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Average Slip Rate and Recurrence Interval of Large-Magnitude Earthquakes on the Western Segment of the Strike-Slip Kunlun Fault, Northern Tibet

by Aiming Lin, Jianming Guo, Ken-ichi Kano, and Yasuo Awata

Abstract Interpretations of satellite remote sensing images, field and trench excavation investigations, and radiocarbon dates constrain the Holocene slip rate and average recurrence interval of large earthquakes on the western segment of the strike-slip Kunlun fault related with the 2001 M_w 7.8 Central Kunlun earthquake, northern Tibet. Streams and gullies developed on the alluvial fans having an average ^{14}C age of ~7000 years are sinistrally offset by up to 115 m along the Kunlun fault. This constrains a slip rate of 16.4 mm/yr for the past ~7000 years. Trenches and ^{14}C ages reveal that at least four seismic faulting events occurred in the past 6200 years and that the penultimate event prior to the 2001 M_w 7.8 earthquake occurred during the past 400 years with an average left-lateral offset of 4–5 m. Coupling the slip rate of 16.4 mm/yr with the average offset of 4–5 m produced by individual large earthquakes, it is estimated that the average recurrence interval of large earthquakes is 300–400 years on the western segment of the Kunlun fault. Our results confirm that the Kunlun fault plays an important role as a major strike-slip fault in accommodating the horizontal eastward extrusion of Tibet.

Introduction

Geological and seismological data increasingly demonstrate that most large earthquakes occur on pre-existing mature active faults, and these faults control the temporal and spatial displacement distributions and the rupture processes of large earthquakes (e.g., Lin *et al.*, 2002, 2003; Kikuchi, 2003). Thus, maps of active faults and related geological structures and tectonic landforms are good indicators of the locations, size, and frequency of future large earthquakes (e.g., Yeats *et al.*, 1997). Detailed studies of slip rate, which give a measure of the long-term activity of a fault, show that slip rates on many faults are uniform on timescales of one to several thousands of years (e.g., Sieh, 1984). Thus, knowledge of the long-term behavior of active strike-slip faults provides important information for seismic-hazard evaluation.

The 2001 magnitude (M_s) 8.1 (M_w 7.8) Central Kunlun earthquake occurred along the Kunlun fault, a typical continental strike-slip fault, northern Tibet, China (Lin *et al.*, 2002, 2003, 2004; Van der Woerd *et al.*, 2002a; Xu *et al.*, 2002) (Fig. 1). Field observations show that a 400-km-long coseismic surface-rupture zone with left-lateral offsets of 4–8 m and maximum 16.3 m occurred on the western segment of the Kunlun fault (Lin *et al.*, 2002, 2003; Lin and Nishikawa, 2006). Both the rupture length and maximum displacement are the largest ever reported for intracontinental earthquakes. Although some previous studies have been focused on the activity of the eastern segments (east of Kunlun Pass) (Fig. 1) of the Kunlun fault (Jia *et al.*, 1988; Zhao, 1996; Van der Woerd *et al.*, 1998, 2000, 2002b; Lin, 1999; Ren *et al.*, 1999), the activity of the 400-km-long western segment is still unknown because of the lack of field data in this remote mountain area.

In this study, we determine the average slip rate and recurrence interval of large earthquakes on the western segment of the Kunlun fault from field and trench investigations and interpretations of Landsat and 1m-resolution IKONOS images.

Activity of the Kunlun Fault

The study area is located in the central Kunlun mountain range, northern Tibet, with an average elevation of >4500 m (Fig. 1). The Kunlun fault strikes east–west to west-northwest–east-southeast over ~1200 km and is considered as one of the major strike-slip faults in accommodating both the northeastward shortening and eastward extrusion of Tibet (e.g., Tapponnier and Molnar, 1977; Meyer *et al.*, 1998; Wang *et al.*, 2001). On the basis of the geometry of the fault trace, the fault is divided into six principal segments 155–400 km long (Van der Woerd *et al.*, 2000) (Fig. 1). The 2001 earthquake ruptures the westernmost segment, called Kusai Hu segment (Fig. 1). The eastern five segments (Fig. 1) have a total length of ~800 km. From studies of satellite images, cosmogenic surface dating and radiocarbon

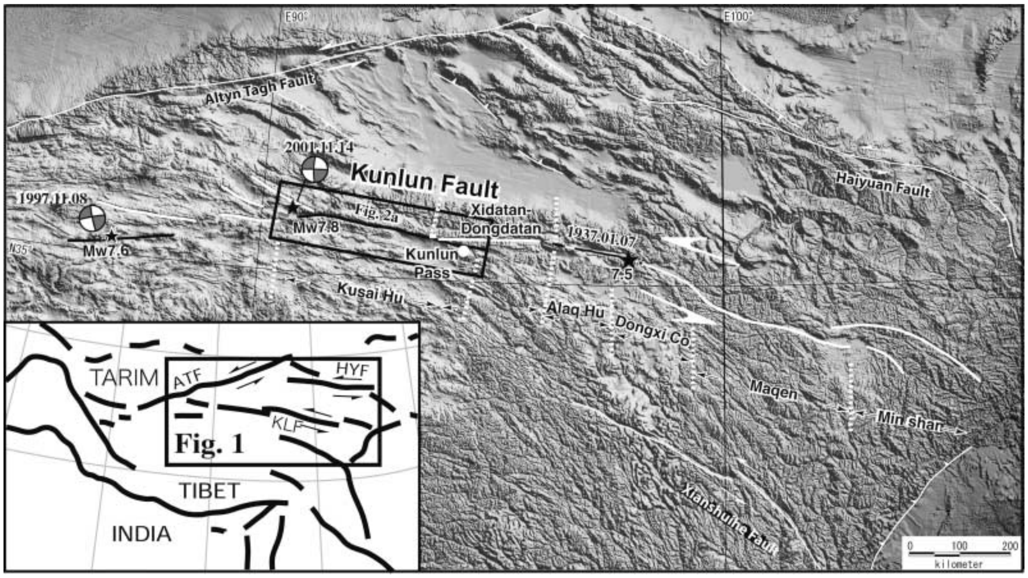


Figure 1. Satellite image showing the tectonic topography of Tibet and adjacent region of the Kunlun fault. Thin black lines from west to east indicate the surface ruptures produced by the 1997, 2001, and 1937 earthquakes, respectively. Beach balls show the focal mechanisms of the 1997 M_w 7.6 and 2001 M_w 7.8 (M_s 8.1) earthquakes. ATF, Altyn Tagh fault; HYE, Haiyuan fault; KLF, Kunlun fault.

dating (Van der Woerd *et al.*, 1998, 2002b), and trenching surveys (Zhao, 1996), the 800-km-long eastern five segments of the Kunlun fault have been inferred to have a Pleistocene-Holocene left-lateral slip rate of 11.5 ± 2.0 mm/yr.

In the study area, typical strike-slip geomorphology is well developed along the Kusai Hu segment as a straight lineament trending east–west to west-northwest–east-southeast on the satellite images (e.g., Tapponnier and Molnar, 1977; Kidd and Molnar, 1988; Lin *et al.*, 2002, 2003, 2004) (Figs. 1 and 2). High-resolution satellite images (Figs. 2 and 3) show that the south-flowing drainage system, south-sloping alluvial fans and terraces, and north–south-trending ridges are systematically deflected and offset along the Kunlun fault. Shutter ridges are well developed on the offset north–south-trending ridges. Streams developed on the alluvial fans are deflected or offset from 50 m to 115 m in the study area (Fig. 3). Offsets of gullies and stream channels of up to 1 km are also observed on the north of Kusai Lake (Kusai Hu, Hu means lake in Chinese) (Fig. 2c; Lin *et al.*, 2002, 2003; Van der Woerd *et al.*, 2002a). A Pleistocene average left-lateral strike-slip rate of 10–20 mm/yr has been roughly estimated for this segment (Kidd and Molnar, 1988).

Two large historic earthquakes ($M \geq 7.5$) that occurred in the past century produced obvious left-lateral offsets along the Kunlun fault. The 1937 M 7.5 Tuosuo Hu earthquake ruptured the 300-km-long Alag Hu and Dongxi Co segments of the Kunlun fault (between 96°E and 99°E; Fig. 1) with a left-lateral offset of 2–7 m (Jia *et al.*, 1988; Lin, 1999). The 1997 M_w 7.6 Manyi earthquake produced a field-measured 120-km-long surface rupture with a maximum offset of 4–5 m along a fault that is located in the southwest of the Kunlun fault and considered as a branch fault of the Kunlun fault system (Xu, 2000) (Fig. 1). A 170-km-long surface-rupture zone with a maximum left-lateral strike slip of 7 m was inferred from satellite synthetic aperture radar interferometry for this earthquake (Peltzer *et al.*, 1999). The 2001 M_w 7.8 Central Kunlun earthquake ruptured the 400-km-long Kusai Hu segment of the Kunlun fault between the 1937 Tuosuo Hu and 1997 Manyi rupture zones (Fig. 1) (Lin *et al.*, 2002, 2003, 2004). The surface-rupture zone consisted of numerous cracks, distinct shear faults, and mole track structures distributed within a zone ranging from 3 m to 550 m with an average left-lateral slip of 4 m to 8 m (Lin *et al.*, 2002, 2003; Lin and Nishikawa, 2006). Field investigations and seismological analysis reveal that the Central Kunlun earthquake had nearly pure strike-slip mechanics and that the temporal and spatial displacement distribution and rupture process are controlled by the pre-existing geological structures of the Kunlun fault (Lin *et al.*, 2003). No large historic earthquakes occurred along the Kusai Hu segment of the Kunlun fault before the 2001 earthquake. Based on cosmogenic and radiocarbon dates and field investigations, it is inferred that great earthquakes of $M \sim 7.5$–8.0 have occurred on the Xidatan-Dongdatan segment (Fig. 1) with an average left-lateral slip of 3–6 m (Guo *et al.*, 2006) and $M \sim 7.5$ on the Dongxi Co segment (Fig. 1) with an average slip of 4.4 m and an average recurrence interval of about 420 years, respectively (Van der Woerd *et al.*, 1998, 2000).

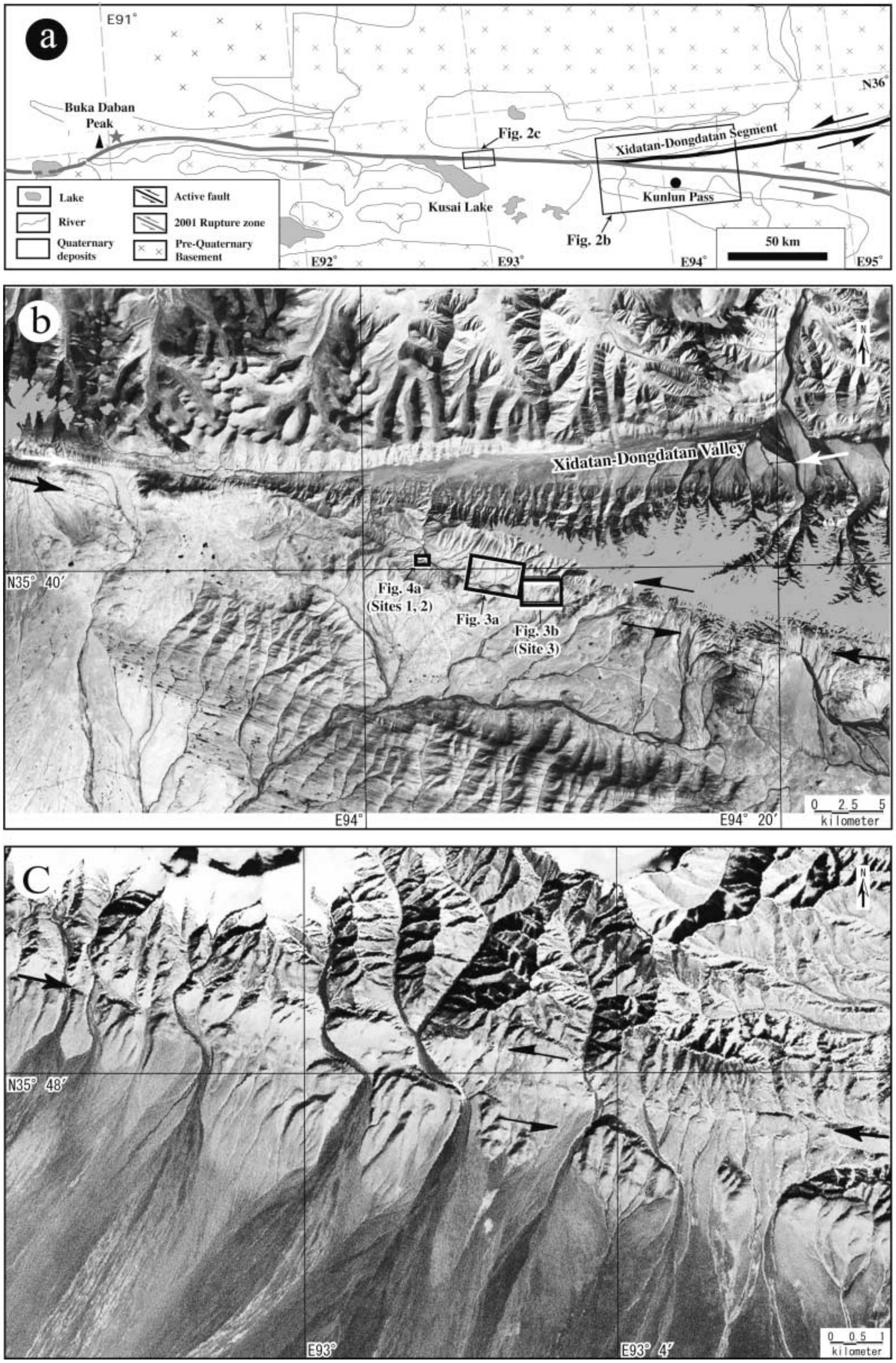


Figure 2. (a) Geological map of the central Kunlun area around the Kusai Hu segment of the Kunlun fault showing geological structures and the surface-rupture zone (black line) of the 2001 M_s 8.1 Central Kunlun earthquake (modified from Chengdu Geological Institute, Geological Academy of China, 1988, and Lin *et al.*, 2003). The star indicates the epicenter of 2001 earthquake (Lin *et al.*, 2003). (b) Landsat images of the study sites around the Kunlun Pass showing the topographic features of the Kunlun fault. Black arrows indicate the 2001 coseismic rupture zone. White arrows indicate the fault trace of the Xidatan-Dongdatan segment. (c) Landsat image showing systematic deflections of south-flowing streams along the Kunlun fault in the study area near north of Kusai Lake.

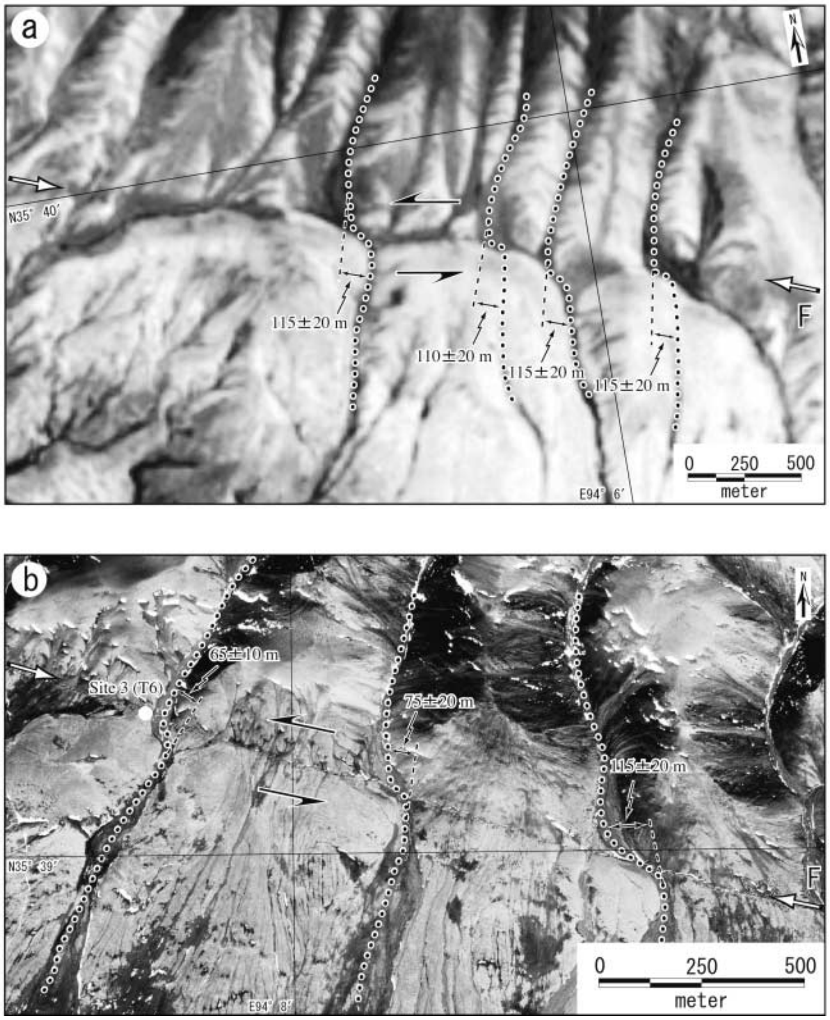


Figure 3. 15m-resolution ASTER image (a) and 1m-resolution IKONOS images (b) showing systematic offset streams and terraces in the area around site 3. The lines of filled circles show the stream channels where the offset amounts were measured. The offset amounts (white-black numbers) were measured using the method described by Maruyama and Lin (2000, 2002), and errors reflect uncertainties. Site 3, trench 6 (T6) excavation location. IKONOS and ASTER image data obtained after the earthquake on 7 October 2002 and 10 September 2002, respectively.

Trench Excavations

Three trench sites near Kunlun Pass (sites 1–3, Figs. 2–4) were chosen for the following three reasons: (1) the typical coseismic surface ruptures and pre-existing fault structures are well developed; (2) fine-grained alluvial deposits favorable for identifying seismic events were observed at outcrops near these sites; and (3) the mechanical shovel used for excavating could be transported to the sites. Near sites 1 and 2, the gullies developed on the alluvial fans are offset sinistrally about 3–7 m horizontally and 0.5–1.0 m vertically across both the 2001 rupture (Fa) and a pre-existing branch fault (Fb), which did not rupture during the 2001 earthquake (Fig. 4). Distinct fault scarps are observed on the alluvial fans along these two faults. Offset gullies and the vivid fault scarp along the Fb fault provide convincing evidence that another large earthquake occurred recently at this site prior to the 2001 earthquake. Four trenches (T1–T4) were excavated at site 1 on the sections across the 2001 surface rupture (Fig. 4c). Traces of the four trenches at site 1 were recorded on the 1m-resolution IKONOS image that was taken on 7 October 2002, one week after trenching (Fig. 4a). An additional trench (T5) was excavated at site 2 across the pre-existing fault scarp (Fb) on 3 September 2003 (Fig. 4). At both sites 1 and 2, the height of trench side (terrace surface) from the current streambeds is <2 m.

To date the alluvial fans into which the offset streams and gullies are incised for estimating the slip rate, a trench (T6) was excavated for collecting samples for radiocarbon dating at site 3 east of the Golmud-Lhasa Highway (Figs. 2b and 3b). Field observations show that this site is a more ideal place for collecting dating samples than other offset gullies in the study area because the fine-grained deposits with datable organic materials are cropped out at this site along the gully but not along the other gullies. The excavation at this site was made on a south-sloping alluvial fan (Fig. 3b) $\sim$8 m above the current streambed.

^{14}C Dating

Twenty-six samples, including 19 organic soil, 2 charcoal, and 5 peat materials, were collected for radiocarbon dating from the exposure walls in the six trenches (Table 1).

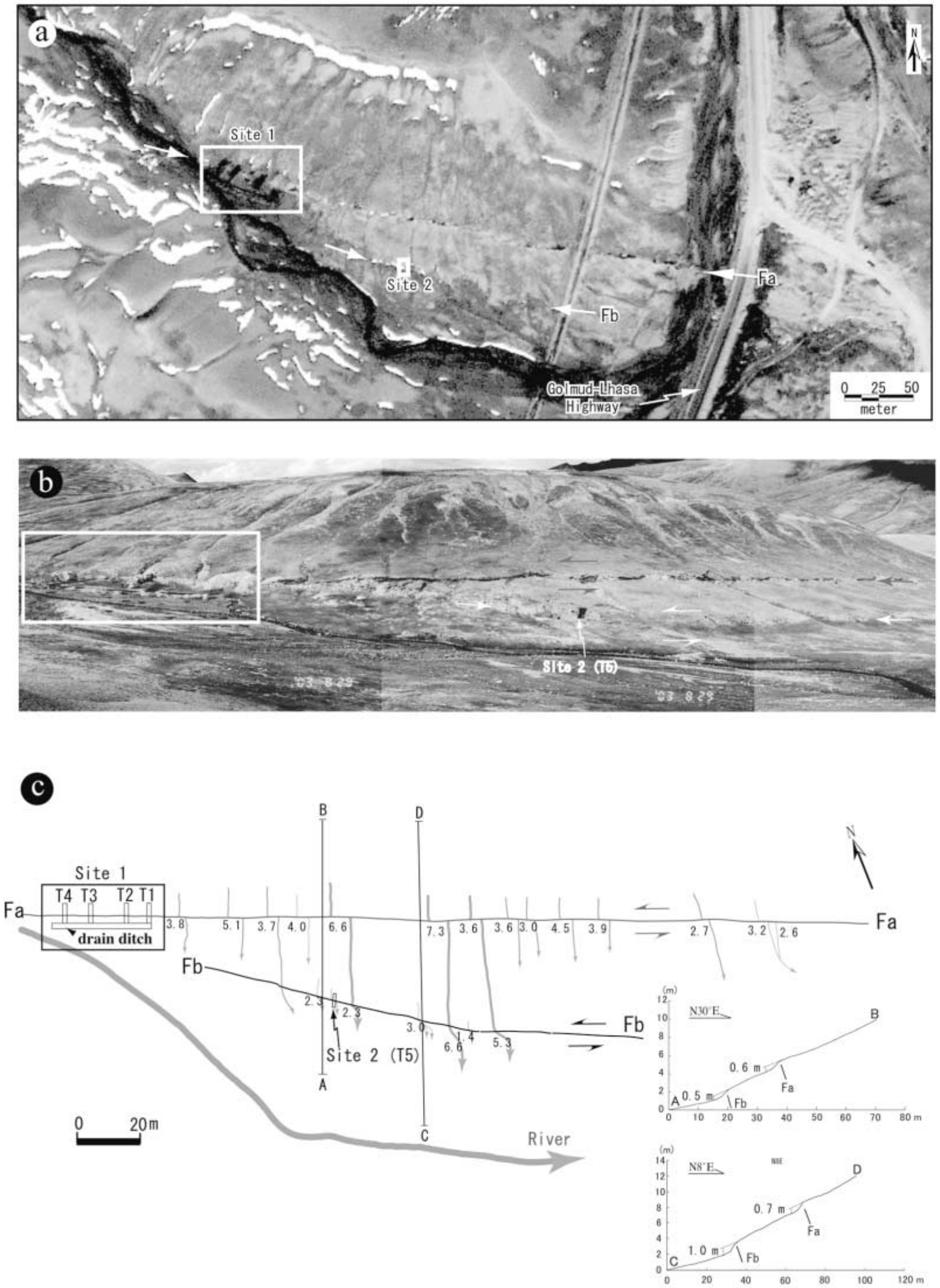


Figure 4. (a) 1m-resolution IKONOS image showing the topographic features of the Kunlun fault trace and trench locations in the area around sites 1 and 2. (b) Overview of sites 1 and 2. Four trenches (T1–T4) were dug on 30 September at site 1, which are recorded on the IKONOS image taken on 7 October 2002. Two distinct fault scarps are developed on the south-sloping alluvial fans along the 2001 coseismic surface rupture (Fa, indicated by red arrows) and the pre-existing fault (Fb, indicated by white arrows). (c) Sketch and topographic profiles (AB and CD) showing offsets (indicated by numbers of 2.3∼7.3 m) of gullies and fault scarps along both the 2001 coseismic surface rupture zone (Fa) and the pre-existing fault (Fb). A drainage ditch was dug for pumping water out of the trenches.

Table 1

Radiocarbon Dates from the Trenches

Sample Date-Code	Stratigraphic Unit	Laboratory ID*	Radiocarbon Age† (yr B.P.)	Calendar Date‡ (yr B.P.)	Description
020926-C03	2	4511	1,980 ± 47	1,822–2,041	organic soil
020926-C04	3	4512	3,888 ± 50	4,152–4,498	organic soil
030826-C05	5	Beta-175295	29,840 ± 320		peat
020926-C06	3	4513	3,851 ± 53	4,083–4,414	organic soil (charcoal)
020926-C07	1	4514	1,336 ± 52	1,145–1,347	organic soil
020926-C08	2	4515	2,209 ± 50	2,069–2,341	organic soil
020926-C11	5	4518	2,4836 ± 174		peat
020926-C12	3	4519	5,080 ± 65	5,660–5,930	organic soil
020926-C13	4	4520	6,185 ± 67	6,898–7,249	organic soil
030826-C14	2	Beta-175296	1,750 ± 40	2,545–1,812	organic soil
030826-C15	5	Beta-175297	23,660 ± 160		peat
020927-C16	1	4521	399 ± 44	317–519	organic soil
020927-C17	3	4522	5,480 ± 61	6,004–6,406	organic soil (charcoal)
020927-C18	5	4523	22,704 ± 216		peat
020927-C21	3	4524	3,306 ± 57	3,397–3,685	organic soil (charcoal)
030827-C22	5	Beta-175298	30,980 ± 350		peat
020927-C24	3	4526	5,791 ± 78	6,409–6,750	organic soil (charcoal)
030827-C25	5	Beta-175299	29,230 ± 290		peat
020927-C26	3	4527	4,919 ± 62	5,487–5,885	organic soil
020928-C28	2	4531	1,871 ± 54	1,632–1,927	organic soil
020101-C31	3	4533	6,979 ± 69	7,674–7,937	charcoal
020101-C33	3	4534	6,116 ± 63	6,762–7,206	organic soil (charcoal)
030829-C01A	4–6	5245	23,763 ± 118		organic soil
030829-C02A	6	5246	12,463 ± 55	14,158–15,432	organic soil
030829-C03A	6	5247	25,892 ± 132		organic soil
030829-C04A	1	5248	461 ± 32	472–539	organic soil

*Samples were analyzed at the Tono Geoscience Center, Japan Nuclear Cycle Development Institute (Laboratory ID: 4511-5248) and Beta Analytic Inc. (Laboratory ID: Beta-175295-175299).

†Radiocarbon ages were measured using accelerator mass spectrometry.

‡Calendar age dendrochronologically calibrated by method A from program of Stuiver *et al.* (1998), with 2 standard deviation uncertainty.

In general, the organic samples are dark brown and occur in thin lenses parallel to the sedimentary layers, with some visible charcoal. The charcoal samples consist of small carbonaceous pieces with other organic material. Vegetation in the vicinity of the study site is mainly composed of small grasses and lichens but no trees, and is therefore considered to be the source of the charcoal and organic materials. Thus, the ages of such organic materials should represent the true formation ages of the alluvial deposits. The peat samples were taken from a peat layer up to 1 m thick that is a continuous layer found in the T1 and T2 trenches. This thick peat layer indicates that there was a stable sedimentary environment like a small lake during its deposition.

^{14}C samples were analyzed at the Tono Geoscience Center, Japan Nuclear Cycle Development Institute (22 samples) and Beta Analytic Inc. (5 samples). ^{14}C ages were measured using accelerator mass spectrometry. Dendrochronologically calibrated calendar ages were obtained by using the program of Stuiver *et al.* (1998). ^{14}C-dating results are shown in Table 1.

Stratigraphy

Sedimentary deposits exposed in the trenches consist of unconsolidated alluvial gravel, silt-sand, peat, and permafrost, which can be divided into six major stratigraphic units from the top to the base in the trenches based on the component, structure, and ^{14}C age of deposits (units 1–6, Figs. 5–11).

Unit 1, the uppermost layer at sites 1 and 2, is composed of yellowish gray silt-sand that 0.5–1.5 m thick (Figs. 5 and 9). Unit 2, which is 0.3–1 m in thickness, consists mainly of fine- to medium-grained sand with some gravels and lenses of gravel layers. The gravels are mostly composed of pebbles of a few centimeters to 10 cm in diameter. In the top of this unit, there is a thin gravel layer that is 20–30 cm thick and is observed in the west wall of the T2 trench (Fig. 6b). Unit 3 is composed of interbedded coarse-grained sand and grave layers, 0.5–1.5 m thick. Locally, there is a gradation in deposits between units 2 and 3. The gravels vary in size from a few centimeters to 50 cm. There are some organic soil lenses with some charcoals in these three units which yielded ^{14}C ages of 400~1,400 yr B.P. in unit 1, 1750–2200 yr B.P. in unit 2, and 3300–7000 yr B.P. in unit 3, respectively (Figs. 5, 6, and 11; Table 1). Unit 4 is mainly composed of gravel with medium- to coarse-grained sand matrix, which is >2 m in thickness. The alluvial fans developed at site 3 are mainly composed of units 3 and 4 deposits. In contrast to the unconsolidated units 1–3, deposits of unit 4 are weakly consolidated. At the base of this unit, there is a thin lense of

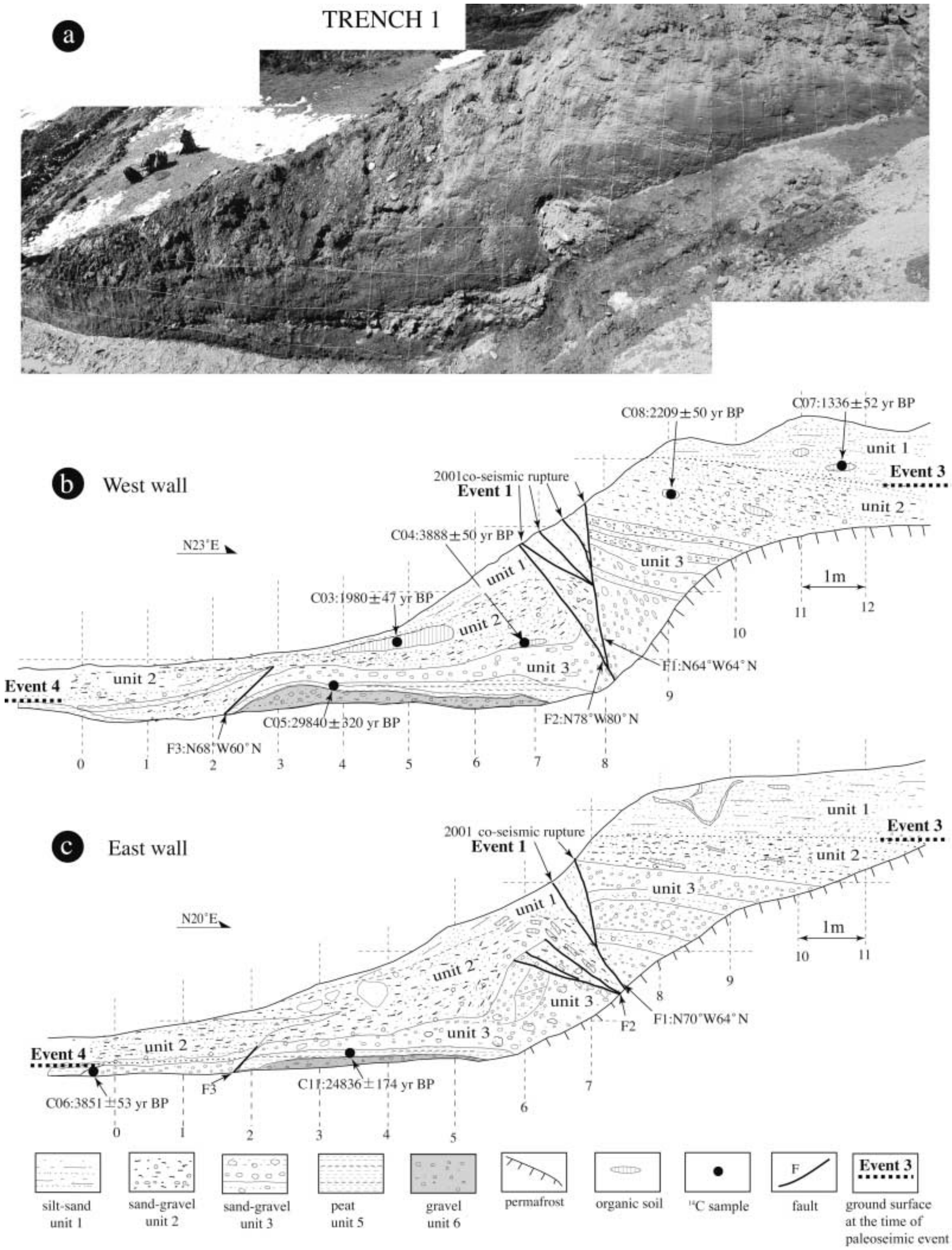


Figure 5. Photograph (a) and corresponding sketches (b), (c) of both walls of trench 1 (T1) across the principal 2001 coseismic rupture at site 1. Ages of samples are in radiocarbon year before present. Details on calibrations of all ^{14}C ages obtained in this study are shown in Table 1.

organic soil which yielded a ^{14}C age of 12,463 yr B.P. (C02A). Unit 5 is a peat layer up to 1 m thick which yielded ^{14}C ages of ~22,000–31,000 yr B.P. (Fig. 5; Table 1). Unit 6 is composed of permafrost sand-gravel which is developed at a depth of >1.5 m and was only exposed at about 30–50 cm thick in the trenches at sites 1 and 2 because the permafrost is too hard to dig. There are some small lenses of organic soil in unit 5 which yielded ^{14}C ages of 23,000–26,000 yr B.P.

Paleoseismicity

Both field investigations and seismological observations have shown that the coseismic displacement distribution is

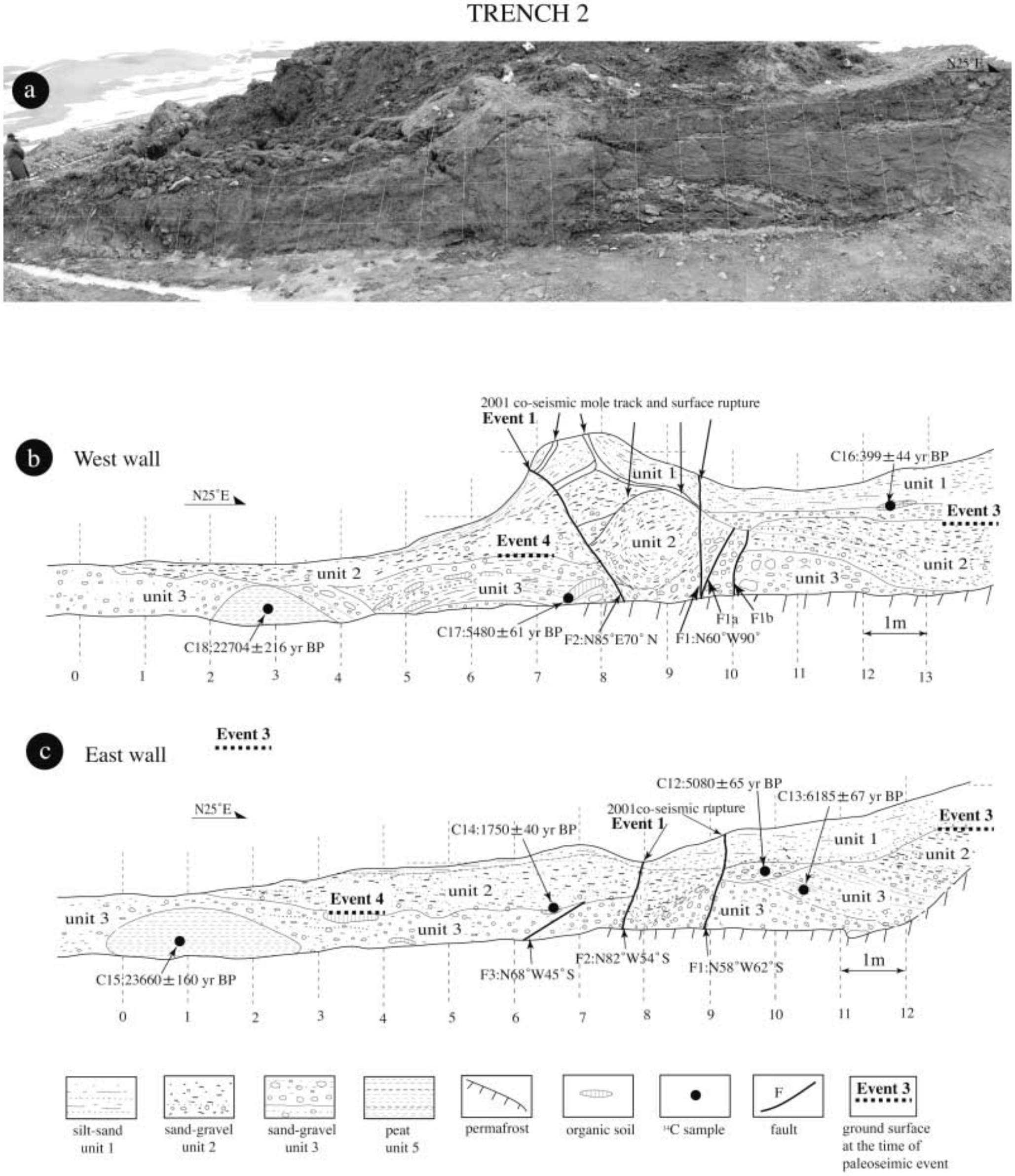


Figure 6. Photograph (a) and corresponding sketches (b), (c) of both walls in trench 2 (T2) across the 2001 coseismic rupture at site 1.

highly variable along the surface rupture produced by the 2001 earthquake (Lin *et al.*, 2002, 2003, 2004). In the study area, typical coseismic mole track structures and 4- to 8-m left-lateral offsets form a complex structural pattern of faulting and folding (Lin *et al.*, 2003, 2004; Lin and Nishikawa, 2006). In addition to the deformation features associated with the 2001 earthquake, we found evidence of prior deformation caused by at least four prehistoric faulting events during the past 6,200 years. We used three principal indicators of prehistoric faulting events: (1) upward termination of faults, (2) disturbance of deposits, and (3) deformation of young topographic surfaces such as alluvial fans and terraces related to faulting and folding.

Event 1

The 2001 Central Kunlun earthquake produced distinct surface ruptures including faulting and folding (mole track) structures that are well exposed in all the trenches (Figs. 5, 6, 7, 8, and 10). The alluvial fan surfaces are vertically offset by F1 and F2 faults. Mole track structures, in general, 0.3–1 m in height, observed immediately after the earthquake by Lin *et al.* (2003, 2004), are well expressed on the west walls of both T 2 and T3 trenches (Figs. 6b and 7c). Some extension cracks are also exposed on the west wall in the T4 trench where a small graben structure formed between F1 and F2 faults (Fig. 8b).

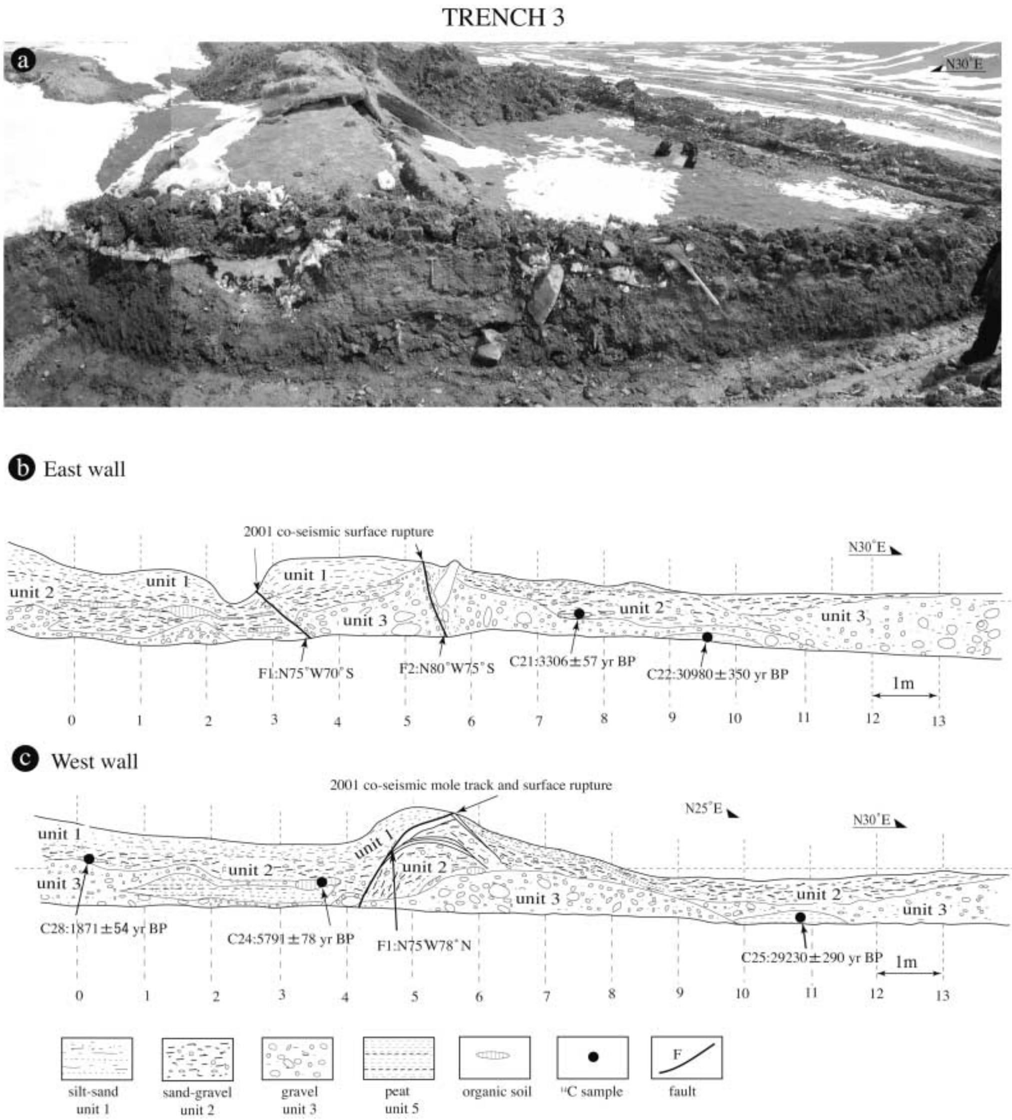


Figure 7. Photograph (a) and corresponding sketches (b), (c) of both walls of trench 3 (T3) across the principal 2001 coseismic rupture at site 1.

Event 2

The best evidence for the earthquake prior to the 2001 earthquake is exposed in the T5 trench, which was excavated across a distinct fault scarp (Fb, Fig. 4) that did not rupture in the 2001 earthquake (Fig. 9). The Fb fault trace joins the Fa fault to the west of the fault scarp (Fig. 4a). The fault scarp is 0.5–1.0 m in apparent height, comparable to that produced by the 2001 earthquake along Fa fault as shown in the topographical profiles (Fig. 4c). South-facing fault scarps are often observed along the strike-slip Kunlun fault and are best explained as a result of the strike-slip offset of the convex south-slopping alluvial fans (Lin *et al.*, 2003). The south-flowing gullies incised into the alluvial fans are offset 1.4–6.6 m (Fig. 4), comparable to the offsets (3–7 m) of gullies produced by the 2001 earthquake along the Fa fault (Fig. 4). It is clear that the left-lateral offsets of the small gullies and the fault scarp along the Fb fault were produced by an event prior to the 2001 earthquake. In trench T5, a main fault, fault F4, and some fractures cut throughout the top layer, but there was no distinct 2001 surface rupture observed immediately after the earthquake along this fault scarp by our group (Fig. 9). We therefore infer that the penultimate event produced the left-lateral strike-slip offsets, fractures, and the fault scarp along the Fb fault, but did not produce offset along the Fa fault. Samples from the top silt layer of unit 1 yielded ^{14}C ages of 399 ± 44 yr B.P. (C16, Fig. 6) and 461 yr B.P. (C04A, Fig. 9) to 1336 ± 52 yr B.P. (C07, Fig. 5). This indicates that the penultimate earthquake occurred during the past 399 ± 44 yr B.P.

Event 3

In trenches T1 and T2 (Figs. 5 and 6), the sand layers of unit 2 and gravel layers of unit 3 are tilted to the north at

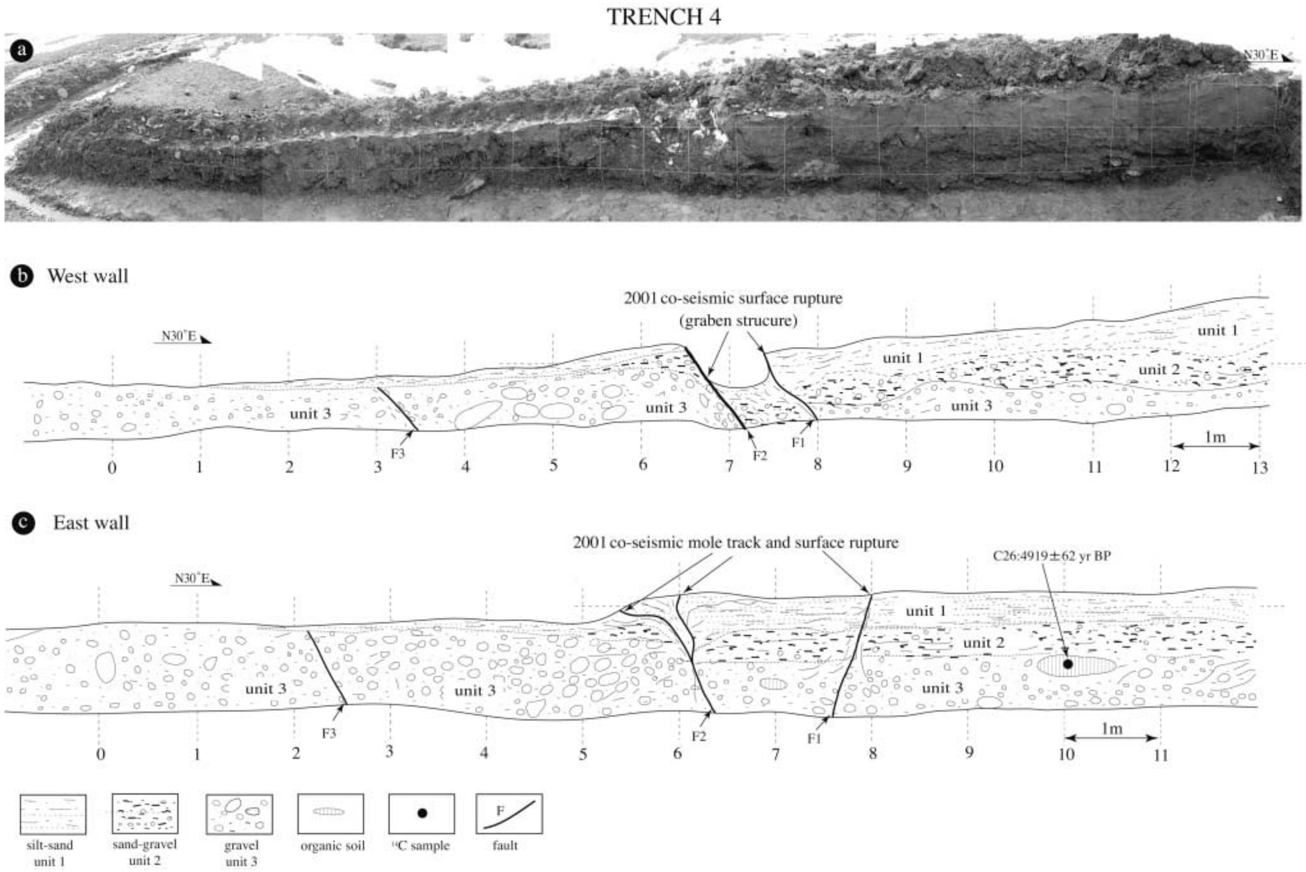


Figure 8. Photograph (a) and corresponding sketches (b), (c) of both walls of trench 4 (T4) across the principal 2001 coseismic rupture at site 1.

an angle of 5–25° and disturbed by the F1a and F1b faults. The north tilting of units 2 and 3 is in the opposite sense to the south-sloping alluvial fan surfaces and unit 2 is overlain by south-dipping silt layer of unit 1. This suggests that units 2 and 3 originally dipped southward and have since been tilted northward (Figs. 5 and 6b). On the west wall of the T2 trench, the F1a and F1b faults cut the main sand-gravel layers of unit 2 but are overlain by a thin gravel layer of unit 2 (Fig. 6). Furthermore, in trenches 1 and 2, there is a wedge- and graben-shaped deposit of units 2 and 3. The wedge-shaped deposits of unit 2 in the west wall of trench 2 show an upward protuberance structure, which mimicks the mole-track formed by the 2001 earthquake. The wedge- and graben-shaped deposits of units 2 and 3 were probably formed within extentional cracks as observed in the 2001 earthquake (Lin *et al.*, 2003). These sedimentary and structural features indicate that there is at least one seismic event which may be the same as the event that caused northward tilting of the sand layers of unit 2. Therefore, we infer that at least one event (event 3) occurred during the period between the deposition of unit 2 (2209 ± 50 yr B.P., C08) and unit 1 (1336 ± 52 yr B.P., C07).

Event 4

Several distinct geological and topographical features indicate that one or more prehistoric earthquakes occurred before event 3. First, in trenches T1, T2, and T3, the sand-gravel layers of units 3 and 4 and the base of unit 2 are displaced by fault F3, which is covered by the silt-sand layers of unit 1 and gravel layers of unit 2 (Figs. 5, 6, and 9). In the T5 trench, faults F1–F3 also cut the base gravel layers of units 2 and 3 but are overlain by the sand layers of unit 1 and sand-gravel layers of unit 2 (Fig. 9). This also shows that a possible event occurred after the formation of sand-gravel layers of units 2 and 3 comparable to that observed in the T2 trench. Second, there is a distinct sedimentary facies change and an apparent vertical offset of 2–2.5 m of unit 3 across faults F1 and F2 (Figs. 5 and 6). It is difficult to produce such a facies change in deposits and large vertical offset by an individual seismic event even the 2001 M_w 7.8 earthquake. Furthermore, on the west wall of trench T1, there is a sharp inflection boundary between units 2 and 3 (Fig. 5c). This sharp boundary was probably a south-facing scarp of ~2.5 m high formed by faulting or folding during

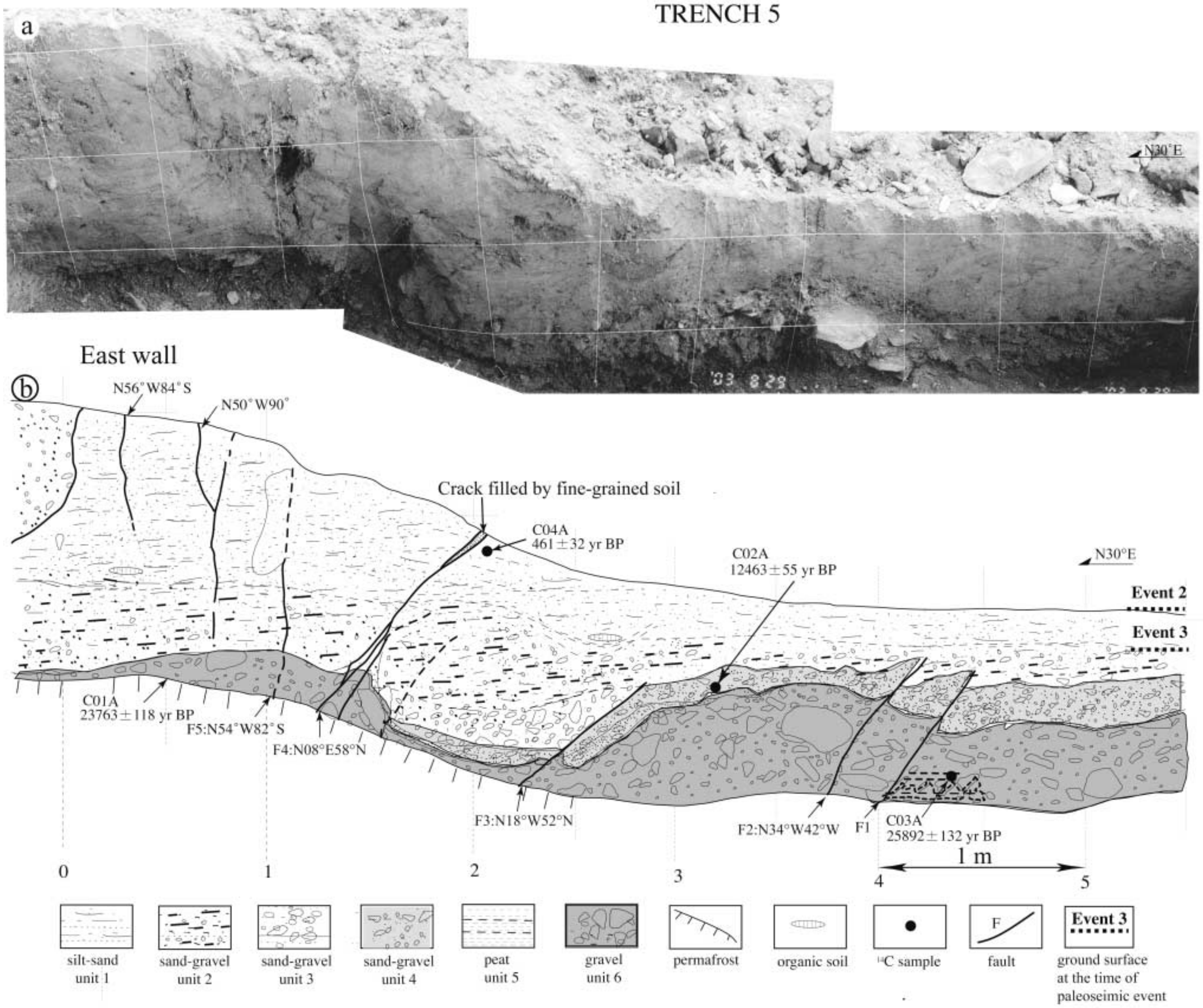


Figure 9. Photograph (a) and corresponding sketch (b) of east wall of trench 5 (T5) across the pre-existing fault scarp at site 2.

the period between units 2 and 3. Topographically, there is a 3- to 3.5-m-high fault-folding scarp observed across both wall sections in trench 1 (Fig. 5). There is, however, only a 0.6- to 0.7-m-high fault-folding scarp produced by the 2001 earthquake in this site (Fig. 4c). These geological and topographical features indicate that about a 2.5-m-high scarp was produced by one or more prehistoric earthquakes after the formation of unit 2. Organic soil and charcoal materials included in units 3 and 2 yielded ^{14}C ages of 3851 ± 53 yr B.P. (C06) and 3888 ± 50 yr B.P. (C04), and 1980 ± 47 yr B.P. (C03) and 2209 ± 50 yr B.P. (C08), respectively (Fig. 5, Table 1). The sedimentary and structural features and ^{14}C age discussed previously constrain that at least one faulting event (event 4) occurred in the period between unit 2 (1980 ± 47 yr B.P.) and unit 3 (3851 ± 53 yr B.P.).

Discussion and Conclusions

Holocene Slip Rate

Estimates of slip rates across strike-slip faults require the matching of displaced geomorphic or geological piercing or reference lines, such as fluvial terraces, abandoned stream channels, apices of alluvial fans, sedimentary facies changes, etc., across the active fault. In the study area, the south-flowing streams and gullies developed on the alluvial fans have been deflected left-laterally up to 115 m (Fig. 3). The largest offset of 115 m observed, therefore, may represent the cumulated displacement since the initiation of stream incising into the alluvial fan. Additionally, the alluvial fans developed along the Kunlun fault generally show an asymmetric shape and sinistral deflection pattern. These geomor-

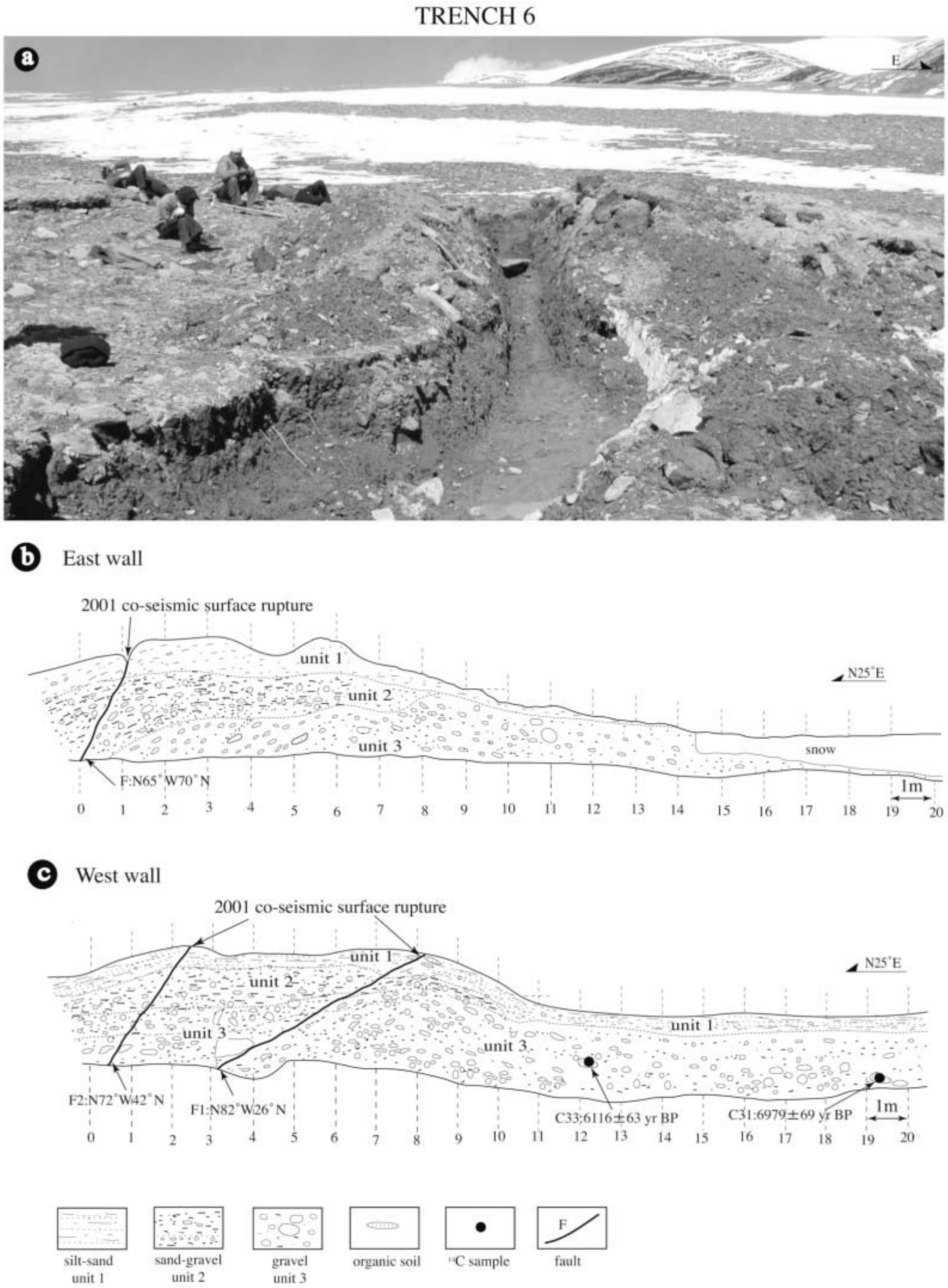
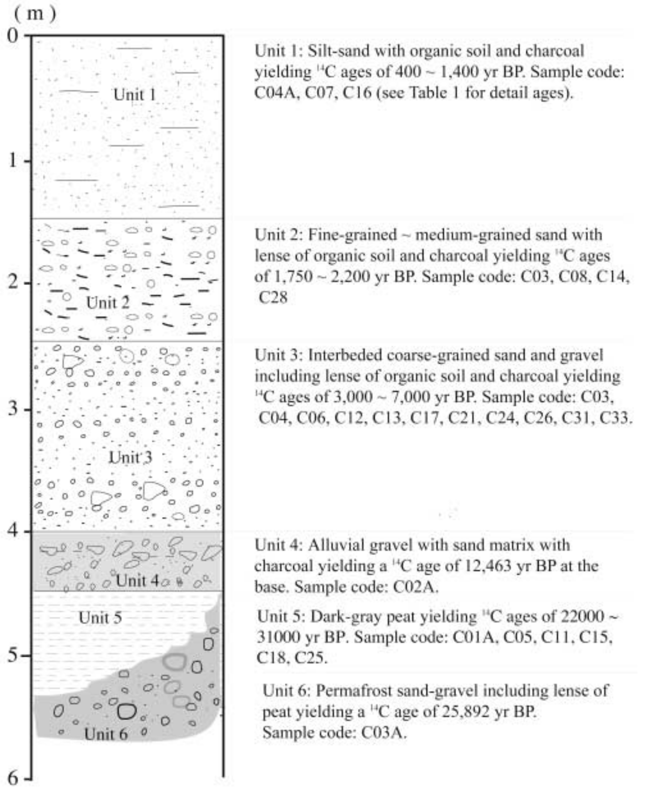


Figure 10. Photograph (a) and corresponding sketches (b), (c) of both walls of trench 6 (T6) across the 2001 coseismic rupture zone at site 3.

phic features indicate that left-lateral offset of up to 115 m has been accumulating on the Kunlun fault since the formation of the alluvial fans.

To estimate slip rate, it is vital to understand the ages of displaced topographic and geological features such as terraces and alluvial fans and deposits that are well developed in the study area. Avouac *et al.* (1993) estimated that the terraces having a height of 7–12 m above the current streambeds in the northern piedmont of the Tian Shan formed during the past 2–12 kyr based on degradation coefficients. On the basis of cosmogenic ray exposure dates (^{10}Be and ^{26}Al) of quartz pebbles in the alluvial deposits, Van der Woerd *et al.* (1998) estimated that terraces having heights of 1.7 m, 4.2 m, and 9.7 m above the current streambeds along the Xidatan-Dongdatan segment of the Kunlun fault east-bounded with the study area were formed about 1778 ± 388



Unit 1: Silt-sand with organic soil and charcoal yielding ^{14}C ages of 400 ~ 1,400 yr BP. Sample code: C04A, C07, C16 (see Table 1 for detail ages).

Unit 2: Fine-grained ~ medium-grained sand with lense of organic soil and charcoal yielding ^{14}C ages of 1,750 ~ 2,200 yr BP. Sample code: C03, C08, C14, C28

Unit 3: Interbeded coarse-grained sand and gravel including lense of organic soil and charcoal yielding ^{14}C ages of 3,000 ~ 7,000 yr BP. Sample code: C03, C04, C06, C12, C13, C17, C21, C24, C26, C31, C33.

Unit 4: Alluvial gravel with sand matrix with charcoal yielding a ^{14}C age of 12,463 yr BP at the base. Sample code: C02A.

Unit 5: Dark-gray peat yielding ^{14}C ages of 22000 ~ 31000 yr BP. Sample code: C01A, C05, C11, C15, C18, C25.

Unit 6: Permafrost sand-gravel including lense of peat yielding a ^{14}C age of 25,892 yr BP. Sample code: C03A.

Figure 11. Generalized stratigraphic column of sedimentary deposits exposed in the six trenches. Units are numbered and described in the text. ^{14}C ages and sample ID numbers are shown in Table 1.

yr B.P., 2914 ± 471 yr B.P., and 5106 ± 290 yr B.P., respectively. Other ^{14}C ages showed that the alluvial terraces and fans with heights of 8–22 m in the Xinjiang regions formed during the past 10–20 kyr (Feng, 1997). The relationships between the height of the terraces and fans from the current streambeds and ^{14}C and cosmogenic dating ages suggest that a stream incision rate during the late Pleistocene-Holocene ranges from 1 mm/yr to 2 mm/yr in the northern Tibetan region. Our results show that the alluvial fans developed in the study area are mainly composed of unconsolidated sand-gravel of units 3 and 4 formed during the past period between 6004–6406 years (C017) and 7674–7937 years (C31). Considering the uncertainty and errors of radiocarbon ages, we use here an average ^{14}C age of ~7000 years as the formation age of alluvial fans in the study area. These topographic features and ^{14}C ages reveal that the maximum 115-m offset of the stream developed on the alluvial fans is the accumulated result of displacements since the initiation of the stream incision of the alluvial fans during the past ~7000 years. Using the offset amounts of the alluvial fans and gullies and the radiocarbon dating ages, we estimate the average left-lateral strike-slip rate of the Kusai Hu segment of the Kunlun fault related to 2001 earthquake to be 16.4 mm/yr during the past ~7000 years. This average slip rate is larger than that (11.7 mm/yr) of the east-neighbored Xidatan-Dongdatan segment estimated by Van der Woerd (2002b) but coincides with the Pleistocene average slip rate of 10–20 mm/yr estimated by Kidd and Molnar (1988).

Average Recurrence Interval of Large Earthquakes

On the basis of topographic, deformational features of strata, and ^{14}C dating ages of terraces and alluvial fans, the recurrence intervals for successive large earthquakes at the study area have been obtained for the Kusai Hu segment of the Kunlun fault. The trench excavation investigations and ^{14}C ages of alluvial deposits obtained in this study indicate that at least four large earthquakes, including the 2001 earthquake, occurred during the past 6200 years and that the penultimate event occurred within the past 399 ± 44 yr B.P. as documented earlier. It is more difficult to assess stratigraphic evidence of the paleoseismicity for a strike-slip fault because some horizontal-slip events were probably obliterated or superimposed due to the hiatus of deposition on alluvial fans in the study vicinity. These four large earthquakes estimated previously, therefore, may only represent partial prehistoric events that are decipherable in the trenches dug in this study.

The average recurrence interval of large earthquakes on the Kusai Hu segment can also be estimated using slip rate and average displacement for large earthquakes along the Kunlun fault. Geomorphic evidence shows that the strike-slip offsets produced by this penultimate event along the pre-existing fault Fb (Fig. 4) vary from 1.4 m to 6.6 m, with an average amount of 4–5 m, which are comparable to those produced by the 2001 M_w 7.8 earthquake observed along the fault Fa. The offsets produced by the 1937 M 7.5 Tuosuo Hu earthquake, which occurred on the 300-km-long Alaq Hu and Dongxi Co segments of the Kunlun fault (between 96°E and 99°E; Fig. 1) are 2–7 m, with an average amount of 3 m (Jia *et al.*, 1988; Lin, 1999). The 1997 M_w 7.6 Manyi earthquake that produced a maximum surface displacement of 4.5 m, generally 2–3 m along the 120 km surface rupture (Xu, 2000). Therefore, we infer that the average displacements of 4–5 m on the pre-existing Fb fault (F2, Fig. 3) were produced by a large-magnitude earthquake similar to the 2001 earthquake. Using the slip rate of 16.4 mm/yr and this average offset of 4–5 m, we estimate that the average recurrence interval of M_w 7.8 earthquakes during the past ~7000 years is 320~410 years.

It seems that there is a discrepancy between the estimated average recurrence interval implied by four events during the past ca. 6200 years and the average interval inferred from the average slip amount caused by an individual event and average slip rate. This discrepancy has two major possible causes. One is the hiatus of the deposition occurring on the alluvial fans in the study area due to small vertical offset and ground subsidence during the paleoseimic events along the strike-slip fault. This hiatus may result in the obliteration or superimposition of horizontal slip events in a stratigraphic succession, and a more complex record that is indecipherable. Second, the old material may have polluted the dating samples, which yield apparent older ^{14}C ages. These two major causes may result in a large number of missing events from the trenches and cause the previous apparent discrepancy in the estimated recurrence interval.

The characteristic earthquake magnitude estimated for the Kusai Hu segment in this study is comparable to that of the east-neighbored Xidatan-Dongdata segment estimated by Van der Woerd *et al.* (2002b). However, the recurrence interval obtained from the Kusai Hu segment is only ~1/3 to 1/2 of that (800–1000 years) estimated for the Xidatan-Dongdatan segment by Van der Woerd *et al.* (2002b). This large interval for the Xidatan-Dongdatan segment may be caused by overestimation on the characteristic offset (9–12 m) produced by an individual large earthquake, because the average offsets produced by three historic earthquakes along the Kunlun fault are not over 5–8 m, even the offset produced by the 2001 M_s 8.1 earthquake. Recently, based on field and trench studies (Fig. 2b), Guo *et al.* (2006) revealed that the characteristic offsets produced along the Xidatan-Dongdatan segment by the most recent earthquake occurred in the past 663 years and are only 3–6 m, which is comparable to those produced by the penultimate earthquake along the Kusai Hu segment as discussed earlier. This new constraint of characteristic offsets shows that the recurrence interval of the Dongdatan-Xidatan segment would be 270–500 years, but not 800–1000 years if the average slip rate of 11.7 mm/yr estimated by Van der Woerd (2002b) is used. The average recurrence intervals of large earthquakes estimated for the Kusai Hu segment, therefore, are also comparable to that of the Xidatan-Dongdata segment.

Global Positioning System (GPS) results show that north Tibet (north of the Kunlun fault) moves east-northeastward at a rate of 5–10 mm/yr, and south-central Tibet moves at a rate of up to 15~25 mm/yr to the east-northeast with respect to Eurasia (Wang *et al.*, 2001). The estimated $M \sim 8$ earthquake recurrence interval of 300–400 years and the left-lateral strike-slip rate of 16.4 mm/yr imply that the differential motion of 10–20 mm/yr between north Tibet and south-central Tibet is mostly accommodated by the Kunlun fault as seismic slip. Our results document and confirm that the Kunlun fault is one of the major strike-slip faults on which strike slip accommodates both the northeastward shortening and eastward extrusion of Tibet (e.g., Tapponnier and Molnar, 1977; Meyer *et al.*, 1998; Wang *et al.*, 2001).

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Institute of Geosciences
Faculty of Science, Shizuoka University
Shizuoka 422-8529, Japan
(A.L., K.K.)

Graduate School of Science and Technology
Shizuoka University
Shizuoka 422-8529, Japan
(A.L., J.G.)

Active Fault Research Center
AIST
Tsukuba 305-8567, Japan
(Y.A.)

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