SEISMOLOGY

Raising Kathmandu

On 25 April 2015 northern Nepal shifted up to 7 m southward and Kathmandu was raised by 1 m. The causal earthquake failed to fully rupture the main fault beneath the Himalaya and hence a large earthquake appears to be inevitable in Nepal's future.

Roger Bilham

For many decades seismologists have warned of a possible damaging earthquake near Kathmandu, in the Himalaya[1,2]. The moment magnitude (M_w) 7.8 Gorkha earthquake — which struck Nepal in April 2015 and resulted in more than 8,700 deaths, destroyed 490,000 houses and 30,000 classrooms, and rendered 3.5 million homeless — was thus not a complete surprise. But many features of the earthquake were indeed surprising. An international workshop (The Gorkha Earthquake 2015, Nepal: Present Knowledge and Way Forward on Future Research) organized by the Nepal Academy of Science and Technology (NAST) and the International Centre for Theoretical Physics (ICTP) was convened on 17 June amid the aftershocks in the ruined capital. Discussions at the workshop led to the worrisome conclusion that this was not the earthquake we were expecting.

The Himalaya Mountains define the collision zone between the Indian Plate and southern Tibet. Tectonic convergence across the mountains occurs at a rate of roughly 18 mm yr^{-1}. Strain accumulated during this convergence is released by occasional great ($M_w > 8$) and major (M_w between 7.0 and 7.9) earthquakes, permitting the Indian plate to descend beneath southern Tibet. Many millions of people live fewer than 15 km above the gently dipping thrust fault on which these earthquakes take place.

Great and major earthquakes occurred in 1255, 1505, 1833, 1934 and 1950 in the region surrounding Kathmandu. But an apparent absence of earthquakes to the west of Kathmandu in the past 500 years suggested that a great earthquake in that region was likely to occur[2]. The epicentre of the 2015 Gorkha earthquake was located 70 km west of Kathmandu, roughly where anticipated. But, vexingly, the quake was too small to be the expected great event. Instead, the quake shares many similarities with the damaging major earthquake that occurred in 1833 north of Kathmandu, with similar magnitude and damage pattern[3].

As discussed at the workshop, the dynamic development of the 2015 earthquake was captured by distant and local seismometers, by synthetic aperture radar imagery and by a dozen global positioning system (GPS) receivers operating near and above the rupture zone (Jean-Philippe Avouac, Cambridge University, UK; Abdelkrim Aoudia on behalf of Eric Lindsey and colleagues, University of California, San Diego, USA). The $M_w = 7.8$ mainshock initiated an eastward-propagating fault rupture that propelled an oval-shaped segment of the Himalaya (approximately 150 km by 65 km in size) southward over the Indian Plate. Although the Gorkha earthquake started out in an anticipated location, no one had suspected that its rupture would pass beneath and beyond Kathmandu eastward, with rupture terminating at the southern edge of the Kathmandu Valley. Two weeks later, an $M_w = 7.3$ aftershock caused further damage to dwellings and hillsides at the eastern end of this rupture.

The area most afflicted is now accessible only by helicopter, owing to the remoteness of mountain villages and impassable conditions on roads and tracks. Landslide experts at the workshop (Christoff Anderson, GFZ Potsdam, Germany; Deo Raj Gurung, International Centre for Integrated Mountain

Development, Nepal; Joshua West, University of Southern California, USA) warned that the approaching monsoon is likely to further destabilize weakened hillsides, worsening damage to rural infrastructure.

The large aftershock on 12 May was one of more than three hundred $M_w > 4$ aftershocks that encircled the rupture zone (Loc Bijay Adikhary, National Seismological Center, Nepal). These aftershocks define the limits of the fault rupture and show that it petered out 10 km beneath the surface, on the southern edge of the near-horizontal thrust fault beneath the city. As a result, a region of accumulated stress not released in the earthquake now sits uncomfortably close to the southern suburbs of Kathmandu (Fig. 1). How this incomplete southward rupture will mature is of great concern. At least three scenarios are possible: stress now stored south of Kathmandu, in the Lesser Himalaya, could potentially fuel another damaging earthquake; the stress could remain stored in the Lesser Himalaya to contribute to a larger, great earthquake in the future; or the stress may diffuse southward benignly as creep.

Major Himalayan earthquakes in 1833 (north of Kathmandu) and in 1905 (northwest of Delhi) likewise failed to rupture to the surface[3,4] and probably also transferred stress into the Lesser Himalaya. This stress cannot remain there indefinitely. A dozen new and ongoing GPS measuring stations have therefore been judiciously placed to monitor the future development of strain south of Kathmandu and in the region to the west of the current rupture (Bishal Upreti, NAST, Nepal). Students from Tribuvhan University in Nepal, in collaboration with the ICTP in Trieste, Italy, and several US Universities are actively involved in these investigations. The teams aim to reverse the pattern of the past few decades when geodesy and seismology in Nepal were the mandate of government departments only. University involvement is essential if young Nepali students are to become future seismologists and earthquake engineers.

Kathmandu is built on sediments of an ancient lake bed that are about 650 m thick. These sediments have amplified seismic waves from distant earthquakes in the past[5] and did so again during larger aftershocks from the 2015 quake. However something entirely different occurred during the mainshock. The bedrock floor of the basin was forced by the earthquake rupture to move in a semicircular-shaped, southward path with a diameter of about 1.5 m. The bedrock movement stopped dead "1.3 m south and 50 cm higher" after 10 seconds, but the sediments in the valley continued to resonate for a further two minutes (Jean-Philippe Avouac, Cambridge University, UK).

Geotechnical engineers (Ramesh Guragain, National Society for Earthquake Technology, Nepal; Deepak Chamlagain, Tribuvhan University, Nepal) at the meeting noted that these slow oscillations, which had periods of about 3 to 5 seconds, were both the undoing and saving of the metropolis. Video recordings confirm that people found it hard to stand during the translation of the city, while slow lurching motions toppled and dismantled many of Kathmandu's heritage temples and traditional buildings. Yet the ground accelerations did not exceed 0.25g (where g is acceleration due to gravity), despite ground velocities in excess of 50 cm s^{-1} (Sudhir Rajaure, Ministry of Mines and Geology, Kathmandu). The slow lurch of this enormous southward and upward pulse was unexpectedly gentle, compared with accelerations of up to 1g estimated from scant historical earthquake accounts.

Despite the low accelerations, the lurching resonance irreparably damaged 97,000 buildings in Kathmandu, including many school buildings. A few hundred schools recently retrofitted by engineers from the National Society for Earthquake Technology survived the earthquake, but hundreds of schools assembled from stone and wet-mud mortar decades before the earthquake did not. Fortunately the earthquake struck at the weekend, when schools were unoccupied.

Unlike in previous major earthquakes, liquefaction and sand venting in the Kathmandu Valley were rare, with only a few instances reported (Deepak Chamlagain, Tribuvhan University, Nepal). Whether this was caused by low ground accelerations or because the water table in Kathmandu in the past several decades has been sinking rapidly as a result of groundwater withdrawal is not clear. Widespread liquefaction occurred in regions south of the mountains where water tables remain close to the surface. The reach

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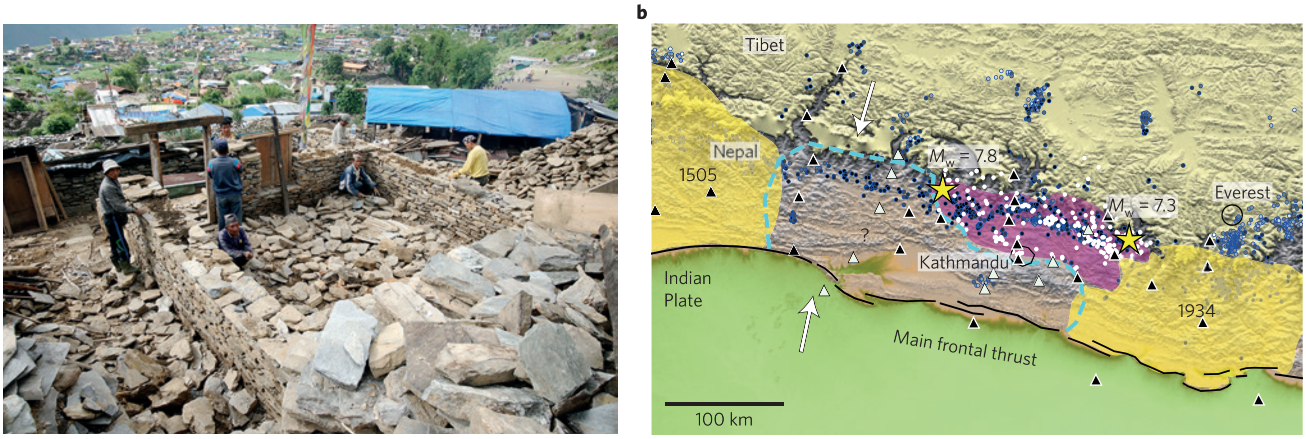

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Figure 1 | The 25 April 2015 Gorkha earthquake, Nepal. **a**, Villagers reconstructing their ruined house near the epicentre of the Gorkha earthquake. Despite Government advice to incorporate earthquake resistant assembly methods, the approaching monsoon has impelled many villagers to reconstruct immediately using the same wet-mud mortar and stones that led to their collapse in the main shock. **b**, Rupture caused by the M_w = 7.8 earthquake and subsequent M_w = 7.3 aftershock (yellow stars) initiated west of Kathmandu and travelled eastward (purple). A decade of micro-earthquakes (blue dots) before the earthquake marks the region of greatest pre-earthquake stress, white dots indicate $M_w > 4$ aftershocks (Loc Bijay Adikhary, National Seismological Center, Nepal; http://www.seismonepal.gov.np/index.php?action=earthquakes&show=recent). Black triangles indicate pre-earthquake GPS stations; white triangles are post-earthquake GPS stations. White arrows show Himalayan convergence at 18 mm yr^{-1}. Observations from the Gorkha earthquake, discussed at the workshop in Kathmandu, indicate that the earthquake incompletely ruptured the region between historical earthquakes to the east (1934, M_w = 8.4) and west (1505, $M_w > 8.6$), shaded yellow. If the unruptured region (blue dashed) ruptures in a single earthquake, it could exceed M_w = 8. Thus, the 2015 earthquake was not the great earthquake anticipated west of Kathmandu.

of the earthquake was immense. It was felt throughout much of India and as far south as Chennai (Stacey Martin, Earth Observatory of Singapore).

Fears of a future large earthquake in western Nepal are on everyone's mind. The meagre historical record indicates that no contiguous great earthquake has immediately followed a Himalayan $M_w \geq 7.5$ earthquake, but immediacy is an elastic measure of time when it comes to forecasting earthquakes. For example, the 1950 $M_w = 8.6$ earthquake in Assam, India, was preceded by an apparently contiguous $M_w = 7.5$ earthquake just three years earlier.

The emerging view from the meeting was that although the mainshock nucleated near the anticipated location, it was not the long-awaited 'big one' in western Nepal. Given our unsettling lack of knowledge about the 2015 earthquake before it occurred, the best recommendation for Nepal's policymakers is to use this opportunity to reconstruct the entire damaged region incorporating earthquake-resistant construction, and to initiate ubiquitous retrofits of village dwellings throughout western Nepal. According to the expectation of workshop participants, another major earthquake to the west of Kathmandu is unavoidable. And this future quake could be much more powerful. ❐

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References

1. Bilham, R. *Himal Magazine* **7,** 26–30 (1994).
2. Bollinger, L. *et al. J. Geophys. Res.* **119,** 7123–7163 (2014).
3. Bilham, R. *Current Sci.* **69,** 101–128 (1995).
4. Wallace, K., Bilham, R., Blume, F., Gaur, V. K. & Gahalaut, V. *Geophys. Res. Lett.* **32,** L15307 (2005).
5. Martin S. & Szeliga, W. *Bull. Seism. Soc. Am.* **100,** 536–569 (2010).