Investigating the impact of discontinuity orientation on fluvial incision processes

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Bedrock rivers play a primary role in shaping the Earth's surface. Bedrock river incision removes the material making up continental land masses, steepens and destabilizes adjacent hillslopes, and can reflect the tectonic and climatic history of a landscape. Therefore, knowledge of the mechanisms by which fluvial bedrock incision is accomplished is fundamental to a robust understanding of landscape evolution, and has been the subject of a large body of work in recent decades. A key observation emerging from these efforts is the paramount importance of bedrock discontinuity networks (fractures, bedding planes, joints, etc.) in dictating the style and efficiency of fluvial bedrock erosion (e.g., Chilton and Spotila, 2022; Dubinski and Wohl, 2013; Whipple et al., 2000). These observations have focused primarily on the spacing of discontinuities, which impacts erodibility by setting the size of blocks which can be hydraulically plucked from the bed: closely spaced discontinuities define small bedrock blocks that are easily removed by the flow, while more sparse discontinuities define larger blocks which require higher shear stresses to erode. A second key characteristic of discontinuity networks is their orientation relative to flow direction. Basic field observations across geomorphic domains (Lane et al., 2015; Miller, 1991; Scott and Wohl, 2019; Weissel and Seidl, 1997, Wohl et al., 2000) and limited laboratory evidence (Dubinski and Wohl, 2013; Lamb et al., 2015) suggest discontinuity orientation is likely to exert a strong influence on erosion and channel form by configuring bedrock block position to favor or inhibit plucking. However, this relationship has not yet been fully examined, in part due to the scarcity of natural settings which exhibit systematic and well-distributed variation of discontinuity orientation while having a limited number of additional confounding variables. Constraining the impact of discontinuity orientation on fluvial erodibility and incision processes is important for understanding landscape evolution in the structurally complex landscapes common across Earth's surface, where folded and faulted underlying geologic structures can impart wide variations in prevailing discontinuity orientation throughout the landscape, sometimes over very short spatial scales.

Therefore, to investigate the effects of discontinuity orientation on fluvial bedrock erodibility, incision processes, and knickpoint expression, we are conducting a series of flume experiments that employ stacked ceramic tiles held at a range of orientations to simulate variable dip angle in layered bedrock undergoing fluvial incision. Tile orientation (i.e., dip angle) is adjusted in each experiment using 3D printed tile-supporting trays placed in the flume (Figure 1). A total of eight configurations will be tested, which span upstream-dipping, downstream-dipping, horizontal, and vertically bedded cases. Hydrologic conditions (discharge, flow velocity, slope, Froude number, etc.) are held constant between each run, while knickpoint evolution and erosive processes are monitored. Specifically, we document individual plucking events, knickpoint celerity (a proxy for bedrock erodibility) and expression, and channel morphology using high-resolution photo- and video-recording tools, including 3D images generated with Structure-from-Motion software. This experimental approach allows for controlled variation of bedrock orientation while holding all other variables constant. Experiments are ongoing, but we hypothesize that discontinuity orientation will impact bedrock erodibility in two ways. First, bedding plane orientation will determine the height-to-downstream length ratio of pluckable blocks, influencing whether toppling (which requires relatively low shear stresses to accomplish) or sliding (which requires higher shear stresses to accomplish) is the favored plucking mechanism. Second, bedding plane orientation will dictate the alignment of gravitational forces acting along the block base relative the flow direction, and therefore act to enhance or inhibit plucking susceptibility. We expect this impact on erodibility to translate to slower knickpoint migration rates for resistant block configurations, and that changes to dominant plucking mechanism will correspond to distinct variations to knickpoint morphology.

Our choice of small (12 mm x 12 mm x 4 mm), stacked ceramic tiles as a bedrock analogue material is motivated by the layered and orthogonally jointed sedimentary rocks that underly local bedrock channels in the Valley and Ridge Province of the Central Appalachians, which often exhibit knickpoints. Knickpoints formed within the block stacks set in the flume under experimental conditions compare well to the morphology and erosional processes we observe in these local real-world knickpoints we seek to represent (Figure 2). The motivation to focus on knickpoint behavior in the flume is two-fold. First, knickpoints function as zones of focused erosion within bedrock channels, accomplishing much of the work of incision as they migrate upstream, and are therefore the logical focal point of studies seeking to understand fluvial incision processes. Second, knickpoints can act as geomorphic signals of baselevel fluctuation: a drop in baselevel (due to sea level fall, tectonic uplift, drainage basin reorganization, etc.) can generate a pulse of incision that subsequently migrates throughout the upstream drainage network, often marked at its upstream boundary by the presence of a knickpoint. Knickpoints are therefore commonly used as interpretive tools to infer complex climatic and tectonic landscape histories. However, to ensure accurate interpretation of these features we must first understand the other factors which may influence their expression within a landscape, such as variable discontinuity orientation. Therefore, through these experiments we hope to demonstrate how the orientation of bedrock discontinuities impacts not only plucking style, thresholds of erosion, and bedrock erodibility, but also knickpoint behavior and expression in a landscape. In doing so this work will represent a significant contribution towards our understanding of fundamental fluvial incision processes and the usefulness of knickpoints as interpretive tools.

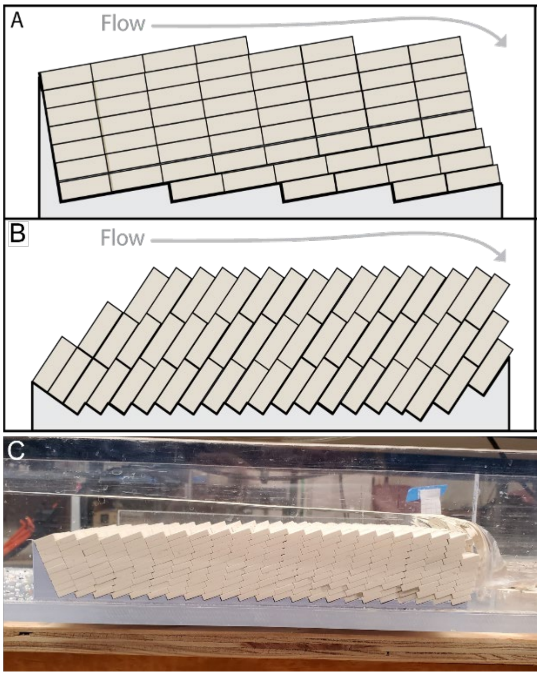

Figure 1. Examples of variable block orientation supported by 3D-printed support trays, shown in cross-section with flow direction from left to right in each image. (A) and (B) show conceptual diagrams illustrating two of the eight orientations to be tested. (C) shows example of concept in flume, demonstrating tiles being held in a shallow upstream-dipping configuration.

Figure 2. Top-down views comparing a knickpoint formed in the flume using ceramic tiles as bedrock analog material (A) to a natural knickpoint within a small bedrock stream in Virginia exhibiting typical plucking behavior (B). Flow is from bottom to top in each photo. Ceramic tiles are roughly 1 cm square.

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