

Supplemental information

Slope-area thresholds

Following the work of Montgomery and Dietrich (1994), it is commonly assumed that channel heads occur at sites of landsliding, in which a threshold of the product of drainage area and local slope is exceeded. In such cases, we expect the slope and drainage area to be inversely related. However, these relationships have not been found in studies of Colorado debris flows and channel heads (Godt and Coe, 2007; Henkle et al., 2011); Coe et al. (2014) also noted that such a relationship was lacking in their analysis of over 1,100 failures during the 2013 event. This is also the case in our analysis (Supplementary Figure 1). It appears that failure locations are controlled instead by complex local site conditions. Anecdotally, we observed that many failures occur just downslope of bedrock outcrops (10-30 m slope distance) that may serve to create subsurface convergence or act as an impermeable surface that accelerates downslope water delivery (the “fire hose” effect defined by Johnson and Rodine, 1984, and observed by Godt and Coe, 2007).

Supplementary Figure 1. Slope and contributing area at failure initiation. Over 90% of these failures represent shallow landsliding on roughly planar slopes. The remaining sites represent either deeper roadcut or streambank landslides, or the highest point of detectable gully incision. Bounding boxes indicate 16th-84th percentile bounds for each study subarea, with median values shown. Sedimentary initiation sites were, on average, slightly less steep and at smaller contributing areas, but neither difference is statistically significant.

Landslide and channel scour depths

Supplementary Figure 2. Histograms of failure initiation and channel scour depths.

Vertical dashed lines indicate mean depths for the respective subareas.

Volume-drainage area relationships and debris flow erosion law

Stock and Dietrich (2006) propose a debris flow erosion law in which erosive power is proportional to the length of the granular flow front. This length increases as a function of total debris flow volume, which in turn increases through channel scour and bulking.

Stock and Dietrich hypothesize that, given increased channel loading from hillslopes and tributaries, debris flow volumes should increase as an exponential function of drainage area. Gabet and Bookter (2008) estimated bulking down six post-fire debris flows and indeed found exponentially increasing volumes with drainage area, although their bulking coefficients were somewhat higher than the range proposed by Stock and Dietrich.

We follow the lead of Gabet and Bookter (2008) in using our volume estimates to assess the reasonableness of an exponential increase in volume with increasing drainage area, expressed in the rearranged formulation of equation (8) from Stock and Dietrich (2006):

$$\frac{V(x)}{V_t} \sim e^{a_1 \left(\frac{A(x)}{A_t} \right)}$$

where V is volume for a given location along the debris flow channel, V_t is the total volume, A is drainage area, A_t is the total drainage area of the debris flow basin, and a_1 is a bulking exponent. This differs from the original formulation in that we normalize

volume by the total volume, as opposed to the initial failure volume; this provides a constant scale for all results, and does not change the shape of the relationship.

We chose eight crystalline debris flow channels to test this relationship, excluding failures in which multiple initiation sites feed into a single channel and those that interacted with roads or other human modifications of the landscape. Of the eight channels, four were well fit by exponential relationships (Supplementary Figure 3).

Bulking exponents ranged from 1.18 to 2.97, in reasonable agreement with the expectations of Stock and Dietrich (2006). The remaining four channels showed linear or roughly logarithmic relationships with drainage area. A power law provided reasonable fit to all curves, although rarely was it the best option for any single curve.

Echoing the results of our analysis across multiple failures, volumes along a given channel increased linearly with distance from the failure (Supplementary Figure 3). This relationship was consistent across the range of relationships with drainage area. We take this to imply that i) the variation in volume-drainage area relationships is primarily a function of the channel network structure, and ii) diffusive hillslope processes likely provided much more sediment to the channels than fluvial or debris flow deposition from small tributary channels. These results also suggest that the debris flow erosion law of Stock and Dietrich (2006) may need to be modified slightly to account for a range of possible bulking trends. However, at present, we do not have any method for estimating a priori what the trend in any given channel may be.

Supplementary Figure 3. Normalized debris flow volume plotted against drainage area and length for eight individual channels. All values are normalized by the value at the outlet of the debris flow channel. In plots in which the volume-drainage area relationship is well described as an exponential, the bulking exponent is indicated. Our name-designation and the coordinates of the outlet location are shown in the upper left of each panel.

Volume as a function of debris flow length and drainage area

The total volume of material evacuated in a failure was highly correlated with both total failure length and the contributing area at the failure outlet. Volume scaled linearly with failure length, reflecting relatively uniform scour depths and channel widths. Volume scaled to the 0.66th power of drainage area. These results were consistent across both study areas. Channel length and drainage area are highly correlated, area increasing nonlinearly with channel length as in most drainage basins ($A \sim L^{1.4}$). The linear relationship between volume and length is a reasonable outcome if channel sediment is primarily supplied by creep of soil into the channel along the channel margins, as opposed to episodic recharge by tributary channels.

The linear relationship of volume with length also provides a physical explanation for the observed trend of decreased mean basin lowering with increasing drainage area (Fig. 4b). Moving down a channel, drainage area increases more rapidly than debris flow volume, leading to decreasing mean lowering. This trend would be offset if debris flow frequency

increases down network, as is commonly measured and modeled (Benda and Dunne, 1997; Stock and Dietrich, 2006).

Supplementary Figure 4. Total debris flow volume vs. total length and drainage area at the failure toe.

Channel recharge and estimates of diffusivity

By imposing an erosion rate acting over a contributing area, we may recast sediment volumes as an equivalent period of steady hillslope erosion. If we then assume that hillslope sediment is uniform and that sediment loaded into hollows or channels remains there until evacuated by rare failures, these times can also be interpreted as recharge intervals. Our assumptions make these minimum estimates. Interpreted as such, they provide a means of estimating the long-term channel recharge rates and implied hillslope diffusivities. Recharge rates range between 0.002 and 0.03 m³/m/yr, with a median of 0.01 m³/m/yr. These recharge rates overlap, albeit on the low end, those observed in the Queen Charlotte Islands over shorter (5-80 year) time intervals (Jakob et al., 2005).

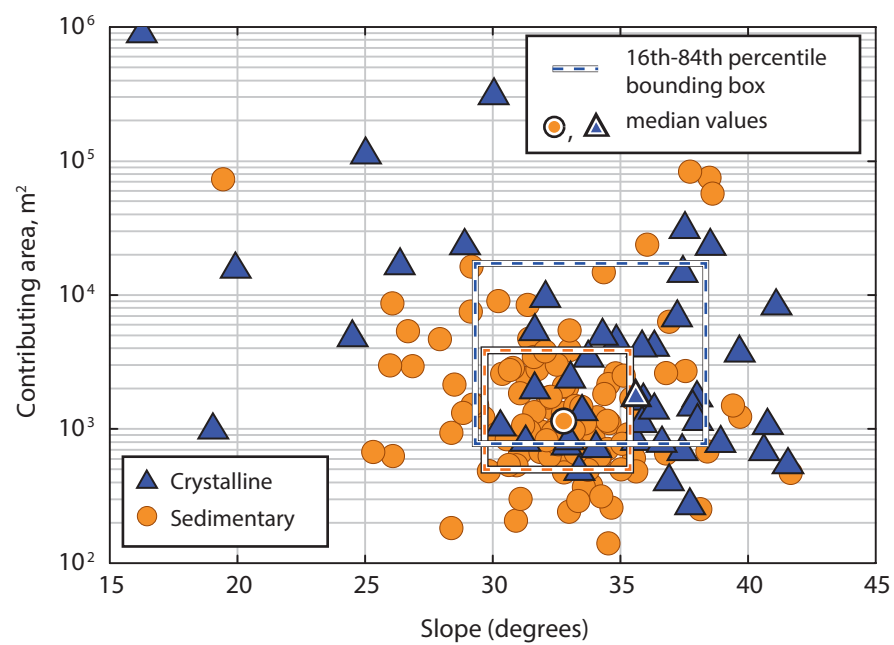
Implied diffusion coefficients range from 0.32-6.0x10⁻² m²/yr, with a median 2.1x10⁻² m²/yr. These values lie within the range of previously estimated diffusion coefficients (Martin and Church, 1997), although they are generally higher than estimates specifically for semi-arid regions (Fernades and Dietrich, 1997). Given the convergent topography and long times involved in our estimation, our values likely integrate historical periods of fire-accelerated sediment motion and sporadic slumps, which would act to increase

apparent diffusion rates (Martin and Church, 1997). As our estimates of channel recharge rates and implied diffusivities are plausible and physically reasonable, we infer that our decision to interpret hillslope erosion times as channel recharge times is likewise reasonable.

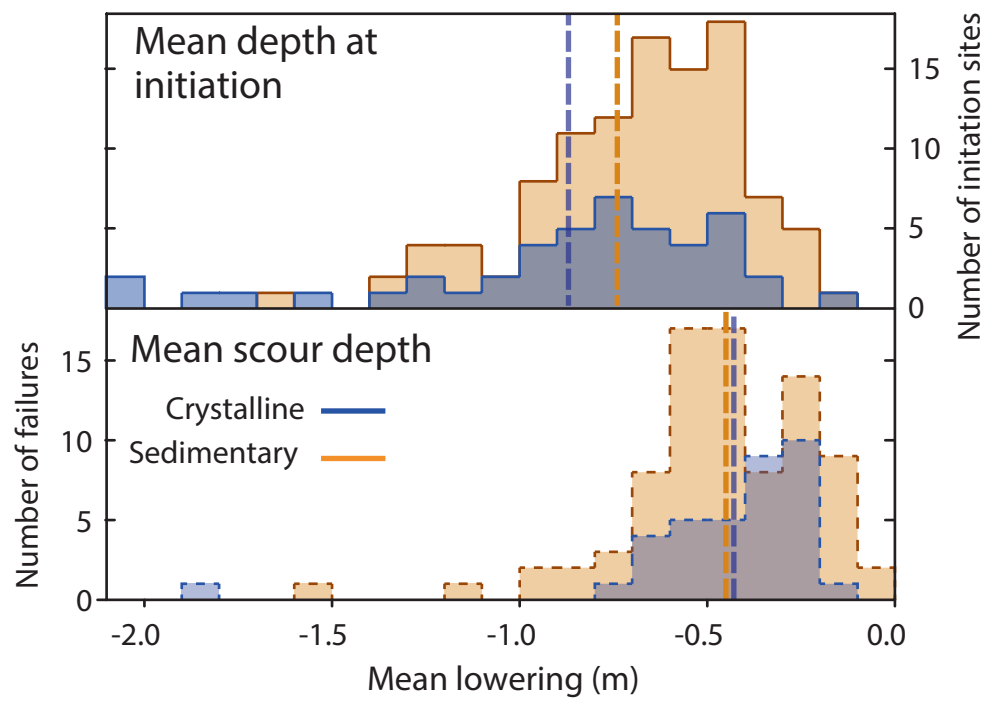
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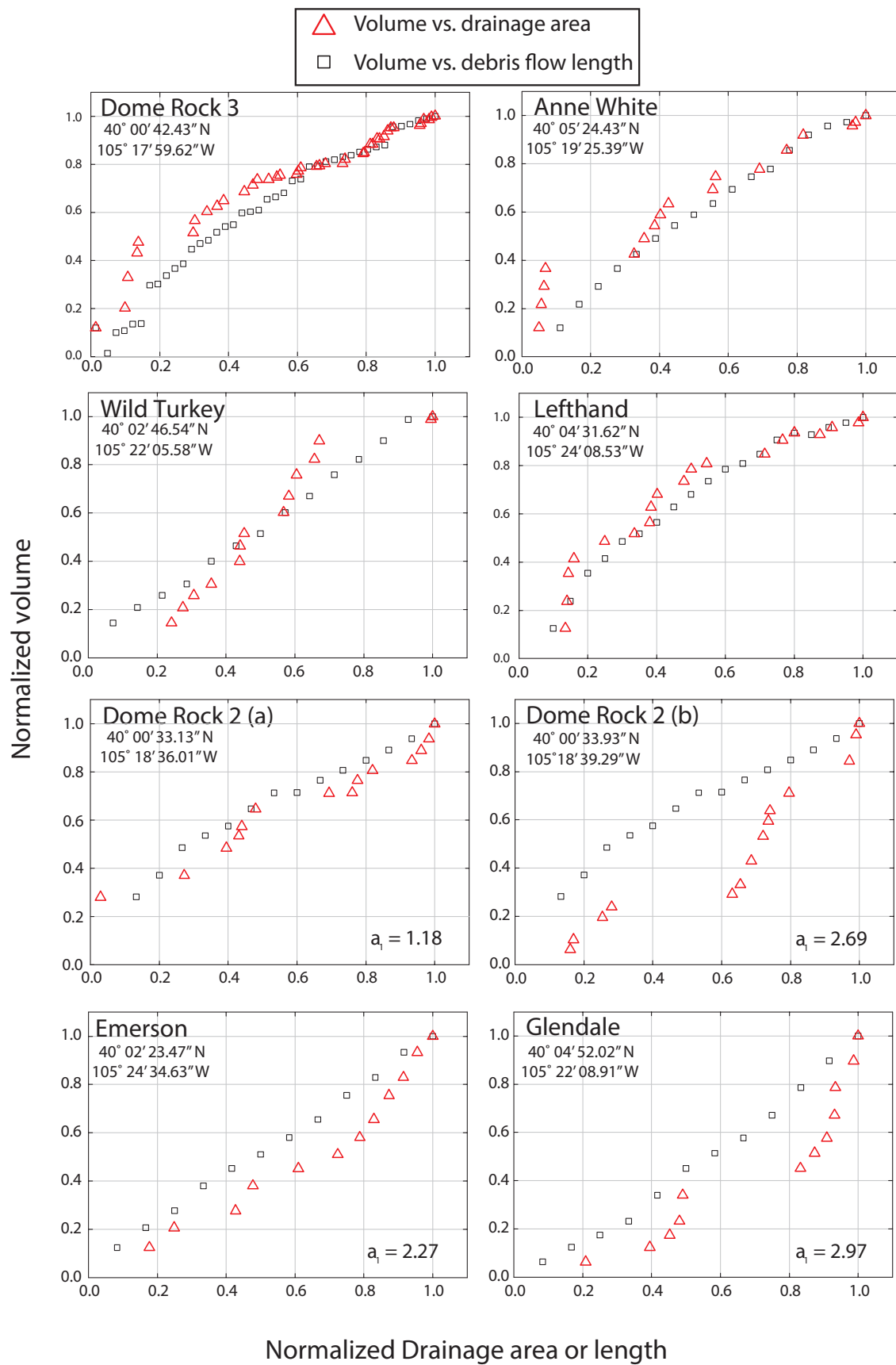
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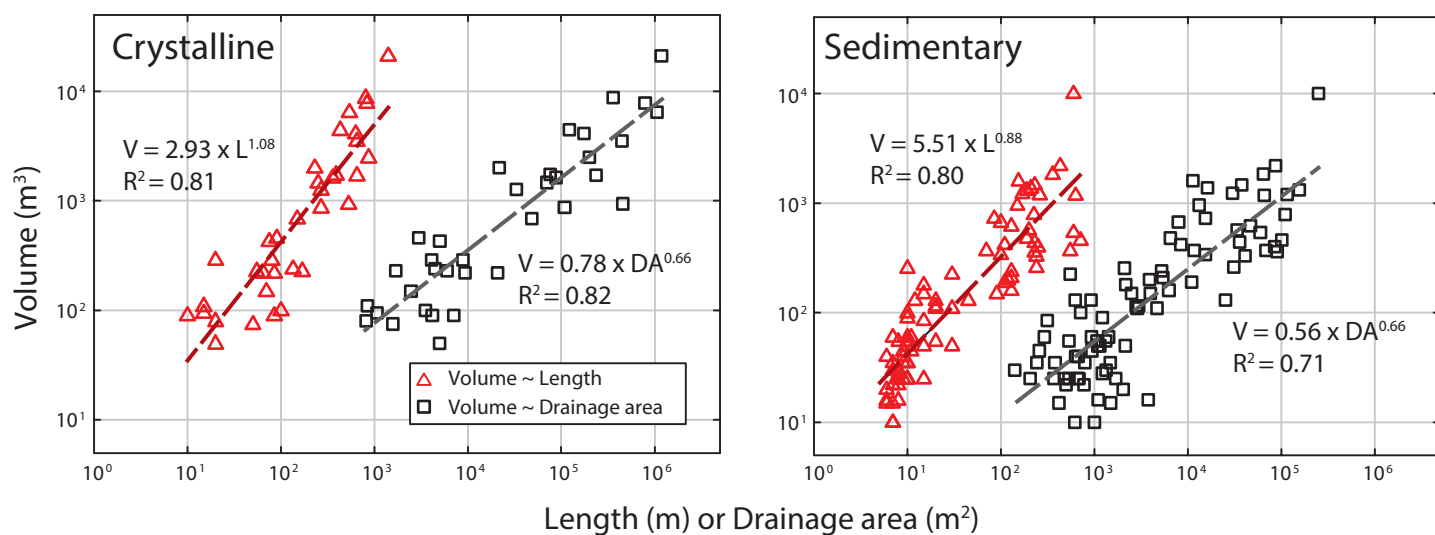
Supplementary Figure 1



Supplementary Figure 2



Supplementary Figure 3



Supplementary Figure 4