Inescapable slow slip on the Altyn Tagh fault

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Abstract. GPS surveys conducted in 1994, 1998, and 2002 on the central portion of the Altyn Tagh fault confirm left-lateral slip rates of 9±4 mm/yr, significantly slower than geological estimates of slip rate for the past several thousand years. The measurements were obtained on a 300-km-long profile between 88° and 91°E within one fault dimension of the Mw=7.6 and Mw=7.8 Kunlun earthquakes of 1997 and 2001. The inferred elastic displacements from these events is incorporated into the interpreted 1994-2002 velocity field. The recent serendipitous occurrence of these two large earthquakes on a sub-parallel fault system suggests that slip on the Kunlun fault may have recently accelerated, thereby reducing the slip rate on the Altyn Tagh fault. However, geodetic data from northern Tibet prior to the 2001 earthquake indicate present-day rates similar to long term rates. This suggests that systematic errors may be present in published geologic slip rate estimates on the Altyn Tagh fault.

1. Introduction

As the boundary between the northern edge of the Tibetan Plateau and the Tarim basin, the 2000-km-long Altyn Tagh fault system is an important component of models describing the Indo-Asian collision and the deformation of Tibet (Figure 1). The discrepancy between geologic and geodetic measurements of slip rate on the Altyn Tagh fault is important in distinguishing between two end-member models of collisional deformation in Tibet. Specifically, studies of the Altyn Tagh fault address the question of whether Indo-Asian convergence is taken up primarily by regionally distributed deformation [eg., Houseman and England, 1993; England and Molnar, 1997] or kinematically by strike-slip fault systems that separate large relatively-undeformed blocks [eg., Avouac and Tapponnier, 1993; Tapponnier et al., 2001].

Geologic investigations that quantify the slip rate on the Altyn Tagh fault by cosmogenic dating of offset Quaternary landforms yield rates in the range of 20-30 mm/yr averaged over several thousand years [Meriaux et al., 2000, 2003]. These values favor a kinematic model of Tibetan deformation and suggest that the Altyn Tagh fault accommodates nearly as much of the Indo-Asian collision as do the Himalaya.

Geodetic estimates of slip rate, however, yield rates that are 2-3 times lower. The geodetic studies consist almost entirely of GPS data obtained in the last decade, although some leveling data have also been used [Bendick et al., 2000]. There have been no major earthquakes on the Altyn Tagh fault for several hundred years [Washburn et al., 2003], and so the assumption is made that the observed surface velocity field precisely quantifies the long-term basal shear strain applied to the seismogenic fault. Bendick et al. [2000] reported a left-lateral slip rate of 9±5 mm/yr, and Shen et al. [2001] found a similar rate of 9±2 mm/yr. Zhang et al. [2004] report even lower geodetic rates on the Altyn Tagh fault: 5.6±1.6 mm/yr at 90°E and 5.0±2.0 mm/yr at 95°E. Slip rates of ~10 mm/yr or less seem to be characteristic of the other large strike-slip faults in Tibet, including the Karakorum and Kunlun fault systems [Zhang et al, 2004]. Thus, the geodetic data suggest that the Indo-Asian convergence is accommodated by crustal thickening and widespread, distributed deformation rather than by rapid slip on faults bounding rigid blocks.

In this study, we return to the GPS profile first measured by Bendick et al. [2000], crossing the Altyn Tagh fault between 88° and 91° E. The data from this profile now consist of three sets of measurements spanning eight years. This purpose of this study is two-fold: to confirm the low slip rate initially reported by Bendick et al. [2000] and to use the strain measurements to provide some constraint on the locking depth of the Altyn Tagh fault.

2. GPS Surveys and Data Analysis

In 1994, fourteen GPS sites were installed along a 300-km profile between 88° and 91° E. The profile crosses the fault obliquely at 38.4°N, 89.9°E (Figure 1). The location and orientation of the GPS profile is largely dictated by logistical constraints in this rugged, remote region of western China. Each site consists of a screw drilled into rock or concrete, with the exception of two sites (HATU and LOBU), in which old survey markers were used. The quality of the GPS points varies greatly, from bedrock to large boulders to man-made structures.

Table 1a. Velocities of GPS points relative to TERR

Station	Longitude (E)	Latitude (N)	Slip rate east (mm/yr)	Slip rate north (mm/yr)
Stations measured 1994 - 1998 (from Bendick et al., 2000)				
LOBU	88.265	39.446	-1.8 ± 1.6	-3.6 ± 3.5
MILA	88.899	39.241	-4.3 ± 1.5	-6.2 ± 3.2
KUMU	38.849	89.141	-5 ± 1.5	-7 ± 3.3
PAXI	89.282	38.614	-13.2 ± 1.6	-13.5 ± 3.5
NICE	89.630	38.468	-4.2 ± 1.9	-7.1 ± 4.4
KLSA	89.905	38.409	-1.5 ± 1.5	-1.8 ± 3.4
SCAN	89.926	38.409	-3.6 ± 2.2	4.1 ± 4.6
SCAS	89.932	38.404	-2 ± 2.9	-3.3 ± 5.3
HAPI	89.968	38.391	-1.5 ± 1.5	-3.5 ± 3.4
TERR	90.085	38.391	0.0	0.0
MULI	90.418	38.376	-0.9 ± 1.5	0.2 ± 3.2
HATU	90.907	38.285	-2.2 ± 1.4	-1.5 ± 3.1
MANG	91.821	37.887	-0.6 ± 1.4	1.4 ± 3.2
Stations measured 1994 - 2002				
LOBU	88.265	39.446	-7.3 ± 19.3	1.8 ± 8.4
MILA	88.899	39.241	-3.5 ± 1.1	-0.6 ± 1.4
PAXI*	89.282	38.614	-3.5 ± 5.6	-1.4 ± 2.4
NICE	89.630	38.468	-3.1 ± 0.4	0.1 ± 0.9
KLSA	89.905	38.409	1.2 ± 0.6	-0.5 ± 1.0
SCAN	89.926	38.409	-0.3 ± 1.5	-1.1 ± 0.7
SCAS	89.932	38.404	0.4 ± 0.3	-1.1 ± 0.5
HAPI	89.968	38.391	0.2 ± 1.2	-0.2 ± 0.8
TERR	90.085	38.391	0.0	0.0
MULI	90.418	38.376	2.0 ± 0.8	-1.1 ± 0.2
HATU	90.907	38.285	0.1 ± 0.2	-2.6 ± 0.2
MANG	91.821	37.887	4.8 ± 1.3	-1.5 ± 0.1
Stations measured 1998-2002				
ROQG	88.153	39.030	-4.4 ± 8.7	-4.6 ± 4.0
POWR	88.849	39.027	-5.1 ± 5.6	-4.0 ± 2.9
HOTL	88.898	39.243	-5.4 ± 7.8	3.2 ± 4.1
SFER	89.056	38.968	-4.3 ± 5.7	-2.5 ± 2.9
COOL	90.131	38.031	0.9 ± 2.8	0.5 ± 1.6

Table 1b. Velocities of GPS points relative to SLUB

Station	Longitude (E)	Latitude (N)	Slip rate east (mm/yr)	Slip rate north (mm/yr)
Stations of the western profile, measured 1998-2002				
SLUB	85.143	37.123	0.0	0.0
ATUB	85.144	37.057	-12.9 ± 12.2	4.6 ± 5.8
SBWM	85.149	37.114	2.4 ± 11.3	13.4 ± 5.7
GRUB	85.156	36.986	-8.9 ± 10.8	-2.0 ± 5.6
QUIS	85.427	37.582	-4.3 ± 16.6	-4.9 ± 6.4
AQIN	85.456	37.387	-12.6 ± 15.3	4.4 ± 6.6

* Velocity calculation for PAXI excludes the 1998 measurement.

Five sites were added to the profile in 1998 (COOL, HOTL, POWR, ROQG, and SFER), and a second 60-km profile of six sites was installed 300 km to the west, at 85° E, in the mountains south of the city of Qiemo. When we returned for the third campaign, we found one station in the main profile (KUMU) had been destroyed by a communications crew. Thus, a total of 23 sites were measured in 2002.

The 2002 survey was conducted with Trimble 4000 and 5700 series GPS receivers. The data were collected at 30 s intervals for 1-5 days at each site, with the entire survey spanning a length of 3.5 weeks. Site TERR, a bedrock control-point located 6 km south of the fault, operated continuously as a local base station, although a power failure disrupted data collection for several days. Measurement of the western profile was plagued by persistent clouds, rain and power failures, and the data from those six sites are quite sparse.

The raw data were analyzed using Bernese 4.2 GPS processing software. Several IGS sites were co-processed as regional constraints, including stations located in Siberia, Tibet, and India. The velocity of each campaign station was determined by comparing the coordinates in 1994 to results from 1998 and 2002. All coordinate differences of the main profile were calculated relative to local control-point TERR (Table 1a). In the western profile, coordinate differences were calculated relative to SLUB (Table 1b). For the stations that were measured in all three campaigns, the coordinate differences were fit to a line using a least-squares method. The fit was weighted by the individual position error of each station in each year. For the stations installed in 1998 and measured twice, the velocity is simply the slope of the line and the error is the combined position error of the 1998 and 2002 surveys. Thus, the errors for the 1998-2002 stations are much larger than the errors for the stations measured in all three campaigns.

Table 2. Kunlun 2001 earthquake slip distribution (from Lin et al., 2002)

Segment	Longitude	Slip (m)
1	90.3	2.0
2	91.0	5.0
3	92.0	6.5
4	93.0	11.0
5	94.0	3.0

To correct for the two large Tibetan earthquakes that occurred between 1994 and 2002, we used the Coulomb 2.0 software [Toda and Stein, 2002] to determine the estimated elastic displacement at each station due to the earthquakes. The Manyi 1997 event was located near 35°and 87° E (Figure 1), with an average slip of ~3.5 m [Peltzer et al., 1999]. The 170-km rupture was 500 km from the survey profile and had little effect on the relative station motions within our survey; even though the values were small (~1-2 mm), the correction was still applied. The 400-km-long Kunlun 2001 earthquake was located at ~36° N, between 90° and 95° E, 250 km from the southeastern end of the main profile and close enough to have a significant effect on the observed relative motion of the survey stations (Figure 1) [Van der Woerd et al., 2002]. To test the sensitivity of our corrections we calculated displacements from an uniform rupture of 5 m and also from a five segment rupture with slip values assigned according to the slip distribution reported by Lin et al. [2002] and Fu and Lin [2003] (Table 2). In subsequent analyses we used the second, more complex corrections, but difference between the two procedures was less than 10%. When the effects of both earthquakes are removed from the observed station motions, the fault-parallel velocities of the site closest to the earthquake, Mangnai (MANG), is increased by about 6 mm/yr, while the velocities of more distant sites, such as Roquiang (ROQG), are increased by about 4 mm/yr. (Figure 2).

The site PAXI resulted in a velocity twice as high as any of its neighboring sites in 1998 [Bendick et al., 2000]. Measurements in 2002 revealed no such velocity anomaly, leading us to conclude that the 1998 measurement at PAXI was contaminated by a misaligned tribrach (Table 1). The site HATU, located within an oil field outside the town of Huatagou, was excluded because of large displacements we infer to have been caused by oil extraction. Finally, data collection at LOBU, an ancient survey marker buried in a sand dune, was interrupted by a sandstorm that both disrupted power and shifted the tripod.

3. Results

The slip rate of the Altyn Tagh fault is found by fitting the station displacements, relative to TERR, to a two-dimensional elastic displacement model [Okada, 1985]. Slip rate and depth are varied to find the values that give the least misfit between the observed and calculated fault-parallel motions. Because of the rather large coordinate error ellipses for some of the sites, especially those for which no least-squares weighted fit was possible, there is a range of values that falls within 1σ of the best fit.

Thefault-locking depth is poorly constrained by our data because two geodetic points at crucial distances were destroyed prior to 2002: KUMU [Bendick et al., 2000] and the unstable point HATU. The loss of these two points results in a dearth of stations between 30 and 100 km from the fault, which prevents a tight constraint on those parts of strain curve best located to constrain locking depth (Figure 3). The best fit to the data is a velocity of 9±4 mm/yr and a depth of 20 km (Figure 3), although any depth greater than 8-10 km and less than about 50 km provides a statistically acceptable fit (Figure 3 inset). Omitting the data with large uncertainties does not change the result, as the model is primarily constrained by stations with errors of ±1-2 mm/yr. Fault-normal convergence is calculated to be 2±2 mm/yr.

4. Discussion and Conclusions

A slow slip rate on the Altyn Tagh fault in the past 8 years (<10 mm/year) has now been confirmed independently by several authors [Bendick et al., 2000; Shen et al., 2001; Zhang et al., 2004], yet published geological rates feature velocities at least twice as fast [Meriaux et al., 2000, 2003]. If both of these velocities are correct, the results require that velocities have slowed on the Altyn Tagh fault in the past few thousand years. A paleoseismological study of major earthquakes on the Altyn Tagh fault in the last 2-3 kyr is tentatively consistent with a slip rate of 1-2 cm/yr, a range that essentially bridges the gap between the geologic and geodetic values [Washburn et al., 2003]. Is a structural mechanism available in northern Tibet that could cause a recent change in slip rate?

One such mechanism might be recent increased slip on a nearby subparallel fault, such as the Kunlun fault. Just as four hundred km of localized coseismic slip on the Kunlun fault had the effect of an instantaneous reduction of slip on the Altyn Tagh fault, an uniform increase of slip of the entire Kunlun fault system in the past several hundred years could have the effect of reducing present day slip on the entire Altyn Tagh fault system. However, Van der Woerd et al. [2000] report a long-term, uniform, constant slip rate of 11.5 mm/yr over the last 40 kyr for much of the length of the Kunlun fault, a value that corresponds to the estimated geodetic rates of ~8-11 mm/yr for the past decade [Zhang et al., 2004]. Thus neither geologic nor geodetic evidence indicates that the Kunlun fault has recently increased in activity.

The remaining possibility is that the entire northern part of the Tibetan plateau has recently slowed due to, for example, a recent reduction in clockwise rotation of the plateau. We have no independent evidence to support this and conclude that our inescapable slow slip rate suggests that published geological velocities may have a systematic error that biases reported slip-velocities to higher rates.

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Figure 1.

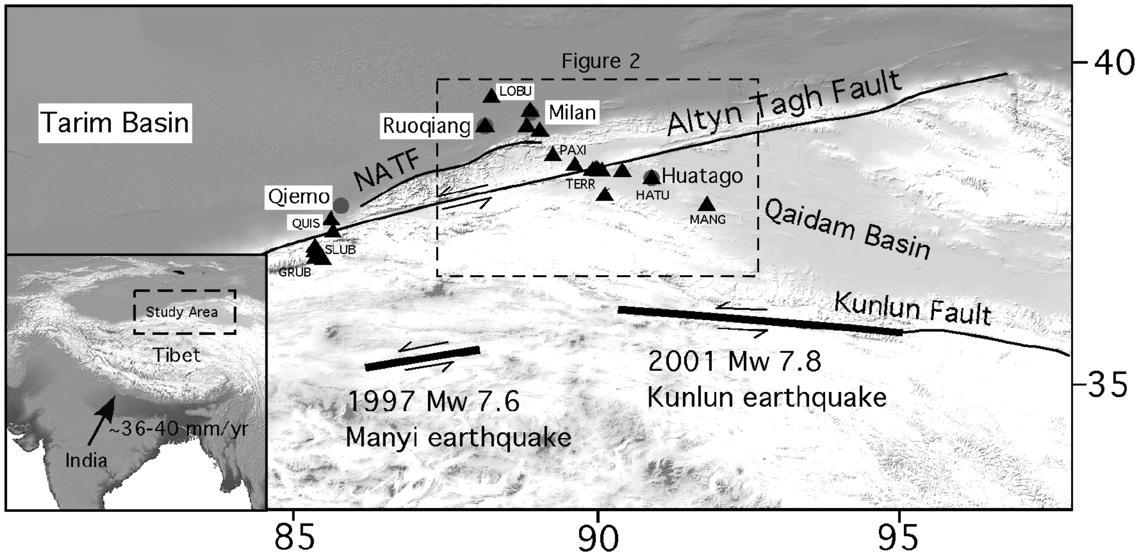

Figure 1. Map of the Altyn Tagh fault system in northern Tibet, with the location of the GPS stations indicated. Locations of the Manyi 1997 and Kunlun 2001 earthquakes, which occurred on separate segments of the Kunlun fault, are from Peltzer et al., 1999; Lin et al., 2002; and Van der Woerd et al., 2002. **(inset)** Map of the Indo-Asia collision, with the study area indicated. Convergence between India and Eurasia is ~36-40 mm/yr (Zhang et al., 2004).

Figure 2.

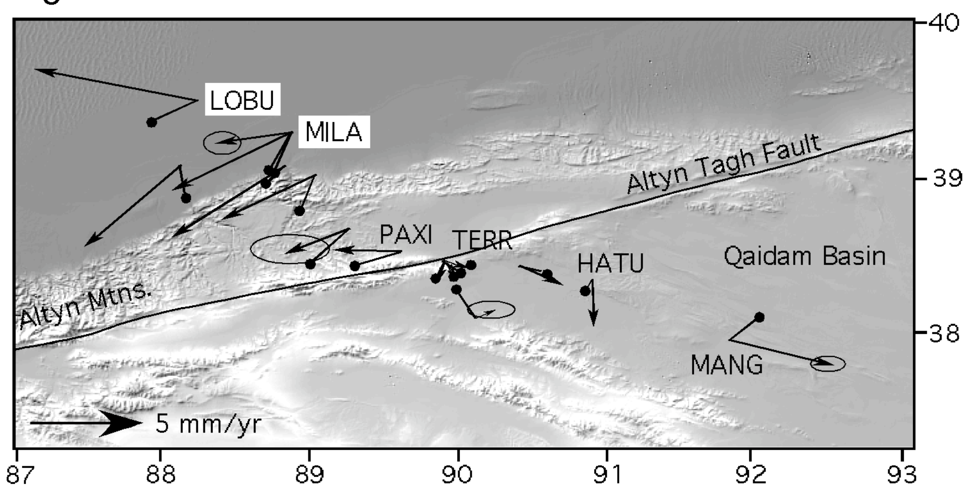

Figure 2. Map of the GPS survey with velocities in mm/yr. Shown are both the station velocities before correcting for the 1997 and 2001 Tibetan earthquakes (circles), and the velocities after the correction is applied (arrows).

Figure 3.

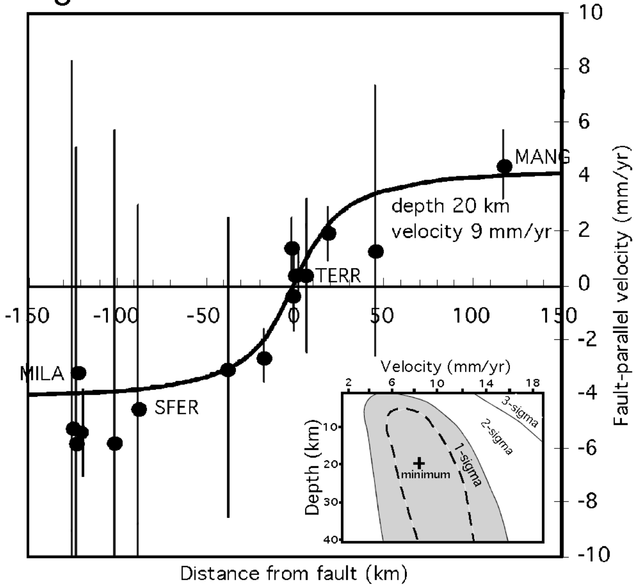

Figure 3. The two-dimensional elastic deformation model is plotted as distance from fault versus fault-parallel velocity, with individual station velocities and errors. The local base station TERR is at 0 km in this model. Many of the stations north of the fault (negative distances) were installed in 1998 and have larger errors, but the model is constrained primarily by the 8-year stations with errors of ±1-2 mm/yr. The best-fit value has a left-lateral strike-slip velocity of 9 mm/yr and a depth of 20 km. **(inset)** Plot of misfit values for the velocity versus depth comparison. There is a wide range of depth values within the 1σ range.