Slip rate and recurrence intervals of the east Lenglongling fault constrained by morphotectonics: Tectonic implications for the northeastern Tibetan Plateau

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ABSTRACT

The Lenglongling fault located in the northeast margin of the Tibetan Plateau plays an important role in accommodating the tectonic deformation of the Tibetan Plateau relative to the Gobi–Ala Shan platform to the north and the North China craton to the east. However, little is known about the fault due to a lack of previous research. In this study we use terrestrial light detection and ranging (LiDAR) data combined with high-resolution remote sensing images to survey offset landforms in the east part of the Lenglongling fault. Microtopographic analysis of well-preserved offset terraces, gullies, ridges, and pluvial fans in the highland environment allows evaluation of single-event slip and multievent cumulative slip.

Our study provides an important assessment of the horizontal offset associated with the latest earthquake and four paleoearthquakes that were identified from a series of offset bedrock terraces by constructing a morphotectonic evolution model. Terrestrial LiDAR data indicate that the east Lenglongling fault follows a characteristic slip model. The single-event slip of this section is ~9.4 m; 7–8 paleoearthquakes are thought to have occurred during the Holocene, and a left-lateral strike-slip rate of 6.6 ± 0.3 mm/yr is estimated.

Combining the slip rate and the single-event slip distribution, we determine a mean recurrence interval of 1430 ± 140 yr for past earthquakes along the east Lenglongling fault. This result is similar to that of the adjacent Gulang fault, but differs slightly from those of other adjacent faults, which may mean that the Lenglongling and Gulang faults compose an integral fault zone. The large number of millennial recurrent active faults in this region heightens the risk of future seismic activity in the northeast Tibetan Plateau.

INTRODUCTION

The Lenglongling fault (LLLF) is located in the northeastern margin of the immense arcuate tectonic zone of the Tibetan Plateau (Fig. 1B). Together with the Tuolaishan, Jinqianghe, Maomaoshan, Laohushan, and Haiyuan faults, the LLLF is part of the Qilian-Haiyuan fault zone (Zheng et al., 2013) (Fig. 1A), an important left-lateral strike-slip fault system in the northeastern Tibetan Plateau. This active tectonic zone accommodates eastward movement of Tibet relative to the Gobi–Ala Shan platform (GASP) to the north (Tapponnier and Molnar, 1977; Zhang et al., 1988a, 1988b). Many strong earthquakes have previously occurred in this region, including the 1920 Haiyuan (M 8.5) and the 1927 Gulang (M 8–8.3) earthquakes. Nevertheless, we know very little about the LLLF compared with the surrounding active faults due to lack of observations. Our current knowledge of the slip rate is controversial, as it spans a large range from 4 to 19 mm/yr (Gaudemer et al., 1995; He et al., 2000; Lasserre et al., 2002; He et al., 2010; Zheng et al., 2013). A 220-km-long seismic gap with significant potential hazard has been identified along the western section of the Qilian-Haiyuan fault zone (Gaudemer et al., 1995). Only two earthquakes have been recorded here, both M 6.4, in 1984 and 2016. However, a series of offset landforms has been identified from high-resolution remote sensing (HRRS) images, as well as in the field (He et al., 2000; Lasserre et al., 2002), that imply that several strong earthquakes struck the LLLF during the Holocene. Single-event slip, mean slip rate, and recurrence intervals of the LLLF are all important parameters for evaluating the future seismic hazard of this region, for understanding the regulatory mechanism of the LLLF in terms of the tectonic deformation of the northeastern Tibetan Plateau, and for constraining the dynamics of the Tibetan Plateau (Molnar and Tapponnier, 1975; Avouac and Tapponnier, 1993; England and Molnar, 1997).

In order to more accurately estimate single-event slip and recurrence intervals, we carried out field work in the eastern part of the LLLF. Terrestrial light detection and ranging (LiDAR) is used to measure the detailed offset landforms with the surrounding active faults due to lack of observations. Our current knowledge of the slip rate is controversial, as it spans a large range from 4 to 19 mm/yr (Gaudemer et al., 1995; He et al., 2000; Lasserre et al., 2002; He et al., 2010; Zheng et al., 2013). A 220-km-long seismic gap with significant potential hazard has been identified along the western
quantitatively determine the slip distribution model and the occurrence of paleoearthquakes. By combining this information with previous dating results, we derive the slip rate and recurrence interval of the LLLF.

GEOLOGICAL SETTINGS

The northeastern Tibetan Plateau has undergone strong tectonic deformation since the Cenozoic Era (Yin et al., 2008). Widespread folding, thrusting, and strike-slip faulting in the Paleogene, Neogene, and Quaternary Periods indicate that this region has been undergoing crustal shortening and shear slip, as well as vertical uplift, which has resulted in typical basin-range structures (Molnar and Tapponnier, 1975; Meyer et al., 1998; Tapponnier et al., 1990, 2001; Yuan et al., 2004). Two groups of structures trending west-northwest and north-northwest make up the tectonic framework of the northeastern Tibetan Plateau. The Qilian-Haiyuan fault zone, one of the most important of the NWW-trending structures, consists of a series of left-lateral en echelon active faults with slight thrust movement from south to north. The LLLF is located in the middle segment of the Qilian-Haiyuan fault zone and is predominantly a left-lateral strike-slip fault that had oblique slip in the west during the Quaternary (Gaudemer et al., 1995). Although the LLLF is less studied, it has undergone strong seismic activity in the Holocene, evidenced by a series of offset landforms including streams, terraces, moraines, and ridges (He et al., 2000; Lasserre et al., 2002; He et al., 2010).

To date, no earthquake larger than M 7.0 has been recorded on the LLLF. The only two seismic records of earthquakes on the LLLF are from the major branch, according to its epicenter depth and the geological map. The 1927 earthquake (M 8.0) of Gulang occurred to the east of the LLLF (Gaudemer et al., 1995). According to historical evidence, a strong earthquake that hit the middle of the Gansu area is thought to be related to the LLLF (Liu et al., 1998).

Quaternary glacial and periglacial processes have strongly contributed to shaping the landforms of northeastern Tibet (Derbyshire et al., 1991; Lehmkuhl et al., 1998; Van Der Woerd et al., 2000, 2002), including the Lenglongling Mountains. Glacial cirques, some still occupied by glaciers, glacial valleys, glaciofluvial tills, and moraines, can be identified along the entire LLLF. Glaciation in the Lenglongling area is divided into two stages: the new ice age and the last glaciation (prior to 11 ka) (Wu, 1984). The last glaciation is divided into three stages (Kang et al., 1992), two of which are large-scale glacial advances that occurred before 38,000 yr ago, and between 38000 and 18,000 yr ago, respectively. Between 14,000 and 12,665 yr ago there was a short-term pause in glaciation, which represents the third stage; the new ice age occurred in China ca. 3110 yr ago (Kang et al., 1992).

METHODOLOGY AND DATA

Trench excavation is the most common method for estimating the behavior and recurrence intervals of a given fault (McCalpin, 2009). However, the LLLF is located in high altitudes where glaciers are widespread. Moreover, the surface rupture of the LLLF is so wide that it is difficult to excavate a trench that would reveal the total number of paleoearthquakes. In this paper we resolve these problems by using a morphotectonic survey. Past amounts of surface slip can be used to reconstruct the rupture history, and this history...
is thought to reflect the future behavior of a given fault (Zielke et al., 2015). By statistically analyzing the amount of single-event and multievent slip, it is possible to reveal the rupture pattern and history of groundrupturing earthquakes on an active fault (Zielke et al., 2010; Klinger et al., 2011; Madden et al., 2013; Scharer et al., 2014). In addition, we can assess the probability of the fault following a characteristic slip model (Schwartz and Coppersmith, 1984; Cowan and McGlone, 1991; Papadopoulos et al., 2003; Turcotte et al., 2010) by analyzing single-event slip distribution and multievent cumulative slip distribution revealed by offset landforms.

With the help of terrestrial LiDAR data and HRRS images, a highly accurate determination of the microscale geomorphologic offset becomes possible. Zielke et al. (2010) analyzed the relationship between single-event and cumulative offsets on the Carrizo segment of the San Andreas fault using airborne LiDAR and HRRS images, and the result indicated that the Carrizo segment of the fault has a characteristic slip (Zielke et al., 2010). Klinger et al. (2011) also concluded that the Fuyun fault adheres to the characteristic slip model, after analyzing high-resolution images. Furthermore, Ren et al. (2016) analyzed clustering of offsets on the Haiyuan fault and their relationship to paleoearthquakes using airborne LiDAR data.

All these studies have highlighted the great potential of this survey method. Therefore, we have evaluated the offset along the eastern LLLF using terrestrial LiDAR data to determine fault rupture patterns of strong earthquakes. Three locations, Taola, Chailong, and Niutou, all with typical offset features such as offset gullies and terraces, were surveyed by terrestrial LiDAR (Fig. 2). In order to ensure high measurement accuracy, we carried out 6 measurements in the Taola site, 8 in the Chailong site, and 16 in the Niutou site. Most of the LLLF is covered by low shrubs or no vegetation, which greatly improves measurement accuracy. The 0.2 m resolution digital elevation model (DEM) is converted from the terrestrial LiDAR point cloud data, which is also used to generate hillshade relief maps for further analysis. Detailed introductions of terrestrial LiDAR measurement and data process procedures are in Appendix 1.

ANALYSIS OF SINGLE-EVENT AND MULTIEVENT SLIP AMOUNTS

The eastern LLLF is characterized by many different offset features, including reverse scarps, offset gullies, pluvial terraces, and bedrock ridges. Fault traces were interpreted using 0.5 m Quickbird satellite and 0.4 m Worldview HRRS images acquired in 2011 and 2012. The fault trace is almost 50 km in length from the easternmost to the middle part of the LLLF, and it is nearly linear and continuous along the V-shaped valley. From the middle to the west part of the fault, the trace is discontinuously distributed and even obscure due to snow cover. However, the offset geomorphologic markers along the entire LLLF are clearly evidenced in the field and remote sensing images. The LLLF is mostly composed of a single dominated fault branch; however, it still can be divided into three segments where the fault geometry is more complex due to several paralleling fault traces. As shown in the HRRS image (Fig. 2), there are two to three parallel fault branches in this section that may be related to the typical flower structure of a strike-slip fault. Among these branches, the northernmost branch is the most apparent. In this study three sites are selected for terrestrial LiDAR measurement to analyze the single-event and multievent cumulative offset along the fault traces (Fig. 2).

Offset Landforms in the Taola Site

There are two northwest-west–trending branches of the fault at the Taola site. The northern branch cuts the pluvial surface and two gullies (G1 and G2) sinistrally by unequal displacements (Figs. 3 and 4). The southern branch cuts the south-southwest–facing hillslope, forming a slight north-northeast–facing scarp opposite the main hillslope (Fig. 3). The northern branch curves toward the southwest and disappears before rejoining the southern branch. The fault network forms a releasing bend, and a small-scale pull-apart basin developed where fine-grained sediment is identified in the field. Geomorphic markers can be used to constrain...
the rupture history (Zielke et al., 2015); therefore, we use risers between the streambeds and pluvial surfaces as markers for reconstructing the pre-earthquake morphology. The piercing lines r1 to r4 and r1' to r4' are used to label the back edges of the different risers. The piercing lines of r1 and r1' were connected to each other before the earthquake event, but are now offset sinistrally (Fig. 5). The same has happened to the piercing lines of r2 and r2', r3 and r3', and r4 and r4'; from the DEMs generated from terrestrial LiDAR data, we estimated displacements of 9.2 m, 10.2 m, 19.2 m, and 18.4 m for the four piercing lines, respectively. Average displacement of 9.7 ± 0.5 m and 18.8 ± 0.4 m for G1 and G2 were estimated subsequently. The estimate of 18.8 ± 0.4 m is a cumulative displacement of multievent slips. However, due to a lack of other evidence, we cannot ascertain whether the 9.7 ± 0.5 m displacement is the result of single-event slip during the latest earthquake or multievent cumulative slip.

Offset Landforms in the Chailong Site

The Chailong site is located to the east of a copper mine where a series of bedrock terraces are sinistrally displaced with a very small component of oblique slip, as shown by the reverse fault scarp. Figure 6A is hillshade relief map generated from the DEMs converted from terrestrial LiDAR data, and Figure 7 represents the HRRS images of the Chailong site. The bedrock terrace predate gully G1 in the piedmont. The postglacial pluvial activity along gully G1 modified the bedrock terrace greatly by the newly formed terraces on both banks. On the east bank of the gully, a series of four displaced bedrock terraces (T0, T1, T2, and T3) are identified downstream of the fault (Fig. 6B). The downstream terraces and its risers on the east side are protected from incision by topography on the upstream side of the fault (Zhang et al., 2007). Terrace T3 has a flat morphology with some boulders above the surface. Terraces T2 and T1 present a similar morphology with relatively flat surfaces, above which are some boulders. Terrace T0 is characterized by a well-preserved morphology within which many mid-size boulders are scattered. On the west bank of the gully, lateral erosion has destroyed evidence of terraces T0 and T2 on the downstream side, and only terraces T0 and T3 can be identified in this quadrant. Upstream of the gully, terraces T0, T2, and T3 are partially preserved on both sides of the gully, whereas terrace T1 has been thoroughly eroded on both sides. On the downstream terraces, there are three risers (T0-T1, T1-T2, and T2-T3) between the four bedrock terrace surfaces on the east bank of the stream channel. However, there are only two risers on the upstream terraces (T0-T2 and T2-T3). Using the DEMs generated from our survey, we estimated cumulative displacements of 37.7 ± 1.9 m for the T2-T3 riser (Fig. 8C). The distance between the T1-T2 riser on the downstream side and the T0-T2 riser on the upstream side is ~29.05 ± 0.45 m (Fig. 8D).

Figure 3. (A) Quickbird satellite images of the Taola site. The rectangle shows the location of digital elevation models in Figure 4 of the offset gullies G1 and G2, measured by terrestrial LiDAR (light detection and ranging). Two fault branches can be interpreted directly from the offset landforms, which dominate the pull-apart basin, as indicated by the white arrow. (B) Geomorphologic interpretation of the Figure 3A.
Figure 4. (A) Detailed hillshade relief map of the two offset gullies in the Taola site. The white eye-shaped symbol shows the location and direction of Figure 5. The thick dashed line denotes fault traces. The white dots are piercing points used to measure the offset risers. (B) Contour map of the offset landforms layered on the 0.2 m resolution digital elevation models. The contour interval is 1 m. The thin dashed lines show the piercing lines used to measure the offset risers. Solid white lines show the thalwegs of gullies G1 and G2. Note that piercing lines r1 to r4 and r1’ to r4’ are connected to each other pre-earthquake and can be used as displacement markers. (C) Morphotectonic reconstruction for an average offset of 9.7 ± 0.5 m using the piercing lines r1 and r2. Note that thalweg of G1 (solid white line in Fig. 4B) is linearly connected across the fault. (D) Morphotectonic reconstruction for an average offset of 18.8 ± 0.4 m using the piercing lines r3 and r4. Note that thalwegs of G1 and G2 (solid white line in Fig. 4B) are linearly connected across the fault.

Figure 5. Photograph from the Taola site showing the piercing lines used to measure offset risers (r1 and r2) and thalweg of gully G1. The thick dashed line denotes the fault trace. The thin dashed lines denote the thalweg lines of the stream. The solid white lines denote the two risers r1 and r2 (offset r1’, r2’ are labeled) between the floodplain and the bilateral terraces. The mean left-lateral slip of the thalweg and the two back edges of the risers is approximately 9.7 ± 0.5 m.
Figure 6. (A) Detailed hillshade relief map of the Chailong site. Black arrows denote fault traces in a west-northwest direction. (B) Geomorphic interpretation of A combined with field investigation. T0 is the floodplain of gully G1. T1, T2, and T3 are surfaces of bedrock terraces produced by G1. Riser T2-T3 was laterally eroded at the end of the stream. S2–1 and S2–2 are surfaces of pluvial fans produced by gully G2. S3–0 is the floodplain of gully G3. S3–1, S3–2, and S3–3 are surfaces of pluvial fans produced by G3. The platform is the oldest terrace of the landforms mentioned shown. The contour interval is 1 m.
Recurrence intervals of the east Lenglongling fault | RESEARCH

Figure 7. (A) Quickbird satellite image of the Chailong site showing the fault traces that offset the streambed and floodplain. The white dots are piercing points used to measure the streambed offset. (B) Morphotectonic reconstruction for an average offset of 9.1 ± 0.4 m using two edges of the streambed. The east side of the streambed was offset by 9.5 m, and the west side was offset by 8.7 m. White arrows in B denote the back slip of the marker along the fault trace to its pre-earthquake morphology. The image scale is approximately 1:2000.

Figure 8. Morphotectonic reconstruction by back slip of the offset bedrock terrace risers. The gully flows from north to south. The image scale is about 1:3000. (A) Morphotectonic reconstruction for an offset of 9.8 ± 0.5 m using riser T0-T1 on the downstream side, corresponding to riser T0-T2 on the upstream side. The front edge of the riser is offset by 10.3 m, and the back edge of the riser is offset by 9.3 m. However, terrace T1 on the upstream has been thoroughly eroded. (B) Morphotectonic reconstruction for an offset of 29.05 ± 0.45 m using riser T1-T2 on the downstream side, corresponding to riser T0-T2 on the upstream side. The front edge of the riser is offset by 28.6 m, and the back edge of the riser is offset by 29.5 m. This value denotes the cumulative slip of terrace T2. (C) Morphotectonic reconstruction for an offset of 37.7 ± 1.9 m using riser T2-T3 on the downstream side, corresponding to riser T2-T3 on the upstream side. The front edge of the riser is offset by 35.8 m, and the back edge of the riser is offset by 39.6 m. White arrows denote the back slip of the markers on the north side along the fault trace, used to constrain the pre-earthquake morphology.
Furthermore, gully G2 was cut off by the LLLF and it is now discon-
fined landform, examples of which are widespread in the Lenglongling area,
including the White River (Kang et al., 1992) and Taola areas (He et al.,
2010), which have similar altitudes. The platform between gullies G4 and
G3 was also offset sinistrally by the LLLF. On the right side of gully G3,
G1 was offset sinistrally by the LLLF and a fault trough ~4–5 m wide
from terraces generated by G4, we refer to it herein as the platform. The
top of the platform is very flat with few boulders on it. It is a typical strati-
fied landform, examples of which are widespread in the Lenglongling area,
including the White River (Kang et al., 1992) and Taola areas (He et al.,
2010), which have similar altitudes. The platform between gullies G4 and
G1 was offset sinistrally by the LLLF and a fault trough ~4–5 m wide
formed on the platform (Fig. 11A). Along the fault trace to the east, a large
ridge between G1 and G2 was sinistrally offset, which blocked gully G2
at the location of a sag pond containing very fine grained sediment (Fig.
11B). Furthermore, gully G2 was cut off by the LLLF and it is now discon-
tinuous downstream where it flows across the fault trace (Fig. 10B). Gully
G3 was also offset sinistrally by the LLLF. On the right side of gully G3,
terraces T0 to T3 can be identified on the upstream side, while only ter-
race T1 can be identified on the downstream side, as shown in Figure 10B.

In order to measure the cumulative slip of the platform and the gullies,
we have to find markers produced before the earthquake to constrain the
displacements. The risers between the floodplain and the platform, as
indicated by piercing lines r1 and r1’, are used to measure the left-lateral
displacement of G1 and the platform. An offset of ~67.1 m is measured by
back slip of the markers to pre-earthquake morphology. As for G2, we take
the right edge of the floodplain (piercing line of r2 and r2’) as the marker
and the cumulative slip is measured as 68.3 m, which is similar to that of
G1 and the platform. Both back edges of the floodplain of G3 are taken as
displacement markers and a cumulative slip of 68.0 ± 1.5 m is derived for
G3. The similar cumulative slip of these landforms indicates that they were
offset en masse in the earthquakes that followed. The average cumulative slip
of the Niutou site, as recorded by these landforms, is 67.9 ± 0.9 m.

Offset Landforms in the Niutou Site

Four gullies were surveyed in the Niutou site, three of which (G1, G2,
and G3) flow southward while the last one (G4) flows eastward (Fig. 10A).
On both sides of gully G4, there are two strips of pluvial and alluvial ter-
races, as shown in Figure 10B. In order to differentiate these old terraces
from terraces generated by G4, we refer to it herein as the platform. The
top of the platform is very flat with few boulders on it. It is a typical strati-
fied landform, examples of which are widespread in the Lenglongling area,
including the White River (Kang et al., 1992) and Taola areas (He et al.,
2010), which have similar altitudes. The platform between gullies G4 and
G1 was offset sinistrally by the LLLF and a fault trough ~4–5 m wide
formed on the platform (Fig. 11A). Along the fault trace to the east, a large
ridge between G1 and G2 was sinistrally offset, which blocked gully G2
at the location of a sag pond containing very fine grained sediment (Fig.
11B). Furthermore, gully G2 was cut off by the LLLF and it is now discon-
inuous downstream where it flows across the fault trace (Fig. 10B). Gully
G3 was also offset sinistrally by the LLLF. On the right side of gully G3,
terraces T0 to T3 can be identified on the upstream side, while only ter-
race T1 can be identified on the downstream side, as shown in Figure 10B.

In order to measure the cumulative slip of the platform and the gullies,
we have to find markers produced before the earthquake to constrain the
displacements. The risers between the floodplain and the platform, as
indicated by piercing lines r1 and r1’, are used to measure the left-lateral

The distance between the Taola site and the Chailong site is ~10 km
and the minimum slips at the two sites (9.7 ± 0.5 m and 9.1 ± 0.4 m), both
of which are measured from the offset streambeds, are approximately the
same. This ~10 m offset was also surveyed by Lasserre et al. (2002) in a
small gully at Xiyinghe in the Ninchanyahuo site, which is ~12 km from
the Taola site in the northwest. Therefore, we consider these displacements
to be the latest slip related to the most recent earthquake event in A.D.
1540. The cumulative offset of G2 at the Taola site is 18.4 ± 0.4 m; if we
deduct the slip of 9.7 ± 0.5 m, an almost equal slip of 9.1 ± 0.9 m remains.

In the Chailong site, the riser offset of 9.8 ± 0.5 m between the T0-T1
eriser on the downstream side and the T0-T2 riser on the upstream side is
not valid due to terrace T1 on the upstream side being completely eroded.
Nevertheless, the cumulative slip of 29.05 ± 0.45 m between the T0-T2
riser on the downstream side and the T0-T2 riser on the upstream side is
thought to reflect the actual cumulative slip of terrace T2. If we deduct the
most recent slip of 9.1 ± 0.4 m from this amount, a total offset of 19.95
± 0.85 m remains, twice the amount of the most recent slip. The earliest
slip event was recorded by terrace T3, and is the difference between risers
T2-T3 and T1-T2. Therefore an offset of 8.65 ± 2.35 m for the earliest
event is estimated. Considering both the Taola and the Chailong sites,
offset of 9.1 ± 0.9 m is assumed as the slip of the penultimate earthquake,
and the remaining cumulative slip of 19.95 ± 0.85 m is considered to be
the sum of the penultimate and the antepenultimate events, which had
similar coseismic slips. The fourth-most recent earthquake caused 8.65
± 2.35 m displacement. Slip amounts of the past four paleoearthquakes
were therefore approximately equal. An average single-event slip of 9.4
Figure 10. Morphotectonic analysis in the Niutou site. (A) Hillshade relief map derived from terrestrial LiDAR (light detection and ranging) point cloud data. White arrows denote fault traces offsetting the terrace and gullies. The two black eye-shaped symbols denote the location and direction of Figures 11A and 11B. (B) Geomorphic interpretation of Figure 10A combined with field investigation. The black solid lines labeled with different numbers signify the piercing lines of terrace (T) risers used to measure the surface displacement, which were offset by earthquakes several times. The contour interval is 1 m. OSL—optically stimulated luminescence. (C) Morphotectonic reconstruction for an average offset of 67.9 ± 0.9 m using the piercing lines of the risers. Brown arrows in the figure denote the back slip of the half images along the fault trace relative to the original location prior to deformation.
± 0.5 m can be concluded by dividing the total cumulative slip (37.7 ± 1.9 m) by the four paleoearthquake events.

In conclusion, only two paleoearthquakes were recorded by landforms in our survey location at the Taola site. However, more paleoearthquakes are thought to be recorded by another fault branch in the south (Fig. 3), where reasonable markers for constraining single-event and multievent slips were not found. In the Chailong site, four paleoearthquakes were recorded by the offset bedrock terraces. Because the slip distributions during four successive earthquakes were so similar, we conclude that rupture on the LLLF in this area obeys a characteristic slip model. According to the offset bedrock terraces and the four events, we construct a morphotectonic evolution model (Fig. 12) of the Chailong site to interpret its morphotectonic evolution and surface rupture history.

The horizontal distance between the Chailong site and the Niutou site is ~3 km, and surface ruptures between the two sites show a linear and continuous distribution. Consequently, the two sites are assumed to have been affected by the same paleoearthquake events, although there are obvious differences in the offset landforms between the two sites. According to the average cumulative slip of 67.9 ± 0.9 m in the Niutou site and an average single-event slip of 9.4 ± 0.5 m in the Chailong site, we infer that 7–8 paleoearthquake events are recorded by offset landforms in this region.

Horizontal Slip Rate

The last glaciation in the Lenglongling area comprised three periods that produced three corresponding moraines (Kang et al., 1992). In the piedmont area, three levels of glaciofluvial terraces were generated along the different moraines, the newest of which is the same age as pluvial terrace T1 of Baishui River in the Lenglongling area (Kang et al., 1992; He et al., 2010). The newest pluvial terrace T1 is a typical type that is widespread in the Lenglongling area. As discussed for the Niutou site, the two strips of platforms on either side of gully G4 belong to pluvial terrace T1. A sample from the bottom of pluvial terrace T1 was dated by Kang et al. (1992) to 12,665 ± 110 14C B.P.; 12 samples from the top of moraine terrace T1 were also dated using 10Be and 26Al (Lasserre et al., 2002), and the 6 oldest clustered around 10,300 ± 339 yr ago. This age was interpreted as the time of last reshaping of the lateral moraine by the glacier, before it withdrew across the fault near the end of the Younger Dryas (11 ka) (Lasserre et al., 2002). The two ages are reasonable and very similar, supplying persuasive evidence for the relationship between glaciofluvial terrace T1 and pluvial terrace T1.

In addition to the previous dating results (Kang et al., 1992; Lasserre et al., 2002), we collected three samples at the Niutou site (Fig. 10B) to constrain the deformation age (Guo et al., 2017). Both optically stimulated luminescence (OSL) and radiocarbon (14C) are very effective methods for Quaternary dating (Walker, 2005). Two OSL samples were collected on the pluvial terrace between G1 and G4 at the buried depths of 0.8 and 2.2 m, both of which are characterized by the uniform lithology containing loess and fine particle size of sand (Table 1). The third sample was collected on the pluvial terrace between gullies G1 and G2, dated by the 14C method. The two OSL dating results (13,100 ± 500 yr ago and 11,600 ± 500 yr ago) are consistent and are in order, and they are very close to the calibrated age of 13,515 ± 60 14C B.P. Moreover, our ages are consistent with previous results (Kang et al., 1992; Lasserre et al., 2002).

Therefore, we use the age of 10,300 ± 339 yr on the top of the terrace to control the age of the upper platform in the Niutou site. The slip rate ranges from minimum to maximum values corresponding to

\[ \frac{\Delta z}{\Delta t} = \frac{\Delta z_m}{\Delta t_m} = \frac{\Delta z_m}{T_m} \]

and

\[ \frac{\Delta z}{\Delta t} = \frac{\Delta z_m}{\Delta t_m} = \frac{\Delta z_m}{T_m} \]

are corresponding errors (Rizza et al., 2011).

Dividing the average cumulative slip of the platform (67.9 ± 0.9 m) by the age on top of the platform (10,300 ± 339 yr) yields a horizontal slip rate of 6.6 ± 0.3 mm/yr. This slip rate result is very close to the average slip rate from GPS (global positioning system) measured between Qilian Mountain and Ala Shan, ~7.5 ± 1.5 mm/yr (Zhang et al., 2002).

Gaudemer et al. (1995) estimated the slip rate of the LLLF by dividing the glacial valley offset in the Ningchanyahuo area (240 ± 40 m), interpreted from SPOT images, by the Last Glacial Maximum (20–14 ka) and yielded a rate of 15.5 mm/yr. However, Hetzel et al. (2002) suggested that landforms in middle Asia would be older than the Last Glacial Maximum, according to the exposure time dated by a series of terraces in the north Tibetan Plateau. This would mean that the rate of Gaudemer et al. (1995) is an overestimation. Lasserre et al. (2002) estimated the slip rate by dividing the geomorphologic offset (200 ± 40 m) by the age of the T1 moraine terrace in Ningchanyahuo (10,300 ± 339 yr) and yielded a slip rate of 19 ± 5 mm/yr. He et al. (2010) confirmed in the field that the offset used by Lasserre et al. (2002) came from moraine terrace T3. Therefore, the slip rate was again overestimated. He et al. (2002) derived a Holocene slip rate of 3.35–4.62 mm/yr using the estimated stratigraphic age. He et al. (2010) again estimated a slip rate of the LLLF during the Holocene of 3.9 ± 0.36 mm/yr using only one offset riser and the age of the bottom of pluvial terrace T1 (12665 ± 110 yr). Both slip rates estimated by He
Recurrence intervals of the east Lenglongling fault | RESEARCH

Figure 12. Morphotectonic evolution processes derived from offset bedrock terraces in the Chailong site. Four paleoseismic events were conserved by the tectonic geomorphology. (A) The original pre-earthquake stage of the geomorphology. The pluvial fan surface, considered to be the oldest terrace, T0, was unaffected by tectonic deformation. (B) The last but fourth seismic event offset the T0 and streambed by left-lateral slip with slight oblique slip. (C) The original pluvial surface T0 was eroded downward by the pluvial activity and bedrock terraces T1 and T0 were formed. The streambed finally developed a linear shape when it crossed over the fault before the antepenultimate earthquake. (D) The antepenultimate seismic event offset T1, T0, and the streambed by left-lateral slip with slight oblique slip. (E) The streambed was eroded downward again by the pluvial activity and bedrock terraces T2, T1, and T0 were formed. Terrace T1 was laterally eroded on the downstream of the west bank. The streambed developed a linear shape when it crossed over the fault before the penultimate earthquake again. (F) The penultimate seismic event offset all the bedrock terraces and streambed again by left-lateral slip with slight oblique slip. (G) The streambed was eroded downward again by the pluviation and the bedrock terraces T3, T2, T1, and T0 were formed. Terrace T1 was laterally eroded except for the one on the downstream of the east bank. Terrace T2 was also laterally eroded on the downstream of the west bank. The streambed developed a linear shape when it crossed over the fault before the antepenultimate earthquake once again. (H) The latest seismic event offset all the bedrock terraces and streambed again by left-lateral slip with slight oblique slip. (I) The current stage of the geomorphology in the Chailong site.

| TABLE 1. OPTICAL STIMULATED LUMINESCENCE DATING RESULTS ON TOP OF PLUVIAL TERRACE BETWEEN G4 AND G1 |
|---------------------------------------------------------------|
| Sample       | Buried depth | Technique | Available slices/total slices | $K_O$ (%) | Water content (%) | Total dose rate (Gy/k.y.) | Equivalent dose* (Gy) | Age (ka) |
|---------------|--------------|-----------|-------------------------------|-----------|------------------|---------------------------|-----------------------|----------|
| NTG-OSL-1     | 2.2          | SAR       | 23/34                         | 1.99      | 3                | 3.1 ± 0.2                 | 40.4 ± 1.0            | 13.1 ± 0.5 |
| NTG-OSL-2     | 0.8          | SAR       | 23/32                         | 2.27      | 3                | 3.1 ± 0.2                 | 36.2 ± 1.1            | 11.6 ± 0.5 |

Note: G—gully; OSL—optically stimulated luminescence; SAR—single aliquot regeneration.

*The equivalent dose was determined using medium-grained quartz.

| TABLE 2. RADIOACTIVE CARBON DATING RESULT ON TOP OF PLUVIAL TERRACE BETWEEN GULLIES G1 AND G2 |
|---------------------------------------------------------------|
| Sample        | Sample location         | Buried depth | $^{14}C/^{12}C$ ratio (%) | $^{14}C$ age (yr B.P.) | Calibrated age ± 2σ (yr B.P.) |
|---------------|-------------------------|--------------|--------------------------|------------------------|-------------------------------|
| NTG-C-1       | Outcrop on top of the platform | 2.0          | –23.3                    | 11,700 ± 40            | 13,515 ± 60                  |

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et al. (2002, 2010) had some deviation associated with the measurement error and age uncertainty of the offset geomorphology. We determined the cumulative slip of the different offset features to a higher precision with terrestrial LiDAR data, making our results more reliable.

Mean Recurrence Intervals

Combining the slip rate and the single-event slip distribution allows us to estimate the average recurrence intervals of past earthquakes on the east LLLF. The distance between the Chailong and Niutou sites is only 3 km and the surface rupture is linear and continuous; therefore, the mean slip rate estimated for the Niutou site is also applied to the Chailong site. By dividing the characteristic slip (9.4 ± 0.5 m) observed in the Chailong site by the Holocene slip rate (6.6 ± 0.3 mm/yr), we get an average recurrence interval of 1430 ± 140 yr. Millennial recurrence of large earthquakes is not unusual in the northeastern Tibetan Plateau. Sections of the Gulang fault, which is adjacent to the east LLLF, revealed 7 Holocene paleoearthquakes and one historic earthquake, determined as 10,743 ± 342 yr ago, 9038 ± 39 yr ago, 6910 ± 438 yr ago, 4847 ± 185 yr ago, 3562 ± 190 yr ago, 2476 ± 194 yr ago, 1505 ± 253 yr ago, and A.D. 1927 (Zheng et al., 2004). Moreover, sections of the western Haiyuan fault revealed that all four previous large events occurred during the past 3500–3900 yr (Liu-Zeng et al., 2007).

Regional Structural Links

As the most frontal marginal tectonic zone of the northeastern Tibetan Plateau, the group of NNW to NNW-trending faults plays an important part in accommodating regional tectonic deformation. The west of this zone (Tuolaishan fault and Sunan-Qilian fault) mainly manifests thrust slip movement, which gradually changes into strike-slip movement eastward along the fault (Fig. 13). In the middle section, the LLLF is mainly characterized by left-lateral strike-slip motion, while the west section presents slight thrusting movement, as shown by the M 6.4 earthquake of January 2016 on the northern branch of the LLLF. The strike-slip motion of the eastern LLLF is strongly supported by our morphotectonic survey.

The LLLF is usually considered to be part of the Qilian-Haiyuan fault zone, which consists of a series of left-lateral en echelon faults (Burchfiel et al., 1991; Ran and Deng, 1998; Lasserre et al., 1999, 2002; Li et al., 2009; Zhang et al., 1991; Zheng et al., 2013) accommodating the eastward movement of the Tibetan Plateau, relative to the GASP to the north (Tappornier and Molnar, 1977; Zhang et al., 1988a, 1988b). Nevertheless, until now there has been no direct geological evidence to indicate the relationship between the LLLF and its adjacent faults, such as the western Tuolaishan fault or the eastern Jinqianghe fault. Surface ruptures of both the eastern end of the LLLF and the western end of the Gulang fault are quite remarkable in the field and both ruptures join together at

Figure 13. Geological environments of the northeastern Tibetan Plateau surrounding the Lenglongling fault (LLLF) and its adjacent active faults. Fault abbreviations: MMSF—Maomaoshan fault; GLF—Gulang fault; JQHF—Jinqianghe fault; LHSF—Laohushan fault; YWSF—Yunwushan fault; NSSF—Niushoushan fault; BYWLSF—Bayanwulashan fault. The LLLF and other adjacent faults are mainly located in the convergent area of the northeastern Tibetan Plateau, the Gobi–Ala Shan platform (GASP), and the North China craton (NCC), affected by movement of the Indian plate, the Eurasian plate, and the Pacific plate, respectively. The numbers of years show the earthquake occurrence intervals, cited from Yuan et al. (1998), Zheng et al. (2004), and Liu-Zeng et al. (2007). Yellow arrows denote global positioning system velocities calculated from Liang et al. (2013), relative to the GASP. The eastern profiles of the HYF (Haiyuan fault) and YWSF (Yunwushan fault) are from Tang et al. (2005) and Wang et al. (2012). The western profiles of the TLSF (Tuolaishan fault) and SN-QLF (Sunan-Qilian fault) are from Yuan et al. (2004) and Zhao et al. (2014). The Moho depth is from Pan and Niu (2011).
the end of the two faults. Moreover, our estimated recurrence interval of the LLLF (1430 ± 140 yr) is almost equal to that of the Gulang fault (~1524 yr; Zheng et al., 2004). Altogether, 7–8 paleoearthquakes are inferred for the eastern LLLF, a conclusion also made for the Gulang fault (7 paleoearthquakes and 1 historical earthquake). The recurrence interval of the Jinqianghe-Maomaoshan fault, to the east of the LLLF, is 1800 yr, decreasing to 1080 yr eastward of the Laohushan (Yuan et al., 1998), and <1000 yr for the Haiyuan fault (Liu-Zeng et al., 2007). We infer that there are many more links between the LLLF and the Gulang fault than any other adjacent faults, and these faults therefore behave more like one integral fault zone. The Gulang fault should therefore be taken into consideration when assessing the Qilian-Haiyuan fault zone. Both the Gulang fault and the Haiyuan-Jinqianghe fault zone regulate the tectonic deformation transferred from the LLLF, thereby playing an important role in accommodating the eastward extrusion of the northeastern Tibetan Plateau relative to the GASP to the north. This eastward component of movement in the northeastern Tibetan Plateau eventually turns southeast, as shown by GPS velocities calculated from Liang et al. (2013), relative to the GASP and the eastern Erdos block of the North China craton for the obstruction of the east (Fig. 13). The region undergoes strong tectonic deformation exerted by the combined dynamics of the north Eurasian plate, the south Indian plate, and the east Pacific plate. We recommend that thorough geological and morphotectonic research should be done in the future to clarify the structural links among these active faults and that more attention should be paid to active faults with millennial recurrence intervals, especially the LLLF.

CONCLUSIONS

Terrestrial LiDAR data and HRRS images give us the opportunity to study three-dimensional microtopographic features in great detail. We carried out terrestrial LiDAR measurements in three sites on the eastern part of the LLLF, where offset landforms are easily distinguished. High-accuracy DEMs of 0.2 m resolution were generated for morphologic analysis. Parameters such as the seismic slip amount, slip rate, and recurrence intervals of the east LLLF were estimated in this study.

The terrestrial LiDAR data showed the offset of the most recent earthquake, which ruptured the streambed and gully in the Chailong and Taola sites. Single-event slip and multievent cumulative slips were evaluated by offset bedrock terrace risers. Morphotectonic analysis indicated that the east of the LLLF obeys a characteristic slip model, with the amount of single-event slip being 9.4 ± 0.5 m. The morphotectonic evolution model of the offset landforms in the Chailong site was constructed accordingly. The mean offset of the Niuotou site is ~67.9 ± 0.9 m. Combining this with the age (10,300 ± 339 yr) of the top of the platform (Lasserre et al., 2002; He et al., 2010), we estimated a left-lateral strike-slip rate of 6.6 ± 0.3 mm/yr for the east LLLF during the Holocene. In total, 7–8 paleoearthquakes have been inferred for the LLLF.

The mean recurrence interval of the east LLLF is ~1430 ± 140 yr for paleoearthquakes during the Holocene, which approximates that of the adjacent Gulang fault. Taking into consideration the millennial recurrence of the Haiyuan, Jinqianghe-Maomaoshan, and Laohushan faults, the northeastern Tibetan Plateau is at extremely high risk of seismic activity, and significant research should therefore be dedicated to this region. All these faults play an important role in accommodating the eastward and subsequent southeastward movement of the Tibetan Plateau, relative to the GASP to the north and the rigid North China craton to the east. We suggest that the LLLF and Gulang faults behave more like one integral fault zone, a theory that requires further geological and geomorphological evidence.

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APPENDIX 1. TERRRESTRIAL LiDAR MEASUREMENT AND DATA PROCESS

In this study, the V-Line 3D Terrestrial Laser Scanner RIEGL VZ-1000 was used to measure the high-accuracy topography. The instrument provides high speed, non-contact data acquisition for ranges of more than 1200 m using a narrow infrared laser beam and a fast scanning mechanism. The scanning distance is set to 400 m with a pulse repetition rate of 360 kHz, the data cloud density of which is high enough to acquire the detailed topography. We carried out 6 measurements in the Taola site, 8 in the Chailong site, and 16 in the Niuotou site. Most of the Lenglongling fault is covered by low shrubs or no vegetation (Fig. 14), which improves measurement accuracy greatly.

In order to acquire a complete image of terrestrial LiDAR measurement, LiDAR data clouds of multistations have to be registered and mosaicked together. We use the RiSCAN PRO software to do the LiDAR image processing in this study. The Multi Station Adjustment (MSA) function tries to improve the registration of the scan positions. For that purpose the orientation and position of each scan position are modified in several iterations in order to calculate the best overall fit for them. To compare the scan positions, the tiepoints, tieobjects, and polylayer objects (reduced point clouds) are used. The data cloud registration error of all the stations is limited to ~2 cm.

The study areas are covered by scrubby shrubs, which have to be removed to generate the digital elevation model (DEM). Therefore, we do the terrain filter to separate off-terrain points (e.g. vegetation, float points in the air due to dust reflection) from terrain points. In the course of the filter process, the distances of the points from an estimated ground surface are analyzed. Based on these distances, the points are classified either as terrain or off-terrain. Note that the filter is not intended to filter large objects without points below their surface because the method used requires a certain amount of terrain points underneath the off-terrain objects. The representation of the terrain surface is restricted to 2.5 dimensions.

When the LiDAR data points are ready, we resample the data clouds to 0.1 m and then export these points to the LAS (laser) format file, which is further used to create a LAS database. Thereafter, a triangulated irregular network (TIN) is exported from the LAS dataset utilizing ArcGIS desktop software (www.esri.com). In addition, we create a raster by interpolating its cell values from the elevation of the input TIN at the specified sampling distance. Here we input 0.2 m as the sampling distance, although even much higher accuracy raster data can be generated. In order to analyze the offset landforms, a shaded relief from a surface raster is created by considering the illumination source angle and shadows. Meanwhile, line feature class of contours (isolines) is also generated from a raster surface with intervals of 2 m. Based on the raster digital elevation model, shaded relief, and the contour lines, we interpret the offset landforms and measure the seismic slips.

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