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Dip angle controls on plucking susceptibility and knickpoint evolution in bedrock rivers

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ABSTRACT

Bedrock river erosion drives landscape evolution across much of Earth's surface. Plucking is a key mechanism of fluvial bedrock erosion, yet our understanding of the controls on plucking is limited. Discontinuity orientation (e.g., dip angle) may significantly influence plucking dynamics, but this remains untested. We present the first direct observations of the impact of dip angle on plucking processes and knickpoint morphodynamics. Using flume experiments, we modeled erosion through dipping bedrock using stacked tiles held at three orientations: upstream-dipping, horizontal, and downstream-dipping. We find that horizontal beds are the most erodible, followed by downstream-dipping then upstream-dipping beds. Dip angle also influences knickpoint slope, bed roughness, armoring dynamics, and flow structure, which all interact to govern knickpoint morphological evolution. These observations demonstrate the profound effects of dip angle on the evolution of plucking-dominated bedrock knickpoints, and inform our understanding of landscape evolution within the many discontinuity-defined landscapes at Earth's surface.

INTRODUCTION

Fluvial erosion of bedrock sets erosion rates within river networks and adjacent hillslopes, thereby driving landscape evolution over much of Earth's surface. This erosion is dominated by plucking of bedrock blocks wherever discontinuities are spaced closely enough to permit plucking (Whipple et al., 2000). Discontinuities are common at scales conducive to plucking (Whipple, 2004), and are defining features of many landscapes (Scott and Wohl, 2019), such as those formed in layered stratigraphy, columnar basalts, or with regional tectonic fabrics. Plucking processes and the discontinuity networks that control them may therefore be among the most significant factors governing landscape evolution across Earth's surface.

Despite the significance of plucking, most experimental studies have focused on erosion by abrasion (Johnson and Whipple, 2007; Gardner, 1983; Wohl and Ikeda, 1997; Sklar and Dietrich, 2001; Finnegan et al., 2007; Grimaud et al., 2016; Scheingross et al., 2019; Inoue et al., 2023), leaving major gaps in our understanding of plucking-dominated bedrock river evolution. In particular, the influence of discontinuity orientation on plucking susceptibility and knickpoint morphology has been hypothesized from field observations (Miller, 1991; Alexandrowicz, 1994; Wohl, 2000; Ortega et al., 2013) and theoretical predictions (Hurst et al., 2021), but remains unresolved. Also uncharacterized are the potentially unique feedbacks between erosion and armoring in plucking-dominated rivers, which, in contrast to abrasion-dominated settings, generate their own armor as erosion occurs.

To fill these gaps in our understanding of plucking-dominated bedrock river evolution, we conducted flume experiments that model knickpoint erosion within layered bedrock set at varying dip angles. We present the first direct observations of the influence of discontinuity orientation on plucking thresholds and knickpoint morphodynamics in layered bedrock rivers.

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METHODS

We conducted two sets of flume experiments to observe how dip angle impacts plucking and knickpoint evolution. Phase I experiments tested the influence of dip angle on block entrainment thresholds, and phase II examined the effects of dip angle on reach-scale knickpoint morphodynamics and plucking mode. Experiments used 12 × 12 × 4 mm ceramic tiles stacked onto 3-D-printed trays to simulate layered, dipping sedimentary bedrock at three orientations: upstream dip (18°), horizontal (0°), and downstream dip (−18°). Detailed methods and videos of experiments can be found in the Supplemental Material[1].

In phase I experiments, support trays were installed within an 18-cm-wide flume with a layer of tiles glued to the surface and a row of free tiles at the knickpoint lip (Fig. 1A). Flow was initiated below the erosion threshold, and discharge increased incrementally every 5 min until all tiles eroded or the flume limits were reached. For each plucking event, we measured flow depth (at the upstream end of the tray), number of tiles removed, and the corresponding discharge (using a flow collection bucket and stopwatch). Each orientation was tested eight times. Discharge measurements were used to compute erosive velocities ($V = Q/A$, where Q is discharge and A is cross-sectional area), which were aggregated from all trials for a given orientation to build an erosive velocity distribution for each orientation. Kruskal-Wallis H-tests (Kruskal and Wallis, 1952) with Dunn's posthoc tests (Dunn, 1964) were used to assess the significance of differences between distributions. We used three metrics to compare the erodibility of each orientation: the velocity at the onset of plucking (V_{ONSET}), the velocity that eroded

[1]Supplemental Material. Detailed descriptions of experiment setup and observations, field survey locations and methods, and links to video recordings of full experiments. Please visit https://doi.org/10.1130/GEOL.S.29396192 to access the supplemental material; contact editing@geosociety.org with any questions.

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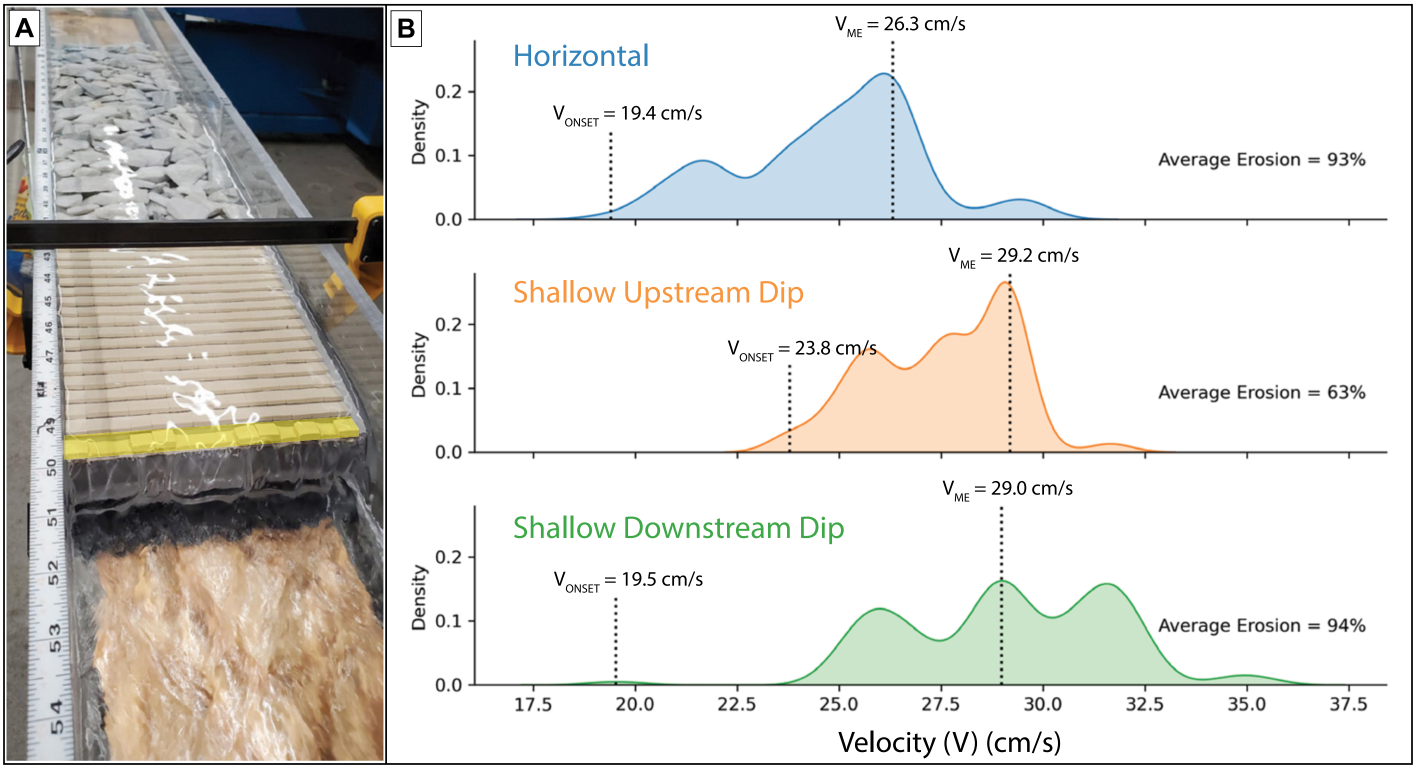

Figure 1. (A) Phase I experiment setup to test the effects of dip angle on block entrainment thresholds; upstream-dipping case shown. Only the tiles at the knickpoint lip (yellow) are free to erode. (B) Erosive velocity distributions generated from histograms of plucked tile counts aggregated across all trials for each orientation and smoothed using a kernel density function. V_{ONSET} marks the onset of erosion, and V_{ME} is the velocity that eroded the most tiles.

the most tiles (V_{ME}), and the average percentage of tiles eroded.

In phase II experiments, tiles were stacked on support trays inside a 22-cm-wide flume to form stacks 5 cm high and 25–33 cm long. Experiments began with the tailgate raised to submerge the stack and prevent erosion as the flume slowly filled. Flow depth gradually decreased as the tailgate lowered at the start of each experiment. Discharge was held constant at ~3800 cm^3/s. Video was recorded to measure erosion rate (by estimating the volume of remaining in situ tiles at regular time intervals), knickpoint longitudinal profiles, and to make qualitative observations of plucking mode, armoring by eroded tiles, and morphologic evolution. Due to the labor-intensive setup (each stack contained ~4700 individually placed tiles), one experiment was conducted for each orientation.

RESULTS

Phase I experiments demonstrate that dip angle impacts plucking susceptibility (Fig. 1B). Statistical tests reveal significant differences in erosive velocity distributions between orientations ($p < 0.05$). In the horizontal case, V_{ONSET} (19.4 cm/s) and V_{ME} (26.3 cm/s) were the lowest of all orientations, and 93% of tiles were eroded. In the upstream-dipping case, V_{ONSET} (23.8 cm/s) and V_{ME} (29.2 cm/s) were the highest of all orientations, and only 63% of tiles were eroded, even at the flume's maximum flow rate (~1850 cm^3/s). The downstream-dipping case produced a broader, flatter erosive velocity distribution. V_{ONSET} was low (19.5 cm/s), and 94% of tiles were eroded, but V_{ME} was comparable to the upstream-dipping configuration (29 cm/s), though not represented by a unique peak.

Phase II experiments demonstrate the influence of dip-influenced morphodynamic feedbacks on knickpoint form and evolution. We observed dip-dependent changes in experimental channel roughness and slope that are qualitatively consistent with analogous field sites in the Appalachian Valley and Ridge Province (eastern United States; Fig. 2). In experimental and natural channels, upstream-dipping beds produce a rough channel bed within and surrounding the knickpoint. Horizontal beds produce a smooth channel upstream and downstream of the knickpoint, but a rough knickpoint where concentrated plucking creates stepped surfaces. Downstream-dipping beds set the knickpoint slope (consistent with others' field observations; e.g., Alexandrowicz, 1994; Wohl, 2008) and therefore produce a smooth knickpoint, but a rough surrounding channel due to prominent upstream-facing steps (Fig. 2E) that migrate downstream (e.g., Miller, 1991).

Dip angle determined plucking mode in all experiments. Upstream-dipping tiles eroded via sliding, often "rocking" (sliding slightly upstream then settling back, often grouped with several vertical neighbors) repeatedly before eroding. Horizontal tiles eroded via sliding (Dubinski and Wohl, 2013), with some vertical entrainment (Wilkinson et al., 2018). Downstream-dipping tiles eroded by pivoting about their downstream neighbor (Wende, 1999) due to stack geometry, in which tiles were by necessity supported at their downstream face.

Dip-influenced interactions between plucking, armoring, knickpoint profile shape, and flow structure controlled the morphologic evolution of phase II experiments (Fig. 3). Each experiment began with a pulse of erosion, as water depth decreased and flow accelerated over the tile stack, and concurrent formation of a downstream tile deposit (Fig. 3). The deposit quickly halted erosion due to (1) armoring of underlying in situ tiles (especially in the downstream-dipping case), and (2) modification of flow through the knickpoint: as the deposit grew, the hydraulic jump that initially formed downstream of the knickpoint in each experiment migrated upstream and increased flow depth (reduced velocity) near the knickpoint. Jump migration was dampened in the downstream-dipping case where the jump was constrained by an upstream-facing step (Fig. 3B). Erosion resumed only after the armor was remobilized (which occurred without a change in flow conditions) and transported

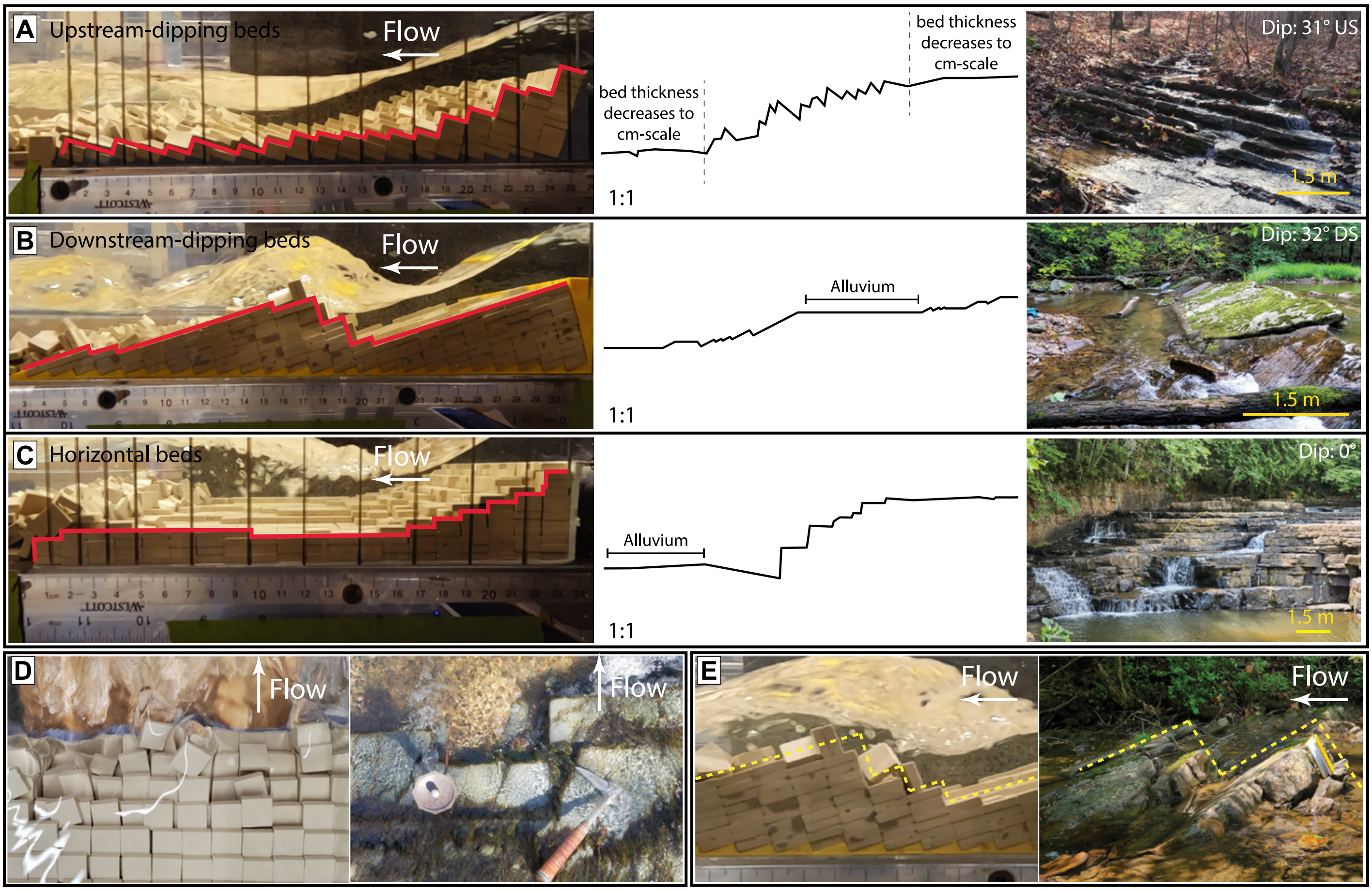

Figure 2. Morphological comparison of experimental and natural knickpoints from the Appalachian Valley and Ridge Province in the eastern United States. (A–C) Experimental (left) and natural (middle) channel profiles, with field photos on the right. (D) Plucking at knickpoint lip. (E) Upstream-facing steps in downstream-dipping beds.

downstream, resetting the flow structure and beginning the cycle anew.

Analysis of erosive and armoring phases of phase II experiments shows that armor removal was the rate-limiting factor for morphological evolution. All orientations show similar erosion rates during erosive phases (despite varying plucking thresholds observed in phase I), but differ in the onset and total duration of armoring phases (Fig. 3A). Armoring by eroded debris became morphologically significant early in the evolution of the downstream-dipping case, with the first armoring phase beginning at 34% erosion of the tile stack, compared to 56% and 57% erosion in the horizontal and upstream-dipping cases. The upstream-dipping case spent the least time in armoring phases—just 16 min, compared to 35 min and 31 min in the horizontal and downstream-dipping cases, respectively.

DISCUSSION

Phase I results indicate a hierarchy of block erodibility as a function of dip angle: horizontal

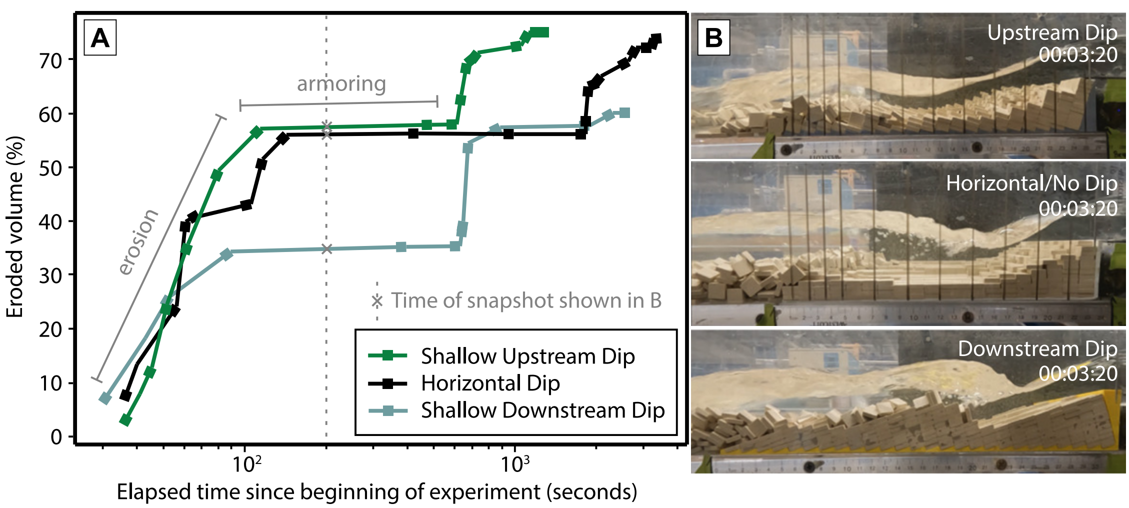

Figure 3. (A) Eroded volume versus time for phase II experiments (testing the effects of dip angle on reach-scale knickpoint morphodynamics and plucking mode) showing cycles of erosion and armoring (little/no erosion). (B) Examples of armoring.

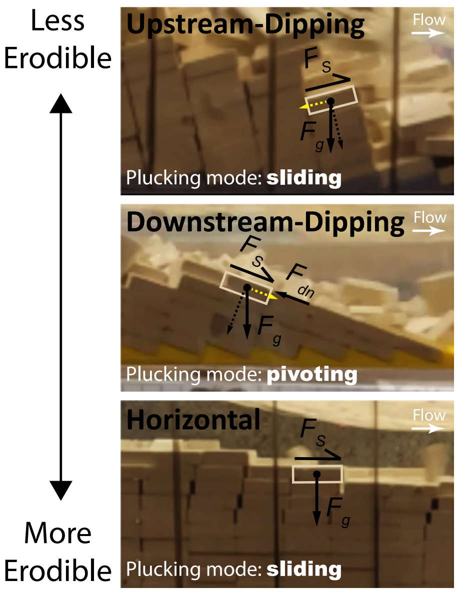

Figure 4. Relationship between the erodibility of a single block and dip angle, due to (1) the orientation of the bed-parallel component of gravity (F_g) relative to bed shear stress (F_S) and (2) primary plucking mode. F_{dn} is the force exerted by the block's downstream neighbor.

beds are the most erodible, upstream-dipping beds the least, and downstream-dipping beds fall in between but have greater threshold variability. We propose that these erodibility differences are due to (1) the orientation of the bed-parallel component of the gravity vector relative to the bed shear stress, and (2) the dominant plucking mode (Fig. 4). In upstream-dipping beds, the bed-parallel component of gravity opposes bed shear stress, causing tiles to fall back into place after partial sliding. In horizontal beds, the gravity vector is relatively normal to the bedding plane and so does not hinder sliding beyond its contribution to friction. In downstream-dipping beds, the bed-parallel component of the gravity vector is aligned with bed shear stress and should promote sliding, but the presence of a downstream neighbor forces plucking via pivoting, a type of vertical entrainment that likely requires more stress than sliding (Lamb et al., 2015). This difference in plucking mode may explain the wide erosive velocity distribution observed in the downstream-dipping case (Fig. 1B)—plucking via pivoting may be heavily influenced by stochastic flow variations and/or flow through the underlying discontinuity network (e.g., Wilkinson et al., 2018). Our observations are consistent with theory (Hurst et al., 2021) and field studies (Wohl, 2000) that suggest upstream-dipping beds are more resistant than downstream-dipping beds, but are the first to quantify variations in erodibility as a function of dip angle for low-aspect-ratio blocks.

Surprisingly, these differences in erodibility are not clearly reflected in phase II experiments, where erosion rates were similar for all orientations. This suggests that (1) where entrainment thresholds are far exceeded, as in phase II experiments, they do not significantly impact erosion rate; and (2) bed armoring can obscure the impact of local bedrock erodibility, an effect often observed in natural settings with substantial hillslope input (Thaler and Covington, 2016; Shobe et al., 2021; Anderson et al., 2023), but which may be uniquely significant in plucking-dominated settings where plucked blocks contribute directly to the armor layer as erosion occurs. However, our experiments likely exaggerate the armoring effect of eroded material as in situ tiles are completely detached, unlike natural bedrock blocks. In nature (and ignoring hillslope inputs; Shobe et al., 2016), we might expect armor to build up more slowly relative to erosion rate than in our experiments because flow conditions powerful enough to cause block detachment might transport a greater fraction of eroded material downstream than we observed.

This connection between the ease of block detachment and rate of armor buildup highlights a ratio that may modulate the morphodynamic significance of sediment cover in plucking-dominated knickpoints: the relative entrainment thresholds of in situ versus deposited blocks. Our experiments suggest that erosion of a detached, in situ knickpoint block requires less stress than re-entrainment of the same block from a downstream deposit (see also Wilkinson et al., 2018). This is likely due to higher flow velocity, lower bed roughness, and less interlocking of blocks within the knickpoint compared to the downstream deposit. Where in situ blocks are more difficult to mobilize than deposited blocks (e.g., where bedding planes are strong), detachment-limited conditions prevail and armor is cleared more quickly than it is produced. Where in situ blocks are easier to mobilize than deposited blocks (e.g., where bedding planes are weak), transport-limited conditions prevail and armor accumulates quickly as blocks are plucked. The magnitude of this entrainment threshold ratio thus helps determine the morphological significance of the armor layer, and the extent to which factors governing plucking susceptibility (dip angle, block interlocking, etc.) shape bedrock rivers.

Even in cases where bed armor is a strong morphological influence, our observations suggest that dip angle still has an important impact on channel evolution through its influence on armoring dynamics. By setting bed profile shape, dip angle indirectly impacts armor distribution and flow structure, and therefore erosion of the armor layer (e.g., by influencing the location of a hydraulic jump, or of an upstream-facing step that traps blocks). Differences in the onset and duration of armor-induced stasis in phase II experiments suggest that armoring effects are most significant in downstream-dipping beds (where armor-induced stasis began at 34% erosion and lasted 31 min), and less so in upstream-dipping beds (where armor-induced stasis began at 57% erosion and lasted just 16 min). These observations suggest that dip angle shapes channel evolution not only through its control on bedrock erodibility, but also by influencing feedbacks between channel form, armoring, and flow structure.

The impacts of dip angle have several implications for the evolution of structurally complex landscapes. Basins with different dominant dip orientations may feature different erosion rates, responses to tectonic and climatic perturbations, and characteristic knickpoint morphologies. Dip angle may influence the preservation and identification of base-level signals as they propagate upstream: shallow downstream-dipping beds that constrain knickpoint slope may prevent the formation of a well-defined knickpoint face, perhaps explaining observations that downstream-dipping beds seem less likely to develop knickpoints (Miller, 1991). Additionally, dip angle may contribute to the asymmetry of homoclinal ridges often observed in fold-and-thrust landscapes, reflecting increased erosional resistance on the steeper anti-dip slope, where beds dip upstream, relative to the dip slope.

CONCLUSIONS

We present evidence from flume experiments that bedding plane dip angle significantly impacts fluvial bedrock plucking and knickpoint morphodynamics. Dip angle sets block mobility thresholds, channel bed roughness, knickpoint slope in the case of downstream-dipping beds, and dominant plucking mode. Dip influences interactions between flow structure, armoring by eroded blocks, and bed profile shape that govern knickpoint evolution. The role of dip angle in bedrock river evolution therefore extends beyond its impact on in situ bedrock erodibility, also shaping complex morphodynamic feedbacks. Finally, bed armor may play a uniquely significant role in plucking-dominated rivers, where armoring by plucked debris can have a major impact on channel evolution independent of hillslope inputs.

We expect the effects of dip angle to be especially pronounced in fold-and-thrust landscapes with extensive, dynamic discontinuity networks. Implications also extend to crystalline bedrock landscapes with distinct, regular joint patterns (e.g., columnar basalts, foliated metamorphic terrains), potentially contributing to characteristic plucking mechanisms, knickpoint morphologies, and landscape evolution trajectories within each. Through its multi-faceted impact on plucking-dominated fluvial erosion, dip angle may play a profound role in shaping discontinuity-defined landscapes.

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