Topography reveals seismic hazard

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The devastating earthquake in the Chinese province of Sichuan struck an area that was not expected to suffer seismic activity of such magnitude. Yet topographic analyses of the region indicate active deformation, suggesting a way of refining maps of earthquake risk elsewhere.

The earthquake that shook the flank of the Longmen Shan mountain range in China's Sichuan Province on 12 May 2008 poses a challenge to geoscientists. Although the margin of the Sichuan Basin was known to be seismically active, an event of this magnitude was not anticipated on published seismic hazard maps[1], probably because such events are relatively infrequent in this setting and because the earthquake occurred along one of the more enigmatic mountain fronts in the world. The topographic front across the Longmen Shan — Chinese for Dragon's Gate Mountains — rivals the Himalayas in relief, yet measurements made using global positioning system (GPS) satellites reveal little to no active convergence across this range[2–4]. This is a surprising and unusual result as most mountain ranges of this scale are associated with rapid convergence between opposing crustal blocks; the Himalayas, for example, absorb a significant portion of the ongoing deformation resulting from the India–Asia collision[5]. Thus, the GPS measurements imply that deformation rates across the range are slow, indicative of relatively modest strain accumulation and seismic hazard.

This observation is at odds with the impression of active tectonic upheaval created by the rugged topography (Fig. 1). Indeed, previous studies in the region dating back to 2000 and 2003 that focused on geomorphic analysis[6,7] inferred that faults in the region must be active, and identified regions of high rock uplift rate[8]. The 2008 earthquake struck along one of the fault systems that had been suggested to accommodate high rates of rock uplift. The topographic analyses therefore provide a crucial tectonic and geomorphic context for the recent earthquake. And they carry potentially important implications for anticipating the most likely locations of future events in the region.

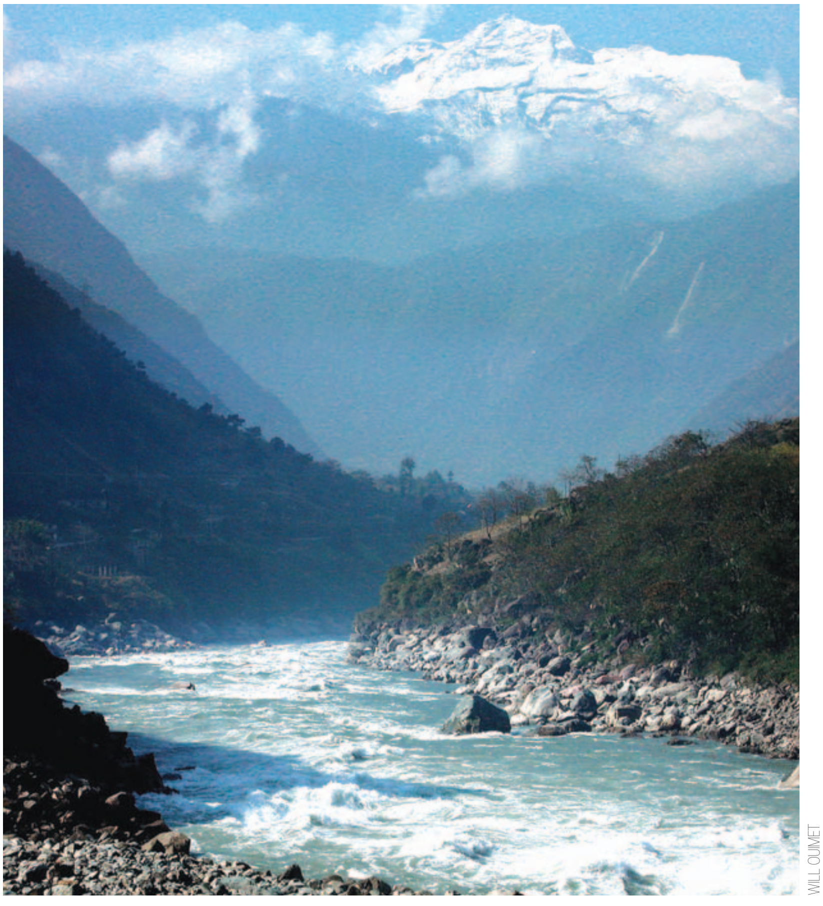

Figure 1 Rugged topography of the Sichuan region of China. View towards the southwest showing rapids through a landslide deposit in the Dadu river gorge and snow capped mountains of the Gonga Massif in the distance. Here, the Dadu River is at ~1,100 m in elevation. Mountain peaks to the west rise to elevations of over 7,000 m within a distance of less than 30 km, making this region one the most dramatic examples of topographic relief on earth.

More generally, we argue that topography itself may signal tectonic activity at depth that is not well recorded by short-term satellite measurements. Several lines of evidence suggest that the mode of crustal thickening in this region of the Tibetan Plateau is unusual in that it is largely driven by flow and deformation in the lower crust[5]. If this hypothesis is correct, faults within the Longmen Shan range could be active, even in the absence of evidence for significant shortening across the mountain range. In such settings, where shortening rates are slow and satellite data may be equivocal, topographic analyses can help guide the identification of potential earthquake risks.

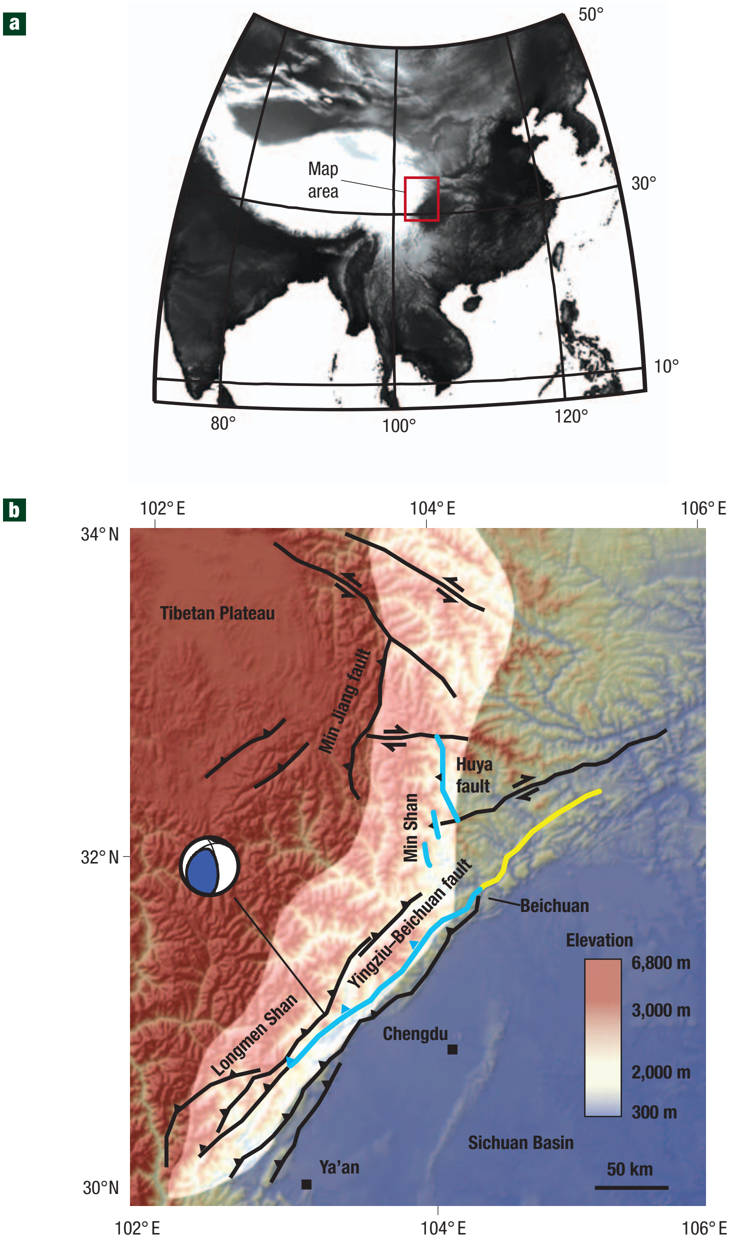

Figure 2 Tectonic and geomorphic setting of the 12 May 2008 Sichuan earthquake. **a**, The red box shows the location of the area discussed in the text. The figure was produced using SRTM (Shuttle Radar Topography Mission) global digital topographic data with a nominal resolution of 90 m. **b**, A shaded relief map of the eastern margin of the Tibetan Plateau derived from topographic data. Active faults are shown as black lines and historic ruptures are colour coded (blues segments show primarily vertical motion and yellow segments show primarily lateral motion). The Sichuan rupture occurred along the Yingxiu–Beichuan fault. The epicentre and focal mechanism ('beachball') for the earthquake is from ref. 9. Changes in motion during this rupture are derived from the USGS finite fault inversion[9], whereas thrust motion along the Huya fault is inferred from ref. 19. Highlighted topography shows the region of high rock uplift (>0.5 mm yr^{-1}) inferred from landscape analysis[7]. Note the correspondence between this region and the location and distribution of slip during the 12 May rupture. This lends credence to the general use of tectonic geomorphology in the identification and characterization of active deformation in mountain belts.

THE SICHUAN EARTHQUAKE

The magnitude 7.9 Sichuan earthquake occurred along the Yingxiu–Beichuan fault system, one of a series of faults that bound the western margin of the Sichuan Basin (Fig. 2). Preliminary field observations suggest that the surface rupture extended for at least 200 km (X. Xiwei, personal communication). The crust to the northwest of the fault was thrust over that to the southeast by almost 5 m. Furthermore, this thrusting occurred in an oblique fashion such that the northwestern block also moved in a northeasterly direction by ~5 m relative to the Sichuan Basin (X. Xiwei, personal communication). Although details of the rupture process during the earthquake remain unclear, preliminary models[9] suggest that the event evolved in time and space from dominantly vertical motion along the southwestern portion of the fault to dominantly lateral motion along the northeastern fault segments.

This transition appears to have taken place approximately midway through the rupture, near the town of Beichuan (Fig. 2b). Although the change in direction of movement along the fault could be exaggerated by modelling a geometrically complex fault array as a single plane, the spatial distribution of aftershocks exhibits a similar pattern[1] (Fig. 2b), suggesting the result is fundamentally robust. Additionally, preliminary investigations of the surface rupture appear to confirm that the vertical component was greater than the lateral component of motion in the south (X. Xiwei, personal communication). This complicated rupture process is significant in that it may have analogues in active mountain ranges elsewhere[10].

TOPOGRAPHIC ANALYSIS

Characterization of the pace, tempo and history of movement on active faults traditionally relies on deformational features that developed within relatively young sediments[9]. Because these records of faulting tend to be confined to low-lying regions where sediments accumulate, assessing the locations and patterns of active deformation within mountainous topography has been notoriously difficult. But powerful new dating tools, such as cosmogenic isotopes, and high-resolution digital elevation models have recently helped decipher the topographic signature that arises from the competition between vertical motion caused by faulting or folding and erosion.

The landscape adjusts to vertical movement in active mountain ranges primarily by changes in the gradients along the bedrock-based river network[11]. Therefore, the steepness of channel profiles extracted from digital elevation models can be used to identify zones that are anomalously steep, which may reveal underlying variations in the rate at which rock is being uplifted[12]. Although the interpretation of such data is not always straightforward[12], these methods have been tested successfully in regions where the pattern of tectonic activity is known *a priori*[13]. And in a way, the 2008 Sichuan earthquake affords one of the highest-fidelity tests of the method to date.

Prior to the tectonic geomorphic work in the Longmen Shan[6,7], little was known about the degree of activity along faults within this mountain range. Ancient deformation more than 65 million years ago is evident from the rock record, but whether there was significant movement along the faults during the past 2 million years has been equivocal[4]. In this situation, analysis of the profiles of bedrock-based rivers throughout the region[7] indicated systematic changes in channel steepness and topographic relief. These changes are most likely to be the manifestation of active rock uplift at the edge of the Tibetan plateau. Moreover, the dramatic change in the steepness of river profiles in the eastern margin of the zone of rugged topography coincides almost exactly with the surface trace of the Yingxiu–Beichuan fault (Fig. 2). This spatial agreement is compelling evidence that this fault — the one that eventually ruptured on 12 May 2008 — is active. Long-term vertical motion along the fault is thus responsible for maintaining steep topography in the Longmen Shan in spite of rapid erosion. Subsequent field work, guided in part by this topographic interpretation, provided confirmation of active deformation along the Yingxiu–Beichuan fault[14].

The transition from vertical slip to a greater lateral component of displacement during the Sichuan earthquake coincides with inferences from the topographic analyses[7] that indicate a change in the orientation and location of active uplift. North of the city of Beichuan, the core of high uplift rates that characterize the Longmen Shan margin turns away from the Sichuan Basin and follows the Min Shan north along the topographic margin of the plateau (Fig. 2). The coincidence between the distribution of deformation due to the earthquake and the pattern of long-term rock uplift identified by topographic analyses is remarkable. Because high uplift rates indicate regions experiencing active deformation that are thus susceptible to earthquakes, analysis of topography in the manner described here may reveal some of the more subtle details of seismic hazard in active mountain ranges.

Topographic analyses cannot stand in isolation. Direct field documentation of active deformation, as available in the case of the Yingxiu–Beichuan fault[14] provides critical corroboration. Although researchers are often quick to (rightly) point out difficulties in the interpretation of tectonics from topography, this event makes clear that landscape analysis can help with the initial identification of active structures and, in some cases, provide constraints on the nature of deformation along them.

FUTURE EARTHQUAKES IN SICHUAN

Collectively, several studies using different methodology have obtained consistent erosion rates[7,15–17] that constrain the vertical motion along faults in the Longmen Shan to at least 0.5 mm yr^{-1}, suggesting that large earthquakes such as the Sichuan event with an average vertical fault slip of 2–4 m could occur once every 4,000 to 8,000 years. These same analyses also highlight additional areas in this region that may be at risk of future earthquakes. In a similar setting to that along the Yingxiu–Beichuan fault, relatively high rates of rock uplift inferred along the Min Shan north of the Sichuan Basin[7] coincide with active faults that flank this margin of the plateau — the Min Jiang and Huya faults (Fig. 2). Both of these fault systems are steep, west-dipping thrust faults that are considered active[6,18], but because their surface traces are located across rugged topography, little is known about their potential for earthquake generation. The easternmost of these faults, the Huya fault, is a likely candidate source of a series of earthquakes that occurred in 1976[19]. Moreover, Late Quaternary sediments along the western flank of the Min Shan record relatively recent tilting across the range that may be associated with movement along this fault system[6].

Although the Huya fault is not typically considered an important seismic hazard in the region (and it does not even appear on some maps), the extent and continuity of the region of high uplift rates (Fig. 2) suggests that this structure may exhibit similar slip rates to those on the Yingxiu–Beichuan fault and thus a similar potential for earthquake hazard. Understanding the paleoseismic history of the Huya fault as well as possible interactions of this fault with the Yingxiu–Beichuan fault should be an urgent priority.

LESSONS FROM SICHUAN

The 12 May 2008 earthquake that struck the Sichuan Province was a surprisingly large and devastating event. However, it also provides a ray of hope in perhaps the most compelling evidence to date that the landscape itself encodes information about the rates and patterns of tectonic activity. Our ability to read these tectonic signatures in erosional landscapes has progressed to the point where quantitative topographic analyses can be a quick and useful tool for identifying zones of active rock uplift and the seismic hazards associated with them. Such analyses can be particularly insightful above blind or hidden faults, in remote mountainous landscapes, and, as the Sichuan event makes all too clear, in regions where even dense geodetic networks indicate little strain accumulation in the upper crust.

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