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# Debris Flows and Landscape Evolution: Insight From Topographic Analysis, Millennial Erosion Rates and Grain-Scale Flow Mechanics

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Although steep valleys are ubiquitous in mountainous terrain, uncertainty remains about the actual processes that incise bedrock to create them. There is mounting evidence that episodic scour by debris flows is a significant transport and erosional process in steepland headwaters, yet there is not an agreed upon mechanical framework to describe how debris flows incise high-gradient valleys. This makes it difficult to predict how a catchment will evolve over time or what the effect of changing land use, climate or tectonics would be. To develop and test quantitative expressions that link debris-flow processes to topographic form, detailed information on morphometry, erosion rates and controlling flow mechanics is required.

Here we present data from field surveys, cosmogenic radionuclide (CRN) derived erosion rates, analysis of digital topographic data and grain-scale numerical modeling that allow us to link topographic form with rates of debris flow erosion and controlling granular mechanics. We take advantage of a unique natural experiment that has allowed erosion rates to be determined for a large number of steep catchments crossing active normal faults in the Central Italian Apennines. Here, existing studies have quantified the rates of fault slip and hence the resulting base-level fall that controls the long-term incision rate of small catchments adjacent to the range-bounding faults. CRN measurements were made in selected catchments to test the assumption of equilibrium between incision rate and fault throw rate. All CRN determined erosion rates near the fault are within error of the fault throw rate. Fault throw rates vary by nearly an order of magnitude between catchments so we can use this combined data set to quantify how measured catchment properties such as incised channel width, depth and slope vary as a function of millennial-scale erosion rate.

To complement this field data set, we use grain-scale numerical modeling to evaluate how changes to channel or flow properties such as channel slope, flow depth, and grain size influence the erosive potential of a flow, and hence long-term incision rates. We use particle impact force and energy flux to the bed as proxies for the erosive potential of the flow. Our simulations reveal that impact force is a strongly increasing and non-linear function of bed slope. In contrast, particle impact flux increases at small slopes, but then decreases linearly as slope increases beyond a threshold value. Steady flows could be generated on a range of slopes, indicating that there is a range of slopes where force is shear-rate dependent. Significant changes in flow properties occur as the flow decelerates from a rapid flow to deposition. We use these findings to develop a mechanical explanation for the measured field relationships between debris flow erosion rates and steepland morphology.