

## RESEARCH ARTICLE SUMMARY

## GEOMORPHOLOGY

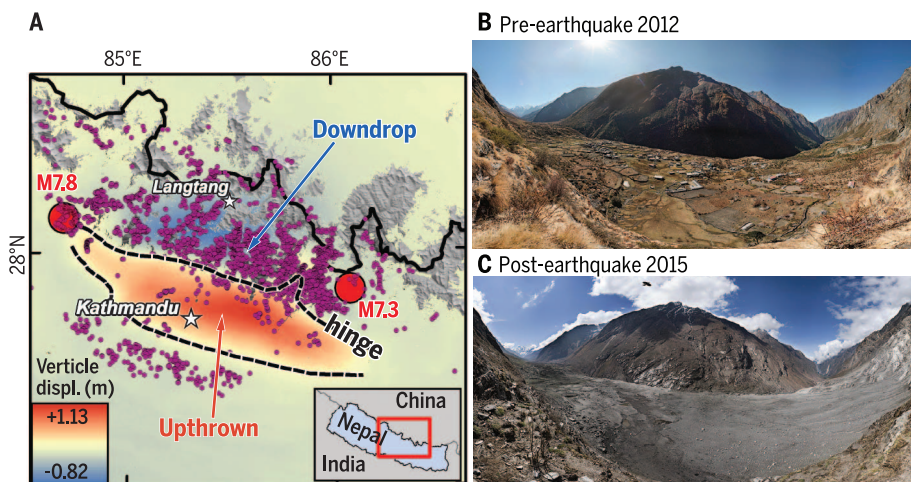
# Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake

J. S. Kargel,\*† G. J. Leonard,\* D. H. Shugar,\*† U. K. Haritashya,\*† A. Bevington, E. J. Fielding, K. Fujita, M. Geertsema, E. S. Miles, J. Steiner, E. Anderson, S. Bajracharya, G. W. Bawden, D. F. Breashears, A. Byers, B. Collins, M. R. Dhital, A. Donnellan, T. L. Evans, M. L. Geai, M. T. Glasscoe, D. Green, D. R. Gurung, R. Heijenk, A. Hilborn, K. Hudnut, C. Huyck, W. W. Immerzeel, Jiang Liming, R. Jibson, A. Kääb, N. R. Khanal, D. Kirschbaum, P. D. A. Kraaijenbrink, D. Lamsal, Liu Shiyin, Lv Mingyang, D. McKinney, N. K. Nahirnick, Nan Zhuotong, S. Ojha, J. Olsenholler, T.H. Painter, M. Pleasants, K. C. Pratima, Q. I. Yuan, B. H. Raup, D. Regmi, D. R. Rounce, A. Sakai, Shangguan Donghui, J. M. Shea, A. B. Shrestha, A. Shukla, D. Stumm, M. van der Kooij, K. Voss, Wang Xin, B. Weihs, D. Wolfe, Wu Lizong, Yao Xiaojun, M. R. Yoder, N. Young

**INTRODUCTION:** On 25 April 2015, the Gorkha earthquake [magnitude ( $M$ ) 7.8] struck Nepal, followed by five aftershocks of  $\geq M$  6.0 until 10 June 2015. The earthquakes killed ~9000 people and severely damaged a 550 by 200 km region in Nepal and neighboring countries. Some mountain villages were completely destroyed, and the remote locations, blocked roads, and landslide-dammed rivers prevented ground access to many areas.

**RATIONALE:** Our "Volunteer Group" of scientists from nine nations, motivated by humanitarian needs, focused on satellite-based

systematic mapping and analysis of earthquake-induced geohazards. We provided information to relief and recovery officials as emergency operations were occurring, while supported by one of the largest-ever NASA-led campaigns of responsive satellite data acquisitions over a vast disaster zone. Our analysis of geohazards distribution allowed evaluation of geomorphic, tectonic, and lithologic controls on earthquake-induced landsliding, process mechanisms, and hazard process chains, particularly where they affected local populations.



**Landslide distribution and effects of a huge landslide.** (A) Landslides (purple dots) are concentrated mostly north of the tectonic hinge-line. Also shown are the epicenters of the main shock and largest aftershock. Displacements are from the JAXA ALOS-2 ScanSAR interferogram (21 Feb and 2 May 2015 acquisitions). (B and C) Before-and-after photographs obtained by D. Breashears in Langtang Valley showing complete destruction of a large part of Langtang village by a huge landslide.

**RESULTS:** We mapped 4312 coseismic and postseismic landslides. Their distribution shows positive associations with slope and shaking intensity. The highest areal densities of landslides are developed on the down-dropped northern tectonic block, which is likely explained by momentary reduction of the normal stress along planes of weakness during downward acceleration. The two largest shocks bracket the high-density landslide distribution, the largest magnitudes of the surface displacement field, and highest peak ground accelerations (PGAs). Landslides are heavily concentrated where PGA was  $>0.6g$  and slope is  $>30^\circ$ . Additional controls on

## ON OUR WEB SITE

Read the full article at <http://dx.doi.org/10.1126/science.aac8353>

landslide occurrence are indicated by their clustering near earthquake epicenters and within specific lithologic units. The product of PGA and the sine of surface slope (defined

as the landslide susceptibility index) is a good indicator of where most landslides occurred. A tail of the statistical distributions of landslides extends to low values of the landslide susceptibility index. Slight earthquake shaking affected vulnerable materials hanging on steep slopes—such as ice, snow, and glacial debris—and moderate to strong shaking affected poorly consolidated sediments deposited in low-sloping river valleys, which were already poised near a failure threshold. In the remote Langtang Valley, some of the most concentrated destruction and losses of life outside the Kathmandu Valley were directly due to earthquake-induced landslides and air blasts. Complex seismic wave interactions and wave focusing may have caused ridgetop shattering and landslides near Langtang but reduced direct shaking damage on valley floors and at glacial lakes.

**CONCLUSION:** The Gorkha earthquake took a tremendous, tragic toll on human lives and culture. However, fortunately no damaging earthquake-caused glacier lake outburst floods were observed by our satellite analysis. The total number of landslides was far fewer than those generated by comparable earthquakes elsewhere, probably because of a lack of surface ruptures, the concentration of deformation along the sub-surface thrust fault at 10 to 15 km depth, and the regional dominance of competent high-grade metamorphic and intrusive igneous rock types. ■

The list of author affiliations is available in the full article online.

\*These authors contributed equally to this work.

†Corresponding author. E-mail: kargel@hwr.arizona.edu (J.S.K.); dshugar@uw.edu (D.H.S.); uharitashya@uayton.edu (U.K.H.)

Cite this article as J. S. Kargel *et al.*, *Science* **351**, aac8353 (2016). DOI: 10.1126/science.aac8353

## RESEARCH ARTICLE

## GEOMORPHOLOGY

# Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake

J. S. Kargel,<sup>1\*†</sup> G. J. Leonard,<sup>1\*</sup> D. H. Shugar,<sup>2\*†</sup> U. K. Haritashya,<sup>3\*†</sup> A. Bevington,<sup>4</sup> E. J. Fielding,<sup>5</sup> K. Fujita,<sup>6</sup> M. Geertsema,<sup>4</sup> E. S. Miles,<sup>7</sup> J. Steiner,<sup>8</sup> E. Anderson,<sup>9</sup> S. Bajracharya,<sup>10</sup> G. W. Bawden,<sup>11</sup> D. F. Breashears,<sup>12</sup> A. Byers,<sup>13</sup> B. Collins,<sup>14</sup> M. R. Dhital,<sup>15</sup> A. Donnellan,<sup>5</sup> T. L. Evans,<sup>16</sup> M. L. Geai,<sup>17</sup> M. T. Glasscoe,<sup>5</sup> D. Green,<sup>11</sup> D. R. Gurung,<sup>10</sup> R. Heijenk,<sup>4</sup> A. Hilborn,<sup>16</sup> K. Hudnut,<sup>18</sup> C. Huyck,<sup>19</sup> W. W. Immerzeel,<sup>20</sup> Jiang Liming,<sup>21</sup> R. Jibson,<sup>22</sup> A. Kääb,<sup>23</sup> N. R. Khanal,<sup>10</sup> D. Kirschbaum,<sup>24</sup> P. D. A. Kraaijenbrink,<sup>20</sup> D. Lamsal,<sup>5</sup> Liu Shiyin,<sup>25</sup> Lv Mingyang,<sup>26</sup> D. McKinney,<sup>27</sup> N. K. Nahirnick,<sup>16</sup> Nan Zhuotong,<sup>28</sup> S. Ojha,<sup>5</sup> J. Olsenholler,<sup>29</sup> T. H. Painter,<sup>5</sup> M. Pleasants,<sup>3</sup> K. C. Pratima,<sup>30</sup> Q. I. Yuan,<sup>25</sup> B. H. Raup,<sup>31</sup> D. Regmi,<sup>32</sup> D. R. Rounce,<sup>33</sup> A. Sakai,<sup>6</sup> Shanguan Donghui,<sup>25</sup> J. M. Shea,<sup>10</sup> A. B. Shrestha,<sup>10</sup> A. Shukla,<sup>34</sup> D. Stumm,<sup>10</sup> M. van der Kooij,<sup>35</sup> K. Voss,<sup>36</sup> Wang Xin,<sup>37</sup> B. Weihs,<sup>38</sup> D. Wolfe,<sup>39</sup> Wu Lizong,<sup>26</sup> Yao Xiaojun,<sup>40</sup> M. R. Yoder,<sup>41</sup> N. Young<sup>42</sup>

The Gorkha earthquake (magnitude 7.8) on 25 April 2015 and later aftershocks struck South Asia, killing ~9000 people and damaging a large region. Supported by a large campaign of responsive satellite data acquisitions over the earthquake disaster zone, our team undertook a satellite image survey of the earthquakes' induced geohazards in Nepal and China and an assessment of the geomorphic, tectonic, and lithologic controls on quake-induced landslides. Timely analysis and communication aided response and recovery and informed decision-makers. We mapped 4312 coseismic and postseismic landslides. We also surveyed 491 glacier lakes for earthquake damage but found only nine landslide-impacted lakes and no visible satellite evidence of outbursts. Landslide densities correlate with slope, peak ground acceleration, surface downdrop, and specific metamorphic lithologies and large plutonic intrusions.

On 25 April 2015 and over the next several weeks, a major series of displacements occurred ~15 km deep along the buried Main Himalayan Thrust without breaking the surface (1–3). The main shock of the Gorkha earthquake [magnitude (*M*) 7.8, U.S. Geological Survey (USGS); epicenter 28.147°N, 84.708°E] was followed by ~257 aftershocks of *M* 3.0, including five *M* 6.0 between 25 April and 10 June 2015. On 12 May, a *M* 7.3 aftershock struck ~150 km ENE of the main shock. The largest earthquakes caused a wide swath of casualties and destruction in Nepal and adjacent India, China, and Bangladesh. Some mountain villages were shaken to complete destruction (4), buried by avalanches and landslides, or destroyed by powerful avalanche and landslide air blasts. The remote locations and blocked roads and rivers meant that ground crews could not immediately access many Himalayan valleys.

We adopted a satellite-based approach to examine the vast damaged region. Satellite imagery was provided by NASA, DigitalGlobe, the Japan Aerospace Exploration Agency (JAXA), MacDonald Dettwiler and Associates (MDA), Planet Labs, Spot Image, and the China National Space Administration, including imagery triggered by the Interna-

tional Charter: Space and Major Disasters ([www.disasterscharter.org](http://www.disasterscharter.org)). A “Volunteer Group” of analysts from nine nations was organized by the University of Arizona under the auspices of Global Land Ice Measurements from Space (GLIMS) (5) initially to assess priority hazard situations and then to build a landslide inventory (6). The group contributed their input of mapped geohazards to a broad ad hoc NASA-led interagency “Response Team.” We scrutinized optical imagery, ranging from 15 to <1 m resolution, from Landsats 7 and 8; the Advanced Spaceborne and Thermal Emission and Reflection Radiometer (ASTER) onboard Terra; Advanced Land Imager on EO-1; WorldView-1, -2, and -3; GeoEye-1; Pleiades; and Gaofen-1 (table S1) and used radar data from ALOS-2 and RADARSAT-2 and topography from the Shuttle Radar Topography Mission (SRTM). Landslides not detectable at these scales would generally have lesser human consequences than would larger landslides.

The Response Team, including the Volunteer Group, undertook one of the broadest and fastest international emergency remote sensing and data analysis campaigns ever led by NASA for any earthquake-affected region (7–9). Parallel, but independent, landslide-mapping efforts have been

undertaken by a joint British Geological Survey–Durham University group (10) and other groups.

During previous earthquake emergencies in mountainous terrain (such as Wenchuan, China and Denali, Alaska), landslides were numerous (9, 11–17), sometimes initiating a process chain of secondary and tertiary geomorphic processes over time spans ranging from minutes to years after the earthquake (18, 19). Landslide-initiated process chains may involve gains in mobilized mass and destructive power through energy and mass transfer cascades. Many documented or inferred examples exist, including rock/ice fall-generated debris avalanches that transformed into debris flows (20, 21) or caused large impoundment lakes and upstream flooding (22), landslide-generated displacement waves and glacier lake

<sup>1</sup>Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ, USA. <sup>2</sup>School of Interdisciplinary Arts and Sciences, University of Washington Tacoma, Tacoma, WA, USA. <sup>3</sup>Department of Geology, University of Dayton, Dayton, OH, USA. <sup>4</sup>Ministry of Forests, Lands and Natural Resource Operations, Prince George, BC, Canada. <sup>5</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA. <sup>6</sup>Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan. <sup>7</sup>Scott Polar Research Institute, University of Cambridge, Cambridge, UK. <sup>8</sup>Institute of Environmental Engineering, Federal Institute of Technology–ETH, Zurich, Switzerland. <sup>9</sup>NASA Marshall Space Flight Center, Huntsville, AL, USA. <sup>10</sup>International Centre for Integrated Mountain Development, Kathmandu, Nepal. <sup>11</sup>NASA Headquarters, Washington, DC, USA. <sup>12</sup>GlacierWorks, Marblehead, MA, USA. <sup>13</sup>The Mountain Institute, Elkins, WV, USA. <sup>14</sup>U.S. Geological Survey, Menlo Park, CA, USA. <sup>15</sup>Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal. <sup>16</sup>Department of Geography, University of Victoria, Victoria, BC, Canada. <sup>17</sup>CVA Engineering, Suresnes, France. <sup>18</sup>Earthquake Science Center, U.S. Geological Survey, Pasadena, CA, USA. <sup>19</sup>ImageCat, Long Beach, CA, USA. <sup>20</sup>Faculty of Geosciences, Utrecht University, Utrecht, Netherlands. <sup>21</sup>State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan, Hubei Province, China. <sup>22</sup>U.S. Geological Survey, Golden, CO, USA. <sup>23</sup>Department of Geosciences, University of Oslo, Blindern, Oslo, Norway. <sup>24</sup>Hydrological Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA. <sup>25</sup>Cold and Arid Regions of Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China. <sup>26</sup>School of Earth Sciences and Engineering, Nanjing University, Nanjing, China. <sup>27</sup>Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin, Austin, TX, USA. <sup>28</sup>School of Geography Science, Nanjing Normal University, Nanjing, China. <sup>29</sup>Department of Geography, Texas A&M University, College Station, TX, USA. <sup>30</sup>Arizona Remote Sensing Center, School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, USA. <sup>31</sup>National Snow and Ice Data Center, University of Colorado, Boulder, CO, USA. <sup>32</sup>Himalayan Research Center, Kathmandu, Nepal. <sup>33</sup>Environmental and Water Resources Engineering, University of Texas at Austin, Austin, TX, USA. <sup>34</sup>Wadia Institute of Himalayan Geology, Dehradun, India. <sup>35</sup>MacDonald Dettwiler and Associates–GSI, Ottawa, Ontario, Canada. <sup>36</sup>Department of Geography, University of California, Santa Barbara, Santa Barbara, CA, USA. <sup>37</sup>College of Architecture and Urban Planning, Hunan University of Science and Technology, Xiangtan, China. <sup>38</sup>Geography Department, Kansas State University, Manhattan, KS, USA. <sup>39</sup>Global Land Ice Measurements from Space (GLIMS) Steward, Alaska Region, Anchorage, AK, USA. <sup>40</sup>College of Geographical Science and Environment, Northwest Normal University, China. <sup>41</sup>Department of Physics, University of California, Davis, CA, USA. <sup>42</sup>Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania, Hobart, TAS, Australia. \*These authors contributed equally to this work. †Corresponding author. E-mail: [kargel@hwr.arizona.edu](mailto:kargel@hwr.arizona.edu) (J.S.K.); [dshugar@uw.edu](mailto:dshugar@uw.edu) (D.H.S.); [uharitashya@udayton.edu](mailto:uharitashya@udayton.edu) (U.K.H.)

outburst floods (GLOFs) (23, 24), and landslide-dammed lake outbursts (25, 26). As debris, ice, and lake and stream water are ingested into an outburst flood, a debris flow or hyper-concentrated slurry flood may result (21). Each geomorphic process in the chain may trigger a subsequent geohazard and extend the damaging reach of the event (27, 28). Process chains involving GLOFs are particularly worrisome.

The Volunteer Group's work focused on systematic mapping of quake-induced geohazards, understanding the geomorphic, lithologic, and tectonic control of their distribution and the identification of communities and infrastructure that might be affected. We analyzed the distribution and character of the geohazards induced by the Gorkha earthquake in Nepal and Tibet using mainly satellite-based findings, supplemented with media reports, eyewitness photography, helicopter-borne field assessments, and modeling of lake outburst flood processes. This paper considers earthquake-related landslides formed before 10 June 2015, when the monsoon arrived in eastern Nepal.

### Landslide mapping and assessment

We mapped the distribution of 4312 earthquake-induced (coseismic and postseismic) landslides

(Fig. 1). We identified six Areas of Interest (AOIs) that include Annapurna, Manaslu, Ganesh Himal, Langtang, Cho Oyu, and Everest (fig. S1) from west to east. The AOIs together cover 375 by 155 km, with divisions set along major valleys. Each AOI team had remote sensing and landslide expertise and was assigned an experienced lead analyst.

Multispectral satellite images from many government and commercial sensors (table S1) were made available through a number of portals, including the DigitalGlobe website, the USGS Hazards Data Distribution System (HDDS), and USGS Global Visualization Viewer (GLOVIS). Additionally, NASA provided access to expedited post-earthquake targeted ASTER imagery within the affected region. Not all locations were surveyed repetitively. We compiled a database and detailed descriptions of each AOI (29).

The highest densities of earthquake-related landslides are distributed in a broad swath between the two largest shocks, where many aftershocks also occurred. Clusters of landslides also exist outside of this zone (Fig. 1). The high landslide densities also lie between three  $>M$  7.0 earthquakes that occurred on 26 August 1833, 25 April 2015, and 12 May 2015, thus highlighting the possible long-term effects of historic quakes.

However, we assessed the landslide occurrences only within the context of the Gorkha earthquake and aftershocks and the terrain characteristics, broadly organized according to (i) surface slopes and the earthquakes' seismic peak ground accelerations (PGAs), (ii) broad-field deformation due to the earthquakes, and (iii) the distribution of underlying landcover, lithology, and tectonic structure.

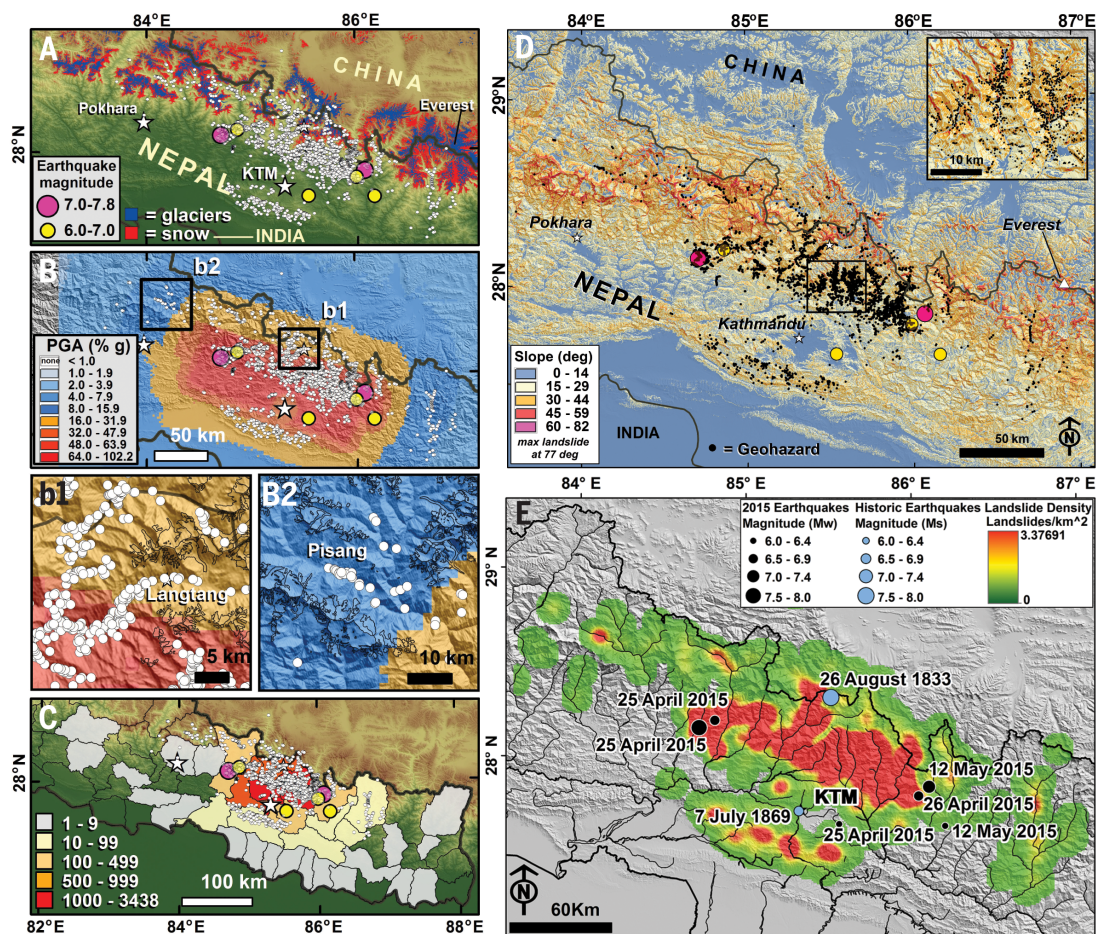
Among the shaking parameters, PGA is just one factor that may control whether landslides occur in response to an earthquake. The specific frequency content, shake duration, PGA direction, and recurrent shocks also may be important (30). Furthermore, the landslides caused by the Gorkha earthquake and aftershocks appear to be far fewer than expected when compared with those of other mountainous regions with similar-magnitude earthquakes (31, 32). This might be due to the lack of surface ruptures induced by the earthquakes and the concentration of deformation along the subsurface thrust fault at 10 to 15 km depth (2).

### Landslide distribution Control by shaking and slope

The locations of the Gorkha earthquake-induced landslides are plotted with landscape physiography and the epicenters of the six largest shocks

**Fig. 1. Location of 4312 earthquake-related geohazards.**

(A) Distribution of glaciers (blue), late-season snowfields (red), landslides (white dots), and main shock and largest aftershock epicenters. The base topography is from the SRTM 90-m gap-filled digital elevation model (33). Glacier extents are from the Randolph Glacier Inventory (RGI) (61). Snowfields were derived from pre-event Landsat-8 visible and near-infrared (VNIR) to short-wave infrared (SWIR) band ratios and topographic masks. (B) (Top) Landslides plotted with local peak ground accelerations induced by the main Gorkha shock or  $M > 6$  aftershocks. PGAs are from the USGS–National Earthquake Information Center ShakeMap (62). (Bottom) Boxes b1 and b2 are enlarged to show details near Langtang and Pisang. (C) Landslides plotted with reported deaths per Nepal district are from the Government of Nepal, Nepal Disaster Risk Reduction Project. (D) Hazard occurrences (black dots) on calculated slopes. (Inset) Detail of hazard-dense region. (E) Smoothed area density (log scale) of earthquake-induced landslides determined by using a neighborhood  $1/8^\circ$  by  $1/8^\circ$  search window ( $\sim 14$  by  $12$  km) in relation to major ( $M \geq 6$ ) epicenters of historic earthquakes and the Gorkha quakes (62). Densities range between 0.01 and 3.37 landslides/km<sup>2</sup>. Higher landslide densities occur locally on scales finer than  $1/8^\circ$ .



(Fig. 1A), PGA (Fig. 1B), reported deaths (Fig. 1C), and slope (Fig. 1D). We also mapped the smoothed landslide density distribution (Fig. 1E) and computed and mapped the susceptibilities of the landscape to earthquake-induced mass movements of ice, snow, or rock (Fig. 2). The computed susceptibilities depend on the product of the sine of slope (33) and the PGA (from the USGS ShakeMap PGA) (Fig. 1B).

Integration of slope and shaking (represented by PGA) within the susceptibility index partly accounts for where landslides occurred (Fig. 2), especially where collapse of high-elevation snow and ice may have been involved (Fig. 2, B and C). The landslide distribution shows the strongest associations with slopes of  $>30^\circ$  (Fig. 1C and fig. S2A), PGA of  $>0.32g$  (Fig. 2A and fig. S2B), and shake-induced landslide susceptibility index of  $>0.16g$  (Fig. 2A). We infer that many of these landslides probably would not have occurred anytime soon without earthquake shaking. The control of landslide occurrences by the steep Himalayan slopes and seismic shaking is unsurprising and similar to other well-documented earthquakes (34). However, landslide susceptibilities differ from quake to quake. These new results detail the relationships of this Himalayan earthquake to seismic and geologic/terrain parameters. As PGA attains several tenths of  $g$ , entire mountainsides can collapse as shake-induced coseismic failures are not restricted to materials and terrains that were already poised near failure. Whereas landsliding on steep, strongly shaken slopes is easily understood, the tail of the landslide distribution to low shaking values, to low slopes, and low (but nonzero) shaking-induced landslide susceptibilities (fig. S2) requires further explanation.

Under any of the following conditions, low seismic PGAs at a few percent of  $g$  may cause failures that lead to a landslide or avalanche if the materials are already near failure.

(i) Granular materials may accumulate near the angle of repose, making them susceptible to coseismic failure owing to an acceleration that would increase shear stress along incipient planes of failure or related to rapid coseismic vibration-induced creep (35).

(ii) Seismic vibrations may cause liquefaction of water-saturated sediment, disturbances to the local hydrology, and coseismic or postseismic flow or rotational slumping (36).

(iii) At the beds of polythermal glaciers, the frictional resisting force may be carried by small frozen domains (37). Sharp accelerations may fracture the bed's frozen attachments, suddenly reducing the frictional force and initiating sliding.

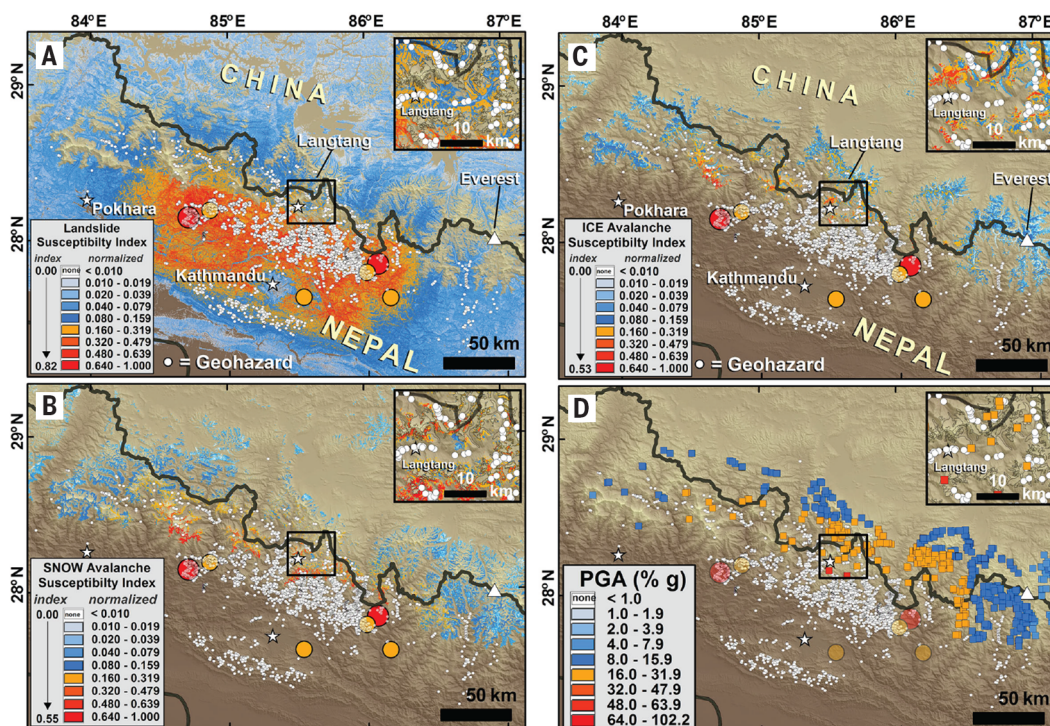
(iv) Motion of rock or ice on fracture planes is resisted by the frictional force at the slip plane (38). Reduction in the normal stress because of downward acceleration, or increase in the down-slope driving shear stress because of slip-plane parallel acceleration, may initiate coseismically triggered slip on steeply sloping slip planes.

(v) Upward acceleration increases the normal stress and may induce transient pressure melting of basal polythermal ice, reducing the frictional force. The subsequent downward seismic acceleration suddenly relieves the normal stress, so that newly produced basal meltwater (which might not refreeze) may initiate sliding (39).

The mechanisms outlined above may produce landslides or avalanches at low but nonzero shaking in granular materials occurring on steep slopes, in water-saturated sediments, and on steeply sloping glaciers. The deadly Mount Everest ice/

snow avalanches on 25 April 2015 exemplify this point, where shaking was a low  $0.09g$  (table S3). Glacier ice and snow are commonly poised near failure as indicated by Everest's history of ice avalanches off steep slopes, including back-to-back years in which there were a record 16 avalanche deaths in April 2014 (triggered by spring melting) and a new record 22 deaths in April 2015 (earthquake-triggered). Many Himalayan glaciers are substantially avalanche-fed, and snow or ice avalanches may occur upon a slight prompt, whether because of heavy winter or monsoon snowfall, spring melting, or slight shaking. The Gorkha earthquake struck soon after another season of spring melting began, increasing the vulnerability to shaking of ice and snow in the Everest area. Landslides in the upper Marsyangdi Valley (described below) also experienced relatively weak shaking ( $0.11$  to  $0.13g$ ) but involved unconsolidated fluvial gravels and lacustrine silts (40).

Seismic reactivation of preseismic landslides, or hydrological reactivation of earthquake-triggered landslides, may be common where landsliding already is present. Hydrological reactivations may be caused by precipitation runoff, spring discharge, or erosional undercutting of river banks. Image time series indicate that many mapped landslides, such as in the Marsyangdi Valley, happened after the main shock. In general, these might be attributable to a host of factors such as aftershocks, failure of earthquake-disturbed hanging glaciers or debuttressed slopes (41, 42), degradation of mountain permafrost and glacier-permafrost interactions (41), extreme precipitation, and stream undercutting of poorly consolidated sediment banks that were already disturbed by the earthquake. These mechanisms involve changes to the



**Fig. 2. Debris landslide susceptibility with mapped hazards.** (A) Susceptibility in units of acceleration divided by  $g$  ( $9.81 \text{ m s}^{-2}$ ). (B) Snow avalanche susceptibility with mapped hazards. Susceptibility is in  $g$ . (C) Ice avalanche susceptibility with mapped hazards. Susceptibility is in  $g$ . (D) Maximum PGA experienced by 491 glacier lakes. Mapped hazards are shown as white dots. Maximum PGA for glacier lakes was  $0.57g$ . (Insets) Detail in Langtang Valley.

supply of groundwater or rates of glacial erosion or ice melt, which have at least indirect links to climate change.

### Control by the broad-field seismic deformation

Another key earthquake phenomenon is the wide-field land surface deformation pattern, which appears to have influenced the distribution of landslides (Fig. 3). The mapped surface deformation was derived from Interferometric Synthetic Aperture Radar (InSAR) (Fig. 3A) (43). While the ALOS-2 InSAR measurement is in the radar line-of-sight, GPS measurements show that the horizontal motion is almost in the along-track direction, so the InSAR displacements in Fig. 3A are almost purely vertical (3). The highest densities of landslides are correlated with the down-dropped block, which is on the back-limb of the hanging wall of the thrust and counterintuitively correlates with the higher Himalaya. Within this block, landslide densities increase southward and then abruptly decrease near the tectonic hinge line, which separates the down-dropped and up-thrown blocks (and also approximates the zone of maximum slip on the fault). RADARSAT-2 data provide the horizontal displacement field over part of the earthquake-affected region and confirm that the largest horizontal displacements (Fig. 3B) are near the hinge line and in the up-lifted block, as defined by vertical deformation (Fig. 3A).

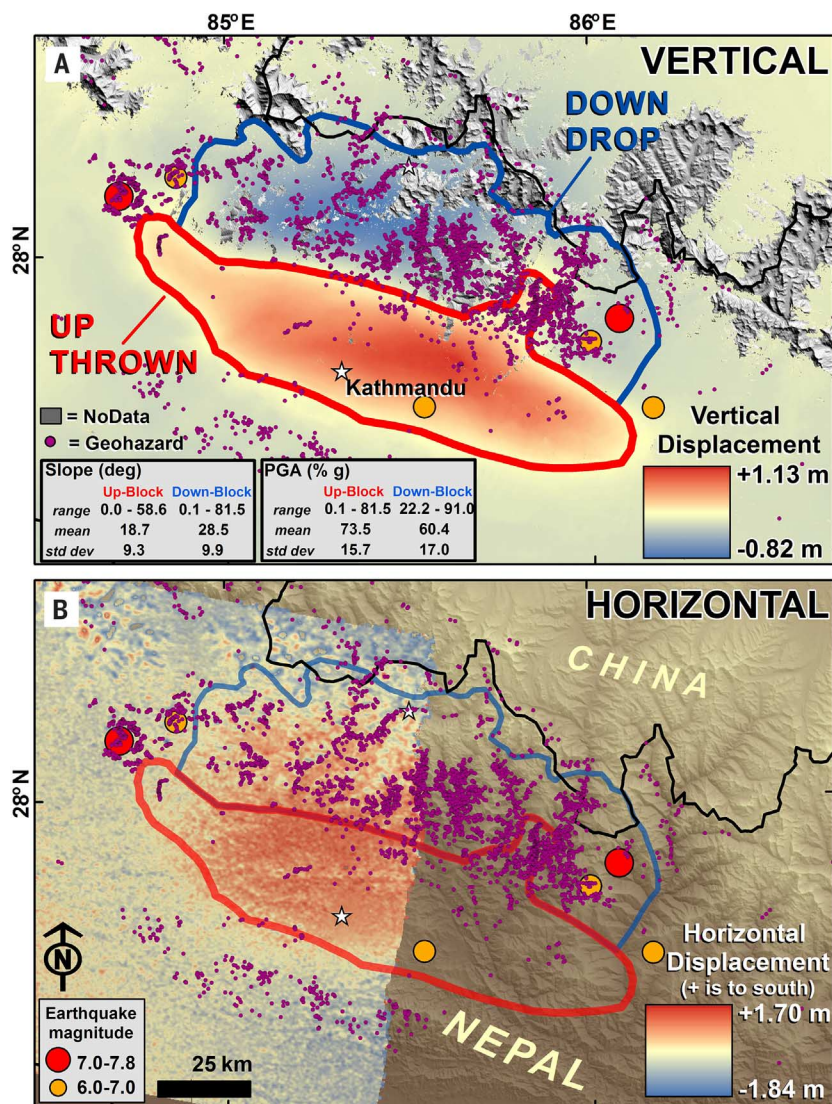
We do not fully understand the distinctive concentration of earthquake-induced landslides in the tectonic down-dropped block of the Gorkha earthquake. The steep slopes within the down-dropped block no doubt contributed to the pattern of landslide densities, but steep slopes are also present in some areas where landslides are few. The net downward acceleration implied by the dropdown possibly caused a momentary reduction in lithostatic stress, hence a reduction of normal stress along inclined planes of weakness. Relief of normal stress could have allowed non-lithostatic shear stress, including lateral seismic acceleration, to initiate motion along landslide failure planes. Because the coefficient of sliding friction is normally less than that of static friction, motion may then continue and drive a landslide. The same mechanism may apply to shaking, and hence, the broad-field deformation may modulate the shaking-induced perturbation of normal stress, again suggesting some integration of multiple causative trigger mechanisms.

The Gorkha earthquake caused fewer landslides than expected on the basis of its magnitude (12, 32), mirroring the unexpected paucity of dwelling destruction (2). The peculiar distribution of the Gorkha earthquake landslides on the down-dropped block (Fig. 3) placed them mainly north of the major population centers, reducing the death toll. For strike-slip events such as the 2010 *M* 7.0 Haiti earthquake (44), landslides were not similarly distributed systematically with respect to the fault plane. For comparison, landslides in the 1994 *M* 6.7 Northridge and 2008 *M* 7.9 Wenchuan earthquakes (11, 12, 45)

were concentrated on the higher mountainous areas of the upthrown block. Both earthquakes were oblique thrust events, like the Gorkha quake. The Wenchuan earthquake induced far more landslides than did the Gorkha earthquake, despite similar steep terrain. These differences might relate to the Gorkha quake's shallow dipping fault and lack of surface rupture (a blind thrust).

The Northridge earthquake was also a blind thrust, and despite being smaller than the Gorkha quake, it produced 11,000 documented landslides (45). Some, mapped by an airborne survey, were smaller than the detection limit in the imagery

used for our survey, in which Digital Globe data were unavailable. The numerous slides caused by the Northridge earthquake may be primarily attributed to uncemented clastic sedimentary compositions dominating the regional lithology, versus more competent high-grade metamorphic and igneous rocks dominating the higher Himalaya. The differing types and densities of vegetation and root binding might also be a factor. In general, differences in earthquake-induced landslide densities can also be related to the number and magnitude of strong high-frequency ground motions, although the paucity of strong-motion



**Fig. 3. Landslide distribution relative to the Earth surface deformation field.** (A) 4312 landslides (purple dots) are concentrated mostly north of the hinge line between the down-dropped block and up-lifted block. Also shown are the epicenters of the main shock and five largest aftershocks. Vertical displacements are from the JAXA ALOS-2 ScanSAR interferogram (21 Feb and 2 May 2015 scenes), which represent almost entirely vertical motion. ALOS-2 interferometry of the Gorkha earthquake and largest aftershock was recently described by Lindsey *et al.* (3). (B) Horizontal motion map based on azimuth shift measurements of the RADARSAT-2 XF acquisitions of 5 April and 29 April 2015. Scale shows motion excluding outliers outside the mean  $\pm 3\sigma$ . Values are positive for SSW azimuths  $>100$  degrees relative to east ( $>S10W$ ). Hence, both the upthrown and down-dropped blocks shifted southward. The areal coverage for the RADARSAT-2 scene is not identical to that of ALOS-2; areas on the eastern side of the scene have no data.

recordings in the cases of both the Gorkha and Wenchuan quakes hampers direct comparison.

### Control by lithology and major fault structure

The local clustering indicates additional controls on landslide occurrence. Lithologic variations, sediment thickness, bedding dip direction relative to slope aspect, extent of physical and chemical weathering including extent of bedrock fracturing, and vegetation cover may be important controlling factors. Lithology affects the occurrence of some landslides. For instance, the Langtang Valley slides involved the failure or ingestion of ice and unconsolidated glacial debris. Another example is the poorly consolidated sediment driving the Marsyangdi Valley landslides.

Fault structures exert indirect control of the clustering of landslides and organization of clusters (Fig. 4). High concentrations of landslides occur within particular Proterozoic metamorphic units and intrusive complexes and also near the surface of several major tectonic features, mainly low-angle thrust faults including the South Tibetan Detachment System (STDS), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT). The latter three

faults splay off the subsurface Main Himalayan Thrust, which is thought to have slipped during these earthquakes (1). However, because none of the Gorkha earthquake fault displacements (main shock or aftershocks) are known to have pierced the surface, the association with the thrust faults might indicate underlying lithological control, in which the faults juxtapose rocks of differing compositions at the surface. Lithologic properties influenced the topographic character of the landscape and how seismic energy is transmitted, particularly through (i) elastic and brittle/elastic properties of the rock, (ii) chemical weathering and its control of erosion and slope, (iii) fracture development and fault displacement, and (iv) seismic wave interactions with topography and lithological structures. Each factor likely contributes, where lithology is a common denominator. A high density of landslides occurs within the upper Lesser Himalaya near to and east from the epicenter of the primary earthquake. Whereas this cluster's proximity to the largest shock's epicenter is evident, the pattern defined by the cluster is closely correlated with the outcrop of the upper Lesser Himalaya, which is composed of low- to medium-grade metamorphosed Proterozoic argillite-calcareous (clay and sand) units and also

of higher-grade metamorphic Proterozoic rocks. The upper Lesser Himalaya here is bounded on the north by the Main Central Thrust, where the overthrust rocks are dominated by Precambrian gneisses, but only near the thrust contact do the latter underlie many landslides.

Many landslides occur south and west of Kathmandu (Fig. 4) near the southern edge of the Kathmandu Nappe [a thrust sheet of Precambrian/Lower Paleozoic metasedimentary rocks, as mapped by Stöcklin (46)]. In these areas, landslides are especially concentrated where Ordovician granitoids have intruded Proterozoic metasediments, suggesting lithological contrast as a controlling feature. Further, there is a notable absence of landslides south of the MBT-MCT south of Kathmandu.

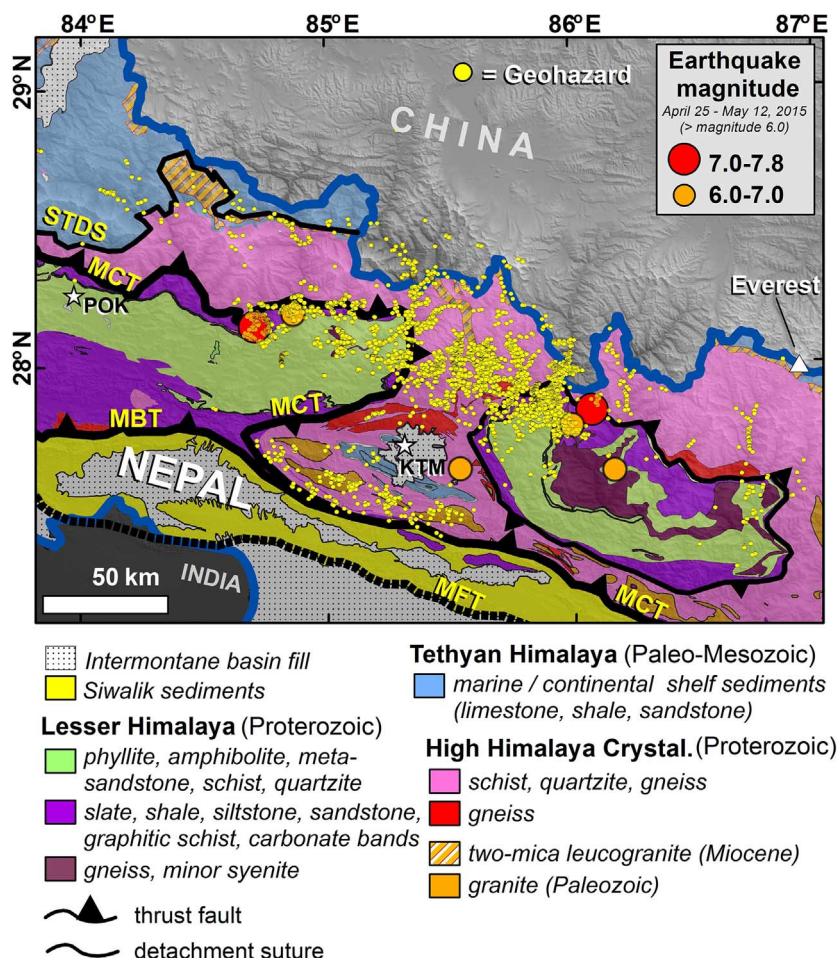
Proterozoic slate, shale, siltstone, sandstone, graphitic schist (Fig. 4, combined as purple) and gneiss (Fig. 4, red)—all layered rock types—host relatively few landslides. Instead, the vast majority of earthquake-triggered landslides occur in the Proterozoic phyllite, amphibolite, metasandstone, and schist rock sequences of the Lesser and High Himalaya (Fig. 4, green and pink) north of Kathmandu. These occur on either side of the MCT. The landslide hotspots (Fig. 1E) comprise a small fraction of the area of this widespread rock unit; steep-sided, high-elevation ridgetops generated some of the landslide hotspots. For example, the Langtang Valley landslides largely originated high on the ridges and near the summits in places where glaciers, glacial debris, and bedrock failed. The lithological controls may manifest through rock mechanics and rock weathering and slope.

Topographic effects, along with different rock types' contrasting *S*, *P*, and surface waves affect landsliding through wave scattering, interference, and heterogeneous energy dissipation. During helicopter overflights, authors B. Collins and R. Jibson (47) observed pervasive ridgetop shattering through much of the near-epicentral landsliding region. Constructive wave interference and the focusing of seismic energy to shatter ridgetops was observed in the Northridge (48) and 1971 San Fernando (49) earthquakes and modeled for the 2005 I-Lan earthquake in Taiwan (50). Last, damage related to wave resonance occurred in the Kathmandu Basin during the Gorkha earthquake (2), and similar resonant effects may have occurred elsewhere at damaging frequencies affected by the spatial scales and geometry of various lithologic units. Human-built structures of different sizes and construction, having distinctive resonant vibrational frequencies, were selectively destroyed (2).

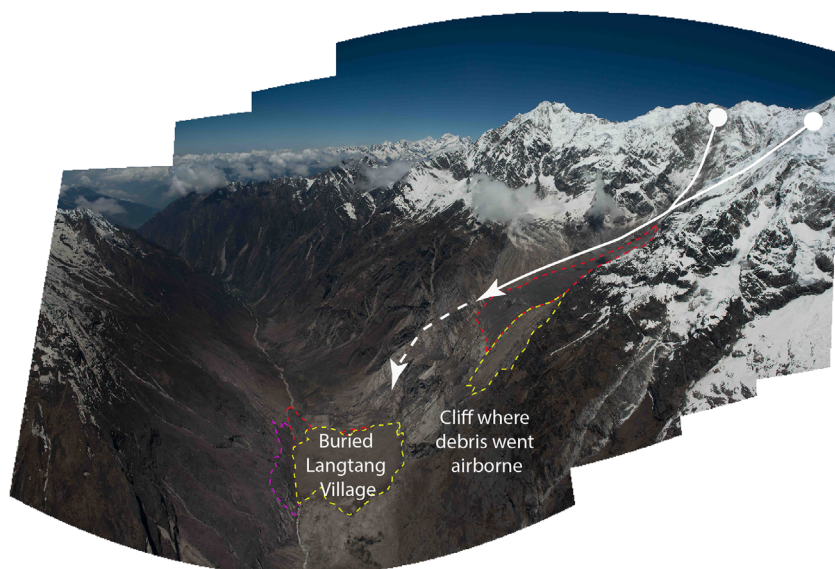
Some major river valleys also have high landslide densities, including along the Marsyangdi and Trishuli rivers. In the Marsyangdi Valley, a high landslide density correlates with relatively gently sloping areas of the valley floor that are covered by poorly consolidated sedimentary deposits.

### Langtang mass movements

The earthquake-induced landslides of the Langtang Valley (Fig. 5 and figs. S3 to S6) were exceptional



**Fig. 4. Landslide occurrence on mapped geologic units.** Geology is from simplified geologic map by (46, 63) and major faults (64).



**Fig. 5. Langtang's landslide flowpaths.** The source areas and flow paths of the two Langtang mass movements (white arrow, dashed where airborne). The red dashed line indicates the extent of the first slide, the yellow dashed line indicates extent of second slide, and the purple dashed line indicates extent of debris run-up. The image is west-facing. [Stitched panorama from 10 May 2015; photos by D. F. Breashears/GlacierWorks]

in their tragic results (more than 350 people killed) and are also among the Gorkha earthquake's best-documented landslides from field- and space-based analysis. Langtang Valley, 70 km north of Kathmandu, is one of Nepal's major trekking regions and hosts benchmark glaciology, hydrology, and meteorology research (51–53). The valley experienced moderate shaking (up to  $\sim 0.26g$  above Langtang village) (Fig. 1B). An analysis of post-event satellite imagery and oblique aerial photographs suggests that coseismic snow and ice avalanches and rockfalls and their powerful concurrent air blasts contributed to the destruction in Langtang Valley (Fig. 5 and figs. S3 to S6) that killed or left missing at least 350 people (54). Panoramic photos of Langtang taken in 2012 and those taken after the earthquake on 12 May 2015 illustrate the magnitude and destruction of the Langtang events (figs. S3 and S4). Further indicating the vast scale of these events, annotated helicopter-borne photos and satellite imagery taken of the valley (Fig. 5 and figs. S5 and S6) illustrate our interpretation of this disaster-within-a-disaster.

Debris from the initial coseismic event covered  $7.51 \times 10^5 \text{ m}^2$  at Langtang alone, including a  $\sim 1\text{-km}$  stretch of the Langtang River. We did not observe stream impoundment in the days after the earthquake, indicating that meltwater and runoff tunneled rapidly through the icy deposit. Photos (D. Breashears) showed that the deposit contained abundant snow and ice. Brightness temperatures modeled from thermal band 10 of Landsat 8 on 30 April 2015 showed lower landslide surface temperatures (270 to 280 K) as compared with those of surrounding terrain (280 to 300 K). The temperature anomalies, pond formation, and moisture of debris resulted from melting.

The primary coseismic event at Langtang village was a combined ice-snow avalanche that initiated near 7000 m. Subsequently, ice and snow entrained rockfall material and descended a low-gradient part of the glacier down to  $\sim 4500 \text{ m}$ . The rock-ice mass then became airborne as it fell off a cliff below 4500 m (Fig. 5). After the material reached the riverbed at  $\sim 3250 \text{ m}$ , it ran up the opposing slope  $\sim 200 \text{ m}$  (fig. S5). The air blasts propagated farther, 400 m up the mountain (fig. S3). From the impact point on the valley floor, devastation extended  $\sim 1 \text{ km}$  up- and downvalley. From the 200-m-high surge of debris on the opposing slope, we estimate a debris speed ( $v$ ) of  $63 \text{ m s}^{-1}$  ( $227 \text{ km h}^{-1}$ ) following Eq. 1

$$v = (2gh)^{0.5} \quad (1)$$

where  $g$  is gravitational acceleration ( $9.8 \text{ m s}^{-2}$ ) and  $h$  is the runup. Air blasts leveled what was not buried in Langtang, including some buildings constructed of stone slab. Wind also completely flattened a small forest, suggesting wind speeds comparable with an EF5 tornado ( $>322 \text{ km hour}^{-1}$  wind speed), which is consistent with freefall drop of the landslide and heavily debris-laden wind over the cliff.

Satellite images provided by Digital Globe (fig. S6) indicate a second large post-main shock mass movement near Langtang village between 8 and 10 May 2015. The source of this landslide may have been a rock detachment from the summit ridge of Langtang-Lirung,  $\sim 6700 \text{ m}$  elevation. The second landslide slightly increased the debris area from  $7.51 \times 10^5$  to  $7.61 \times 10^5 \text{ m}^2$ .

Nearby settlements of Singdum and Mundu (fig. S6) were also damaged by air blasts from the Langtang Valley mass movements. The larger settlement of Kyangjin was also badly damaged by

an air blast created by another avalanche that originated from the eastern ridge of Langtang-Lirung. Devastation in the air-blasted zones, as captured in several photos (fig. S3), is indicative of the huge energy involved. The first Langtang landslide mass may be  $\sim 3.3 \times 10^9 \text{ kg}$  (area  $\sim 750,000 \text{ m}^2$ , assumed mean thickness  $\geq 2 \text{ m}$ , density  $2200 \text{ kg m}^{-3}$ ). With a direct fall of  $\sim 1 \text{ km}$ , the release of gravitational potential energy was  $\geq 3.2 \times 10^{13} \text{ J}$  (7.6-kiloton TNT equivalent). During freefall and impact, the main transfer of energy could only have been to the atmosphere and directly on the surface, the effects of which we sadly observed.

### Landslide blockages of rivers: Marsyangdi and Tom rivers (Nepal) and Gyirong Zangbo/Trishuli River (Tibet)

We identified recurrent landslides along the upper Marsyangdi River in the Annapurna region. These are a different type of landslide than those in Langtang Valley. At least 20 mass movements intersected the river in the 10 days after the main shock (Fig. 6). The rapid sequence of similar failures demonstrates that the quakes in some way disturbed the unconsolidated sediments (40) along the river; perhaps by altering the hydrology or opening soft-sediment fractures, which then were exploited by spring seepage and erosion and rotational failures.

The Marsyangdi Valley experienced relatively weak shaking (to  $\sim 0.13g$ ) (Fig. 1B and table S3), which triggered nine small landslides along a 16-km stretch of the upper Marsyangdi River between Humde and Bratang (Fig. 6). The landslides were identified from a WorldView-2 satellite image 27 April 2015, 2 days after the earthquake, but were not present in a Landsat 8 image 4 days prequake. Thus, we considered them primary effects of the main shock. Some slumps constricted but did not greatly obstruct the river. One landslide (Fig. 6),  $\sim 2.2 \text{ km}$  upstream of Lower Pisang village, caused a small impoundment (135 m long,  $\sim 2 \times 10^3 \text{ m}^2$ ).

Five more landslides reached the river between 27 April and 2 May 2015, including one  $\sim 200 \text{ m}$  wide, which caused a complete blockage  $\sim 1.9 \text{ km}$  upstream of Lower Pisang. The impoundment grew to  $\sim 550 \text{ m}$  long and 30 to 40 m wide ( $\sim 1.4 \times 10^4 \text{ m}^2$ ) (Fig. 6). Six new landslides occurred by 4 May, and the lake increased to  $\sim 2.5 \times 10^4 \text{ m}^2$  and 1100 m long, the same as measured again on 28 May 2015. Upstream, several smaller impoundments indicated a further hazardous situation in which a dam breach could initiate a succession of lower dam breaches and the inundation of Lower Pisang village.

Ground photographs (Fig. 6B) show a predominantly fine-grained landslide (47), likely composed of fluvial and lacustrine sediments from former dammed lakes (40). The steep headwall, back-tilted trees, and a sharp detachment at the head of the landslide indicate that the slide is a rotational slump, a common failure mode in poorly supported, unconsolidated sediments.

The appearance of eleven post-main shock landslides and growth of the impoundment lake represent secondary and tertiary effects of the earthquake and indicate that the region is susceptible to long-term slope instability and future landslides.

We observed many other earthquake-induced landslide blockages of rivers. In one case, a 450-m-wide landslide blocked the lower Tom River near Ghap, Manaslu Conservation Area, Nepal, creating an impoundment lake that stirred urgent humanitarian concerns. Satellite imagery from 3, 5, 7, and 8 May has allowed monitoring of the dammed lake. Between 3 and 8 May, the lake grew from  $\sim 5.7 \times 10^4$  to  $\sim 6.6 \times 10^4$  m<sup>2</sup>. The nearby village of Ghap, located downstream of the confluence of the Tom and Budhi Gandaki rivers, fortunately showed no flood damage by 16 May, indicating that even though the lake was draining through a narrow outlet, the dam erosion was gradual. A satellite image from 8 June and subsequent media coverage shows that most of the lake had drained without severe consequences.

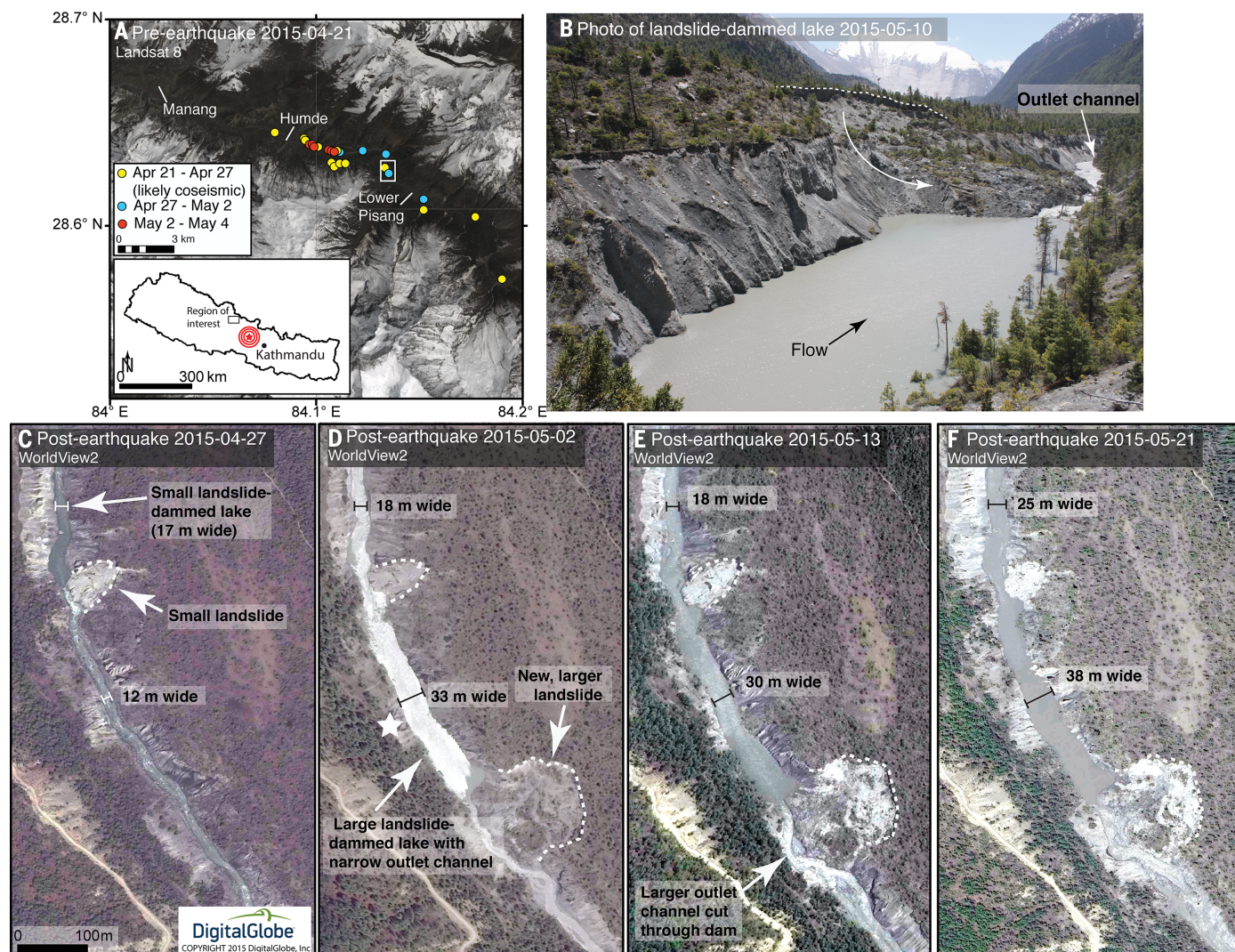
The Gorkha earthquake and its many aftershocks also triggered dozens of landslides into the south-flowing Gyirong River, China (Trishuli

River downstream in Nepal). One landslide dammed the river  $\sim 1.5$  km south of Chongsecun, a few kilometers north of the Nepalese border, causing development of a 450 by 50 m impoundment lake (28.363N, 85.360E,  $\sim 2600$  m above sea level). The landslide destroyed  $\sim 200$  m of the road connecting Chongsecun to the China-Nepal border crossing at Resuo. Boulders and debris were displaced downslope, forming a landslide scar  $\sim 700$  m long and a deposit 250 by 300 m. Several landslides and a landslide-dammed lake also developed south of the Chongsecun slide at or near the Resuo border crossing in Nepal (28.275N, 85.379E,  $\sim 1,810$  m above sea level) and blocked the road near the Resuo bridge. Fortunately, the dam was incised by the river, and with mitigation efforts by engineers, there was no further damage. Another landslide on the same river near Resuo was triggered by a rainstorm on 28 April 2015, with the terrain conditioned by the  $M$  7.8 Gorkha

earthquake. The landslide dammed the Trishuli River and blocked the road from Gyirong County to Resuo Port. These features near Chongsecun and Resuo exemplify the transboundary process chains of some induced hazards. The interruption of cross-border commerce is a major tangible earthquake impact in addition to the damage to infrastructure and the loss of life.

### Glacier lakes stability

Many GLOFs have been recorded in the Himalaya since the mid-20th century (55). The lakes' moraine dams, commonly situated at the angle of repose, are fragile and prone to outburst because of either sudden collapse or piping erosion, or to gradual degradation due to climatic warming and thaw. Avalanche and landslide-generated displacement waves in the lake are thought to be a common trigger for moraine dam failure (56). Thus, when the largest earthquakes happened,



**Fig. 6. Landslide-dammed lake on the Marsyangdi River.** Map and satellite imagery and ground photographs of landslides and landslide-dammed lakes on upper Marsyangdi River. (A) Map. White box locates (C), (D), (E), and (F). (B) Ground photograph (courtesy M. Gotame, Manang villager) from 10 May 2015, showing the landslide-dammed lake looking south. The white dashed line is the head scarp (visible is the steep headwall), and the curved arrow shows the inferred flow path of the rotational slump. (C, D, E, and F) High-resolution WorldView-2 images of the river, showing delayed occurrence of the large landslide and lake formation. The white star in (D) locates (B). River widths are given at two locations.

many experts were concerned that shaking may have weakened or collapsed unconsolidated moraine dams of glacial lakes, or may have triggered large displacement waves and GLOFs.

Fortunately, we identified few earthquake effects on glacier lakes. We examined pre- and postquake satellite images of 491 lakes [locations drawn mainly from the inventory of Fujita *et al.* (57)]. The visibility of 15 lakes in our database was unclear (partially shadowed or poor resolution image), but their downstream drainages showed no signs of GLOFs. Only nine of 491 were physically hit by landslides or avalanches. Of these, ice avalanches may have ejected water from two small ponds near Everest, and debris fell onto the frozen surfaces of other lakes without further effect. No lakes in the current satellite survey produced a GLOF as a result of the earthquake. GLOFs generally do not trigger at modeled PGAs up to  $0.57g$  (Fig. 2D). This unexpected result may relate to seismic wave interactions with the topography, where for shallow hypocenters, PGAs (i) are reduced on valley floors and (ii) are rapidly reduced by shielding across mountain ranges caused by wave scattering on the topography and petrologic structure (50, 58).

Furthermore, we closely examined three large moraine-dammed glacial lakes (Thulagi, Rolpa, and Imja) (Fig. 7), which have been extensively surveyed, studied, and monitored because of their GLOF risk (55). At Thulagi Lake in the Manaslu region (just west of the Tom River blockage described above) and Imja Lake in the Everest region, no damage was immediately evident in postquake satellite imagery. However, a small glacial lake on Lhotse Glacier (south of Everest) drained on 25 May 2015, which resulted in an anomalous rise in stream level (59). Small supraglacial ponds commonly drain suddenly because of ice fracturing or other glacier dynamics, and it is unclear whether this event was earthquake-related.

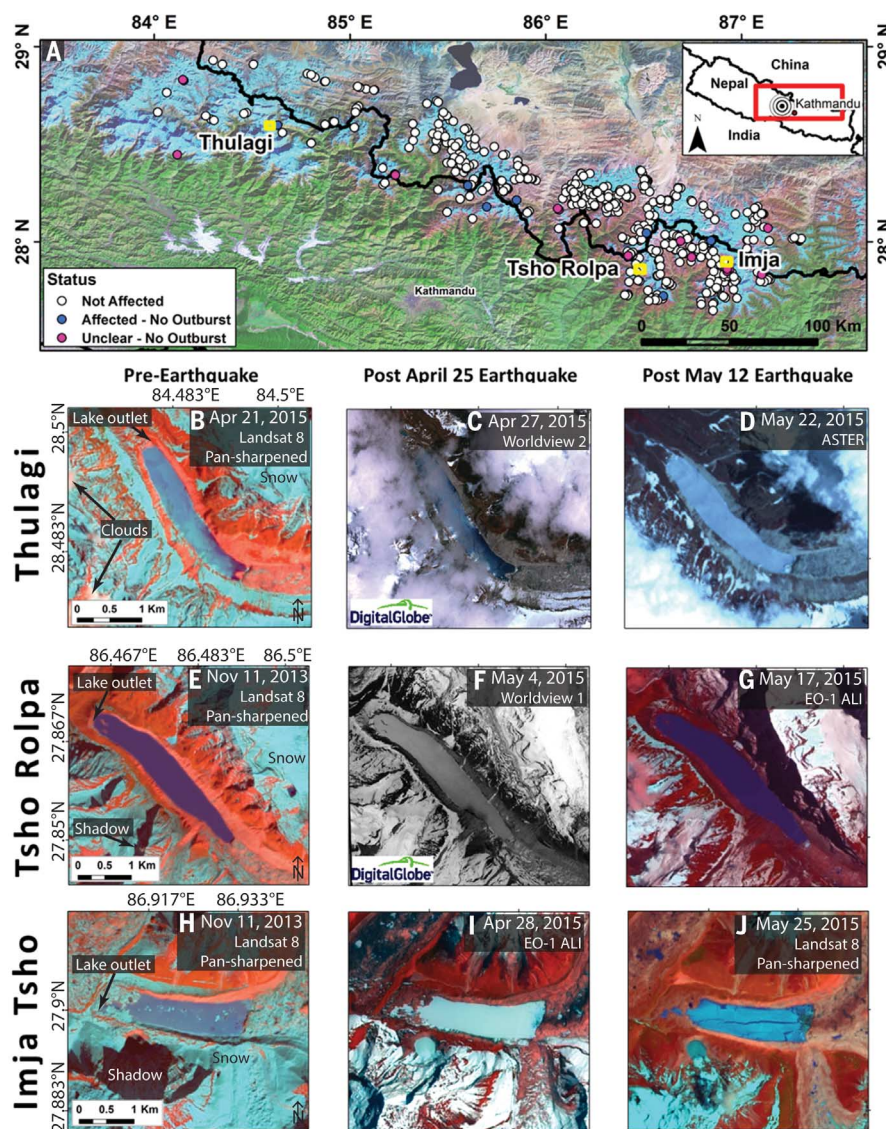
We were especially concerned about Tsho Rolpa, located at the terminus of Trakarding Glacier in the Rolwaling Valley, because of its location near the giant aftershock's ( $M$  7.3 on 12 May) epicenter. We found no evidence of damage to Tsho Rolpa's damming moraine from examination of WorldView 1 satellite images taken 9 days after the initial earthquake, on 4 May 2015, and the NASA's EO-1 satellite image taken 5 days after the  $M$  7.3 aftershock on 17 May. Postquake field photographs taken by USGS on 27 May show that the moraine was intact, and the lake was nearly brim-full (Fig. 8A). Another USGS photograph (Fig. 8B) shows fractures on the moraine dam, but because no ice exists in this part of the moraine, these tension cracks appear to have been caused by slumping of moraine material toward the lake (1 to 1.5 m horizontal and  $\sim 0.5$  m vertical), probably because of an earthquake but not likely to be a problem. The satellite imagery and field photographs do not demonstrate any big new additional concerns about the lake. We would not observe small GLOFs and minor damage to moraines in satellite images because of limitations in resolution. Furthermore, neither satellite and ground nor helicopter-borne inspections can easily detect

interior (subsurface) structural damage that make the metastable lakes even more subject to outburst.

## Summary and conclusions

Rapid, systematic mapping allowed us to investigate earthquake-induced geohazard processes and provide information to relief and recovery officials on the same timeframe as those operations were occurring. This work thus contrib-

uted to effective, timely guidance to in-country authorities responsible for response and recovery. Key findings were relayed through NASA, USGS, and the U.S. Agency for International Development (USAID), to Nepal-based experts at ICIMOD (International Centre for Integrated Mountain Development) and DHM (Department of Hydrology and Meteorology, Government of Nepal) and to the Prime Minister of Nepal.



**Fig. 7. Lake survey for earthquake damage.** (A) Overview of study area, showing location of 491 surveyed lakes. (B to J) Pre-earthquake images (right column), post-main shock images (center column), and post-12 May aftershock images (left column) for the largest glacial lakes in Nepal. (B) to (D), Thulagi Lake. (E) to (G) Tsho (Lake) Rolpa, and (H) to (J) Imja Tsho. (B) Landsat 8 image of Thulagi Lake, 21 April 2015. (C) Worldview 2 image of Thulagi Lake, 27 April 2015. (D) ASTER image of Thulagi Lake, 22 May 2015. (E) Landsat 8 image of Tsho Rolpa, 11 November 2013. (F) Worldview 1 image of Tsho Rolpa, 4 May 2015. (G) EO-1 ALI image of Tsho Rolpa 17 May 2015. (H) Landsat 8 image of Imja Tsho, 11 November 2013. (I) EO-1 ALI image of Imja Tsho, 28 April 2015. (J) Landsat 8 image of Imja Tsho, 25 May 2015. A large crack developed in the lake ice on Imja Tsho, although such cracks are normal with spring thaw. Landsat 8 scenes are panchromatic band 8 sharpened images (resolution 15 m) using band combinations [7,5,3] (SWIR, NIR, Green). WorldView 2 false color composite scene uses band combination [7, 5, 3] (NIR, Red, Green). WorldView 1 image is the panchromatic band. ASTER image (resolution 15 m) uses bands [3N, 2, 1] (NIR, Red, Green). EO-1 ALI scenes use panchromatic band 1 (resolution 10 m) and band combination [8, 6, 4] (SWIR, NIR, Green).

The mapped features document the large geographic extent of the Gorkha earthquake's effect on hazardous Earth surface processes and constrain their geophysical limits and geomorphic, tectonic, and lithologic controls. The distribution of induced landslides shows positive associations with slope and shaking intensity. More broadly, the highest areal densities of landslides are developed primarily on the downdropped northern tectonic block. This is likely explained by momentary reduction during downward acceleration of the normal stress along planes of weakness. The largest two shocks bracket the landslide distribution because they are within the displacement field and highest PGAs. Additional controls of landslide distribution are indicated by their clustering within specific bedrock and sur-

ficial lithologies, including Proterozoic metamorphic rocks and Ordovician granitoids, in proximity to earthquake epicenters, with high PGAs, and perhaps with seismic wave scattering and interferences.

In the remote valleys of the higher Himalaya, the most concentrated losses were directly due to the induced mass movements and air blasts rather than shaking. Seismic wave interactions may have contributed to destruction in Langtang Valley and other locations because of wave focusing and ridgetop shattering but may have reduced direct shaking damage in valley floors and at glacial lakes.

The distribution of Gorkha earthquake-related landslides and the terrain susceptibilities to earthquake-induced mass movements provide

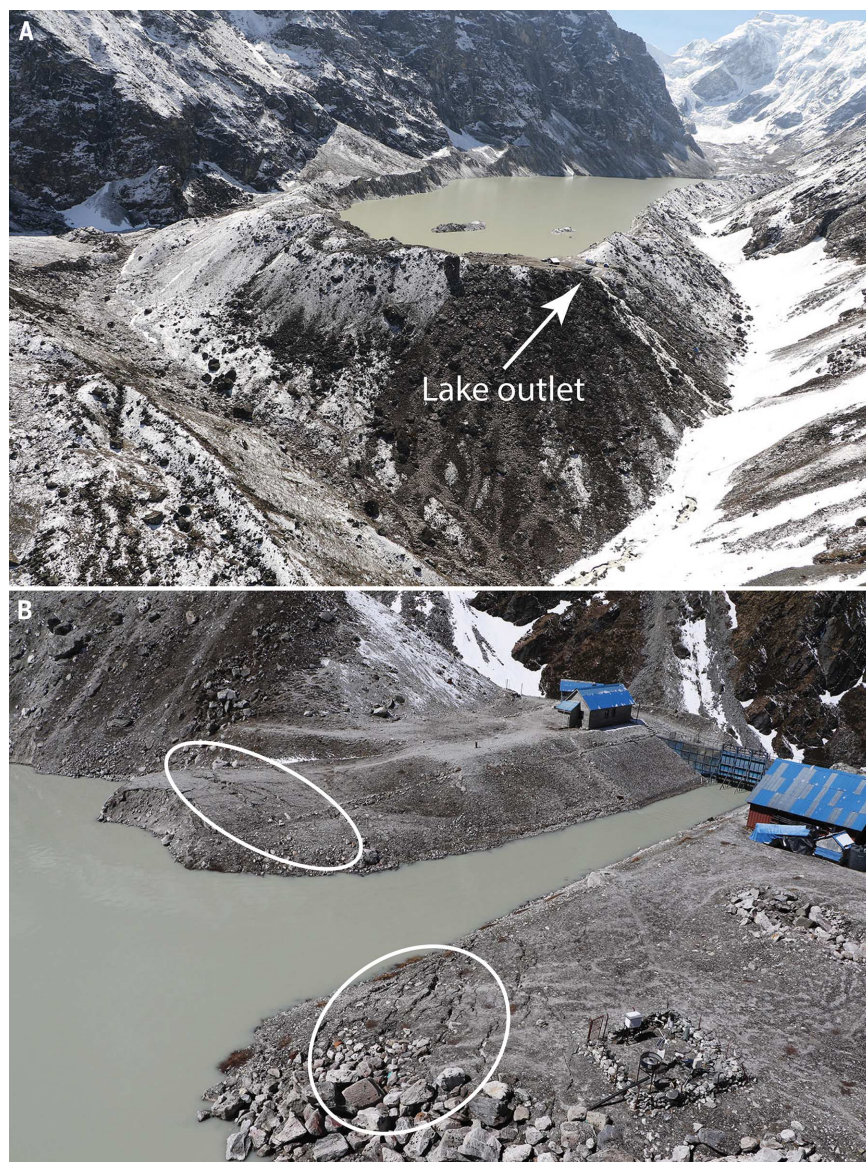
a basis from which to predict future patterns of landsliding of earthquake-weakened ice, rock, and unconsolidated sediments, especially as aftershocks, precipitation, and snowmelt events continue over the next few years. Hydrological processes such as frost shattering and rockfalls at high elevations and riverbank undercutting and rotational slumping in valleys may exploit earthquake-induced damage and trigger more landslides. Conversely, high-magnitude shaking-related landslides, such as ridgetop failures that affected Langtang Valley, may be less common going forward, unless additional strong aftershocks or high-elevation melting affect seismically shattered rocks. However, earthquake-related landsliding may fade below the regional background frequency of landslide activity in the next one to several years.

The Gorkha earthquake caused fewer landslides than comparable earthquakes elsewhere, although some of Nepal's largest mass movements in recent millennia may have been triggered by earthquakes (60). Details of earthquake location relative to geology and topographic relief appear to be crucial in determining the magnitude of earthquake-induced hazards.

Although the Gorkha earthquake's tragic toll on human lives and culture cannot be understated, some fortunate facts are that not a single large GLOF was unleashed and the total number of landslides was far fewer than generated by comparable earthquakes (56). Whether the same will hold for a hypothetical future large Himalayan earthquake is uncertain. However, future earthquakes generated on the shallow Main Himalayan Thrust are not apt to generate many or any GLOFs unless the magnitude is greater than the Gorkha earthquake's or the hypocenter and zone of maximum slip is closer to the lakes, thus circumventing the shielding by Himalayan relief. The potential exists for immense landslides and river blockages, which may pose the greatest mountain hazard.

### Materials and methods

We mapped 4312 landslides from high- and medium-resolution satellite imagery (Landsat 8, WorldView, and others) in the weeks after the *M* 7.8 main shock. Landslide locations were mapped as points, with attributes including nearest village, dates of imagery used to constrain timing, and whether the mass movement produced or could produce a secondary hazard (for example, a dammed lake). Using a previously published database and the multispectral satellite data, we also assessed damages to glacial lakes. The distribution of landslides was examined in the context of the geology (structure and lithology), the distribution of snow and ice, topographic slopes, and peak ground accelerations modeled for the Gorkha earthquake and its largest aftershock. Seismic and shake intensity data combined with slope were used to model geohazard susceptibility indices. All data, including previously published InSAR-measured ground displacements, were analyzed within a geographic information system.



**Fig. 8. Field visit identifies light damage at Tsho (lake) Rolpa.** (A) Post-earthquake image of Tsho Rolpa appears identical to its appearance shortly before the earthquake. (B) Two areas of fractures (outlined in white)—believed formed by the 12 May 2015 aftershock—were observed from a helicopter on the engineered part of the end moraine during an inspection undertaken by USGS at Tsho Rolpa. Photos are from 27 May by B. Collins (USGS), courtesy of USAID—Office of Foreign Disaster Aid.

## REFERENCES AND NOTES

- R. M. Parameswaran *et al.*, Seismotectonics of the April–May 2015 Nepal earthquakes: An assessment based on the aftershock patterns, surface effects and deformational characteristics. *J. Asian Earth Sci.* **111**, 161–174 (2015). doi: [10.1016/j.jseas.2015.07.030](https://doi.org/10.1016/j.jseas.2015.07.030)
- J. Galetzka *et al.*, Slip pulse and resonance of the Kathmandu basin during the 2015 Gorkha earthquake, Nepal. *Science* **349**, 1091–1095 (2015). doi: [10.1126/science.aac6383](https://doi.org/10.1126/science.aac6383); pmid: [26249228](https://pubmed.ncbi.nlm.nih.gov/26249228/)
- E. O. Lindsey *et al.*, Line-of-sight displacement from ALOS-2 interferometry:  $M_w$  7.8 Gorkha Earthquake and  $M_w$  7.3 aftershock. *Geophys. Res. Lett.* **42**, 6655–6661 (2015). doi: [10.1002/2015GL065385](https://doi.org/10.1002/2015GL065385)
- K. Jaiswal, D. Wald, D. D'Ayala, Developing empirical collapse fragility functions for global building types. *Earthq. Spectra* **27**, 775–795 (2011). doi: [10.1193/1.3606398](https://doi.org/10.1193/1.3606398)
- J. S. Kargel, G. J. Leonard, M. P. Bishop, A. Käbb, B. H. Raup, *Global Land Ice Measurements from Space* (Springer-Verlag, Berlin Heidelberg, 2014).
- E. L. Harp, D. K. Keefer, H. P. Sato, H. Yagi, Landslide inventories: The essential part of seismic landslide hazard analyses. *Eng. Geol.* **122**, 9–21 (2011). doi: [10.1016/j.enggeo.2010.06.013](https://doi.org/10.1016/j.enggeo.2010.06.013)
- J. A. N. van Aardt *et al.*, Geospatial disaster response during the Haiti earthquake: A case study spanning airborne deployment, data collection, transfer, processing, and dissemination. *Photogramm. Eng. Remote Sensing* **77**, 943–952 (2011).
- G. Cecchine *et al.*, "The U.S. Military Response to the 2010 Haiti Earthquake - Considerations for Army Leaders" (RAND Corporation, 2013).
- H. P. Sato, E. L. Harp, Interpretation of earthquake-induced landslides triggered by the 12 May 2008,  $M_{7.9}$  Wenchuan earthquake in the Beichuan area, Sichuan Province, China using satellite imagery and Google Earth. *Landslides* **6**, 153–159 (2009). doi: [10.1007/s10346-009-0147-6](https://doi.org/10.1007/s10346-009-0147-6)
- British Geological Survey, Nepal earthquake response 2015 (2015); available at [www.bgs.ac.uk/research/earthHazards/epom/NepalEarthquakeResponse.html](http://www.bgs.ac.uk/research/earthHazards/epom/NepalEarthquakeResponse.html).
- R. N. Parker *et al.*, Mass wasting triggered by the 2008 Wenchuan earthquake is greater than orogenic growth. *Nat. Geosci.* **4**, 449–452 (2011). doi: [10.1038/ngeo1154](https://doi.org/10.1038/ngeo1154)
- C. Xu, X. Xu, X. Yao, F. Dai, Three (nearly) complete inventories of landslides triggered by the May 12, 2008 Wenchuan  $M_{7.9}$  earthquake of China and their spatial distribution statistical analysis. *Landslides* **11**, 441–461 (2014). doi: [10.1007/s10346-013-0404-6](https://doi.org/10.1007/s10346-013-0404-6)
- R. M. Yuan *et al.*, Density distribution of landslides triggered by the 2008 Wenchuan earthquake and their relationships to peak ground acceleration. *Bull. Seismol. Soc. Am.* **103**, 2344–2355 (2013). doi: [10.1785/0120110233](https://doi.org/10.1785/0120110233)
- E. L. Harp *et al.*, Landslides and liquefaction triggered by the  $M_{7.9}$  Denali Fault earthquake of 3 November 2002. *GSA Today* **13**, 4–10 (2003). doi: [10.1130/1052-5173\(2003\)013<0004:LALTB>2.0.CO;2](https://doi.org/10.1130/1052-5173(2003)013<0004:LALTB>2.0.CO;2)
- R. W. Jibson, E. L. Harp, W. Schulz, D. K. Keefer, Landslides triggered by the 2002 Denali fault, Alaska, earthquake and the inferred nature of the strong shaking. *Earthq. Spectra* **20**, 669–691 (2004). doi: [10.1193/1.1778173](https://doi.org/10.1193/1.1778173)
- D. H. Shugar, J. J. Clague, The sedimentology and geomorphology of rock avalanche deposits on glaciers. *Sedimentology* **58**, 1762–1783 (2011). doi: [10.1111/j.1365-3091.2011.01238.x](https://doi.org/10.1111/j.1365-3091.2011.01238.x)
- F. C. Dai *et al.*, Spatial distribution of landslides triggered by the 2008  $M_{8.0}$  Wenchuan earthquake, China. *J. Asian Earth Sci.* **40**, 883–895 (2011). doi: [10.1016/j.jseas.2010.04.010](https://doi.org/10.1016/j.jseas.2010.04.010)
- D. H. Shugar, B. T. Rabus, J. J. Clague, D. M. Capps, The response of Black Rapids Glacier, Alaska, to the Denali earthquake rock avalanches. *J. Geophys. Res.* **117** (F1), F01006 (2012). doi: [10.1029/2011JF002011](https://doi.org/10.1029/2011JF002011)
- R. N. Parker *et al.*, Spatial distributions of earthquake-induced landslides and hillslope preconditioning in the northwest South Island, New Zealand. *Earth Surf. Dynamics* **3**, 501–525 (2015). doi: [10.5194/esurf-3-501-2015](https://doi.org/10.5194/esurf-3-501-2015)
- S. G. Evans *et al.*, Catastrophic detachment and high-velocity long-runout flow of Kolka Glacier, Caucasus Mountains, Russia in 2002. *Geomorphology* **105**, 314–321 (2009). doi: [10.1016/j.geomorph.2008.10.008](https://doi.org/10.1016/j.geomorph.2008.10.008)
- W. Haeblerli *et al.*, The Kolka-Karmadon rock/ice slide of 20 September 2002: An extraordinary event of historical dimensions in North Ossetia, Russian Caucasus. *J. Glaciol.* **50**, 533–546 (2004). doi: [10.3189/172756504781829710](https://doi.org/10.3189/172756504781829710)
- J. S. Kargel *et al.*, Satellite monitoring of Pakistan's rockslide-dammed Lake Gojal. *Eos Trans. AGU* **91**, 394–395 (2010). doi: [10.1029/2010EO0430002](https://doi.org/10.1029/2010EO0430002)
- V. Vilimek, M. L. Zapata, J. Klimes, Z. Patzelt, N. Santillán, Influence of glacial retreat on natural hazards of the Palcacocha Lake area, Peru. *Landslides* **2**, 107–115 (2005). doi: [10.1007/s10346-005-0052-6](https://doi.org/10.1007/s10346-005-0052-6)
- M. Carey, Living and dying with glaciers: People's historical vulnerability to avalanches and outburst floods in Peru. *Glob. Planet. Change* **47**, 122–134 (2005). doi: [10.1016/j.gloplacha.2004.10.007](https://doi.org/10.1016/j.gloplacha.2004.10.007)
- S. A. Dunning, N. J. Rosser, D. N. Petley, C. R. Massey, Formation and failure of the Tsatichhu landslide dam, Bhutan. *Landslides* **3**, 107–113 (2006). doi: [10.1007/s10346-005-0032-x](https://doi.org/10.1007/s10346-005-0032-x)
- J. T. Weidinger, in *Natural and Artificial Rockslide Dams*, S. G. Evans, R. L. Hermanns, A. Strom, G. Scarascia-Mugnozza, Eds. (Springer, Berlin Heidelberg, 2011), pp. 243–277.
- M. Geertsema, J. J. Clague, Pipeline routing in landslide-prone terrain. *Innovations* **15**, 17–21 (2011).
- K. Hewitt, Disturbance regime landscapes: Mountain drainage systems interrupted by large rockslides. *Prog. Phys. Geogr.* **30**, 365–393 (2006). doi: [10.1191/0309133306pp486ra](https://doi.org/10.1191/0309133306pp486ra)
- Materials and methods are available as supplementary materials on Science Online.
- Y. Ogata, Statistical models for earthquake occurrences and residual analysis for point processes. *J. Am. Stat. Assoc.* **83**, 9–27 (1988). doi: [10.1080/01621459.1988.10478560](https://doi.org/10.1080/01621459.1988.10478560)
- D. K. Keefer, Investigating landslides caused by earthquakes—A historical review. *Surv. Geophys.* **23**, 473–510 (2002). doi: [10.1023/A:101274710840](https://doi.org/10.1023/A:101274710840)
- C. Xu, X. Xu, J. B. H. Shyu, Database and spatial distribution of landslides triggered by the Lushan, China  $M_{w}$  6.6 earthquake of 20 April 2013. *Geomorphology* **248**, 77–92 (2015). doi: [10.1016/j.geomorph.2015.07.002](https://doi.org/10.1016/j.geomorph.2015.07.002)
- A. Jarvis, H. I. Reuter, A. Nelson, E. Guevara, Hole-filled seamless SRTM data v4 [International Centre for Tropical Agriculture (CIAT), 2008]; available at <http://srtm.csi.cgiar.org>
- P. Meunier, N. Hovius, J. A. Haines, Topographic site effects and the location of earthquake induced landslides. *Earth Planet. Sci. Lett.* **275**, 221–232 (2008). doi: [10.1016/j.epsl.2008.07.020](https://doi.org/10.1016/j.epsl.2008.07.020)
- H. T. Chou, C. F. Lee, S. C. Chen, in *Earthquake-Induced Landslides: Proceedings of the International Symposium on Earthquake-Induced Landslides*, K. Ugai, H. Yagi, A. Wakai, Eds. (2013), pp. 45–57.
- L. Chen *et al.*, Liquefaction macrophenomena in the great Wenchuan earthquake. *Earthq. Eng. Vib.* **8**, 219–229 (2009). doi: [10.1007/s11803-009-9033-4](https://doi.org/10.1007/s11803-009-9033-4)
- P. L. Moore, N. R. Iverson, D. Cohen, Ice flow across a warm-based/cold-based transition at a glacier margin. *Ann. Glaciol.* **50**, 1–8 (2009). doi: [10.3189/172756409789624319](https://doi.org/10.3189/172756409789624319)
- H. Blatter, G. K. C. Clarke, J. Colinge, Stress and velocity fields in glaciers: Part II. Sliding and basal stress distribution. *J. Glaciol.* **44**, 457–466 (1998).
- N. Bo, J. Persson, in *Sliding on Ice and Snow: Physical Principles and Applications* (Springer, Berlin, 1998), p. 391.
- J. T. Weidinger, Predesign, failure and displacement mechanisms of large rockslides in the Annapurna Himalayas, Nepal. *Eng. Geol.* **83**, 201–216 (2006). doi: [10.1016/j.enggeo.2005.06.032](https://doi.org/10.1016/j.enggeo.2005.06.032)
- P. Deline *et al.*, in *Snow and Ice-Related Hazards, Risks and Disasters*, W. Haeblerli, C. Whiteman, J. F. Shroder, Eds. (Elsevier, Amsterdam, 2015), pp. 521–561.
- M. Geertsema, M. Chiarle, in *Treatise on Geomorphology*, J. F. Shroder, M. Stoffel, R. A. Marston, Eds. (Elsevier, Amsterdam, 2013), vol. 7, pp. 217–222.
- C. Liang, "Interferogram for ALOS-2-track 48-swath ScanSARNominal14MHz; Feb 22, 2015 to May 3, 2015," UNAVCO InSAR Product, (2015). doi: [10.7283/S2KW2R](https://doi.org/10.7283/S2KW2R)
- R. W. Jibson, E. L. Harp, "Field reconnaissance report of landslides triggered by the January 12, 2010, Haiti earthquake" (U.S. Geological Survey Open-File Report 2011-1023, Reston, VA, 2011).
- E. L. Harp, R. W. Jibson, Landslides triggered by the 1994 Northridge, California earthquake. *Bull. Seismol. Soc. Am.* **86**, S319–S332 (1996).
- J. Stöcklin, Geology of Nepal and its regional frame: Thirty-third William Smith Lecture. *J. Geol. Soc. London* **137**, 1–34 (1980). doi: [10.1144/gsjgs.137.1.0001](https://doi.org/10.1144/gsjgs.137.1.0001)
- B. D. Collins, R. W. Jibson, "Assessment of existing and potential landslide hazards resulting from the April 25, 2015 Gorkha, Nepal earthquake sequence" (U.S. Geological Survey Open-File Report 2015-1142, Reston, VA, 2015).
- J. P. McCalpin, E. W. Hart, "Ridge-top spreading features and relationship to earthquakes, San Gabriel Mountains region, Southern California - Part B: Paleoseismic investigations of ridge-top depressions," *Final Technical Report, Contract 1434-HQ-GR-1026, National Earthquake Hazards Reduction Program* (U.S. Geological Survey, 2002).
- R. D. Nason, in *The San Fernando, California, earthquake of February 9, 1971, U.S. Geological Survey Professional Paper 733* (U.S. Geological Survey, Washington, DC, 1971), pp. 97–98.
- S.-J. Lee, D. Komatitsch, B.-S. Huang, J. Tromp, Effects of topography on seismic-wave propagation: An example from northern Taiwan. *Bull. Seismol. Soc. Am.* **99**, 314–325 (2009). doi: [10.1785/0120080020](https://doi.org/10.1785/0120080020)
- W. W. Immerzeel, L. Petersen, S. Ragettli, F. Pellicciotti, The importance of observed gradients of air temperature and precipitation for modeling runoff from a glacierized watershed in the Nepalese Himalayas. *Water Resour. Res.* **50**, 2212–2226 (2014). doi: [10.1002/2013WR014506](https://doi.org/10.1002/2013WR014506)
- K. Fujita, T. Nuimura, Spatially heterogeneous wastage of Himalayan glaciers. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 14011–14014 (2011). doi: [10.1073/pnas.1106242108](https://doi.org/10.1073/pnas.1106242108); pmid: [21808042](https://pubmed.ncbi.nlm.nih.gov/21808042/)
- S. Ragettli *et al.*, Unraveling the hydrology of a Himalayan catchment through integration of high resolution in situ data and remote sensing with an advanced simulation model. *Adv. Water Resour.* **78**, 94–111 (2015). doi: [10.1016/j.adwatres.2015.01.013](https://doi.org/10.1016/j.adwatres.2015.01.013)
- C. Cadwalladr, "Nepal earthquake: The village wiped off the map in a few terrifying seconds," *The Guardian*, 16 May 2015.
- ICIMOD, *Glacial Lakes and Glacial Lake Outburst Floods in Nepal* (International Centre for Integrated Mountain Development, Kathmandu, Nepal, 2011), pp. 99.
- J. J. Clague, S. G. Evans, A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quat. Sci. Rev.* **19**, 1763–1783 (2000). doi: [10.1016/S0277-3791\(00\)00090-1](https://doi.org/10.1016/S0277-3791(00)00090-1)
- K. Fujita *et al.*, Potential flood volume of Himalayan glacial lakes. *Nat. Hazards Earth Syst. Sci.* **13**, 1827–1839 (2013). doi: [10.5194/nhess-13-1827-2013](https://doi.org/10.5194/nhess-13-1827-2013)
- S. Ma, R. J. Archuleta, M. T. Page, Effects of large-scale topography on ground motions as demonstrated by a study of the San Gabriel Mountains, Los Angeles, California. *Bull. Seismol. Soc. Am.* **97**, 2066–2079 (2007). doi: [10.1785/0120070040](https://doi.org/10.1785/0120070040)
- A. C. Byers, D. C. McKinney, E. A. Byers, "Post-earthquake assessment: Imja, Tsho Rolpa, and Thulagi glacial lakes in Nepal" (U.S. Agency for International Development, 2015).
- W. Schwanghart *et al.*, Repeated catastrophic valley infill following medieval earthquakes in the Nepal Himalaya. *Science* **351**, 147–150 (2015).
- A. Arendt *et al.*, "Randolph Glacier Inventory—A dataset of global glacier outlines: version 4.0" (Global Land Ice Measurements from Space, Boulder, CO, 2014).
- U.S. Geological Survey, Earthquake Hazards Program (2015); available at <http://earthquake.usgs.gov>.
- M. R. Dhiyal, *Geology of the Nepal Himalaya—Regional Geology Reviews* (Springer, 2015).
- L. S. Walsh, A. J. Martin, T. P. Ojha, T. Fedenczuk, Correlations of fluvial knickzones with landslide dams, lithologic contacts, and faults in the southwestern Annapurna Range, central Nepalese Himalaya. *J. Geophys. Res.* **117**, F01012 (2012). doi: [10.1029/2011JF001984](https://doi.org/10.1029/2011JF001984)

## ACKNOWLEDGMENTS

J.S.K., G.J.L., and U.K.H. thank the NASA SERVIR Applied Science Team and NASA Cryosphere Program for support. D.H.S. thanks the Hakai Institute for support. Part of this research was sponsored by the NASA Earth Surface and Interior focus area and performed at the Jet Propulsion Laboratory, California Institute of Technology. We gratefully acknowledge support from several "citizen scientists" who provided key observations and reports from various locations in Nepal: D. Rai, J. B. Rai, N. Sapkota, M. Dhan Rai, and M. Gotame, who made on-site inspections and photo documentation of Thulagi (Dona) Lake, Rolpa Lake, Kali Gandaki, and "Lower Pisang" landslide dammed lake. ASTER data are courtesy of NASA/GSFC/METI/Japan Space Systems, the U.S./Japan ASTER Science Team, and GLIMS. We especially laud DigitalGlobe's decision to acquire and make available a vast volume of data for analysis related to Gorkha earthquake response. We thank C. Liang for processing the ALOS-2 wide-swath interferogram. Original ALOS-2 data are copyright 2015 JAXA. This study was partially supported by core funds of ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland, and the United Kingdom. This study was partially supported by the Hundred Talents Program of the Chinese Academy of Sciences (grant 784) and the National Natural Science Foundation of China (grants 41431070 and 41321063). The two chief databases produced by this work are available at ICIMOD (landslides, <http://rds.icimod.org/Home/DataDetail?metadatald=24055>; and glacial lakes, <http://rds.icimod.org/Home/DataDetail?metadatald=24065>).

## SUPPLEMENTARY MATERIALS

[www.sciencemag.org/content/351/6269/aac8353/suppl/DC1](http://www.sciencemag.org/content/351/6269/aac8353/suppl/DC1)  
Materials and Methods  
Figs. S1 to S6  
Tables S1 to S3

20 June 2015; accepted 27 November 2015  
Published online 17 December 2015  
[10.1126/science.aac8353](https://doi.org/10.1126/science.aac8353)

## Supplementary Material for

### Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake

J. S. Kargel,\* G. J. Leonard, D. H. Shugar,\* U. K. Haritashya,\* A. Bevington, E. J. Fielding, K. Fujita, M. Geertsema, E. S. Miles, J. Steiner, E. Anderson, S. Bajracharya, G. W. Bawden, D. F. Breashears, A. Byers, B. Collins, M. R. Dhital, A. Donnellan, T. L. Evans, M. L. Geai, M. T. Glasscoe, D. Green, D. R. Gurung, R. Heijenk, A. Hilborn, K. Hudnut, C. Huyck, W. W. Immerzeel, Jiang Liming, R. Jibson, A. Kääb, N. R. Khanal, D. Kirschbaum, P. D. A. Kraaijenbrink, D. Lamsal, Liu Shiyin, Lv Mingyang, D. McKinney, N. K. Nahirnick, Nan Zhuotong, S. Ojha, J. Olsenholler, T. H. Painter, M. Pleasants, Pratima KC, QI Yuan, B. H. Raup, D. Regmi, D. R. Rounce, A. Sakai, Shanguan Donghui, J. M. Shea, A. B. Shrestha, A. Shukla, D. Stumm, M. van der Kooij, K. Voss, Wang Xin, B. Weihs, D. Wolfe, Wu Lizong, Yao Xiaojun, M. R. Yoder, N. Young

\*Corresponding author. Email: kargel@hwr.arizona.edu (J.S.K.); dshugar@uw.edu (D.H.S.); uharitashya1@udayton.edu (U.K.H.).

Published 17 December 2015 on *Science Express*  
DOI: 10.1126/science.aac8353

#### **This PDF file includes:**

Materials and Methods  
Figs. S1 to S6  
Tables S1 to S3

## MATERIALS AND METHODS

### **Geohazard inventory, mapping, and database**

4,312 landslide locations were mapped by six analyst teams organized around six Areas of Interest (Fig. S1). Landslide single points primarily indicate the location of deposits. This stems from our primary humanitarian motivation to identify locations of possible river blockage and village destruction, which is more frequent in valleys and lower mountain elevations where deposits occur.

Table S1 lists the number and type of images that were available for this study and the number used. Many more images were evaluated with null results. Thousands of unused images are available for future evaluation of Gorkha earthquake-related geohazard chronologies. Many additional images in Google Earth were heavily utilized for validation/quality assessment. Images vary in properties and quality (spectral, spatial, temporal, and radiometric resolution; sensor gains and DN range; cloud cover; look angles; geometric correction, and orthorectification). Analysts used GIS or remote sensing software of their choosing to scan for co-seismic and post-seismic geohazard features and cross-checked them against pre-earthquake imagery. We expended considerable effort to minimize omissions, false positives, and redundancies, and to establish the chronology of landslide development. Google Earth's timeline was useful to screen out pre-seismic landslides and confirm likely co-seismic and post-seismic ones.

Ten days of aerial and ground investigations were undertaken over limited areas by a team led by author B. Collins (USGS); their helicopter traverses, incorporating guidance provided by the Volunteer Group, allowed verification and qualification of our data and interpretations. Author D. Breashears conducted independent reconnaissance and acquired some of the photos used here. The reconnaissance verified many satellite-mapped landslides but also indicated many small landslides that we had not identified mainly due to limited resolution.

Our first response to the earthquake was humanitarian in nature and had no relation to scientific inquiry; this changed only after the emergency had eased and we had accumulated a very interesting body of data. During the intense first weeks of our response, 2-hour teleconferences were held (daily for the first three weeks, then biweekly to weekly) among disaster response officials from NASA, USGS, USAID, and other U.S. agencies, and experts from academia (together, the Response Team). Subgroups formed, to which several authors belonged, to facilitate communication among experts in Earth surface deformation, induced hazards, satellite image tasking, and other emergency activities. Several authors took major roles with one or more working groups and the broader NASA-led response. Subgroups worked interactively, disseminated analysis results and received and distributed information produced by the volunteer analysts on sites of urgent concern.

Before the ad hoc structure had a chance to form, within about a day after the earthquake, information was passed from the Volunteers to NASA that Langtang Valley was in trouble and that other Himalayan valleys were likely also severely affected. This information led initially to focused satellite targeting, then blanket repeat imaging of the whole earthquake-affected mountain area of Nepal and neighboring countries. Specific tips also emanated from experts connected with classified satellite assets. A separate set of communication lines extended from the volunteer group to experts in Nepal (mainly at

ICIMOD and DHM), to local resident “citizen-scientists” who were able to help, and to the Prime Minister of Nepal. ICIMOD and NASA each issued a series of urgent press releases prepared by the volunteers that were aimed at calming the public where needed and otherwise provided information required by the public and emergency response officials. The press releases were vetted by NASA and/or ICIMOD, with input from DHM and Nepalese experts. Hence, there was a rapidly organized web of communications that worked surprisingly well, mainly due to the Volunteers' unselfish sharing of analysis results and willingness to work under exceptional emergency conditions, and due to end users' urgent need for information.

The volunteer teams' identification of landslides as co/post-seismic (vs. pre-seismic) was fairly reliable based on validation by the first four authors. Inter-operator and inter-sensor inconsistency may affect the numbers of missed or variably clustered small landslides. In future work, we expect that both cooperation with and competition amongst other research groups will produce improved databases and analysis results. As more satellite data becomes available, we expect that our database can be utilized to study detailed time-series of post-seismic landslide evolution.

For each landslide or geohazard identified, a set of attributes was recorded, including:

1. Hazard\_ID: Latitude and longitude to three or four decimal places, and the date of the first identified satellite image to contain the feature (DDMMYYYY), formatted as: Lat.Lon.FirstDate.
2. Group\_ID: Name of the AOI;
3. Lat\_dd: Latitude to three (or four) decimal places;
4. Lon\_dd: Longitude to three (or four) decimal places;
5. Country: Country in which the geohazard is located;
6. Npl\_Adm4: Nepal administrative district, based on the Global Administrative Areas GIS shapefile (<http://www.gadm.org/home>).
7. Chn\_Adm: China administrative district, based on the Global Administrative Areas GIS shapefile.
8. Village: Nearest village to be impacted (e.g. downstream of dammed lake), based on OpenStreetMap data (<http://download.geofabrik.de/asia/nepal.html>) or Google Earth, commonly Digital Globe imagery
9. Analyst: Name(s) of analysts who worked on the specific feature.
10. Image\_post: Filename of first post-earthquake image to contain the feature. If more than one scene analyzed, all scene IDs recorded.
11. Image\_post\_dat: Date (DDMMYYYY) of earliest post-earthquake scene to contain feature.
12. Image\_pre: Filename of latest pre-earthquake scene not containing feature.
13. Image\_pre\_dat: Date (DDMMYYYY) of latest pre-earthquake scene not containing feature.
14. Hazard\_type: Qualitative description of the feature, either as avalanche, landslide, landslide complex, rock avalanche.
15. Reactivate: Qualitative determination of whether the post-earthquake feature was a reactivation of an earlier landslide. (yes/no)
16. Water\_hzd: Qualitative description of whether the feature directly affects a waterway (yes/no).

17. Visib\_dam: Qualitative description of whether a dam across a river is present (yes/no/partial).
18. New\_water: Qualitative description of whether water has begun to pond upstream of a dam (yes/no).
19. Infra\_hzd: Qualitative description of whether the feature directly affects infrastructure (yes/no).
20. Dat\_qual: Qualitative description of the imagery quality (high/med/low).
21. Risk: subjective classification of the potential risk posed by the feature and follow-on hazards (low/med/high). Features flagged as 'high' were typically examined by other Lead Analysts for confirmation.
22. Descry\_comm: Brief description of the hazard and/or additional comments.
23. Group\_agency: Group identifier to maintain authorship in event of merged datasets ('NASA\_ICIMOD\_Volunteer').

### **Glacier lakes inventory, mapping, and database**

The Nagoya University team of the Volunteer Group inspected images of 467 of Nepal's high altitude lakes for indications of GLOFs or landslide impacts and direct or delayed response to the Gorkha earthquake and aftershocks. An inventory compiled by Fujita et al. (58) was utilized as a guide allowing for the quick identification and study of lakes. The volunteer team acquired Worldview 1, 2, and 3 scenes (courtesy of Digital Globe) to manually evaluate GLOF risks for each lake from Mt. Makalu in the east to Mt. Annapurna in the west as originally inventoried by Fujita et al. (58), plus some lakes that are not in that inventory. Both pre-and post-earthquake images were inspected to identify possible changes in moraine structure and outlet channel width, signs of downstream flooding, increased number and size of icebergs in the lake, large cracks in the glacier terminus zone, lateral moraine collapse, moraine slumping, and other evidence of damage to the damming moraine, adjacent glacier, or adjoining mountainsides. A database was compiled, which characterized post-earthquake condition and a risk assessment for each lake. A second independent survey was conducted by a team of volunteer analysts from the University of Dayton. Their survey of several hundred lakes, consisting of mostly the same lakes as the Nagoya survey plus 24 additional lakes, found much the same results. A preliminary assessment of three of Nepal's most dangerous lakes was made based on Landsat 8 OLI, ASTER, and ALI images (Figs. 7B-J).

### **Earthquake-induced geohazard susceptibility index computation**

#### *Seismic and shake intensity data*

Seismic data relating to earthquake and aftershock events, including epicenters, depths, time-of-event, and shake intensity were acquired from the USGS Earthquake Hazards Program (35) (Table S2). USGS ShakeMap data (Fig. 1B) are available in ASCII format and contain metrics of shake velocity and acceleration amplitudes posted at regularly spaced grid nodes (including peak ground acceleration, PGA, which we used in our analysis).

#### *Topographic data and slope determination*

Slopes were determined using Shuttle Radar Topography Mission (SRTM) 3-arc second (~90 meter) gap-filled DEMs available through the Consultative Group for International Agricultural Research, Consortium for Spatial Information (CGIAR-CSI) (32).

#### *Generation of Hazards Susceptibility Indices*

Gridded values of the seismically induced PGA, measured in percent  $g$  (gravitational acceleration), were collected for the local highest PGA for the primary M7.8 Gorkha earthquake and the subsequent five aftershocks  $> M6.0$  up to the 12 May 2015 M7.3 aftershock (Table S2). Gridded PGA was converted to continuous raster format and posted on 2000 m cell spacing.

The shake zone covers 155,000 km<sup>2</sup>, delineated by areas containing USGS PGA  $\geq 0.03 g$ . Hazard susceptibility maps (Fig. 2) were computed across the shaken zone for each SRTM 90-m cell:

$$HazardSusceptibility = PGA_{MAX} * (\sin(Slope_{SRTM}))$$

where PGA is from the USGS shake model (measured in fraction of  $g$ ) and  $PGA_{MAX}$  is the largest PGA in each 2000-m grid cell for the six overlapping  $> M6.0$  earthquakes and aftershocks. Slope is from the 90-m SRTM DEM. Table S3 summarizes the hazard susceptibilities for several landslides described in the Research Article. We calculated, normalized, and binned mass movement hazard susceptibility index values associated with i) ice avalanches, ii) snow avalanches, or iii) debris landslides.

The ice- and snow-dominated mass movement data are incomplete due to (i) difficult detection when avalanches are superposed over snow, (ii) short lifetimes when emplaced at low elevations, and (iii) problematic attribution of cause except where eyewitness reports are available. For example, the massive, deadly Everest ice/snow avalanches from 25 April 2015 are readily detected in WorldView scenes taken within days of the event, but had almost disappeared 4 weeks later.

$PGA_{MAX} = 0.03 g$  is our threshold limit of concern based on the recognition that earthquake-induced ice avalanches occurred at PGA down to the levels near Mt Everest ( $\sim 0.03$ - $0.09 g$ ), but not many mass movements occurred in less intensely shaken areas.

#### *Land Cover Classification*

Glacier Ice was extracted from version 4.0 of the Randolph Glacier Inventory (34).

Snow: Two pre-earthquake Landsat-8 color-composite mosaics generated from mostly cloud-free 2013-2014 imagery were provided by the USGS EROS Data Center for the NASA-led Response Team: a band 543-RGB, and a band 432-RGB mosaic (30 meter resolution). A normalized difference snow index (NDSI) was generated from LS8 VNIR-SWIR bands 3, 6, and 8 ( $Index = [B3 - B6] / [B3 + B6]$ ) and thresholded at  $\geq 0.10$ , which classified most of the snow-cover. Some water and clouds, mis-classified as snow, were removed with an SRTM elevation mask to eliminate areas  $< 4580$  m; a slope = 0 mask; filtering to remove snow areas  $< 0.002$  km<sup>2</sup>; and manual editing. Since the glacier ice fraction was also contained mainly within the broader snow-cover class, the RGI ice cover was subtracted from the snow area.

Land: All remaining area (not ice or snow) was classified as land.

#### *Lithologic mapping*

We followed a geological generalization and structural fault data from (46, 47).

#### *Data integration and mapping properties*

Multispectral imagery and DEMs were inspected for accurate co-registration; only one minor translational (XY) shift was required for Landsat 8 image bands and mosaics. Susceptibility index maps were resampled to 30 m and projected into a custom Albers equal area conic projection with a WGS 1984 datum.

#### **Peak Ground Acceleration (PGA): artifacts, caveats, and alternatives**

PGA is key in our landslide susceptibility analysis, but it is poorly constrained due to sparse intensity observations and lack of strong-motion measurements. USGS-computed ground motions were estimated primarily by Ground Motion Prediction Equations (GMPEs). Local sparse macroseismic reports/measurements ('did you feel it' shake reports) were integrated into the models. The USGS shake model for the main M7.8 shock may over-weight PGA locally, causing circular anomalies of high shaking within zones of moderate shaking. The model does not consider wave interactions with the topography and geologic structure, so local structure in PGA is not represented. Hence, the USGS ShakeMap has high regional and local uncertainties. Despite artifacts and lack of detail, we found PGA to be useful in assessment of landscape susceptibilities to mass movements. Considering the broad geographic coverage provided by the USGS ShakeMap, we used their model to compute shake-induced mass movement susceptibilities.

Noting the artifacts and limitations in the USGS ShakeMap, and aiming to develop better estimates of the extent and distribution of damage to buildings, fatalities, and rebuilding costs, researchers developed a preliminary inferred PGA map (35), which may be applied in future work. The inferred PGA over Nepal was determined by using observations of collapsed buildings from the National Geospatial-Intelligence Agency and building exposure estimates developed by ImageCat to determine the distribution of collapsed buildings. Composite damage functions were derived from USGS Pager collapse fragility functions (e.g., following 4) and weighted by the structural distribution of building types for the region's various development patterns.

PGA probabilistic forecasts for future earthquakes, especially aftershocks, are straightforward and computationally tractable. Forecast and probabilistic ground motion intensity maps can be produced for postulated scenarios and ensemble models to show likely ground motions or damage (e.g., landslides) thresholds (e.g., 29).

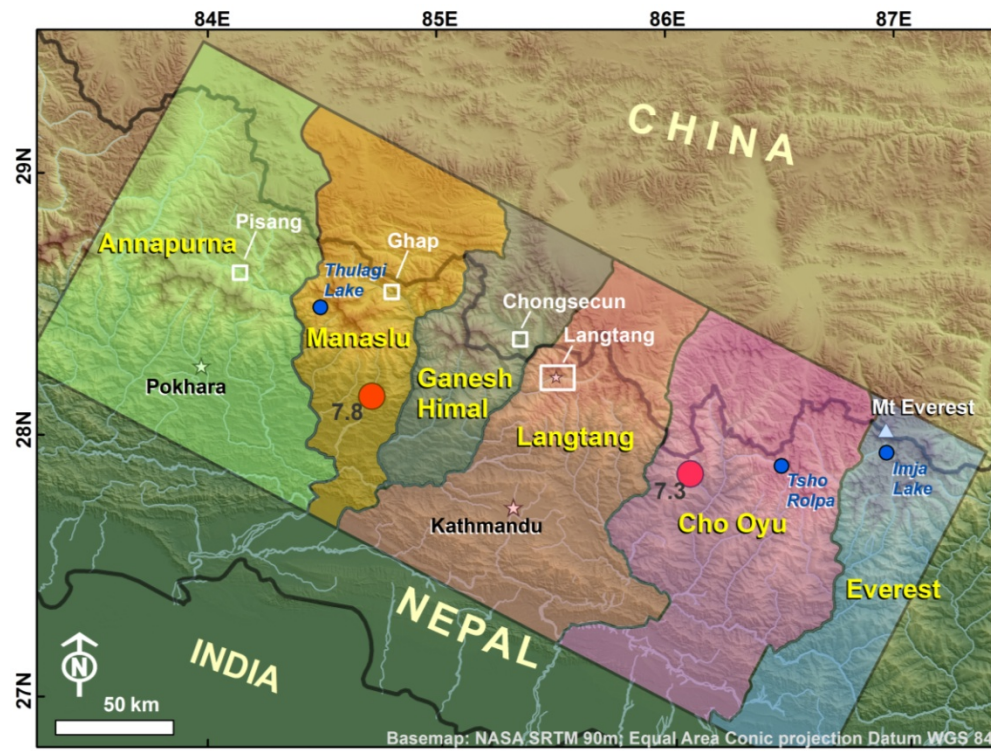
In sum, the modeling approaches are rooted alternatively in (i) pure geophysics amended by limited empirical observations (our adopted approach), (ii) inferences from observed and modeled damage, and (iii) probabilistic forecasts of future quakes and damage. In future work each approach will be informed and improved by the distribution of landslides.

### **Fatality distribution as an independent check of the USGS ShakeMap**

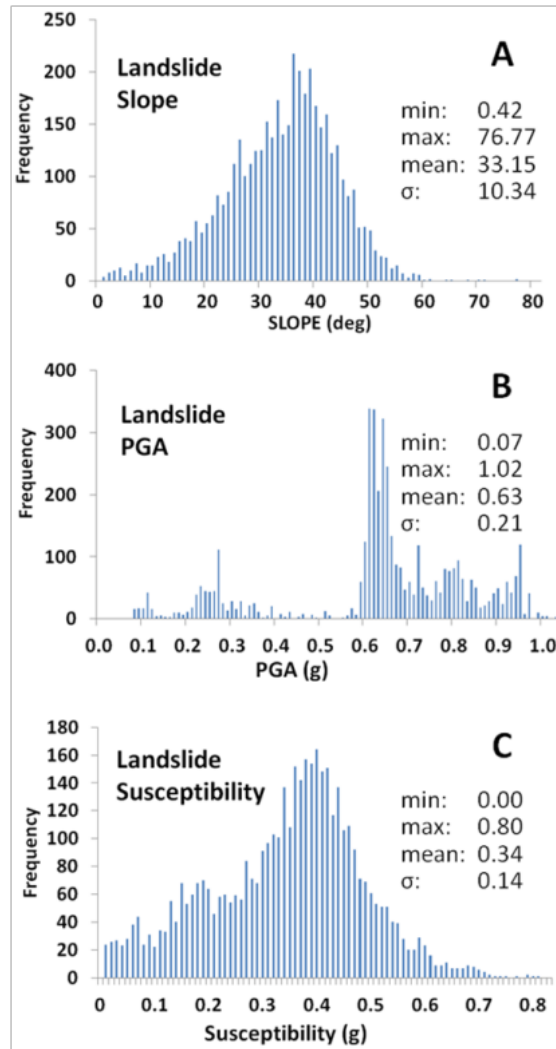
The first fatality estimates for the Gorkha earthquake made by USGS relied on their ShakeMap (Fig. 1B), which we also used. Those death toll estimates were highly uncertain, initially indicating a 65% chance of fatalities ranging from 1,000 to 100,000. Ultimately, the death toll was in the middle, logarithmically. The main shock on 25 April killed 8,674 people in Nepal (including at least 164 foreigners), 130 in India, 27 in China, and 4 in Bangladesh. More than 99% of the deaths occurred in a 550 x 200 km swath, but scattered deaths occurred more widely across 1200 x 400 km. Subsequent aftershocks prior to 12 May killed 21 more in Nepal, and the giant 12 May aftershock killed an additional 163 in Nepal, 62 in India, 1 in China, and 2 in Bangladesh. At least 279 people remain missing. Fatality data were updated to 6 June 2015, collected from several sources, mainly a compilation by Earthquake-Report.com. About 99% of the total 9084 deaths from all the quakes and induced landslides occurred in a swath that roughly matches the east-west extent of the landslide distribution and the USGS ShakeMap (Fig. 1C); the correlation supports the use of the USGS ShakeMap, with due consideration of the caveats and potential improvements. Landslide-related deaths are partly connected with shake but also with slope, which is roughly anti-correlated with population density. Hence, the north-south extent of the high-density death distribution is different from the ShakeMap due to demographics, e.g., sparse populations in the higher Himalaya, and terrain slope properties.

### **Disclaimer**

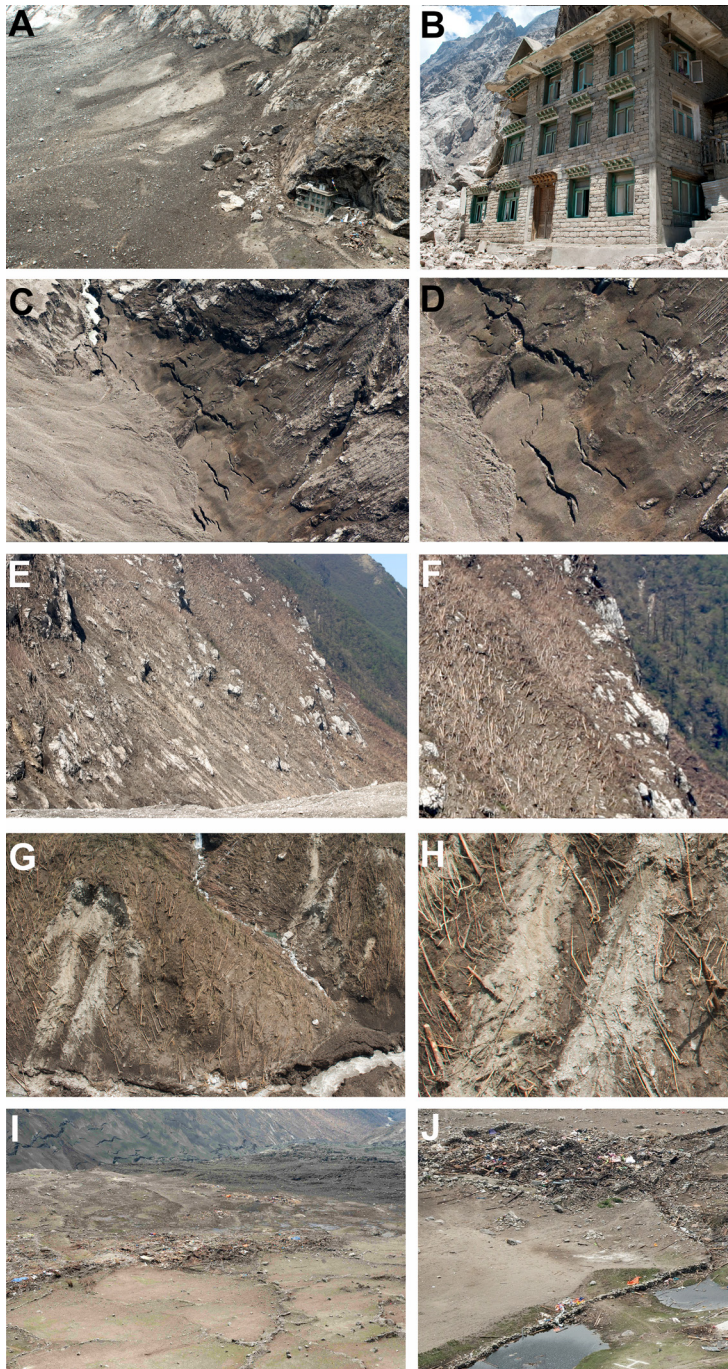
The views and interpretations in this publication are those of the authors. They are not necessarily attributable to any of the authors' institutions and do not imply the expression of any opinion by these institutions concerning the legal status of any country, territory, city or area of its authority, or concerning the delimitation of its frontiers or boundaries, or the endorsement of any product.



**Fig. S1.** Volunteer Image Analyst Group AOIs, locations of Case Study areas and glacier lakes described below, and epicenters of two largest earthquakes between 25 April - 30 May 2015.



**Fig. S2. Histograms of landslide occurrences.** Landslides with respect to: (A) slope, (B) peak ground acceleration, and (C) landslide susceptibility index. All plots  $n = 4312$ .

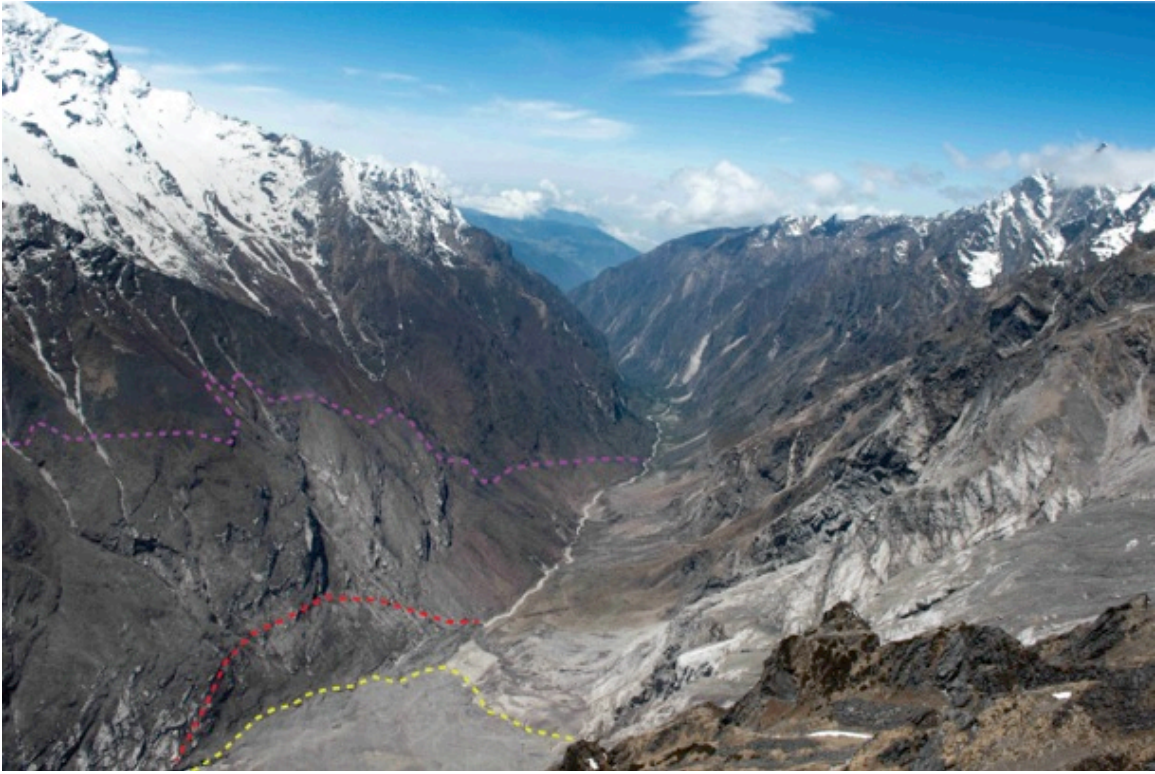


**Fig. S3. Destroyed Langtang.** (A) Proximal landslide deposit (the landslide head) against steep slopes on the north side of Langtang. The sole surviving structure in Langtang was protected by the cliff (lower right of panel A). (B) Sole surviving structure has typical stone-slab construction on a foundation. (C, D) Distal (toe) part of the landslide. The Langtang River (known locally as the Langtang Khola) has tunneled beneath the landslide. The deposit flowed onto landslide wind-deposited debris, which has formed crevasses due to slumping toward the river. (E,F) Forest of small trees flattened by a powerful blast of debris-laden, landslide-driven wind. (G,H) Small post-seismic landslide and the wind-flattened forest. (I,J) Completely demolished wind-

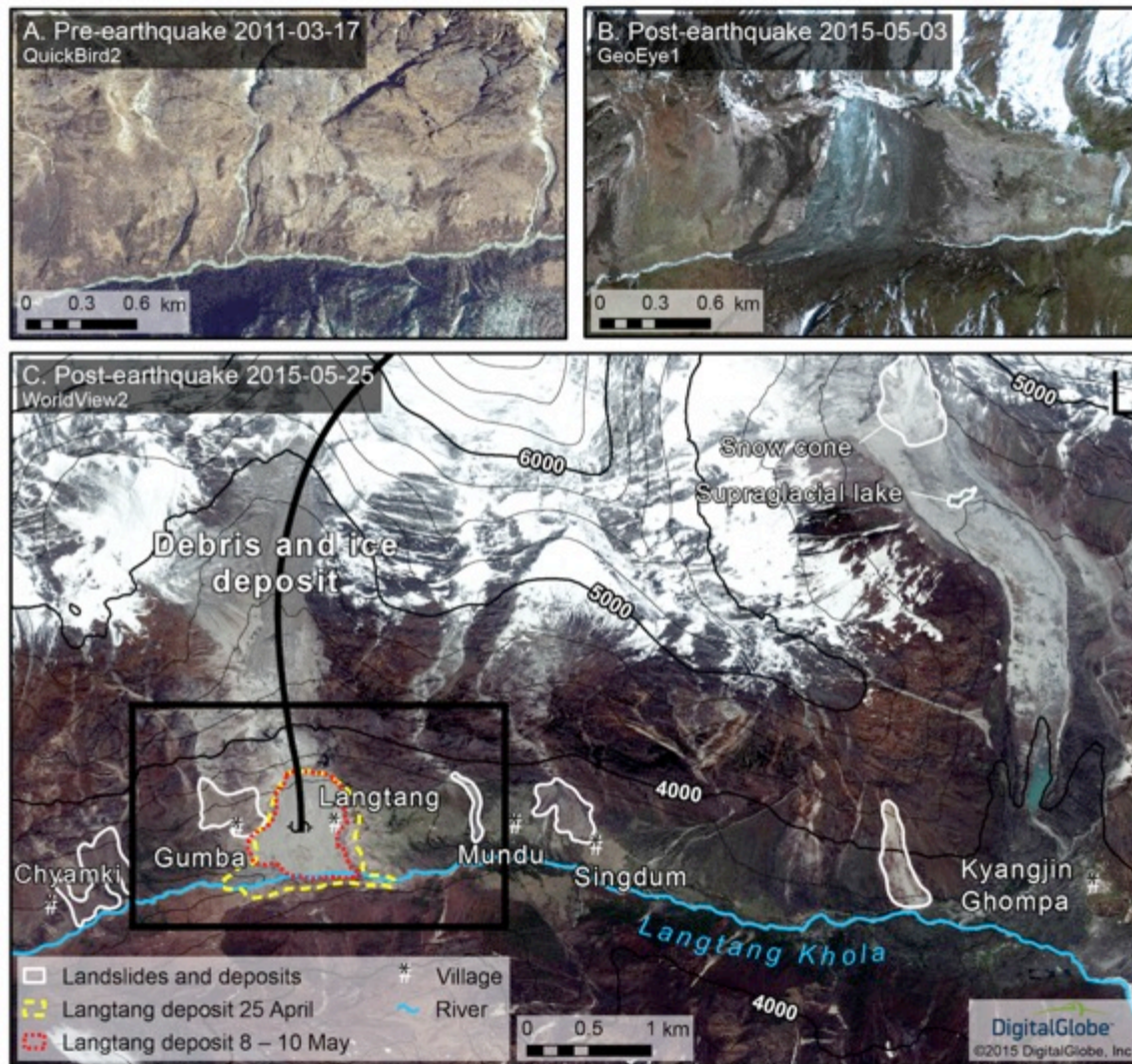
blasted part of Langtang. Panels E and F by Randall Jibson. Others by D. Breashears (7 May 2015).



**Fig. S4.** Before and after photographs of Langtang Valley, showing burial and destruction of a large part of Langtang village. Photographs by D. Breashears.



**Fig. S5. Extent of airblasts.** West-facing aerial photo showing the extents of the air blast (dashed red line), the initial debris deposits and run-up (dashed purple line), and the secondary rockslide (dashed yellow line; photo 10 May 2015: D.F. Breashears/GlacierWorks).



**Fig. S6. Satellite images of the upper Langtang Valley.** (A) Area of Langtang village prior to the earthquake on 17 March 2011. (B) Same area on 3 May 2015, after the earthquake. (C) Overview image/map of the upper Langtang Valley on 25 May 2015, annotated with a key avalanche flow route (black line). Images courtesy of Digital Globe.

**Table S1. List of satellite sensors, platforms, and images used by and available to analysts for landslide analysis\***

Period	Sensor/Product	Images Used	Images Available
Pre-earthquake	Gaofen-1	1	1
	EO1 ALI	2	2
	GeoEye 1	2	15
	Planet Labs	--	3091
	LANDSAT 7	1	1
	LANDSAT 8	9	30
	WorldView 1	2	21
	WorldView 2	9	163
	WorldView 3	3	18
	LANDSAT 8 Mosaic	2	2
<b>Totals</b>		<b>31</b>	<b>3344</b>
Post-earthquake	EO1 ALI	4	32
	Planet Labs	--	7
	LANDSAT 7	3	10
	LANDSAT 8	6	68
	Terra ASTER	1	58
	WorldView 1	2	204
	WorldView 2	30	1066
	WorldView 3	4	561
	GeoEye 1	2	18
	Pleiades	--	1
	RADARSAT 2	--	2
	SPOT 6	--	4
<b>Totals</b>		<b>52</b>	<b>2031</b>

\* In addition, many of these same images, and a total of 7 WorldView 1, 60 WorldView 2, and 28 WorldView 3 images were used for the glacier lakes analysis.

**Table S2. Primary earthquake and aftershocks (> M6), April 25 - May 12, 2015**

USGS CUSP-ID	Mag	Epicentral Lat (dd)	Epicentral Lon (dd)	Date	Time (UTC)	W bound	S bound	E bound	N bound
us20002926	7.8	28.15	84.71	Apr-25 2015	06:11:26	81.7079	25.5013	87.7079	30.7933
us20002bi4	6.1	27.63	85.54	Apr-25 2015	06:15:22	82.5398	24.9705	88.5398	30.2865
us2000292y	6.6	28.19	84.86	Apr-25 2015	06:45:21	81.8645	25.5497	87.8645	30.8357
us200029bt	6.7	27.78	86.00	Apr-26 2015	07:09:10	82.9971	25.127	88.9971	30.437
us20002ejl	7.3	27.84	86.08	May-12 2015	07:05:19	83.0772	25.1848	89.0772	30.4888
us20002ek5	6.3	27.62	86.17	May-12 2015	07:36:53	83.1659	24.96	89.1659	30.276

USGS seismic data (35)

**Table S3: Sample of induced hazard events, or nonevents, and their local earthquake influences**

Location	Hazard Feature	Susceptibility Index ( <i>g</i> )	PGA (% <i>g</i> )	Comment
Langtang, Nepal	landslide / air blast	0.05 - 0.20	25.8*	village completely destroyed (many casualties)
Pisang, Nepal	landslides	0.03 - 0.10	10.5-13.3	series of dammed lakes in Marsyangdi R.
Chongsecun, China	landslides	0.10 - 0.15	22.1	Dammed lake
Resuo Bridge	landslides	0.15 - 0.20	26.2	Roads blocked
Everest Base Camp	avalanche / air blast	0.03 - 0.08	9.5	Portion of BC destroyed (casualties)
Imja Lake, Nepal	none identified	NA	8.8	intact
Tsho Rolpa, Nepal	none identified	NA	18.2	Intact, but ground fractures on moraine dam
Thulagi Lake, Nepal	none identified	NA	22.7	intact
Unidentified small lake near Lhotse Glacier	Small outburst flood	NA	9.3	Small outburst flood (from supraglacial pond?) caused alarm but no damage

\*represents only PGA values above the now demolished Langtang village; maximum values within the broader Langtang Valley are locally > 60% *g*.

## References and Notes

1. R. M. Parameswaran, T. Natarajan, K. Rajendran, C. P. Rajendran, R. Mallick, M. Wood, H. C. Lekhak, Seismotectonics of the April–May 2015 Nepal earthquakes: An assessment based on the aftershock patterns, surface effects and deformational characteristics. *J. Asian Earth Sci.* **111**, 161–174 (2015). [doi:10.1016/j.jseaes.2015.07.030](https://doi.org/10.1016/j.jseaes.2015.07.030)
2. J. Galetzka, D. Melgar, J. F. Genrich, J. Geng, S. Owen, E. O. Lindsey, X. Xu, Y. Bock, J. P. Avouac, L. B. Adhikari, B. N. Upreti, B. Pratt-Sitaula, T. N. Bhattarai, B. P. Sitaula, A. Moore, K. W. Hudnut, W. Szeliga, J. Normandeau, M. Fend, M. Flouzat, L. Bollinger, P. Shrestha, B. Koirala, U. Gautam, M. Bhattarai, R. Gupta, T. Kandel, C. Timsina, S. N. Sapkota, S. Rajaure, N. Maharjan, Slip pulse and resonance of the Kathmandu basin during the 2015 Gorkha earthquake, Nepal. *Science* **349**, 1091–1095 (2015). [Medline doi:10.1126/science.aac6383](https://doi.org/10.1126/science.aac6383)
3. E. O. Lindsey, R. Natsuaki, X. Xu, M. Shimada, M. Hashimoto, D. Melgar, D. T. Sandwell, Line-of-sight displacement from ALOS-2 interferometry: Mw7.8 Gorkha Earthquake and Mw7.3 aftershock. *Geophys. Res. Lett.* **42**, 6655–6661 (2015). [doi:10.1002/2015GL065385](https://doi.org/10.1002/2015GL065385)
4. K. Jaiswal, D. Wald, D. D'Ayala, Developing empirical collapse fragility functions for global building types. *Earthq. Spectra* **27**, 775–795 (2011). [doi:10.1193/1.3606398](https://doi.org/10.1193/1.3606398)
5. J. S. Kargel, G. J. Leonard, M. P. Bishop, A. Kääb, B. H. Raup, *Global Land Ice Measurements from Space*. (Springer-Verlag, Berlin Heidelberg, 2014).
6. E. L. Harp, D. K. Keefer, H. P. Sato, H. Yagi, Landslide inventories: The essential part of seismic landslide hazard analyses. *Eng. Geol.* **122**, 9–21 (2011). [doi:10.1016/j.enggeo.2010.06.013](https://doi.org/10.1016/j.enggeo.2010.06.013)
7. J. A. N. van Aardt *et al.*, Geospatial disaster response during the Haiti earthquake: A case study spanning airborne deployment, data collection, transfer, processing, and dissemination. *Photogramm. Eng. Remote Sensing* **77**, 943–952 (2011).
8. G. Cecchine *et al.*, “The U.S. Military Response to the 2010 Haiti Earthquake - Considerations for Army Leaders,” (RAND Corporation, 2013).
9. H. P. Sato, E. L. Harp, Interpretation of earthquake-induced landslides triggered by the 12 May 2008, M7.9 Wenchuan earthquake in the Beichuan area, Sichuan Province, China using satellite imagery and Google Earth. *Landslides* **6**, 153–159 (2009). [doi:10.1007/s10346-009-0147-6](https://doi.org/10.1007/s10346-009-0147-6)
10. British Geological Survey, Nepal earthquake response 2015 (available from <http://www.bgs.ac.uk/research/earthHazards/epom/NepalEarthquakeResponse.html>). (2015).
11. R. N. Parker, A. L. Densmore, N. J. Rosser, M. de Michele, Y. Li, R. Huang, S. Whadcoat, D. N. Petley, Mass wasting triggered by the 2008 Wenchuan earthquake is greater than orogenic growth. *Nat. Geosci.* **4**, 449–452 (2011). [doi:10.1038/ngeo1154](https://doi.org/10.1038/ngeo1154)
12. C. Xu, X. Xu, X. Yao, F. Dai, Three (nearly) complete inventories of landslides triggered by the May 12, 2008 Wenchuan Mw 7.9 earthquake of China and their spatial distribution statistical analysis. *Landslides* **11**, 441–461 (2014). [doi:10.1007/s10346-013-0404-6](https://doi.org/10.1007/s10346-013-0404-6)

13. R. M. Yuan, Q.-H. Deng, D. Cunningham, C. Xu, X.-W. Xu, C.-P. Chang, Density distribution of landslides triggered by the 2008 Wenchuan earthquake and their relationships to peak ground acceleration. *Bull. Seismol. Soc. Am.* **103**, 2344–2355 (2013). [doi:10.1785/0120110233](https://doi.org/10.1785/0120110233)
14. E. L. Harp, R. W. Jibson, R. E. Kayen, D. K. Keefer, B. L. Sherrod, G. A. Carver, B. D. Collins, R. E. S. Moss, N. Sitar, Landslides and liquefaction triggered by the M 7.9 Denali Fault earthquake of 3 November 2002. *GSA Today* **13**, 4–10 (2003). [doi:10.1130/1052-5173\(2003\)013<0004:LALBT>2.0.CO;2](https://doi.org/10.1130/1052-5173(2003)013<0004:LALBT>2.0.CO;2)
15. R. W. Jibson, E. L. Harp, W. Schulz, D. K. Keefer, Landslides triggered by the 2002 Denali fault, Alaska, earthquake and the inferred nature of the strong shaking. *Earthq. Spectra* **20**, 669–691 (2004). [doi:10.1193/1.1778173](https://doi.org/10.1193/1.1778173)
16. D. H. Shugar, J. J. Clague, The sedimentology and geomorphology of rock avalanche deposits on glaciers. *Sedimentology* **58**, 1762–1783 (2011). [doi:10.1111/j.1365-3091.2011.01238.x](https://doi.org/10.1111/j.1365-3091.2011.01238.x)
17. F. C. Dai, C. Xu, X. Yao, L. Xu, X. B. Tu, Q. M. Gong, Spatial distribution of landslides triggered by the 2008 Ms 8.0 Wenchuan earthquake, China. *J. Asian Earth Sci.* **40**, 883–895 (2011). [doi:10.1016/j.jseaes.2010.04.010](https://doi.org/10.1016/j.jseaes.2010.04.010)
18. D. H. Shugar, B. T. Rabus, J. J. Clague, D. M. Capps, The response of Black Rapids Glacier, Alaska, to the Denali earthquake rock avalanches. *J. Geophys. Res.* **117** (F1), F01006 (2012). [doi:10.1029/2011JF002011](https://doi.org/10.1029/2011JF002011)
19. R. N. Parker, G. T. Hancox, D. N. Petley, C. I. Massey, A. L. Densmore, N. J. Rosser, Spatial distributions of earthquake-induced landslides and hillslope preconditioning in the northwest South Island, New Zealand. *Earth Surface Dynamics* **3**, 501–525 (2015). [doi:10.5194/esurf-3-501-2015](https://doi.org/10.5194/esurf-3-501-2015)
20. S. G. Evans, O. V. Tutubalina, V. N. Drobyshev, S. S. Chernomorets, S. McDougall, D. A. Petrakov, O. Hungr, Catastrophic detachment and high-velocity long-runout flow of Kolka Glacier, Caucasus Mountains, Russia in 2002. *Geomorphology* **105**, 314–321 (2009). [doi:10.1016/j.geomorph.2008.10.008](https://doi.org/10.1016/j.geomorph.2008.10.008)
21. W. Haeberli, C. Huggel, A. Käb, S. Zraggen-Oswald, A. Polkvoj, I. Galushkin, I. Zotikov, N. Osokin, The Kolka-Karmadon rock/ice slide of 20 September 2002: An extraordinary event of historical dimensions in North Ossetia, Russian Caucasus. *J. Glaciol.* **50**, 533–546 (2004). [doi:10.3189/172756504781829710](https://doi.org/10.3189/172756504781829710)
22. J. S. Kargel, G. Leonard, R. E. Crippen, K. B. Delaney, S. G. Evans, J. Schneider, Satellite monitoring of Pakistan's rockslide-dammed Lake Gojal. *Eos Trans. AGU* **91**, 394–395 (2010). [doi:10.1029/2010EO430002](https://doi.org/10.1029/2010EO430002)
23. V. Vilímek, M. L. Zapata, J. Klimes, Z. Patzelt, N. Santillán, Influence of glacial retreat on natural hazards of the Palcacocha Lake area, Peru. *Landslides* **2**, 107–115 (2005). [doi:10.1007/s10346-005-0052-6](https://doi.org/10.1007/s10346-005-0052-6)
24. M. Carey, Living and dying with glaciers: People's historical vulnerability to avalanches and outburst floods in Peru. *Global Planet. Change* **47**, 122–134 (2005). [doi:10.1016/j.gloplacha.2004.10.007](https://doi.org/10.1016/j.gloplacha.2004.10.007)

25. S. A. Dunning, N. J. Rosser, D. N. Petley, C. R. Massey, Formation and failure of the Tsatichhu landslide dam, Bhutan. *Landslides* **3**, 107–113 (2006). [doi:10.1007/s10346-005-0032-x](https://doi.org/10.1007/s10346-005-0032-x)
26. J. T. Weidinger, in *Natural and Artificial Rockslide Dams*, S. G. Evans, R. L. Hermanns, A. Strom, G. Scarascia-Mugnozza, Eds. (Springer, Berlin Heidelberg, 2011), pp. 243–277.
27. M. Geertsema, J. J. Clague, Pipeline routing in landslide-prone terrain. *Innovations* **15**, 17–21 (2011).
28. K. Hewitt, Disturbance regime landscapes: Mountain drainage systems interrupted by large rockslides. *Prog. Phys. Geogr.* **30**, 365–393 (2006). [doi:10.1191/0309133306pp486ra](https://doi.org/10.1191/0309133306pp486ra)
29. Materials and methods are available as supplementary materials on *Science Online*.
30. Y. Ogata, Statistical models for earthquake occurrences and residual analysis for point processes. *J. Am. Stat. Assoc.* **83**, 9–27 (1988). [doi:10.1080/01621459.1988.10478560](https://doi.org/10.1080/01621459.1988.10478560)
31. D. K. Keefer, Investigating landslides caused by earthquakes - A historical review. *Surv. Geophys.* **23**, 473–510 (2002). [doi:10.1023/A:1021274710840](https://doi.org/10.1023/A:1021274710840)
32. C. Xu, X. Xu, J. B. H. Shyu, Database and spatial distribution of landslides triggered by the Lushan, China Mw 6.6 earthquake of 20 April 2013. *Geomorphology* **248**, 77–92 (2015). [doi:10.1016/j.geomorph.2015.07.002](https://doi.org/10.1016/j.geomorph.2015.07.002)
33. A. Jarvis, H. I. Reuter, A. Nelson, E. Guevara, Hole-filled seamless SRTM data v4 (available at <http://srtm.csi.cgiar.org>). (International Centre for Tropical Agriculture (CIAT), 2008).
34. P. Meunier, N. Hovius, J. A. Haines, Topographic site effects and the location of earthquake induced landslides. *Earth Planet. Sci. Lett.* **275**, 221–232 (2008). [doi:10.1016/j.epsl.2008.07.020](https://doi.org/10.1016/j.epsl.2008.07.020)
35. H. T. Chou, C. F. Lee, S. C. Chen, in *Earthquake-Induced Landslides: Proceedings of the International Symposium on Earthquake-Induced Landslides*, K. Ugai, H. Yagi, A. Wakai, Eds. (2013), pp. 45–57.
36. L. Chen, X. Yuan, Z. Cao, L. Hou, R. Sun, L. Dong, W. Wang, F. Meng, H. Chen, Liquefaction macrophenomena in the great Wenchuan earthquake. *Earthq. Eng. Eng. Vib.* **8**, 219–229 (2009). [doi:10.1007/s11803-009-9033-4](https://doi.org/10.1007/s11803-009-9033-4)
37. P. L. Moore, N. R. Iverson, D. Cohen, Ice flow across a warm-based/cold-based transition at a glacier margin. *Ann. Glaciol.* **50**, 1–8 (2009). [doi:10.3189/172756409789624319](https://doi.org/10.3189/172756409789624319)
38. H. Blatter, G. K. C. Clarke, J. Colinge, Stress and velocity fields in glaciers: Part II. Sliding and basal stress distribution. *J. Glaciol.* **44**, 457–466 (1998).
39. N. Bo, J. Persson, in *Sliding on Ice and Snow: Physical Principles and Applications*. (Springer, Berlin, 1998), pp. 391.
40. J. T. Weidinger, Predesign, failure and displacement mechanisms of large rockslides in the Annapurna Himalayas, Nepal. *Eng. Geol.* **83**, 201–216 (2006). [doi:10.1016/j.enggeo.2005.06.032](https://doi.org/10.1016/j.enggeo.2005.06.032)
41. P. Deline *et al.*, in *Snow and Ice-Related Hazards, Risks and Disasters*, W. Haeberli, C. Whiteman, J. F. Shroder, Eds. (Elsevier, Amsterdam, 2015), pp. 521–561.

42. M. Geertsema, M. Chiarle, in *Treatise on Geomorphology*, J. F. Shroder, M. Stoffel, R. A. Marston, Eds. (Elsevier, Amsterdam, 2013), vol. 7: Mountain and Hillslope Geomorphology, pp. 217-222.
43. C. Liang, "Interferogram for ALOS2-track 48-swath ScanSARNominal14MHz; Feb 22, 2015 to May 3, 2015," UNAVCO InSAR Product, 10.7283/S2KW2R (2015).
44. R. W. Jibson, E. L. Harp, "Field reconnaissance report of landslides triggered by the January 12, 2010, Haiti earthquake," (U.S. Geological Survey Open-File Report 2011-1023, Reston, VA, 2011).
45. E. L. Harp, R. W. Jibson, Landslides triggered by the 1994 Northridge, California earthquake. *Bull. Seismol. Soc. Am.* **86**, S319–S332 (1996).
46. J. Stöcklin, Geology of Nepal and its regional frame: Thirty-third William Smith Lecture. *J. Geol. Soc. London* **137**, 1–34 (1980). [doi:10.1144/gsjgs.137.1.0001](https://doi.org/10.1144/gsjgs.137.1.0001)
47. B. D. Collins, R. W. Jibson, "Assessment of existing and potential landslide hazards resulting from the April 25, 2015 Gorkha, Nepal earthquake sequence," (U.S. Geological Survey Open-File Report 2015-1142, Reston, VA, 2015).
48. J. P. McCalpin, E. W. Hart, "Ridge-top spreading features and relationship to earthquakes, San Gabriel Mountains region, Southern California - Part B: Paleoseismic investigations of ridge-top depressions," *Final Technical Report, Contract 1434-HQ-GR-1026, National Earthquake Hazards Reduction Program* (U.S. Geological Survey, 2002).
49. R. D. Nason, in *The San Fernando, California, earthquake of February 9, 1971, U.S. Geological Survey Professional Paper 733*. (U.S. Geological Survey, Washington, DC, 1971), pp. 97-98.
50. S.-J. Lee, D. Komatitsch, B.-S. Huang, J. Tromp, Effects of topography on seismic-wave propagation: An example from northern Taiwan. *Bull. Seismol. Soc. Am.* **99**, 314–325 (2009). [doi:10.1785/0120080020](https://doi.org/10.1785/0120080020)
51. W. W. Immerzeel, L. Petersen, S. Ragetti, F. Pellicciotti, The importance of observed gradients of air temperature and precipitation for modeling runoff from a glacierized watershed in the Nepalese Himalayas. *Water Resour. Res.* **50**, 2212–2226 (2014). [doi:10.1002/2013WR014506](https://doi.org/10.1002/2013WR014506)
52. K. Fujita, T. Nuimura, Spatially heterogeneous wastage of Himalayan glaciers. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 14011–14014 (2011). [Medline](https://pubmed.ncbi.nlm.nih.gov/21611111/) [doi:10.1073/pnas.1106242108](https://doi.org/10.1073/pnas.1106242108)
53. S. Ragetti, F. Pellicciotti, W. W. Immerzeel, E. S. Miles, L. Petersen, M. Heynen, J. M. Shea, D. Stumm, S. Joshi, A. Shrestha, Unraveling the hydrology of a Himalayan catchment through integration of high resolution in situ data and remote sensing with an advanced simulation model. *Adv. Water Resour.* **78**, 94–111 (2015). [doi:10.1016/j.advwatres.2015.01.013](https://doi.org/10.1016/j.advwatres.2015.01.013)
54. C. Cadwalladr, Nepal earthquake: the village wiped off the map in a few terrifying seconds. (The Guardian, 2015).
55. ICIMOD, *Glacial Lakes and Glacial Lake Outburst Floods in Nepal*. (International Centre for Integrated Mountain Development, Kathmandu, Nepal, 2011), pp. 99.

56. J. J. Clague, S. G. Evans, A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quat. Sci. Rev.* **19**, 1763–1783 (2000). [doi:10.1016/S0277-3791\(00\)00090-1](https://doi.org/10.1016/S0277-3791(00)00090-1)
57. K. Fujita, A. Sakai, S. Takenaka, T. Nuimura, A. B. Surazakov, T. Sawagaki, T. Yamanokuchi, Potential flood volume of Himalayan glacial lakes. *Nat. Hazards Earth Syst. Sci.* **13**, 1827–1839 (2013). [doi:10.5194/nhess-13-1827-2013](https://doi.org/10.5194/nhess-13-1827-2013)
58. S. Ma, R. J. Archuleta, M. T. Page, Effects of large-scale topography on ground motions as demonstrated by a study of the San Gabriel Mountains, Los Angeles, California. *Bull. Seismol. Soc. Am.* **97**, 2066–2079 (2007). [doi:10.1785/0120070040](https://doi.org/10.1785/0120070040)
59. A. C. Byers, D. C. McKinney, E. A. Byers, “Post-earthquake assessment: Imja, Tsho Rolpa, and Thulagi glacial lakes in Nepal,” (U.S. Agency for International Development, 2015).
60. W. Schwanghart, A. Bernhardt, A. Stolle, P. Hoelzmann, B. R. Adhikari, C. Andermann, S. Tofelde, S. Merchel, G. Rugel, M. Fort, Oliver Korup, Repeated catastrophic valley infill following medieval earthquakes in the Nepal Himalaya. *Science* (2015). [10.1126/science.aac9865](https://doi.org/10.1126/science.aac9865)
61. A. Arendt *et al.*, “Randolph Glacier Inventory – A Dataset of Global Glacier Outlines: Version 4.0,” (Global Land Ice Measurements from Space, Boulder, CO, 2014).
62. U.S. Geological Survey, Earthquake Hazards Program (available from <http://earthquake.usgs.gov>). (2015).
63. M. R. Dhital, *Geology of the Nepal Himalaya*. Regional Geology Reviews (Springer, 2015).
64. L. S. Walsh, A. J. Martin, T. P. Ojha, T. Fedenczuk, Correlations of fluvial knickzones with landslide dams, lithologic contacts, and faults in the southwestern Annapurna Range, central Nepalese Himalaya. *J. Geophys. Res.* **117** (F1), F01012 (2012). [doi:10.1029/2011JF001984](https://doi.org/10.1029/2011JF001984)