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Slip rate on the Kunlun fault at Hongshui Gou, and recurrence time of great events comparable to the 14/11/2001, Mw~7.9 Kokoxili earthquake

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Abstract

A field study of the surface rupture of the 14 November 2001, Mw~7.9 Kokoxili (or Kunlun Shan) earthquake near Hongshui Gou (35.9° N, 92.2° E), a site with exceptional geomorphic offsets long identified on SPOT images, yields bounds on this earthquake return time and on the slip-rate along the Kusai Hu segment of the Kunlun Fault. Measurements of the sinistral coseismic and cumulative offsets of four distinct strath-terrace risers and of rill channels incised in the adjacent fan bajada, complemented by post-earthquake, metric-resolution satellite image restoration, are 3 ± 0.5 m, 6 ± 1 m, 31 ± 2 m, 63 ± 5 m, and 110 ± 10 m. The smallest offset is unambiguously that of the 14/11/2001 earthquake. The 31 and 63 m riser offsets, which have thermoluminescence ages of 2885 ± 285 and 5960 ± 450 yr, respectively, imply an average slip rate of 10.0 ± 1.5 mm/yr, almost identical to that found 200 km eastwards, in Xidatan, using ^{10}Be cosmogenic dating of surface pebbles. The repetitive seismic slip (~3 m) implies an average recurrence time of 300 ± 50 yrs for earthquakes comparable to the 14/11/2001 event. This new data increases the body of evidence suggestive of local characteristic slip during large earthquakes and firmly corroborates the millennial eastward extrusion rate (1 cm/yr) of north-central Tibet relative to the Qaidam.

Keywords: Slip-rate; Characteristic slip; Earthquake recurrence; Kunlun fault; Tibet

1. Introduction

On 14 November 2001, a great earthquake (Mw~7.9) struck the Kokoxili region of the northern

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Tibetan Plateau [1–5]. It was the largest in China since the Zayu (or Assam) earthquake (Mw~8.6) of 15/08/1950, near the Sino-Indian border of southeast Tibet. Fieldwork and mapping using Ikonos satellite images [2,6,7] confirm that it ruptured ~430 km (Fig. 1A) of the western stretch of the Kunlun fault (mainly the

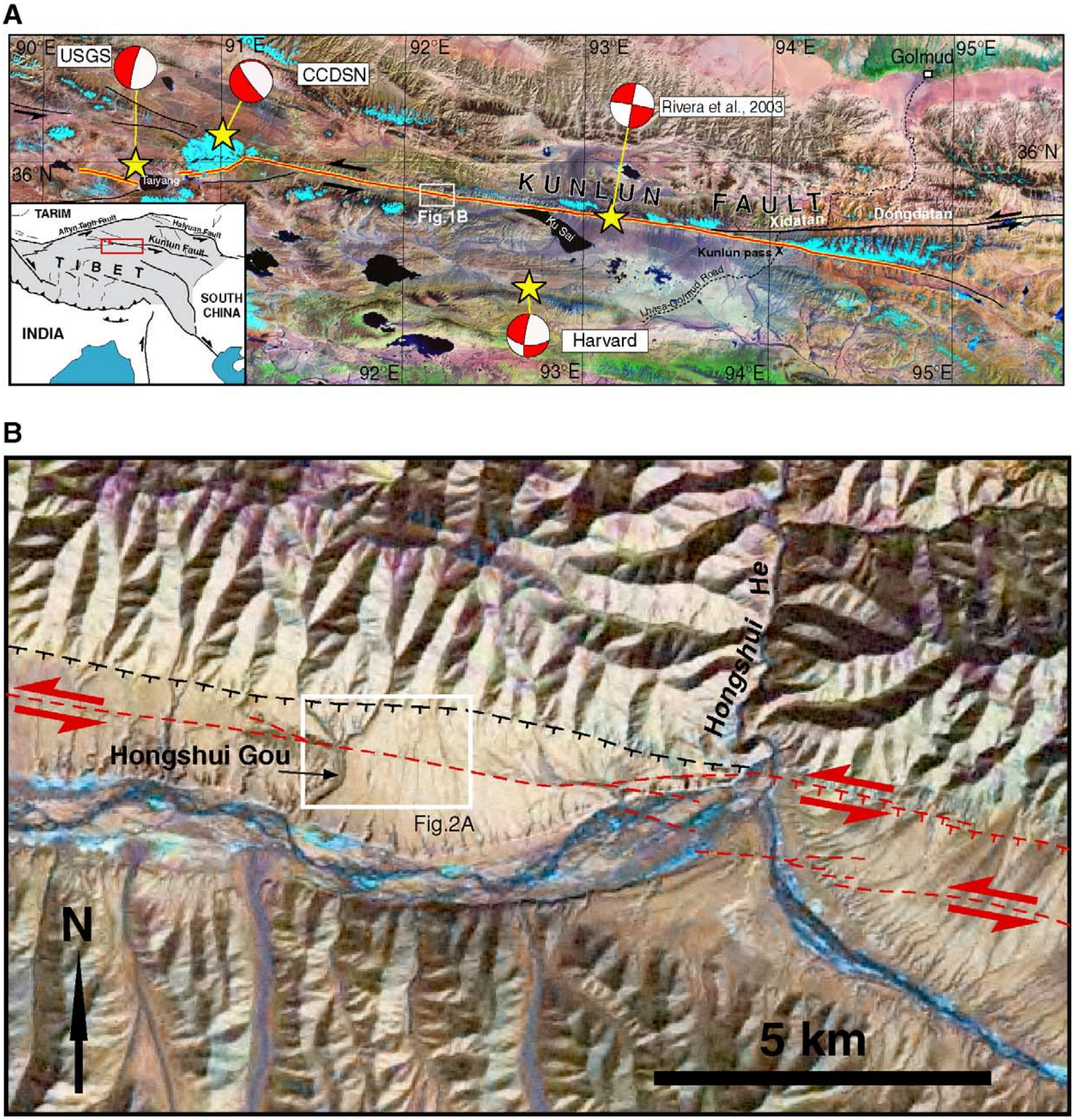


Fig. 1. (A) Simplified map of 2001, Mw = 7.9 Kokoxili earthquake rupture (red line), mostly along Kusai Hu segment of the Kunlun fault. Determined epicenters and centroids (indicated by stars) are located with corresponding focal mechanisms (USGS: US Geological Survey; CCDSN: Center of China Digital Seismograph Network). Inset is location of figure in framework of active Tibet tectonics. (B) Enlarged Landsat image of Hongshui He area. Box indicates location of site study area. Red dashed lines correspond to fault strands ruptured by Kokoxili earthquake. Note that Hongshui Gou site is located just west of termination of slip-partitioned stretch [3,7].

Kusai Hu segment). This rupture length (90° 10′ E to 94° 50′ E) ranks the earthquake as the largest strike-slip event in Asia, larger even than the Khangai–Bolnai earthquake of July 1905 in Mongolia.

The left-lateral Kunlun fault, which extends roughly east–west for about 1600 km south of the Kunlun Shan, contributes to the eastward extrusion of central Tibet relative to regions to the north (e.g., [8–10]). The slip rate on the fault has been a matter of debate, with early GPS studies implying present-day rates as slow as ≈6 mm/yr [11], and geomorphic dating, millennial rates about twice as fast: 10–12 mm/yr [9,12,13].

Like the North Anatolian fault in Turkey, the Kunlun fault is currently in an active phase of its seismic cycle. In the 65 years prior to 2001, five earthquakes of magnitudes between 6.3 and 7.6 had already ruptured different segments of the fault [8,14–16]. Two of these shocks were particularly large. The 1937 Tuosuo Lake earthquake ($M \approx 7.5$) ruptured the Dongxi Co (or Tuosuo Lake) segment of the fault, producing a 180-km-long surface rupture (97.5° E to 99.5° E), with a maximum left-lateral slip of 7 m [16]. The 1997 Manyi earthquake (M_w 7.6), four years only before the Kokoxili earthquake, produced a 170-km-long surface break (86° E to 88° E), also with a maximum slip of 7 m [15,17]. It ruptured a fault which we interpret to be one splay of the Kunlun fault horse-tail west of 91° E [9]. Although there is no historical event recorded on the Dongdatan–Xidatan segment of the fault (between the Kusai and Tuosuo lakes segments), cosmogenic dating of alluvial terrace surfaces and minimum riser offsets in Xidatan imply that this segment generates $M \approx 8$ earthquakes with a millennial return time [9,12,13].

In this paper we present a detailed analysis of the 2001 coseismic and cumulative offsets of terrace risers and stream or rill channels at Hongshui Gou, a particularly remarkable site on the Kusai Hu segment of the fault about 200 km west of the Kunlun Pass (Figs. 1B and 2). Although this site had long been singled out for its morphotectonic clarity on SPOT images [9,13,18], no detailed field study had been undertaken prior to the 2001 earthquake.

The offset values obtained in the field with standard techniques are corroborated and complemented by back-slip restorations performed with high resolution (1 m pixel) Ikonos satellite images, demonstrating for the first time the potential of such images to study quantitatively earthquake surface ruptures. Thermoluminescence (TL) dating of fine deposits (loess, in part reworked by wash, and silts) sampled a few tens of centimeters below the terrace surfaces, on top of the uppermost layers of gravels, yields bounds on the ages of abandonment of the terrace surfaces. Together with the offsets, the ages are used to constrain the time-integrated slip-rate at the site and to assess the average recurrence time of events comparable to that of November 2001.

2. Geological setting of the Hongshui Gou confluence, and 2001 earthquake rupture

At Hongshui Gou (about 35.9° N, 92.2° E), nearly 5000 m a.s.l., the Kunlun fault cuts the valley of two small tributaries of the Hongshui He, one of the rare large rivers to cross the Kunlun range and reach the Qaidam basin. Over a distance of ~3 km east of the confluence of these two streams, sinistral slip on the fault has produced a range of multiple cumulative offsets (Figs. 2A, B, and 3), the largest of which measurable on panchromatic, 10 m-resolution SPOT satellite images (Appendix B in [9]).

Investigation of the 2001 earthquake surface rupture along this stretch reveals spectacular coseismic deformation (Figs. 2B, C and 4). In the field and on the Ikonos images (Fig. 2), the fresh, ~100° E-striking 2001 break precisely follows the well-defined, rectilinear, cumulative fault trace that was already clear on the SPOT images prior to the earthquake. Locally, the earthquake induced no obvious reactivation of the range-front fault (Fig. 1B) [3], in contrast with the spectacular slip-partitioning observed to the east [7,19]. Though fairly complex in detail, the rupture is essentially single-stranded. It is characterized by a ~10–15 m wide array of “en échelon”, anastomosing and overlapping, trans-tensional and tensional cracks, a feature typical of the breaks of many large strike-slip events (e.g. [17,18,20–22]). The right-stepping geometry of the cracks reflects the near-surface expression of nearly pure left-lateral slip at shallow depth (Fig. 2B, C and D). Shallow north-dipping accommodation thrusts are observed only at the base of the large cumulative scarp on the left bank of the Hongshui

Gou east stream (Figs. 2D and 5). Localized uplift, likely due to thrust warping parallel to the fault, is also visible south of the rupture on one of the highest and broadest terrace surface (T3), for a distance of at least 100 m (Figs. 2A and 5).

Incision by the streams exposes the geology of the fault zone in section. West of the confluence, the fault is nearly vertical and juxtaposes steep, folded and schistose Neogene red sandstones (N, Fig. 2A and C) that contain left-laterally sheared phacoids and

A

B

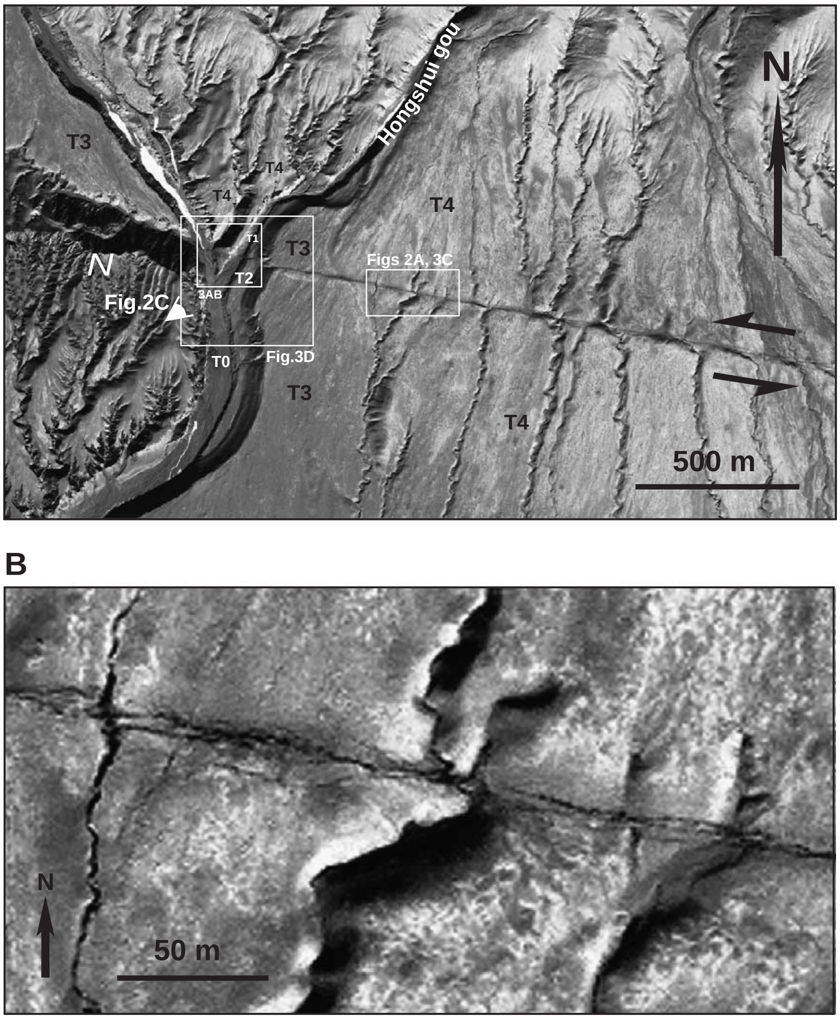
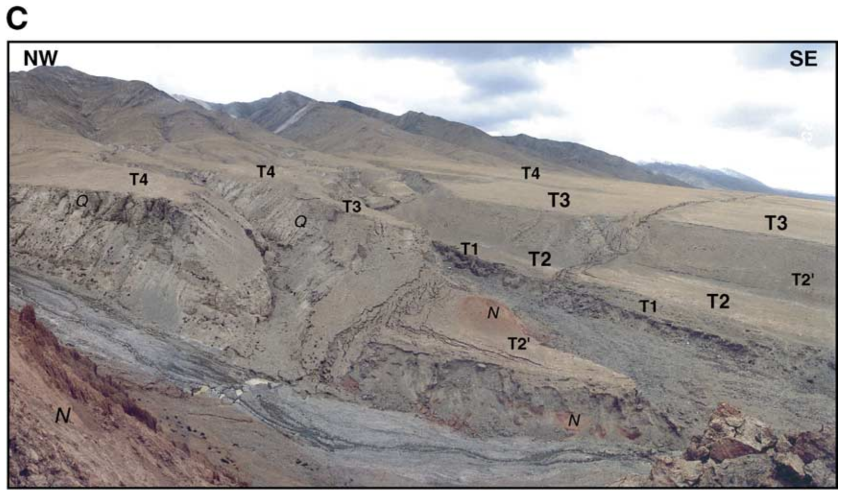


Fig. 2. (A) Ikonos image of Hongshui Gou site, taken less than two months after 14/11/2001 earthquake. High resolution, 1m-pixel size makes it possible to accurately map both earthquake rupture and cumulative geomorphic offsets. Boxes show locations of Figs. 2 and 3. (B) Enlarged Ikonos image (≈x10 relative to A) showing details of 2001 rupture along fault trace. Trans-tensional, mostly right-stepping cracks are visible along rupture zone. Note multi-metric offsets of even smallest streams. (C) View, looking northeast, of 2001 surface rupture across Hongshui Gou confluence. Ground shaking caused collapse of free-faced riser. Also note cracks parallel to most riser edges. Neogene red beds (N) are exposed beneath strath terraces T2, T2′, T2″ and T3 south of the fault. Distinct terrace levels are numbered. (D) Detailed field map of rupture zone and cracks superimposed on Ikonos image. Main rupture is outlined mostly by right-stepping cracks, but local thrusting and gentle fold up-warp occur south of rupture, east of stream. High-angle cracks following west side of steep risers south of fault trace may be related to distributed deformation and rotation away from main rupture zone.



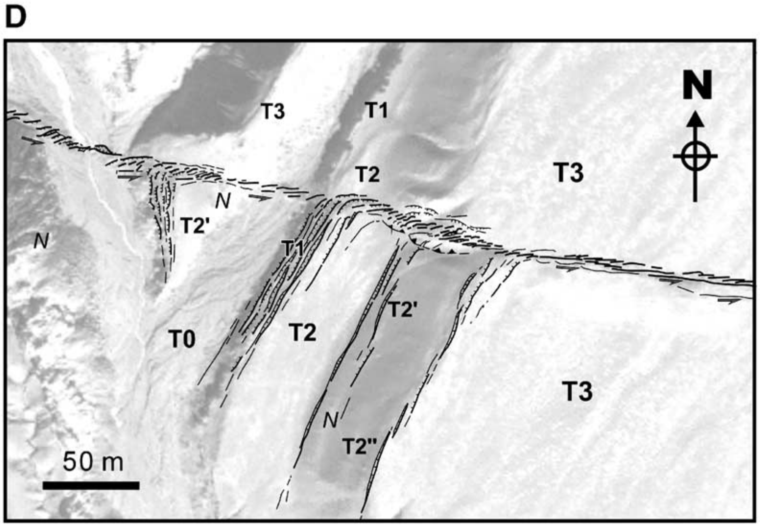


Fig. 2 (*continued*).

foliated cataclasites injected by pseudo-tachylite veins [23], to the south, with indurated, Quaternary conglomerates, gently inclined towards the south, to the north. The gentle dip of these well-bedded, fluvial conglomerates is depositional. They have accumulated as a result of damming by a growing fold, which warps and exhumes the older red beds, forming a push-up hill several tens of meters high south of the fault (Fig. 2A).

East of the confluence, the geomorphic landscape is simpler and dominated by a flight of inset terraces deposited by the eastern stream. We mapped as many as 6 terrace levels and sublevels (T1 to T4), of increasing elevation above the present-day stream bed (T0), (Figs. 2A, C, D, and 5). The brick-red Neogene sandstones crop out also in the interfluve north of the confluence, just south of the fault (Fig. 2C), where they have been partly abraded by the western stream and capped by a 1 to 2 m-thick layer of gravels whose top defines a strath terrace whose level is comparable to that of T2′ on the left bank of the confluence. Though largely covered by recent colluvium, Neogene red beds are still visible east of the confluence, especially beneath terrace levels T2′ and T3 downstream from the fault (Fig. 2C and D). This indicates that most, if not all, of the six

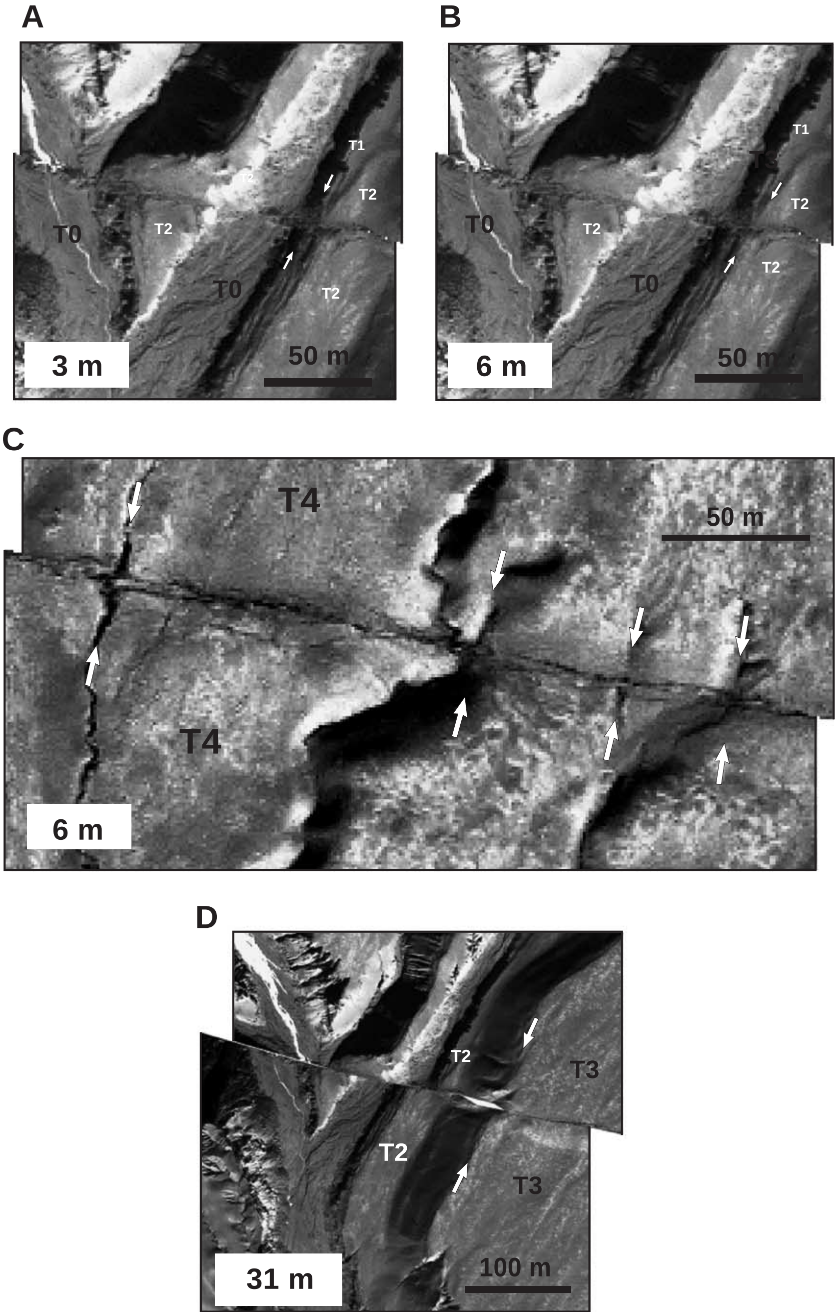


Fig. 3. Offsets confirmed by or deduced from Ikonos image backslip. (A), (B). 3 and 6 m offset reconstruction (white arrows) of T1/T0 and T2/T1 risers, respectively. (C) 6 m backslip also realigns small, short (hence young) gully channels on T4. (D) 31 m of backslip restore integrity (top, slope, and base) of T3/T2 riser. (E) 63 m of back-slip reconstruct continuity of T4/T3 riser, and of at least 2 rill channels east of it. (F) 110 m realigns four deepest and longest rill channels incised into T4, and other features farther east.

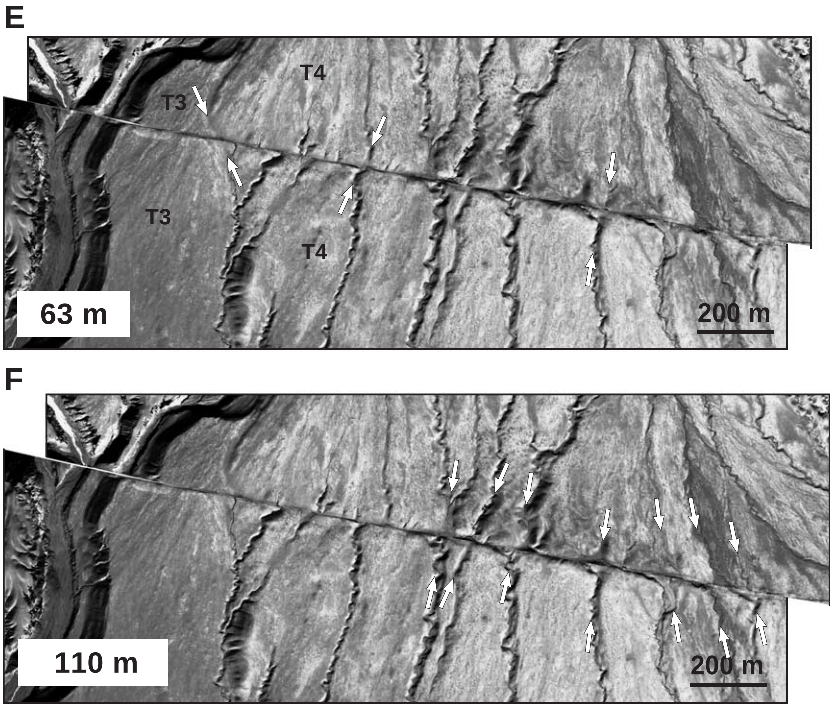


Fig. 3 (*continued*).

terrace levels and sub-levels emplaced south of the fault and east of the eastern stream at Hongshui Gou are strath terraces.

Due to strong ground shaking, parts of the steepest risers collapsed near the fault (Figs. 2C, D and 4). Such shaking probably also caused the formation of

Fig. 4. Field measurements of 14/11/2001 co-seismic offset, and of penultimate offset. Photograph, looking north, of T2/T1 and T1/T0 riser offsets. Riser tops are underlined. Offset of T2/T1 is twice that of T1/T0.

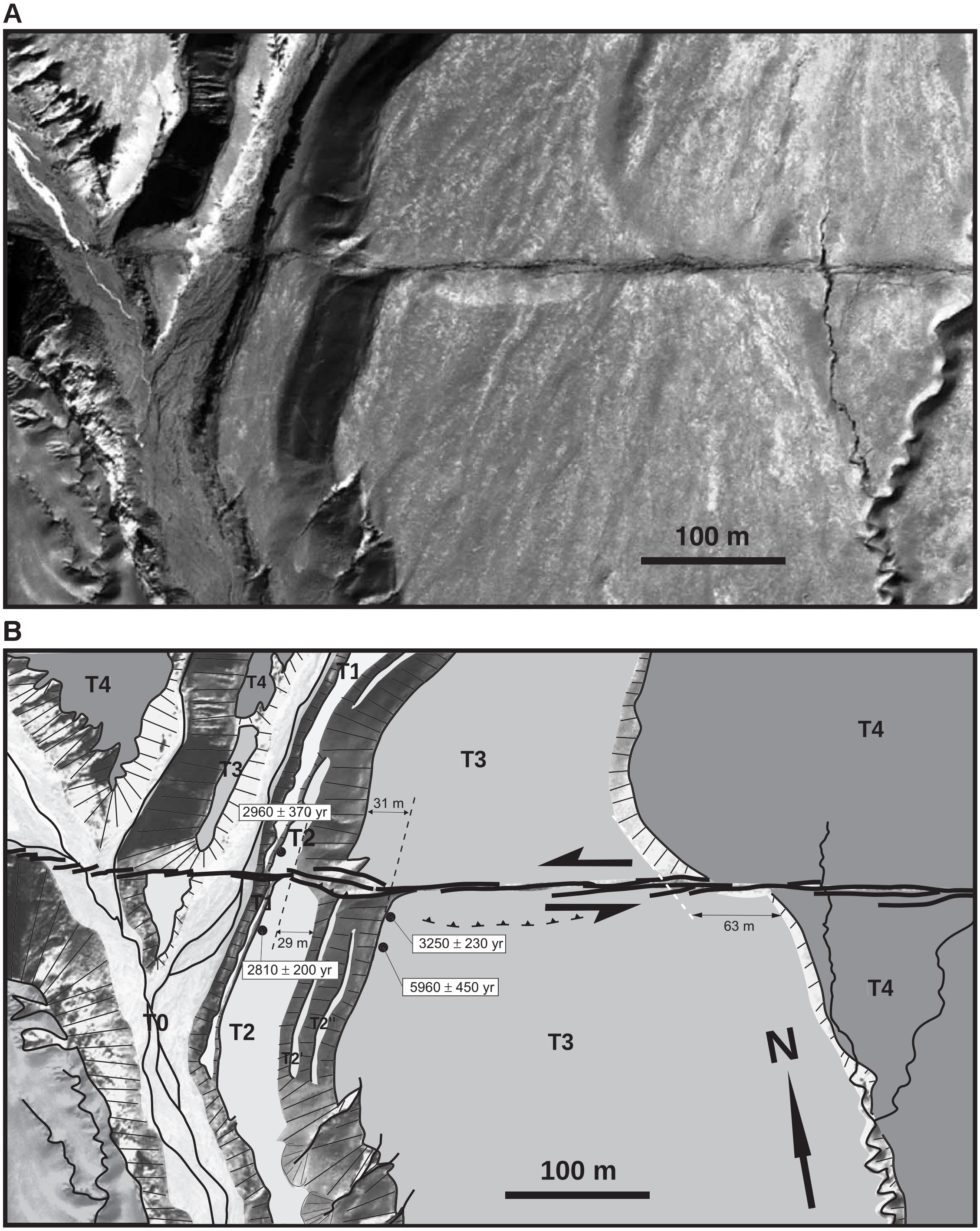


Fig. 5. (A) Enlarged Ikonos image of eastern part of Hongshui Gou confluence with (B) corresponding geomorphic field map, showing different terrace levels offset by the Kunlun fault. Black dots indicate locations of sampling pits for thermo-luminescence dating on T2 and T3, with corresponding ages.

the cracks that run parallel to the base or top of several risers, in the vicinity of the fault (Fig. 2C).

3. Quantitative geomorphic study: terrace riser offsets and inset terraces ages

3.1. Surface morphology and offsets

The four main terrace levels (T1-4) abandoned by the eastern stream at Hongshui Gou are well preserved east of that stream (color shades on Fig. 5). In classic fashion (e.g., [9]), terraces treads south of the fault were progressively displaced eastwards by sinistral slip, away from the downstream fluvial channel, as the eastern stream kept incising evenly north and south of the fault, becoming entrenched along the same course on the west side of the terraces (Figs. 2A and 5). The distinct terrace surfaces are remarkably smooth and flat, and can be unambiguously matched up and downstream from the fault (Figs. 2 and 5). They are separated by well-defined, linear risers, which are cleanly cut by the fault, providing a rare opportunity to use geomorphic techniques to quantify the time-dependent cumulative buildup of offset by successive earthquakes.

The local base level is the active flood channel of both streams (T0), across which the surface break was still pristine six months after the 14/11/2001 earthquake (Figs. 2C, D, 4 and 5). The next, youngest terrace level (T1), ~5 m above that channel, forms a narrow ledge along the steep, free-faced eastern bank of the eastern stream (Figs. 2C, D, 4 and 5). The corresponding T1/T0 riser yields the most useful piercing points to constrain co-(and post-, if any) seismic slip at Hongshui Gou due to the 2001 event.

The second terrace level (T2), though only ~1–2 m above T1 and separated from it by a more gentle, degraded riser, is clear from the distinctive veneer of fine, light-beige deposits that covers most of it (Figs. 2C, D, 4 and 5). This level is more than twice as wide south than north of the fault, implying that stream incision stalled for a significant period of time.

The smooth slope of the ~15 m-high riser that separates T2 from T3 is mantled by colluvium. Downstream from the fault, this west-facing slope is beveled by two narrow benches which correspond to two additional terrace remnants, T2′ and T2″, ~5 and ~10 m, respectively, above the level of T2 (Figs. 2C, D and 5). The existence of these two isolated, abandoned shoulders, which have no match immediately upstream, provides evidence for rapid riser demise due to left-lateral slip. The top and base of the T3/T2 riser can be unequivocally traced or linearly extrapolated to the fault trace, providing a pair of good piercing points. The very broad surface of T3 is streamlined with shallow channels that trend parallel to the eastern stream where it crosses the fault (Figs. 2A and 5A). It is covered with a layer of light-beige deposits (mostly wind-blown loess), which is thicker and less patchy than that observed on T2 (Figs. 2C and 4).

The highest terrace (T4) is separated from T3 by a smooth riser, 4–6 m high, whose base is followed by a fairly wide, flat-floored channel that veers into a broad S-shape upon crossing the fault (Figs. 2A and 5). South of the fault, this channel has been partly rejuvenated by regressive erosion. Smooth streamlines on T4 diverge away from the outlet of the eastern stream at the range front, indicating that this terrace surface, which is locally the highest, was emplaced as a piedmont fan. There is no major riser east of T4/T3 (Fig. 2A). Together, these geomorphic characters testify to a fairly long period of widespread deposition onto a broad, open piedmont bajada surface at the foot of the range, with only moderate incision prior to the abandonment of T3. Accordingly, the S shape of the T4/T3 riser implies that, as the stream stayed at a steady level for a significant period of time, lateral cutting along the eastern edge of the T3 floodplain was able to smooth the dogleg offset accumulating as a result of repeated earthquakes.

The surface of T4, and of the adjacent fan bajada to the east, is incised by deep, meandering gullies or rills of different depths, sizes, and consequently, ages. All of them are younger than the bajada and result from headward retreat of new catchments. All have been cut and displaced by left lateral motion on the fault, recording the largest cumulative offsets observed near the site (Figs. 2 and 3).

The principal risers mapped on Fig. 5 (T1/T0, T2/T1, T3/T2 and T4/T3) show increasing amounts of offset, as expected, as one follows the fault trace eastwards. The smallest offset, of the youngest riser (3 ± 0.5 m), (Figs. 2C, 3A and 4), is that due to the

Kokoxili earthquake. No modification of that riser's offset due to summer flooding had yet occurred when the site was first visited by one of us (LH) in 2002. The uncertainty on the measurement (made with a tape in the field) is principally due to cracking, and to collapse of the riser's free face near the rupture. The field measurement is consistent with the number obtained by restoring the rectilinearity of T1/T0 on the Ikonos image (Fig. 3A). A slightly smaller amount (2.5 m) is found on the less well-defined left bank of the western stream (Fig. 2C).

The sinistral offset of the next riser east of the stream, T2/T1, is 6 ± 1 m in the field (Figs. 2B, C, 3B, C and 4). Back slipping by this amount restores not only the continuity and alignment of this riser across the fault trace (Fig. 3B), but also that of four young rills, which have retreated only about 50 m north of the fault on T4 (Figs. 2B and 3C). We interpret these 6 m offsets to represent the cumulative slip of the 2001 and penultimate earthquakes. The existence of the latter event is manifest in the field from the CCW swing of the rill channels near the fault, a deviation clearly anterior to the sharp breaks of the 2001 earthquake.

In the field, the offset of the distal edges of the colluvial wedges at the base of the T3/T2 and T3(T2″,T2′)/T2 risers is 29 ± 2 m (Fig. 5). That of the western limits of T3 is 31 ± 3 m. On the Ikonos image, 31 m of back-slip provides the best restoration of the entire slope of the T3/T2 riser from top to bottom (Fig. 3D). Although the smooth limit of the colluvium on T2 is not a very sharp marker and the T3/T2 riser-top north of the fault has been degraded by incision, the near coincidence of the three values makes the offset estimate rather robust, and imply that the incision of the entire riser height, including beveling and abandonment of the narrow, intermediate T2′ and T2″ benches downstream from the fault only, occurred quite rapidly. We conclude that the offset of the T3/T2 riser since T2 was abandoned is 31 ± 2 m.

Though it crosses the fault at a lower angle, the oldest riser, T4/T3, can be restored by a cumulative back-slip of 63 ± 5 m on the Ikonos image (Figs. 3E, and 5). Restoration of this amount of offset also realigns the channels of two fairly long-lived, regressive rills entrenched into T4, and of another one farther east (Fig. 3E).

Finally, the main channels of the three deepest rills on the bajada, which form a cluster of regressive catchments with headwaters at the range-front, about halfway between Hongshui Gou and the next large stream valley eastwards (Figs. 1B and 2A), are offset by 110 ± 10 m (Fig. 3F). This amount of back-slip restores the continuity of at least three similar channels to the east. Note that 110 m of sinistral displacement does not fully restore the rectilinearity of T4/T3 away from the fault, implying that offsets of even greater size, worthy of further study, are recorded in the surface morphology east of Hongshui Gou.

3.2. Dating of terrace abandonment

Four loess/silt samples were collected on T2 and T3 for thermoluminescense (TL) dating [24]. T1-1 and T1-2 were retrieved from T2, down and upstream from the fault, respectively (Fig. 5A). They were taken at the bottom of pits about 30 cm deep, above the terrace gravels. Both samples yield compatible TL ages of 2810 ± 200 yr and 2960 ± 370 yr, respectively (Table 1). T2-1 and T2-2 were taken on T3 at similar depth (~40 cm) south of the fault, also above gravels. They yield disparate ages of 3250 ± 230 yr and 5960 ± 450 yr, respectively (Fig. 5A, and Table 1).

We interpret the two TL ages on T2, which are similar within error, to reflect the age of abandonment of this terrace, which is 6–7 m above the present streambed, and take the average of the two values (2885 ± 285 yr) to date the abandonment. For T3, we take the older age (T2-2, 5960 ± 450 yr) to be that of abandonment of the terrace, and infer that the younger age (T2-1, 3250 ± 230 yr) is that of posterior, wind-blown loess, or of wash that ponded later on top of

Table 1
Thermoluminescence (TL) dating of 4 silt samples collected on top of the terraces T3 and T2 at Hongshui Gou site

Sample number	Equivalent dose (Gy)	Dose rate (Gy. a^{-1})	Luminescence age (ka)
T1-1 (T2)	11.48	0.00409	2.81 ± 0.2
T1-3 (T2)	10.59	0.00358	2.96 ± 0.37
T2-1 (T3)	13.53	0.00416	3.25 ± 0.23
T2-2 (T3)	25.43	0.00427	5.96 ± 0.45

Processing of samples was completed in the Thermoluminescence Laboratory at the Institute of Geology of the China Seismological Bureau in Beijing. Age uncertainty is 1σ. TL testing systems were produced by Daybreak Co., USA.

the surface. While it is clear that the fine deposits capping T2 and T3 were not deposited by the stream, we did not date the gravels beneath. Hence, in a strict sense, the TL abandonment ages should be considered lower bounds.

4. Millenial slip-rate, characteristic slip and recurrence time of great earthquakes at Hongshui Gou

With the possible exception of the highest terrace, T4, which was emplaced as a fan, all the terraces south of the fault at Hongshui Gou are straths. Strath terraces, by definition, do not fill preexisting topography [25]. Hence, strath riser offsets usually do not predate the abandonment of the strath terrace at their base, which is the time at which they become passive markers of the displacement along the fault (e.g., Fig. 4 in [9]). The age of the 31 ± 2 m offset of the T3/T2 riser is therefore the abandonment age of T2 (2885 ± 285 yr). Similarly, the 63 ± 5 m cumulative offset of the T4/T3 terrace riser must have accrued since 5960 ± 450 yr BP.

After subtraction of the 3 m offset of the 2001 earthquake, the two offset/age ratios yield nearly identical slip-rate values of 9.7 ± 2 mm/yr and 10.1 ± 1.6 mm/yr, respectively. In the last 6000 yr, the average slip-rate on the Kusai Hu segment of the Kunlun fault at Hongshui Gou thus appears to have been constant and equal to 10.0 ± 1.5 mm/yr. This rate is close to that obtained at six other sites along three distant stretches of the fault towards the east (11.5 ± 2.0 mm/yr; [9]), (Fig. 6).

Because it is determined with an unambiguous piercing line, the 3 ± 0.5 m, 2001 offset of T1/T0 is better constrained than the somewhat smaller, yet compatible, value measured on the east bank of the western stream. Although this value is somewhat larger than the average seismic dislocation (2–3 m) deduced from inversion of seismograms along the western stretch of the rupture [5], and than other surface measurements reported on adjacent stretches of the fault between 92.1° E and 92.3° E (1.8 m) [1,2], there can be no doubt that it represents the sum of the 14/11/2001 earthquake co-seismic and post-seismic slip across the dated terraces whose riser offsets we use to determine the slip rate. A value of 3 ± 1 m, smoothed over patches of 5 × 5 km^2, is also locally deduced from radar interferometry [26]. The fact that five cumulative horizontal offsets turn out to be exactly twice as large, 6 ± 1 m (Figs. 2B, 3 and 4),

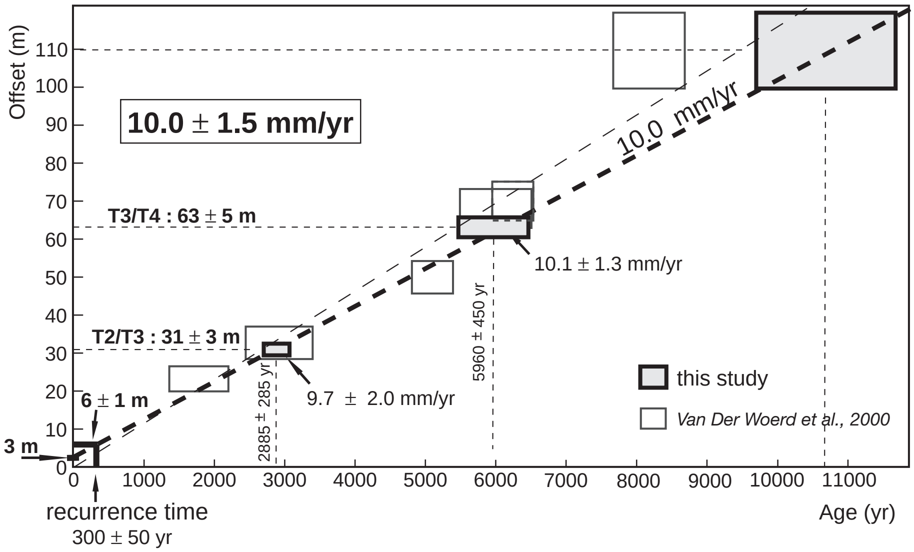


Fig. 6. Constraints on late Holocene left-slip rate on Kusai Hu segment of Kunlun fault. Shaded boxes (this study) define an average slip-rate of 10.0 ± 1.5 mm/yr in the last 6000 years, fully consistent with cosmogenic exposure dating of terrace riser offsets in Xidatan, eastwards along Kunlun fault (open boxes). Co-seismic (3 ± 0.5 m) and smallest cumulative offset (6 ± 1 m) imply locally characteristic slip, and repetition of large earthquakes with recurrence time of 300 ± 50 years.

implies that the penultimate event had the same amount of slip. We conclude that, at Hongshui Gou, the repetitive surface-slip of large events comparable to the 14/11/2001 earthquake is 3 m. Given the 10.0 ± 1.5 mm/yr rate, such great earthquakes (M_w 7.9, [27]) would recur every 300 ± 50 yrs, on average, with locally characteristic slip (Fig. 6).

5. Summary and discussion

From both a geological and geomorphic point of view, the qualitative and quantitative evidence for late Cenozoic and active motion on the Kunlun fault at Hongshui Gou is remarkable. Sinistrally sheared and folded Neogene red-beds are in vertical contact with Quaternary fanglomerates. Exhumed cataclasites within the strongly deformed Neogene indicate that the Kokoxili earthquake surface rupture follows a deep shear zone marking the southern edge of the Kunlun range.

Two distinct strath terrace riser offsets of different ages constrain the millennial, average slip-rate on the Kusai segment of the Kunlun fault to be 10 ± 1.5 mm/yr. Moreover, they imply that this rate has been constant in the last 6000 yrs. The rate obtained at Hongshui Gou is almost identical, within error, to those determined on three other segments of the fault, up to 800 km farther east (11.5 ± 2.0 mm/yr) [13,9]. This confirms that the Late Holocene left-lateral extrusion rate between Tibet and Qaidam is about 1 cm/yr (e.g., [9,10,12,13,28–30]), rather than half this value [11], in better agreement with recently reassessed GPS measurements (e.g., [31]). Note that this Holocene rate would also be compatible with the inferred lower range of long-term Pleistocene rates (10–20 cm/yr) [32].

As noted above, the fact that the TL dates obtained at Hongshui Gou come from silts sampled above fluvial gravels might be taken to imply that the abandonment ages we assign to the terraces are too young, which would result in overestimating the slip rate. But this is unlikely since the rate found just east of the Kunlun pass is 11.6 ± 0.6 mm/yr [9,12], and one would expect a slight increase in rate west of the junction with the Kunlun Pass fault (Fig. 1A). In fact, it is remarkable that the TL abandonment ages of T2 (2885 ± 285 yr) and T3 (5960 ± 450 yr) at Hongshui Gou coincide, within error, to the 2914 ± 471 yr and 5750 ± 650 yr abandonment age ranges of the corresponding T2 and T3 terrace surfaces in Xidatan and Dongdatan [9,12], (Fig. 6). Furthermore, using the rate found at Hongshui Gou to infer the age of T4 would yield 11 ± 1.5 ka, a value comparable to that found for the highest post-glacial fan level in Xidatan (12.6 ± 2.3 ka), and for another post-glacial terrace dated with ^{14}C west of Maqen (11.1 ± 0.16 ka) [9]. This is consistent with the geomorphic resemblance of the terrace flights in both places, T3 and higher levels being broad upper-surfaces above high risers, while T2 and lower levels, where present, are narrow ledges deeply inset into T3. It confirms that, in two areas 250 km apart, and in spite of local differences in incision rates, the landscapes responded to the same, regional climatic forcing [9], with abundant deposition triggered by post-glacial warming followed by stronger incision after the end of the Early Holocene optimum (e.g., [33]).

Correlatively, the comparison between Hongshui Gou and Xidatan–Dongdatan, provides another welcome reliability cross-test of two different dating techniques (Thermo-luminescence and $^{10}Be + ^{26}Al$ cosmogenic nuclides). Our new results confirm that neither method is biased since both yield compatible ages.

Our estimate of a regular recurrence interval of 300 ± 50 yr for events comparable to the Kokoxili earthquake of 14 November 2001, rupturing much of the length of the Kusai segment of the Kunlun fault, is based on the slip-rate derived from dated cumulative offsets of the left bank of the eastern Hongshui Gou stream combined with the measurement, using the same marker, of two identical coseismic slip-amounts, implying a locally characteristic slip of 3 ± 0.5 m. The penultimate earthquake likely occurred at the turn of the 17th century (1701 ± 50 AD), a time at which it would have gone unreported in a remote pastoral region then devoid of villages or religious shrines, accounting for the absence of a record in Chinese historical catalogs.

On two other segments of the Kunlun fault, the same approach has led to similar conclusions regarding seismic behaviour, i.e. stress relaxation on occasion of large, similar events occurring at regular intervals, even though the characteristic slip amounts, hence event size and recurrence time found differ. On the Xidatan–Dongdatan segment, both trenching results [34] and dated surface offsets imply the occurrence of four M ~8 earthquakes with 10 ± 2 m slip and 850 ± 200 yr return time in the last 4000 yr, the last one dating back to more than 300 yr ago (i.e., prior to ~1700 AD), while M ~7.5 earthquakes with 4.4 ± 0.4 m of slip likely recur every 420 ± 60 yr on the Dongxi segment farther east [9,12,13,35]. The Hongshui Gou example thus provides one more instance supporting the inference that very large earthquakes result from the cascading failure of fault patches whose individual slip functions are roughly invariant, even though not all earthquakes need be identical through consecutive cycles, because they may not rupture each time the same adjacent patches or segments, which yields the observed variability between earthquake sequences [36].

If supported by further study, the significant difference (by a factor of ~3) between the return times of great earthquakes on the adjacent Kusai and Xidatan segments of the fault would imply that rupture of the former does not always trigger that of the latter. That the Kunlun Pass area might correspond to a prominent barrier for rupture propagation is not surprising because this is the place where the active fault leaves the southern edge of the Kunlun range to penetrate into it. If triggering had not occurred in 1700 and in 1400, which the smoothed out surface deformation of T2 and lower terraces in Xidatan suggests, then the Xidatan–Dongdatan segment of the fault would really be on the very verge of slipping, a possibility whose likelihood is also strongly supported by the fast eastward propagation of rupture during the 14/11/2001 event [37], its dog-tail overshooting [38] of the Kunlun Pass junction, possibly a dynamic effect [39], and the increase in Coulomb stress produced east of that pass by the termination of rupture [1–3].

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Appendix A. Thermoluminescence dating

A.1. Laboratory sample processing

The fine grain method [40,41] was adopted for sample preparation. Samples weighing ≈ 100 g were crushed and sieved, using a 200 mesh, in a darkroom (red light). A ≈ 20 g portion of the sieved powder was set aside to measure the concentrations of radiometric uranium (U), thorium (Th) and potassium (K), to obtain the annual dose (AD). The rest was treated first with 30% H_2O_2 to remove organic matter, then with 50% HCl to remove carbonates and break up aggregates, and finally washed in distilled water 3 or 4 times. Fine grains in the range 4–11 μm were collected and dried in an oven at a temperature below 50 °C. From these grains, 24 sub-samples weighing ≈ 2 mg each were prepared for TL measurements, by deposition from acetone onto aluminum discs (10 mm-diameter, 0.5 mm-thickness).

A.2. Determination of equivalent dose (ED)

The "residual" luminescence method [42] was used to determine the equivalent dose (ED). TL emission was measured for 5 natural samples (N), 5 β-irradiated natural samples (N+βi), and 5 α-irradiated samples (N+αi). An average value was taken for each group. All TL measurements were made with the Daybreak TL System and in a darkroom (red-light). β irradiations were carried out using a 462.5×10^7 Bq,

$^{90}Sr/^{90}Y$ plaque source and α irradiations were made in vacuum using a 185×10^5 Bq ^{244}Cm α plaque source. The measurement error is about 10%. Each sub-sample was heated to 450 °C at a controlled heating rate (5 °C/s) in an atmosphere of ultra-pure nitrogen. The equivalent dose was measured every other 10 °C for each sample within the 200–400 °C range of glow temperature. A broad plateau was observed on the glow curve for all samples.

A.3. Determination of environmental dose rate (AD-Annual Dose) and TL ages

The environmental dose rate of the sample was calculated from the relationship between dose rate and U, Th and K concentrations [43]. The U and Th concentrations were measured using an α counter, and the K concentration, a flame photometer. Each sample was corrected for water content [44] and cosmic ray contribution [45]. The TL age were then derived from the equation t (ka) = ED / AD. All the measurements were done in the TL Laboratory at the Institute of Geology of the China Seismological Bureau in Beijing.

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