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Bedrock fracture density and limits to landslide magnitude

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The role of bedrock fractures and rock-mass strength is often considered a primary influence on the efficiency of surface processes. Quantifying bedrock characteristics at hillslope scales, however, has proven exceedingly difficult. Here, we present a new field-based method for quantifying bedrock fracture densities within the shallow subsurface based on seismic refraction surveys. We examine variations in subsurface fracture patterns in both Fiordland and the Southern Alps of New Zealand in order to better constrain the influence of bedrock properties in governing rates and patterns of landslides, as well as the morphology of threshold landscapes. We argue that tectonic forces produce uniform and pervasive bedrock fracturing with depth, whereas geomorphic processes produce strong fracture gradients focused within the shallow subsurface. Additionally, we argue that hillslope strength and stability are functions of both the intact rock strength and the density of bedrock fractures, such that for a given intact rock strength, a threshold fracture-density exists that delineates between stable and unstable rock masses for a given slope angle. Slope distributions in both Fiordland and the Southern Alps of New Zealand reveal near equivalent modal slope values of $\sim$32°. Landslide magnitude-frequency distributions, however, define order-of-magnitude differences between the regions, with Fiordland experiencing considerably smaller and less frequent landsliding events. Landslide-driven denudation rates of $\sim$9 mm/yr in the western Southern Alps and $\sim$0.3 mm/yr in Fiordland approximate the rock-uplift rates for each region. The near-normal slope distributions and apparent equivalence between rates of uplift and landslide-driven erosion suggest that both regions are at threshold slopes. Their similar modal slopes further suggest that they are characterized by equivalent rock-mass strength, despite striking differences in lithology. Our shallow seismic analysis reveals that in the Southern Alps, tectonic forces have pervasively fractured intrinsically weak rock to the verge of instability, such that the entire rock mass is susceptible to failure and landslides can potentially extend to great depths. In Fiordland, conversely, tectonic fracturing of the strong intact rock has produced fracture densities less than the regional stability threshold, such that bedrock from depth is relatively stable and less likely to fail by landslide. Therefore, in Fiordland, bedrock failure generally occurs only when geomorphic fracturing further reduces the rock-mass strength by increasing the fracture density within the shallow subsurface. This dependence on geomorphic fracturing results in bedrock landslides that are generally limited to shallow depths within this geomorphically weakened zone. Our data suggest that the density of bedrock fractures at the Earth's surface helps modulate threshold slope angles, whereas the depth of bedrock fracturing influences the magnitude and frequency of the landslide response to tectonic rock uplift.