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Earthquakes drive focused denudation along a tectonically active mountain front

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ABSTRACT

Earthquakes cause widespread landslides that can increase erosional fluxes observed over years to decades. However, the impact of earthquakes on denudation over the longer timescales relevant to orogenic evolution remains elusive. Here we assess erosion associated with earthquake-triggered landslides in the Longmen Shan range at the eastern margin of the Tibetan Plateau. We use the M_w7.9 2008 Wenchuan and M_w6.6 2013 Lushan earthquakes to evaluate how seismicity contributes to the erosional budget from short timescales (annual to decadal, as recorded by sediment fluxes) to long timescales (kyr to Myr, from cosmogenic nuclides and low temperature thermochronology). Over this wide range of timescales, the highest rates of denudation in the Longmen Shan coincide spatially with the region of most intense landsliding during the Wenchuan earthquake. Across sixteen gauged river catchments, sediment flux-derived denudation rates following the Wenchuan earthquake are closely correlated with seismic ground motion and the associated volume of Wenchuan-triggered landslides ($r^2 > 0.6$), and to a lesser extent with the frequency of high intensity runoff events ($r^2 = 0.36$). To assess whether earthquake-induced landsliding can contribute importantly to denudation over longer timescales, we model the total volume of landslides triggered by earthquakes of various magnitudes over multiple earthquake cycles. We combine models that predict the volumes of landslides triggered by earthquakes, calibrated against the Wenchuan and Lushan events, with an earthquake magnitude–frequency distribution. The long-term, landslide-sustained "seismic erosion rate" is similar in magnitude to regional long-term denudation rates (~0.5–1 mm yr^{-1}). The similar magnitude and spatial coincidence suggest that earthquake-triggered landslides are a primary mechanism of long-term denudation in the frontal Longmen Shan. We propose that the location and intensity of seismogenic faulting can contribute to focused denudation along a high-relief plateau margin.

1. Introduction

Mountain erosion affects rates and patterns of crustal deformation including seismogenic faulting (Steer et al., 2014) and flexural-isostatic responses (Molnar and England, 1990), and influences the geological carbon cycle and consequently the climate system (Raymo et al., 1988; Wang et al., 2016). Large earthquakes are thought to play an important role in the denudation of tectonically-active mountain ranges because they cause widespread landslides that generate large volumes of clastic sediment (Keefer, 1994; Larsen et al., 2010; Hovius et al., 2011; Parker et al., 2011; Wang et al., 2015a). Delivery of landslide debris to rivers and its subsequent fluvial evacuation can increase erosion rates over years to decades (Hovius et al., 2011; Wang et al., 2015a). However, over longer timescales relevant to orogenic evolution (10^4–10^6 yr), the role of earthquakes in denudation remains less well constrained, even though the volume of seismically triggered landslides may be sufficient to partly or wholly counteract seismically induced rock uplift (Parker et al., 2011; Hovius et al., 2011; Li et al., 2014; Marc et al., 2016a).

Detailed mapping of landslides (e.g., Keefer, 1994; Parker et al., 2011; Li et al., 2014; Xu et al., 2015) and hydrological gauging

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of sediment fluxes (e.g., Hovius et al., 2011; Wang et al., 2015a) capture the aftermath of individual events. Across multiple events, landslide volume scales with earthquake magnitude (Keefer, 1994; Malamud et al., 2004; Marc et al., 2016b). Combined with return time statistics for earthquakes, this scaling relationship can yield an estimate of long-term landslide rate that should reflect a "seismic erosion rate" associated with repeated earthquakes, assuming fluvial evacuation of landslide debris (Keefer, 1994; Malamud et al., 2004; Lavé and Burbank, 2004; Li et al., 2014; Marc et al., 2016a). Keefer (1994) found that seismic erosion rates are comparable to fluvial sediment yields measured in several regions. Cosmogenic nuclide and thermochronology datasets allow us to expand this approach to consider denudation rates measured over longer timescales that encompass multiple earthquakes and that are more relevant to mountain belt evolution. In this study, we focus on the Longmen Shan region of central China, where the 2008 M_w7.9 Wenchuan and 2013 M_w6.6 Lushan earthquakes allow us to make estimates of seismic erosion rates. We evaluate both the spatial distribution and magnitude of these rates in the context of datasets from fluvial sediment fluxes, cosmogenic nuclides, and low-temperature thermochronology (Kirby et al., 2002; Ouimet et al., 2009; Godard et al., 2010; Liu-Zeng et al., 2011; Wang et al., 2015a).

The steep Longmen Shan mountain range defines the eastern margin of the Tibetan Plateau. This region has been at the nexus of contentious debates over the importance of motion along shallow faults versus ductile flow of lower crust for collisional mountain building (e.g., Clark and Royden, 2000; Hubbard and Shaw, 2009). Focused denudation along the steep topographic front of such plateau margins may exert an important influence on deformation (e.g., Beaumont et al., 2001). However, the relative roles of tectonic and climatic drivers of denudation – and thus the link between climate and the geodynamic processes – remain unresolved, both for the Longmen Shan (Ouimet et al., 2009; Godard et al., 2010; Liu-Zeng et al., 2011) and elsewhere. We aim to gain new general insight into the long-term role of seismic erosion in tectonically active mountains as well as how it may contribute to focused denudation along the eastern margin of the Tibetan plateau.

2. Setting

With elevations rising to higher than 5 km over a 50 km horizontal distance, the eastern Longmen Shan flank represents one of Earth's steepest plateau margins (Clark and Royden, 2000; Densmore et al., 2007; Burchfiel et al., 2008). Several Yangtze headwater rivers (mainly the Min Jiang, Fu Jiang, Tuo Jiang, Qingyi Jiang and Dadu He) drain from the Longmen Shan into the Sichuan Basin (Fig. 1a). A series of dextral-thrusting, oblique-slip faults bound the mountain front and comprise the Longmen Shan fault system (Densmore et al., 2007; Burchfiel et al., 2008). The bedrock geology consists mainly of Proterozoic basement granitoids and high-grade metamorphic rocks, metamorphosed sedimentary rocks of a Paleozoic passive margin sequence, unmetamorphosed sedimentary rocks associated with a Mesozoic foreland-basin succession, and limited Cenozoic sediments (Burchfiel et al., 2008). Climatically, the Longmen Shan range is located at the transition between the domains dominated by the east Asian monsoon and the westerlies. Across the Longmen Shan, average annual rainfall decreases from the margin ($\sim$1100 $\mathrm{mm\,yr^{-1}}$) towards the plateau (as low as $\sim$600 $\mathrm{mm\,yr^{-1}}$) (Liu-Zeng et al., 2011). This regional climate pattern is largely determined by the high topography, which acts as an orographic barrier and may also affect atmospheric circulation by heating of the atmosphere (Molnar et al., 2010 and the references therein). Precipitation is highly seasonal, with most rainfall during the wet season from June to September.

The M_w7.9 Wenchuan earthquake on May 12th, 2008 initiated in the southern Longmen Shan, near the town of Yingxiu, and ruptured northeastward for $\sim$270 km along the Longmen Shan fault system (Fig. 1a) (Burchfiel et al., 2008; Shen et al., 2009). The strong ground motion triggered $>$56,000 landslides in the steep mountainous topography (Fig. 1a) (Parker et al., 2011; Li et al., 2014; Xu et al., 2014). These seismically induced landslides introduced large volumes of clastic sediment into the fluvial system, estimated to total $\sim$3 $\mathrm{km^3}$ (Li et al., 2014). Prior work has aimed to understand the effects on sediment transport. Li et al. (2014) documented the spatial pattern and volume of landsliding, and Li et al. (2016) assessed the connectivity of these landslides to the river network as a means of understanding their behavior as sediment sources. Wang et al. (2015a) used data from the Chinese Hydrology Bureau to quantify suspended sediment transport rates. After the Wenchuan earthquake (2008–2012), suspended sediment fluxes from the Min Jiang, Fu Jiang and Tuo Jiang catchments increased by 3 to 7 times compared to pre-earthquake levels (2006–2007). Based on ^{10}Be concentrations in quartz from Min Jiang riverbed sands, West et al. (2014) suggested that bedload transport rates had increased by a similar order of magnitude to those of suspended load. The present study takes advantage of this prior work, including the landslide inventory and sediment fluxes, in order to compare spatial patterns of denudation across a range of timescales.

We use the M_w6.6 Lushan event as an additional constraint on the magnitude of seismic erosion rates. The Lushan earthquake occurred on April 20th, 2013 in the southern Longmen Shan, 80 km south of the Wenchuan epicenter (Fig. 1a). This event initiated on a ramp in the range-front blind thrust fault, in the footwall of the Wenchuan rupture (Wang et al., 2014). As in the Wenchuan event, widespread landsliding occurred in the southern Longmen Shan range during the Lushan earthquake. Xu et al. (2015) reported more than 20,000 co-seismic landslides, with a total area of 18.88 $\mathrm{km^2}$ and an estimated volume of 0.042 $\mathrm{km^3}$ across the region affected by the Lushan earthquake.

3. Materials and approaches

3.1. Landslide inventory

For the Wenchuan earthquake, co-seismic and immediately post-seismic landslides (within six months after the earthquake) were mapped by Li et al. (2014). Landslide volumes were calculated from empirical landslide area-volume scaling relations (e.g., Larsen et al., 2010). We assume that mapped landslides mainly resulted from the Wenchuan mainshock because we find that aftershocks contributed $<$5% of the total seismic moment release across the Longmen Shan, based on the seismic catalog spanning over six months following the mainshock (CSN Catalog, 2015). This finding is consistent with observations from other earthquakes that suggest most landslides occur during the mainshock (e.g., Roback et al., 2017). Additional volume associated with post-seismic (e.g., storm-triggered) landslides is likely to be on the order of a few percent of the total landslide volume (Li et al., 2016 and the references therein).

For the landsides triggered by the Lushan earthquake, we refer to the landslide inventory compiled by Xu et al. (2015), who also used empirical scaling relationships reported in Larsen et al. (2010) to estimate volumes from a landslide map based on satellite imagery. Xu et al. (2015) mapped Lushan landslides using images collected from April–May 2013, around five years after the Wenchuan earthquake but immediately after the Lushan event. There is little overlap between the mapping extents and the intensive shaking zones for the Lushan and Wenchuan events (Li et al., 2014;