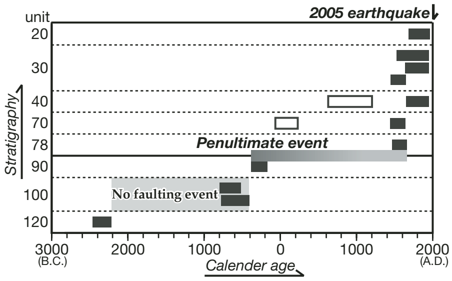

Figure 5. Summary of age constraints on penultimate event. Samples for each unit are selected to have no contradiction of stratigraphic order as shown in Table DR2 (see footnote 1). Black rectangles indicate calibrated ages for the younger carbon dating samples in 2σ ranges and white rectangles denote preferred older ages according to gradual deposition rate between unit 78 and unit 30 under the depositional environment around the site. Shaded rectangle represents timing of penultimate event. Note that age constraint for penultimate event is loosely constrained between 300 and 2200 yr B.P.; however, no other faulting events during past 4 k.y. are recognizable (see footnote 1).

earthquakes appear to have been associated with ~5 m of displacement (Fig. 4). It is our sense from these observations that the Balakot-Bagh fault accommodates less displacement in smaller earthquakes than observed along the simpler arcuate section of the Indo-Asian collision zone to the west.

In addition, our estimation on a geological slip rate of ~3 mm/yr obtained from trench data suggests that the source fault of the 2005 event is a significant, but not the major structure accommodating convergence over ~10 mm/yr (e.g., Bettinelli et al., 2006; Wesnousky et al., 1999; Lave and Avouac, 2000; Bilham et al., 1997) across the Indo-Asian boundary at this longitude (see also detailed explanations in the GSA Data Repository). Southeast of the 2005 epicentral area, a large earthquake (Mw 7.6) occurred in A.D. 1555 near Srinagar (Ambraseys and Jackson, 2003). This event was probably generated by the Himalayan Frontal fault and released the accumulated strain across the Himalayan arc (Ambraseys and Jackson, 2003). Since then, strain equivalent to an Mw 8 earthquake with slip >6 m has probably accumulated in the 2005 rupture area (Bilham and Wallace, 2005). However, the size of the 2005 earthquake and the recurrence behavior do not seem to catch up with the estimated strain. It thus appears that the 2005 Kashmir earthquake has not released sufficient accumulated strain to significantly reduce the likelihood of other similar sized earthquakes in the region in the near future.

Another important implication of the present study is that a relatively small earthquake generated on an active intraplate fault, rather than on gigantic plate-boundary faults, can in fact cause severe damage with more than 74,000 deaths. For example, south of the 2005 earthquake, the Jhelum fault extends for ~40 km and appears to be an active regional fault (i.e., Kumahara and Nakata, 2006), although it did not rupture in 2005, and it was not expressed by seismicity. We lack paleoseismological data for the Jhelum fault; however, judging from Coulomb stress changes associated with the 2005 earthquake, the static stress on this fault increased following the 2005 event (Parsons et al., 2006). Extensive mapping of active faults and higher density paleoseismic and geodetic strain data would provide indispensable information in evaluating the long-term seismic risk to the region and understanding the seismotectonics of the complex margin of the Indo-Asian collision zone.

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