Fluvial terrace riser degradation and determination of slip rates on strike-slip faults: An example from the Kunlun fault, China

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[1] The use of displaced fluvial terrace risers to determine slip rates along strike-slip faults depends on knowing when risers become passive markers. Typically, chronologic constraints from terrace deposits only place bounds on this age; consequent slip rates may be highly uncertain. Along the Kunlun fault, in northeastern Tibet, we demonstrate that consideration of riser degradation can augment terrace chronology and improve the precision of slip-rate estimates. Multiple offset risers and ^{14}C age determinations from terrace treads yield a narrow range of slip rates of 4.5 ± 0.5 m/kyr at one site, but permit a wide range of allowable rates (3–10 m/kyr) in an adjacent drainage. Using a locally calibrated sediment transport rate of 3.2–5.4 m^2/ka, we show that riser morphology at this latter site is consistent with degradation since abandonment of the upper terrace tread. Our analysis indicates that slip rates at this site are ∼5 ± 2 m/kyr. **Citation:** Harkins, N., and E. Kirby (2008), Fluvial terrace riser degradation and determination of slip rates on strike-slip faults: An example from the Kunlun fault, China, *Geophys. Res. Lett.*, *35*, L05406, doi:10.1029/2007GL033073.

1. Motivation

[2] Rates of displacement on fault systems are primary among data that we use to understand the dynamics of active lithospheric deformation. For example, the degree to which India-Asia convergence is accommodated by displacement along major intracontinental strike-slip faults largely depends on estimates of the slip-rates along these structures [e.g., *Avouac and Tapponnier*, 1993; *England and Molnar*, 2005; *Meade*, 2007; *Thatcher*, 2007]. Similarly, inferences of lithospheric rheology from post-seismic deformation [e.g., *Hilley et al.*, 2005; *Pollitz et al.*, 2001] requires knowing the average rate of fault slip over multiple seismic cycles.

[3] The widespread distribution and relatively simple initial geometry of fluvial terraces make them one of the most commonly used markers of fault offset over timescales of 10^4–10^5 yr [e.g., *Lensen*, 1964a; *Mason et al.*, 2006; *Mériaux et al.*, 2004; *Van der Woerd et al.*, 2000]. Along faults exhibiting lateral displacement, one is forced to rely on displacement of the terrace riser (the steep slope that separates adjacent terrace treads). Although these features make excellent piercing points, relating their age to readily-datable fluvial deposits is difficult [*Lensen*, 1964a, 1964b]. A number of workers have considered this problem [e.g., *Cowgill*, 2007; *Kirby et al.*, 2007; *Lensen*, 1964a, 1964b; *Mériaux et al.*, 2004, 2005; *Van der Woerd et al.*, 2000, 2002], and all have recognized that it must be true that the "age" of a terrace riser (taken here as the time at which fluvial erosion at the base of the riser ceases) lies somewhere between the timing of abandonment of the bounding treads. However, most workers typically assume that the cessation of lateral erosion of the riser occurs close in time to abandonment of the lower tread [e.g., *Mason et al.*, 2006; *Mériaux et al.*, 2004; *Van der Woerd et al.*, 2002], leading to a maximum estimate of the allowable slip rate. This interpretation may be an overestimate, however, if protection of the riser from lateral attack by the stream allows displacement to accumulate during occupation of the lower terrace tread [e.g., *Cowgill*, 2007; *Lensen*, 1964b]. Although a number of authors have suggested that this effect may help explain discrepant geologic and geodetic estimates of slip rate on major Asian strike-slip faults [*England and Molnar*, 2005; *Thatcher*, 2007; *Zhang et al.*, 2007], few studies have unequivocally demonstrated this possibility.

[4] Erosional degradation of the riser itself has the potential to provide a direct constraint on the time since the riser was last eroded by the channel [e.g., *Avouac and Peltzer*, 1993]. Scarps developed in unconsolidated alluvial material degrade via slope-dependent sediment transport [*Culling*, 1960], such that their gradients reflect the efficiency of local transport processes integrated over the age of the scarp. Although numerous studies have considered the application of various sediment transport rules to the dating of fault scarps, shorelines and terrace risers [e.g., *Andrews and Bucknam*, 1987; *Avouac et al.*, 1996; *Avouac and Peltzer*, 1993; *Bucknam and Anderson*, 1979; *Culling*, 1960; *Hanks and Wallace*, 1985; *Nash*, 1980], none have yet exported this understanding to the study of strike-slip faults. Our results demonstrate that analysis of riser morphology can, in some cases, refine estimates of the age of terrace risers and thus improve slip-rate estimates.

2. Background and Approach

[5] On the basis of displaced fluvial terrace risers at multiple sites along the central Kunlun fault, *Van der Woerd et al.* [2000, 2002] suggested that the left-lateral slip rates along this major intracontinental fault system are relatively uniform at 10–12 m/kyr (Figure 1). However, recent work by *Kirby et al.* [2007] along the eastern segments of the fault suggests that the Late Pleistocene – Holocene slip-rate decreases systematically eastward from ∼5 m/kyr to ∼2 m/kyr at 101° and 102°E, respectively. These authors interpreted this pattern to reflect decreasing displacement near the fault tip.

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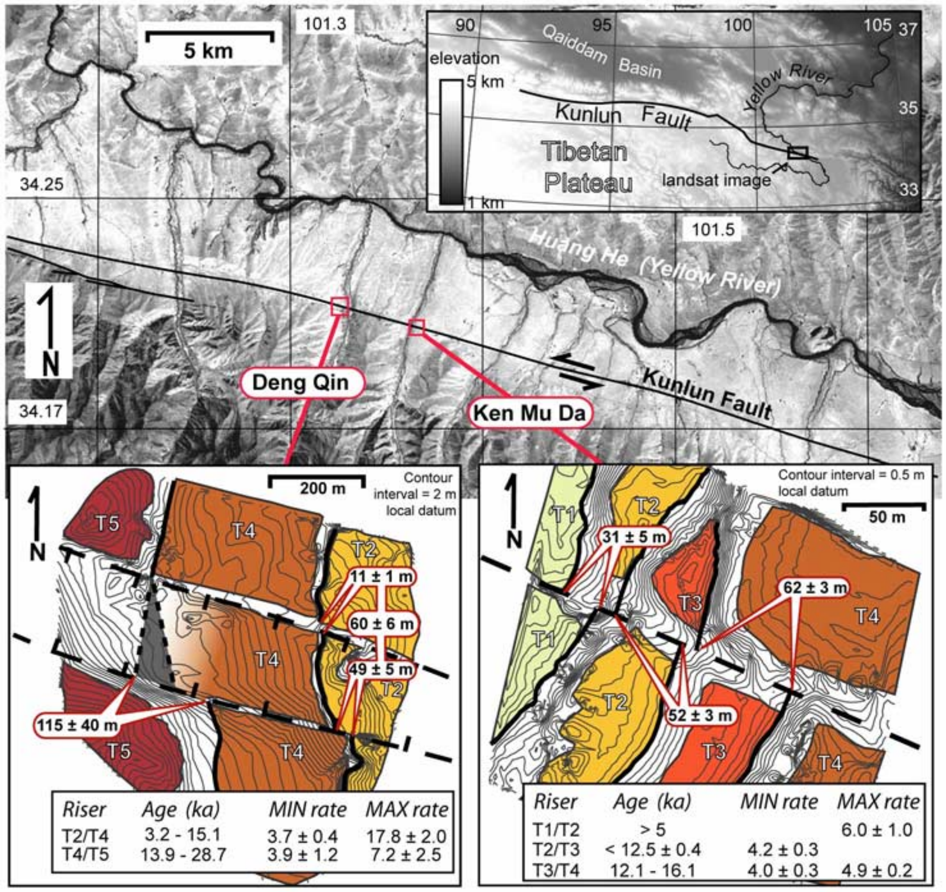

Figure 1. A LANDSAT TM scene provides the background for the larger image and displays that location of the (left) Deng Qin and (right) Ken Mu Da sites. On site maps, terraces are interpreted on topographic base maps compiled from kinematic GPS survey data, note the scale change between the two maps. Traces of the fault are dashed, the surveyed slope breaks at riser toes are highlighted in bold, and the riser offsets measured from these break lines are shown. Minimum and maximum allowable slip-rates from each of the offset risers are based on measured offsets over the full range of possible riser ages. Rates are given in m/kyr. The inset is a shaded relief map of the northeastern Tibetan Plateau displaying the trace of the Kunlun fault and the location of the larger image.

[6] In this study, we present new slip rate estimates from an additional site along the eastern Kunlun fault, close in proximity to the western site of *Kirby et al.* [2007] (Figure 1). Terrace chronology at this new site leads to widely varying estimates of slip rate, and may lend support to either a high rate [e.g., *Van der Woerd et al.*, 2002] or a low rate [e.g., *Kirby et al.*, 2007]. In order to address this problem, we combine high-resolution topographic surveys with ^{14}C chronology of terrace deposits to evaluate terrace riser ages based on their morphologies at each site.

3. Slip Rates on the Kunlun Fault Near 101°E

[7] Slip rates along the eastern Kunlun fault between 99° and 102°E are known from only two locations (Figure 1). Near 100°E, *Van der Woerd et al.* [2002] utilized displacement of a "morainic ridge", inferred to have been deposited between 20 and 11 ka, to estimate a slip rate of 12.5 ± 2.5 m/kyr at this site. In contrast, recent estimates of slip rate at a site ~100 km farther east along the fault (near 101.3°, see Figure 1) utilized progressively displaced fluvial terrace risers along a tributary of the Yellow River, locally named Ken Mu Da [*Kirby et al.*, 2007]. Constraints on terrace abandonment provided by ^{14}C samples from terrace treads and overlying loess allowed these authors to infer that left-lateral slip rates over the latest Pleistocene and Holocene have been ~5 ± 1 m/kyr at this site.

[8] Here we present a second estimate of slip rate near 101°E, in the Deng Qin drainage, located 3 km west of Ken Mu Da (Figure 1). The Deng Qin valley hosts a flight of five terrace surfaces. In contrast to Ken Mu Da, terrace treads here are broad, extensive surfaces, and offset terrace risers are preserved on the west side of the valley, such that fault slip displaces downstream risers away from the axis of the valley. The fault at this location exhibits two sub-parallel strands that bound a broad, shallow graben. Terrace surfaces on either side of the graben are graded with one another, indicating that net vertical displacement across the fault zone is small. Slope break-lines at the base of risers were surveyed with a laser ranger and used to quantify riser displacements. Potential uncertainties associated with the choice of which part of the riser (base, midpoint, or crest) to use as a piercing line are small relative to uncertainties associated with projection of the riser across the fault. The

T2/T4 riser is offset by 11 ± 1 m and 49 ± 5 m along the north and south fault strands, respectively, with a total left-lateral offset of 60 ± 6 m (Figure 1). The T4/T5 riser is obscured between the two fault strands; projection of the break line associated with this riser yields a relatively imprecise offset of 115 ± 40 m.

[9] Radiocarbon samples extracted from terrace treads provide a chronology of terrace abandonment (see Table S1 in the auxiliary material[1]). A minimum age of the lowest, T2 surface, is provided by a sample extracted from the loess on this surface that yielded an age of 3,370 ± 95 cal YBP. Two samples, dated at 15,138 ± 697 cal YBP and 14,515 ± 581 cal YBP, were extracted from the gravel and loess/gravel contact capping the T4 surface, respectively. These samples tightly bracket terrace abandonment at ~14.5 ka, similar to correlative surfaces at Ken Mu Da [*Kirby et al.*, 2007]. Finally, shells extracted from near the base of the loess on the T5 surface yielded an age of 28,470 ± 300 cal YBP and provide a minimum abandonment age of the T5 surface.

[10] Together, riser offsets and radiocarbon chronology allow us to place bounds on the slip rate of the Kunlun fault at this site. Allowable rates using the T2/T4 riser are 3.7 ± 0.4 m/kyr and 17.8 ± 2 m/kyr. Displacement of the T4/T5 riser yields only somewhat more precise rates of 3.9 ± 1.2 m/kyr and 7.2 ± 2.5 m/kyr. These new slip rates on this segment of the Kunlun Fault encompass those from Ken Mu Da (5 ± 1 m/kyr [*Kirby et al.*, 2007]), just 3 km away. Given that terrace surfaces are nearly isochronous between the two sites, it seems unlikely that these differences reflect spatial or temporal variation in fault slip-rate. Rather, we attribute the relative imprecision of slip rate estimates at Deng Qin to reflect the epistemic uncertainty of how to assign an age to the terrace risers themselves [e.g., *Hanks and Thatcher*, 2006].

4. Terrace Riser Degradation

[11] Our analysis follows a large body of work on the downslope transport of non-cohesive material (see *Hanks* [2000] for a review). Assuming that terrace risers in unconsolidated alluvium quickly ravel to the angle of repose following cessation of lateral erosion by the channel and that subsequent degradation is accomplished by slope-dependent sediment transport, one can, in principle, estimate the age of the riser. The evolution of riser gradients is typically described as a mass-transport process in which the flux of material down a topographic gradient is linearly related to local slope (S) and a bulk material transport coefficient K (in units of mass/distance * time).

$$q_s = K \partial z / \partial x \quad (1)$$

[12] Assuming conservation of mass (which is valid in the case where material removed from the top of a riser is deposited at the riser toe) and dividing through by a sediment density (ρ), the change in elevation of a point along a profile with time can therefore be described by the diffusion equation cast in terms of z (elevation) and x (distance along a profile);

$$\partial z / \partial t = \partial (q_s/\rho) / \partial x = \kappa \partial_z^2 / \partial x^2 \quad (2)$$

[13] Where κ is a coefficient of diffusion (in units of L^2/t) with empirically determined values in alluvium that range from 0.1–16.0 m^2/k.y, depending on material cohesion, climate, and biota [*Hanks*, 2000; *Pelletier et al.*, 2006].

[14] As the shape of a riser profile is a function of both its age (t) and κ value, we describe riser morphology in terms of the product of the two variables (κt – the 'degradation coefficient' of *Avouac* [1993] and *Arrowsmith et al.* [1996]). In the analysis that follows, we consider the T1/T2 and T2/T4 risers from the north side of the fault at Ken Mu Da, the T2/T3 and T3/T4 risers from the south side of the fault at Ken Mu Da, and the T2/T4 riser on the north side of the fault at Deng Qin in our analysis. Two, high-resolution topographic surveys were conducted across each riser, using a kinematic differential GPS; the resulting profiles were compared with the results of forward models to determine a 'best-fit' κt value (Figure 2), defined as the degradation coefficient that minimizes the RMS misfit between modeled and observed riser gradients. We report the 95% range of 'best-fit' κt values for each riser based on probability distribution functions computed using standard deviations in observed survey point elevations. Details of the model setup, analysis, and results can be found in the auxiliary material. We also considered a non-linear sediment transport rule [e.g., *Andrews and Bucknam*, 1987; *Hanks and Andrews*, 1989; *Roering*, 2004], but the results were not substantively different.

4.1. Local Calibration of κ

[15] A locally calibrated value for the transport coefficient (κ) was derived based on surveyed riser profiles and bounding terrace ages at Ken Mu Da. Surveyed profiles of the T1/T2, T2/T3, T2/T4, and T3/T4 risers are best fit by κt values of 13–16, 26–36, 45–58, and 54–68 m^2 (respectively) (Figure 2d). Incorporating uncertainties in the ages of bounding terrace surfaces, these κt values indicate a range of κ between 1.7 and 5.4 m^2/ka. We interpret the lower bounding value of κ in this range (i.e. slowest transport rate) to represent an unrealistically low value. First, the determination is something of an outlier and is based upon a single, maximum estimate of the age of the riser (from the overlying tread). Moreover, this riser separates the T4 and T2 treads; the T3 terrace has been obliterated at this locality, suggesting that riser must be younger than abandonment of the T3 tread. Finally, if we assign the age of the T3 terrace to this riser, we can explain its shape with a κ between 3.6 and 4.6 m^2/ka. Given that these values are within uncertainty identical to other risers at the site, we consider that the most likely range of κ at Ken Mu Da is between 3.2–5.4 m^2/kyr. These values fall within the published range of diffusion coefficients for northern Tibet (2.3–7.5 m^2/kyr [*Avouac and Peltzer*, 1993; *Avouac and Tapponnier*, 1993]).

[16] Best-fit κt values are progressively larger for older riser profiles at Ken Mu Da, indicating that risers are progressively more degraded with age. Interestingly, the

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL033073.

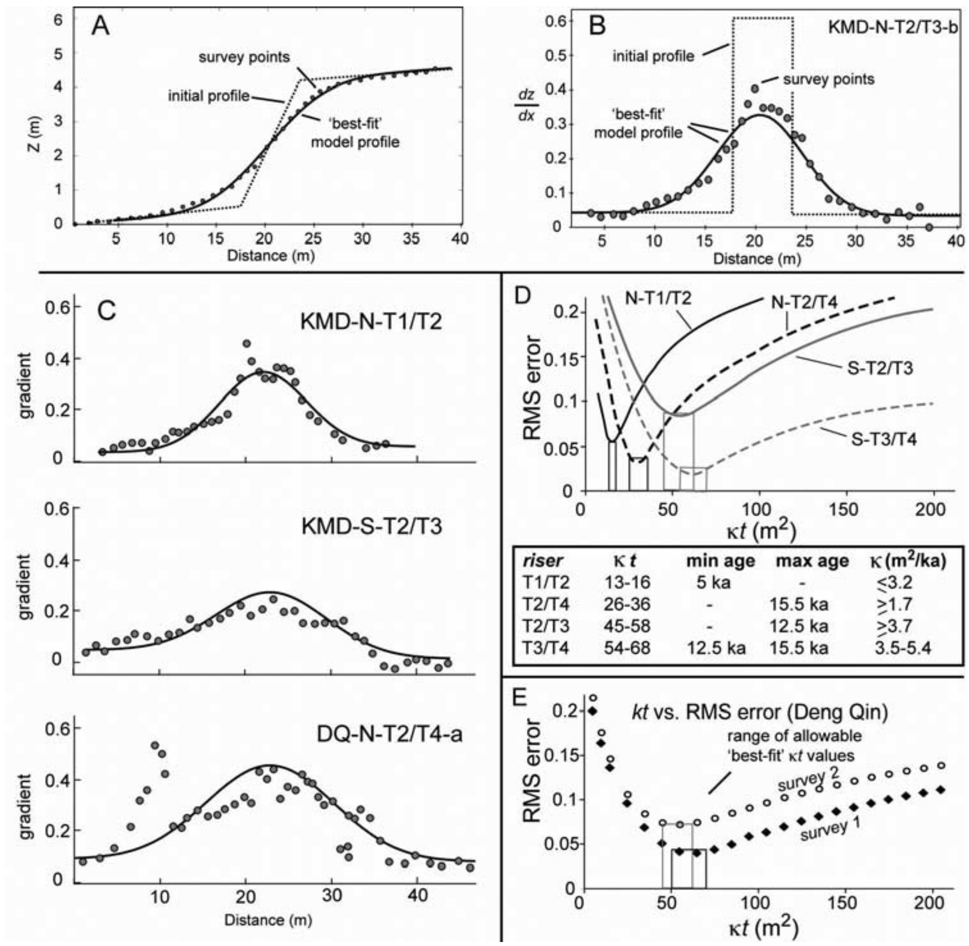

Figure 2. (a) Elevation vs. distance plot displaying the profile of a surveyed riser, the assumed initial riser form at zero age, and the 'best-fit' forward modeled riser profile. (b) Gradient vs. distance plot of the same profiles shown in Figure 2a. (c) Other gradient vs. distance plots of some of the risers analyzed in this study. Results from the linear model runs are shown for the T1/T2 and T2/T3 risers at Ken Mu Da (KMD) on the north (N) and south (S) sides of the fault, and one of the surveys of the T2/T4 riser at Deng Qin. (d) Calculated RMS misfits (errors) between surveyed riser profiles and model results under a range of κt values for the four risers surveyed at Ken Mu Da. Boxes delineate the 95% confidence interval range of best-fit κt values for each profile. The best-fit ranges of κt values each riser are combined with riser age constraints to derive a locally calibrated range of κ values. (e) Computed RMS errors between riser slopes and slopes modeled over a range of κt values, from both surveys of the T2/T4 riser at Deng Qin. Boxes delineate the 95% confidence interval range of best-fit κt values for each profile.

higher range of κ values determined for risers on the south side of the fault imply preferentially greater amounts of riser degradation. If κ values are in fact relatively constant on both sides of the fault, then these differences imply that risers have been degrading for longer periods of time on the south side of the fault than similarly age-bounded risers on the north side of the fault. This effect is potentially a result of preferential protection of riser faces on the south side of the fault from lateral erosion during host channel occupation of lower terrace surfaces.

4.2. Age of the Offset Risers at Deng Qin

[17] The relative success of this analysis leads us to ask the question – what range of ages are consistent with the degree of riser degradation at Deng Qin? A range of degradation coefficients of 49–70 m^2 adequately captures the shape of the T2/T4 riser at Deng Qin (Figure 2e). Taking the locally calibrated range of κ values observed at Ken Mu Da, we estimate an age range for this riser of 9.1–21.9 ka. Obviously, the riser cannot be older than the upper terrace surface; our radiocarbon chronology from the tread of T4 (see auxiliary material) thus restricts the allowable age to ~9.1–14.5 ka.

5. Discussion and Implications

[18] Our results demonstrate that analysis terrace riser diffusivity can be a powerful approach to refining age estimates for displaced terrace risers. Below, we discuss the implications of our study for both slip rates on the Kunlun fault and for the general case of using terrace risers to reconstruct fault slip.

5.1. Slip-Rates at Deng Qin

[19] Our analysis of riser degradation at Deng Qin suggests that the T2/T4 riser was relatively protected from

lateral erosion during occupation of the lower (T2) surface. We consider this situation to likely be more common than typically assumed [e.g., *Mason et al.*, 2006; *Mériaux et al.*, 2005]; as pointed out by *Cowgill* [2007], protection of the downstream riser is favored in settings where fault slip displaces the riser away from the axis of the valley. The age estimates derived from diffusive modeling of the T2/T4 riser (9.1 – 14.5 ka) suggest that allowable slip rates at this site are 3.7 – 7.3 m/kyr. We note that these rates are similar to the range of values (5 ± 1 m/kyr) that *Kirby et al.* [2007] inferred from displaced risers at Ken Mu Da. Thus, we have additional confidence that this rate is a reasonable estimate for slip rates along this segment of the Kunlun fault during the latest Pleistocene and Holocene. Overall our results demonstrate that, despite the wide range of uncertainties associated with riser degradation, analysis of riser morphology can provide substantial improvements to estimates of slip rate at sites where epistemic uncertainty associated with terrace chronology is large [e.g., *Cowgill*, 2007].

5.2. Diachroneity of Riser 'Age'

[20] Our results reveal a preferential protection of riser faces from lateral erosion on the south side of the fault at Ken Mu Da and on the north side of the fault at Deng Qin. We believe this is consistent with these risers having been displaced by fault motion away from the path of the stream, thus making them less likely to experience lateral erosion during occupation of the lower floodplain. Comparatively, the risers on the north side of the fault at Ken Mu Da are less degraded than those south of the fault, implying that these risers were preferentially exposed to erosion due to fault displacement. Although this may be simply a function of the vagaries of fluvial incision at Ken Mu Da, the difference in riser shape suggests that the end-member interpretation of utilizing the lower-terrace age to estimate slip rates results in an overestimate of the actual slip rate at this site.

6. Conclusions

[21] Our results place new constraints on the slip rate along the eastern Kunlun fault and demonstrate how terrace riser degradation can be exploited to refine slip rates determined from displaced fluvial terrace risers. Measurements of displaced risers coupled with ^{14}C chronology of terrace abandonment at a new site along the Kunlun fault, along the Deng Qin river, provide only broad constraints on the millennial slip rate of $\sim$3 – 10 m/kyr. Analysis of riser degradation at a nearby site allow local calibration of a slope-dependent transport coefficient (κ) of 3.2 – 5.4 m^2/ka. Application of this range of κ values to modeling of riser degradation at the Deng Qin site constrains the age of this riser to 9.1 – 14.5 ka, and yields a more precise assessment of slip rates at this site of 5.5 ± 1.7 m/kyr. These results provide additional evidence that the slip rate along the Kunlun fault decreases from its central to eastern segments [*Kirby et al.*, 2007] and highlight the utility of morphologic analysis in the interpretation of lateral slip-rates from offset terrace risers.

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