Geophysical Research Letters

Constraining the Kunlun Fault slip-rate

Geological techniques provide bounds on average slip-rates over periods of several thousand years or more. While attempting to derive a long-term slip-rate of cumulative offsets along much of the length of the Kunlun Fault located just north of Tibet, Van der Woerd et al. [2000] find that the offsets of 13 distinct geomorphic markers dated at 6 sites are consistent with a uniform, constant slip rate of 11.5 mm/yr over a time-span of 40,000 years and a distance of 600 km along the fault. The slip-rate of more than 1 cm/yr implies that a third to half of the eastward component motion of Tibet relative to the Gobi is absorbed. The authors provide evidence that confirms that the Xidatan-Dongdatan segment of the Kunlun Fault ruptures during massive earthquakes, with characteristic slip and a recurrence interval of 900 years.

AUGUST 15, 2000

Volume 27 Number 16

AMERICAN GEOPHYSICAL UNION

Uniform Slip-Rate along the Kunlun Fault: Implications for seismic behaviour and large-scale tectonics

J. Van der Woerd[1], F. J. Ryerson[1], P. Tapponnier[2], A.-S. Meriaux[2], Y. Gaudemer[2], B. Meyer[2], R. C. Finkel[1], M. W. Caffee[1], Zhao Guoguang[3], Xu Zhiqin[4]

Abstract A long-term slip-rate is derived from concordant ^{10}Be, ^{26}Al and ^{14}C dating of cumulative offsets along much of the length of the Kunlun Fault. Values at 6 sites indicate uniform slip (11.5 ± 2.0 mm/yr) since ~40 kyr BP. This relatively high slip rate corresponds to a first-order discontinuity in the Asian crustal velocity field. M~8 and M~7.5 earthquakes on 2 segments of the fault recur with characteristic slip (~10 ± 2 m and 4.4 ± 0.4 m) every ~850 and ~420 yrs, respectively.

Introduction

The Kunlun, Altyn Tagh, and Haiyuan strike-slip faults bound the north side of Tibet (Figure 1, inset), [e.g., *Tapponnier and Molnar,* 1977]. All have been the site of great earthquakes ($7.5 \leq M \leq 8.7$) this century and in the past [*Gu et al.,* 1989]. Their 1000-2000 km lengths and relationship to growing mountain ranges suggest that they control the growth of the Tibetan plateau [*Meyer et al.,* 1998]. A low P-wave velocity anomaly beneath the central Altyn Tagh Fault [*Wittlinger et al.,* 1998], as well as SKS-wave splitting anisotropy parallel to the Kunlun and Altyn Tagh faults [*McNamara et al.,* 1994; *Herquel et al.,* 1999], suggest that both extend as shear zones to the base of the lithosphere. Nevertheless, controversy surrounds the role these faults play in accommodating Indo-Asian convergence. Whether they define first-order discontinuities in the lithospheric velocity field [*Avouac and Tapponnier,* 1993; *Meyer et al.,* 1998], or absorb small enough displacements that the deformation of Asia may be treated as that of a viscous fluid [*England and Molnar,* 1997], is under question. The most desired, and up to now missing, evidence needed to resolve this problem are accurate, long-term slip rates determined at a number of sites sufficient to characterize the large-scale behavior of the faults.

Only geological techniques [e.g., *Sieh and Jahns,* 1984; *Weldon and Sieh,* 1985] can provide bounds on average slip-rates over periods of several thousand years or more, enough to span – and smooth out – many seismic cycles, the duration of which is often ≥ 500 yrs on continental faults [e.g., *Peltzer et al.,* 1988; *Zhang et al.*, 1988; *Lasserre et al.,* 1999]. We summarize here results of offset measurements and surface marker ages that help constrain the rate of slip on the Kunlun Fault over a length of 600 km and a time-span longer than 30,000 years.

Ages and offsets of geomorphic markers

In the field, we studied three of the six segments of the Kunlun Fault (Figure 1). At six selected sites, the extremes of which lie 600 km apart, we measured cumulative sinistral offsets of either terrace risers or morainic ridges cut by the fault. ^{10}Be and ^{26}Al cosmogenic dating of quartz-rich pebbles and radiocarbon dating of fossil organic material were used to determine terrace surface ages. Together with the offsets, the ages yield the time-integrated slip-rate on the fault.

Sites 1-3, between 94 and 95°E, span ~50 km of the western, Xidatan-Dongdatan segment (II) of the fault, which stretches for 160 km east of the Kunlun Pass, at elevations above 4000 m (II, Figure 1). Here, the N80-90°E striking fault trace short-cuts a former pull-apart trough, the Xidatan-Dongdatan valley, which is floored by coalescent alluvial fans fed by glacial outwash streams flowing north from the ~6000 m-high Burhan Budai Shan [*Van der Woerd et al.,* 1998]. At the three sites, flights of inset strath terraces were abandoned by the streams as they continued to incise their most ancient fans. The terrace risers, which strike N10°W to N30°E, are cleanly offset by the fault. The cumulative riser-offsets, which range between 24 ± 3 and 110 ± 10 m (Table 1), increase with distance from, and elevation above, the present stream beds.

From quartz pebbles sampled on profiles parallel to the fault both up- and downstream from it, we obtained 93, mostly concordant, ^{10}Be and ^{26}Al surface exposure ages. Overall, the mean Al-Be ages range between 205 and 40,900 yrs. Sample ages on each terrace level, whether up- or downstream, group into clusters whose statistically well-defined average ages, excluding outliers, constrain the times of terrace abandonment. The mean Al-Be average ages of the terraces are 1788 ± 388, 2914 ± 471, and 5106 ± 290 yr, at site 1 [*Van der Woerd et al.,* 1998], 6276 ± 262, 8126 ± 346, and 12614 ± 2303 yr at site 2 (Figure 2) and 4837 ± 857 and 6043 ± 553 yr at site 3.

At each site, the abandonment ages increase with the riser offsets (Figure 2). The number of samples on each terrace was large enough to identify and discard outliers. Such outliers appear to come either from reworking of older terraces and glacial deposits upstream in the catchments or, in one case, from re-invasion of a low-level terrace by flooding [*Van der Woerd et al.,* 1998]. The latter, very young, ages provide an upper bound to pre-depositional cosmic-ray exposure. This bound (< 200 yr) is smaller than the typical uncertainty on all older ages – hence negligible – and consis-

[1]Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, USA
[2]Institut de Physique du Globe de Paris, Paris, France
[3]Institute of Crustal Dynamics, China Seismological Bureau, Beijing, China
[4]Institute of Geology, Ministry of Land and Resources, Beijing, China

Paper number 1999GL011292.
0094-8276/00/1999GL011292$05.00

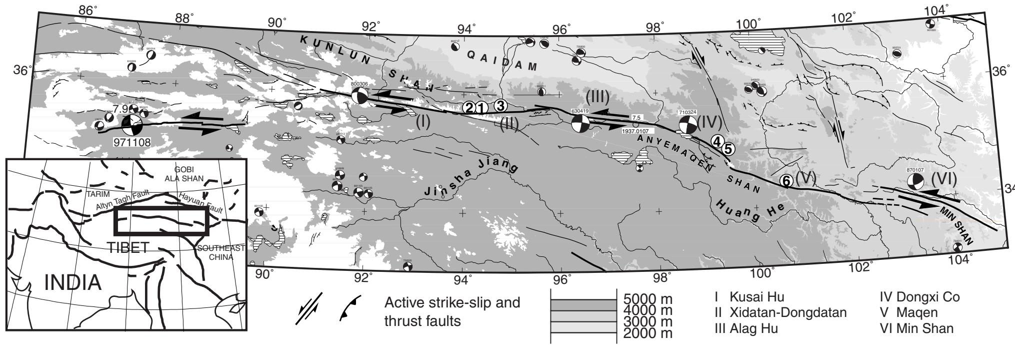

Figure 1. Simplified map of Kunlun Fault in Northern Tibet. Numbers refer to field sites. Roman numerals, to first order fault-segments.

tent with rapid transport and minimal storage time in the short and steep catchments upstream from the fault.

Because at sites 1 to 3 the terraces are strath, the riser offset ages are those of the lower terraces. The 6 risers thus dated constrain the slip-rate to be 11.6 ± 0.8 mm/yr on average (12.1 ± 2.6, 11.9 ± 1.0, and 10.8 ± 1.5 mm/yr, at sites 1, 2, and 3, respectively), (Figure 2 and Table 1).

Sites 4 (Nianzha He) and 5 (Xiadawu) lie 20 km apart along the central, Dongxi-Anyemaqen segment of the fault, near 99°E (IV, Figure 1). Here, the fault trace strikes N120-130°E for about 155 km, and is marked everywhere by the fresh mole tracks of the M=7.5, 1937 earthquake. The two sites are located where the fault crosses two large fluvial valleys, about halfway between the 30 by 10 km pull-apart sag filled by Dongxi lake, and the 40 km-long restraining bend that causes the rise of the Anyemaqen range (6280 m), (Figure 1). The terraces are clear straths at site 4, but fills at site 5 (Figure 3). They are coated with loess and thick soil and do not contain enough quartz pebbles for cosmic-ray exposure dating. Instead, we dated 15 charcoal pieces, 2 bone fragments, and freshwater snail shells with ^{14}C. Since such subsurface samples were retrieved in the uppermost gravel layers beneath the loess or soil, they provide upper bounds on the terrace abandonment ages, which range between 6748 ± 22 (T1', site 5) and 37000 ± 900 yr (T2, site 5; Figure 3).

The correlation between terraces on either side of the fault, the shapes, heights, and trends of the terrace risers, as well as the ratio between horizontal and vertical offsets on the fault (Dh/Dv), were accurately constrained by 28 and 22 total-station profiles at sites 4 and 5, respectively [e.g. *Van der Woerd et al.,* submitted]. The cumulative offsets of the principal risers, which intersect the fault at high angle, range from a minimum of 11.3 ± 0.5 m (site 4) to as much as 400 ± 5 m (site 5, Figure 3). At site 5, the dip component of slip on the fault is negligible. At site 4, on the other hand, the fault is transpressive, with Dh/Dv $= 10 \pm 1$. Because we found no datable material on T1, the age of the T1'/T1 riser offset at site 4 was interpolated using this Dh/Dv ratio and the mean radiocarbon age of T1" (8477 ± 44 yr BP). As in the Xidatan-Dongdatan valley, the ages of the constraining terraces (at the risers' bases at site 4, at their tops at site 5) increase with the magnitude of the riser offsets (Table 1).

Overall, the 5 geomorphic markers dated at the 2 sites between Dongxi Co and Anyemaqen Shan yield consistent

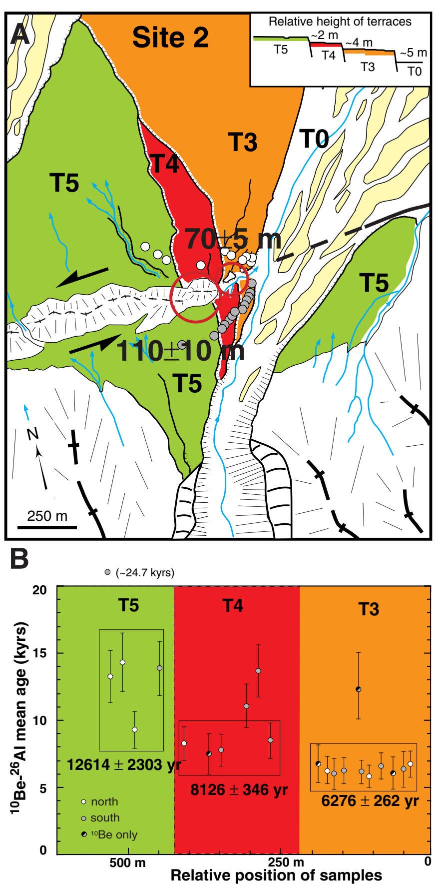

Figure 2. Sketch map (A) and sample age distributions (B) for site 2 (segment II). White and gray circles indicate relative positions of quartz pebbles sampled on terrace surfaces on either side of fault. Relative strath terrace ages (colour) increase from active stream bed (T0, white) to T5 (green).

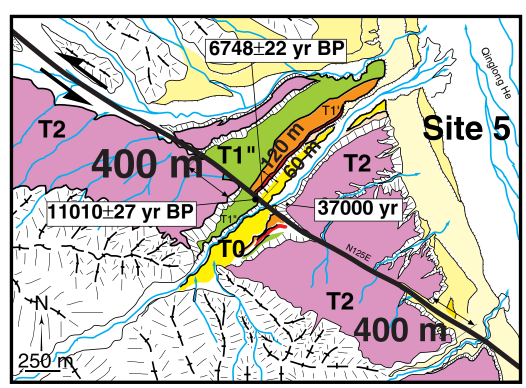

Figure 3. Sketch map of site 4 along Dongxi segment (IV, on Figure 1). Riser offsets range from 60 to 400 m and radiocarbon ages of fill terraces from 6.7 to 37 kyrs.

Table 1. Measured offsets, with corresponding cosmogenic or ^{14}C average ages and calculated slip-rates.

Offset (m)	^{26}Al-^{10}Be (yr)	^{14}C age (yr BP)	Slip-rate (mm/yr)
		Site 1	
24±3	1788±388	···	13.5±4.6
33±4	2914±471	···	11.3±3.2
50±10	< 5106±290	···	> 9.8±2.5
		Site 2	
70±5	6276±262	···	11.2±1.3
110±10	8126±346	···	13.5±1.8
		Site 3	
47±5	4837±857	···	9.7±2.8
68±5	6043±553	···	11.3±1.9
		Site 4	
57±2	···	< 5565±2245	> 10.3
90±10	···	8477±44	10.2±1.6
		Site 5	
60±5	···	< 6748±22	> 8.9±0.7
120±5	···	< 11010±27	> 10.9±0.5
400±5	···	< 37000±900 [a]	> 10.8
		Site 6	
180±20	···	> 11156±158 and < 20 kyr	12.5±3.5

[a] Uncalibrated ^{14}C age.

slip-rates of 10.2 ± 1.6 and 10.9 ± 0.5 mm/yr, comparable, within uncertainty, to those found 400 km to the west in the Xidatan-Dongdatan Valley (Figure 2 and Table 1).

The eastern, N110°E-striking Maqen segment of the fault (V, Figure 1) continues to cut across high ground (∼4000 m a.s.l) for 270 km past the Anyemaqen range. Near 100°30'E, about 30 km east of Maqen, the main fault-strand offsets by 180 ± 20 m a low-level lateral moraine (Figure 4). A young ^{14}C top-soil age of 4851 ± 20 yr BP, protruding surface boulders, and the fresh, well preserved shapes of the two offset morainic ridges imply that they were emplaced during the Last Glacial Maximum (∼20 ka BP in northern Tibet [*Thompson et al.,* 1997], at the time of farthest advance of the now extinct glacier. That the two ridges are disconnected requires that their offset postdates the glacier's withdrawal. We dated the highest outwash terrace (T3) dammed north of the fault by the offset. The oldest charcoal fragment found, ∼0.6 m-deep in gravels beneath loess, yields a ^{14}C age of 11156 ± 157 yr BP (Table 1). The glacier thus retreated across the fault sometime between 20 and 11 ka BP, which implies a slip-rate of 12.5 ± 3.5 mm/yr, similar to those found at the first five sites.

Characteristic slip and recurrence time of large earthquakes

In Xidatan and Dongdatan, tape measurements yield minimum sinistral offsets of 8 to 12 m, compatible with those (∼10 m) found by *Kidd and Molnar* [1988] and *Zhao* [1996]. At 18 localities along this stretch of the fault, we also found cumulative horizontal offsets 2 or 3 times greater than 9, 10, 11 and 12 m. We interpret such least common denominator values, which vary by less than 20% from site to site, to represent the similar coseismic surface-slip of large events. Trenching elsewhere in Xidatan [*Zhao,* 1996] implies the occurrence of 4 large events in the last 4000 yr, the last one before the 278 ± 87 yr-old flash-flood at site 1 since no mole tracks are observed on T1. All the quantitative evidence collected thus confirms that the Xidatan-Dongdatan segment of the Kunlun Fault ruptures during great earthquakes (M∼8), with characteristic slip (Δu ∼10 ± 2 m), and with a recurrence interval of 850 ± 200 yr (Figure 5) [*Van der Woerd et al.,* 1998].

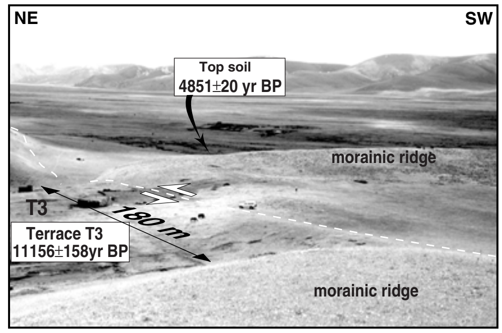

Figure 4. View, towards SE, of offset LGM lateral moraine at site 6, along Maqen segment (V) of Kunlun Fault. Cumulative offset and ^{14}C ages are indicated.

Concurrent evidence exists along the Dongxi-Anye-maqen segment of the fault, which ruptured during the January 7, 1937, $M = 7.5$ earthquake. Fourteen total-station profiles of offset rills on the lowest terrace T'0 at site 4 show two statistically different clusters of coherent horizontal and vertical offset values, each with δh ∼11 δv, and with one set of values almost exactly twice the other (δh ∼4.4 ± 0.4 m and δv ∼0.4 ± 0.1 m; δh ∼8.9 ± 0.6 m and δv ∼0.8 ± 0.2 m, respectively). Thus, not only do the rills record the last (1937) and penultimate earthquakes that broke across the Nianzha He valley, but these two events had nearly identical slip. The 11.3 m offset of the degraded T1/T'0 riser might result from 3 such events (3 x 4.4 = 13.2 m). We conclude that earthquakes with characteristic slip also rupture the Dongxi Co segment of the fault. Their sizes and repeat times, however, are different from those inferred in Xidatan and Dongdatan. The 1937, M ∼7.5 earthquake, with δh∼4.4 ± 0.4 m and δv ∼0.4 ± 0.1 m at Nianzha He, would be typical. Given the local slip-rate of 10.3 mm/yr, this earthquake would recur every ∼420 yrs, with the previous event in 1515 ± 70 AD, and the next due around 2350 AD (Figure 5).

Conclusion

The offsets of 13 distinct geomorphic markers dated at 6 sites with 3 different techniques are consistent with a uniform, constant slip-rate of 11.5±2.0 mm/yr over a time-span of 40,000 years and a distance of 600 km along the Kunlun

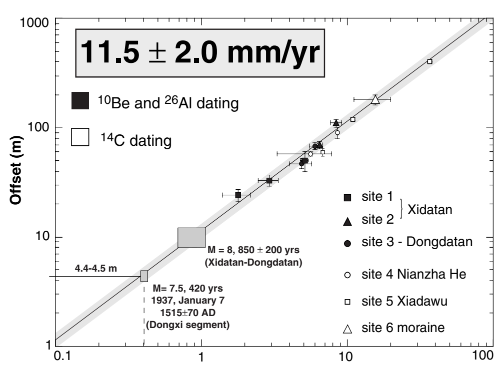

Figure 5. Average slip-rate calculated from 13 dated offsets at 6 sites over a distance of 600 km along Kunlun Fault. Offsets and related ages correspond to values in Table 1. Boxes show sizes and recurrence times of M∼8 and M∼7.5 earthquakes at sites 1 and 4 on Xidatan (II) and Dongxi (IV) segments of fault, respectively.

Fault (Figure 5, Table 1). On two segments (II and IV) an apparently regular recurrence (Tr ~420 and 850 yrs) of large earthquakes with characteristic slip ($\Delta u \sim 10 \pm 2$ m and 4.4 ± 0.4 m) and different magnitudes (M~7.5 and 8) appears to typify the seismic behavior of the fault in the last few thousand years. The slip-rate values found corroborate that obtained at a first, pilot site in Xidatan (site 1) [*Van der Woerd et al.,* 1998], and are compatible with a Pleistocene average rate of 10-20 mm/yr inferred west of the Kunlun Pass [*Kidd and Molnar,* 1988]. Since we did not reach the 210 km-long, Alag Hu segment of the fault between sites 3 and 4, it is possible that the similarity of the rates determined on either side, to the east or west, is coincidental. The sinistral slip rate might reach a maximum on that segment, which is located in the middle part of the fault, but the fact that the rates do not decrease between either sites 3 and 2 or 4 and 6 makes this unlikely. Rather, the geomorphic signature of the fault and offsets mapped elsewhere on SPOT images suggest that the rate constrained at just a few localities in the field can be extrapolated over 11° of longitude to much of the fault-length (~1200 km), encompassing each six, 150-270 km-long, principal segments separated by first order geometrical complexities (restraining bends, push-ups, pull-aparts), (Figure 1). A uniform rate over such a distance is not particularly surprising since, in contrast with, for instance, the Altyn Tagh Fault [*Meyer et al.,* 1998], the Kunlun Fault does not shed off major oblique strands or meet with other large active faults that might take up significant fractions of its movement. Only west of 91°E or east of 102°E, does it divide into several splays along which the overall slip, which becomes distributed, might decrease (Figure 1). In any event, the fact that the sinistral slip-rate on the 1200 km-long continuous stretch of the fault is $\geq$ 1 cm/yr confirms that it absorbs 1/3 to 1/2 of the eastward component of motion of Tibet relative to the Gobi [*Avouac and Tapponnier,* 1993; *Peltzer and Saucier,* 1996] and is compatible with the inference that it is a lithospheric discontinuity [*Meyer et al.,* 1998].

Acknowledgments. This work was supported by Institut National des Sciences de l'Univers (CNRS, Paris, France), the Ministry of Geology and Mineral Resources (Chinese Academy of Geological Sciences, Beijing, China), and the French Ministry of Foreign Affairs. FJR, RCF and MC acknowledge support from the Institute of Geophysics and Planetary Physics at LLNL operating under the auspices of DOE contract ENG-7405. We thank K. Sieh for helpful review and discussions that improved the original manuscript. This is IPGP contribution No. 1653 and IGPP contribution UCRL-JC-136818.

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J. Van der Woerd, F. J. Ryerson, R. C. Finkel and M. W. Caffee, IGPP, LLNL, L-202, 7000 East Avenue, Livermore, CA 94550, USA (e-mail: vanderwoerd2@llnl.gov)

P. Tapponnier, A.-S. Meriaux, Y. Gaudemer, B. Meyer, Institut de Physique du Globe de Paris, 4 Place Jussieu, 75252 Paris Cedex 05, France

Zhao Guoguang, Institute of Crustal Dynamics, China Seismological Bureau, Beijing 100085, China

Xu Zhiqin, Institute of Geology, Ministry of Land and Resources, Beijing 100037, China

(Received December 29, 1999; revised March 17, 2000; accepted May 8, 2000.)