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Topographic controls on erosion rates in tectonically active mountain ranges

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Abstract

The functional relationship between erosion rate and topography is central to understanding both controls on global sediment flux and the potential for feedback between tectonics, climate, and erosion in shaping topography. Analysis of a high-resolution (10-m-grid) DEM transect across the convergent orogen of the Olympic Mountains reveals a non-linear relation between long-term erosion rates and mean slope, similar to a model for hillslope evolution by landsliding in steep terrain. The DEM data also reveal a relation between mean slope and mean local relief. Coarser-scale (1-km-grid) global analysis of the relation between erosion rate and mean local relief reveals different trends for areas with low erosion rates and tectonically active mountain ranges, with the composite relation being well-described by non-linear models. Together these analyses support the emerging view that erosion rates adjust to high rates of tectonically driven rock uplift primarily through changes in the frequency of landsliding rather than hillslope steepness, and imply that changes in local relief play a minor role in controlling landscape-scale erosion rates in tectonically active mountain ranges.

Keywords: erosion; slopes; relief; tectonics; mountains

Geomorphologists have generally recognized a strong connection between slope morphology and erosion rates since early workers argued that greater relief and steeper slopes lead to faster erosion [1,2]. This view remains intuitively appealing, but few studies have presented quantitative data pertinent to assessing such relations over spatial and temporal scales relevant to the evolution of tectonically active landscapes. Instead, these traditional assumptions regarding linkages between slope morphology and erosion rates are being challenged by recent work documenting both strongly coupled feedback between erosional processes and tectonic forcing [3–10] and an emerging view that topographic relief and erosion rates may become decoupled when landsliding allows hillslope lowering to keep pace with river incision [11–13]. Evaluating the general applicability of this new view is important because of implications for climatically driven increases in erosion rates to enhance relief and thereby influence global cli-

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mate [14–16]. Here we report a global analysis of the general relationship between local relief and erosion rate, and a more detailed analysis of a tectonically active mountain range that provides an exceptional opportunity to evaluate the effects of topography and tectonic forcing on erosion rates over geologic time scales. Our analysis shows that landscape-scale erosion rates vary non-linearly with mean slope, thereby confirming that a strong topographically mediated feedback limits the local relief (i.e., hillslope steepness rather than overall range height) that can be created by rapid rock uplift in the steep topography of tectonically active mountain ranges.

Previous analyses of landscape-scale erosion rates focused on inter-related measures of mean elevation, relief, local relief, and slope. In a widely cited paper, Ahnert [17] reported a linear relation between erosion rate and mean local relief (the difference in elevation measured over a specified length scale) for mid-latitude drainage basins. Ahnert's relation was subsequently bolstered with additional data drawn primarily from the central and eastern United States [18]. In an independent analysis, Summerfield and Hulton [19] reported that local relief and runoff are the dominant controls on erosion rate for major world drainages. In addition, Schumm [20] reported a relation between erosion rate and drainage-basin relief. Pinet and Souriau [21] reported that erosion rates are correlated with mean elevation and suggested that different relations characterize tectonically active and inactive mountain ranges. Many workers model hillslope erosion rates as a function of either elevation or slope in large-scale studies of interactions between tectonics and erosion [22–31].

Other studies have either reported evidence for, or adopted theoretical formulations based on a decoupling of erosion rate and slope morphology in steep, landslide-prone terrain. Carson's [32,33] expositions on the concept of threshold hillslopes implied that in soil-mantled landscapes, material properties of the soil impose a limiting upper bound on slope angles, so that slope steepness was controlled by soil strength. Schmidt and Montgomery [11] showed that large-scale bedrock strength could limit the development of local relief in a mountain range and inferred that landsliding could limit the incision of river valleys in steep terrain by lowering ridgelines at the rate of river incision. Burbank et al. [12] found that mean slope did not vary across areas with significant variability in river incision rates, observations they interpreted to indicate the development of strength-limited, or threshold, hillslopes along the gorge of the Indus River. Montgomery [13] found that mean slope varied by only a few degrees across areas with strong gradients in long-term exhumation rates in the core of the Olympic Mountains. A number of landscape-evolution models represent hillslope erosion rates with either critical slope thresholds or non-linear expressions that asymptotically approach a limiting hillslope angle [34–36]. Roering's [37,38] recent hillslope studies point to non-linear transport as governing hillslope development in steep terrain. Taken together, these studies imply that Ahnert's [17] linear relationship between local relief (or slope) and erosion rate should have only limited relevance to long-term, landscape-scale erosion rates in the steep topography of tectonically active mountain ranges.

The Olympic Mountains have a well-constrained pattern of long-term steady-state erosion rates determined by low-temperature thermochronometry [39] and comparable shorter-term river incision rates derived from incised straths [9]. The range has retained a long-term steady state between accretion and erosion for the past 14 Myr, a period long enough to imply that the topography of the range has been in approximately steady state for much of that time [39]. In addition, high-resolution, 10-m-grid digital elevation models are available for the entire range, making the Olympic Mountains an ideal location for investigating relations between landscape morphology and long-term erosion rates. Although alpine glaciation influenced the central portion of the range, mean slopes calculated over both extensively glaciated and relatively unglaciated areas in the core of the range differ by only a few degrees [13] and, therefore, the glacial legacy does not strongly influence mean slopes at this scale. We calculated mean slopes from the distribution of values for individual 10-m-grid cells within a 10-km-diameter analysis window (a length scale selected to span the width of the largest valleys in the range) for each point on a long-term erosion rate transect parallel to the tectonic convergence direction across the range.

Long-term erosion rates along this transect define two distinct domains, with a well-defined trend between mean slope (S) and erosion rate (E) that steepens above $S = 25°$ (Fig. 1). At $S < 25°$, a simple linear relation describes the slope dependence of the erosion rate ($E = 0.04+0.02S$, $R^2 = 0.86$, $P < 0.001$, where E is in mm yr^{-1} and S is in degrees). A steeper, weak but significant relationship holds for $S > 25°$ ($E = -0.70+0.05S$, $R^2 = 0.21$, $P < 0.006$), and there is no correlation for $S > 30°$ ($R^2 < 0.01$, $P < 0.785$). Hence, we conclude that for the Olympic Mountains there is a linear relation between mean slope and long-term erosion rate at low slopes and either a weak relation, or a strongly non-linear relation at steep slopes. Highly structured residuals for a regression over the entire slope range show that the composite relation is poorly represented by a single linear relation.

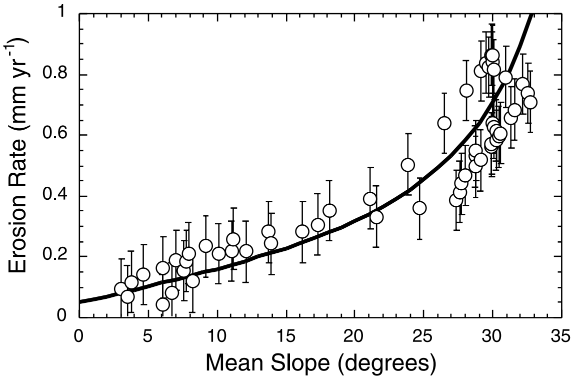


Fig. 1. Plot of long-term erosion rate versus mean slope for a transect across the Olympic Mountains. Erosion rate data are from low-temperature thermochronometry [39]. Mean slope values were determined for a 10-km-diameter area from a composite 10-m-grid DEM of the range around points spaced every 2 km along a transect across the range beginning from 47.5335°N., 235.6463°W. Solid line represents model fit using Eq. 1 with $E_0 = 0.05$ mm yr^{-1}, $K = 0.6$ mm yr^{-1}, and $S_c = 40°$. Error bars represent an uncertainty in erosion rates of 0.1 mm yr^{-1}.

The distinct kink in the data set from the Olympic Mountains at a hillslope gradient of about 25° coincides with a slope just steep enough to sustain shallow landsliding by debris flows [40]. Roering et al. [37] introduced a non-linear hillslope transport model that describes sediment flux on hillslopes by a combination of linearly diffusive processes and landsliding. For their model, local erosion rate is dependent on the local curvature of the landscape. Nonetheless, we find that the functional form of their flux equation provides a good description of our erosion rate data for the Olympics. Thus, we propose:

$$E = E_0 + \frac{KS}{[1-(S/S_c)^2]} \qquad (1)$$

as an empirical function relevant for predicting erosion rates at the regional scale, where K is a rate constant and S_c is a limiting hillslope gradient, and E_0 is the background erosion rate due to chemical weathering. Reported values of E_0 range from 0.016 to 0.059 mm yr^{-1} for six major drainage basins in the Olympics [41]. These data for the Olympic Mountains provide the first direct evidence for a non-linear, landscape-scale relation between mean slope and long-term erosion rate.

The high-resolution DEM of the steep terrain of the Olympic Mountains also provides an opportunity to investigate the relation between mean slope and mean local relief (R_z), the latter of which can be calculated with reasonable accuracy from even relatively coarse grid-size DEMs [42]. For the well-drained, highly dissected topography of the Olympic Mountains, linear regression mean slope and mean local relief (both calculated over a 10-km-diameter area) reveals $S = 4+0.014\ R_z$ (where S is in degrees and R_z is in meters; $R^2 = 0.81$, $P < .0001$). Hence, coarse-scale analyses relating erosion rate to mean local relief can be calibrated to facilitate comparison to the more physically meaningful measure of local slope. But as mean slope is more strongly influenced by DEM grid size than is mean local relief [42], the relation between mean slope and mean local relief is expected to be grid-size dependent. Substituting mean local relief (also calculated over a 10-km-diameter analysis window) for S in Eq. 1 yields:

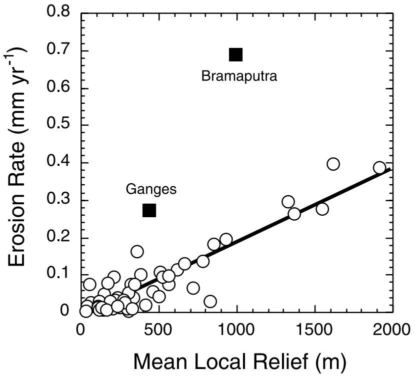


Fig. 2. Plot of erosion rate versus mean local relief for data from mostly tectonically inactive areas (open circles) compiled from Summerfield and Hulton [19] and Pazzaglia and Brandon [18], which include data updated from Ahnert [17]. Excluding tectonically active settings, such as data for the Ganges and Bramaputra rivers (solid squares), regression of erosion rate (E) versus mean relief (R_z) yields a relation of $E = 0.2R_z$ ($R^2 = 0.90$, $P < 0.0001$), where E is in mm yr^{-1} and R_z is in km.

$$E = E_0 + \frac{KR_z}{[1-(R_z/R_c)^2]} \tag{2}$$

where R_c is a limiting local relief.

We compiled and analyzed data from prior studies of the relation between erosion rate and mean local relief defined over comparable length scales [17–19]. Data compiled from previous work primarily represent tectonically inactive areas and fall along a well-defined linear trend similar to that originally reported by Ahnert [17] (Fig. 2). However, the previous data from Ganges and Bramaputra rivers, which have their headwaters in the Himalaya, plot well above the trend defined by the other data. Although factors such as lithology, climate, runoff, and vegetation all influence erosion rates [43–45], mean local relief (and therefore mean slope) is a primary control on erosion rates in these landscapes.

We also investigated the global relation between local relief and erosion rate for tectonically active mountain ranges using the 30 arc-second GTOPO30 digital elevation model. We calculated local relief as the difference between the minimum and maximum elevation within a 10-km-diameter circle for each grid cell for the central Himalaya, the Himalayan portion of the Indus River drainage basin, the Olympic Mountains, Taiwan, the British Columbia Coast Range, the Denali portion of the Alaska Range, and the New Zealand and European Alps, and the central portion of the western slope of the New Zealand Alps. Erosion rates for these tectonically active areas are based on published rates derived from sediment yields, bedrock river incision rates, and low-temperature thermochronometry [12,39,46–53].

Ahnert's linear correlation between erosion rate and local relief does not hold for data from tectonically active areas (Fig. 3). Instead, those erosion rates plot well above Ahnert's relation but consistently have mean local relief of 1000 to

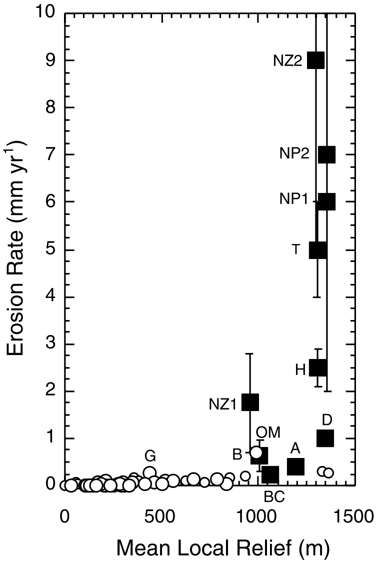


Fig. 3. Same data as in Fig. 2 but with the addition of solid squares representing mean values of long-term erosion rates (error bars span range of data) reported in published sources for the tectonically active convergent areas of the southern island of New Zealand Alps (NZ1 from Tippett and Kamp [53]), the western slope of the New Zealand Alps (NZ2 from Hovius et al. [48]), central Himalaya (H) [52], the Himalayan portion of the Indus River drainage basin from (NP1 from Burbank et al. [12] and NP2 from Shroder and Bishop [49]), the Olympic Mountains (OM) [39], Taiwan (T) [46], the Denali portion of the Alaska Range (D) [47]; and the European Alps (A) [50]. Data points from Fig. 3 for the Ganges (G) and Bramaputra (B) rivers are shown for reference. The extent of the area of active tectonic uplift for Central Himalaya, Olympic Mountains, and Taiwan was defined by areas above 200 m elevation. The areas analyzed for the New Zealand and European Alps were based on the area of dissected uplands that physiographically define each range.

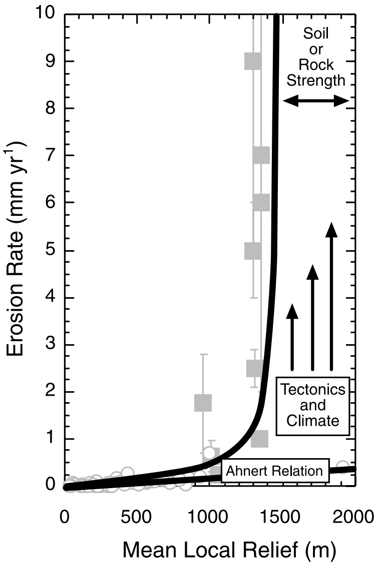


Fig. 4. Same data as Fig. 3 but with solid line representing model fit using Eq. 2 with $E_0 = 0.01$ mm yr^{-1}, $R_c = 1500$ m, and $K = 2.5 \times 10^{-4}$ mm yr^{-1}. Labels illustrate influence of changes in material properties and external forcing by tectonics or climate in the context of the model.

1500 m. Using $R_c = 1500$ m and an E_0 value of 0.01 mm yr^{-1} based on the mean chemical denudation rate for the world's thirty-five largest drainage basins, as reported by Summerfield [54], Eq. 2 provides a reasonable fit to the overall form of the composite global data set (Fig. 4). In the context of the model, landscape-scale material strength variations control R_c and therefore the position of the inflection and asymptotic rise in the relation beyond which either tectonic uplift or climatically driven processes could result in large changes in erosion rate with less change in mean local relief than predicted by extrapolating relations from lower gradients. A key conclusion is that Ahnert's relationship appears to work well in tectonically inactive low-erosion-rate landscapes, but provides only a lower limit for erosion rates in tectonically active landscapes.

An alternative way to view the relation between erosion rate and mean local relief is as a power-law relation (Fig. 5). For mean local relief > 100 m erosion rate varies with mean local relief, but there is an order-of-magnitude variability in erosion rate, presumably due to factors such as differences in erodibility, vegetation, precipitation, and runoff. A power-law regression for the combined data set for $R_z > 100$ m yields a relation of $E = 1.4 \times 10^{-6}\ R_z^{1.8}$, where E is in mm yr^{-1} and R_z is in meters ($R^2 = 0.66$, $P < 0.0001$). This relation also indicates a strongly non-linear relation between mean local relief and erosion rate, but underestimates erosion rates at high mean local relief. Both of these views–development of threshold slopes or a non-linear power-law relation–imply that in high-relief landscapes small changes in mean local relief (or slope) lead to large changes in erosion rate.

We also calculated the spatial distribution of local relief within a 10-km-diameter circle of every grid cell for the major terrestrial land masses of Asia, Europe, and North and South America. Viewed globally, the distribution of mean local relief corresponds to tectonic setting, with tectonically active mountain belts having mean local relief of 1000–2000 m (Fig. 6). While the general segregation of topographic relief by tectonic setting is neither novel nor surprising, it is striking that mountain belts have similar local relief inde-

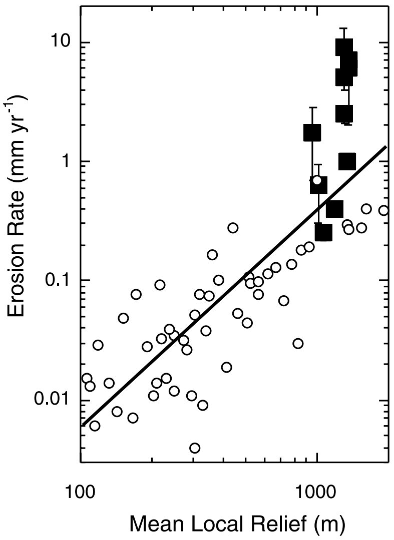
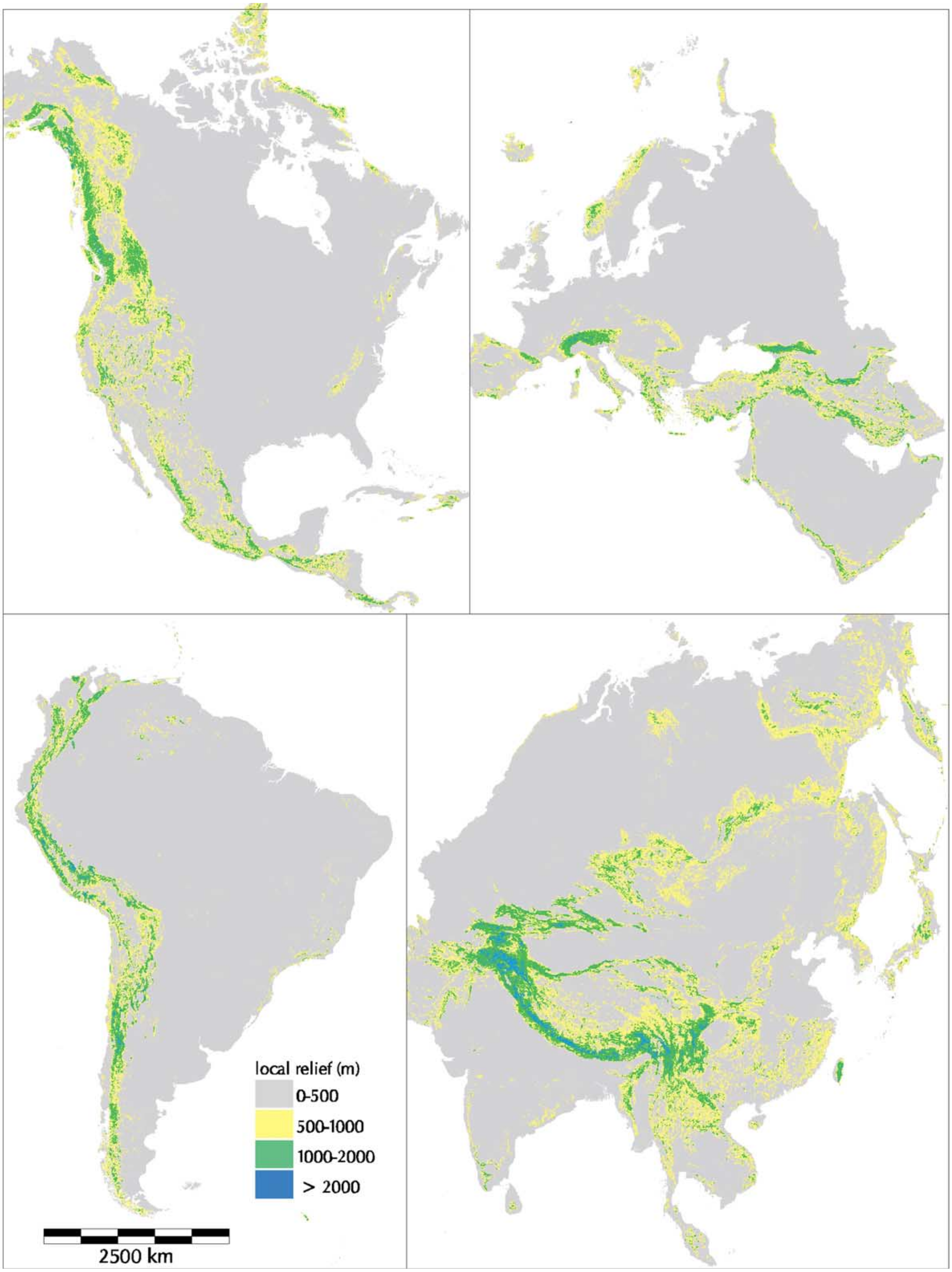


Fig. 5. Log–log plot of erosion rate vs. mean local relief for the same data as in Figs. 4 and 5. Power-law regression of composite data set yields $E = 1.4 \times 10^{-6}\ R_z^{1.8}$, where E is in mm yr^{-1} and R_z is in meters ($R^2 = 0.66$, $P < 0.0001$). Range of one standard error for regression coefficient is 4.1×10^{-6}–4.9×10^{-7} and 1.6–2.0 for the regression exponent.


local relief (m)
0-500
500-1000
1000-2000
> 2000
2500 km

pendent of the specific tectonic context or climate zone. Only in a few areas of extremely rapid rock uplift and bedrock river incision does mean local relief exceed 2000 m. The cumulative global distribution of mean local relief (Fig. 7) shows that $< 2\%$ of Earth's land mass has $R_z > 1500$ m and $< 5\%$ has $R_z > 1000$ m, indicating little potential for climate change to significantly increase the global distribution of relief by altering the local relief of mountainous terrain. It appears that mean local relief in steep terrain tends to be limited to 1000–2000 m due to either the development of threshold slopes, or the rarity of geologically environments capable of sustaining steep topography under long-term erosion rates > 10 mm yr^{-1}. As a high-relief terrain grows, it becomes progressively more difficult to generate greater relief, thereby limiting local relief and imposing a natural limit set by typical rates of rock uplift and erosion.

Our analysis supports the view that there are two fundamentally different types of landscapes with distinct geomorphological controls on landscape-scale erosion rates. Hillslope processes set the pace of landscape lowering in low-relief, low-gradient landscapes where erosion rates are linearly related to mean slope or local relief. In contrast, small changes in relief can result in large changes in erosion rates in steep, high-relief landscapes, thereby restricting the variability of relief in areas with different long-term erosion rates. Where river incision keeps pace with rock uplift, the rate of tectonic forcing will set the landscape-scale erosion rate by refreshing the gradient of landslide-dominated slopes. If erosion cannot keep pace with rock uplift, then mass will accumulate until the relief of the range becomes limited by the thermal–mechanical properties of the crust and a plateau develops [55], at which point the range can grow laterally but will rise no further. These distinct modes of landscape dynamics imply that changes in climate or tectonic forcing can influence landscape-scale erosion rates in low-relief landscapes through changes in hillslope steepness, whereas in high-relief landscapes, changes in rock uplift rate influence erosion rates through adjustments in the frequency of slope failure. Finally, the non-linear coupling of slope morphology and erosion rate in areas of very rapid rock uplift demonstrates that hillslopes generally tend to approximate, if not achieve, threshold slopes in tectonically active mountain ranges. From this, we conclude that there is little potential for major increases in local relief in tectonically active landscapes because the local relief of mountainous regions is generally already close to the upper limit that either soil or rock strength can support, or that tectonic processes can sustain.

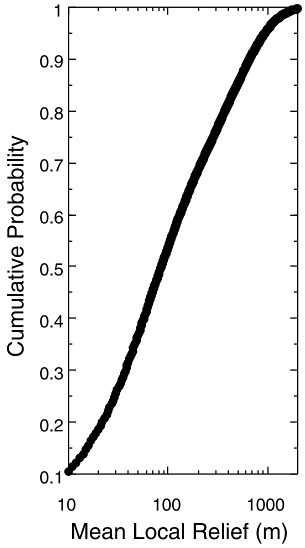


Fig. 7. Cumulative probability distribution of mean local relief defined over a 10-km-diameter circle for North America, Europe, South America, and Asia derived from GTOPO30 data set.

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Fig. 6. Maps of the global distribution of mean local relief defined over a 10-km-diameter circle for North America, Europe, South America, and Asia. Scale bar and legend pertain to all four panels. Topography from the GTOPO30 data set. This figure can be approximately converted to a global-scale slope map using the relationship calibrated for the Olympic Mountains (see text), although local relief values (shown here as determined with a relatively coarse, approx. 1-km grid DEM) would be larger if determined using a 10 m DEM as used in the Olympics.

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