DATA REPOSITORY: Supporting data, detailed explanations and references for 'Long recurrence interval of faulting beyond the 2005 Kashmir earthquake around the northwestern margin of the Indo-Asian collision zone'

by

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NET SLIPS OF THE RECENT TWO EARTHQUAKES

Based on the strata exposed in the trenches, our best measurement of the net slip is 5.4 m for the 2005 earthquake (Fig. 4, Table DR-3). The amount of vertical separation in the trench for unit 60 through 30 is the same as the height of the coseismic scarp at 1.8 m. Horizontal shortening is estimated at 3.9 m for the ground and 5.1 m for the top of Unit 70 (Fig. 4, Table DR-3). These measurements yield a minimum net slip of 3.9 m and a best estimate of 5.4 m. Nearby the trench site, horizontal shortening of a row of fence posts was measured at 4.6 m (Loc. 147; Kaneda et al., 2008) and similar amount of space-geodetic estimates of 5.4 ± 0.6 m and 4.0± 0.7 m are also reported nearby the site (Avouac et al., 2006). Thus, the net slip estimate from the trench is in the range of field measurements and space-geodetic measurements just after the earthquake.

To estimate the net slip during the penultimate event, we subtracted the slips of the 2005 earthquake from cumulative offset and shortening of Unit 90 (Fig. 4, Table DR-3). The measurement method is the same as that of Tsutsumi et al. (2005). Because the deformation zone of the penultimate event is wider than the length of the trench, the horizontal shortening of 1.9 m is the minimum estimate for the penultimate event. Assuming the dip of the faults at 20 degrees, we can calculate a net slip of 5.0 m converted from a vertical separation of 1.7 m. Thus, we obtained vertical separation of 1.7 m, horizontal shortening of 1.9 m at the minimum and net slip of 5.0 m associated with the penultimate event.

DETAILED EXPLANATIONS ON AGE CONSTRAINT

As we briefly described, radiocarbon ages and historical accounts of the 500-year-old fort in Muzaffarabad loosely constrain the penultimate age range between 500 and 2200 yBP. If the actual age of the penultimate event is near the younger end of the range, it allows the possibility aperiodicity or clustering in the repeated occurrence of earthquake displacements at the site with interval longer than 2000 years (Fig. 5, Table DR-2). 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 about 2000 years at the site.

Based on our observation of geomorphic and geologic environment around the site, the latter case that the depositional age of Unit 78 is close to 2000 yBP is much more likely. The presence of soil development on sand-rich layers Units 78, 60 and 40 suggests the occurrence of several flood events separated by periods of quiescence greater than a few hundred years (Fig. 3, Table DR-2). In addition, the flood deposits seem to have seldom covered the site since the L1 terrace surface formation and the incision of Neelum River, because the site is located in an abandoned channel on the L1 terrace surface over 20 m higher than present riverbed (Figs. 2, DR-1). No drastic environmental or climatic change has been reported since the Younger Dryas in northern Pakistan and around the Himalayan range, except Little Ice Age in medieval times (e.g. Kamp et al., 2004; Lewis et al., 2005). Thus, it is very hard to accept that successive fluvial terraces L2 to L4 developed after the Little Ice Age (Figs. 2 and DR-1). Thick, over three meter, fine sediment above Unit 78 seems to have gradually deposited at the site since ca. 2200 yBP. In this case, the younger samples of ca. 300-400 yBP for Units 78 and 70, maybe 190 yBP for Unit 40 as well, do not represent the actual depositional ages, although it is difficult to constrain the reason.

SLIP RATE ESTIMATION BASED ON TRENCH DATA

Tentatively, a geological slip rate of 3–11 mm/yr is obtained from trench data with the assumption that the similar amount of net slip of the 2005 event is repeated at an interval between 500 and 2200 yr. The cumulative net slips of the recent two events since at least ~4000 yr alternatively yield ~3 mm/yr at the maximum. Though the estimates involve significant uncertainty, it is close to ~3 mm/yr based on the average interevent interval and the preferred age constraint on the penultimate event. This is in accord with slip rate estimate at 1.4–4.1 mm/yr based on deformed fluvial terraces by Kaneda et al. (2008). Thus, the slip rate is close to an order of magnitude less than the geodetic rate of ~14 mm/yr near our study area (Bettinelli et al., 2006), and the geologic shortening rate of over ~10 mm/yr (Wesnousky et al., 1999; Lave and Avouac, 2000; Kumar et al., 2001) and the geodetic rate of ~20 mm/yr across the central Himalayan arc (Bilham et al., 1997; Wang et al., 2001).

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Captions

TABLE DR-1. LITHOLOGICAL DESCRIPTIONS OF UNITS.

TABLE DR-2. RADIOCARBON DATES. Dating was carried out by the accelerator mass spectrometry method. Calibrated ages are shown in ranges that represent one sigma and are based on the calibration program OxCal3.5 (Ramsey, 2000) and the dataset of Stuiver et al. (1998). E and W represent the walls of the 2006 trench, and W2 means the western walls of the 2007 trench. 'Lab. Code' indicates job number used by Beta Analytic Co. Ltd. Stratigraphically contradict dates are in Italic. Dashed and solid horizontal lines indicate stratigraphic units and the penultimate event horizon, respectively. The $\Delta\,^{13}C$ value with an asterisk denotes a sample for which the value is unavailable and assumed to be –25.0 ‰.

TABLE DR-3. SUMMURY OF SLIP MEASUREMENT.

Figure DR-1. Geomorphological map around the trench site. Solid yellow lines denote boundaries of geomorphological units. Base map of CORONA satellite photo is after Kumahara and Nakata (2006). Tick marks indicate erosional scarp. Note that trench site is located on an abandoned channel on the fluvial L1 terrace surface, and fault traces exhibit branching with a front-migrated thrust and a concealed fault at the base of fold scarp cutting the L1 surface. We opened the trenches across the front thrust ruptured in 2005 earthquake. No visible rupture and deformation were observed at the base of fold scarp behind the trenches. The relatively complicated fault traces around the site are probably related with the curving geometry of fault traces at lateral ramp and accordingly flexure, anticline and syncline develop on the fluvial terraces.

Figure DR-2. Photomosaics and logs of the 2006 trench walls. The grid interval in the figure is 1 m. Red lines indicate faults, and numerals denote stratigraphic units including artificial deposits with hatched. The walls were originally inclined at ca. 60º, then we projected stratigraphic features to a vertical plane on the recorded logs. Radiocarbon dates are also shown (without yBP) and stratigraphically contradict dates are in Italic. See also Fig. 3 and Table DR-2 for dating samples. The east wall has been flipped to enable comparison with the west wall. Two faulting events, including the 2005 Kashmir earthquake, are identifiable. The penultimate event is distinguished from the 2005 event by cumulative monoclinal deformation below Unit 90, upward termination of faults and thickening of Unit 70 as growth strata. The faulting is specifically confined between the deposition of Unit 90 and Unit 80 which is interpreted as colluvium derived from the top of the scarp.

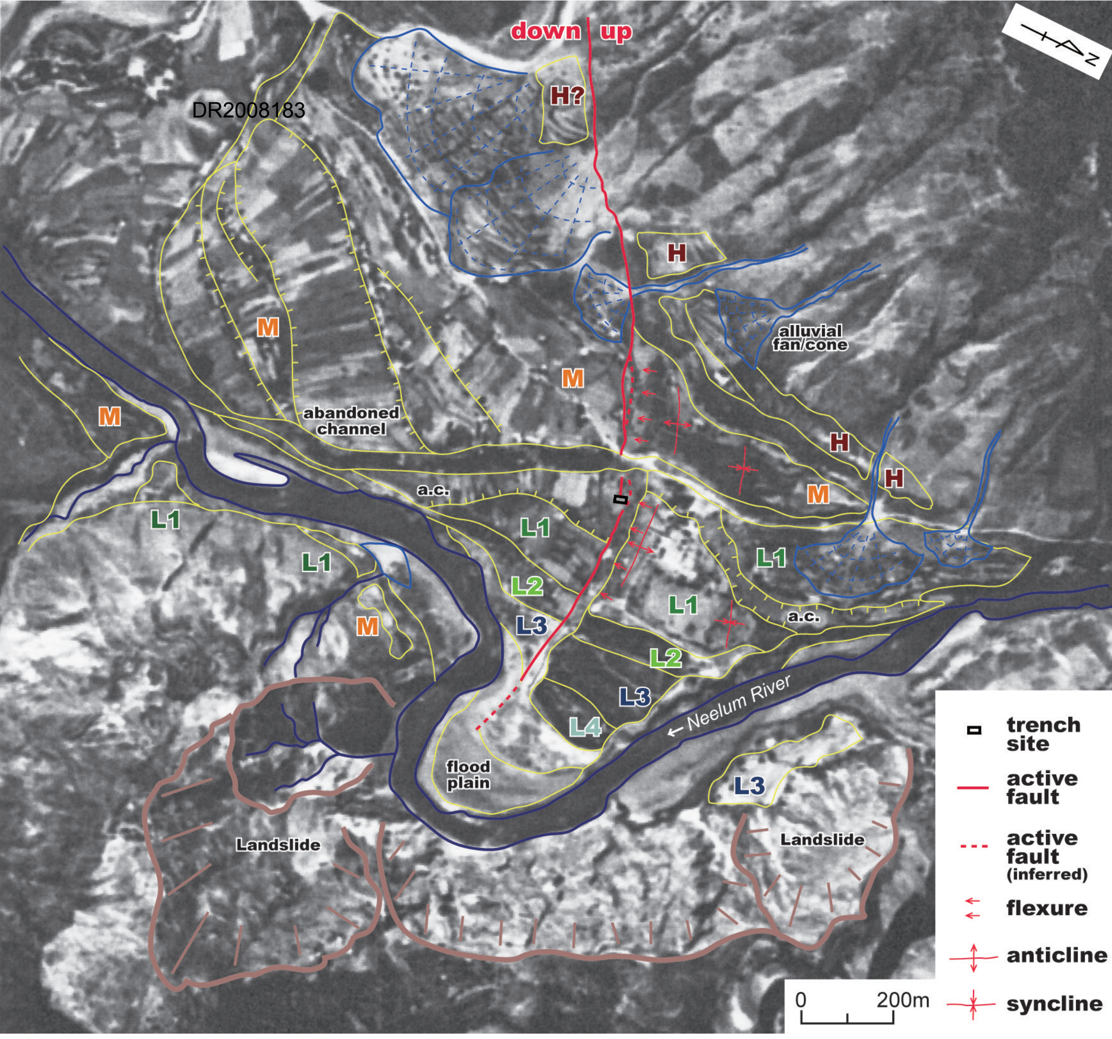
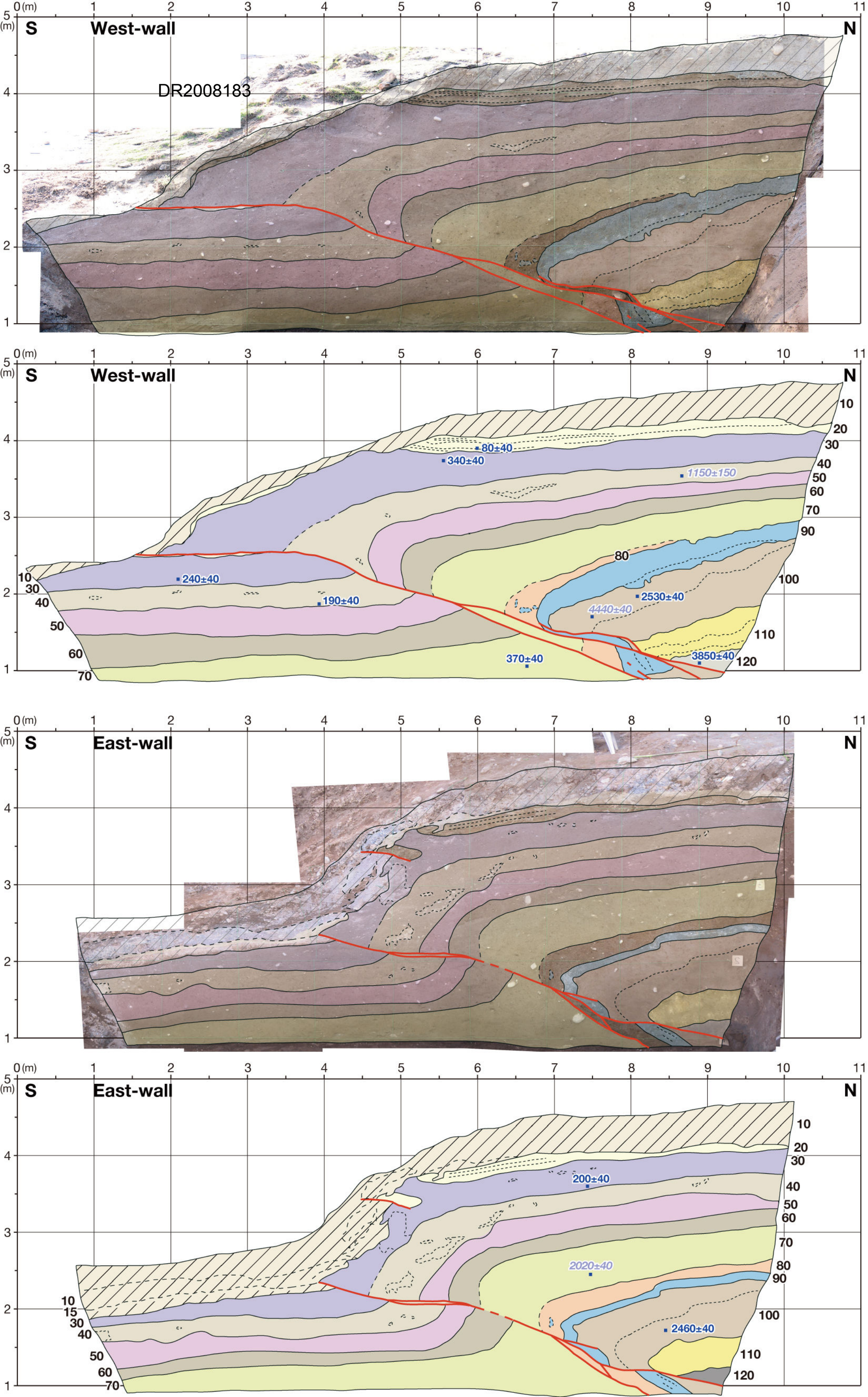


Fig. DR-1 Kondo et al.



S
West-wall
N
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0 (m)
1
2
3
4
5
6
7
8
9
10
11
5 (m)
S
West-wall
N
80±40
340±40
1150±150
240±40
190±40
4440±40
2530±40
370±40
3850±40
10
20
30
40
50
60
70
80
90
100
110
120
S
East-wall
N
S
East-wall
N
200±40
2020±40
2460±40
10
15
20
30
40
50
60
70
80
90
100
110
120

TABLE DR-1 LITHOLOGY AND DESCRIPTIONS

Unit	Descriptions
5	Colluvium after the 2005 earthquake, derived from artificial deposit.
10	Light gray artificial deposit. Very poorly-sorted sand and gravel. Pavement of road constructed before the 2005 earthquake.
15	Light brown artificial fill exposed just on the east wall of the 2006 trench. Poorly-sorted coarse sand and granules.
20	Laminated fine and medium sand to silt with humus. Exposed just on hanging wall side.
30	Yellowish light brown rigid sand with granules, partly including gray sand patches
40	Brown sand and gravel. Coarse sand and granule with pebbles and cobbles. Weak soil horizonation in uppermost part with pottery shards.
50	Brown massive sand, rarely including pebbles and cobbles.
60	Dark brown to black sand. Uppermost part is humic rich soil A horizon. Buried soil.
70	Brown loose, massive, well-sorted sand. Thickness of the foot wall is thicker than that of the hanging wall side. Groth strata.
78	Light brown to gray sand and granule with weak soil devellopment. Mainly exposed on foot wall side.
80	Very poorly-sorted sand with blocky patches derived from unit 90 sand & gravel. Matrix consists of medium to coarse sand. Partly includes cobbles. Colluvium.
90	Sand and gravel. Well-sorted sand, granule and sub-angular pebbles. Interbeded with silty sand.
100	Gray medium sandy silt. Divided into two sub-units; upper layer is silty and lower is sandy.
110	Yellowish sand and gravel composed of limestone. Very poor-sorted gravel with interbedded gray silty sand.
120	Black humic rich silty sand. Numerous bioturbation in uppermost part.

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TABLE DR2 RADIOCARBON DATES

Unit	Wall	Grid Cordinates (X, Y)	Lab. Code	Material	$\Delta^{13}C$ (‰)	**Conv. ^{14}C (yBP)**	Calibrated Age (1sigma)	Calibrated Age (2sigma)
20	W	6.00 - 3.90	217867	charcoal	-25.2	**80 ± 40**	AD 1950 - 1690	AD 1960 - 1680
30	E	7.54 - 3.60	215986	charcoal	-24.0	**200 ± 40**	AD 1950 - 1660	AD 1950 - 1640
30	W	2.10 - 2.20	217869	charcoal	-26.4	**240 ± 40**	AD 1670 - 1640	AD 1950 - 1530
30	W	5.56 - 3.73	217868	charcoal	-10.2	**340 ± 40**	AD 1640 - 1480	AD 1650 - 1450
40	W	1.78 - 3.97	217870	charcoal	-26.4	**190 ± 40**	AD 1950 - 1660	AD 1950 - 1650
40	*W*	*8.67 - 3.54*	*217821*	*charcoal*	*-25.0**	***1150 ± 150***	*AD 1020 - 690*	*AD 1200 - 620*
70	W	6.65 - 1.05	217872	charcoal	-13.0	**370 ± 40**	AD 1630 - 1460	AD 1640 - 1440
70	*E*	*7.58 - 2.45*	*215985*	*charcoal*	*-25.2*	***2020 ± 40***	*AD 30 - BC50*	*AD 70 - BC110*
70	*W2*	*2.22 - 2.65*	*230070*	*sediment*	*-16.9*	***4320 ± 40***	*BC 2900 - 2920*	*BC 2880 - 3020*
78	W2	8.44 - 2.52	230071	charcoal	-23.4	**300 ± 40**	AD 1650 - 1520	AD 1660 - 1470
78	*W2*	*10.80 - 2.53*	*230072*	*sediment*	*-17.4*	***5640 ± 220***	*BC 4270 - 4720*	*BC 3980 - 4990*
90	W2	18.00 - 4.02	230073	charcoal	-24.6	**2200 ± 40**	BC 200 - 360	BC 170 - 380
100	E	8.52 - 1.72	217874	charcoal	-26.6	**2460 ± 40**	BC 420 - 760	BC 410 - 780
100	W	8.09 - 1.97	215987	charcoal	-25.0*	**2530 ± 40**	BC 560 - 790	BC 520 - 800
100	*W*	*7.50 - 1.72*	*217873*	*humus*	*-21.1*	***4440 ± 40***	*BC 3020 - 3270*	*BC 2920 - 3340*
100	*W2*	*11.00 - 0.75*	*230074*	*sediment*	*-19.8*	***5200 ± 40***	*BC 3970 - 4040*	*BC 3960 - 4050*
120	W	8.90 - 1.10	215988	humus	-19.0	**3850 ± 40**	BC 2220 - 2460	BC 2220 - 2460

TABLE DR-3 SUMMARY OF SLIP MEASUREMENT

Top of Unit / Reference	Vertical separation (m)	Horizontal shortening (m)	Strike-slip offset (m)	Net slip (m)		Remarks
				dip=20º	VS+HS	
ground surface	2.2	4.6	0.6	-	5.1	A row of fence posts by Kaneda et al. (2008).
space-geodetic	-	5.6	-	-	5.6	1.9 km north of the site, with error of ± 0.6 m. by Avouac et al. (2006).
ground surface	1.8	> 3.9	-	5.3	4.3	Horizontal shortening is the minimum value.
70	1.7	5.1	-	5.0	5.4	Best estimate value from the trench data.
90	1.7	> 1.9	-	5.0	2.5	Substracting from cumulative. Shortening is the minimum value.