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Causes of unusual distribution of coseismic landslides triggered by the Mw 6.1 2014 Ludian, Yunnan, China earthquake

Xiao-li Chen[a,*], Chun-guo Liu[b], Ming-ming Wang[c], Qing Zhou[a]

[a] Key Lab of Active Tectonics and Volcano, Institute of Geology, China Earthquake Administration, Beijing 100029, China
[b] China Earthquake Networks Center, Beijing 100045, China
[c] Sichuan Earthquake Administration, Chengdu 610041, China

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ABSTRACT

The Mw 6.1 2014 Ludian, Yunnan, China earthquake triggered numerous coseismic landslides that do not appear to be associated with any previously known seismogenic fault. Traditional models of triggering for seismically generated landslides do not provide a reasonable explanation for the landslide pattern observed here. Here the Newmark method is applied to a grid to calculate the minimum accelerations required for slope failures throughout the affected region. The results demonstrate that for much of the study area, the distribution of failure prone slopes is similar to the actual pattern of coseismic landslides, however there are some areas where the model predicts considerably fewer failures than occurred. We suggest that this is a result of the complex source faults that generated the Ludian earthquake, which produced a half-conjugate rupture on nearly EW- and NNW trending faults at depth. The rupture directed much of its seismic moment southeast of the epicenter, increasing ground shaking and the number of resulting landslides.

1. Introduction

The occurrence of a coseismic landslide is a result of the seismic, geologic, and geomorphic properties of both a source earthquake and an affected hill slope (Keefer, 1984). The source fault controls the shaking pattern, and thus controls the frequency and distribution of landslides. Coseismic landslides most often occur along or in close proximity to the surface rupture zones of large earthquakes, as documented in the 1999 Mw 7.6 Chi-Chi, Taiwan (Khazai and Sitar, 2003; Wang et al., 2003), 2002 Mw 7.9 Denali, Alaska (Jibson et al., 2006), 2005 Mw 7.6 Kashmir (Sato et al., 2007), and 2008 Mw 7.9 Wenchuan, China earthquakes (Huang and Li, 2009; Yin et al., 2009; Qi et al., 2010; Dai et al., 2011; Gorum et al., 2011). The type of rupture also has an effect on the distribution of coseismic landslides; for example, coseismic landslides are often concentrated on the hanging wall of a thrust fault, whereas those associated with a strike-slip rupture occur within a narrow zone along both sides of the fault (e.g. Harp and Jibson, 1996; Jibson et al., 2004; Tatard and Grasso, 2013; Chen et al., 2014a, 2014b).

Not all earthquakes produce landslides along surface ruptures. The 2014 Mw 6.1 Ludian earthquake in Yunnan, China triggered more than 1024 landslides each with areas ≥100 m^2 (C. Xu et al., 2014) that did not concentrate along a known fault, and instead were spread across two river valleys several kilometers from the epicenter of the main shock. This event did not produce measurable surface rupture, and its aftershocks were spatially scattered, and did not appear to cluster along a well-defined fault plane. As there is no clearly defined source fault in this event (Fang et al., 2014; X.W. Xu et al., 2014; Zhang et al., 2015), it has previously been difficult to understand the cause of the scattered distribution of these landslides. Our previous work used the percent area affected by landslides (relative landslide-area ratio), to show that the local topography and geology, particularly along the steep river valleys of the Ludian area, partly explains the unusual dispersion of coseismic landslides (Chen et al., 2015), however this approach ignored the effects of the complicated seismic source of the Ludian earthquake (X.W. Xu et al., 2014; L.S. Xu et al., 2014; Fang et al., 2014; Zhang et al., 2015).

Peak ground acceleration has a large impact on the occurrence of landslides during earthquakes (Keefer, 2000). As the intensity of landsliding scales linearly with peak ground acceleration, regional patterns of coseismic landslides can reflect the seismic properties of the earthquake that triggered them (Meunier et al., 2007, 2013). This concept was demonstrated during two Japanese earthquakes (the 2008 Mw 6.8 Iwate-Miyagi and 2004 Mw 6.6 Chuetsu earthquakes) where exceptional instrumental records of strong ground motion demonstrate that the intensity and directionality of surface waves are primarily

* Corresponding author.
E-mail address: chenxl@ies.ac.cn (X.-l. Chen).

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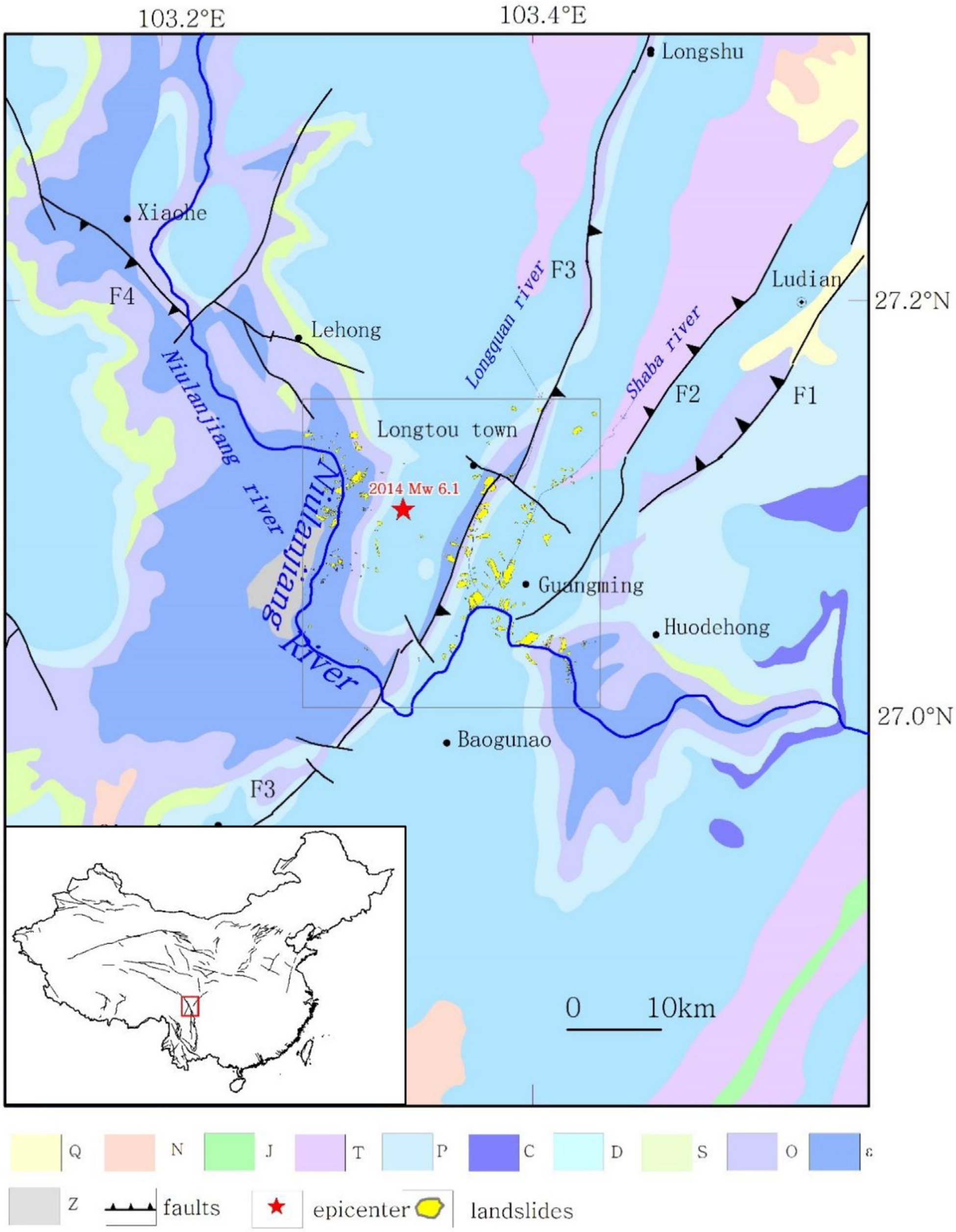

Fig. 1. Map showing the geologic setting and coseismic landslides in the area around the epicenter of the Mw 6.1 2014 Ludian earthquake (Inset: The tectonic background in China; red box shows the study area). Geology: Q: Quaternary. N: Neogene. J: Jurassic. T: Triassic. P: Permian. C: Carboniferous. D: Devonian. S: Silurian. O: Ordovician. Є: Cambrian. Z: Sinian. F1: Sayuhe fault. F2: Zhaotong-Ludian fault. F3: Longshu fault. F4: Baogunao-Xiaohe fault. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

responsible for the observed landslides (Meunier et al., 2013).

In this work, using the spatial distribution of landslides triggered by the 2014 Mw 6.1 Ludian earthquake, we attempt to use seismically triggered landslides to model the seismic source. Using the Newmark method (Newmark, 1965), which uses a force balance approach to model the seismic performance of planar block failures of hill slopes, we map the landslide susceptibility of the study area and compare it to the spatial distribution of the landslides triggered by the 2014 Ludian quake. The results demonstrate again that the local terrain only partly accounts for the distribution of the observed landsides. We show that the complex source structure likely played an important role in determining the pattern of coseismic slope failures.

2. Landslides triggered by the Mw 6.1 2014 Ludian earthquake

The 2014 Mw 6.1 Ludian earthquake occurred in southwestern China, near the southeastern margin of the Tibetan Plateau (Fig. 1), a steep mountainous landscape with many intermountain basins (Chang et al., 2016). The Niulanjiang River flows through the Ludian area from southeast to northwest, incising 1200–3300 m into the mountains, and carving steep valleys along its course. Sixty percent of slopes in the region range from 10° to 30°, while gradients steeper than 40° are restricted to the banks of the Niulanjiang River and its tributaries. In the northern and eastern portions of the study region, the terrain is relatively gentle, dominated by small mountains and hills with most slopes gentler than 20° (Fig. 2).

Pre- and post-earthquake satellite images and air photos show that more than 1024 landslides each with individual areas of at least 100 m^2