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Why so few? Landslides triggered by the 2002 Denali earthquake, Alaska

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ABSTRACT

The 2002 M_w 7.9 Denali Fault earthquake, Alaska, provides an unparalleled opportunity to investigate in quantitative detail the regional hillslope mass-wasting response to strong seismic shaking in glacierized terrain. We present the first detailed inventory of ~1580 coseismic slope failures, out of which some 20% occurred above large valley glaciers, based on mapping from multi-temporal remote sensing data. We find that the Denali earthquake produced at least one order of magnitude fewer landslides in a much narrower corridor along the fault ruptures than empirical predictions for an M ~8 earthquake would suggest, despite the availability of sufficiently steep and dissected mountainous topography prone to frequent slope failure. In order to explore potential controls on the reduced extent of regional coseismic landsliding we compare our data with inventories that we compiled for two recent earthquakes in periglacial and formerly glaciated terrain, i.e. at Yushu, Tibet (M_w 6.9, 2010), and Aysén Fjord, Chile (2007 M_w 6.2). Fault movement during these events was, similarly to that of the Denali earthquake, dominated by strike-slip offsets along near-vertical faults. Our comparison returns very similar coseismic landslide patterns that are consistent with the idea that fault type, geometry, and dynamic rupture process rather than widespread glacier cover were among the first-order controls on regional hillslope erosional response in these earthquakes. We conclude that estimating the amount of coseismic hillslope sediment input to the sediment cascade from earthquake magnitude alone remains highly problematic, particularly if glacierized terrain is involved.

1. Introduction

Glaciated mountain belts offer rich and diverse archives of Quaternary environmental change. Particularly the reconstruction of the extent and timing of glacial fluctuations from diagnostic sediments and landforms has had a strong research tradition with many vital implications for independently constraining paleoclimatic time series. Even so a growing number of studies that highlight the potential for confusing glacial moraines as classic paleoclimatic proxies with deposits from catastrophic landslides—and vice versa—has spurred fresh enquiries into the role of controls other than climatic on glacier dynamics (Hewitt, 1999; Tovar et al., 2008; Reznichenko et al., 2012). The same goes for detailed studies of the interactions between glacial and hillslope processes such as the formation of catastrophic rock-ice avalanches (Evans et al., 2009; Fischer et al., 2013) or the effect of supraglacial rock-avalanche debris on glacial advances or stagnation (Hewitt, 2009; Shulmeister et al., 2009; Vacco et al., 2010; Shugar et al., 2012; Menounos et al., 2013) that may eventually compromise interpretations solely devoted to unraveling paleoclimatic fluctuations. In this context, the study of earthquake impacts in glaciated terrain offers particularly fascinating insights into the manifold feedbacks at the interface between seismology, glaciology, and Quaternary geomorphology. For one, widespread deglaciation is known to trigger crustal response and glacioisostatic rebound, which in turn may prompt fault (re-)activation in tectonically active mountain belts (Sauber and Molnia, 2004; McColl et al., 2012). Also,

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strong earthquakes provide sufficient ground acceleration to cause regional hillslope mass-wasting even in glaciated areas where most of the precipitation is falling as snow, and heavy rainfall is a less likely alternative trigger of widespread rock and ice instability (van der Woerd et al., 2004). Little is known, for example, about whether and how thick ice cover contributes to buffering incoming seismic waves and therefore the earthquake-triggered release of hillslope debris into the glacial sediment cascade. Uhlmann et al. (2013) estimated that nearly three quarter of the high contemporary supraglacial sediment flux on glaciers in the Chugach Mountains, south-central Alaska, may have originated from earthquake shaking. However, McColl et al. (2012) argued that thick ice caps can repress coseismic shaking and reduce landslide volumes, and also that with less ice cover (~50% of local topographic relief buried) this effect becomes minute. Refining such estimates requires comprehensive sediment budgets in glaciated environments. Studying the direct mass-wasting impacts of historic earthquakes is one of the avenues to unravel better the relevance of episodic seismic disturbances in glaciated mountain belts.

The M_w 7.9 Denali Fault earthquake struck south-central Alaska and the Alaska Range at 13:12 local time (22:12 UTC) on November 3, 2002. It was one of the largest earthquakes in U.S. history, rupturing three major faults over a distance of 340 km in 100 s. The earthquake hypocenter was at a depth of 5 km on an ENE striking plane (18.44° N, 72.57° W, U.S. Geological Survey, 2002; Fig. 1). The Alaska Earthquake Information Center linked the location and mechanism to the rupture of multiple faults, and mainly the right-lateral Denali Fault, which is part of a system of active intracontinental strike-slip faults accommodating contemporary slip rates of 8–9 mm yr^{-1} along the North American–Pacific plate boundary.

Inversion of strong-motion data, GPS data, and surface offset measurements revealed that the earthquake consisted of three subevents standing out as areas with above-average coseismic slip (Hreinsdottir et al., 2006; Frankel, 2004; Ozacar and Beck, 2004; Fig. 1). Seismic shaking originated from thrust motion on the north-dipping Susitna Glacier Fault near the epicenter, with an average dip slip of 4 m (Haeussler et al., 2004). The subsequent M_w 7.3 subevent ~60–100 km E of the epicenter entailed a 226-km rupture of the Denali Fault with right-lateral slip at the surface averaging 4.5–5.1 m. A maximum offset of 8.8 m was recorded ~40 km W of the Denali-Totschunda Fault branch, where the third M_w 7.6 sub-event originated (Eberhart-Phillips et al., 2003; Frankel, 2004; Haeussler et al., 2004; Hreinsdottir et al., 2006). Fault rupture propagated for another 66 km along the Totschunda Fault, where right-lateral surface offsets averaged 1.7 m (Eberhart-Phillips et al., 2003; Haeussler et al., 2004).

About 1000 landslides were attributed to the Denali earthquake based on an aerial reconnaissance shortly after, including seven rock avalanches with a total volume of nearly 80 × 10^6 m^3 that traveled onto the Black Rapids, McGinnis, and West Fork Glaciers (Harp et al., 2003; Jibson et al., 2004, 2006). However, no substantially complete landslide inventories for this earthquake were done. This earthquake provides exceptional opportunities to

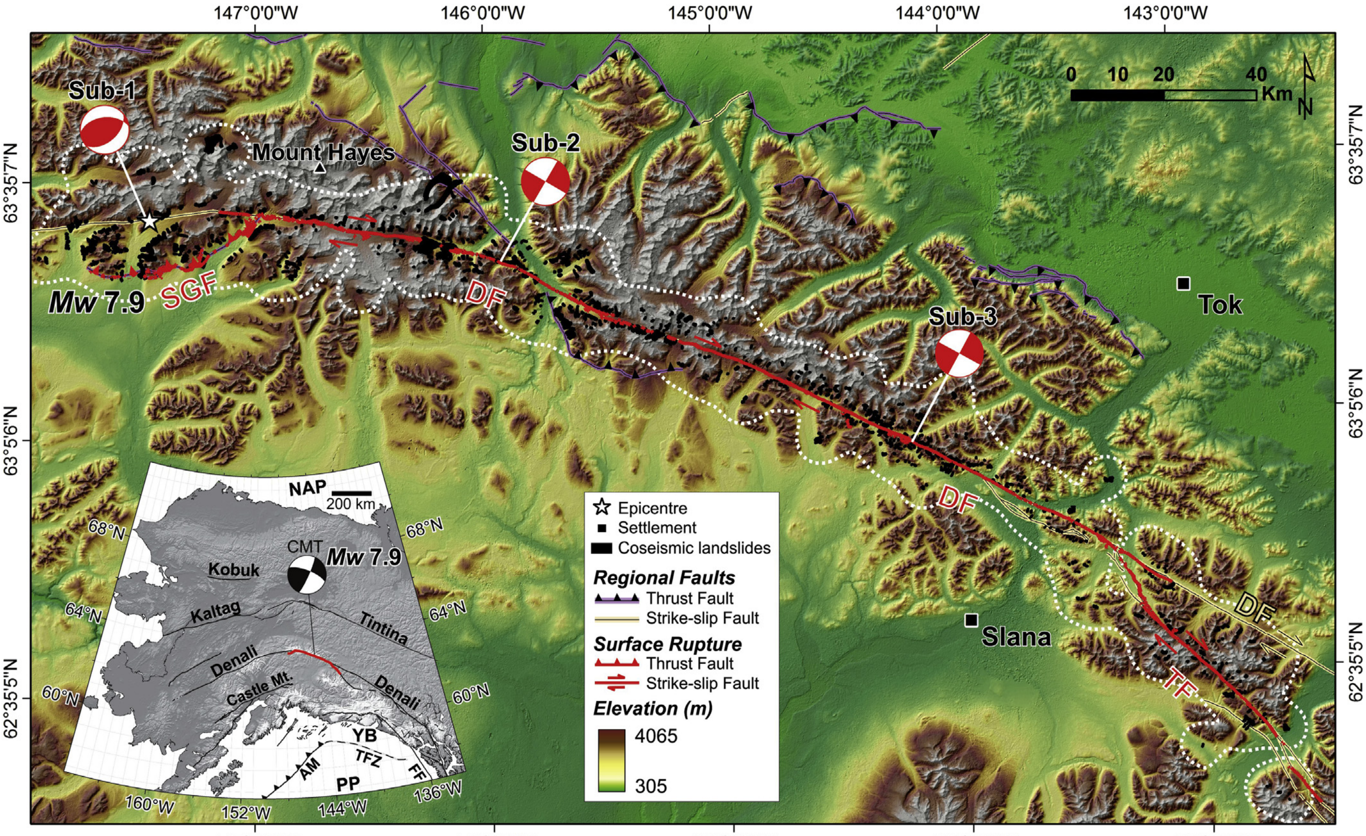

Fig. 1. Distribution of ~1580 landslides triggered by the 2002 Denali Fault earthquake, and tectonic setting of the study area. Red lines are surface traces of coseismic rupture (Haeussler, 2009); beach balls show focal mechanism of the first-motion solution (Sub-1), and the two largest sub-events from waveform inversion (Sub-2, and Sub-3; Eberhart-Phillips et al., 2003). Dashed white lines delimit coseismic landslide densities >0.01 km^{-2}. Inset shows major tectonic boundaries between North American Plate (NAP), Pacific Plate (PP), and Yakutat Block (YB); focal mechanism is Harvard CMT solution; AM: Alaska megathrust, FF: Fairweather Fault, TFZ: Transition fault zone between Alaska and Yukon terranes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)