Introduction to the Focus Section on the 2015 Gorkha, Nepal, Earthquake

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ABSTRACT

It has long been recognized that Nepal faces high earthquake hazard, with the most recent large ($M_w > 7.5$) events in 1833 and 1934. When the 25 April 2015 M_w 7.8 Gorkha earthquake struck, it appeared initially to be a realization of worst fears. In spite of its large magnitude and proximity to the densely populated Kathmandu valley, however, the level of damage was lower than anticipated, with most vernacular structures within the valley experiencing little or no structural damage. Outside the valley, catastrophic damage did occur in some villages, associated with the high vulnerability of stone masonry construction and, in many cases, landsliding. The unexpected observations from this expected earthquake provide an urgent impetus to understand the event itself and to better characterize hazard from future large Himalayan earthquakes. Toward this end, articles in this special focus section present and describe available data sets and initial results that better illuminate and interpret the earthquake and its effects.

INTRODUCTION

Seismic hazard has long been recognized to be high along the Himalayan arc, with a certainty that, along with its neighbors, Nepal would inevitably experience earthquakes as large as, and even larger than, the 1934 Nepal–Bihar event, the magnitude of which has been estimated at M_w 8.1–8.4 (e.g., Chen and Molnar, 1977; Chitrakar and Pandey, 1986; Bilham *et al.*, 2001; Sapkota *et al.*, 2013; Bollinger *et al.*, 2014; Moss *et al.*, 2015). Although this awareness has provided the impetus for both scientific investigations and risk mitigation efforts, both geophysical monitoring and progress toward improved resilience have been hampered by resource limitations. Spurred in part by political pressures, the population of the Kathmandu valley has mushroomed from ~1.6 million in 2001 to 2.5 million in 2011. Concurrent development of the building stock, much of which is highly vulnerable, has exacerbated risk. Although Nepal has a building code and most municipalities have a building permit process, more than 98% of buildings in Nepal are built by owners working with local craftsmen, and municipalities do not have the capacity to evaluate plans for engineering design (Dixit, 2004). Throughout the region, the quality of construction design and materials is pervasively low.

When the M_w 7.8 Gorkha earthquake struck on 25 April 2015, it appeared to be precisely the earthquake that experts had long feared would take a devastating toll on the country. The earthquake was centered to the west of the densely populated Kathmandu valley and propagated to the east, rupturing the décollement underlying the valley at a depth of only 12–15 km (Avouac *et al.*, 2015). Although the earthquake did take a heavy toll throughout Nepal, the loss of life and damage were not as catastrophic as had been expected based on detailed scenarios (e.g., Wyss, 2005) or extrapolations of losses from earlier earthquakes (e.g., Bilham *et al.*, 2001). Key questions regarding ground motions thus arise: What was the nature of mainshock ground motions, and what is the explanation for their apparently unexpected character? Why was damage in the Kathmandu valley and other parts of Nepal not more severe? Can this event help us to better understand past large earthquakes in the region and Himalayan seismotectonics in general? What lessons can be drawn about the likelihood of future earthquakes and their associated hazard? Discussion of these questions is already underway within Nepal and among the international community (e.g., Bilham, 2015) and will clearly continue for years to come.

Modern instrumental data, in particular from within Nepal, will be critical to address these difficult questions. Unfortunately near-field data are limited, with much of the most important data from local and close regional distances not freely available. The primary goal of this special focus section is to document, describe, and present preliminary analysis of freely available data sets that were collected before, during, and after the mainshock. These studies provide an improved characterization of the earthquake and its effects.

OVERVIEW OF CONTRIBUTIONS

Following any significant earthquake, the U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC) uses available global and local data to characterize the event and its effects as quickly as possible and disseminates information to concerned parties. NEIC products are distributed primarily via the Web and are utilized widely by the international community. Hayes *et al.* (2015) presents an overview of the NEIC

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response to the Gorkha earthquake, including a discussion of impact assessment using the Prompt Assessment of Global Earthquakes for Response system (Earle *et al.*, 2009).

Initial NEIC locations for the mainshock and aftershocks were not well constrained because the closest immediately available station was in Lhasa, Tibet, at a distance of ~650 km from the mainshock epicenter. As described by both Hayes *et al.* (2015) and Dixit *et al.* (2015), mainshock and aftershock locations were improved by incorporation of local data collected on instruments installed prior to the mainshock by the USGS and by the National Society for Earthquake Technology, Nepal, working in partnership with the USGS. These data were recorded on a single conventional strong-motion (NetQuakes) instrument that had been installed at a U.S. Embassy facility (Galetzka *et al.*, 2015; Dixit *et al.*, 2015) and on low-cost microelectromechanical-systems accelerometers at three sites in the Kathmandu area (Dixit *et al.*, 2015).

In addition to using local recordings to improve aftershock locations, Dixit *et al.* (2015) further illustrate how the data can help address key questions involving ground motions. Although Galetzka *et al.* (2015) conclude that mainshock ground motions were dominated by long-period energy due to the character of source radiation in combination with long-period basin effects, this interpretation begs the question of why the response of the former lakebed zone was also predominantly at periods longer than expected from earlier studies (e.g., Bhandary *et al.*, 2014). Comparing mainshock and aftershock data, Dixit *et al.* (2015) conclude the response of Kathmandu Valley during the mainshock was pervasively nonlinear.

The character of mainshock ground motions in Kathmandu Valley is further illuminated by an important recording from the Department of Mines and Geology office in central Kathmandu, which is made available to the community via the electronic supplement to Dixit *et al.* (2015). Bhattarai *et al.* (2015) present and describe recordings from the mainshock and 12 May 2015 M_w 7.3 aftershock from this instrument. The recordings are consistent in character with those from the NetQuakes instrument, providing an important validation for the fidelity of both recordings. They conclude that long-period energy (≈4 s period) during the mainshock represents the fundamental-mode resonance of Kathmandu Valley, while pointing out that more detailed analysis incorporating additional data not yet available to the community (e.g., Nobuo *et al.*, 2015) will be needed to fully understand the observations.

The availability of instrumental data provides critical constraints on the nature of ground motions, but the limited volume of this data provided the impetus for an exhaustive characterization of macroseismic intensities based on detailed accounts of damage (Martin *et al.*, 2015). Only limited intensity data were collected by the USGS Community Internet Intensity Map system (also known as "Did You Feel It?"; Wald *et al.*, 1999). To constrain the intensity distribution more fully and carefully, Martin *et al.* (2015) collected accounts from conventional news outlets, as well as social media, and interpreted European Macroseismic Scale (EMS) intensities (Grünthal, 1998) in keeping with practices described by Martin and Szeliga (2010). Musson *et al.* (2010) showed EMS intensities are consistent with modified Mercalli intensities. This analysis yields an intensity distribution constrained at over 3000 locations throughout the region. The resulting data set, the largest conventional intensity data set compiled to date for any earthquake, confirms mainshock intensities within and outside of Kathmandu Valley were generally moderate (EMS 6–7), with intensities exceeding EMS 8 only in rare instances. Martin *et al.* (2015) further compare the observed intensity distribution with intensities from the 1833 and 1934 earthquakes.

Moss *et al.* (2015) further documents the nature of mainshock ground motions and their effects, focusing on assessment of geotechnical effects led by the Geotechnical Extreme Events Reconnaissance (GEER) program. They present an extensive documentation of landslides undertaken via helicopter reconnaissance. A few tens of thousands of landslides occurred, which Moss *et al.* (2015) conclude was generally in keeping with expectations for an event of this magnitude. Considering the performance of infrastructure, the GEER team concludes that most of the damage to roads and hydrofacilities was due to landslides. The death toll from landsliding was, however, much lower than the toll taken by landslides caused by the 2005 Kashmir, Pakistan, earthquake (~26,000; see Mahmood *et al.*, 2015), suggesting the overall incidence and severity of landsliding throughout Nepal, was at the lower end of the level expected (also see Collins and Jibson, 2015). Detailed observations of liquefaction similarly reveal that, while soil failure did occur in Kathmandu Valley, the amount and scale of liquefaction was lower than expectations.

The above studies thus tell a consistent story: mainshock ground motions and intensities were generally moderate (EMS 6–7), not only in Kathmandu Valley, but also throughout the near-field region. As a result, damage, liquefaction, and landsliding were significantly lower than had been expected given the magnitude of the earthquake and its proximity to Kathmandu Valley. The damage distribution is further illuminated by Yun *et al.* (2015), who analyze Synthetic Aperture Radar (SAR) data collected four and nine days after the earthquake to produce damage proxy maps. Their results also suggest that much of the damage in remote areas was caused by landslides. The resulting maps have been used by numerous international organizations for disaster assessment and response planning.

Several other papers focus on improving the characterization of the mainshock rupture. Angster *et al.* (2015) presents results of a field survey that commenced nine days after the mainshock. Their field survey confirmed the earthquake produced no surface rupture on the Main Frontal thrust (MFT) fault to the south, providing important confirmation of inferences based on Global Positioning System (GPS) and other available data (Avouac *et al.*, 2015). They additionally undertook field surveys within Kathmandu Valley, identifying and mapping in detail one 1-km northeast-trending surface fracture, which they interpret to be the result of localized extension, not deep-seated tectonic displacement. Moss *et al.* (2015)

describe this feature as well, including preliminary trenching results.

Zhang *et al.* (2015) use teleseismic, GPS, and SAR data to develop a slip model for the Gorkha earthquake and 12 May aftershock. Their results illuminate the details of the mainshock and aftershock ruptures, identifying regions of low slip that they suggest might result from barriers. They use this slip model to consider the coulomb stress changes on the MFT due to the Gorkha sequence and its implications for future earthquakes on the MFT. He *et al.* (2015) use regional and teleseismic waveforms to demonstrate the potential for rapid source characterization to improve early ShakeMaps using teleseismic *P* waves recorded at regional distances. They also present the results of backprojection analysis from arrays in Alaska, Australia, and Europe. The results of these studies are generally consistent with the mainshock rupture properties determined by Hayes *et al.* (2015). Backprojection results from He *et al.* (2015), as well as Avouac *et al.* (2015), demonstrate the value of this increasingly popular method for imaging source properties in data-limited regions. Results from different arrays and analyses are generally consistent but do reveal some differences that will need to be explored by future synoptic studies.

Rounding out the special issue, Bossu *et al.* (2015) describe how the smartphone-based information service LastQuake contributed to rapid assessment of the earthquake and its effects and fostered engagement with the public. LastQuake detects and characterizes felt events by considering web traffic patterns on earthquake information websites, as well as soliciting responses to their multilingual online questionnaire. Especially in data-limited regions, this and other citizen-science approaches offer enormous potential, not only for outreach, but also for collection of data to complement traditional-monitoring networks.

In conclusion, the articles in this focus section provide a comprehensive documentation of several key data sets and reconnaissance field investigations. In keeping with the intent that *Seismological Research Letters* (*SRL*) be published as a service to the *Seismological Society of America* (*SSA*) community, the data sets described in this special focus section are all freely available, providing critically important data to the world community of earthquake professionals seeking to understand this earthquake and its effects. The articles also present preliminary results that illuminate the Gorkha earthquake and its effects. Consideration of disparate data sets reveals that near-field ground motions, and therefore the extent of damage and landsliding, were lower than expected given the magnitude of the Gorkha earthquake and its proximity to not only Kathmandu Valley, but also to much of Nepal. These initial results raise critical questions for seismogenesis as well as seismic hazard: What accounted for the long-period nature of the ground motions? Will ground motions from future large Himalayan events—or events on décollement faults elsewhere in the world—be similar in nature to those from this event, or could they be potentially more severe? In light of the results from this earthquake, what lessons can be drawn about historical earthquakes? Is the characteristic earthquake model appropriate for the Himalaya plate boundary? Further work will be needed to address these and other questions. The data sets documented in this volume and elsewhere will provide critical constraints for a development of a synoptic understanding of this important and enigmatic event and its lessons.

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