TECTONIC GEOMORPHOLOGY

Landslides limit mountain relief

Despite variable forcing by tectonics, the height of mountain ranges seems to be limited. Satellite imagery suggests that landsliding rates adjust to large changes in uplift, acting to maintain hillslopes of similar steepness.

Josh Roering

The height of mountain ranges provides a fundamental challenge not only to adventurers and adrenaline junkies, but also to geologists who seek to understand what limits the elevation of these peaks[1]. The tectonic upheaval that gives birth to mountain ranges causes rock to barrel upwards at rates approaching one centimetre per year. The valleys between the peaks are continuously worn away by rivers and glaciers, but something else must prevent the intervening mountains from attaining stratospheric heights. An appealing explanation suggests that, as the bounding valleys experience downcutting from rivers or glaciers, slope failures limit the steepness of adjacent hillslopes and thus regulate the height of mountains[2]. However, given the different timescales involved in uplift, fluvial erosion and landsliding, testing this model has proved challenging. Writing in *Nature Geoscience*, Larsen and Montgomery[3] use landslide measurements from the rapidly rising Namche Barwa massif in the eastern Himalayas to show that landslide erosion adjusts by a factor of ten to match variations in rock uplift and valley incision.

The concept of threshold hillslopes is simple enough to demonstrate in a sand pit or, better yet, on the beach. If you and a companion begin excavating on either side of a mound of dry sand, you'll soon form two angle-of-repose slopes separated by a sharp ridge line that caps your miniature mountain range. Now, if both of you manage to double (or even quadruple) your pace of excavation, you will detect no change in the steepness of the slopes, but you will observe that sand cascading off the slopes inundates each of your trenches twice (or four times) as quickly as it did previously. In essence, the sand avalanches keep pace with your rate of excavation, whereas the slope angle and trench-to-ridgeline height remain unchanged (Fig. 1).

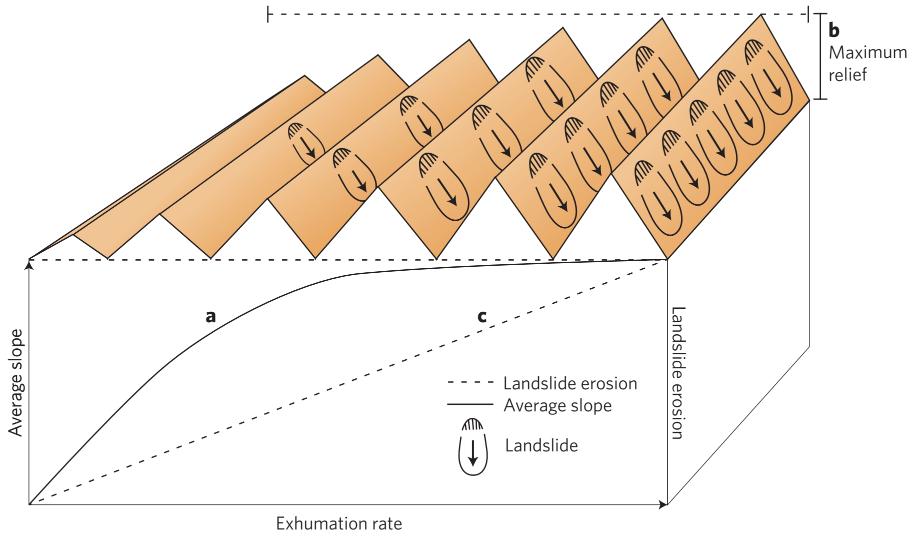

Figure 1 | Peaks in balance. As uplift rates increase (**a**), the relief of the mountain range will rise, but up to only a certain point (**b**). This upper limit to topographic development is commonly attributed to the attainment of a threshold hillslope[5], beyond which landslide erosion (**c**) will keep pace with uplift and stream incision, limiting the height of the mountain range. Larsen and Montgomery[3] demonstrate this hypothesis in the Namche Barwa, showing that despite a substantial variation in the rate of uplift and stream power, hillslopes vary by no more than 10%. They use satellite images to identify the extensive landsliding that reduces the relief in the quickly rising region.

Translate these benign sand avalanches on the beach into bedrock landslides of more than 10^8 m^3 in volume careening down hillslopes and you have the threshold-slope concept. It has few, if any, detractors, but supporting evidence has been indirect[4,5] and the dynamic coupling of landslide erosion and valley downcutting largely undocumented. In most situations, demonstrating this coupling is problematic because mountainous terrain takes millions of years to evolve. In contrast, landslides are heavily influenced by more frequently fluctuating factors such as rainfall events and earthquakes, as well as variations in rock properties across a small spatial scale. Furthermore, the large slope failures that can account for much of the range's erosional budget occur infrequently. To prevent these factors from obfuscating the trends required to test the threshold-slope model, you need a rapidly evolving location with a profound and well-documented gradient in the rate of rock uplift and valley incision. A ~150-km-wide active fold in Namche Barwa provides such a site. Across the fold, mineral cooling ages, which generally reflect uplift and erosion, decrease by an order of magnitude whereas estimates of fluvial stream power increase by the same amount. This identifies the region as a broad zone of rapid rock uplift and high river incision[6], relative to the surrounding area.

Larsen and Montgomery[3] assessed how hillslopes might accommodate such profound variations in erosion rate in the absence of a significant morphologic adjustment, using an array of remote sensing data, including declassified spy satellite images, to map more than 15,000 landslides and estimate their volumes. In most settings, the relatively short observation period (1974 to 2007) afforded by the imagery would be insufficient to capture landslide patterns relevant to geological timescales. But the pace of landscape evolution in Namche Barwa is hard to miss. According to Larsen and Montgomery's analysis, rates of landslide erosion increase by an order of magnitude across the zone of high rock uplift and increased stream power despite there being only a minor (~10%) increase in average slope angle. They suggest that the increased stream power and incision spur high rates of landsliding, which acts to maintain slope angles at threshold values akin to the angle of repose. Furthermore, Larsen and Montgomery identified an area of extensive landsliding associated with an outburst flood in 2000. The flood seems to have excavated considerable amounts of material, reinforcing the link between rivers and hillslopes, a rarely emphasized aspect of the threshold-slope model.

With the link between landslides and mountain topography more firmly established, a number of new avenues of research open up. For instance, potential feedbacks between factors that can trigger landslides — such as earthquakes and storms — and topography should be explored. For example, the rapid uplift in Namche Barwa could be associated with high seismic activity, which might facilitate the high rates of landsliding observed. Furthermore, similar techniques should allow us to assess whether the erosion required to balance the rapid uplift is accomplished by particularly large, deep or simply more frequent landslides. Variations in the properties of landslides in this area — if observed — could determine if rock properties such as fracture density or the grade of metamorphism reached by the rock mass affect geomorphologic processes. Alternatively, it has been proposed that high rates of erosion may actually drive rapid rock exhumation, but it remains to be shown how this feedback may emerge in the absence of focused erosion from a strong climate gradient[7].

Larsen and Montgomery[3] have made important strides in documenting a clear and robust pattern of mountain-scale erosion for hillslopes of nearly uniform slope angle. That rates of landsliding — a highly stochastic geomorphic process — mirror a long-term trend in rock exhumation driven by tectonic forcing comes as a surprise. ❐

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ENVIRONMENTAL SCIENCE

Mercury in flux

Mercury concentrations in the Arctic atmosphere exhibit a pronounced peak during summer. Model simulations suggest that this can be explained only if boreal rivers deliver large quantities of mercury to the Arctic Ocean.

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Arctic Ocean biota contain some of the highest concentrations of mercury in aquatic ecosystems globally. These high levels of mercury may affect the health of Arctic peoples and wildlife alike[1]. Yet no significant sources of anthropogenic mercury have been identified in the Arctic region. Unlike other heavy metals, however, elemental mercury can be found in the atmosphere as a gas, with a lifetime of the order of one year. Thus mercury — anthropogenic or natural — can travel far from its emission source. In recent years, the idea has taken hold that most of the mercury in the Arctic Ocean comes from the atmosphere[1]. Writing in *Nature Geoscience*, Fisher and colleagues[2] challenge this assumption and argue that circumpolar rivers deliver even larger quantities of mercury to the Arctic Ocean.

In polar regions, atmospheric mercury levels fall dramatically at the onset of the polar sunrise, owing to the oxidation and subsequent deposition of elemental mercury. Upon snow melt, this deposited mercury may run off into the marine ecosystem where it becomes available to biota. The discovery of these atmospheric mercury depletion events in the 1990s led to the suggestion that the Arctic is a sink for anthropogenic mercury emitted in the mid-latitudes[1]. Since then, research efforts have focused on monitoring and understanding the atmospheric dynamics of Arctic mercury[3].

Although atmospheric mercury depletion events over the Arctic Ocean are now recognized as a widespread phenomenon, their importance in driving mercury into the marine ecosystem has been called into question[4]. It is now known that around 80% of the mercury deposited on snow during atmospheric mercury depletion events is chemically reduced in the presence of sunlight and re-emitted to the atmosphere in its gaseous, elemental form[4]. The spring minimum in atmospheric mercury concentrations is followed by a pronounced summer maximum[5]. The combined re-emission of mercury from snow and evasion from Arctic waters and soils has been suggested to explain these seasonal dynamics[4].

In parallel to this research into Arctic mercury dynamics, sophisticated models of the global mercury cycle have been developed. These models include descriptions of biogeochemical mercury transformations in atmospheric, marine and terrestrial reservoirs, and are capable of simulating seasonal trends in mercury transport and deposition on a regional to global scale[6].

Fisher and colleagues[2] use one of these models, the GEOS–Chem (Goddard Earth Observing System–Chem) global chemistry and transport model, to simulate seasonal mercury dynamics in the Arctic region in unprecedented detail. Although the model captures the atmospheric mercury depletion in spring, it fails to pick up the summertime peak seen in observations. This peak in atmospheric mercury concentrations cannot be explained by mid-latitude export, because summertime concentrations at lower latitudes are significantly smaller than those seen in the Arctic. Furthermore, neither the re-emission of mercury deposited during spring nor emissions from the ocean can explain this summertime peak, according to a careful evaluation of the uncertainties associated with measurements of these fluxes. Rather, the model results, combined