Large landslides lie low: Excess topography in the Himalaya-Karakoram Ranges

Jan Henrik Blöthe*, Oliver Korup, and Wolfgang Schwanghart

Institute of Earth and Environmental Sciences, University of Potsdam, 14476 Potsdam, Germany

*Current address: Department of Geography, University of Bonn, 53115 Bonn, Germany

jan.bloethe@uni-bonn.de

Excess topography

Excess topography measures for each grid cell in a digital elevation model (DEM) the rock-column height above an arbitrarily defined threshold slope surface. The threshold slope surface is an idealized surface that we derive from a given DEM. The threshold surface only contains inclinations that are lower or equal than the arbitrarily set threshold inclination. The elevations of the threshold surface are constrained by the DEM elevations and the threshold inclination such that (1) the elevation of the threshold and DEM input surface coincide for a given grid cell if the slopes between this grid cell and all others are less or equal the threshold slope; and (2) elevations of the threshold surface fall below the DEM input surface in grid cells rising above the surrounding topography at angles steeper than the threshold inclination. In case (2), we calculate the threshold surface elevation as the minimum elevation of all surrounding locations plus the maximum allowed topographic rise (threshold inclination) along the distance separating the locations. This threshold inclination can be thought of “an average effective angle of internal friction which controls hillslope stability” (Burbank et al., 1996). The threshold slope surface \( \hat{z} \) at a specific location \((x, y)\) is calculated by a minimum filter with additive offsets (Figs. DR4, DR5):

\[
\hat{z}(x, y) = \min_{(s, t) \in (-\infty, \infty)} \{z(x + s, y + t) + s \sqrt{s^2 + t^2}\},
\] (1)

(1)
where \( z \) is the surface elevation, \( s \) and \( t \) refer to the cardinal distances within a window centered at \( x, y \), and \( s_t \) is the tangent of the threshold slope angle. Excess topography \( z_E \) is calculated as the difference between the actual and the threshold slope surface:

\[
 z_E(x, y) = z(x, y) - \hat{z}(x, y). \tag{2}
\]

For practical purposes, we calculated equation (1) using a 2D order-statistics image filter with additive offsets (see `ordfilt2` function in the MATLAB image processing toolbox; MATLAB, version R2012a, The MathWorks Inc., Natick, MA, 2000), and a square kernel with an odd side length of 201 pixels. This kernel size was found sufficiently large to avoid overestimating the idealized surface for a threshold slope angle of 30°. The excess topography algorithm will be available in the MATLAB TopoToolbox 2 (Schwanghart and Scherler, 2014).

Although we calculated excess topography for different threshold angles (Fig. 2D), the sparse data on slope stability in the study area prevented us from speculating about differing threshold angles for individual lithologies. Even comparable bulk lithologies may give rise to large bedrock landslides at substantially different inclinations owing to local differences in rock-mass strength (see Fig. 6 in Korup et al., 2007).

**Landslide inventory and volume-area scaling**

Besides slope failures mapped from high-resolution remote sensing data (www.google.com/earth), our regional landslide inventory contains large landslides in the Himalaya-Karakoram ranges documented in previous work (Fort et al., 1989; Hewitt, 1998; Phartiyal et al., 2005; Weidinger, 2006a; Hewitt et al., 2008; Dortch et al., 2009; Hewitt, 2009; Hewitt et al., 2011; Weidinger et al., 2014). Key diagnostic criteria for detecting and mapping landslide scars and deposits include (1) hummocky and asymmetric deposits; (2) steep and freshly eroded or scree-covered, amphitheatere-shaped head scarps; (3) distinct changes in hillslope drainage density and dissection; (4) asymmetric lakes or ponds on valley floors; and (5) abrupt changes in channel-reach morphology (van Westen et al., 2008). In order to estimate the volume of debris contained in the 492 landslides in our data set, we derive a scaling
relationship between volume and area from published data on landslide volume and area for the Himalayan orogen, drawing on 114 published data (Ibetsberger, 1996; Walder and O’Connor, 1997; Hewitt, 1998; Shroder, 1998; Fort, 2000; Hodges et al., 2004; Weidinger, 2006a; Weidinger, 2006b; Mitchell et al., 2007; Hewitt et al., 2008; Dortch et al., 2009; Hewitt, 2009; Hewitt et al., 2011; Weidinger et al., 2014). We obtained a scaling relationship of the form \( V = bA^s \), where \( V \) is volume [m\(^3\)], \( A \) is area [m\(^2\)], \( b \) is the intercept [m\(^{-2}\)], and \( s \) is the scaling exponent, from bootstrapped median regression, with bootstrapped means and standard errors of \( s = 1.33 \pm 0.13 \), and \( \log b = -0.40 \pm 0.90 \) [a.u.]. We used this scaling relationship with Monte Carlo-based error propagation (\( n = 2500 \) simulations) to estimate the total volume of hillslope material mobilized by large slope failures in our study area.

We acknowledge that our inventory covers only part of the potentially heavy-tailed distribution of hillslope mass wasting in the Himalaya-Karakoram Ranges (HKR). We anticipate that landslides such as rock fall, debris flows, and debris slides that are smaller, though more frequent, than the ones we mapped also contribute to denuding the landscape. However, the geomorphic traces of these smaller landslides are far from well defined in the remote sensing imagery such that we found a comprehensive mapping of slope-failure deposits across their full size range intractable. We further suspect that the average residence times of landslide deposits will scale with their volume such that geomorphic evidence of smaller landslides is likely to be eradicated faster from the landscape. Absolute age constraints on some of the larger landslides indicate that the deposits from the larger rock-slope failures may reside in the landscape for at least several millennia (Hewitt et al., 2011), thus complicating comprehensive estimates of the erosional budget of mass wasting in the HKR. Judging from earlier estimates on the contribution of large rock-slope failures to the overall denudation rates in active mountain belts (Korup et al., 2007), however, we are confident that our inventory of large landslide deposits reflects a significant fraction of the overall mass turnover in the study area. This is based on a comparison between to the estimated contemporary sediment flux from the Indus River that drains our study area \((0.15 - 0.22 \text{ km}^3 \text{ yr}^{-1})\) (Milliman and Meade 1983; Garzanti et al. 2005) and the total volume of debris contained in the landslide deposits mapped that we estimate to be \(>250 \text{ km}^3\).
Simplistically assuming that the removal of this volume alone would feed the sediment flux, it would take at least 1,000 years to be completely flushed from the study area.

**Major lithologic units**

We derived the major lithologic units for each landslide from maps of regional geology (for detailed accounts see e.g. Yin, 2006), including the Tertiary Kohistan and Ladakh Batholiths; the Indus-Tsangpo Suture Zone and its western extension, the Main Mantle Thrust, which mark the boundary between Indian passive margin units of the High Himalayan Crystalline and the Tethyan Sedimentary Sequence in the south, and the Eurasian active margin units in the north; the Karakoram Terrane; and the volcanic-sedimentary Lhasa Terrane.

**Contemporary glacier cover**

We used a digital glacier inventory compiled from several studies in the Himalaya-Karakoram ranges (Mool et al., 2001; Frey et al., 2012; Bhambri et al., 2013) to compare the distribution of the mapped landslides to the contemporary glacier cover. Median glacier elevation was calculated based on elevation values extracted from SRTM90 digital topographic data (www.viewfinderpanoramas.org).
Supplementary Tables

Table DR1. Elevation distribution, landslides, and excess volume for the six segments of the study area.

<table>
<thead>
<tr>
<th>Study area compartment</th>
<th>No. 1</th>
<th>No. 1</th>
<th>No. 3</th>
<th>No. 4</th>
<th>No. 5</th>
<th>No. 6</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area and Elevation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total area of compartment [km$^2$]</td>
<td>21106</td>
<td>24419</td>
<td>16736</td>
<td>21065</td>
<td>25434</td>
<td>19712</td>
<td>128472</td>
</tr>
<tr>
<td>25$^{th}$ elevation percentile [m]</td>
<td>3594</td>
<td>3075</td>
<td>3793</td>
<td>3945</td>
<td>4377</td>
<td>4773</td>
<td></td>
</tr>
<tr>
<td>50$^{th}$ elevation percentile [m]</td>
<td>4176</td>
<td>3966</td>
<td>4315</td>
<td>4601</td>
<td>5002</td>
<td>5169</td>
<td></td>
</tr>
<tr>
<td>75$^{th}$ elevation percentile [m]</td>
<td>4629</td>
<td>4673</td>
<td>4775</td>
<td>5126</td>
<td>5409</td>
<td>5497</td>
<td></td>
</tr>
<tr>
<td><strong>Landslides</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of landslides</td>
<td>42</td>
<td>83</td>
<td>56</td>
<td>100</td>
<td>108</td>
<td>103</td>
<td>492</td>
</tr>
<tr>
<td>Landslide volume in compartment [km$^3$]</td>
<td>37.93</td>
<td>92.19</td>
<td>45.92</td>
<td>70.24</td>
<td>18.82</td>
<td>13.36</td>
<td>278.47</td>
</tr>
<tr>
<td>Average volume per landslide [km$^3$]</td>
<td>0.90</td>
<td>1.11</td>
<td>0.82</td>
<td>0.70</td>
<td>0.17</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td><strong>Excess volume [km$^3$]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28$^\circ$</td>
<td>2223</td>
<td>2805</td>
<td>1193</td>
<td>1447</td>
<td>1191</td>
<td>534</td>
<td>9394</td>
</tr>
<tr>
<td>30$^\circ$</td>
<td>1761</td>
<td>2224</td>
<td>936</td>
<td>1135</td>
<td>897</td>
<td>375</td>
<td>7328</td>
</tr>
<tr>
<td>32$^\circ$</td>
<td>1371</td>
<td>1727</td>
<td>724</td>
<td>876</td>
<td>656</td>
<td>252</td>
<td>5606</td>
</tr>
<tr>
<td>35.5$^\circ$</td>
<td>839</td>
<td>1050</td>
<td>444</td>
<td>539</td>
<td>355</td>
<td>115</td>
<td>3342</td>
</tr>
<tr>
<td>39.8$^\circ$</td>
<td>422</td>
<td>527</td>
<td>235</td>
<td>287</td>
<td>159</td>
<td>44</td>
<td>1674</td>
</tr>
<tr>
<td>45$^\circ$</td>
<td>168</td>
<td>211</td>
<td>105</td>
<td>128</td>
<td>58</td>
<td>15</td>
<td>685</td>
</tr>
</tbody>
</table>

Supplementary Figures

Figure DR1. A: Estimated landslide volume versus local topographic relief in 10-km search radius around bedrock slope failures. B: Estimated landslide volume and C: vertical drop height of landslide versus west-to-east distance along swath profile. Gray lines in (A), (B), and (C) indicate quantile regression models for the 5$^{th}$ and 95$^{th}$ (dotted), 25$^{th}$ and 75$^{th}$ (dashed) and 50$^{th}$ (solid) percentile.
Figure DR2. Swath profile of topographic relief expressed as maximum elevation range within a 10-km radius, covering the study area as in Fig. 1. Gray shading shows relief quantiles in 10% increments; thick and thin gray lines are median, and minimum/maximum relief, respectively. Landslides are shown as dots, color coded to major lithology; triangles give positions of rock-glacier toes.

Figure DR3. Distribution of the fraction of total excess volume in 250-m bins of elevation. A: Data for inset (B) in Fig. 4. B: Data for inset (C) in Fig. 4. Shading of data points indicates volume stored per unit area [km$^3$/km$^2$]; horizontal lines are 25$^{th}$, 50$^{th}$, and 75$^{th}$ percentiles of the elevation distribution.
Figure DR4. Calculation of excess topography from 1D elevation profile. A: Idealized threshold slope surface (red line) and original topography (black line). B: Idealized threshold slope surface (red line) and kernel result with additive offset (blue line). Both panels feature two example locations (dashed vertical lines labeled 1 and 2), for which the threshold slope surface is calculated.

Figure DR5 (excesstopography.gif, online only). Animated derivation of excess topography for an elevation profile crossing from Gamugah surface to Nanga Parbat (see Fig. 2 and Fig. 3 in the main text for location). Upper panel shows the DEM profile and the cone-shaped moving window with offsets calculated with an arbitrarily set 30° threshold inclination. Lower panel shows the threshold surface (red line) and the moving window with additive offsets (blue line). Red cross indicates position of minimum value in the moving window. If this position deviates from the center of the moving window (dashed gray line) the threshold surface is lower than the actual topographic surface. For comparison, the threshold surface is plotted in the upper panel at the end of the animation.
Supplementary References


