Timing of the Luanshibao Giant Landslide in eastern Tibet: the evidence from paleoseismology

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Abstract. Giant paleo-landslides, generally regarded as evidence for strong events of seismic ground motion, can provide clues of paleoearthquakes on active faults. Paleo-landslide timing is commonly used to retrace the rupture history of an active fault. The Luanshibao (LSB) landslide is located in the eastern Tibetan Plateau on the Maoyaba fault, an important segment of the western Litang fault zone with a dominantly left-lateral strike-slip motion of about 4 mm/yr. The LSB giant landslide has been proposed to result from a large earthquake on the Maoyaba fault. However, the paleoearthquakes on the Maoyaba fault remain unknown. We excavated three large trenches across the Maoyaba fault and reconstruct the Maoyaba fault's rupture history using the OxCal model of sequential radiocarbon dates. The ages of the faulting events in the three trenches are very similar. Our paleoseismological results demonstrate that at least five surface-rupturing events occurred at 620–485, 2540–1880, 3385–2905 cal BP, 5260–4415, and 12240–8895 cal BP. These data suggest that the major LSB landslide is probably related to a large earthquake (Mw ~7.2) of 3385–2905 cal BP. Also, the ¹⁰Be exposure ages of bounders on the LSB landslide surface are somewhat older than our trenching result, probably because of non-ignorable inherited components of nuclides on the landslide boulders.
1. Introduction

Large earthquakes can cause severe secondary disasters like landslides by causing surface rupture along the seismogenic fault. The 2008 Wenchuan earthquake (Mw 7.9), for example, caused a 300-kilometer-long surface break along the Longmen Shan fault zone [1], with massive landslides blocking rivers and burying villages and counties [2]. The earthquake magnitude and rupture history are recorded in some features of these massive landslides. To restore strong earthquake histories on an active fault, massive paleo-landslides are used. The LSB giant landslide on the Maoyaba fault, an essential segment of the NW-striking Litang fault zone in eastern Tibet, is famous for its splendid landforms. It has a volume of 0.64–0.94×10⁸ m³ and exhibits a long runout and rock avalanche features [3–5], making many researchers propose that it should result from a large earthquake on the Maoyaba fault. However, the age of the LSB landslide remains a hot debate. Guo et al. [3] used radiocarbon dating to determine the age of three samples taken from the lower part of a sag pond on the upper part of the LSB landslide. Zeng et al. [6] took eight 10Be samples from the tops of large bounders on the landslide and determined a 3.5 ka exposure age. Cui [7] also conducted exposure dating on six boulder samples collected from various locations on the landslide surface, yielding an exposure age of around 3.7 ka. Zhao et al. [8] used trenching techniques to try to link the LSB landslide to a paleo-event at 3635 387 a BP, but their paleo-event ages are uncertain. However, it is hard to assess the dates of the LSB landslide event because the paleoearthquakes on the Maoyaba fault are unclear.

This study maps the detailed trace of the Maoyaba fault based on the interpretation of high-resolution satellite imagery and field observations. Next, we dug three trenches to reconstruct the Holocene paleoearthquakes of the Maoyaba fault with radiocarbon dating and OxCal modeling. Finally, we compared the exposure ages of the landslide to the paleoearthquake history of the Maoyaba fault. Finally, we established and investigated the relationship between the LSB landslide and the activity of the Maoyaba fault. This study will provide insights into the timing of the paleo-landslides along an active fault.

2. Regional tectonics and displaced landforms

The Litang fault zone in eastern Tibet is part of the Sichuan-Yunnan block, which is bordered on the north and east by the large-scale left-lateral strike-slip Xianshuihe–Anninghe–Zemuhe–Xiaojiang fault system, and on the west and south by the right-lateral strike-slip Red River fault zone. The northeast-striking Lijiang fault zone divides the Sichuan-Yunnan block into two subblocks: Western Sichuan and Southern Yunnan. The Litang fault zone in the Western Sichuan subblock runs roughly parallel to the Xianshuihe fault zone and strikes northwest. Displaced landforms show that in the late Quaternary, the Litang fault zone was dominated by a left-lateral strike-slip rate of about 4 mm/yr, implying that strain partitioning played an important role in eastern Tibet.

The Litang fault zone has experienced a number of large earthquakes. The 1948 earthquake (Ms7.3), for example, ruptured the southern segment of the Litang fault, resulting in 41 kilometers of surface ruptures [9]. An earthquake (Ms7.1) ruptured the central Litang
fault in 1890, resulting in 50 km of surface ruptures [9]. The Maoyaba fault is the northwest segment of the Litang fault zone and bounds the northern boundary of the Maoyaba Basin. Xu et al. [9] suggested, using tree rings counting on trees growing on the youngest scarps, that the last large earthquake along the Maoyaba segment occurred before 1886. But no more evidence for the last event was reported. Xu et al. [9] proposed that the Maoyaba fault has a similar slip rate and the sense of fault activity to the central Litang fault zone, but Chevalier et al. [10] suggested that this fault is dominant with normal faulting of 0.6 ± 0.1 mm/yr with a negligible left-lateral component in the Holocene.

3. Paleoseismological results
Fault scarps, offset channels and terraces, and displaced moraines characterize the Maoyaba fault, which defines the northern boundary of the Maoyaba Basin (Figure 1). Free scarps along the fault trace indicate that the last event is not too old. Three trenches were excavated at Jinqing and eastern Luanshibao to study Holocene seismic activity and fault behavior.

3.1. Jinqing site
At Jinqing Village, three terraces (T1–T3) are well preserved along the Jinqing River (Figure 2). The fault cuts these terraces and produces clear scarps with a height of ~1.8 m. We dug a trench TC1 across the scarp on terrace T1. The strata exposed on the west and east walls exposed in trench TC1 are similar and consist of bedrock, unconsolidated alluvial sand and gravel, and cultivated soils.

The deformation in this trench is concentrated on a small fault zone (Figure 3). Paleoseismic events are identified by infilled fissures, upward termination of faults, and sediment disturbance. We can only find one surface-faulting event since the deposition of the terrace gravel in unit 3 based on the above indicators. Displaced units 3 and 2, as well as infilled fissures, characterize this event (E1). The related sediments were covered by subsequent subunits 6–1 and 1. From the stratigraphic relations, therefore, E1 postdates unit 2 and predates subunit 6–1. Radiocarbon dating and OxCal modeling indicate that E1 occurred after 1095±110 cal BP. From the height of the scarp and the displacement of unit 2, the vertical offset for event E1 is about 1.8 m.
Figure 1. Detailed trace of the Maoyaba fault from the interpretation of high-resolution satellite imagery and field observation.

Figure 2. Displaced landform of the Maoyaba fault near Jinqing Village. See the site in Figure 1.

Trench TC2 was opened across the fault scarp on terrace T2 (Figure 2). Both walls of the trench have a similar feature. The strata are divided into seven units based on their stratigraphical relationship and the relation with the fault zone. The fault zone consists of two branches (Figure 4). Three events can be identified from this trench based on the colluvial wedge and upward termination of faults. The earliest event (E3) is characterized by displaced
units 6 and 7 and subsequent swamp deposit (unit 5). The penultimate event (E2) is inferred from displaced unit 5 and subsequent colluvial wedge (subunit 4–3). The last event (E1) is demonstrated by the colluvial wedge (unit 3). Numerous radiocarbon ages and OxCal modeling show that E3, E2 and E1 occurred at 5620–2985 cal BP, 2905–1910 cal BP, and 1755–205 cal BP, respectively.

**Figure 3.** Stratigraphy of trench TC1. See trench site in Figure 2. (a) Trench photo; (2) trench log. U1, dark gray soil with gravel; U2, gray-brown sand, and gravel with horizontal bedding; U3, gray alluvial gravel; U4, tawny alluvial sand and gravel; U5, bedrock; U6, mixed sand, and gravel representing infilled fissure and subsequent colluvium.

**Figure 4.** Stratigraphy of trench TC2. See trench site in Figure 2. U1, dark gray soil with grassroots; U2, reddish-brown sandy clay with gravel; U3, colluvial gravel; U4, gray-brown sand with gravel; U5, reddish-brown swamp sandy clay with gravel; U6, alluvial sand and gravel with horizontal bedding; U7, bedrock.

**3.2. Eastern Luanshibao site**
The Maoyaba fault is marked by a linear feature, including linear scarps and fault trough (Figure 5). The slope wash and sediments from gullies filled into the trough, generating a platform on the slope. Trench TC3 was opened across the fault trough on the slope. The east and west walls of trench TC3 are similar. From their stratigraphical relationship and the relation with the fault zone, the strata include seven units. The deformation is focused on a narrow zone, and the fault has a reverse component (Figure 6). Oriented gravels mark the fault.

![Figure 5. Displaced landform of the Maoyaba fault near trench TC3. See the site in Figure 1.](image)

From this trench (Figure 6), five events can be identified based on upward termination of faults, colluvial wedges, and their deformation by subsequent faulting. E5 is characterized by displaced unit 7 and subsequent colluvial wedge. The displaced colluvial wedge of E5 and the subsequent colluvial wedge define E4. The deformed colluvial wedge of E4 and subsequent colluvial wedge define E3. The deformed colluvial wedge of E3 and subsequent colluvial wedges define E2. The last event (E1) is demonstrated by displaced unit 2 and subsequent swamp sediment (unit 1). A series of radiocarbon ages and OxCal modeling show that events from E5 to E1 occurred at 12240–8825 cal BP, 6835–4425–cal BP, 3385–2540 cal BP, 2540–1090 cal BP, and 620–485 cal BP, respectively.
Figure 6. Stratigraphy of trench TC3. See trench site in Figure 5.  
U1, swamp sandy soil; U2, dark gray sand with gravel; U3, dark gray sand with coarse sand and fine gravel; U4, gray sandy clay filled with organic sediments; U5, blackish gray sandy clay; U6, slope wash fine sand; U7, slope wash granite gravel.

4. Discussion

4.1. Paleoeartquakes on the Maoyaba fault

The completeness of a paleoseismic sequence is vital for studying fault behavior [11, 12]. Our three trenches at two sites indicate a good consistency. Trench TC1 only records the last event E1 per the results of trenches TC2 and TC3. Thus, events E2 and E3 are concurrent in trenches TC2 and TC3. In addition, the trench TC3 is in a sedimentary environment where the deposition from the slope and gullies will fill the space in the trough produced after the faulting. In this situation, no intense erosion could occur, and the deposits after any faulting would be well preserved in the trough. Therefore, the faulting sequence in trench TC3 is probably complete. Our three trenches and OxCal modeling indicate that the Maoyaba fault underwent five paleoearthquakes (E1–E5) in the Holocene and occurred at 620–485 cal BP, 2540–1880 cal BP, 3385–2905 cal BP, 5260–4415 cal BP, and 12240–8895 cal BP, respectively.

From the five surface-ruptured events, the Maoyaba fault may be suitable for a cluster model. In the past ~5000 yrs, the four large earthquakes occurred on the fault with a recurrence interval of 1000–1600 yrs, while before ~5 ka, only one event ruptured the Maoyaba fault. Suppose the whole fault ~60 km long is completely ruptured. In that case, the Maoyaba fault is estimated to be a moment magnitude of these surface-faulting events of Mw ~7.2 based on the empirical relationship of quantitative parameters and magnitude [13].

4.2. The age of the LSB landslide

The age of the LSB landslide has been intensively studied in previous studies. Guo et al. [3] used radiocarbon dating of three samples from the lower part of a sag pond on the upper part of the LSB landslide to constrain its age to be before about 2 ka. Exposure ages of
boulders on a landslide are regarded to be a direct dating result. Zeng et al.[6] collected eight $^{10}$Be samples from the top of large bounders on the landslide and constrained a mean exposure age of $3510 \pm 346$ a, while Cui[7] also used $^{10}$Be dating of six boulder samples from different positions on the surface of the landslide and yielded an exposure age of $3700 \pm 300$ a. Zhao et al.[8] also tried to connect the LSB landslide to one paleoearthquake occurring at $3635 \pm 387$ a BP from some trenches. But paleo-events in their trenches do not follow the paleoseismological technique and include considerable uncertainties. We exclude this age for the LSB landslide in our following discussion.

We compare our paleoseismic data to previous estimates of the LSB landslide's age (Figure 7). These findings show that the LSB landslide is most likely linked to Maoyaba fault event E3. Furthermore, the landslide's exposure ages are slightly older than the age of event E3. The difference could be due to inherited nuclide components on the landslide boulders.

Figure 7. Comparison of the results of timing of Luanshibao landslide and paleoearthquake study.

5. Conclusions

Based on the obtained data and field observations, we drew the following conclusions:

1) The Maoyaba fault underwent five paleoearthquakes (E1–E5) in the Holocene and occurred at 620–485 cal BP, 2540–1880 cal BP, 3385–2905 cal BP, 5260–4415 cal BP, and 12240–8895 cal BP, respectively. The moment magnitude ($M_w$) of these paleoearthquakes is $\sim$7.2.
2) Based on the exposure ages and trenching results, the LSB landslide could be linked to event E3 at 3385–2905 cal BP.
3) Inherited nuclide components on the landslide boulders may not be negligible leading to an overestimation of a landslide's age.

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