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Paleoseismology and slip rate of the western Tianjingshan fault of NE Tibet, China

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A B S T R A C T

We present results from a detailed investigation of the horizontal displacement distribution, timing of paleoearthquakes and left-lateral slip rate on the western Tianjingshan fault. Measurements of 240 offset streams and ridges confirm that the fault is left-lateral and record evidence of repeated ~3–4 m coseismic offsets along the 60–km–long fault. This suggests that ~6 earthquakes may have occurred along the entire western Tianjingshan fault with repeated occurrence of earthquakes of Mw 7.2–7.5. Structural and stratigraphic relationships exposed in our five trenches in combination with previously reported studies further indicate that the fault has ruptured in as many as six paleoearthquakes since the late Quaternary. Paleoseismic data show that the average recurrence interval for Holocene earthquakes is approximately 5,000 yr. The most recent earthquake along the western Tianjingshan fault occurred ~1.2 ± 0.1 kyr BP, indicating that this fault segment did not rupture in the M 7.5 historical earthquake of 1709 that ruptured the central Tianjingshan fault. We estimate that the Holocene slip rate of the western Tianjingshan fault is ~1.1–1.2 mm/yr based on measurements of the age and offset of stream channels. Compared with the relatively fast slip rate of the Haiyuan fault (~4–6 mm/yr), we suggest that the Tianjingshan fault acts as an essential active fault accommodating the sinistral displacement and crustal shortening deformation in NE Tibet.

1. Introduction

The major left-lateral Altyn-Tagh and Haiyuan faults strike along the northern and northeastern margins of the Tibetan Plateau, respectively (Fig. 1A). The Tianjingshan fault splays eastward off the north side of the Haiyuan fault (Fig. 1B) and marks the northernmost strike-slip fault boundary associated with the northeast margin of the Tibetan Plateau. The Tianjingshan fault is defined by a series of discontinuous Holocene active fault traces, which extends for a distance of 240 km, approximately from Gulang in the west to Tongxin city in the east. The fault is divided into four sections based on fault geometry and geomorphology (Li and Li, 2015); from west to east, these are the northern Changlingshan fault (N-CLF), and the western (W-TJSF), central (C-TJSF), and eastern (E-TJSF) Tianjingshan faults (Fig. 1B). On October 14, 1709, the M 7.5 Zhongwei (Ningxia) earthquake killed > 2000 people and produced a left-lateral surface rupture ~30–60 km long along a portion of the central Tianjingshan fault (C-TJSF) (W.Q. Zhang et al., 1988; Zhang et al., 2015; Fig. 1B). Numerous studies have described the well-preserved surface ruptures (Nie and Lin, 1993; W.Q. Zhang et al., 1988), established the average recurrence intervals (2000–4000 yr, Min et al., 2001; Zhou and Liu, 1987; Wang et al., 1990), and defined the slip rates (~2 ± 0.5 mm/yr; Chai et al., 1997; Li, 2005) of the C-TJSF.

The 60-km-long western Tianjingshan fault (W-TJSF) has received less attention than the C-TJSF. Chai et al. (2003) observed that the W-TJSF traverses, but does not cut, the Great Wall of China (built in 1598 CE during the Ming Dynasty) and with geomorphic observations concluded that the most recent rupture along the W-TJSF occurred more than 400 yr ago and did not rupture in the 1709 earthquake. The W-TJSF has an average strike of ~N90°E and is composed of five sub-parallel fault strands separated by pull-apart basins of different sizes (Du et al., 2007). The individual fault strands are designated from west to east as F1 to F5 (Fig. 1C). The average strike of the western Tianjingshan fault is about N90°E. It remains unknown whether the relative

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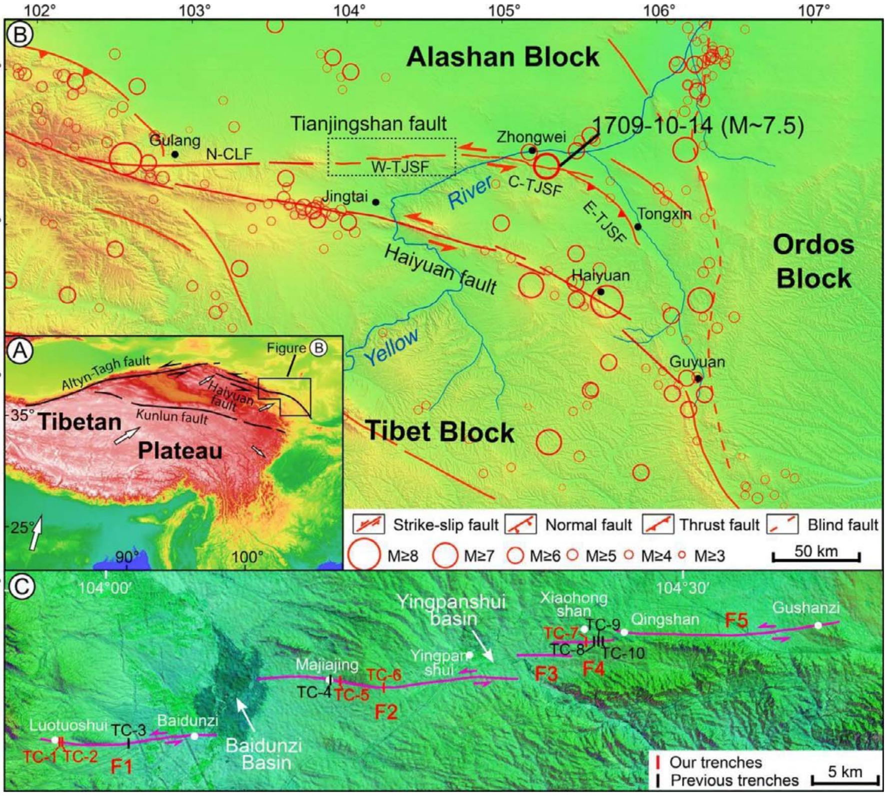

Fig. 1. Tectonic setting of the study area. (A) Regional tectonic map of the study area on the Tibetan Plateau. The black box shows the location of (B). (B) Topographic and tectonic map of northeastern Tibet showing the major active faults. Sections of the fault discussed in the text are labeled: W-TJSF, western Tianjingshan fault; C-TJSF, central Tianjingshan fault; E-TJSF, eastern Tianjingshan fault; NCLF, northern Changlingshan fault; Red circles are epicenters of earthquakes (M ≥ 3) from the China Earthquake Networks Center catalog (and from Gu et al. (1983). The epicenter of the 1709 M 7.5 earthquake on the C-TJSF is highlighted. Dashed black box shows the location of (C). (C) Active fault traces of the W-TJSF: F1, Jingtai subsegment; F2, Guanguanling subsegment; F3, Shajing subsegment; F4, Zhongwei subsegment; F5, Qinshan–Gushanzi subsegment. Red bars are trenches excavated in this study. Black bars are trenches excavated in previous studies. Numbers correspond to trenches TC-1 through TC-10. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scarcity of instrumentally recorded earthquakes along the W-TJSF, between Luotuoshui and Gushanzi (Fig. 1B and C), implies that the fault is locked, and therefore might pose a significant potential seismic hazard to the heavily populated Jingtai and Zhongwei regions, or reflects that the fault is experiencing a seismically calm period, and would not produce a large earthquake in the near future.

In this paper, we present geomorphic evidence of repeated slip at more than 16 sites along the traces of the western Tianjingshan fault (W-TJSF). We then combine new paleoseismic observations, obtained by trenching, with previously reported observations (Chen et al., 2006; Du et al., 2007; Unpublished results, IGCEA et al., 2003; Min et al., 2001) to interpret the past rupture history and the recurrence intervals of large surface-rupturing earthquakes on the W-TJSF. Additionally, we measure the age and offset of an older stream channel to estimate the W-TJSF slip rate. The results provide a basis to discuss the behavior of the fault within the context of existing earthquake recurrence models and the tectonic role of the fault along the northeast margin of the Tibetan Plateau.

2. Methods

We measured offset geomorphic features along the W-TJSF using tape measures and laser rangefinders in the field, as well as Google Earth imagery, and structure-from-motion (SfM) models (Supplementary Material S1 and Figs. S1–S3). Fault traces F3 and F5 are typically modified by surface mining, so our measurements are limited to those made along segments F1, F2, and F4. The offset measurement results are presented in Section 3.1. Five trenches (TC-1, TC-2, TC-5, TC-6, and TC-7) were excavated, using both hand tools and machine excavators, across the active fault scarps, mainly along the F1, F2, and F4 segments. The location of each trench is shown in Fig. 1C. Before trenching, the fault-trace geometry and surface geomorphic units were mapped and topographic profiles were measured across the fault scarps at each site. The walls of each trench were scraped and cleaned and the exposures were marked with a 1-m string grid prior to logging. The sedimentary layers in each trench were differentiated as individual units based on color, grain size, sorting, texture, bedding thickness, and other features such as liquefaction (Table S1). The sequence of ground-rupturing events was then defined on the basis of stratal cross-cutting relationships, sediment thickness changes, soft-sediment deformation, fissures, and sand liquefaction. In each trench, the interpreted paleoearthquakes are designated as E1, E2, etc., with E1 being the youngest. Optically stimulated luminescence (OSL) ages of sediment samples collected from the trenches are used to constrain the ages of the stratigraphic units, and hence the interpreted events. All samples were processed and analyzed in the Luminescence Dating Laboratory at the State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration (CEA), Beijing, using conventional pretreatment techniques (see Lu et al. (2007) and Yang et al. (2012) for the detailed experimental procedures). The OSL results and details of methodology are summarized in Supplementary Material S1 and Table S2.

3. Results

3.1. Geomorphic evidence for paleoearthquakes from offset measurements

Numerous offset geomorphic features can be observed, both in the field and from Google Earth imagery, along the W-TJSF. For example, Fig. 2 shows that a series of stream channels emerging from small hills composed of late Neogene and early Pleistocene sediments are displaced by the fault. The enlarged circles in Fig. 2 indicate recent left-lateral stream offsets. As a result, these offset features of different sizes offer us a good opportunity to better document the seismic behavior and the occurrence of past large earthquakes on the W-TJSF.

The 240 offset measurements are summarized in Supplementary Table 3. To quantitatively determine the relationship between along-strike offset distribution and individual paleoearthquakes, we plot our offset measurements as a function of distance along each fault segment (Fig. 3A). In Fig. 3A, symbols with shaded background connected by vertical dashed lines are measurements of multiple offsets made at the same site; whereas, sites exhibiting only one single offset are marked by