TECTONIC GEOMORPHOLOGY

The hills came tumbling down

Large earthquakes can build mountains, but they can also trigger landslides that wear landscapes away. An analysis from the 2008 Wenchuan earthquake shows that landslides destroyed more topography than was created by uplift.

William B. Ouimet

The topographic evolution of mountain belts is most simply viewed as a competition between the tectonic processes that build topography up and the erosional processes that break it down and carry sediments away. In active mountain ranges, these erosional processes consist mainly of bedrock incision and sediment transport by steep rivers, mass wasting in the form of landslides and glacial abrasion; the contribution of each varies through time owing to the variations in climate that drive them. Mountains grow when the uplift associated with tectonic processes outpaces erosion; remain steady when erosion and uplift balance each other; and shrink when erosion exceeds uplift. Writing in *Nature Geoscience*, Parker and colleagues[1] report that the volume of material displaced from the Longmen Shan Mountains, China, by landslides associated with the 2008 Wenchuan earthquake exceeded the volume of rock uplift caused by the fault movements, suggesting a net destruction of topography.

Tectonics, erosion and climate interact in a number of ways to influence the world's mountain ranges. In the most basic formulation, topographic growth driven by tectonics is kept in check by the erosion it promotes. More dynamic interactions arise when uplifting topography influences and directs climate patterns that control the erosion, and when erosion itself changes the stress state of the deforming mountain range[2]. Advances in numerical modelling, remote sensing, geochronology and thermochronology provide the modern tools needed to study topographic evolution and estimate rates and volumes of erosion and uplift. These techniques allow tectonic geomorphologists to evaluate the condition of steady-state balance between topographic growth and erosion in mountain belts around the world[3], and to address the relationships between erosional efficiency and the shape and structure of mountain ranges[4]. More provocatively, these tools can be used to diagnose a clear tectonic response to climate change[5,6]. Most of this work looks at mountain evolution through a long-term lens, considering millions of years; studies of large, short-term changes in topography, such as coseismic uplift and mass wasting caused by earthquakes, are generally lacking.

Parker and colleagues[1] assessed just this type of short-term change during the catastrophic M_w 7.9 2008 Wenchuan earthquake in Sichuan, China. Owing to the steep terrain that characterizes the Longmen Shan Mountains, the earthquake triggered an enormous number of landslides. To assess the scale of mass wasting, Parker and colleagues mapped 13,800 km^2 of landslides with high-resolution satellite imagery. They combined their detailed mapping of landslides with estimates of the relationship between the area of the landslide and the volume of material displaced to calculate the total volume of rock eroded by landsliding during the event and recently thereafter (Fig. 1). Over the same area, they used a form of remote sensing known as synthetic aperture radar — which measures displacement of the ground surface over time — to estimate the volume of topographic growth caused by the earthquake. When compared, the two volumes indicate that the earthquake produced more erodible material than it added through coseismic rock uplift.

Determining whether this means the mountain range is in steady state or now undergoing topographic decay depends on the fate of the eroded material. The region affected by the earthquake is not glaciated at present, so rivers and hillslope erosion are responsible for wearing away the landscape. Because the Longmen Shan landscape is dominated by steep topography, gravity-driven erosion of steep hillslopes accounts for most of the erosion in the area. Ordinarily, the rivers transport downstream all of the sediment that is supplied to them from the upstream reaches and from the adjacent hillslopes, and incise the valleys at rates that are sufficient to maintain the steep relief and thus maintain hillslope erosion rates. However, the 2008 earthquake has disjointed this process by drastically accelerating the delivery of debris from the hillslopes to the river channels. The result is piles of coarse landslide debris up and down river valleys for the fluvial network to contend with.

River channels now have the burden of removing most of this sediment. If the channels and associated floods and debris flows do evacuate the landslide material before the next big earthquake strikes — as Parker and colleagues argue is reasonable — the earthquake will have reduced both the volume of rock and the mean elevation of topography in the mountain range. If, however, the debris is not carried away, the sediment will linger and the net effect of this Wenchuan

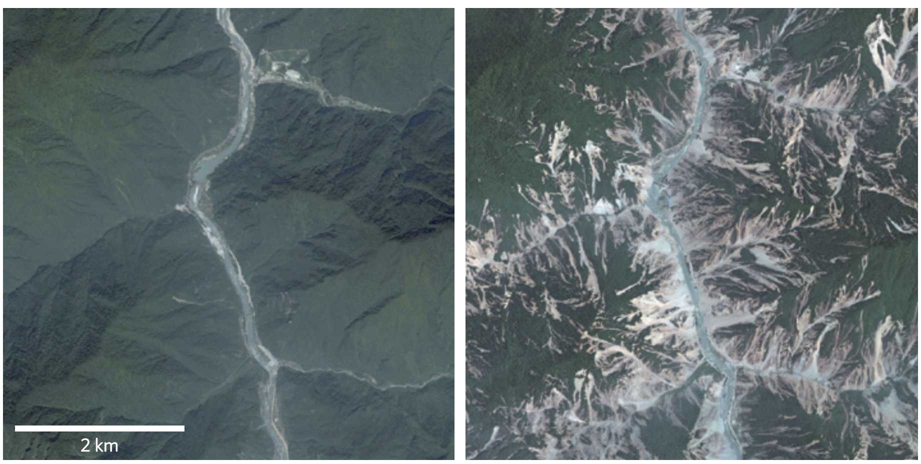

Figure 1 | Landslides associated with the Wenchuan earthquake. Left: 9 September 2005; right: 3 June 2008. This satellite imagery pair, taken 24 km N–NE of the epicentre, highlights one of >60% landslide density areas studied by Parker and colleagues[1] where the imbalance between volume added through coseismic rock uplift and rock eroded by landslides would be greatest. © Digital Globe.

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earthquake will fall short on the predictions of Parker and colleagues. The legacy of this event would then be one of reduced relief and lower mean elevations, but not necessarily one of negative mass balance.

Whether the earthquake added or removed mass therefore depends on the time needed for the rivers to remove the excess sediment and the recurrence interval of similar earthquake and landslide events. Both are superimposed on natural variations in the climate of the region — wetter, cooler climates could lead a different magnitude of landslide material displaced during earthquakes, as well as more efficient evacuation of landslide sediment. Understanding these timescales is the key to understanding the long-term evolution of topography in the Longmen Shan mountain range, already an enigmatic margin of the Tibetan Plateau[7]. There is a spatial correlation between the presence of steep river channels and higher rates of rock uplift in the earthquake region. This suggests that the local landscape is adjusted to reflect a balance between erosion and tectonics[8]. The spatial pattern of coseismic rock uplift and landslide erosion observed for the earthquake is consistent with this correlation, but the large volume of mass wasting documented by Parker and colleagues indicates a short-term imbalance between the magnitudes of erosion and uplift. For the long-term balance to exist, it would seem additional rock uplift from fault movement is needed, but not at the cost of more mass wasting and erosion.

Parker and colleagues[1] have emphasized the role of landslides in dictating landscape evolution in steep, actively deforming mountains, particularly those in which active faulting plays an important role in mountain building processes. There is growing evidence[9] that large earthquakes with the potential for massive coseismic landslides deserve to join the ranks of catastrophic floods and climate cycles as events that regularly punctuate landscape evolution and make the erosion of mountains discontinuous over millennial to ten-thousand-year timescales. ❐

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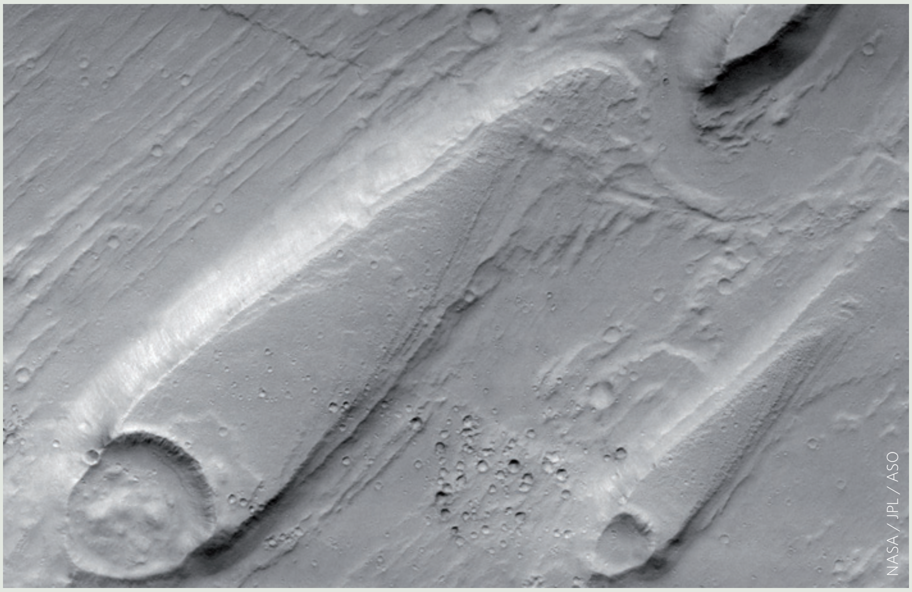
PLANETARY SCIENCE

From shore to shelf

Identifying past oceans and lakes on Earth is — relatively — easy. Cliffs and road cuts reveal rocks rife with fossils and minerals formed in water. Seismic data reveal buried shorelines and channels. And radioactive elements allow us to assess when these markers were deposited. Finding former bodies of water on other planets is markedly more challenging. Spectral data can hint at the presence of aqueous minerals, but most evidence comes from satellite images of planetary landforms that resemble fluvial or marine features found on Earth.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The presence of such analogous surface morphology has led to the suggestion that the northern plains of Mars were once covered by vast oceans. Deep chasms in the Chryse Planitia and Valles Marineris regions have been interpreted as outburst channels that fed ground water or molten ice into the ocean basin. But these features may not be signs of a shoreline at all: Lorena Moscardelli and Lesli Wood of the University of Texas, Austin, suggest that elongated mounds near the chasms are more consistent with channel formation in a continental slope setting (*Geology* **39,** 699–702; 2011).

The martian channels look like flood remnants, but also bear a striking resemblance to submarine channels found on Earth. Dotted among these channels are triangular elevated features termed teardrop-shaped islands. Moscardelli and Wood show that these martian landforms are geometrically similar to erosional shadow remnants found on the continental shelf near Trinidad. The Caribbean erosional remnants formed during a mass wasting event in the distal reaches of the Orinoco Delta, and similar processes could have been at work in the martian plains.

Traces of mass wasting events are present elsewhere in the northern martian plains, namely in the form of chaotic terrains in the upper limbs of the outflow channels near Chryse Planitia. This surface morphology is consistent with channel collapse and underwater transport of sediments.

If the channels were indeed carved under water, we may need to redraw the outlines of the hypothesized ancient martian ocean, and raise estimates of the volume of water that once occupied it.

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