

1 Geomorphic, Tectonic, and Geologic Controls of Geohazards Induced 2 by Nepal's 2015 Gorkha Earthquake

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21 ABSTRACT

22 The Gorkha earthquake (M 7.8) on 25 April 2015 and later aftershocks struck
23 South Asia, killing ~9,000 and damaging a large region. Supported by a large
24 campaign of responsive satellite data acquisitions over the earthquake disaster zone,
25 our team undertook a satellite image survey of the earthquakes' induced geohazards
26 in Nepal and China and an assessment of the geomorphic, tectonic, and geologic
27 controls on quake-induced landslides. Timely analysis and communication aided
28 response and recovery and informed decision makers. We mapped 4312 co-seismic
29 and post-seismic landslides and surveyed 491 glacier lakes for earthquake damage,
30 but found only 9 landslide-impacted lakes and no visible satellite evidence of
31 outbursts. Landslide densities are correlated with slope, peak ground acceleration,
32 surface dropdown, and specific metamorphic lithologies and large plutonic
33 intrusions.

36 Introduction

37 On 25 April 2015 and over the next several weeks, a major series of
38 displacements occurred ~15 km deep along the buried Main Himalayan Thrust without
39 breaking the surface (*I-3*). The main shock of the Gorkha earthquake (M 7.8, USGS;
40 epicenter 28.147°N, 84.708°E) was followed by ~257 aftershocks >M 3.0 including 5
41 ≥M 6.0 between 25 April and 10 June 2015. On 12 May, a M 7.3 aftershock struck ~150
42 km ENE of the main shock. The largest earthquakes caused a wide swath of death and
43 destruction in Nepal and within adjacent India, China, and Bangladesh. Some mountain

44 villages were shaken to complete destruction (c.f., 4), buried by avalanches and
45 landslides, or destroyed by powerful avalanche and landslide air blasts. The remote
46 locations and blocked roads and rivers meant that ground crews could not immediately
47 access many Himalayan valleys, and aircraft were insufficient for rapid assessment.

48 A satellite-based approach was adopted to examine the vast damaged region.
49 Satellite imagery was provided by NASA, DigitalGlobe, the Japan Aerospace
50 Exploration Agency (JAXA), MacDonalD Dettwiler and Associates (MDA), Planet Labs,
51 Spot Image, and the China National Space Administration, including imagery triggered
52 by the International Charter: Space and Major Disasters (<http://www.disasterscharter.org>).
53 A “Volunteer Group” of analysts from nine nations was organized by the University of
54 Arizona under the auspices of Global Land Ice Measurements from Space (GLIMS) (5)
55 initially to assess priority hazard situations and then to build a landslide inventory (6).
56 The group—most of the authors—contributed their input of mapped geohazards to a
57 broad ad hoc NASA-led interagency “Response Team.” To date, the group has
58 scrutinized optical imagery, ranging from 15 m resolution to <1 m, from Landsats 7 and 8,
59 the Advanced Spaceborne and Thermal Emission and Reflection Radiometer (ASTER)
60 onboard Terra, Advanced Land Imager on EO-1, WorldView-1, -2, and -3, GeoEye-1,
61 Pleiades, and Gaofen-1 (Table S1), and utilized radar data from ALOS-2 and
62 RADARSAT-2, and topography from the Shuttle Radar Topography Mission (SRTM).
63 Landslides not detectable at these scales would generally have lower human
64 consequences than larger landslides.

65 The Response Team, including the Volunteer Group, undertook one of the
66 broadest and fastest international emergency remote sensing and data analysis campaigns
67 ever led by NASA for any earthquake-affected region (7-9). Parallel, but independent
68 landslide mapping efforts have been undertaken by a joint British Geological Survey-
69 Durham University group (10) and other groups.

70 During previous earthquake emergencies in mountainous terrain (e.g., Wenchuan,
71 China; Denali, Alaska), landslides were numerous (9, 11-17), sometimes initiating a
72 process chain of secondary and tertiary geomorphic processes over time-spans ranging
73 from minutes to years after the earthquake (18). Landslide-initiated process chains may
74 involve gains in mobilized mass and destructive power through energy and mass transfer
75 cascades. Many documented or inferred examples exist, including rock/ice fall-generated
76 debris avalanches that transformed into debris flows (19, 20) or caused large
77 impoundment lakes and upstream flooding (21); landslide-generated displacement waves
78 and glacier lake outburst floods (GLOFs) (22, 23); and landslide-dammed lake outbursts
79 (24, 25). As debris, ice, lake and stream water are ingested into an outburst flood, a debris
80 flow or hyper-concentrated slurry flood may result (e.g. 20). Each geomorphic process in
81 the chain may trigger a subsequent geohazard and extend the damaging reach of the event
82 (26, 27). Process chains involving GLOFs are particularly worrisome.

83 The Volunteer Group’s work focused on systematic mapping of quake-induced
84 geohazards, understanding the geomorphic, lithologic and tectonic control of their
85 distribution, and the identification of communities and infrastructure that might be
86 affected. Using mainly satellite-based findings, supplemented with media reports and
87 eyewitness photography, a rapid field assessment by the U.S. Geological Survey (USGS),
88 and modeling of lake outburst flood processes, we analyze the distribution and character
89 of the geohazards induced by the Gorkha earthquake in Nepal and Tibet.

90

91 **Landslide mapping and assessment**

92 We mapped the distribution of 4,312 earthquake-induced (co-seismic and post-
93 seismic) landslides (Fig. 1). Six Areas of Interest (AOIs) were identified; including from
94 west to east: Annapurna, Manaslu, Ganesh Himal, Langtang, Cho Oyu, and Everest (Fig.
95 S1). The AOIs together cover 375 x 155 km, with divisions set along major valleys. Each
96 AOI team had remote sensing and landslide expertise and was assigned an experienced
97 lead analyst. Volunteer image analysts were distributed based on interest, experience, and
98 need.

99 Multispectral satellite images from many government and commercial sensors
100 (Table S1) were made available via a number of portals, including the DigitalGlobe
101 website, the USGS Hazards Data Distribution System (HDDS), and USGS Global
102 Visualization Viewer (GLOVIS). Additionally, NASA provided access to expedited post-
103 earthquake targeted ASTER imagery within the affected region. The database and AOI
104 details are described in (28).

105 The highest densities of earthquake-related landslides are distributed in a broad
106 swath between the two largest shocks, where many aftershocks occurred as well; clusters
107 of landslides also exist outside of this zone (Fig. 1). The high landslide densities also lie
108 between three >M7.0 earthquakes that occurred on 26 August 1833, 25 April 2015 and 12
109 May 2015. This point is worth considering in the context of possible long-term effects of
110 historic quakes. However, we assessed the landslide occurrences only within the context
111 of the Gorkha earthquake and aftershocks and the terrain characteristics, broadly
112 organized according to (i) surface slopes and the earthquakes' seismic peak ground
113 accelerations (PGAs), (ii) broad-field deformation due to the earthquakes, and (iii) the
114 distribution of underlying landcover, lithology and tectonic structure.

115 As a caveat, among the shaking parameters, PGA is just one factor that may
116 control whether land surface failures occur in response to an earthquake. The specific
117 frequency content, shake duration, PGA direction, and recurrent shocks also may be
118 important (c.f., 29). Furthermore, the landslides caused by the Gorkha earthquake and
119 aftershocks appear to be far fewer than expected when compared to other mountainous
120 regions with similar magnitude earthquakes (30, 31). This might be due to the lack of
121 surface ruptures induced by the Gorkha earthquake and the concentration of deformation
122 along the subsurface thrust-fault at 10-15 km depth (2).

123

124 **Landslide distribution: control by shaking and slope**

125 The locations of the Gorkha earthquake-induced landslides are plotted in Figure 1
126 with landscape physiography and the epicenters of the six largest shocks (1A), PGA (1B),
127 reported deaths (1C), and slope (Fig. 1D). Fig. 1E represents the smoothed landslide
128 density distribution. We also computed and mapped the susceptibilities of the landscape
129 to earthquake-induced mass movements of ice, snow, or rock (Fig. 2). The computed
130 susceptibilities depend on the product of the sine of slope (32) and the PGA (from the
131 USGS ShakeMap PGA, Fig 1B). The distribution of lakes that were examined in satellite
132 images for earthquake-related damage is shown on a base map of PGA in Fig. 2D
133 (discussed below).

134 Integration of slope and shaking (represented by PGA) within the susceptibility
135 index partly accounts for where landslides occurred (Fig. 2), especially where collapse of
136 high-elevation snow and ice may have been involved (Figs. 2B, 2C). The landslide
137 distribution shows the strongest associations with slopes $>30^\circ$ (Fig. 1C, 3A), PGA >0.32
138 g (Fig. 2A, 3B), and shake-induced landslide susceptibility index >0.16 g (Fig. 2A). We
139 infer that many of these landslides probably would not have occurred anytime soon
140 without earthquake shaking. The control of landslide occurrences by the steep Himalayan
141 slopes and seismic shaking is unsurprising and similar to other well-documented
142 earthquakes (33). However, landslide susceptibilities differ from quake to quake. These
143 new results detail the relationships of this Himalayan earthquake to seismic and
144 geologic/terrain parameters.
145

146 **Fig. 1. Location of 4312 earthquake-related geohazard.** (A) Distribution of glaciers (blue), late-season
147 snowfields (red), landslides (white dots), and main shock and largest aftershock epicenters. The base
148 topography is from the SRTM 90 m gap-filled DEM (32). Glacier extents are from the Randolph Glacier
149 Inventory (RGI) (34). Snowfields were derived from pre-event Landsat-8 VNIR-SWIR band ratios and
150 topographic masks. (B) Landslides plotted with local peak ground accelerations induced by the main
151 Gorkha shock or $>6M$ aftershocks. PGAs from U.S. Geological Survey's USGS-NEIC ShakeMap (35).
152 Inset panels b1 and b2 are enlarged to show details near Langtang and Pisang. (C) Landslides plotted with
153 reported deaths per Nepal district are from the Government of Nepal, Nepal Disaster Risk Reduction
154 Project. (D) Hazard occurrences (black dots) on calculated slopes. Inset shows detail of hazard-dense
155 region. (E) Smoothed area density (log scale) of earthquake-induced landslides determined using a
156 neighborhood $1/8^\circ \times 1/8^\circ$ search window (~ 14 km \times 12 km) in relation to major ($\geq M6$) epicenters of
157 historic earthquakes and the Gorkha quakes (35). Densities range between 0.01 - 3.37 landslides/km².
158 Higher landslide densities occur locally on scales finer than $1/8^\circ$.
159

160 **Fig. 2. Debris landslide susceptibility with mapped hazards.** (A) Susceptibility in units of acceleration
161 divided by g (9.81 m s^{-2}). (B) Snow avalanche susceptibility with mapped hazards. Susceptibility in g. (C)
162 Ice avalanche susceptibility with mapped hazards. Susceptibility in g. (D) Maximum PGA experienced by
163 491 glacier lakes. Mapped hazards shown as white dots. Maximum PGA for glacier lakes was 0.57g. Insets
164 show detail is Langtang Valley.
165

166 As PGA attains several tenths of g, shake-induced coseismic failures are not
167 restricted to materials and terrains that were already poised near failure; whole
168 mountainsides can collapse. Whereas landsliding on steep, strongly shaken slopes is
169 easily understood, the tail of the landslide distribution to low shaking values, to low
170 slopes, and low (but non-zero) shaking-induced landslide susceptibilities (Fig. 3) requires
171 further explanation. The mechanisms outlined below may produce landslides or
172 avalanches at low but non-zero shaking in granular materials occurring on steep slopes, in
173 water-saturated sediments, and on steeply sloping, basally melted glaciers. The deadly
174 Mount Everest ice/snow avalanches on 25 April 2015 exemplify this point, where
175 shaking was a low 0.09 g (Table S3). Slopes there are steep, and glacier ice and snow are
176 commonly poised near failure as indicated by Everest's history of ice avalanches,
177 including back-to-back years of record 16 avalanche deaths in April 2014 (triggered by
178 spring melting) and 22 in April 2015 (earthquake-triggered). Many Himalayan glaciers
179 are substantially avalanche-fed, and snow or ice avalanches may occur upon a slight
180 prompt, whether due to heavy winter or monsoon snowfall, or spring melting, or slight
181 shaking. The Gorkha earthquake struck soon after another year of spring melting began,
182 and Everest's ice and snow probably again was near collapse. Landslides in the upper

183 Marsyangdi Valley (described below) also experienced relatively weak shaking (0.11-
 184 0.13 g), but involved unconsolidated fluvial gravels and lacustrine silts (36).
 185 Under the following conditions, low seismic PGAs—a few percent of g —may cause
 186 failures that lead to a landslide or avalanche if the materials are already near failure:
 187 [1] Granular materials may accumulate near the angle of repose, making them
 188 susceptible to coseismic failure due to lateral acceleration in a direction opposing the
 189 slope or related to rapid coseismic vibration-induced creep (37).
 190 [2] Seismic vibrations may cause water-saturated sediment to undergo liquefaction,
 191 disturbances to the local hydrology, and coseismic or postseismic flow or rotational
 192 slumping (38).
 193 [3] For polythermal glaciers, the frictional resisting force may be carried by small basally
 194 frozen domains (39). Sharp lateral accelerations may fracture the bed’s frozen
 195 attachments, thereby suddenly reducing the frictional force and initiating sliding.
 196 [4] Motion of basally melted glaciers or of rock on fracture planes is resisted by the
 197 frictional force at the slip plane (40). Reduction in the normal stress due to
 198 downward acceleration, or increase in the lateral driving shear stress due to seismic
 199 lateral acceleration may initiate coseismic slip on steeply sloping slip planes.
 200 [5] Upward acceleration increases the normal stress and may induce transient pressure
 201 melting of basal polythermal ice, thereby reducing the frictional force; the
 202 subsequent downward seismic acceleration suddenly relieves the normal stress, such
 203 that pressure-melted basal ice (which might not refreeze) may initiate sliding (41).

204
 205 **Fig. 3. Histograms of landslide occurrences.** Landslides with respect to: (A) slope, (B) peak ground
 206 acceleration, and (C) landslide susceptibility index. All plots $n = 4312$.
 207

208 Seismic reactivation of pre-seismic landslides, or hydrological reactivation of
 209 earthquake-triggered landslides may be common where landsliding already is frequent.
 210 Hydrological reactivations may be caused by precipitation runoff, spring discharge, or
 211 erosional undercutting of river banks. Image time series indicate that many mapped
 212 landslides, e.g., in the Marsyangdi Valley (Fig. 11), were post-main shock. In general
 213 these might be attributable to a host of factors, e.g., aftershocks; failure of earthquake-
 214 disturbed hanging glaciers or debuttressed slopes (42, 43); degradation of mountain
 215 permafrost and glacier-permafrost interactions (42); extreme precipitation; and stream
 216 undercutting of poorly consolidated sediment banks that were already disturbed by the
 217 earthquake. These mechanisms involve the supply of ground water or glacial erosion or
 218 melting of ice; hence, there must be links to climate change, however indirect.
 219

220 **Landslide distribution: control by the broad-field seismic deformation**

221 Another key earthquake phenomenon is the wide-field land surface deformation
 222 pattern, which appears to have influenced the distribution of landslides (Fig. 4). The
 223 mapped surface deformation was derived from Synthetic Aperture Radar Interferometry
 224 (InSAR, Fig. 4A). While the ALOS-2 InSAR measurement is in the radar line-of-sight,
 225 GPS measurements show that the horizontal motion is almost on the along-track direction,
 226 so the InSAR displacements in Fig. 4A are almost purely vertical (c.f., 3). The highest
 227 densities of landslides are correlated with the downdropped block, which is on the back-

228 limb of the hanging wall of the thrust structure and counter-intuitively correlates with the
229 higher Himalaya. Within this block, landslide densities increase southward and then
230 abruptly decrease near the tectonic hingeline, which separates the downdropped and
231 upthrown blocks (and also approximates the zone of maximum slip on the fault).
232 RADARSAT-2 data provide the horizontal displacement field over part of the
233 earthquake-affected region and confirm that the largest horizontal displacements (Fig.
234 4B) are near the hingeline and in the uplifted block as defined by vertical deformation
235 (Fig. 4A).

236 The distinctive concentration of earthquake-induced landslides in the tectonic
237 downdropped block of the Gorkha earthquake is not fully understood. The steep slopes
238 within the downdropped block no doubt contributed to the pattern of landslide densities,
239 but steep slopes are also present in some areas where landslides are few. A possibility is
240 that the net downward acceleration implied by the dropdown caused a momentary
241 reduction in lithostatic stress, hence a reduction of normal stress along inclined planes of
242 weakness. Relief of normal stress could have allowed nonlithostatic shear stress,
243 including lateral seismic acceleration, to initiate motion along landslide failure planes.
244 Because the coefficient of sliding friction is normally less than that of static friction,
245 motion may then continue and drive a landslide. The same mechanism may apply to
246 shaking, and hence, the broad-field deformation may impose a modulation on the
247 shaking-induced perturbation of normal stress, again suggesting some integration of
248 multiple causative trigger mechanisms.

249 The Gorkha earthquake caused fewer than expected landslides for an earthquake
250 of that magnitude (e.g., 12, 31), mirroring the relative paucity of destruction of dwellings
251 compared to what may have been expected (2). The peculiar distribution of the Gorkha
252 earthquake landslides on the downdropped block (Fig. 4) placed them mainly north of the
253 major population centers, no doubt reducing the death toll. For strike-slip events such as
254 the 2010 M7.0 Haiti earthquake (44), landslides were not similarly distributed
255 systematically with respect to the fault plane. In the 1994 M6.7 Northridge and 2008
256 M7.9 Wenchuan earthquakes (11, 12, 45), which like the Gorkha quake were both
257 oblique thrust events, landslides were concentrated on the up-thrown block, which were
258 also the higher, mountainous areas. The M7.9 Wenchuan 2008 earthquake induced far
259 more landslides than the Gorkha earthquake, despite similar steep terrain. These
260 differences might relate to the Gorkha quake's shallow dipping fault and lack of surface
261 rupture (a blind thrust).

262 The Northridge earthquake was also a blind thrust, and despite being smaller than
263 the Gorkha quake, it produced 11,000 documented landslides (45). Some, mapped by an
264 airborne survey, were smaller than the detection limit in the imagery used for our survey
265 where Digital Globe data were unavailable. The numerous slides caused by the
266 Northridge earthquake may be primarily attributed to uncemented clastic sedimentary
267 compositions dominating the regional lithology, versus more competent high-grade
268 metamorphic and igneous rocks dominating the higher Himalaya. The differing types and
269 densities of vegetation and root binding might also be a factor. In general, differences in
270 earthquake-induced landslide densities can also be related to the number and magnitude
271 of strong high-frequency ground motions, though the paucity of strong-motion recordings
272 in the cases of both the Gorkha and Wenchuan quakes hampers comparison.

273

274 **Fig. 4. Landslide distribution relative to the Earth surface deformation field.** (A) 4312 landslides
275 (yellow dots) are concentrated mostly north of the hinge-line between the downdropped block and uplifted
276 block. Also shown are the epicenters of the main shock and five largest aftershocks. Displacements are
277 from the JAXA ALOS-2 ScanSAR interferogram (21 Feb 21 and 2 May 2015 scenes), which represent
278 almost entirely vertical motion. ALOS-2 interferometry of the Gorkha earthquake and largest aftershock
279 was recently described by Lindsey et al. (3). (B) Horizontal motion map based on azimuth shift
280 measurements of the Radarsat-2 XF acquisitions of 5 April 5 and 29 April 2015. Scale shows motion
281 excluding outliers outside the mean $\pm 3\sigma$. Values are positive for SSW azimuths >100 degrees v. east.
282 Hence, both the upthrown and downdropped blocks shifted southward.

283

284 **Landslide distribution: control by lithology and major fault structure**

285 The local clustering indicates that there are additional controls on landslide
286 occurrence. Lithologic variations, sediment thickness, bedding dip direction relative to
287 slope aspect, extent of physical and chemical weathering, and vegetation cover may be
288 important controlling factors. No doubt, lithology has affected the occurrence of some
289 landslides; e.g., failure of, or ingestion of ice and unconsolidated glacial debris was
290 involved in the Langtang Valley slides, and poorly consolidated sediment dominated in
291 the Marsyangdi Valley landslides (both are discussed below). We now consider bedrock
292 lithology and the indirect control by fault structure (Fig. 5).

293 Fault structures exert indirect control of the clustering of landslides and
294 organization of clusters. Figure 5 shows high concentrations of landslides within
295 particular Proterozoic metamorphic units and intrusive complexes (described below) and
296 close to the surface traces of several major tectonic features, mainly low-angle thrust
297 faults including the South Tibetan Detachment System (STDS), Main Central Thrust
298 (MCT), Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT); the latter
299 three faults splay off the subsurface Main Himalayan Thrust, which is thought to have
300 slipped during these earthquakes (1). However, because none of the Gorkha earthquake
301 fault displacements (main shock or aftershocks) are known to have pierced the surface,
302 the association with the thrust faults might indicate underlying lithological control, where
303 the faults, over geologic time, have juxtaposed rocks of differing compositions at the
304 surface. Lithologic properties influence the topographic character of the landscape and
305 how seismic energy is transmitted, particularly through their (i) elastic and brittle/elastic
306 properties, (ii) chemical weathering and control on erosion and slope, (iii) fracture
307 development and fault displacement, and (iv) seismic wave interactions with topography
308 and lithological structures. Each factor likely contributes, where lithology is a common
309 denominator.

310

311 **Fig. 5. Landslide occurrence on mapped geologic units.** Geology from simplified geologic map by (46,
312 47)) and major faults (48).

313 A high density of landslides occurs within the upper Lesser Himalaya near and
314 east from the epicenter of the primary earthquake. Whereas this cluster's proximity to
315 the largest shock's epicenter is evident, the pattern defined by the cluster is closely
316 correlated with the outcrop of the upper Lesser Himalaya, which is composed of low- to
317 medium-grade metamorphosed Proterozoic argillic-calcareous (clay + sand) units and
318 with adjacent higher grade metamorphic Proterozoic rocks. The upper Lesser Himalaya

319 here is bounded on the north by the Main Central Thrust, where the overthrust rocks
320 are dominated by Precambrian gneisses, but only near the thrust contact does the latter
321 contain many landslides. Lithological control on landslide is evident, perhaps especially
322 where there is strong lithological contrast.

323 Many landslides occur south and west of Kathmandu (Fig 5) near the Main
324 Central Thrust (MCT) of the Kathmandu Nappe (a thrust sheet of Precambrian/Lower
325 Paleozoic meta-sedimentary rocks as mapped by Stöcklin (46). In these areas, landslides
326 are especially concentrated where Ordovician granitoids have intruded metasediments,
327 suggesting lithological contrast as a controlling feature. Remarkably, the north side of
328 the Kathmandu Nappe, though containing a similar sequence of rocks (but lacking large
329 granitoid intrusions), was not as strongly affected by earthquake-related landsliding; yet it
330 was closer to the primary shock.

331 Proterozoic slate, shale, siltstone, sandstone, and graphitic schist—all layered
332 rock types—host a low density of landslides (Fig. 5). Landslides have the most
333 heterogeneous distribution in the rock sequence indicated in Fig. 5 as Proterozoic phyllite,
334 amphibolite, metasandstone, and schist (and mapped by Stöcklin (46) as Precambrian
335 gneisses). The landslide density in this undifferentiated metamorphic rock sequence
336 ranges from very low to very high. The landslide hotspots comprise a small fraction of
337 the area of this widespread rock unit. Steep-sided, high-elevation ridgetops generated
338 some of the landslide hotspots in this geologic unit; for example Langtang Valley
339 landslides largely originated high on the ridges and near the summits in places where
340 glaciers, glacial debris, and bedrock failed. The lithological controls may be manifested
341 through rock mechanics and rock weathering and slope.

342 Wave interactions and influences on landsliding may also have been affected by
343 different rock types' contrasting speeds of s-, p-, and surface waves, resultant scattering
344 and wave interference, and heterogeneous energy dissipation as seismic waves traversed
345 the rugged Himalayan topography. Supporting the idea of local wave interactions, during
346 helicopter overflights authors B. Collins and R. Jibson (49) observed pervasive ridgetop
347 shattering through much of the landsliding region. In the Northridge earthquake (50)
348 ridgetop shattering was attributed to constructive wave interference and the focusing of
349 seismic energy into ridges. This phenomenon has also been modeled for the case of an
350 earthquake in a rugged area of Taiwan (51). Finally, damage related to wave resonance
351 occurred in the Kathmandu Basin during the Gorkha earthquake (2), and similar resonant
352 effects may have occurred elsewhere at damaging frequencies affected by the spatial
353 scales and geometry of various lithologic units. Human-built structures of different sizes
354 and construction, having unique resonant vibrational frequencies, were selectively
355 destroyed.

356 Some major river valleys also have high landslide densities, including along the
357 Marsyangdi and Trishuli rivers. In the Marsyangdi Valley, as described below, a high
358 landslide density correlates with relatively low-sloping areas of the valley floor that are
359 covered by poorly consolidated sedimentary deposits.

360

361 **Langtang mass movements**

362 The earthquake-induced landslides of the Langtang Valley (Figs. 6, 7) were
363 exceptional in their tragic results (over 350 killed) and are also among the Gorkha

364 earthquake's best documented landslides from field- and space-based analysis. Langtang
365 Valley, 70 km north of Kathmandu, was one of Nepal's major trekking regions and
366 hosted benchmark glaciology, hydrology, and meteorology research (52-54). The valley
367 experienced moderate shaking (up to ~0.26 g above Langtang village, Fig. 1B). An
368 analysis of post-event satellite imagery and oblique aerial photographs suggests that co-
369 seismic snow and ice avalanches and rockfalls and their massive concurrent air blasts
370 contributed to the destruction in Langtang Valley (Figs. 6, 7, 8, 9, 10) that killed or left
371 missing at least 350 people (55). Panoramic photos of Langtang taken in 2012 or
372 rendered from pre-seismic scenes in Google Earth, and those taken after the earthquake
373 on 12 May 2015 illustrate the magnitude and destruction of the Langtang events (Figs. 6,
374 7). Further indicating the vast scale of these events, annotated helicopter-borne photos
375 and satellite imagery taken of the valley (Figs. 8, 9, 10) illustrate our interpretation of this
376 disaster.

377
378 **Fig. 6. Pre- and post-earthquake panoramic photos from the base of the cliff above Langtang village.**
379 Photos by D.F. Breashears/GlacierWorks

380
381 Debris from the initial co-seismic event covered $7.51 \times 10^5 \text{ m}^2$ (Fig. 6) at Langtang
382 alone, including a ~1 km stretch of the Langtang Khola (river). Stream impoundment was
383 not observed in the days following the earthquake, thus indicating that meltwater and
384 runoff tunneling rapidly cut through the icy deposit. Photos (D. Breashears) showed that
385 the deposit contained large amounts of snow and ice. Melting resulted in the formation of
386 ponds, moist debris, and cold surface temperature anomalies of the landslide
387 (temperatures in the 270s K) relative to surrounding terrain (280s-290s K) according to
388 the brightness temperatures derived from thermal band 10 of Landsat 8 on 30 April 2015.

389 At Langtang village, the primary coseismic event was a combined ice-snow
390 avalanche, which initiated near 7000 m. Subsequently, rockfall material was entrained
391 with ice and snow and descended a low-gradient part of the glacier near ~4500 m. The
392 rock-ice mass then became airborne as it fell off a cliff below 4500 m (Fig. 8). After the
393 material reached the riverbed at ~3250 m, it ran up the opposing slope ~200 m (Fig. 9).
394 The air blasts propagated farther, 400 m up the mountain (Fig. 7). From the impact point
395 on the valley floor, devastation extended ~1 km up- and downvalley. From the 200 m
396 high surge of debris on the opposing slope we estimate a debris speed (v) of 63 m s^{-1} (227
397 km h^{-1}) following Eq. 1:

398
399
$$v = (2gh)^{0.5}$$

400
401 where g is gravitational acceleration (9.8 m s^{-2}), and h is the runup. Landslide winds
402 leveled what wasn't buried in Langtang, including some buildings constructed of stone
403 slab; wind also completely flattened a small forest, thus suggesting wind speeds
404 equivalent to an EF5 tornado (i.e., $>200 \text{ mph}$, $>89 \text{ m/s}$, $>322 \text{ km/h}$ wind speed),
405 consistent with freefall drop of the landslide and heavily debris-laden wind over the cliff.

406 Satellite images provided by Digital Globe (e.g., Fig. 10) indicate a second large
407 post-mainshock mass movement near Langtang village sometime before 25 May 2015.
408 The source of this landslide may have been a rock detachment from the summit ridge of
409 Langtang-Lirung, ~6700 m elevation. The second landslide slightly increased the debris

410 area from $7.51 \times 10^5 \text{ m}^2$ to $7.61 \times 10^5 \text{ m}^2$. At least one other large post-seismic landslide in
411 the valley took place between 8-10 May 2015.

412

413 **Fig. 7: Destroyed Langtang.** (A) Proximal landslide deposit (the landslide head) against steep slopes on
414 the north side of Langtang. The sole surviving structure in Langtang was protected by the cliff (lower right
415 of panel A). (B) Sole surviving structure has typical stone-slab construction on a foundation. (C, D) Distal
416 (toe) part of the landslide. The Langtang River has tunneled beneath the landslide. The deposit flowed
417 onto landslide wind-deposited debris, which has formed crevasses due to slumping toward the river. (E,F)
418 Forest of small trees flattened by a powerful blast of debris-laden, landslide-driven wind. (G,H) Small
419 post-seismic landslide and the wind-flattened forest. (I,J) Completely demolished wind-blasted part of
420 Langtang. Panels E and F by Randall Jibson. Others by David Breashears (7 May 2015).

421

422 Nearby settlements of Singdum and Mundu (Fig. 10) were also damaged by air
423 blasts from the Langtang Valley mass movements. The larger settlement of Kyangjin was
424 also badly damaged by an air blast created by another avalanche that originated from the
425 eastern ridge of Langtang-Lirung. Devastation in the air-blasted zones, as captured in
426 several photos (Fig. 7) is indicative of the huge energy involved. The first Langtang
427 landslide mass may be $\sim 3.3 \times 10^9 \text{ kg}$ (area $\sim 750,000 \text{ m}^2$, assumed mean thickness $\geq 2 \text{ m}$,
428 density 2200 kg m^{-3}). With a direct fall of $\sim 1 \text{ km}$ the release of gravitational potential
429 energy was $\geq 3.2 \times 10^{13} \text{ J}$ (7.6-kiloton TNT equivalent). During freefall and impact, the
430 main transfer of energy could only have been to the atmosphere and directly on the
431 surface, the effects of which we sadly observed.

432

433 **Fig. 8. Langtang's landslide flowpaths.** The source areas and flow path of the two Langtang mass
434 movements (white line, dashed where airborne). Red dashed line indicates the extent of the first slide;
435 yellow dashed line indicates extent of second slide; purple dashed line indicates extent of debris run-up.
436 West facing image. Stitched panorama from 10 May 2015; photos by D.F. Breashears/GlacierWorks.

437

438 **Fig. 9. Extent of airblasts.** West-facing aerial photo showing the extents of the air blast (dashed red line),
439 the initial debris deposits and run-up (dashed purple line), and the secondary rockslide (dashed yellow line);
440 photo 10 May 2015; D.F. Breashears/GlacierWorks).

441

442 **Fig. 10. Satellite images of the upper Langtang Valley.** (A) Area of Langtang village prior to the
443 earthquake on 17 March 2011. (B) Same area on 3 May 2015, after the earthquake. (C) Overview
444 image/map of the upper Langtang Valley on 25 May 2015, annotated with a key avalanche flow route
445 (black line). Images courtesy of Digital Globe.

446

447 **Landslide blockages of rivers: Marsyangdi and Tom Khola rivers (Nepal) and** 448 **Gyirong Zangbo/Trishuli River (Tibet)**

449 Recurrent landslides were identified along the upper Marsyangdi River in the
450 Annapurna region. These are a different type of landslide than present in Langtang
451 Valley. At least twenty mass movements intersected the river in the 10 days following the
452 main shock (Fig. 11). The rapid sequence of similar failures demonstrates that the quakes
453 in some way disturbed the unconsolidated sediments (36) along the river, perhaps by
454 altering the hydrology or opening soft-sediment fractures, which then were exploited by
455 spring seepage/erosion and rotational failures.

456 The Marsyangdi Valley experienced relatively weak shaking (to ~ 0.13 g, Fig. 1B,
457 Table S3), which triggered nine small landslides along a 16-km stretch of the upper
458 Marsyangdi River between Humde and Bratang (Fig. 11). The landslides were identified
459 from a WorldView-2 satellite image 27 April 2015, two days after the earthquake, but
460 were not present in a Landsat 8 image four days pre-quake; thus, they are considered
461 primary effects of the main shock. Some slumps constricted but did not greatly obstruct
462 the river. One landslide (Fig. 11) ~ 2.2 km upstream of Lower Pisang village caused a
463 small impoundment (135 m long, $\sim 2 \times 10^3$ m²).

464 Between 27 April and 2 May 2015, five more landslides reached the river,
465 including one ~ 200 m wide, which caused a complete blockage ~ 1.9 km upstream of
466 Lower Pisang. The impoundment grew to ~ 550 m long and 30-40 m wide ($\sim 1.4 \times 10^4$
467 m²) (Fig. 11). Six new landslides upstream then increased the lake to $\sim 2.5 \times 10^4$ m² and
468 1100 m long, the same as measured again on 28 May 2015. Upstream, several smaller
469 impoundments indicated a further hazardous situation where a dam breach could initiate a
470 succession of lower dam breaches and the inundation of Lower Pisang village.

471 Ground photographs (Fig. 11B) show a predominantly fine-grained landslide,
472 likely composed of fluvial gravels and lacustrine silts from former dammed lakes (36).
473 The steep headwall, back-tilted trees, and a sharp detachment at the head of the landslide
474 indicate that the slide is a rotational slump, a common failure mode in poorly supported,
475 unconsolidated sediments.

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

479 Many other cases of earthquake-induced landslide blockages of rivers occurred.
480 In one case, a 450 m-wide landslide blocked the lower Tom Khola (river) near Ghap,
481 Manaslu Conservation Area, Nepal, creating an impoundment lake that stirred urgent
482 humanitarian concerns. Satellite imagery from 3, 5, 7 and 8 May have allowed
483 monitoring of the dammed lake. Between 3 and 8 May, the lake grew from $\sim 5.7 \times 10^4$ m²
484 to $\sim 6.6 \times 10^4$ m². The nearby village of Ghap, located downstream of the confluence of
485 the Tom Khola and Budhi Gandaki rivers, fortunately showed no flood damage by 16
486 May, indicating that even though the lake was draining through a narrow outlet, the dam
487 erosion was gradual. A satellite image from 8 June and subsequent media coverage shows
488 that most of the lake had drained without severe consequences.

489 The Gorkha earthquake and its many aftershocks also triggered dozens of
490 landslides into the south-flowing Gyirong River, China (= Trishuli River downstream in
491 Nepal). One landslide dammed the river ~ 1.5 km south of Chongsecun, a few kilometers
492 north of the Nepalese border, causing development of a 450 x 50 m impoundment lake
493 (28.363N, 85.360E, $\sim 2,600$ m asl). The landslide destroyed ~ 200 m of the road that
494 connected Chongsecun to the China-Nepal border crossing at Resuo. Boulders and debris
495 were displaced downslope, forming a landslide scar ~ 700 m long and a deposit 250 x 300
496 m. Several landslides and a landslide-dammed lake also developed south of the
497 Chongsecun slide on or near the Resuo border crossing in Nepal (28.275N, 85.379E,
498 $\sim 1,810$ m asl) and blocked the road near the Resuo bridge. A field reconnaissance team
499 from the Chinese Ministry of Land and Resource visited the Resuo landslide on 4-5 May
500 2015 and estimated the landslide deposit to be $\sim 2.7 \times 10^6$ m³. This ranks it as the Chinese
501 side's largest landslide of the Gorkha earthquake and aftershocks. Fortunately, the dam

502 was incised by the river, and with mitigation efforts by engineers there was no further
503 damage.

504 Another landslide on the same river near Resuo was triggered by a rainstorm on
505 28 April 2015, with the terrain conditioned by the M7.8 Gorkha earthquake. The
506 landslide dammed the Trishuli Khola (river) and blocked the road from Gyirong County
507 to Resuo Port.

508 Due to these landslides, residents north of the border were trapped, unable to
509 travel by road north or south, unable to leave the dangerous earthquake-racked mountain
510 area. The interruption of cross-border commerce is a major tangible earthquake impact in
511 addition to the physical damage to infrastructure and the loss of life.

512 These features near Chongsecun and Resuo exemplify the transboundary process
513 chains of some induced hazards. Here, an earthquake in one country (Nepal), aggravated
514 by rainstorms and perhaps aftershocks, triggered secondary and tertiary hazards
515 (landslides and landslide-dammed lakes) in another country (China) and on the border.
516 Together they pose new hazards and economic disruptions to both countries.

517

518

519 **Fig. 11. Landslide-dammed lake on the Marsyangdi River.** Map and satellite imagery and ground
520 photographs of landslides and landslide-dammed lakes on upper Marsyangdi River. (A) Map. White box
521 locates panels C, D, E, and F. (B) Ground photograph (courtesy Mukhya Gotame, Manang villager) from
522 10 May 2015, showing the landslide-dammed lake looking south. White dashed line is the head scarp (note
523 steep headwall) and curved arrow shows inferred flow path of the rotational slump. (C,D,E,F): High-
524 resolution WorldView-2 images of the river, showing delayed occurrence of the large landslide and lake
525 formation. White star in D locates panel B. River widths are given at two locations.

526

527

528 **Fig. 12. Lake survey for earthquake damage.** Upper panel A) Overview of study area showing location
529 of 491 surveyed lakes. Lower panels B-J) pre-earthquake images (right column), post-main shock images
530 (center column) and post-12 May aftershock images (left column) for the largest glacial lakes in Nepal, B-
531 D), Thulagi Lake, E-G) Tsho (Lake) Rolpa, H-J) Imja Tsho. B) Landsat 8 image of Thulagi Lake, 21 April
532 2015. C) Worldview 2 image of Thulagi Lake, 27 April 2015. D) ASTER image of Thulagi Lake, 22 May
533 2015. E) Landsat 8 image of Tsho Rolpa, 11 November 2013. F) Worldview 1 image of Tsho Rolpa, 4 May
534 2015. G) EO-1 ALI image of Tsho Rolpa 17 May 2015. H) Landsat 8 image of Imja Tsho, 11 November
535 2013. I) EO-1 ALI image of Imja Tsho, 28 April 2015. J) Landsat 8 image of Imja Tsho, 25 May 2015. A
536 large crack developed in the lake ice on Imja Tsho, though such cracks are normal with spring thaw.
537 Landsat 8 scenes are panchromatic-band-8-sharpened images (resolution 15 m) using band combinations
538 [7,5,3] (SWIR, NIR, Green). WorldView 2 false color composite scene uses band combination [7, 5, 3]
539 (NIR, Red, Green). WorldView 1 image is the panchromatic band. ASTER image (resolution 15 m) uses
540 bands [3N, 2, 1] (NIR, Red, Green). EO-1 ALI scenes use pan-sharpened band 1 (resolution 10 m) and
541 band combination [8, 6, 4] (SWIR, NIR, Green).

542

543

543 **Glacier lakes stability**

544 Many glacial lake outburst floods (GLOFs) have been recorded in the Himalaya
545 since the mid-20th century (56). It is widely considered that the lakes' moraine dams—
546 commonly situated at the angle of repose—are fragile and prone to outburst due either to
547 sudden collapse or piping erosion, or to gradual degradation due to climatic warming and
548 thaw. Avalanche/landslide-generated displacement waves are thought to be a common
549 trigger for moraine dam failure (57). Thus, when the largest earthquakes happened, we
550 and many experts were concerned that shaking may have weakened or collapsed

551 unconsolidated moraine dams of glacial lakes, or may have triggered large displacement
552 waves and GLOFs.

553 Fortunately, few earthquake effects on glacier lakes were identified. We
554 examined pre- and post-quake satellite images of 491 lakes (locations drawn mainly from
555 the inventory of Fujita et al. (58)). Only nine were physically hit by landslides or
556 avalanches. Of these, ice avalanches may have ejected water from two small ponds near
557 Everest, and debris fell onto the frozen surfaces of other lakes without further effect. To
558 our knowledge, as of early September 2015 no lakes in the satellite survey produced a
559 GLOF as a result of the earthquake. GLOFs were primarily not triggered at modeled
560 PGAs up to 0.57 g (Fig. 2D). This unexpected result may relate to seismic wave
561 interactions with the topography, where, for shallow hypocenters, PGAs (i) are reduced
562 on valley floors, and (ii) are rapidly reduced by shielding across mountain ranges caused
563 by wave scattering on the topography and petrologic structure (51, 59). The visibility of
564 15 lakes in our database was unclear (partially shadowed or poor resolution image) but
565 their downstream drainages showed no signs of GLOFs.

566 Furthermore, we closely examined three large moraine-dammed glacial lakes
567 (Thulagi, Rolpa, and Imja, Fig. 12), which have been extensively surveyed, studied, and
568 monitored due to their GLOF risk (e.g., 56). At Thulagi Lake in the Manaslu region (just
569 west of the Tom Khola (river) blockage described above) and Imja Lake in the Everest
570 region, no damage was immediately evident in post-quake satellite imagery. However,
571 based on local media and a Sherpa leader, a small glacial lake south of Everest,
572 apparently a pond on Lhotse Glacier, drained on 27 May 2015, which resulted in an
573 anomalous rise in stream level. Small supraglacial ponds commonly drain suddenly due
574 to ice fracturing or other glacier dynamics, and it is unclear if this event was earthquake-
575 related. Besides the 491 lakes for which we have some kind of satellite observation, 24
576 other lakes had no clear image and so are unsurveyed.

577
578 **Fig. 13. Field visit identifies light damage at Tsho (lake) Rolpa.** (A) Post-earthquake image of Tsho
579 Rolpa appears identical to its appearance shortly before the earthquake. (B) Two areas of fractures
580 (outlined in white)—believed formed by the 12 May 2015 aftershock— were observed on the engineered
581 part of the end moraine from a helicopter during an inspection undertaken by the U.S. Geological Survey at
582 Tsho Rolpa. Photos from 27 May by Brian Collins (USGS), courtesy of USAID-OFDA (Office of Foreign
583 Disaster Aid).

584
585 Tsho Rolpa, located at the terminus of Trakarding Glacier in the Rolwaling
586 Valley, has been especially worrisome due to its location near the giant aftershock's
587 epicenter. Examination of WorldView 1 satellite images taken on 4 May—nine days after
588 the initial earthquake, and the NASA's EO-1 satellite image taken 17 May—five days
589 after the M7.3 aftershock—shows no definitive evidence that Tsho Rolpa's damming
590 moraine was damaged. Post-quake field photographs taken by the USGS on 27 May
591 show that the moraine was intact, and the lake was nearly brim full, as usual (Fig. 13A).
592 Another USGS photograph (Fig. 13B) shows fractures on the moraine dam—but not of a
593 type likely to be a problem. Since no ice exists in this part of the moraine, these cracks
594 appear to have been caused by slumping of moraine material toward the lake (1-1.5 m
595 horizontal and ~0.5 m vertical), probably due to earthquake. The satellite imagery and
596 field photographs do not demonstrate any new big additional concerns about the lake.

597 A caveat is that a small GLOFs and minor damage to moraines would not be
598 visible in satellite images. Furthermore, none of the methods applied to date—satellite
599 and ground or helicopter-borne inspections— can easily detect interior (subsurface)
600 structural damage that may make the metastable lakes even more subject to
601 outburst. “Absence of evidence is not evidence of absence,” a controversial quote made
602 famous by Carl Sagan, is clearly pertinent to our absent evidence of significant Gorkha
603 earthquake damage to lakes. We simply have not seen such evidence but cannot
604 conclude that there is no damage.

605

606 **Future Gorkha-earthquake-related landslides**

607 In coming years, hydrological processes may exploit earthquake-induced damage
608 and trigger more landslides (e.g., frost shattering and rockfalls at high elevations,
609 riverbank undercutting and rotational slumping in valleys). Conversely, high-magnitude
610 shaking-induced landslides, such as ridgetop failures that affected Langtang Valley, may
611 be less significant, unless additional strong aftershocks strike or unless high-elevation
612 melting takes place within seismically shattered rocks. However, earthquake-related
613 landslides will soon fade into the regional background frequency of landslide activity.

614 The incidence of landsliding was less for this earthquake than for some
615 comparable quakes elsewhere, and no large GLOFs were generated. Whether the same
616 will hold for a hypothetical future large Himalayan earthquake is uncertain. However,
617 future earthquakes generated on the shallow Main Himalayan Thrust are not apt to
618 generate many or any GLOFs unless the magnitude is greater than the Gorkha
619 earthquake’s or the hypocenter and zone of maximum slip is closer to the lakes, thus
620 circumventing the shielding by Himalayan relief. Ridgetop shattering is probably a
621 general behavior during big earthquakes. The potential exists for immense landslides and
622 river blockages, which may pose the greatest mountain hazard.

623

624 **Summary and Conclusions**

625 Our rapid, systematic mapping allowed us to investigate earthquake-induced
626 geohazard processes and provide information to relief and recovery officials on the same
627 timeframe as those operations were occurring. This work thus contributed to effective,
628 timely guidance to in-country authorities responsible for response and recovery. Key
629 findings were relayed through NASA, USGS, and the U.S. Agency for International
630 Development, and to Nepal-based experts at ICIMOD (International Centre for Integrated
631 Mountain Development) and DHM (Department of Hydrology and Meteorology,
632 Government of Nepal) and to the Nepal Prime Minister.

633 The mapped features document the large geographic extent of the Gorkha
634 earthquake’s impact on hazardous Earth surface processes and constrain their geophysical
635 limits and geomorphic, tectonic and geologic controls. The distribution of induced
636 landslides shows positive associations with slope and shaking intensity. More broadly the
637 highest areal densities of landslides are developed primarily on the downdropped
638 northern tectonic block. This might be explained by momentary reduction during
639 downward acceleration of the normal stress along planes of weakness. The largest two
640 shocks are bookends on the landslide distribution, as they are with the displacement field
641 and highest PGAs. Additional controls of landslide distribution are indicated by their

642 clustering within specific bedrock and surficial lithologies including Proterozoic
643 metamorphic rocks and Ordovician granitoids; in proximity to earthquake epicenters;
644 with high PGAs; and perhaps with seismic wave scattering and interferences.

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

650 The distribution of Gorkha earthquake-related landslides and the terrain
651 susceptibilities to earthquake-induced mass movements provides a basis from which to
652 predict future patterns of landsliding of earthquake-weakened ice, rock, and
653 unconsolidated sediments, especially as aftershocks and precipitation and snowmelt
654 events continue over the next few years. Whereas the Gorkha earthquake's tragic toll on
655 human lives and culture cannot be understated, some fortunate facts are that not a single
656 major GLOF was unleashed and the total number of landslides was far fewer than
657 generated by comparable earthquakes (56).

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660

661 **Data Availability**

662 The two chief databases produced by this work (landslides and glacial lakes) will be
663 redundantly available, immediately upon publication, at two web portals, one at ICIMOD
664 and one at Marshall Space Flight Center.

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667

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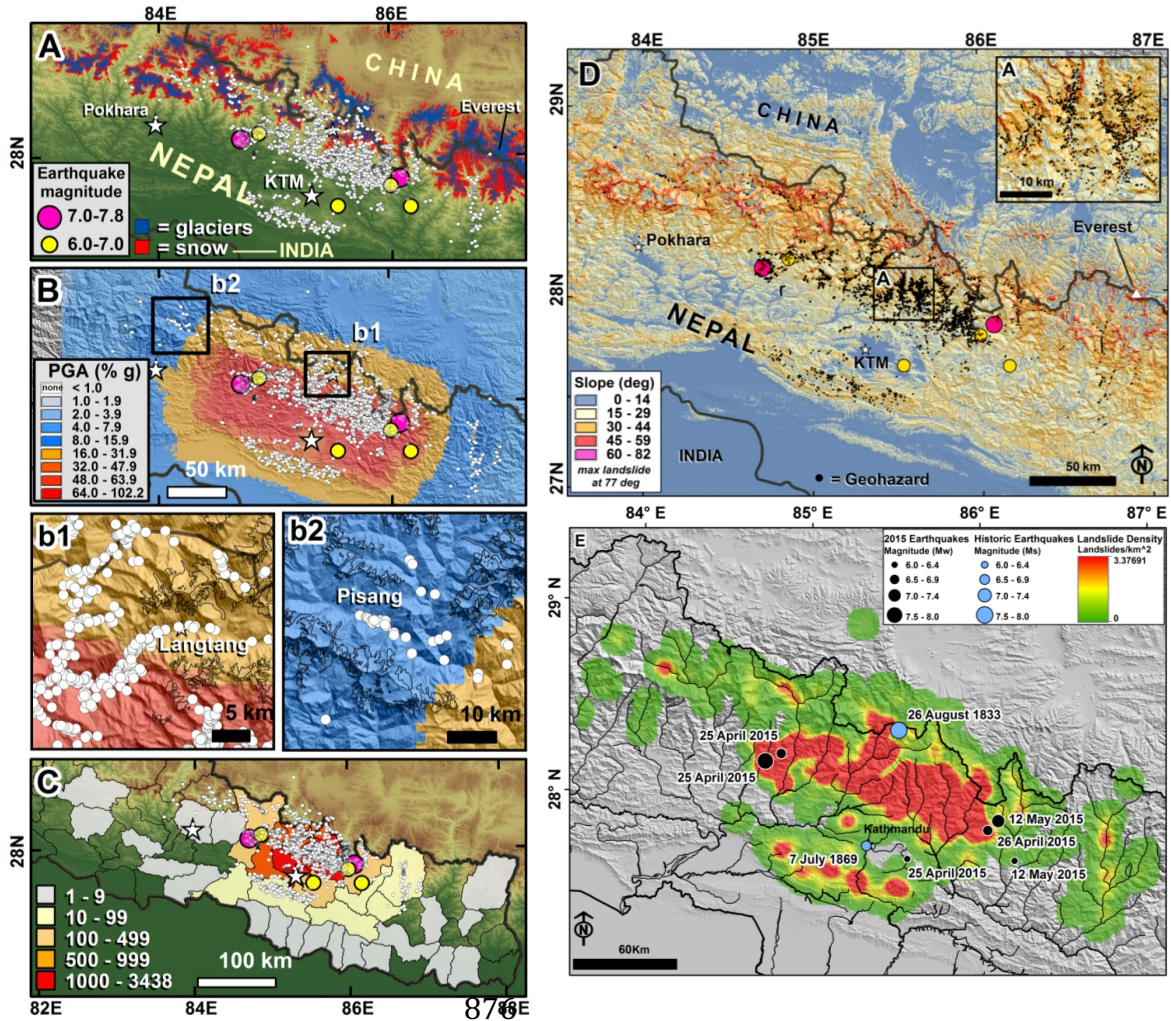


Fig. 1.

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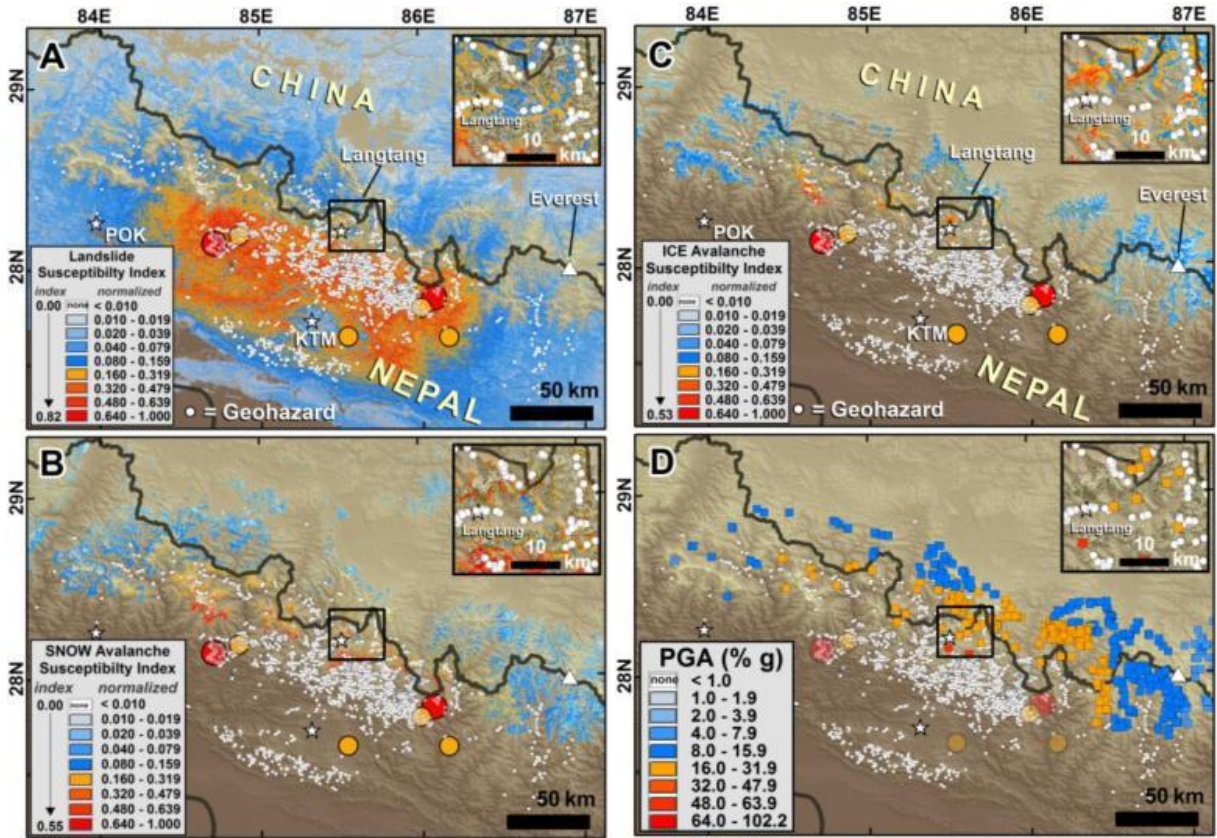
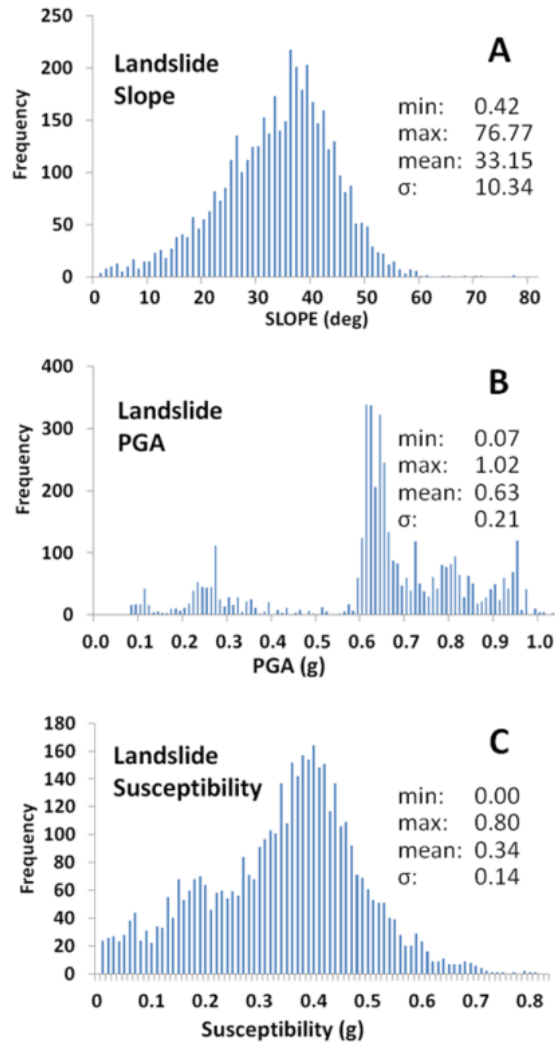


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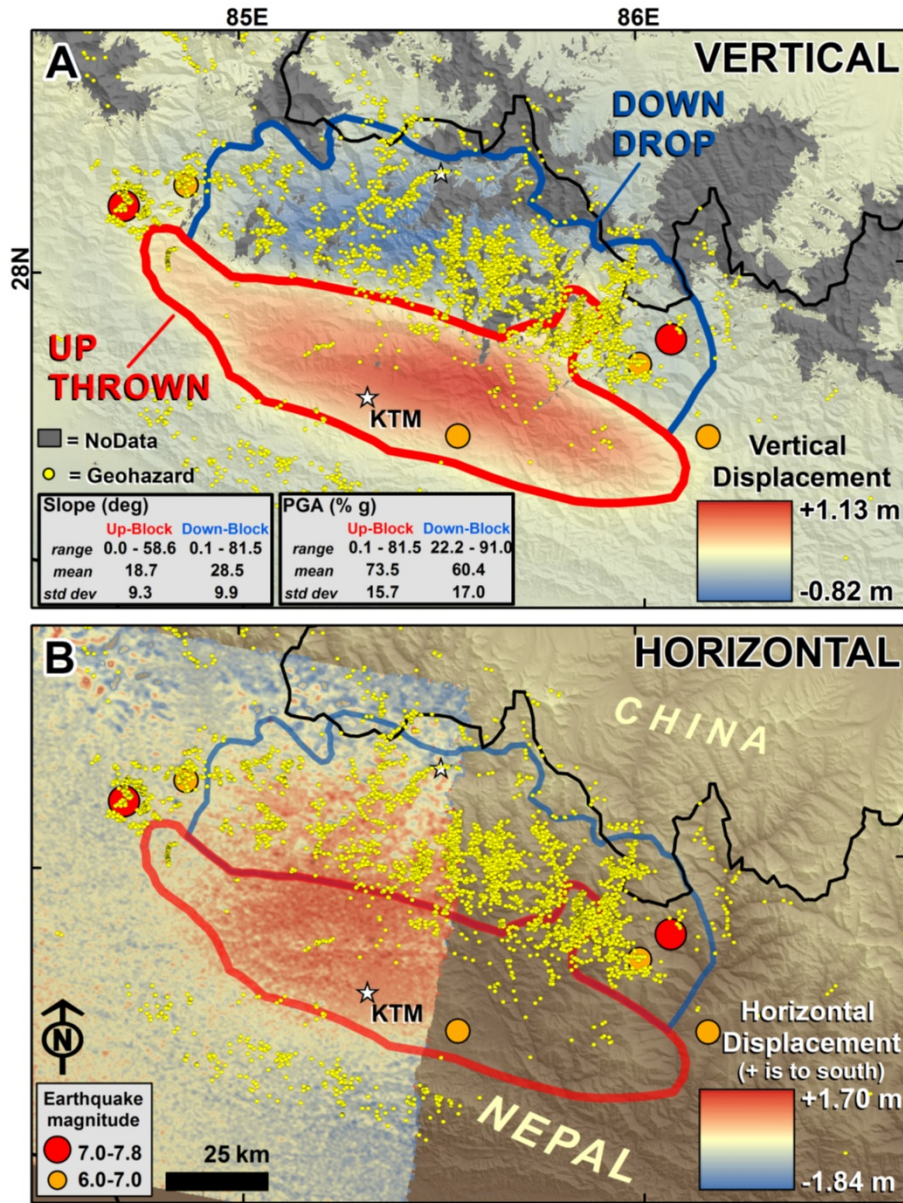
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Fig. 3.

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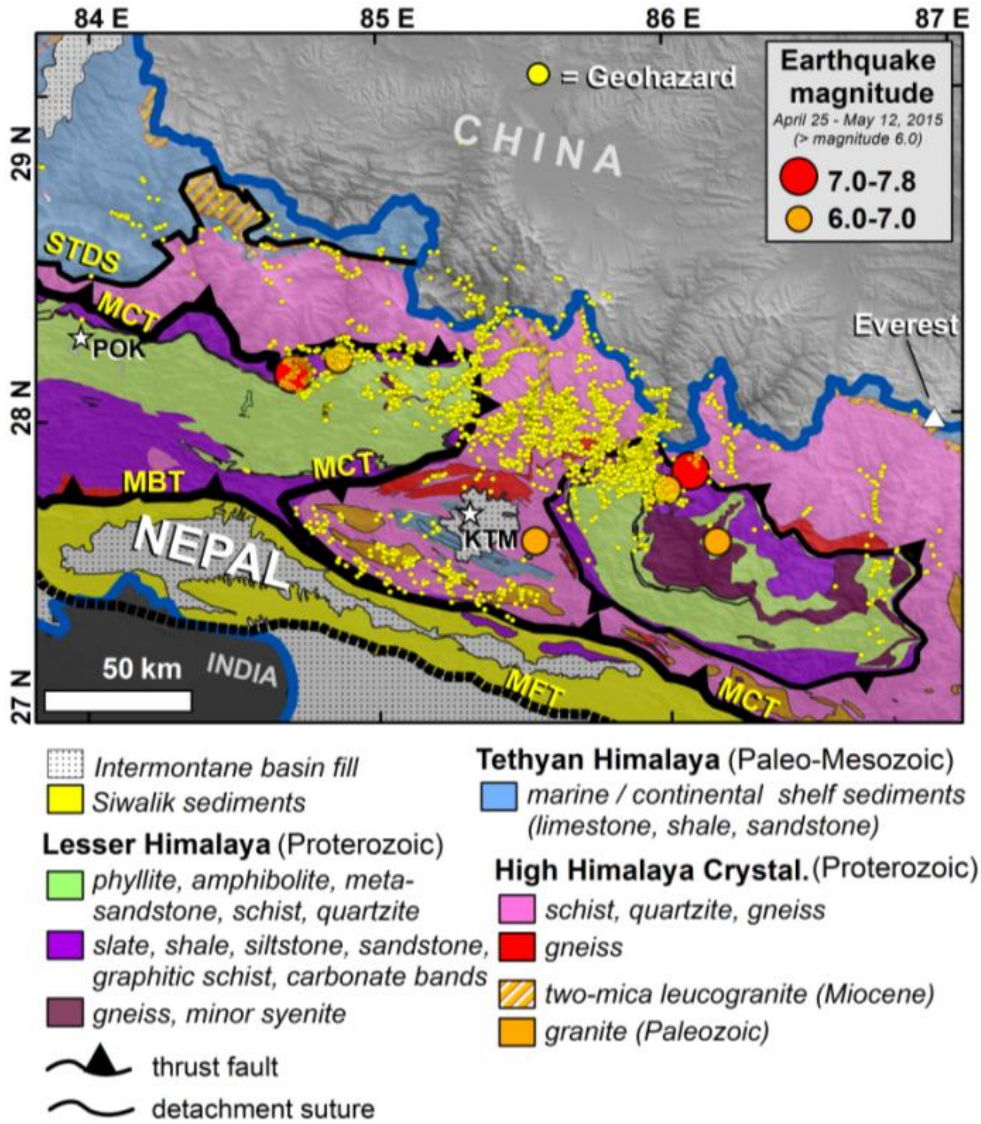


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941 Fig. 4.

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955 Fig. 5.

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Fig. 6.

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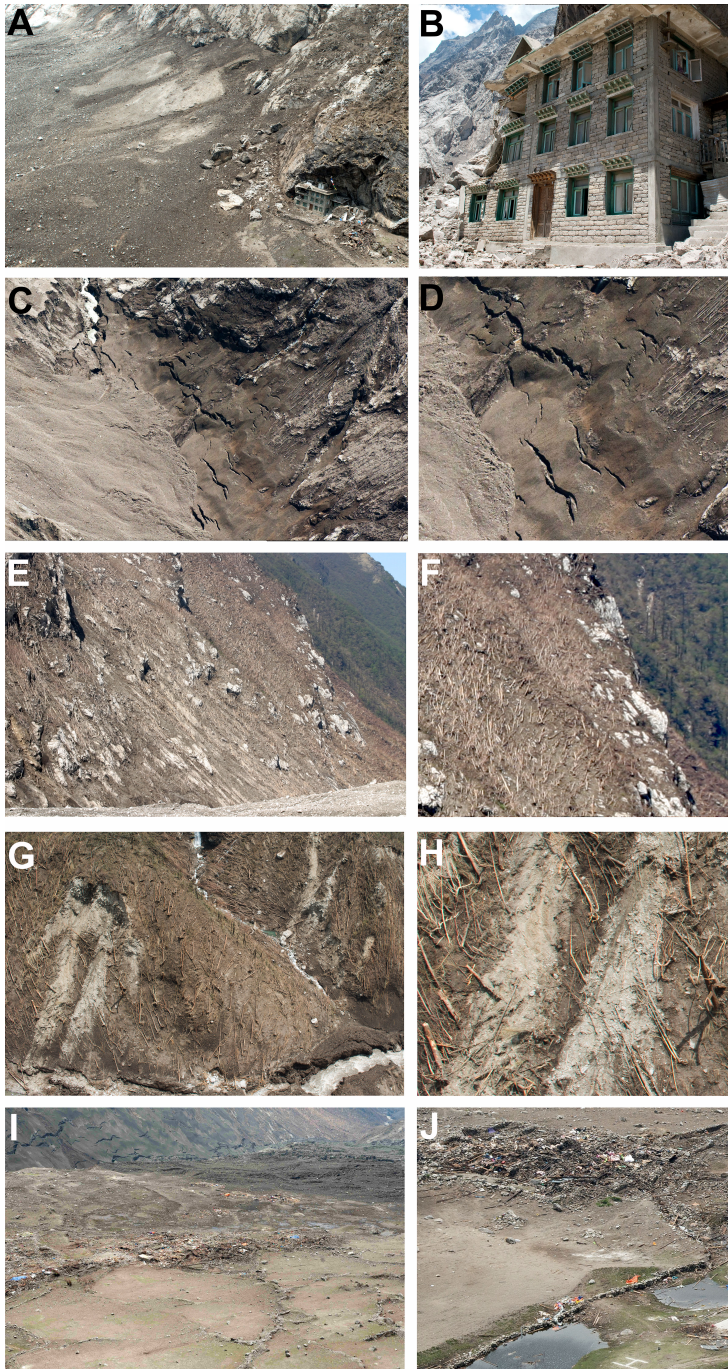
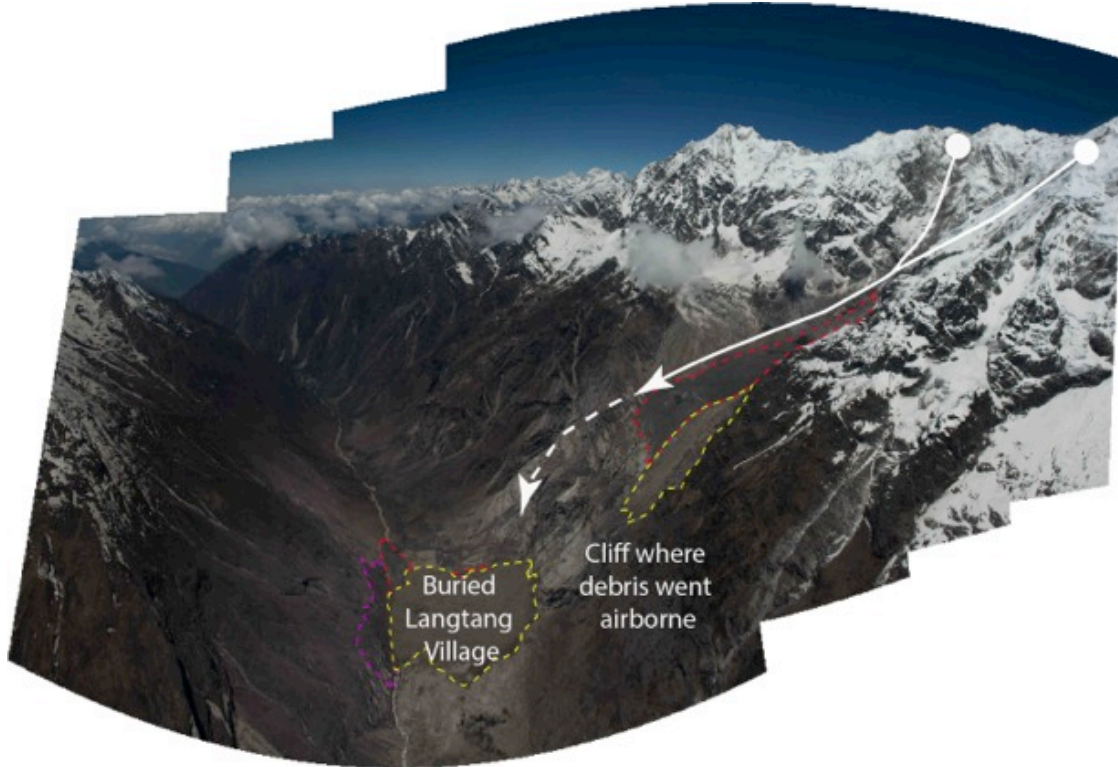


Fig. 7:

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Fig. 8.

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Fig. 9.

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Fig. 10.

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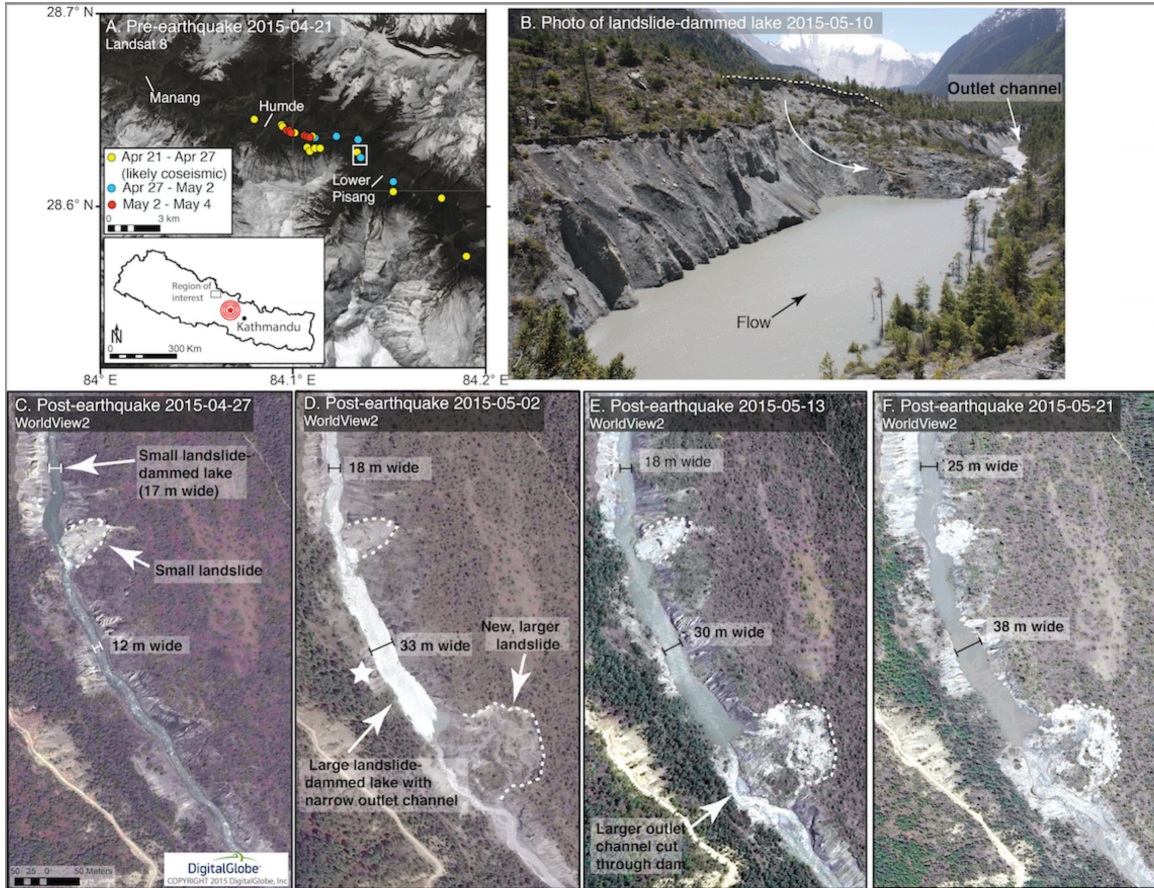


Fig. 11.

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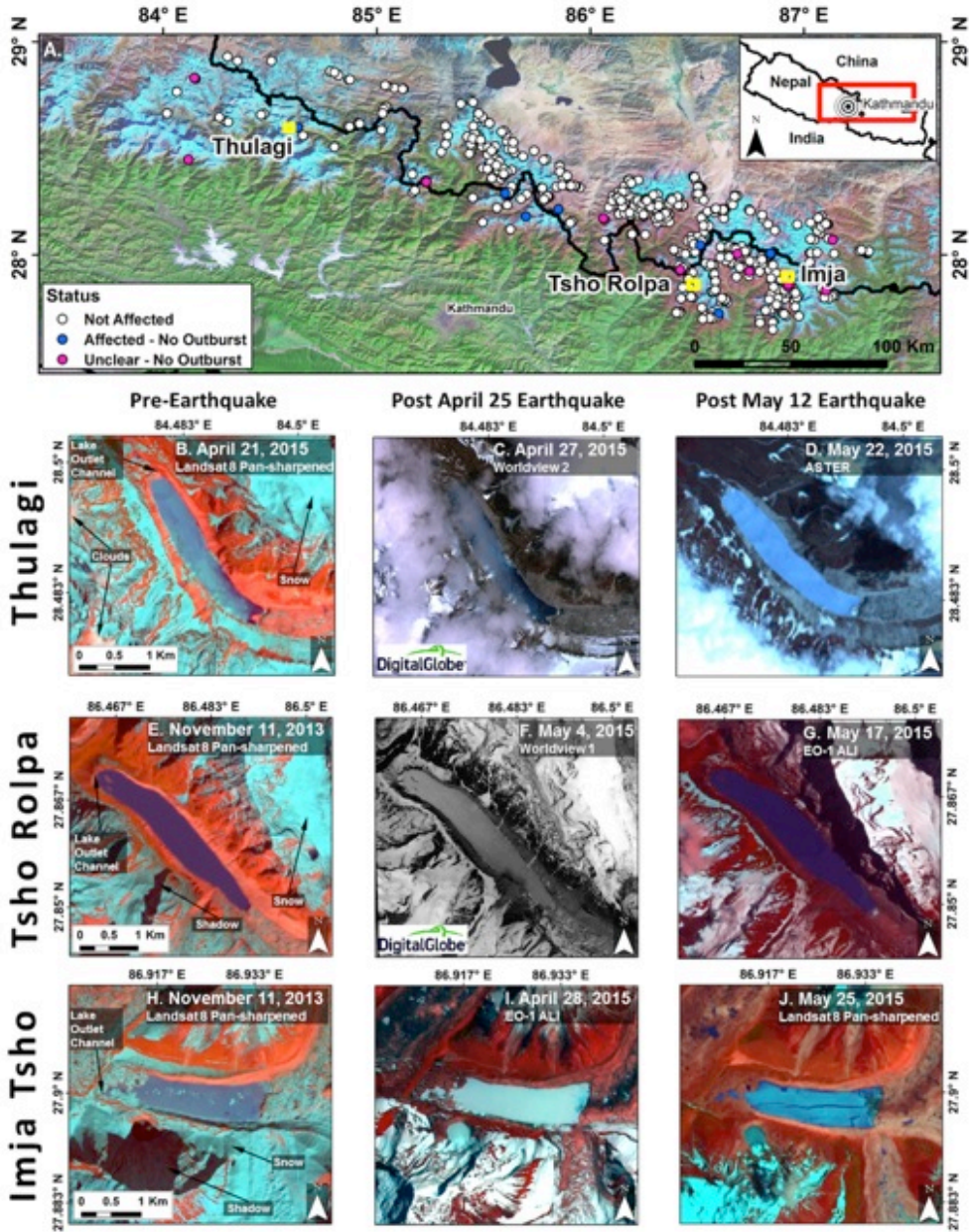
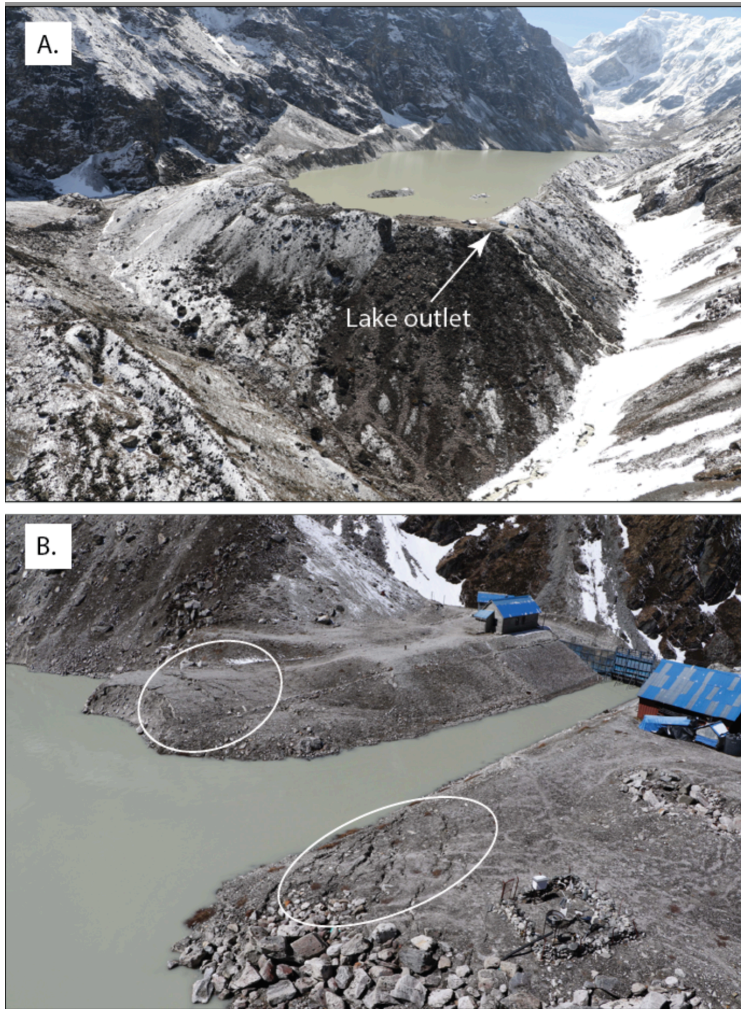


Fig. 12.

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Fig. 13.