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Giant landslides, topography, and erosion

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Landslides provide a means to study tectonic and climatic forcing on hillslopes in mountainous terrain. It has been proposed that hillslopes in tectonically active mountain belts adjust to an increase in the rate of uplift and bedrock incision by means of more frequent landslides rather than by progressive slope steepening. According to this concept, hillslopes reach a threshold state conducive to slope failure which is insensitive to differences in uplift, climate, or lithology. Such threshold hillslopes have been reported from the northwest Himalaya, the Olympic Mountains, and the New Zealand Southern Alps, and several numerical models of landscape evolution have treated landsliding as a process dependent on a critical inclination or hillslope height. Little has been done, however, to validate the relationship between actual landslide occurrences and relief constraints.

Here, we test this concept at its upper size limit by examining the spatial relations among giant landslides, mean local relief, and long-term erosion rates, using compiled data for more than 270 of the largest catastrophic terrestrial landslides on Earth; the minimum volume for inclusion in our dataset was arbitrarily set at 10^8 m^3. Our analysis indicates that more than half of these giant landslides have occurred in the steepest 2% of the Earth's land surface. On average, they affect the steepest 9% of mountain belts, where values of mean local relief closely approximate theoretical limits set by rock-mass strength. A nonlinear relationship between orogen-scale erosion rates and mean local relief implies that giant landslides are linked to some of the highest erosion rates on Earth. In both tectonically active mountain belts and volcanic arcs, the largest catastrophic failures, which we assume to constitute $<0.01\%$ of the total population, have contributed, on average, $>3\%$ of the total erosion during the Holocene. The volume of individual landslides, however, is unrelated to erosion rates. Hence increases in topographic relief, and thus erosion, will not necessarily cause larger slope failures.

Correspondingly, giant landslides also occur in areas of low or "subcritical" relief, i.e. well below theoretically possible limits of slope angle or mean local relief. There, a combination of low rock-mass strength, extensive low-angle discontinuities, rapid fluvial incision, or tectonic loading may cause large slope failures, which thus reset hillslope relief independently of threshold hillslopes. Simple limit-equilibrium back analyses suggest that, given sufficiently available seismic energy, giant catastrophic landslides are not exclusively limited to areas of maximum relief and uplift, and may occur during most stages of orogenic development.