Segmentation and termination of the surface rupture zone produced by the 1932 Ms 7.6 Changma earthquake: New insights into the slip partitioning of the eastern Altyn Tagh fault system

Jiaxin Du1,2,*, Bihong Fu1,4,*, Qiang Guo1,*, Pilong Shi1,*, Guoliang Xue2,*, and Huan Xu1,†
1CAS KEY LAB OF DIGITAL EARTH SCIENCE, AEROSPACE INFORMATION RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES, BEIJING 100094, CHINA
2UNIVERSITY OF CHINESE ACADEMY OF SCIENCES, BEIJING 100049, CHINA

ABSTRACT

The 1932 Ms 7.6 earthquake struck the active Changma fault in the NE Tibetan Plateau, and produced a distinct surface rupture along the fault zone. However, the segmentation and termination of the surface rupture zone are still unclear. In this paper, the active tectonic analyses of multiple satellite images complemented by field investigations present the 120-km-long surface rupture zone, which can be divided into five discrete first-order segments, ranging from 14.4 to 39.56 km in length, linked by step-overs. Our results also indicate that the 1932 rupture zone could jump across step-overs 0.3–4.5 km long and 2.2–5.4 km wide in map view, but was terminated by a 6.3-km-wide restraining step-over at the eastern end. The left-lateral slip rates along the mid-eastern and easternmost segments of the Changma fault are 3.43 ± 0.5 mm/yr and 4.49 ± 0.5 mm/yr since 7–9 ka, respectively. The proposed tectonic models suggest that the slip rates on the Changma fault are similar to the slip rate on the eastern segment of the Altyn Tagh fault system near the junction point with the Changma fault. These results imply that the Changma fault plays a leading role in the slip partitioning of the easternmost segment of the Altyn Tagh fault system.

INTRODUCTION

The Cenozoic tectonic deformation resulting from continuous India–Asia collision has built the remarkable topography in the Tibetan Plateau (Molnar and Tapponnier, 1975; Harrison et al., 1992; Clark and Royden, 2000; Yin and Harrison, 2000; Tapponnier et al., 2001). The Altyn Tagh fault (ATF) system and the Qilian Shan fault (QLSF) belt are two major fault sets along the CMF (Hou et al., 1986; Lanzhou Institute of Seismology, National Bureau of Seismology, 1992). The Cenozoic tectonic deformation resulting from continuous India–Asia collision has built the remarkable topography in the Tibetan Plateau (Molnar and Tapponnier, 1975; Harrison et al., 1992; Clark and Royden, 2000; Yin and Harrison, 2000; Tapponnier et al., 2001). The Altyn Tagh fault (ATF) system and the Qilian Shan fault (QLSF) belt are two major fault sets along the CMF (Hou et al., 1986; Lanzhou Institute of Seismology, National Bureau of Seismology, 1992). The 1932 Ms 7.6 Changma earthquake produced a N70°W striking coseismic surface rupture zone along the Changma fault (CMF) (Hou et al., 1986; Peltzer et al., 1988) (Figs. 1 and 2). Numerous publications have documented the surface rupture zone with complex left-lateral en-echelon patterns, showing the channels, gullies, and scarps of 2.1–3.3 m up to 5.5 m coseismic offsets along the CMF (Hou et al., 1986; Kang, 1986; Peltzer et al., 1988; Luo et al., 2013; Lanzhou Institute of Seismology, National Bureau of Seismology, 1992). However, the segmentation, propagation, and termination of the coseismic surface rupture along the CMF remain unclear, limiting a better understanding of the role the CMF plays in the tectonic transformation in the NE Tibetan Plateau.

On the basis of the spatial distribution and continuities, a previous study carried out by the Lanzhou Institute of Seismology, SSB (1992) divided the CMF surface rupture zone into three discrete segments, each extending 40–50 km in length. Their field work also found the extensional tracks, coseismic scarps, and bulges developed within the surface rupture zone (Hou et al., 1986; Lanzhou Institute of Seismology, National Bureau of Seismology, 1992). The 14C dating age of upper and lower terraces, estimated to be 12,000–15,000 yr B.P and 7000–9000 yr B.P., together with the streams of 20–40 m left-lateral offsets, yielded an average Holocene left-lateral slip rate of 3.3–4.3 mm/yr along strike of the CMF (Lanzhou Institute of Seismology, National Bureau of Seismology, 1992). Other studies proposed that the surface rupture zone was composed of four reverse S-shaped segments, based on the geometric features and structural deformations along the CMF (Zheng, 2009; Luo et al., 2013). Their results indicated that the left-lateral slip rates of beheaded stream channels and thrust rates of fault scarps were 1.17 ± 0.07 mm/yr and 0.14 ± 0.02 mm/yr, respectively, on the aban- doned alluvial fan along the western CMF (Zheng, 2009; Zheng et al., 2013). The left-lateral slip rates of offset stream channels increased gradually from 1.33 ± 0.39 mm/yr to 3.68 ± 0.41 mm/...
yr from west to east, implying that the structural deformations along the CMF have absorbed the slip of the ATF system (Luo et al., 2013).

The previously mentioned studies focused on the geologic and geomorphic features of the surface rupture zone. But the discontinuities developed along the surface rupture zone are important for understanding the segmentation of the surface rupture zone (Segall and Pollard, 1980; DePolo et al., 1991; Zhang et al., 1991, 1999; Fu et al., 2005). These discontinuities are mainly characterized by complex step-overs and bends with great impacts on the initiation, propagation, and termination of coseismic ruptures (Barka and Kadinsky-Cade, 1988; Wesnousky, 1988; Harris and Day, 1993; Zhang et al., 1999; Duan and Oglesby, 2005, 2006; Lozos et al., 2011; Elliott et al., 2018). Numerical geological models agree with the field observations that large earthquakes could easily propagate through step-overs with widths of <4 km, but could be arrested by those ones with widths of >5 km (Crone and Haller, 1991; Zhang et al., 1991; Lettis et al., 2002; Duan and Oglesby, 2006; Wesnousky, 2006; Elliott et al., 2009). In order to study the segmentation and termination of the surface rupture zone, more detailed analyses of discontinuities developed within the surface rupture zone are needed. These results can provide significant implications for the role the CMF plays in the tectonic transition of the ATF system.

In this paper, we first interpret the segmentation and geometric and geomorphic features of the CMF rupture zone in detail based on high-resolution satellite images and field observations. Then, CMF slip rates will be estimated using age dating data and slip displacements. Finally, we explore the reasons for the termination of the 1932 Changma co-seismic surface rupture zone, and propose a new tectonic model to explain the role the CMF played in the slip partitioning of the ATF system.

GEODETICAL SETTING

The left-lateral strike-slip CMF with a south-westward dip of thrust faulting was observed in the northeastern Tibetan Plateau (Tapponnier and Molnar, 1977; Peltzer and Tapponnier, 1988) (Figs. 1 and 2A). The NWW-trending fault propagated through numerous streams and rivers, such as the Shule, Daheigou, Anmen, Shiyou, Ya'er, and Xishuixia rivers, from west to east (Fig. 2A). The Quaternary alluvial fans, stream channels, and ridges appear to have displacements varying from 3 to 400 m (Peltzer et al., 1988; Lanzhou Institute of Seismology, National Bureau of Seismology, 1992) (Fig. 2B). The structural deformation of warping rivers, gullies, and surface ruptures as well as bulges and scarpas correspond well to long-term horizontal and vertical motion on the CMF since the late Quaternary (Lanzhou Institute of Seismology, National Bureau of Seismology, 1992). Moreover, the recurrence interval for large earthquakes with magnitude 7–7.5 along the CMF was roughly estimated to be 1000–2620 years during the Holocene (Hou et al., 1986; Kang, 1986; Peltzer et al., 1988; Luo et al., 2016).

In the western end of the CMF, the 1600 km-long ATF system started left-lateral motion.
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Figure 2. (A) First-order segmentation of surface rupture zone related to the 1932 M\textsubscript{S} 7.6 earthquake along the CMF between 96°33' and 97°46'E as shown in Landsat TM mosaic image. The active faults shown on this map were modified from Hetzel et al. (2004) and Yin et al. (2008a). (B) Spatial distribution of surface rupture zone along the CMF (geological information partially modified from geological map of Gansu Bureau of Geological and Mineral Resources, 1969, 1972). LJW-CLG segment—Lujiawan-Chouliugou segment; DHGR segment—Daheigou River segment; SGQ-MSJ segment—Sangequan-Moshiju segment; CSLG-SYR segment—Choushuiliugou-Shiyou River segment; SYR-XSX segment—Shiyou River-Xishuixia segment. The 1932 Changma earthquake and 2002 Yumen earthquake events shown on the map were obtained from National Centers for Environmental Information (NCEI).
In this study, multiple sources of satellite remote sensing data obtained by the Landsat Thematic Mapper/Enhanced Thematic Mapper (TM/ETM*), Satellite pour l’observation de la terre (SPOT), Worldview, Quickbird as well as Geoeye, were used to interpret remarkable geometric and geomorphic features of the surface rupture zone along the CMF. The spatial resolution of these images ranges from 0.5 m to 30 m. In addition, the Digital Elevation Model (DEM) obtained from the Shuttle Radar Topography Mission, the Global DEM generated from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER GDEM), and the DEM data obtained from the unmanned aerial vehicle (UAV) have spatial resolutions of 90 m, 30 m and 4 cm, respectively, which enable us to precisely document the displacements of terraces riser, channels, and streams along the fault trace. Based on the geologic and geomorphic analyses of these multiple remote sensing data complemented by a geologic map with a scale of 1:200,000 (Gansu Bureau of Geology and Mineral Resources, 1965–1979), we mapped the geometric and kinematic features of the surface rupture zone in different scales. Particularly, we documented the step-overs with different sizes along the rupture zone in detail. In order to estimate the age of these displaced geomorphic surfaces, fourteen 14C dating samples and five Optically Stimulated Luminescence (OSL) samples were collected from clay and loess of lower terraces T9. The 14C dating of the charcoal samples was carried out at Beta Analytic Radiocarbon Dating Laboratory, United States. The OSL testing works for quartz samples were completed at the OSL Research Laboratory of Geology and Geophysics, Chinese Academy of Science. The age dating data from the lower terraces T9 determined the youngest age of the offset (Cowgill, 2007). Combined with the estimates of displacements, the maximum Quaternary slip rates of the CMF were yielded (Cowgill, 2007). The results of OSL data and 14C dating data are represented in Tables 1 and 2, respectively.

**RESULTS**

The interpretation of satellite images showed a 120-km-long surface rupture zone along strike of the CMF from Lujiaowan (39°51′35″N, 96°33′10″E) to Xishuxia (39°31′9″N, 97°46′14″E) (Fig. 2A). The 1932 earthquake broke it into five reverse S-shaped first-order segments, according to the geometric features of discontinuities (Fig. 2B). From west to east, these include the Lujiaowan-Chouliugou (LJW-CLG), Daheigou River (DHGR), Sangequan-Moshijiu (SGQ-MSJ), Choushuiliugou-Shiyi River (CSLG-SYR) and Shiyou River-Xishuxia (SYR-XXS) segments, respectively, as shown in Figure 2B. These 14.4–39.6-km-long first-order segments are separated from one another by 0.3–4.5-km-long and 2.2–5.4-km-wide step-overs. Each first-order segment can be further divided into second-order segments of 2.5–18.8 km in length, linked by step-overs or bends of less than 2 km in width (Figs. 3 and 4).

**Segmentation of CMF Surface Rupture Zone**

**Lujiaowan-Chouliugou Segment**

The LJW-CLG segment (between 96°33′ and 96°54′E), the westernmost part of the surface rupture zone, extends ~39.56 km as shown in Figure 3A. It can be further divided into three second-order segments, from west to east, each 10.2–16.2 km long with strike of N30°-70°W.

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**Table 1. Optically Stimulated Luminescence (OSL) Dating Results of Loess Samples Collected Along the Changma Fault**

| Sample number | Latitude (°) | Longitude (°) | Locality | Depth* (m) | Material dated | U (ppm) | Th (ppm) | K (%) | Water content (%) | Cosmic ray (Gy/ka) | Dose rate (Gy/ka) | De (Gy) | Optical age (ka) |
|---------------|--------------|---------------|----------|------------|---------------|---------|---------|------|-----------------|-----------------|-----------------|--------|----------------|
| SGQ01W        | 39.6389      | 97.3278       | Choushuiliugou | 0.7        | Quartz       | 2.38    | 10.4    | 1.77 | 13              | 0.31            | 3.00 ± 0.15    | 28.19 ± 2.75 | 9.4 ± 1.0       |
| SGQ02W        | 39.6389      | 97.3278       | Choushuiliugou | 0.2        | Quartz       | 2.11    | 10.9    | 1.94 | 17              | 0.31            | 3.01 ± 0.16    | 21.21 ± 3.08 | 7.0 ± 1.1       |
| SGQ03E        | 39.6389      | 97.3278       | Choushuiliugou | 0.9        | Quartz       | 2.62    | 10.7    | 2.02 | 16              | 0.31            | 3.19 ± 0.17    | 29.40 ± 3.51 | 9.2 ± 1.2       |
| XSS04E        | 39.5141      | 97.7345       | Xishuxia     | 1.8        | Quartz       | 2.51    | 11.5    | 2.22 | 12              | 0.32            | 3.53 ± 0.18    | 26.89 ± 1.44 | 7.6 ± 0.6       |
| XSS05E        | 39.5141      | 97.7345       | Xishuxia     | 1.1        | Quartz       | 2.27    | 10.6    | 2.09 | 19              | 0.32            | 3.10 ± 0.17    | 19.20 ± 1.68 | 6.2 ± 0.6       |

*Depth below the surface where the samples were collected.
†Testing for quartz samples using Single-aliquot Regenerative-dose Protocol was performed at the OSL Research Laboratory of Geology and Geophysics, Chinese Academy of Science.
(Fig. 3B). At the western part of the LJW-CLG segment, numerous offset stream channels were found around the Xiaokouzi site (Fig. 3). To the eastern part of the LJW-CLG segment, the left-lateral offset of a small gully was measured to be 6 ± 0.4 m at Chouluiougou (see field photo in Fig. 3A). Eastward to the Shule River, the Quickbird image shows that the LJW-CLG and DHGR segments are linked by a 4.5 ± 0.1 km-long and 3.4 ± 0.1 km-wide left-stepping step-over (Fig. 2; Table 3).

**Daheigou River Segment**

Located northeast of Shule River, the N45°-80°W-striking DHGR segment (between 96°58’ and 97°7’E) runs ~17.1 km long (Fig. 4A). The rupture zone can be further divided into three discontinuous second-order segments ranging from 2.4 to 8.6 km long (Fig. 4B). In the western part of the DHGR segment, the Quickbird images show that a series of left-stepping en-echelon fissures striking N70°W are linked by small step-overs or bends (Figs. 4B and 5A). In the central part of the DHGR segment, a 18-m-long and 462-m-wide right-stepping step-over forms across the rupture zone (see field photo in Fig. 7A). In the central part of the DHGR segment, a series of left-stepping step-overs were found among the second-order segments (Fig. 6B). Toward the easternmost portion of the DHGR segment, a large right-stepping step-over was observed by field observation (see location of field photo in Fig. 10A). The geomorphic analyses of the satellite images and field observations showed the coseismic left-stepping surface ruptures along the eastern segment of the CMF (see field photo in Fig. 10A). The geomorphic analyses of high-resolution images obtained by the UAV show that terraces riser \( T_1 \) in front of the ridges match well after restoring a 35 ± 2.6 m offset (Figs. 11A–11C). The loess and clay samples of terraces \( T_1 \) were collected for OSL and \(^{14}\)C dating (Tables 1 and 2; Figs. 11D–11G, see location of samples collected in Fig. 11A). The 6–28 m left-lateral displacements of gullies along the CMF were measured by DEM obtained by UAV (Figs. 12 and 13). In the easternmost part of the SYR-XSX segment, a large right-stepping step-over with a length of 3.5 ± 0.1 km and a width of 6.3 ± 0.1 km arrested the surface rupture near Xishuixia River (97°46’E) (Fig. 2; Table 3).

**Shiyou River-Xishuixia Segment**

Continuously eastward to the Shiyou River, the 34.9-km-long SYR-XSX segment (between 97°25’ and 97°46’E) can be further divided into four second-order segments, varying from 6 to 11.5 km long (Fig. 10A). Detailed interpretation of the SPOT6 image shows that hundreds of meters-wide step-overs developed at the boundaries among the second-order segments from Ya’er to Baiyang rivers (Fig. 10B). To the easternmost portion of the SYR-XSX segment, a gully across the rupture zone was left-laterally displaced 6.2 ± 0.5 m, as measured in the field (see location of field photo in Fig. 10A). Both our interpretation of the satellite images and field observations showed the coseismic left-stepping surface ruptures along the eastern segment of the CMF (see field photo in Fig. 10A). The geomorphic analyses of high-resolution images obtained by the UAV show that terraces riser \( T_1 \) in front of the ridges match well after restoring a 35 ± 2.6 m offset (Figs. 11A–11C). The loess and clay samples of terraces \( T_1 \) were collected for OSL and \(^{14}\)C dating (Tables 1 and 2; Figs. 11D–11G, see location of samples collected in Fig. 11A). The 6–28 m left-lateral displacements of gullies along the CMF were measured by DEM obtained by UAV (Figs. 12 and 13). In the easternmost part of the SYR-XSX segment, a large right-stepping step-over with a length of 3.5 ± 0.1 km and a width of 6.3 ± 0.1 km arrested the surface rupture near Xishuixia River (97°46’E) (Fig. 2; Table 3).

### TABLE 2. \(^{14}\)C DATING RESULTS ALONG THE CHANGMA FAULT

| Sample number | Laboratory number | Latitude (°) | Longitude (°) | Locality | Depth* (m) | Material dated | Variables: \(^{14}\)C/\(^{12}\)C (‰) | Radiocarbon age† (2σ) (cal yr BP) | Calendar age§ (cal yr BP) (2σ) (95%) |
|---------------|------------------|-------------|-------------|----------|-----------|---------------|----------------------------|---------------------------------|---------------------------------|
| C1E           | Beta-448132      | 39.5141     | 97.7345     | Xishuixia| 1.5       | Charcoal      | -22.6               | 6140 ± 30                      | 7160–6945                       |
| C2W           | Beta-448137      | 39.5141     | 97.7345     | Xishuixia| 2.1       | Charcoal      | -24.7               | 2560 ± 30                      | 2750–2705                       |
| C3W           | Beta-448138      | 39.5141     | 97.7345     | Xishuixia| 1.86      | Charcoal      | -24.2               | 2390 ± 30                      | 2490–2345                       |
| C4W           | Beta-448139      | 39.5141     | 97.7345     | Xishuixia| 1.42      | Charcoal      | -21.3               | 2030 ± 30                      | 2055–1920                       |
| C5E           | Beta-448133      | 39.5141     | 97.7345     | Xishuixia| 1.9       | Charcoal      | -21.8               | 2870 ± 30                      | 3070–2920                       |
| C6W           | Beta-448140      | 39.5141     | 97.7345     | Xishuixia| 1.98      | Charcoal      | -24.2               | 3000 ± 30                      | 3320–3305                       |
| C7W           | Beta-448141      | 39.5141     | 97.7345     | Xishuixia| 3         | Charcoal      | -26.2               | 5700 ± 30                      | 6555–6410                       |
| C9E           | Beta-448135      | 39.5141     | 97.7345     | Xishuixia| 0.5       | Charcoal      | -22.4               | 2970 ± 30                      | 3215–3060                       |
| C10E          | Beta-448136      | 39.5141     | 97.7345     | Xishuixia| 0.7       | Charcoal      | -21                  | 2800 ± 30                      | 2965–2845                       |
| XXXC2A        | Beta-448130      | 39.5141     | 97.7345     | Xishuixia| 1.5       | Charcoal      | -22.7               | 6050 ± 30                      | 6975–6830                       |
| XXXC4A        | Beta-448131      | 39.5141     | 97.7345     | Xishuixia| 0.7       | Charcoal      | -24.2               | 1200 ± 30                      | 1230–1210                       |
| SGQC1E        | Beta-448142      | 39.6389     | 97.3278     | Choushiougou| 0.5  | Charcoal | -23.4               | 6610 ± 30                      | 7570–7435                       |
| SGQC2E        | Beta-448143      | 39.6389     | 97.3278     | Choushiougou| 0.5  | Charcoal | -23.1               | 2690 ± 30                      | 2850–2750                       |
| HYZC4N        | Beta-448144      | 39.6389     | 97.3278     | Choushiougou| 0.7  | Charcoal | -24.8               | 6720 ± 30                      | 7615–7565                       |

*Depth below the surface where the samples were collected.
†Accelerator mass spectrometry measurement was completed by Beta Analytic Radiocarbon Dating Laboratory, USA.
§Calendar ages were calibrated at the 2σ confidence level using IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP (Reimer et al., 2013).
Figure 3. (A) Spatial distribution of the surface rupture zone along the LJW-CLG segment mapped from SPOT6 mosaic image. The location of field photo in Figure 12A is shown. (B) Image interpretation of active tectonic map displaying the geometry of second-order segmentations along the LJW-CLG segment.
Figure 4. (A) Spatial distribution of the surface rupture zone along the DHGR segment interpreted from SPOT6 mosaic image. The location of field photo in Figure 12B is shown. (B) Image interpretation of active tectonic map showing the geometry of second-order segmentations along the DHGR segment.
Late Quaternary Slip Rate of CMF

In this study, the maximum Quaternary slip rates on the CSLG-SYR and SYR-XSX segments were estimated using the offsets of lower terraces riser T₁ and age dating data (Cowgill, 2007). The calculation formula is:

\[
\text{Slip rate} = \frac{\text{Offset}}{\text{age}}. 
\]

The reconstructed terraces riser T₁ had 31 m and 35 m left-lateral displacements on the CSLG-SYR and SYR-XSX segments as shown in Figures 9 and 11. Considering the 4-m coseismic offsets caused by the 1932 earthquake event (Luo et al., 2013; Lanzhou Institute of Seismology, National Bureau of Seismology, 1992), the long-term displacements should be 27 ± 2.3 m and 31 ± 2.6 m on these two segments, respectively. The abandonment age of a lower terrace can be regarded as the youngest age of displacement and the estimates of slip rate constrains the maximum displacement rate (Cowgill, 2007; Zhang et al., 2008).

In the CSLG-SYR segment, the loess deposit ages (9.4 ± 1.0 ka and 7.0 ± 1.1 ka) of terraces T₁ were obtained from OSL samples SGQ01W and SGQ02W (Figs. 9C and 9D). Meanwhile, the \(^{14}\)C sample HYZC4N gave the dating results of terraces T₁ as 7615–7565 yr B.P. (Figs. 9E and 9F). We used these results together with the 27 ± 2.3 m offset to estimate the left-lateral slip rate as 2.87 ± 0.4 mm/yr, 3.86 ± 0.7 mm/yr, and 3.56 ± 0.3 mm/yr, for samples SGQ01W, SGQ02W, and HYZC4N, respectively (Fig. 9G). Hence, on the CSLG-SYR segment, the average left-lateral slip rate of lower terrace riser T₁ was calculated as 3.43 ± 0.5 mm/yr, which may be the maximum slip rate of the offset (Cowgill, 2007). This slip rate is slightly smaller than the 3.68 ± 0.41 mm/yr result, which was estimated by using the 16 ± 1 m offset lower terrace riser T₁ and age dating of 3270 ± 95 yr B.P. (Luo et al., 2013). However, the field observations and dating results showed that the deposits of lower terrace T₁ should have started around 9.4 ± 1.0 ka rather than being younger than 3 ka (Fig. 9D). Thus, multiple slip rates were used in this work to determine the average slip rate of terrace riser T₁, which can provide better upper boundaries for the slip rates of this segment.

In the SYR-XSX segment, the OSL dating age of terraces T₁ loess samples XSX05E and XSX04E were 6.2 ± 0.6 ka and 7.6 ± 0.6 ka, B.P. (Figs. 9E and 9F). We used these results together with the 27 ± 2.3 m offset to estimate the left-lateral slip rate as 2.87 ± 0.4 mm/yr, 3.86 ± 0.7 mm/yr, and 3.56 ± 0.3 mm/yr, for samples SGQ01W, SGQ02W, and HYZC4N, respectively (Fig. 9G). Hence, on the CSLG-SYR segment, the average left-lateral slip rate of lower terrace riser T₁ was calculated as 3.43 ± 0.5 mm/yr, which may be the maximum slip rate of the offset (Cowgill, 2007). This slip rate is slightly smaller than the 3.68 ± 0.41 mm/yr result, which was estimated by using the 16 ± 1 m offset lower terrace riser T₁ and age dating of 3270 ± 95 yr B.P. (Luo et al., 2013). However, the field observations and dating results showed that the deposits of lower terrace T₁ should have started around 9.4 ± 1.0 ka rather than being younger than 3 ka (Fig. 9D). Thus, multiple slip rates were used in this work to determine the average slip rate of terrace riser T₁, which can provide better upper boundaries for the slip rates of this segment.

**TABLE 3. STEP-OVERS ALONG THE CHANGMA FAULT**

| Step-over name             | Latitude (°) | Longitude (°) | Width (km) | Error (km) | Length (km) | Error (km) | Type               |
|----------------------------|--------------|---------------|------------|------------|-------------|------------|--------------------|
| Shule River step-over      | 39.7054      | 96.9392       | 3.4        | 0.3        | 4.5         | 0.3        | Releasing step-over |
| Daheigou River step-over   | 39.6452      | 97.1283       | 2.2        | 0.2        | 0.32        | 0.02       | Restraining step-over |
| Anmen River step-over      | 39.6315      | 97.2842       | 2.5        | 0.2        | 0.81        | 0.1        | Releasing step-over |
| Shiyou River step-over     | 39.5573      | 97.4326       | 5.4        | 0.4        | 2.3         | 0.2        | Restraining step-over |
| Xishuixia River step-over  | 39.4866      | 97.7672       | 6.3        | 0.5        | 3.5         | 0.3        | Restraining step-over |

**Figure 5. Interpretation of Quickbird mosaic images showing the detailed geometric features of DHGR segment.** (A) Ruptures appearing as left-stepping en-echelon pattern in the western part of DHGR segment. (B) Ruptures displaying as right-stepping en-echelon pattern in the middle part of DHGR segment. (C) Ruptures appearing as right-stepping en-echelon pattern in the eastern part of DHGR segment.
respectively (Figs. 11D and 11E). The age of 
$^{14}$C loess sample C1E was estimated as 7.05 ± 0.61 ka (Figs. 11F and 11G). The C9E sample 
was not used for age dating since it was col-
lected from the clay above the loess and could 
not represent the age of loess itself (Fig. 11G).
The left-lateral slip rates for samples XSX05E, 
XSX04E, and C1E were calculated to be 5 ± 0.6 
mm/yr, 4.08 ± 0.5 mm/yr, and 4.40 ± 0.4 mm/
yr, respectively, combined with these age dat-
ing results and the 31 ± 2.6 m left-lateral offset 
of terrace risers $T_1$ (Fig. 11H). As discussed 
previously, the long-term average slip rate is 
4.49 ± 0.5 mm/yr on the SYR-XSX segment 
(Fig. 11H). A previous study constrained the 
slip rates of offset ridges as 4.6 ± 1.4–5.5 ± 2.2 
mm/yr on the eastern section of CMF since 
the last glacial retreat (~10 ka) (Peltzer et al., 
1988). However, these rates were proven to be 
quite high, as the ridge displacements must have 
accumulated before the last glacial retreat (Luo 
et al., 2013). Hence, the maximum slip rate on 
the eastern section of CMF was 4.49 ± 0.5 mm/
yr or at least not more than 5 mm/yr.

**DISCUSSION**

The Segmentation, Length, and Slip 
Displacements of Surface Ruptures 
Related to the Changma Earthquake

The segment geometry, length, and slip 
displacements of surface ruptures are critical for 
the study of earthquakes (Eberhart-Phillips et al., 
2003; Fu et al., 2005). The surface rupture zones 
caused by historically large earthquakes with magnitudes >7 appear to have multi-segment...
Figure 7. (A) Interpretation of Quickbird mosaic image showing the bend developed in the west of SGQ-MSJ segment. Location of field photo in Figure 12C is shown. (B) A bend developed between two discrete second-order segments along the SGQ-MSJ segment. Location of field photo in Figure 12D is shown. (C) Field measures and image interpretation showing offset gullies near the Dahuitiaogou site.
Figure 8. (A) Spatial distribution of the surface rupture zone along the CSLG-SYR segment mapped from SPOT6 mosaic image. Location of field photo in Figure 12E is shown. (B) Image interpretation of active tectonic map showing the geometry of second-order segmentations along the CSLG-SYR segment.
patterns (Lettis et al., 2002; Fu et al., 2005). The 1932 Ms 7.6 Changma earthquake nucleated around the Xiaokouzi site and propagated a bilateral rupture to the east and west (Lanzhou Institute of Seismology, National Bureau of Seismology, 1992) (Fig. 2A). The coseismic surface rupture caused by the 1932 earthquake has been well preserved over the past nearly 90 years. The surface rupture zone can be divided into five discrete first-order segments varying in length from 14.4 to 39.6 km. The first-order rupture segments could be subdivided into several second-order segments linked by left-lateral releasing step-overs and bends (Figs. 5, 7, and 12). Field observations also showed an increase in the scale of the rupture from west to east (Fig. 12). Moreover, our interpretation of satellite images and field investigations showed that gullies or channels have a 6–15 m coseismic offset within the Changma rupture zone (Figs. 7 and 12). The changes in the size of these offsets might also record the propagation and stress mechanisms of coseismic ruptures (Zhang et al., 1991). Particularly, the longest continuous ruptures on the easternmost segment are associated with pure left-lateral strike slip faulting, whereas the western part of the CMF is characterized by strike-slip and reverse faulting components (Peltzer et al., 1988) (Figs. 2 and 10).
These observations were also consistent with (1994), earthquakes with moment magnitudes with an average coseismic offset of 3–4 m. Based on the regression equations proposed by Wells and Coppersmith (1994), earthquakes with moment magnitudes >7.4 can produce surface ruptures of >100 km in length and generate average coseismic slip displacements of offset >3.3 m. The regression equations (Wells and Coppersmith, 1994) are:

\[
M = 5.08 + 1.16 \times \log \text{(SRL)}
\]

and

\[
M = 6.93 + 0.82 \times \log \text{(AD)},
\]

where M = moment magnitude, SRL = surface rupture length, and AD = average displacement.

The field investigations for this work identified the 120-km Changma surface rupture zone with an average coseismic offset of 3–4 m. These observations were also consistent with previous results (Luo et al., 2013; Lanzhou Institute of Seismology, National Bureau of Seismology, 1992). The moment magnitude of the 1932 Changma earthquake was calculated as 7.4–7.5 using the regression equations, rupture length, and coseismic offset. The estimate of moment magnitude fits the regression relationship. These results provide valuable insights for evaluating and predicting the possibility of large earthquakes on strike-slip faults.

The Influence of Step-Overs on Rupture Propagation and Termination

Previous workers have suggested that a step-over plays a key role in determining coseismic rupture dynamics (Wensoulsky, 2006; Oglesby, 2008). On the one hand, numerous studies indicated that a step-over with width >4 km could effectively stop coseismic rupture (Segall and Pollard, 1980; Sibson, 1985; Wensoulsky, 1988, 2006; Harris and Day, 1993; Sieh et al., 1993; Letts et al., 2002; Oglesby, 2008). In addition, the ability of a rupture to jump across step-overs decreases exponentially as the width of step-overs increases (Bruce and Dieterich, 2007). On the other hand, some studies proposed that the restraining and releasing step-overs have different impacts on the continuity of coseismic surface ruptures (Harris and Day, 1993; Oglesby, 2005; Wensoulsky, 2006). Rupture propagation is much more difficult in a restraining step-over than in a releasing step-over, even though the releasing step-over is wider than the restraining step-over (Harris et al., 1991; Harris and Day, 1993; Oglesby, 2005). Further studies also discovered that the stress heterogeneity accumulated in a releasing step-over could enable a rupture to jump across the step-over, whereas the stress pattern of a restraining step-over is more efficient at arresting a rupture (Duan and Oglesby, 2006; Wensoulsky, 2006).

In this work, our results show that there are five first-order segments along the CMF, which are linked by step-overs of different sizes (Fig. 14A). Some of these step-overs, such as the Shule River step-over (3.4 ± 0.3 km wide), the Daheigou River step-over (2.2 ± 0.2 km wide), and the Anmen River step-over (2.5 ± 0.2 km wide), are <4 km wide, while the Shiyou River step-over has a width of 5.4 ± 0.4 km (Figs. 14B–14E). These results imply that the 1932 Changma earthquake could rupture through step-overs >5 km wide. However, the rupture propagation was arrested by the 3.5 ± 0.3–km-long and 6.3 ± 0.5–km-wide Xishuixia River step-over at the easternmost end of the rupture (Fig. 14F). Geomorphic interpretations showed that the Xishuixia...
New insights into the slip partitioning of the eastern Altyn Tagh fault system

Figure 11. (A) The UAV image showing the geomorphic features of surface rupture zone along the eastern SYR-XSX segment and the location of samples collected from the terraces T₁. (B) Image interpretation showed the 35 ± 2.6 m left-lateral offset of terrace risers T₁ on the eastern SYR-XSX segment. The real offset should be 31 ± 2.6 m omitted 4 m coseismic offset caused by 1932 earthquake (Luo et al., 2013; Lanzhou Institute of Seismology, National Bureau of Seismology, 1992). T₁ — river bed; T₂ — lower terraces; T₃ — upper terraces. (C) Reconstructed T₁ showing a 35 ± 2.6 m horizontal offset occurred along the eastern SYR-XSX segment after being restored. (D) Photograph of samples collected from the Xishuixia site for OSL age dating. (E) Profile sketch displaying strata features and OSL dating site for OSL age dating. (F) Photograph of ¹⁴C samples collected from the Xishuixia site. (G) Profile sketch displaying strata features and ¹⁴C dating data of samples. (H) The slip rates of T₁ around Xishuixia site.

A

XSX04E
XSEX05E
C1E, C9E

B

C

D

E

F

G

H

Average slip rate of T₁, 4.49±0.5 mm/yr

Surface rupture

Tributary

Sample

Contours

Stream

| Age (ka) | 0 | 2 | 4 | 6 | 8 |
|---------|---|---|---|---|---|
| Slip rate (mm/yr) | 5.00±0.6 | 4.49±0.5 | 4.40±0.4 | 4.38±0.5 | 4.30±0.5 |

Legend:
- Red: XSEX04E
- Blue: XSEX05E
- Green: C1E

50 cm
Figure 12. Photographs showing left-lateral offsets and surface ruptures observed along the CMF. (A) The offset channel at Chouliugou (see location in Fig. 3A). (B) The displaced gully west of Xiaoheigou (see location in Fig. 4A). (C) The offset gully developed at west of Sangequan (see location in Fig. 7A). (D) Surface ruptures at the east of Sangequan (see location in Fig. 7B). (E) Surface ruptures at the east of Choushuiliugou (see location in Fig. 8A). (F) The offset channel located west of Xibanjiegou (see location in Fig. 10A). (G) Coseismic surface ruptures developed west of Baiyang River (see location in Fig. 10A). (H) Coseismic surface ruptures located near the Xihshuixia River (see location in Fig. 10A). Red solid line—fault trace; white dotted line—indication of offset; black line—channel or gully; white arrow—indication of surface rupture.
River step-over is a restraining step-over with a mountain peak as high as ~4927 m. It suggests that both the large size and restraining mechanism of the Xishuixia River step-over contributed to the termination of the 1932 coseismic rupture.

Previously discussed results show that a rupture caused by an earthquake with a magnitude >7 could propagate through a step-over with a width >5 km, implying that the assumption that rupture propagation can be effectively stopped by step-overs with widths >4 km needs to be reconsidered. Therefore, this point must be taken into account for the prediction and assessment of future earthquake risks.

**Implications for the Tectonic Transition between the CMF and the ATF System**

Numerous studies indicated that slip rates decreased from 11 mm/yr to 4.8 mm/yr, then down to 0–2 mm/yr along the ATF system (between 84° to 98°E) (Xu et al., 2005; Cowgill, 2007; Zhang et al., 2007; Cowgill et al., 2009; Gold et al., 2009, 2011; Hetzel et al., 2002; Darby et al., 2005; Zheng, 2009; Zhang et al., 2014; Cheng et al., 2015, 2016) (Fig. 15). Most of these argue that the tectonic deformation of thrust or strike-slip faults developed in the Qaidam Basin and QLSF belt is the main reason for slip decrease (Burchfiel et al., 1989; Yin and Harrison, 2000; Xu et al., 2005; Yin et al., 2008b; Cheng et al., 2015; Cunningham et al., 2016; Zuza et al., 2016; Yu et al., 2017).

For example, Xu et al. (2005) indicated that the significant fall of slip rates occurred at three junction points, including the Subei (SB), Shibaocheng (SBC), and Changma (CM) junctions (Fig. 16). These junction points linked the ATF system and those adjacent faults west of the QLSF belt, including Danghe Nanshan fault, Yema River-Daxue Shan fault, and CMF (Hetzel et al., 2002; Darby et al., 2005; Zheng, 2009; Zhang et al., 2014; Cheng et al., 2015, 2016) (Figs. 15 and 16). Structural analysis showed that the ATF system and its adjacent thrust and strike-slip faults, the Sanweishan and Nanjieshan faults, formed an asymmetric half-flower.
Figure 14. (A) ASTER GDEM map showing step-overs among these first-order segments of surface rupture along the CMF. (B) Quickbird2 image displaying the left-stepping releasing Shule River step-over. (C) The right-stepping restraining Daheigou River step-over as shown in the Quickbird2 image. (D) SPOT6 image represents the left-stepping releasing Anmen River step-over. (E) Worldview2 image showing a large pressure Shiyou River step-over. (F) SPOT6 image showing the large right-stepping restraining Xishuixia River step-over around the eastern end of the CMF.
structure dominated by non-strain partitioned left-lateral transpression that affected the deformation of the northeast Tibetan Plateau foreland (Cunningham et al., 2016). The oblique-extrusion deformation model for the Hexi Corridor to the north of Tibetan Plateau and southern Gobi Alashan proposed that both the reverse and strike-slip faults in this area have absorbed the slip on the ATF system accommodated with the crustal shortening (Yu et al., 2016, 2017).

To explore the role the CMF played in the slip partitioning of the ATF system, a three-dimensional tectonic model related to tectonic deformation of the ATF system and its adjacent faults in the western part of QLSF belt was proposed (Fig. 17). Currently, these active faults present thrust faulting with rates less than 1 mm/yr in the west QLSF belt (Zheng, 2009). Toward the east, their motions change to strike-slip faulting with average slip rates of 1–3 mm/yr (Hetzel et al., 2004; Zheng, 2009). In particular, both this study and other previous studies (Luo et al., 2013; Zheng et al., 2013) indicate that the CMF shows a change from dominant thrust (0.14 ± 0.02 mm/yr) and strike-slip faulting (1.17 ± 0.07 mm/yr) toward the east. In addition, it is noticeable that the left-lateral slip rate is 4.49 ± 0.5 mm/yr along the eastern segment of the CMF, which is similar to the slip rate of ~4.8 mm/yr on the ATF system around the CMF junction (Fig. 17). This means that the major slip of the ATF system may transfer into the CMF. These results imply that the CMF plays a major role in slip partitioning of the ATF system as compared with other active faults. In addition, we infer that a 3–4 mm/yr slip of the ATF system may have been absorbed by the CMF through the transformation from thrust to strike slip faulting. Therefore, we believe that the slip on the eastern ATF system has been partially transferred into the CMF, accommodated with slip partitioning and the NNE–SSW compressional stress (Fig. 17).
CONCLUSIONS

In this study, the geometric and geomorphic features, segmentation, and termination of the 1932 Changma earthquake surface rupture zone were well documented, which provides new insights into the tectonic transition in the NE Tibetan Plateau as follows.

(1) The surface rupture zone produced by the 1932 Changma earthquake can be divided into five discontinuous first order segments with lengths of 14.4–39.56 km. The rupture could propagate through 0.3–4.5-km-long and 2.2–5.4-km-wide step-overs, but was terminated by a 6.3-km-wide restraining step-over with high relief in the easternmost portion of the CMF.

(2) Left-lateral slip rates of 3.43 ± 0.5 mm/yr and 4.49 ± 0.5 mm/yr since the Holocene were calculated in the mid-east and easternmost segments of the CMF.

(3) A new tectonic model proposed that a slip of 3–4 mm/yr on the ATF system has been mainly absorbed by the CMF, suggesting that the CMF plays a leading role in the slip partitioning of the eastern segment of the ATF system.

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