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Landslides triggered by the 8 October 2005 Kashmir earthquake

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Abstract

The 8 October 2005 Kashmir earthquake triggered several thousand landslides. These were mainly rock falls and debris falls, although translational rock and debris slides also occurred. In addition, a sturzstrom (debris avalanche) comprising ~80 million m^3 buried four villages and blocked streams to create two lakes. Although landsliding occurred throughout the region, covering an area of >7500 km^2, the failures were highly concentrated, associated with six geomorphic–geologic–anthropogenic settings, including natural failures in (1) highly fractured carbonate rocks comprising the lowest beds in the hanging wall of the likely earthquake fault; (2) Tertiary siliciclastic rocks along antecedent drainages that traverse the Hazara–Kashmir Syntaxis; (3) steep (>50°) slopes comprising Precambrian and Lower Paleozoic rocks; (4) very steep (»50°) lower slopes of fluvially undercut Quaternary valley fills; and (5) ridges and spur crests. The sixth setting was associated with road construction. Extensive fissuring in many of the valley slopes together with the freshly mobilized landslide debris constitutes a potential hazard in the coming snowmelt and monsoon seasons. This study supports the view that earthquake-triggered landslides are highly concentrated in specific zones associated with the lithology, structure, geomorphology, topography, and human presence.

Keywords: Kashmir; Earthquake; Landslides; Himalaya

1. Introduction

At 8:50 a.m. (03:50 UTC) on 8 October 2005, an earthquake with a moment magnitude of 7.6, located in northern Pakistan (34.493°N., 73.629°E., depth of 26 km), shook Kashmir (USGS, 2006a: Fig. 1). This was the deadliest earthquake in South Asia's recent history, with >86,000 fatalities, >69,000 people injured, >32,000 buildings destroyed, and 4 million people left homeless. The earthquake triggered thousands of landslides throughout the region in an area of >7500 km^2, causing »1000 fatalities, destroying roads, and disrupting communications. Assessing the nature and distribution of landslides and other geomorphic consequences of such an event is essential for seismic hazard mitigation, for risk assessment and management, and

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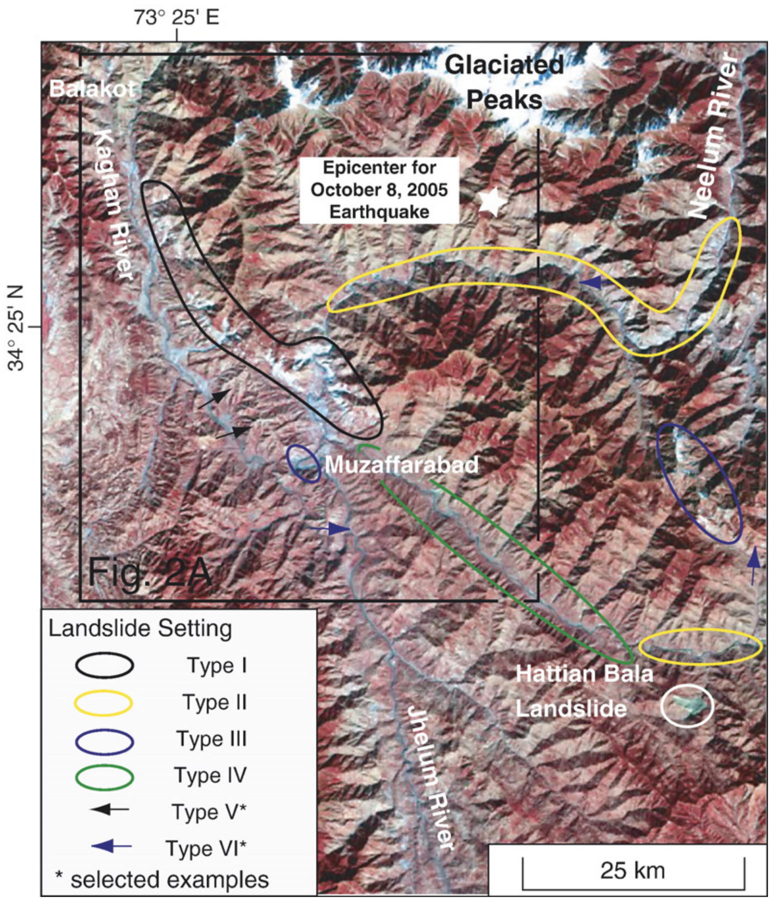

Fig. 1. ASTER image (taken 27 October 2005) of the main study area showing the location of the epicenter of the Kashmir earthquake and highlighting the areas of main landsliding. The image covers the extent of the study area.

for determining the role of earthquakes in landscape evolution. We visited the region in November and December 2005 to study the geomorphic consequences of the earthquake. Our research focused on characterizing the distribution and nature of the earthquake-triggered landslides. This paper describes the nature and distribution and characteristics of the landsliding produced by the earthquake.

2. Study area

Our study focused on an area of Azad Kashmir, N. Pakistan, covering an area of >750 km^2 that was centered on the earthquake's epicenter (Figs. 1 and 2). This region was chosen because ASTER and Quickbird imagery showed it to be the most affected by landsliding. The area is dominated by the Hazara–Kashmir Syntaxis, which is enclosed by the Main Boundary Thrust (MBT) with Tertiary clastics of the Murree Formation in the footwall of the MBT (Calkins et al., 1975; Hussain and Khan, 1996; Hussain et al., 2004). Other rocks within the syntaxis include dolomites and siliclastics of the Muzaffarabad Formation (Precambrian), Abbottabad Formation (Cambrian), and Lockhart Limestone (Paleocene) and shales of the Patala Formation (Paleocene). Structurally, rocks above the MBT comprise the Precambrian metasedimentary sequence of the Hazara and Tanawal Formations and the Cambrian Mansehra Granite. The earthquake epicenter was located on the northwestern side of the syntaxis along the NW–SE trending Kashmir Boundary Thrust (KBT), which was reactivated during the Kashmir earthquake (Baig, 2006; Yeats et al., 2006). This is supported by Synthetic Aperture Radar data, which shows a 90 km-long NW-SE trending belt of deformation with a general displacement of >1 m, reaching a maximum of 6 m north of Muzaffarabad (Fujiwara et al., 2006).

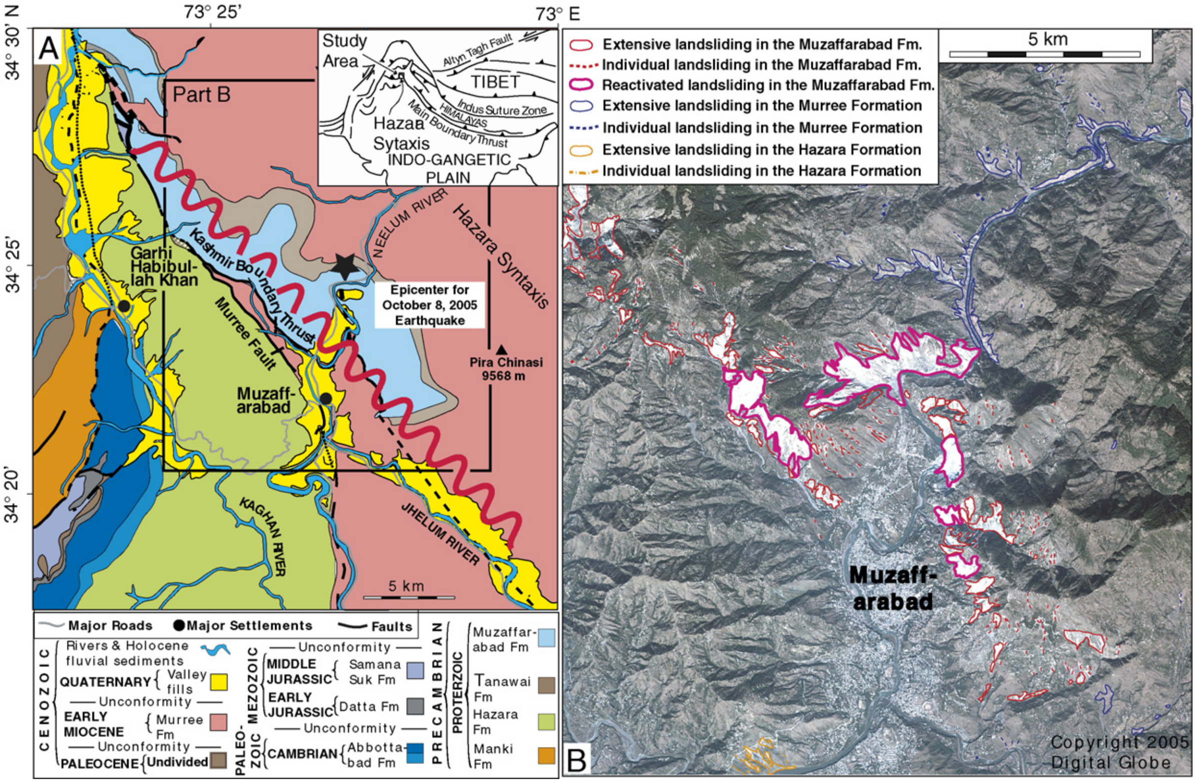

Fig. 2. (A) Simplified geological map of part of the study area (adapted after Calkins et al., 1975; Hussain and Khan, 1996; Hussain et al., 2004) and (B) Quickbird image showing the region of most extensive landsliding. The area of maximum surface rupture and uplift is indicated by the red wavy line (after Geographical Survey Institute, 2006; Avouac et al., 2006).

The study area is located within the Lesser Himalaya, which is deeply dissected with main valley floor altitudes rising from ~500 to >2000 m asl. Steep glaciated peaks are present rising to >3000 m asl, with a relative relief that exceeds 2500 m. The Jhelum River and its two tributaries (the Neelum and Kaghan Rivers) flow eastward, traversing the Hazara Syntaxis to form deep antecedent valleys before flowing southward along broader valleys to the Indo-Gangetic Plain. The lower stretches of the valleys slopes (for several hundred meters above the main streams) of the antecedent drainages are steeply incised with slopes exceeding 50°. Above these lower stretches, the slopes become less steep (commonly 10–25°) before reaching the steeper (>50°) high glaciated slopes. Valley fills reaching thicknesses of several hundred meters are present along the main valleys, representing two sets of dissected and cannibalized alluvial fans that radiate from the tributary valleys. These alluvial fans are truncated at their toes and are entrenched to their heads, resulting in numerous subvertical slopes comprising bouldery fanglomerates. There are three main types of deposits in the area. These include valley fills derived from alluvial fans; fluvial terraces with horizontal upper surfaces and very rounded clasts; and extensive colluvium deposits, particularly abundant on slopes formed from the Murree Formation.

The climate is monsoonal with an annual precipitation at Muzaffarabad (at ~700 m asl) of ~1500 mm, with more than one-third of the precipitation falling as rain during July and August (District Census Report, 1998). Precipitation falls as snow at altitudes >1500 m asl during the winter (December to March). At the highest altitudes, snow drifts exceeding several meters in thickness are present during the winter. At Muzaffarabad, the mean maximum and minimum temperatures in January are 16 °C and 3 °C and in June 38 °C and 22 °C, respectively (District Census Report, 1998). The earthquake occurred during the post-monsoon season, when weather conditions are mild (maximum and minimum temperatures between 22 °C and 16 °C) with little precipitation (≤100 mm for the month). However, in the evening after the earthquake, Muzaffarabad and the immediate area experienced a heavy

Table 1
Types of landslides examined in the field study (terminology after Varnes, 1978)

	Rock fall	Debris fall	Earth fall	Mixed fall (rock/debris/ earth)	Rotational rock slide	Translational rock slide	Debris slide	Mixed slide (rock/debris/ earth)	Rock flow	Debris flow	Sites where human activity caused or contributed to failures
Number of failures	922	243	3	37	14	39	23	1	1	10	93 sites
Percentage of total failures	71.3	18.8	0.2	2.9	1.1	3.0	1.8	0.1	0.1	0.8	53% of sites

rainstorm that lasted for about 30 min. However, there are no meteorological data to quantify this rainfall event.

3. Landslide types

We examined 1293 landslides at 174 locations to produce a landslide inventory in the field quantifying the types of failures (Table 1[1]). This inventory was used for ground-truthing of ASTER (15 m resolution) and Quickbird (~2.5 m resolution) satellite imagery to provide a more comprehensive regional assessment of the landsliding. Most (>90%) of the landslides triggered by the earthquake were rock and debris falls (as classified according to Varnes, 1978); their sizes range from individual boulder falls to extensive failures covering many thousands of square meters. Debris slides and debris flows also occurred throughout the region. Most failures were shallow, typically involving the top few meters of weathered bedrock, regolith, and soil. Many of the failures were still active during our study, and rockfall events were common. Although ASTER and Quickbird imagery shows that landslides triggered by the earthquake occur throughout a region of >7500 km^2, they cluster in distinct geomorphic–geologic–anthropogenic settings (Fig. 2). We refer to each of these as "landslide settings" and each are described below. The largest single failure (the Hattian Bala landslide) occurred in the Parhore Valley, burying the villages of Nainan (Dandbeh), Buthsher, Bale, and Lodhiabad and ~450 inhabitants. Because of its size and significance, it is described separately.

3.1. Landslide setting I

In this setting, landslides occurred along a ~25-km-long, NW–SE trending belt extending from ~5 km SW of Muzaffarabad to Balakot (Figs. 1, 2, and 3A). The failures were mainly rock falls, with a few (~1%) rock and debris slides. These failures occurred in the Muzaffarabad Formation, which forms steep valley slopes, many >50°, above the main rivers or the alluvial and valley fills. The Muzaffarabad Formation comprises thinly bedded and highly fractured dolomite constituting the lower beds in the hanging wall of the KBT.

3.2. Landslide setting II

Landslides in this setting occurred in the Murree Formation along natural lower valley slopes in areas where the Neleem, Kaghan, and Jhelum Rivers are antecedent to the Hazara–Kashmir Syntaxis (Fig. 3B). The valley slopes commonly are >50° and have long stretches (several hundreds of meters) that rise from the actively eroding streams. The Murree Formation varies from undeformed competent beds to tightly folded and highly cleaved and fractured strata, and at some locations pencil cleavages have formed. Most failures are rock falls and slides, although debris slides are also common.

3.3. Landslide setting III

Natural failures in the high and/or fluvially incised slopes in the highly fractured and cleaved rocks of the Hazara Formation comprise this setting (Fig. 3C). At many locations, the cleavage is tightly folded and pencil cleavages are often developed. These are most evident in the Lamnian Valley and its tributary on the north side of the Jhelum River and on the ridge separating the Jhelum and Kaghan Rivers west of Muzaffarabad. Impressive rock falls are present at both locations.

3.4. Landslide setting IV

This landslide setting is confined to the very steep (»50°) lower slopes of the Quaternary valley fills that have been undercut by rivers and streams (Fig. 3D). Most failures are of debris fall type. These produce talus cones and those that reach the active streams to form

[1] A database of landslides containing a photographic record is available at ftp://ftp.spatial/umt.edu/kashmir/ and doi:10.1016/j.geomorph.2007.04.007. These data are also available from the authors.

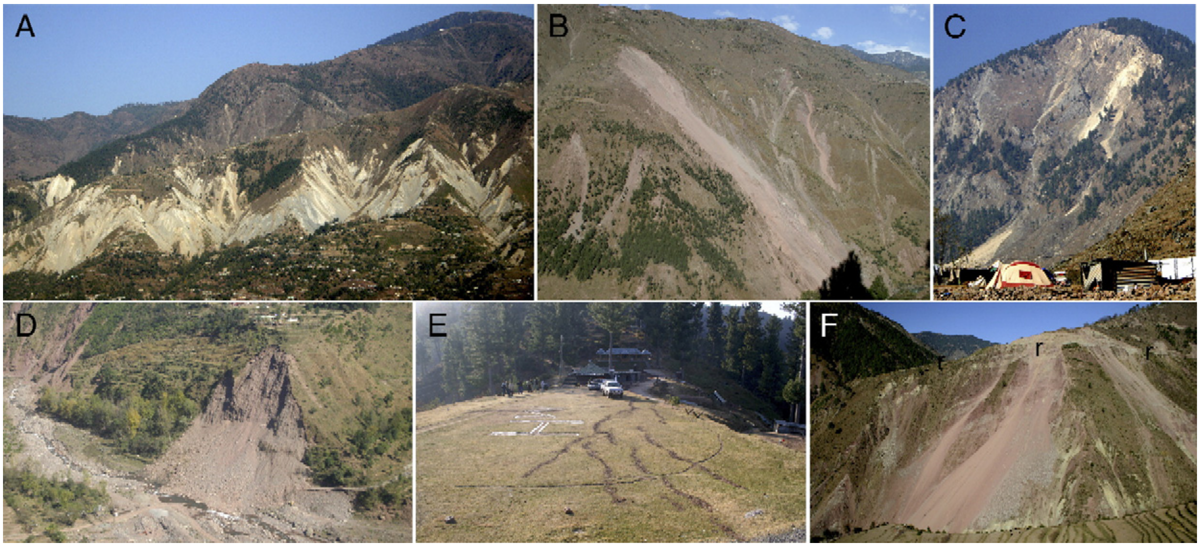

Fig. 3. Views of the main landslide settings showing rock and debris falls: (A) type I east of Muzaffarabad; (B) type II in the Murree Formation in the Neelum Valley; (C) type III in the Lamnian Valley; (D) type IV producing talus cones from a Quaternary valley fill in the Jhelum Valley; (E) type V showing fissuring (filled with brown sediment shortly after the earthquake) on Muhra Sadiq Spur south of Chakothi; and (F) type VI showing slope failures along a stretch of road (="r") northeast of Balakot in the Kaghan Valley.

rapids. The failures are generally small, comprising an areas of debris that are <100 m wide and <100 m long.

3.5. Landslide setting V

Natural failures including mainly small rock falls (<100 m^2) and shallow (the failure surface is <3 m deep) rock slides are common on many of the ridge and spur crests throughout the region and is very extensive on midslope regions. Extensive fissuring is present on most of the affected ridges and spurs. This fissuring is very extensive on midslope regions, with openings that commonly exceed 10 cm in width, are mostly a few meters deep, and form small graben (shallow sackungen).

The most extensive fissuring is associated with the Muzaffarabad Formation along the west side of the Kaghan Valley between Muzaffarabad and Balakot (Fig. 3E). There is also extensive fissuring on slopes around Muzaffarabad and above the lakes at the Hattian landslide. The fissuring frequently defines convex upspur/ridge sets that converge and delimit the margins of potential future failures.

3.6. Landslide setting VI

Landsliding was most common along the roads that traverse slopes that commonly exceed 50° (Fig. 3F). Road construction involves extensive stretches of cut and fill, involving excavating notches into the weathered bedrock on one side and using the excavated material as fill to support the opposite side of the road. The steep cuts and adjacent slopes have failed along nearly every stretch of road that occupies steep slopes (>50°). Furthermore, the outside margins of many of the roads have failed and/or are extensively fissured because the fill was not compacted enough during the construction.

3.7. Hattian landslide

The Hattian landslide failed from an ESE-facing slope comprising rocks of the highly jointed and fractured Murree Formation, creating a scar >1 km long, >200 m wide, 60–80 m deep, and sloping southeastward between 60–70° (Fig. 4). The debris, which fills the main valley and part of a tributary valley, is ~130 m thick, is hummocky, and rises to form a prominent ridge on the eastern side of the valley. The margins of the landslide debris are well defined and steep (25–40°). The debris has dammed two drainages, producing extensive lakes. Spillways are being constructed through these to reduce the hazard of breaching of the dams and flooding (Harp and Crone, 2006). The landslide surface debris is very angular, comprising meter-size blocks of sandstone in a matrix of crushed sandstone, siltstone, and mudstone. In places, meter-sized boulders are fractured into jigsaw-like assemblages. Corn fields, smashed houses, and trees (some still rooted and upright) are scattered across the surface of the landslide deposit. Bands of similar lithologies can be traced across the

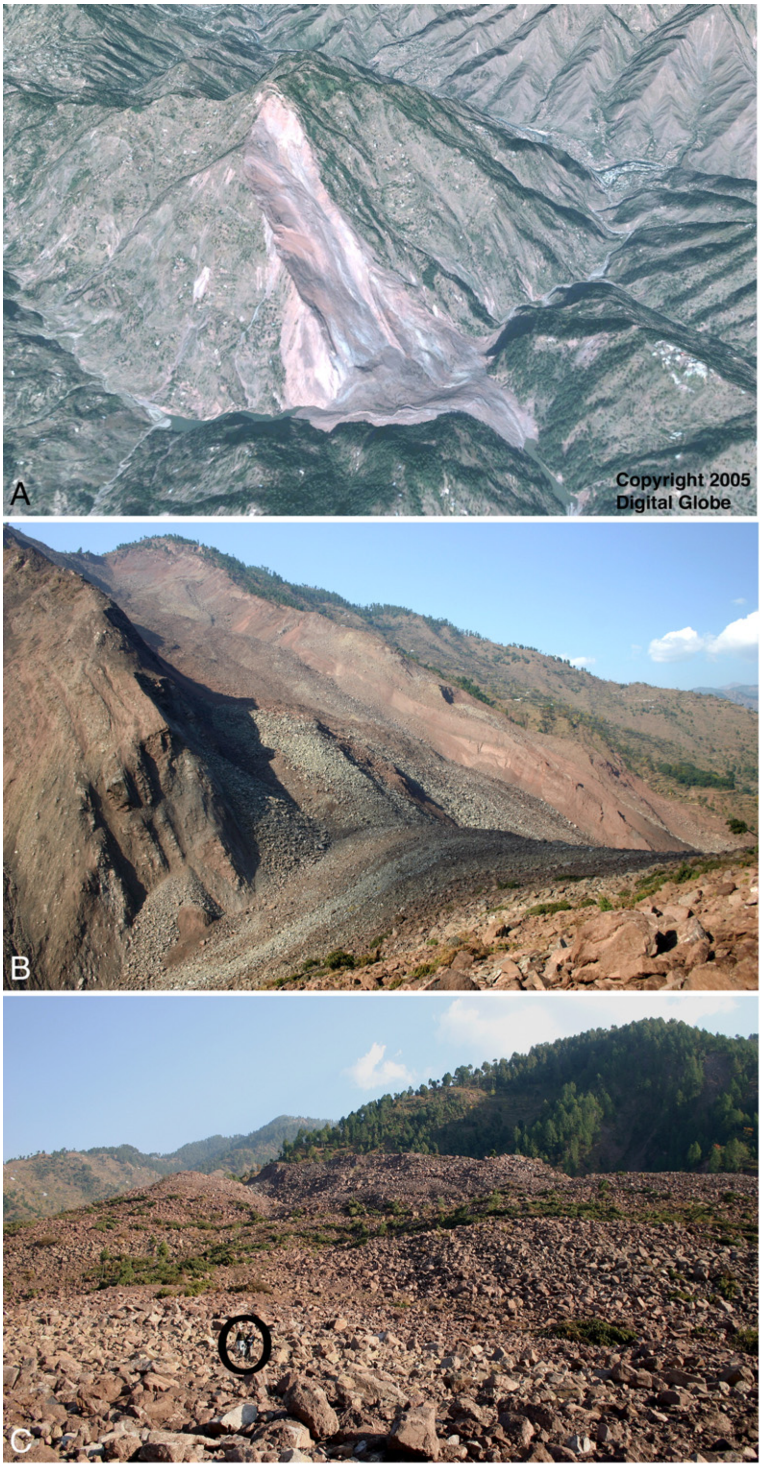

Fig. 4. The Hattian landslide showing (A) a Quickbird image draped on a (pre-event) digital elevation model (SRTM2, void filled) to illustrate the nature of the failure, (B) the failure zone, and (C) surface debris characteristics (the circle encloses two people for scale).

width of landslide deposit, and boulders are covered with a centimeter-thick layer of red silt. A recent excavation to construct a spillway to release the lake waters to reduce the potential of catastrophic dam burst and flooding shows that below the surface the landslide material is almost solely silt- and sand-sized particles, with some cobbles. Pre-earthquake ASTER and Quickbird imagery shows that this is an area of preexisting smaller landslides.

3.8. Regions of little failure

Many of the slopes throughout the region show little evidence of any landsliding or fissuring. These occur mainly in the footwall rocks of the MBT and on midslopes where the gradients are generally <20°, on forested and deforested slopes. We saw little evidence of extensive landsliding on the steep and high, glaciated peaks between the Neelem and Kaghan Rivers. However, we were only able to observe these slopes on a short helicopter flight, which included observations of several small individual failures; it is possible that larger failures were obscured by snow cover.

4. Discussion

The distribution of landslides supports earlier studies of earthquake-triggered landslides, which suggests that although earthquake-triggered landslides are abundant throughout an extensive area from the epicenter, they are concentrated in specific zones associated with the bedrock geology, geomorphology, topography, and human factors (Keefer, 1984, 1998; Rodriguez et al., 1999; Jibson et al., 2004a,b).

The only previous quantitative studies of the geomorphic consequences of large earthquakes in Himalaya were undertaken by Owen et al. (1995, 1996) and Barnard et al. (2001) shortly after the 1991 and 1999 Garhwal earthquakes. These studies showed that earthquake damage was concentrated on alluvial fans, along the lower stretches of the valley slopes, whereas the most common geomorphic hazard was due to rock and debris falls. Owen et al. (1996) and Barnard et al. (2001) calculated the equivalent net lowering (denudation) of the landscape by mapping and measuring the amount of sediment produced and moved during and shortly after the earthquakes. They concluded that this was small compared to earthquake-induced landsliding in other mountainous regions, such as around the Pacific Rim (Keefer, 1984, 1994, 1998; Rodriguez et al., 1999; Jibson et al., 2004a,b). Furthermore, by mapping and measuring monsoon- and human-induced landslides, Owen et al. (1996) and Barnard et al. (2001) were able to deduce that long-term denudation rates and sediment flux resulting from human and monsoon activity in the region was far more significant than earthquake-induced mass movements and associated processes. These studies, therefore, questioned the relative importance of earthquake-induced landforms and processes in landscape evolution of the Himalaya.

Although it was not possible in the field to map every landslide triggered by the Kashmir earthquake and to measure the volume of material mobilized, the number and extent of landsliding in this study far exceeds that of the Garhwal earthquakes. This suggests that the two previous Himalayan studies may be atypical in the areal extent of landsliding that occurs during large earthquakes. The Garhwal earthquakes occurred in similar Himalaya settings to the Kashmir earthquake (M_s=7.7, depth=26 km), but were smaller (M_s=7.1, depth=~20 km; and M_s=6.6, depth=~15 km) (USGS, 2006b). It is possible that there is a threshold for the earthquake magnitude that is needed in a Himalayan setting to produce widespread landsliding and that this was exceeded during the Kashmir earthquake.

Our study shows that most landslides were small (<1000 m^2 in area) rock and debris falls and that relatively few (~10%) translational slides and landslides of other types occurred (Table 1). Only one extremely large (≈80×10^6 m^2 in area; Harp and Crone, 2006) failure (the Hattian Bala landslide) occurred. This has characteristics of a typical sturzstrom (cf. Rouse, 1984). The fragmented nature of the landslide debris and accumulation up the eastern side of the valley suggest that debris moved at very high velocities (likely »10 m/s). This landslide was structurally controlled and occurred in a plunging syncline because of the intersection of steep north-dipping bedrock and jointing (Harp and Crone, 2006).

Many studies throughout the Himalaya and adjacent mountains describe extremely large (several square kilometers) landslide complexes (Owen et al., 1995; Barnard et al., 2001; Hewitt, 1999), and although the Kashmir and Garhwal earthquakes did trigger several large failures they were not commonplace. Either greater magnitude earthquakes are responsible for the extremely large failures and/or they are the result of other processes such as glacial erosion and paraglacial readjustment of the landscape.

The most common setting for landslides in the Kashmir earthquake was associated with road construction with 53% of all sites showing some evidence of human activity contributing or helping to initiate a landslide (Table 1). This helps support the view of Keefer (1984), Owen et al. (1996), and Barnard et al. (2001) that human modification of the landscape by road construction is one of the most influential factors in helping to initiate landslides in tectonically active regions.

The extensive fissuring produced during the earthquake resulted in more landsliding during the 2006 snowmelt and monsoon seasons, and large volumes of landslide-generated debris were produced and resedimented by floods during these seasons. This resulted in major landscape modification and is described in Kamp et al. (in preparation). Furthermore, the volume of rock and sediment mobilized and net landscape erosion that occurred during the earthquake in the subsequent snowmelt and monsoon seasons is described in Khattak et al. (in preparation). Our landslide inventory (Appendix 1) should aid future researchers who may examine the evolution of the earthquake-triggered landslides over the coming years.

5. Conclusion

The landslides triggered by the 8 October 2005 Kashmir earthquake comprised mainly rock falls and debris falls, although translational rock and debris slides also occurred, and were present throughout an area of >7500 km^2. The landslides, however, were concentrated in six geomorphic–geologic–anthropogenic settings. These included failures in (i) highly fractured carbonate rocks of the lowest beds in the hanging wall of the likely earthquake fault; (ii) Tertiary siliciclastic rocks along antecedent drainages that traverse the Hazara–Kashmir Syntaxis; (iii) steep (>50°) slopes comprising Precambrian and Lower Paleozoic rocks; (iv) very steep (»50°) lower slopes of fluvially undercut Quaternary valley fills; (v) ridges and spur crests; and (vi) associated with road construction. With the exception of a sturzstrom (debris avalanche; the Hattian landslide) that comprises ~80 million m^3, most landslides were small (<1000 m^2 in area). Anthropogenic excavations and terracing was important in helping to initiate landslides in >50% of the locations examined in our study. This study supports the view that earthquake-triggered landslides are highly concentrated in specific zones associated with the lithology, structure, geomorphology, topography and human presence.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.geomorph.2007.04.007.

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