Characteristic slip distribution and earthquake recurrence along the eastern Altyn Tagh fault revealed by high-resolution topographic data

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ABSTRACT

The seismic cycle model is roughly constrained by limited offset data sets from the eastern Altyn Tagh fault with a low slip rate. The recent availability of high-resolution topographic data from the eastern Altyn Tagh fault provides an opportunity to obtain distinctly improved quantitative, dense measurements of fault offsets. In this paper, we used airborne light detection and ranging data and unmanned aircraft vehicle photogrammetry to evaluate fault offsets. To better constrain the large earthquake recurrence model, we acquired dense data sets of fault displacements using the LaDiCaoz_v2.1 software. A total of 321 offset measurements below 30 m highlight two new observations: (1) surface-slip of the most recent earthquake and multiple events exhibit both short-wavelength (m-scale) and long-wavelength (km-scale) variability; and (2) synthesis of offset frequency analysis and coefficient of variation indicate regular slip events with ~6 m slip increment on fault segments to the west of the Shulehe triple junction. The distribution of offsets and paleoseismological data reveal that the eastern Altyn Tagh fault exhibits characteristic slip behavior, with the characteristic slip of ~6 m and a recurrence period ranging from 1170 to 3790 years. Paleoseismic recurrence intervals and slip increments yield mean horizontal slip-rate estimates of 2.1–2.6 mm/yr for fault segments to the west of the Shulehe triple junction. Assuming a 10 km rupture depth and a 30 GPa shear modulus, we estimated a characteristic slip event moment magnitude (Mw) of ~7.6. Finally, we discuss the interaction mechanism between Altyn Tagh fault (strike-slip) and the NW-trending thrust faults (reverse faults) that caused the sudden decrease of sinistral slip rate at the Shulehe and Subei triple junctions; our results support the eastward “lateral slip extrusion” model.

INTRODUCTION

Identifying earthquake recurrence behavior is significant for seismic hazard assessments and understanding fault-rupture processes (Stein and Wysession, 2009; Burbank and Anderson, 2011; McCalpin, 2012; Zielke et al., 2012). Geomorphic offsets that have been displaced by coseismic surface rupture can be analyzed to identify earthquake recurrence behavior (e.g., Klinger et al., 2011; Haddon et al., 2016; Ren, 2016). One of the most widely applied earthquake recurrence models (Sieh, 1996) is the characteristic earthquake model, which suggests the repetition of same-size offset increments along a given fault (Schwartz and Coppersmith, 1984; Sieh and Jahns, 1984; Wesnousky, 1994). Obtaining a sufficient and precise along-fault offset data set is vital to identify long-term earthquake recurrence behavior. Furthermore, knowledge of along-fault slip distribution during a single earthquake or multiple earthquakes is important for other reasons, including a better understanding of the relationship between earthquake size and coseismic displacements (e.g., Peltzer and Tapponnier, 1988; Tapponnier et al., 2001; Manighetti et al., 2005; Li et al., 2012; Stewart et al., 2018) and fault kinematics and fault mechanics (e.g., Armijo et al., 1989; Van der Woerd et al., 1998; Gaudemer et al., 1995; Manighetti et al., 2001; Replumaz et al., 2001; Van Der Woerd et al., 2002; Hubert-Ferrari et al., 2002; Manighetti et al., 2005; Stewart et al., 2018).

Unfortunately, reconstructions of along-fault slip accumulation and derived earthquake recurrence models are usually non-unique (Zielke et al., 2015). The non-uniqueness arises from several sources, including insufficient density offset measurements and the non-uniqueness inherent in offset reconstructions (Rockwell et al., 2002; Haeussler et al., 2004; Zielke et al., 2010; Elliott et al., 2012; Oskin et al., 2012; Gold et al., 2013; Rockwell and Klinger, 2013; Toda and Tsutsumi, 2013). Recently, the explosion in high-resolution topographic data collection and processing techniques, especially airborne light detection and ranging (LiDAR) and semi-automatic offset-measurement approaches, such as LaDiCaoz (Zielke and Ramon, 2012) and “3D_fault_offsets” (Stewart et al., 2018), has reduced the non-uniqueness of such measurements (Zielke et al., 2015).

New high-resolution topographic data from airborne LiDAR along the eastern Altyn Tagh fault (ATF) in arid western China, supplemented with unmanned aircraft vehicle photogrammetry data–derived drone images, illuminate hundreds of clearly offset small-scale geomorphic features along the fault trace (Fig. 1). We follow the methodology of Zielke and Arrowsmith (2012) to evaluate the along-fault displacement distribution of the most recent earthquake and to...
measure larger, cumulative offsets. Here, we present slip measurements along 150 km of the eastern Altyn Tagh fault. Our goal is to discuss the earthquake recurrence behavior of the eastern Altyn Tagh fault by synthesizing offset distribution, fault segmentation, and paleoseismological data.

**GEOLOGICAL BACKGROUND**

The Altyn Tagh fault is an intracontinental sinistral strike-slip fault that forms a major boundary fault between Tibetan Plateau and Tarim Basin on the northern margin of the Tibetan Plateau (Fig. 1A) (Molnar and Tapponnier, 1975; Tapponnier et al., 2001). The ATF plays a significant role in the eastward extrusion of the Tibetan Plateau and accommodates the ongoing northward convergence of the Indian plate into the Eurasian plate (Fig. 1A) (Molnar and Tapponnier, 1975; Molnar and Tapponnier, 1977; Avouac and Tapponnier, 1993).

This paper focuses on the easternmost segment of the ATF, which is the key component of the structural transformation between the sinistral slip on the ATF and convergence across the thrust faults of the Qilian Shan, Daxue Shan, and Danghe nan Shan (Fig. 1B). The ~180-km-long eastern ATF is divided into five subsegments based on the presence of step-over and intersecting reverse faults known as triple junctions (e.g., McKenzie and Morgan, 1969; N.14°

![Figure 1](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/doi/10.1130/GES02116.1/4907638/ges02116.pdf)

Figure 1. (A) Simplified tectonic map of the Tibetan Plateau. (B) Tectonic and geomorphic map of the eastern Altyn Tagh fault (ATF). The white rectangle represents the extent of high-resolution topographic data. Earthquake data derived from Jia and Yufang (2017). Detailed map of faults in the northeastern margin and ATF is modified from Luo et al. (2019). Blue lines indicate drainage. SH—Subei–Hongliu Valley; HS—Hongliu Valley–Shibaocheng; SB—Shibaocheng–Bago Valley; BS—Bago Valley–Shulehe River; SC—Shulehe River–Chijin.
Raterman et al., 2007), namely, the Subei–Hongliu Valley (SH), Hongliu Valley–Shibaocheng (HS), Shibaocheng–Bago Valley (SB), Bago Valley–Shulehe River (BS), and Shulehe River–Chijn (SC) segments (Fig. 1B). The historical record of earthquakes in this area is incomplete prior to 1900, and there has been a lack of surface-rupturing earthquakes on the ATF (Xu et al., 2015) since 1609 (Fig. 1B).

The slowly changing, arid landscape along the eastern ATF ensures maximum preservation of offset features, reducing the non-uniqueness of feature restorations and the interpretation of paleoearthquake slip events. However, few constraints exist on the paleoseismic activity of the eastern ATF (Chinese State Bureau of Seismology, 1992; Luo et al., 2019). During a regional mapping-surveying project (Chinese State Bureau of Seismology, 1992), researchers measured fault offsets with a tape, but without precise location information.

The slip rate of the ATF declines as it approaches its eastern termination. Reported slip rates exceed 8 mm/yr west of the Subei triple junction (Fig. 1B) (Washburn et al., 2003; Mériaux et al., 2004; Wallace et al., 2004; Cowgill, 2007; Zhang et al., 2007; Gold et al., 2011), declining to between 2.2 and 4.8 mm/yr on the BS segment (Xu et al., 2005; Zhang et al., 2007; He et al., 2013), and <2.2 mm/yr to the east (Zhang, 2016), ultimately terminating near Chijn (Fig. 1B).

## DATA AND METHODS

### High-Resolution Topographic Data

Airborne LiDAR data (P1, P2, P3, P4, P7, and P9; detailed information provided by Fig. S1 in the Supplemental File) were collected with a Harri68i LiDAR system. The data cover a 1-km-wide swath for 150 km along the eastern Altyn Tagh fault. We supplemented the LiDAR data with unmanned aircraft vehicle (UAV) imagery collected with a Phantom 3 Professional platform equipped with a 12-megapixel camera. Each photograph taken by the camera was precisely located by GPS using WGS84 geographic coordinates. The images were processed to obtain a sub-decimeter structure-for-motion (SFM) model following the workflow of Röder et al. (2017).

#### LaDiCaoz_v2.1 Analyses

We used the MATLAB-based tool and graphical user interface LaDiCaoz_v2.1 (Haddon et al., 2016) (http://sites.google.com/site/olafzielkephd/ladicaoz_v2) to measure the horizontal slip and estimate associated uncertainties from offset landforms along the eastern ATF. Minimum and maximum offset values were determined by matching river channel margins upstream and downstream of the fault, following the method of Zielke et al. (2015). The simplified workflow of LaDiCaoz_v2.1 is described in Figure S2 in the Supplemental File. In total, we measured 371 displaced geomorphic markers including 321 offsets (optimal horizontal displacement less than 30 m) (detailed information provided in the tables in the Supplemental File). Due to space constraints, all 321 offset-measurement results are not presented here; instead, several offset examples are highlighted in the following paragraph.

### Offset Frequency-Analysis Modeling

In order to identify individual earthquakes from large data sets of offset measurements that contain natural variability, the data were analyzed using probability and statistics (McGill and Sieh, 1991; Zielke et al., 2010; Klinger et al., 2011; Salisbury et al., 2012; Ren, 2016; Kurtz et al., 2018). The probability distribution of offsets along the fault was created using an asymmetric Gaussian distribution for each offset, summing the individual offset probability distributions and normalizing the area beneath the resulting curve to one (Fig. 2) (as in Equation 1):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-x_0)^2}{2\sigma^2}},$$

where $f(x) = \text{PDF}$ (probability distribution function), $m = H_{\text{max}}, \sigma = H_{\text{min}}, \tau = H_{\text{max}}$, and $e$ is Euler's number.

To account for uncertainty in offset estimations, we used the offset value as a mean and $\sigma, \tau$ (the standard deviations) to represent the uncertainties derived from minimum and maximum displacement measurements, respectively (Kurtz et al., 2018). Because the area under the individual PDF curve is 1, the resulting PDF curve is truncated at zero to ensure the area under the curve is 1.
the larger cumulative slip has a "flatter" curve, and when we sum individual PDF curves for all offsets, usually only one peak for the youngest event can be identified from the cumulative offset probability density (COPD) (as in Kurtz et al., 2018). Thus, recognition of a slip pattern associated with individual earthquake events may be hindered by noise or erroneous measurements (Schwartz and Coppersmith, 1984; McGill and Sieh, 1991; Zielke et al., 2010; Klinger et al., 2011; Salisbury et al., 2012; Kurtz et al., 2018). Therefore, in order to identify paleoearthquake events from probability distribution function, first, we truncated individual offset PDFs (the red curve) by \( H_{\min} \) and \( H_{\max} \) (Fig. 2); then, we stacked and summed to generate the cumulative offset probability density (COPD), as in Equation 2:

\[
\text{COPD} = \sum_{i=1}^{n} \text{PDF}(i).
\]

Several studies (e.g., McGill and Sieh, 1991; Klinger et al., 2011; Zielke et al., 2015) have shown that earthquake events can be distinguished by identifying peaks in the COPD.

## RESULTS

### Coseismic and Cumulative Offsets

At the Wulangxiu site (location labeled on the LiDAR data in Fig. S1 [footnote 1]), the fault trace shows two splays. There is no obvious horizontal offset at the northern splay (trace indicated by arrows in Fig. 3B), but the southern branch systematically displaces drainage systems (Fig. 3B). The preservation quality of the gully banks suggests that this gully is relatively...
young, and the quality of the deflections suggests that it has only been displaced by the most recent earthquake (Fig. 3D). The LiDAR data indicate a 5.5 m offset for the gully (Fig. 3C). At the Buerge site (location indexed in Fig. S1), all channels are systematically displaced by the fault (Figs. 4A and 4B). The preservation quality and size of the small gullies indicate that these channels were probably displaced by a single event. LiDAR measurements indicate that the gully was left-laterally displaced 5.6 m (Fig. 4C).

Compared to single-event offsets, cumulative offsets are usually better preserved by geomorphic markers such as river terraces and/or the development of a large gully or ridge, which are more likely to have been repeatedly displaced by multiple earthquakes (Li et al., 2012; Ren, 2016). In this study, we only selected those geomorphic markers that could be easily identified.

At Xiarilapai site 1 (location indexed in Fig. S1 [footnote 1]), terrace risers are displaced by the fault (Fig. 5D). The channel is wider here compared to its width at the Wulangaxiu site (Fig. 5A), which suggests a longer fault displacement history at Xiarilapai 1 than at Wulangaxiu. By reconstructing the hill-shade map and slope map, the horizontal offset of the terrace riser is calculated to be 11.9 m (Fig. 5D). At the Harihade site (location shown in Fig. S1), the fault trace is straight and clear (Figs. 6A and 6D). The terrace riser and gully are both left-laterally displaced by the fault (Fig. 6A). Using 16.8 m of back-slip reconstruction, the hill-shade map shows that the original river flowed across the fault trace (Fig. 7C). At Xiarilapai site 2 (location shown in Fig. S1), the same channel is shallower and wider (Fig. 7D) than the channel at Wulangaxiu (Fig. 3D), which also suggests a cumulative displacement history.
Figure 5. Xiarilapai site 1: (A) the location and strike of the fault (cyan line), trends of both the upstream and downstream areas (yellow line), and location of the profiles (red line and blue line) on the hill-shade relief map with contours; (B) slope map with the location and strike of the fault (black arrows) and field photo direction; (C) 11.9 m backslip on the hill-shade map with contours; and (D) field photo showing the fault trace (red arrows) and earthquake offset. The inset curves show the misfit function (lower misfit indicates a better offset reconstruction) indicating the optimal horizontal value of 11.9 m; blue lines with arrow indicate drainage.
Our measurements show that this stream has been left-laterally displaced by 13.4 m (Fig. 7C).

**Correlation with Data from Other Sources**

In order to validate the results from LaDiCaoz_v2.1, the obtained values were compared to independent measurements from prior studies. We measured two sites in the field and compared previously published measurements from two sites (Meyer et al., 1996; Seong et al., 2011). To augment these measurements, we re-measured a randomly selected subset of sites using the “3d_fault_offsets” tool published by Stewart et al. (2018). As the amount of offset increases, deviation away from the one-to-one line (or identity line) also increases (Fig. 8). These discrepancies are mainly related to different assumptions regarding fault position and pre-earthquake channel morphology (Zielke et al., 2015).

**Offset Frequency Analysis**

The LiDAR data (P1, P2, P3, P4, P7, P8, and P9) and UAV data (P5 and P6) cover four fault segments (HS, SB, BS, and SC) along the eastern ATF (Fig. 9). For each fault segment, we summed the probability distributions of <30 m offsets to produce a COPD, to identify possible single-event paleoseismic offsets (Zielke et al., 2012; Haddon et al., 2016; Ren, 2016; Kurtz et al., 2018). The COPD plots vary with different peaks by fault segment (Fig. 9). Along the HS segment, we find four clearly separated COPD peaks, centered at 6.3 m, 11.8 m, 17.8 m, and 22.4 m (Fig. 9). Three peaks are clear on the SB segment at 6.2 m, 12.1 m, and 18.4 m, with a fourth speculative peak at 23.1 m (Fig. 9). On the BS segment, three clear peaks are again observed, centered at 5.9 m, 11.6 m, 18.1 m, with a speculative fourth peak at 27.1 m (Fig. 9). The SC segment exhibits only two clear peaks at 5.3 m and 10.8 m, with speculative peaks at 18.7 m, 21.7 m, and 28.8 m (Fig. 9). The height of the COPD peaks...
decay exponentially with increasing cumulative fault slip (Fig. 9); this common phenomenon can be explained by the fact that the longer the period of time that offset markers undergo erosion, the more poorly they will be preserved (Klinger et al., 2011). To correlate a COPD peak to a corresponding paleoseismic event, we assumed that the smallest local offset along the entire fault represents slip associated with the most recent event, and that the frequency of production of geomorphic markers exceeds the earthquake recurrence rate (Ren, 2016). Applying these assumptions, we interpret the remarkably consistent COPD peak of ~6 m along the entire eastern ATF to be indicative of average offsets associated with the most recent event. Peaks centered at ~12 m and ~18 m (i.e., multiples of 6 m) suggest that ~6 m displacement may be characteristic of slip events along the eastern ATF.

## DISCUSSION

### Along-Fault Slip Variations

Along-fault slip variations have been measured for many historic strike-slip earthquakes (Wallace, 1987; Jones and Wesnousky, 1992; Rockwell et al., 2002; Haeussler et al., 2004; Lin et al., 2009; Liu-Zeng et al., 2009; Xu et al., 2009; Ren, 2016) and often exhibit short-wavelength (m-scale) variation. Along the HS segment, our slip measurements are sufficiently dense to show short-wavelength variability (m-scale) that can be associated with the most recent event (black thin line, lower left of Fig. 9). This long-wavelength (km-scale) slip variation lies within broader changes, as illustrated by the dark-gray stripes that define groups of similar measurements along each segment (Fig. 9).
Along-fault slip distribution of a single event may be related to fault zone conditions, prior earthquake surface-rupture history, or irregularities in fault geometry (Bürgmann et al., 1994). The short-wavelength (m-scale) changes in along-fault surface slip should be attributed to very shallow-depth physical conditions along the rupture plane, and the non-elastic response of near-surface lithology to coseismically imposed high strains, rather than being interpreted to reflect rupture characteristics at seismogenic depths (Zielke et al., 2015). Studies show that the long-wavelength (km-scale) changes in along-fault surface slip may be attributed to changes in constitutive relationships that dominate the rupture process at seismogenic depths and to the presence of complex fault geometries such as fault terminations, step-overs, restraining bends, and triple junctions (Klinger et al., 2006; DuRoss et al., 2016). The systematic along-strike decline in the magnitude of slip along the BS segment, approaching the Shulehe triple junction, may be such a response. The average slip of the most recent event on the SC segment is 5.3 m, which is lower than the ~6 m displacement observed on other fault segments. This lack of sinistral displacement may indicate that slip on this segment has been structurally transformed into local crustal shortening in association with the active thrusting that occurs within the Qilian Shan (Xu et al., 2005).

Aside from the most recent events, the clear separation of COPD peaks suggests that additional single-event offsets may be identified. The COPD peaks on the HS, SB, and BS segments are well separated, while the COPD peaks on the SC segment are ambiguous (Fig. 9). The cumulative-slip COPD peaks on the HS, SB, and BS segments all appear to be separated by approximately average increments with small 1 sigma standard deviation, respectively: HS segment = 5.6 ± 0.7 m, SB segment = 5.8 ± 0.7 m, and BS segment = 6.8 ± 1.5 m (Fig. 9). Overall, this result indicates little variation in slip per event along most of the eastern ATF. Less clear COPD peaks along the easternmost SC segment may be a result of eastward-tapering displacement toward the tip of the ATF.

Regularities of Cumulative Offsets

To evaluate the regularity of cumulative offsets, we followed the method described in previous studies (e.g., Blasi et al., 2002; Becker et al., 2013; Zielke et al., 2015) to calculate the coefficient of variation (CV). CV values reliably capture variation in a data set in a normalized, non-dimensional way, using CV = std (data)/mean (data), where std (data) and mean (data) are the standard deviation and mean of the data, respectively. A value of CV = 0 represents perfect regularity, whereas CV = 1 indicates random behavior (Zielke et al., 2015), i.e., larger CV values indicate more random behavior, and smaller CV values indicate more regular behavior.

We calculated the CV for horizontal slip across each of the study fault segments, as shown in Figure 9. The observed cumulative offsets along the HS and SB segments show a CV value of 0.13, indicating a remarkably regular repetition of large (5.6 ± 0.7 m to 5.8 ± 0.7 m) slip events (Fig. 9). This value is similar to the CV of ~0.13 calculated for the Fuyun fault, which displays characteristic slip (Zielke et al., 2015). The BS segment has a CV value of 0.22, indicating a quasi-regular recurrence of large (6.8 ± 1.5 m) slip events (Fig. 9). The BS segment value corresponds approximately to the CV of ~0.13 calculated for the Fuyun fault, which displays a quasi-regular recurrence of large (6.8 ± 1.5 m) slip events (Fig. 9). The SC segment has a CV value of 0.36, indicating a more variable slip recurrence compared to the HS, SB, and BS segments (Fig. 9).

The similar high-regularity recurrence of slip on the HS, SB, and BS segments, which all have CV values of less than 0.3 and clear COPD peaks, shows that these segments underwent similar large earthquake recurrence histories. The lack of sufficiently wide (>3 km) geometrical discontinuities that can completely stop earthquake rupture (Wesnousky, 2006) along the HS, SB, and BS segments indicates that these segments probably rupture synchronously. The more variable slip recurrence and ambiguous COPD peaks on the SC segment allow for multiple interpretations, including both independent single-rupture events and synchronous rupture with the western HS, SB, and BS segments. This multiple-rupture scenario can be attributed to the Shulehe triple junction acting as a barrier that stops the propagation of rupture with a certain probability (Wesnousky, 2006, 2008).

Extents of Rupture Events

Our offset measurements, expressed as COPD plots, indicate clear peaks of fault slip centered on multiples of ~6 m. Although the groupings of measurements...
Figure 9. Horizontal offset (optimal value <30 m) distribution measured from the light detection and ranging (LiDAR) along the eastern Altyn Tagh fault (ATF) and the corresponding peaks deduced from the cumulative offset probability density (COPD). The dashed lines show that the number of offsets increases exponentially with increasing cumulative slip (or with increasing time). The gray stripes indicate visually grouped offsets, and the light-gray stripes indicate speculative grouped offsets; the sinusoidal dark lines and gray stripes represents the variation in single-event slip and cumulative slip, respectively. Blue lines with an arrow indicate drainage. BS—Bago Valley–Shulehe River; HS—Hongliu Valley–Shibaocheng; SB—Shibaocheng–Bago Valley; SC—Shulehe River–Chijin.
along the HS and SB segments show remarkable slip repetition, with a CV of ~0.13, we must be cautious interpreting the larger, older peaks as necessarily the result of single events similar to the most recent event. Paleoseismological data and segmentation of the fault should also be considered (Akçiz et al., 2010; Ren, 2016).

We collected information from eight paleoseismological trenches from the literature, of which, six were reported in Chinese State Bureau of Seismology (1992), and the two additional trenches in Luo et al. (2019) (Fig. 10). The summary of paleoseismological results reveals seven events on the SH, HS, and SB segments, with long (>1000 yr) gaps in time between events: 2720–2800 yr B.P. (event 1), 4180–4970 yr B.P. (event 2), 6140–7510 ± 600 yr B.P. (event 3), 11,300 ± 150 yr B.P. (event 4), 12,540 ± 130–12,590 ± 190 yr B.P. (event 5), 15,100 ± 600 yr B.P. (event 6), and 18,620 ± 500–18,780 ± 260 yr B.P. (event 7). On the BS and SC segments, only one event has been reported, ranging in age from 5000 to 10,060 yr B.P. (Fig. 10).

Although there is only one event reported in the paleoseismological results, the Shipenwan step-over (width far less than 3 km) is not sufficiently large to stop the propagation of earthquake rupture (Wesnousky, 2006) (Fig. 10), and based on the previous discussion of the calculated CV values, we interpret that the SH, HS, SB, and BS segments probably experience synchronous rupture. The time series of identified earthquakes exhibit long recurrence periods, ranging from 1170 to 3790 years on the SH, HS, SB, and BS segments. Such a
long recurrence favors the production of geomorphic markers between events. Therefore, we investigated the correlations between COPD peaks (Fig. 9) and the number of events (Fig. 10) that were identified in the paleoseismological results. While enough geomorphic markers may form between earthquakes, it can still be difficult to correlate trench events with geomorphic offsets due to the different resolution and preservation capabilities of both records. Usually it is more plausible that surface-rupture earthquakes can be identified in the paleoearthquake trench but not in geomorphology; however, in this study, the obvious COPD peaks (multiples of ~6 m) along the HS, SB, and BS segments and high repetition of offsets with CV value <0.3 suggest that these COPD peaks (multiples of ~6 m) indicate individual surface-rupture events. Therefore, we believed it is reasonable to correlate trench data (paleoearthquake events) and geomorphic data (COPD peaks).

Based on these correlations, the four most recent events on the SH, HS, SB, and BS segments (Fig. 9) show a remarkable regularity, with ~6 m characteristic slip and a recurrence period ranging from 1170 to 3790 years (Fig. 10). Due to insufficient paleoseismological data and ambiguous COPD peaks on the SC segment, the recurrence behavior on these two segments remains unclear. However, the most recent documented event on the SC segment appears to correlate to the antepenultimate event on the segments to the west of Shulehe triple junction (Fig. 10). This correlation suggests that at least one of the four prior events ruptured all five segments. Because there are no large barriers to stop the propagation of earthquake rupture, we suggest that event 3 ruptured all five segments (Fig. 10). Considering that the SC segment displays more variable CV than the western segments, we think this rupture scenario is the most plausible interpretation. However, because of the incompleteness of the paleoseismic data, we cannot exclude the possibility that events 1, 2, 4, 5, 6, and/or 7 also ruptured to the eastern end of the ATF (Fig. 10).

The rate of slip indicated by our observations is ~18 m (cumulative offsets of the past three events) in ~7 k.y. (EQ3 in Fig. 10) using only clear inter-event times, or ~24 m (cumulative offsets of the past four events) in ~11.3 k.y. (EQ4 in Fig. 10) using all offset peaks and earthquake ages (Fig. 10). These rates of 2.1–2.6 mm/yr are lower than the slip rates of ~4 mm/yr estimated from offset geomorphic markers along the easternmost ATF (Meyer et al., 1996; Xu et al., 2005; Seong et al., 2011), and considerably lower than the slip rates of 10 ± 2 mm/yr reported farther west (e.g., Zhang et al., 2007).

Estimation of Paleoeartquake Magnitude

Whether the eastern Altyn Tagh fault ruptured partially or completely in the identified slip events, the amount of displacement per event indicates that these were large earthquakes. We estimate the seismic moment \( M_0 \) (in dyn-cm) as the product of the shear modulus \( \mu \), rupture area \( A \), and average co-seismic slip \( \delta \), \( M_0 = \mu \cdot A \cdot \delta \) (Kanamori and Anderson, 1975), using a shear modulus of 30 GPa (Sieh, 1978). Assuming a down-dip rupture extent of 10 km (following Sieh, 1978; Zielke and Ramon, 2012) and 180 km fault rupture length (i.e., across the SH, HS, and BS segments), we determine a moment magnitude \( M_w \) of 76 (\( M_w = [\log_{10}(M_0) – 9.05]/1.5 \)) (Hanks and Kanamori, 1979), where \( M_0 \) is in units of N-m.

Interaction between Strike Faults and Reverse Faults

A number of studies have noted a decrease in the left-lateral slip rate eastward along the Altyn Tagh fault (Burchfiel et al., 1989; Tapponnier et al., 1990; Meyer et al., 1996; Meyer et al., 1998; Mériaux et al., 2004; Zhang et al., 2007; Xu and Zhu, 2019). To explain the eastward decrease of slip rate along the Altyn Tagh fault, Meyer et al. (1998) and Xu et al. (2005) invoked the rules of plate tectonics and suggested that the surface kinematics and slip transfer between faults obey a “lateral slip extrusion” model; while Zhang et al. (2007) is inclined to support a “continuous deformation” model according to the components of GPS velocity parallel to the Altyn Tagh fault. An important difference between the two models is whether the eastward-decreasing styles of slip rates are continuous or sudden.

In this study, the offset distribution pattern changed bounded by the Shulehe triple junction, which exhibited that COPD peaks of the SC segment began to be blurry with a large CV of 0.36 (Fig. 9), and we think the larger CV value can be explained by the fact that smaller horizontal offset with a relatively constant uncertainty will yield a more blurry COPD peak (Fig. 9). Compared with straight fault traces of the HS, SB, and BS segments (shown in the P1–P7 transects of Fig. S1 (footnote 1)); fault traces with more splays and zigzags of the SC segment (shown in the P8 and P9 transects of Fig. S1) also suggest a lower sinistral slip rate and higher vertical-slip component. Geological slip-rate measurements (Zhang, 2016) also indicated that the Shulehe-Chijin segment has more vertical components and lower sinistral slip rate than the HS, SB, and BS segments.

The eastward-decreasing sinistral slip rate (Washburn et al., 2003; Wallace et al., 2004; Xu et al., 2005; Cowgill, 2007; Zhang et al., 2007; Gold et al., 2011; He et al., 2013; Zhang, 2016) suggests continental surface deformation mostly occurred at localized locations, such as triple junctions (Fig. 11). Abrupt decreases in sinistral slip rates are hypothesized across Shulehe triple junction and Subei triple junction, where movements are absorbed by convergence across Qilian shan thrust faults and Danghe nan shan thrust fault (Xu et al., 2005) (Fig. 11). The decrease pattern of the sinistral slip rate across triple junctions from west to east is compatible with the shortening rate measured along the NW-trending thrust faults and is better explained by the “lateral slip extrusion” model (Fig. 11).

CONCLUSIONS

We used high-resolution topography data to evaluate the most recent seismic event and cumulative offsets along the Altyn Tagh fault from Hongliu...
Valley to its termination near Chijin. The offset measurements were validated against measurements from prior studies, limited field observations, and alternative restoration approaches. Based on the analysis of 321 offsets with less than 30 m cumulative offset, we identified evidence for four paleoseismic slip events. Where slip measurements were sufficiently dense, the most recent event exhibited both shorter- and longer-period spatial variation of along-fault surface slip. The short-wavelength (m-scale) variability may be related to very shallow-depth physical conditions along the fault, while long-wavelength (km-scale) variability is attributed to the changes in constitutive relationships that dominate the rupture process at seismogenic depth and to fault geometry complexities such as fault terminations, step-overs, restraining bends, and triple junctions with thrust faults. Peaks in cumulative offset probability density data showed repeating slip events that had ~6 m displacement, most clearly expressed on the Hongliu Valley–Shibaocheng segment, the Shibaocheng–Bago Valley segment, and the Bago Valley–Shulehe segment to the west of Shulehe triple junction. The distribution of offset and paleoseismological data together revealed that the eastern Altyn Tagh fault exhibits characteristic slip behavior with repeating ~6 m slip events. Assuming a down-dip rupture extent of 10 km, these events were produced by earthquakes of Mw ~7.6. The interaction mechanism between strike faults and reverse faults—that sinistral slip rate across triple junctions from west to east is compatible with the shortening rate measured along the NW-trending thrust faults—supports the “lateral slip extrusion” model.

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REFERENCES CITED
Akçiz, S. O., Ludwig, L. G., Arrowsmith, J. R., and Zielke, O., 2010, Century-long average time intervals between earthquake ruptures of the San Andreas fault in the Carrizo Plain, California: Geology, v. 38, no. 9, p. 787–790, https://doi.org/10.1130/G30995.1.
Armijo, R., Tapponnier, P., and Han, T., 1989, Late Cenozoic right-lateral strike-slip faulting in southern Tibet: Journal of Geophysical Research. Solid Earth, v. 94, p. 2787–2838, https://doi.org/10.1029/JB094iB03p02787.
Avouac, J.-P., and Tapponnier, P., 1993, Kinematic model of active deformation in central Asia: Geophysical Research Letters, v. 20, p. 895–898, https://doi.org/10.1029/93GL01028.
Bisai, G. P., Weldon, R. J., Fumal, T. E., and Setz, G. G., 2002, Paleoseismic event dating and the conditional probability of large earthquakes on the southern San Andreas fault, California: Bulletin of the Seismological Society of America, v. 92, no. 7, p. 2761–2781, https://doi.org/10.1785/0120020000605.
Burbank, D. W., and Anderson, R. S., 2011, Tectonic Geomorphology (Second Edition): Wiley Online Library, 454 p., https://doi.org/10.1002/9781444345063.
Burchfiel, B. C., Quidong, D., Molnar, P., Royden, L., Yipeng, W., Peizhen, Z., and Weiqi, Z., 1989, Intracrustal detachment within zones of continental deformation: Geology, v. 17, no. 6, p. 748–752, https://doi.org/10.1130/0091-7613(1989)017<0648:IDWZOC>2.3.CO;2.
Research Paper

Bürgmann, R., Pollard, D.D., and Martel, S.J., 1994, Slip distributions on faults: Effects of stress gradients, inelastic deformation, heterogeneous host-rock stiffness, and fault interaction: Journal of Structural Geology, v. 16, no. 12, p. 1675–1690, https://doi.org/10.1016/0191-8141(94)90134-1.

Chinese State Bureau of Seismology, 1992, The Altny Tagh Active Fault System: Special Publication, Seismological Bureau of China, Beijing: Seismology Publishing House, 319 p. (in Chinese).

Cowgill, E., 2007, Impact of rizer reconstructions on estimation of secular variation in rates of strike-slip faulting: Revisiting the Chercen River site along the Altny Tagh Fault, NW China: Earth and Planetary Science Letters, v. 254, no. 3, p. 239–255, https://doi.org/10.1016/j.epsl.2006.09.015.

Duffield, C.B., Persons, S.F., and van der Woerd, J., 2008, Co-seismic ruptures of the 12 May 2008, M-s 8.0 Wenchuan earthquake, Sichuan: West-east crustal shortening on oblique, parallel thrusts along the eastern edge of Tibet: Earth and Planetary Science Letters, v. 286, no. 3–4, p. 355–370, https://doi.org/10.1016/j.epsl.2009.07.017.

Kurtz, R., Klinger, Y., Ferry, M., and Ritf, J.F., 2018, Horizontal surface-slip distribution through several seismic cycles: The Eastern Bogd fault, Gobi-Altaii, Mongolia: Tectonophysics, v. 734–735, p. 167–182, https://doi.org/10.1016/j.tecto.2018.03.011.

Li, H., Van der Woerd, J., Sun, Z., Li, J., Tapponnier, P., Pan, J., Liu, D., and Chevalier, M.-L., 2012, Co-seismic and cumulative offsets of the recent earthquakes along the Karakax left-lateral strike-slip fault in western Tibet: Gondwana Research, v. 21, p. 64–67, https://doi.org/10.1016/j.gr.2011.07.025.

Lin, A.M., Ren, Z.K., Jia, D., and Wu, X.J., 2009, Co-seismic thrusting and slip rupture along the eastern segment of the Altny Tagh fault, China: Journal of Asian Earth Sciences, v. 37, p. 866–878, https://doi.org/10.1016/j.jseaes.2008.11.009.

Liu-Zeng, J., Zhang, Z., Wen, L., Tapponnier, P., Sun, J., Xing, X., Hu, G., Xu, Q., Zeng, L., Ding, L., Li, Z., and England, P.C., 2012, Spatial and temporal distribution of earthquake ruptures on the eastern segment of the Altny Tagh fault, China: Journal of Asian Earth Sciences, v. 173, p. 263–274, https://doi.org/10.1016/j.jseaes.2019.01.005.

McCalpin, J., 2012, Paleoseismology, Second Edition: Environmental & Engineering Geoscience, v. 18, p. 311–312, https://doi.org/10.2113/geseosees.18.3.311.

McGill, S.F., and Sieh, K., 1991, Surficial offsets on the Eastern Garlock Fault associated with prehistoric earthquakes: Journal of Geophysical Research. Solid Earth, v. 106, p. 13,667–13,696, https://doi.org/10.1029/99JB00471.

McKenzie, D.P., and Morgan, W.J., 1989, Evolution of triple junctions: Nature, v. 224, p. 125–133, https://doi.org/10.1038/224125a0.

McGill, S.F., and Sieh, K., 1991, Surficial offsets on the Central and Eastern Garlock Fault associated with prehistoric earthquakes: Journal of Geophysical Research. Solid Earth, v. 96, p. 21,597–21,621, https://doi.org/10.1029/91JB00209.

Meyers, P., P., 2004, Rapid slip along the central Altny Tagh Fault: Morphocoelelogenic evidence from Cherchen He and Sulamu Tagh: Journal of Geophysical Research. Solid Earth, v. 109, https://doi.org/10.1029/2003JB002558.

Meyers, P., Tapponnier, P., Gudmundsson, G., and H, G., 1997, Rate of left-lateral movement along the east segment of the Altny Tagh fault, east of 96°E (China): Geophysical Journal International, v. 127, no. 1, p. 1–29, https://doi.org/10.1111/j.1365-246X.1996.00151.x.

Molnar, P., and Tappan, P., 1975, Cenozoic tectonics of Asia: Effects of a continental collision: Science, v. 189, p. 419–426, https://doi.org/10.1126/science.189.4201.419.

Molnar, P., and Tappan, P., 1977, Relation of tectonics of eastern China to India-Eurasia collision: Applcation of slip-line field theory to large-scale continental tectonics: Geology, v. 5, p. 212–216, https://doi.org/10.1130/0091-7163(1977)5<212:ROTOC2.0.CO;2.

Montone, P., Crone, A.J., and Personius, S.F., 2004, Surface rupture and slip distribution of the Denali and Totschunda faults in the November 2002 M 7.9 earthquake, Alaska: Bulletin of the Seismological Society of America, v. 94, p. 523–552, https://doi.org/10.1785/0120040626.

Peltzer, G., and Tapponnier, P., 1988, Formation and evolution of strike-slip faults, rifts, and basins during the India-Asia collision: Tectonics, v. 7, no. 1, p. 1–47, https://doi.org/10.1029/TC07i001p00016.

Qiu, J., and K, W., 2004, Evidence for a seismic barrier model from MW similar to 7.8 Kokoxili (Tibet) earthquake slip-distribution: Earth and Planetary Science Letters, v. 230, no. 1, p. 203–215, https://doi.org/10.1016/j.epsl.2004.09.011.

Raterman, N.S., Cowgill, E., and Lin, D., 2007, Variable structural style along the Karakoram fault system: Science, v. 256, p. 83–86, https://doi.org/10.1126/science.256.5053.83.
Rockwell, T.K., and Klinger, Y., 2013, Surface rupture and slip distribution of the 1940 Imperial Valley earthquake, Imperial fault, Southern California: Implications for rupture segmentation and dynamics: Bulletin of the Seismological Society of America, v. 103, p. 629–640, https://doi.org/10.1785/0120120192.

Rockwell, T.K., Lindvall, S., Dawson, T., Langridge, R., Lettis, W., and Klinger, Y., 2002, Lateral offsets on surveyed cultural features resulting from the 1989 Loma Prieta and DuRose earthquakes, Turkey: Bulletin of the Seismological Society of America, v. 92, no. 1, p. 79–94, https://doi.org/10.1785/0120000809.

Röder, M., Hill, S., and Latfii, H., 2017, Best practice tutorial: Technical handling of the UAV “DJI Phantom 3 Professional” and processing of the acquired data: Würzburg, University of Würzburg, 36 p., https://doi.org/10.1134/GR.2.2.36355.81680.

Salisbury, J.B., Rockwell, T.K., Middleton, T.J., and Hudnut, K.W., 2012, LiDAR and field observations of slip distribution for the most recent surface ruptures along the central San Jacinto Fault: Bulletin of the Seismological Society of America, v. 102, p. 598–619, https://doi.org/10.1785/0120110068.

Schwartz, D.P., and Coppersmith, K.J., 1984, Fault behavior and characteristic earthquakes—Examples from the Wasatch and San Andreas fault zones: Journal of Geophysical Research. Solid Earth, v. 89, p. 5681–5698, https://doi.org/10.1029/JB089iB07p05681.

Seong, Y.B., Kang, H.C., Ree, J.H., Yi, C., and Yoon, H., 2011, Constant slip rate during the late Quaternary along the Sulu He segment of the Altyn Tagh Fault near Changma, Gansu, China: The Island Arc, v. 20, no. 1, p. 94–106, https://doi.org/10.1111/j.1440-1738.2010.00743.x.

Sieh, K., 1996, The repetition of large-earthquake ruptures: Proceedings of the National Academy of Sciences of the United States of America, v. 93, no. 9, p. 3764–3771, https://doi.org/10.1073/pnas.93.9.3764.

Sieh, K.E., 1978, Slip on San Andreas fault associated with great 1857 earthquake: Bulletin of the Seismological Society of America, v. 68, no. 5, p. 1421.

Sieh, K.E., and Johns, R.H., 1984, Holocene activity of the San Andreas fault at Wallace Creek, California: Geological Society of America Bulletin, v. 95, no. 8, p. 883–896, https://doi.org/10.1130/0016-7606(1984)95<883:HAOSAF>2.3.CO;2.

Stein, S., and Wyssession, M., 2009, An Introduction to Seismology, Earthquakes, and Earth Structure: Wiley-Blackwell Publishing, 510 p.

Stewart, N., Gaudemer, Y., Manighetti, I., Serreau, L., Vincendeau, A., Dominguez, S., Matteo, L., and Malavieille, J., 2018, “3D_Fault_Offsets, “ a Matlab code to automatically measure lateral and vertical fault offsets in topographic data: Application to San Andreas, Owens Valley, and Hoys fault systems: Journal of Geophysical Research. Solid Earth, v. 123, p. 815–836, https://doi.org/10.1002/2017JB014863.

Tapponnier, P., Meyer, B., Avouac, J.P., Peliter, G., Gaudemer, Y., Guo, S., Xiang, H., Yin, K., Chen, Z., Cai, S., and Dai, H., 1990, Active thrusting and folding in the Qilian Shan, and decoupling between upper crust and mantle in northeastern Tibet: Earth and Planetary Science Letters, v. 97, p. 382–403, https://doi.org/10.1016/0012-821X(90)90053-Z.

Tapponnier, P., Zhiqin, X., Roger, F., Meriaux, B., and Jingsui, Y., 2001, Tapponnier, P., Zhiqin, X., Roger, F., Meyer, B., Gaudemer, Y., Finkel, R.C., Caffee, M.W., Zhao, G.G., and Xu, Z.Q., 2002, Uniform postglacial slip-rate along the central 600 km of the Kunlun Fault (Tibet), from 39Be, and 10C dating of river offsets, and climatic origin of the regional morphology: Geophysical Journal International, v. 148, p. 356–388, https://doi.org/10.1046/j.1365-246x.2002.01565.x.

Wallace, K., Yin, G., and Bilham, R., 2004, Inescapable slow slip on the Altyn Tagh fault: Geophysical Research Letters, v. 31, https://doi.org/10.1029/2004GL019724.

Wallace, R.E., 1987, Grouping and migration of surface faulting and variations in slip rates on faults in the Great-Basin Province: Bulletin of the Seismological Society of America, v. 77, p. 868–876.

Washburn, Z., Arrowsmith, J.R., Dupont-Nivet, G., Feng, W.X., Qiao, Z.Y., and Zhengle, C., 2003, Paleoseismology of the Xorxol Segment of the Central Altyn Tagh Fault, Xinjiang, China: Annals of Geophysics, v. 46, p. 1015–1034.

Wesnousky, S.G., 1994, The Gutenberg-Richter or characteristic earthquake distribution, which is it?: Bulletin of the Seismological Society of America, v. 84, no. 6, p. 1940–1959.

Wesnousky, S.G., 2006, Predicting the endpoints of earthquake ruptures: Nature, v. 444, p. 358–360, https://doi.org/10.1038/nature05271.

Wesnousky, S.G., 2008, Displacement and geometrical characteristics of earthquake surface ruptures: Issues and implications for seismic-hazard analysis and the process of earthquake rupture: Bulletin of the Seismological Society of America, v. 98, p. 1669–1632, https://doi.org/10.1785/0120070111.

Xu, C., and Zhu, S., 2019, Temporal and spatial movement characteristics of the Altyn Tagh fault inferred from 21 years of InSAR observations: Journal of Geodesy, v. 93, no. 8, p. 1147–1160, https://doi.org/10.1007/s00190-019-01232-2.

Xu, X., Wang, F., Zheng, R., Chen, W., Yu, G., Chen, G., Tapponnier, P., Van Der Woerd, J., Meriaux, A.S., and Ryerson, F.J., 2005, Late Quaternary sinistral slip rate along the Altyn Tagh fault and its structural transformation model: Science in China. Series D, Earth Sciences, v. 48, p. 384, https://doi.org/10.1360/02ys0436.

Xu, X., Xu, C., Yu, G., Wu, X., Li, X., and Zhang, J., 2015, Primary surface ruptures of the Ludian Mw 6.2 Earthquake, southeastern Tibetan Plateau, China: Seismological Research Letters, v. 86, no. 6, p. 1822–1835, https://doi.org/10.1785/022015038.

Xu, X.W., Wen, X.Z., Yu, G.H., Chen, G.H., Klinger, X., Hubbard, J., and Shaw, J., 2009, Coseismic reverse- and oblique-slip surface faulting generated by the 2008 Mw 9.0 Wenchuan earthquake, China: Geology, v. 37, no. 6, p. 515–518, https://doi.org/10.1130/G25462A.1.

Zhang, N., 2016, Geometry and kinematics of the Eastern End of the Altyn Tagh Fault: Beijing, Institute of Geology, China Earthquake Administration, p. 45–63.

Zhang, F.-Z., Molnar, P., and Xu, X., 2002, Late Quaternary and present-day rates of slip along the Altyn Tagh Fault, northern margin of the Tibetan Plateau: Tectonics, v. 26, no. 5, https://doi.org/10.1029/2006TC002014.

Zielke, O., Klinger, Y., and Arrowsmith, J.R., 2012, LaDiCoaz and LiDARimage—MATLAB GUIs for LiDAR data handling and lateral displacement measurement: Geosphere, v. 8, p. 206–221, https://doi.org/10.1130/GES00686.1.

Zielke, O., Arrowsmith, J.R., Ludwig, L.G., and Akcz, S.O., 2010, Slip in the 1857 and earlier large earthquakes along the Carrizo Plain, San Andreas fault: Science, v. 327, p. 1119–1122, https://doi.org/10.1126/science.1182781.

Zielke, O., Arrowsmith, J.R., Ludwig, L.G., and Akcz, S.O., 2012, High-resolution topography-derived offsets along the 1857 Fort Tejon Earthquake rupture trace, San Andreas fault: Bulletin of the Seismological Society of America, v. 102, p. 1135–1154, https://doi.org/10.1785/0120110230.

Zielke, O., Klinger, Y., and Arrowsmith, J.R., 2015, Fault slip and earthquake recurrence along strike-slip faults—Contributions of high-resolution geomorphic data: Tectonophysics, v. 638, p. 43–62, https://doi.org/10.1016/j.tecto.2014.11.004.