The influence of bedrock topography on grain entrainment in bedrock-alluvial channels

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Introduction

Sediment grains are entrained when the entraining drag and lift forces are greater than the resisting grain weight. For a grain on a bedrock surface, the magnitude of these forces depends on the bedrock surface topography. Surface topography is commonly represented by the standard deviation of surface elevations (σ_z), but the impact of σ_z on grain entrainment has not been systematically tested.

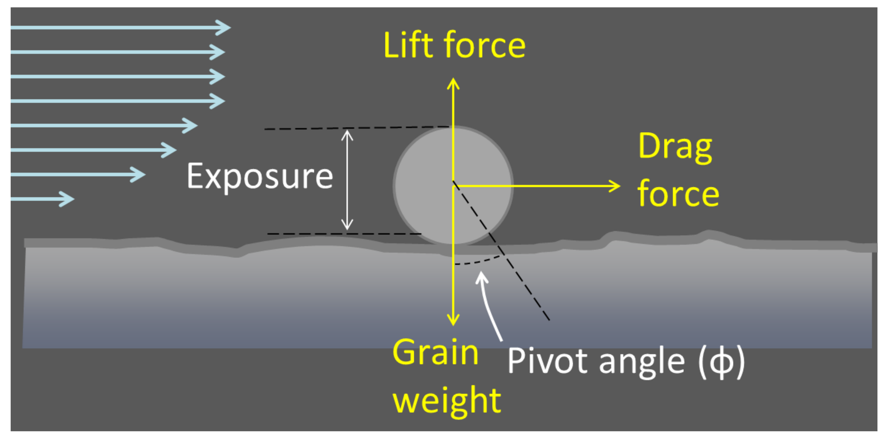

Fig. 1: Forces acting on a grain sitting on a bedrock surface. The surface topography affects both grain exposure and pivot angle.

Methods

We replicated the topographies of two different bedrock channels in the laboratory. The rivers were surveyed and sections of channel were 3D printed. A tilt table was used to measure the pivot angles of grains on these printed surfaces, with and without sediment cover.

Fig. 2: The two field locations

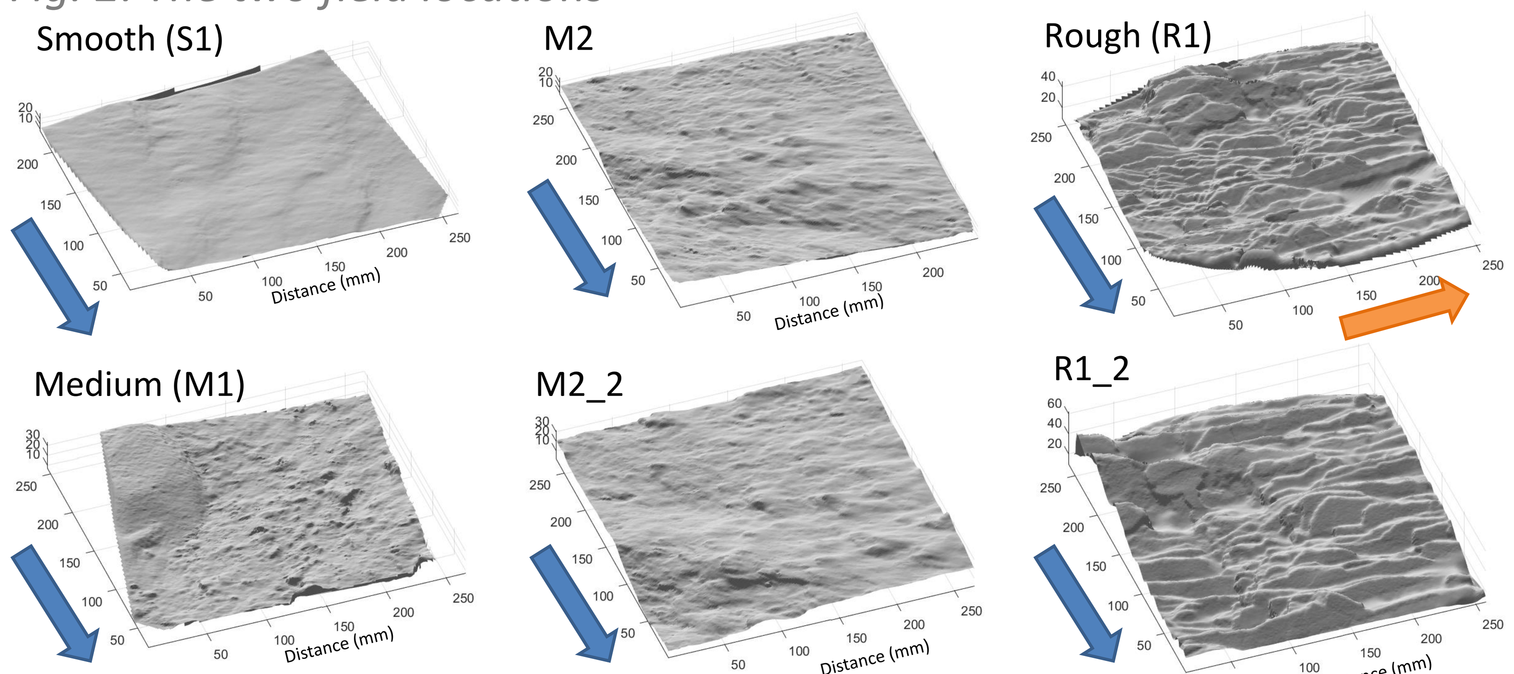

Fig. 3: The six printed surfaces. M2_2 and R1_2 are parts of M2 and R1 printed at twice scale. Blue arrows are pivot direction. R1 was also pivoted along orange arrow.

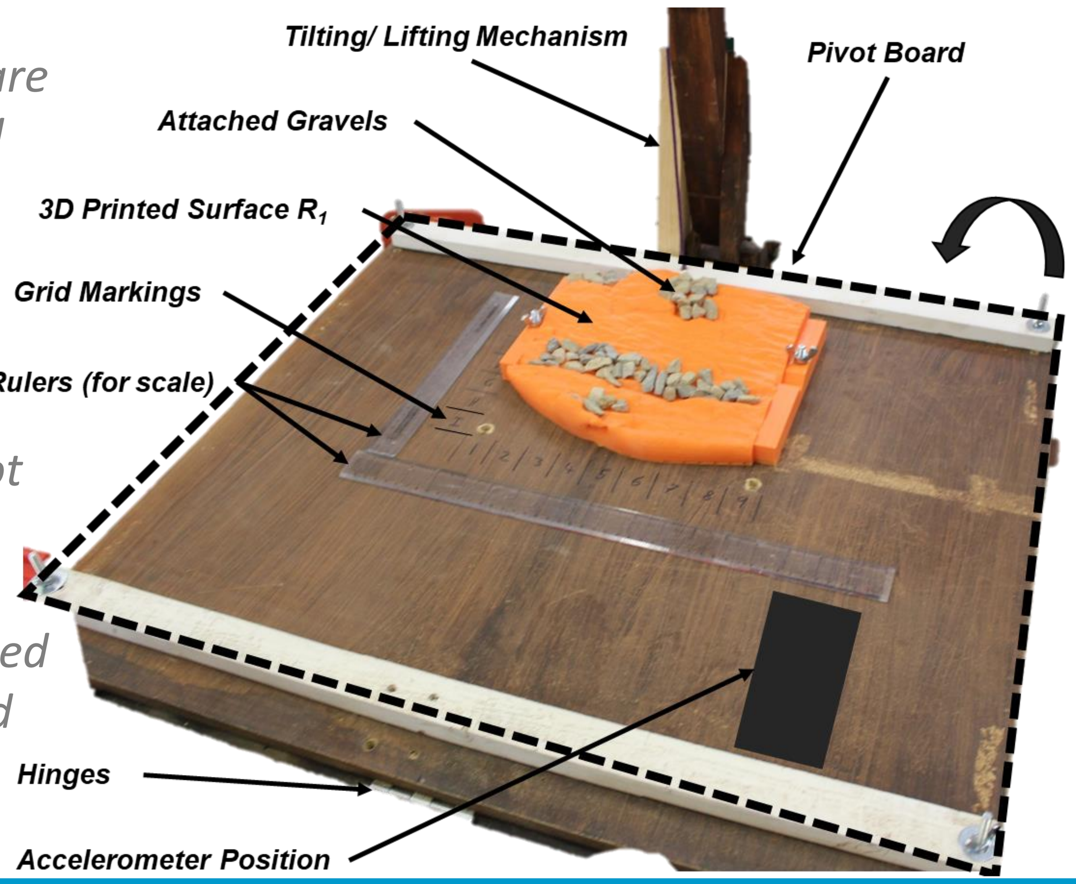

Fig 4: Tilt table set-up. Pivot angles were measured in each of 81 cells across the surface. Four grain sizes used on each surface. S1, R1 and R1_2 also tested with 25% to 100% sediment cover.

Results

Pivot angles primarily increased with increased surface roughness (Fig. 5) . But, for each surface the smallest grains do not always have the largest pivot angles. For R1 the pivot direction was important.

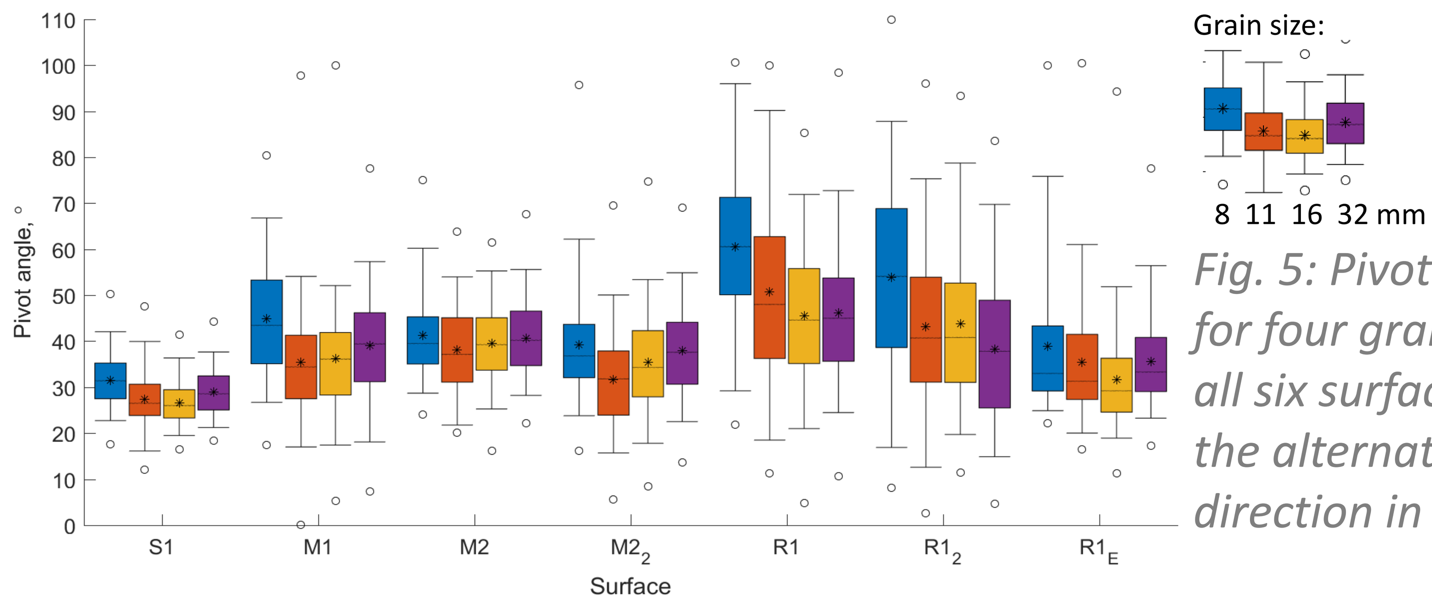

Fig. 5: Pivot angles for four grain sizes on all six surfaces (R1E is the alternative pivot direction in Fig. 3.)

The overall pattern of mean pivot angle as a function of D/σ_z is similar to that seen in alluvial studies, but D/σ_z doesn't explain all variation in mean pivot angle between surfaces. Altering σ_z to incorporate tilt direction produces a slightly stronger relationship (Fig. 6).

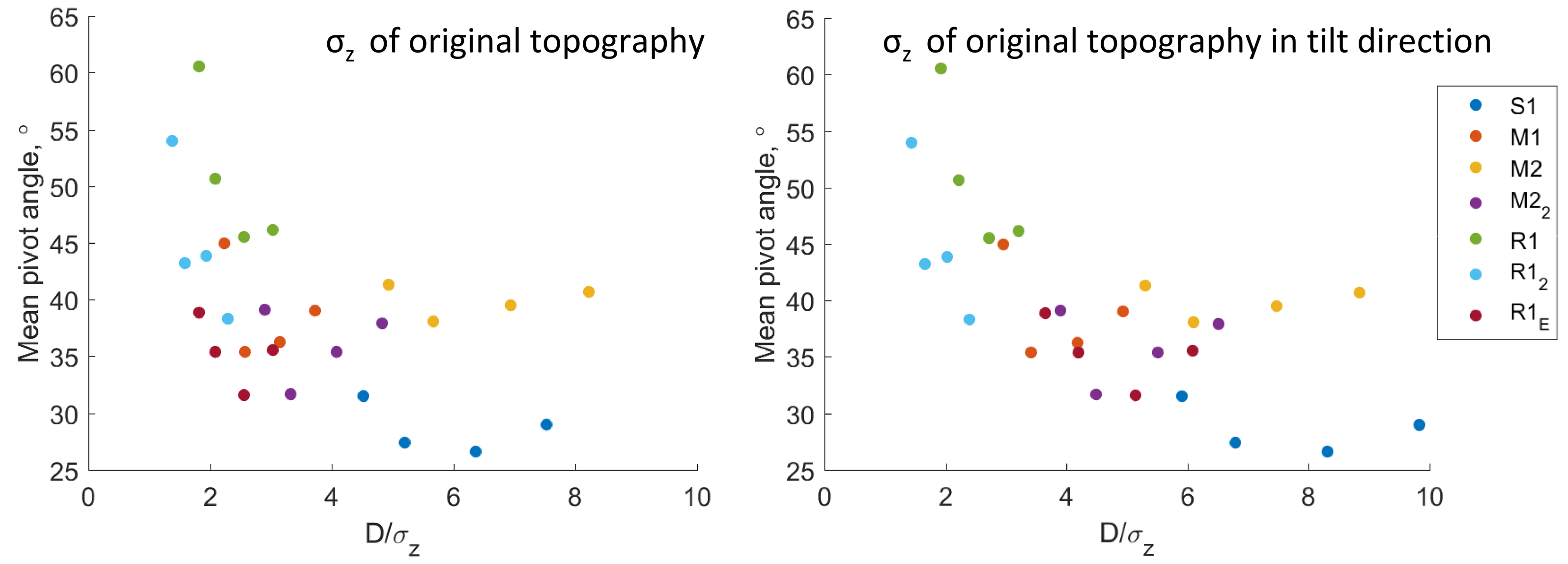

Fig. 6: Mean pivot angles against D/σ_z, and D/σ_z calculated in the tilt direction.

Next, we applied a high pass filter to the surfaces before calculating σ_z (Fig. 7), because grain pivot angles are more likely to be affected by shorter topographic wavelengths. A 30 mm high pass filter best collapses the data (Fig. 8).

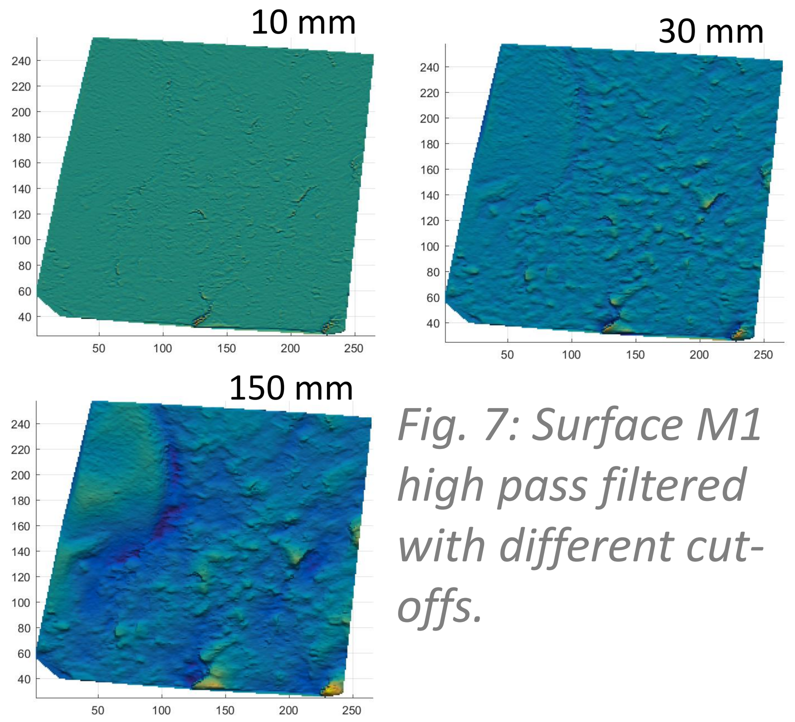

Fig. 7: Surface M1 high pass filtered with different cut-offs.

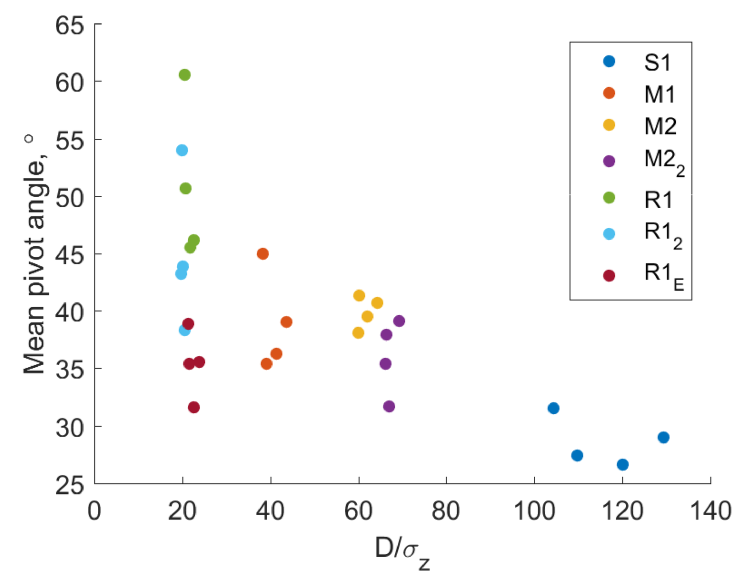

Fig. 8: Mean pivot angles against D/σ_z, where σ_z is calculated along the tilt direction and after 30 mm high pass filtering.

We also looked for relationships between σ_z and pivot angle for each individual cell across each surface (e.g. Fig. 9), but generally found no significant relationships, regardless of the applied filter size.

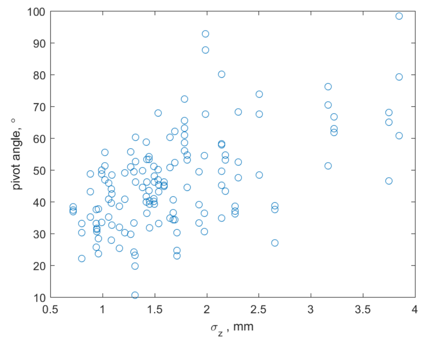

Fig. 9: Example relationship between individual pivot angles and σ_z for each surface cell.

We used Kircher's (1990) entrainment model to calculate critical shear stresses (τ_c) for the grains. Parameterising the model with only the measured pivot angles produces distributions of τ_c (Fig. 10) that are similar to the patterns of pivot angles (Fig. 5).

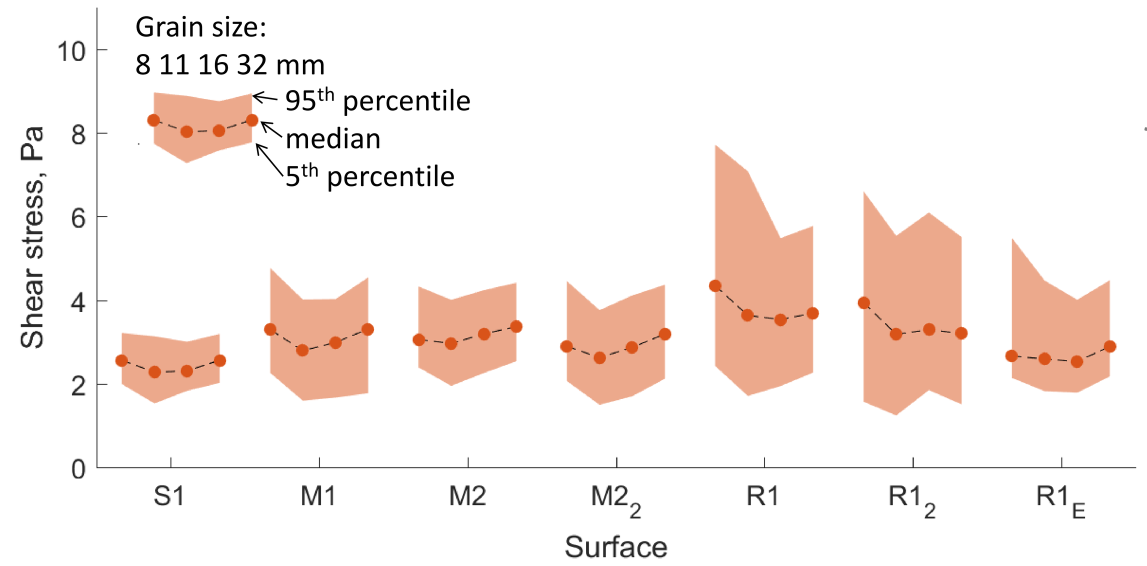

Fig. 10: predictions of τ_c from the Kirchner entrainment model, incorporating only measured variability in pivot angles between surfaces.

But, τ_c is also determined by the influence of the surface on the flow, and so we incorporated grain exposure and roughness length z_0 values (calculated from σ_z) into the entrainment model (Fig. 11).

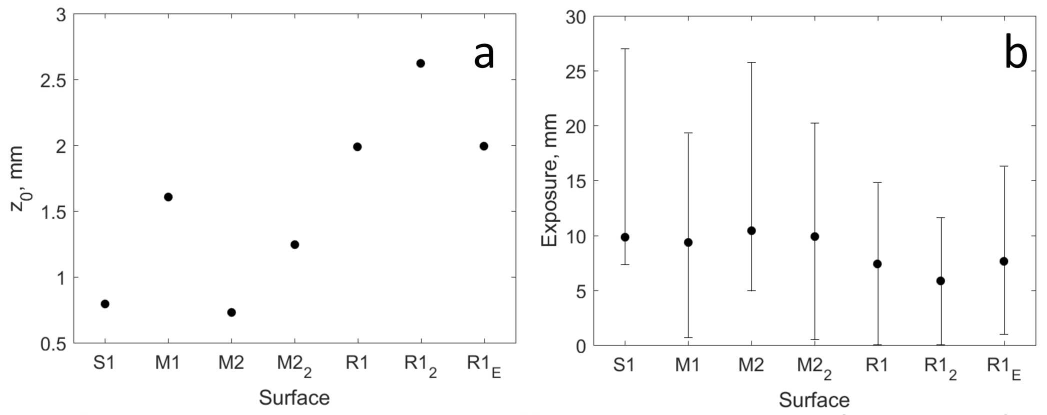

Fig. 11: a) Roughness length (z_0) and b) grain exposure for all surfaces. b) is height of grain top above upstream surface elevation (median, 5th and 95th percentiles)

After incorporating all parameters (Fig. 12), the variability of τ_c for a given surface is determined by the range of pivot angles and exposure values, but z_0 has the largest impact on median values of τ_c.

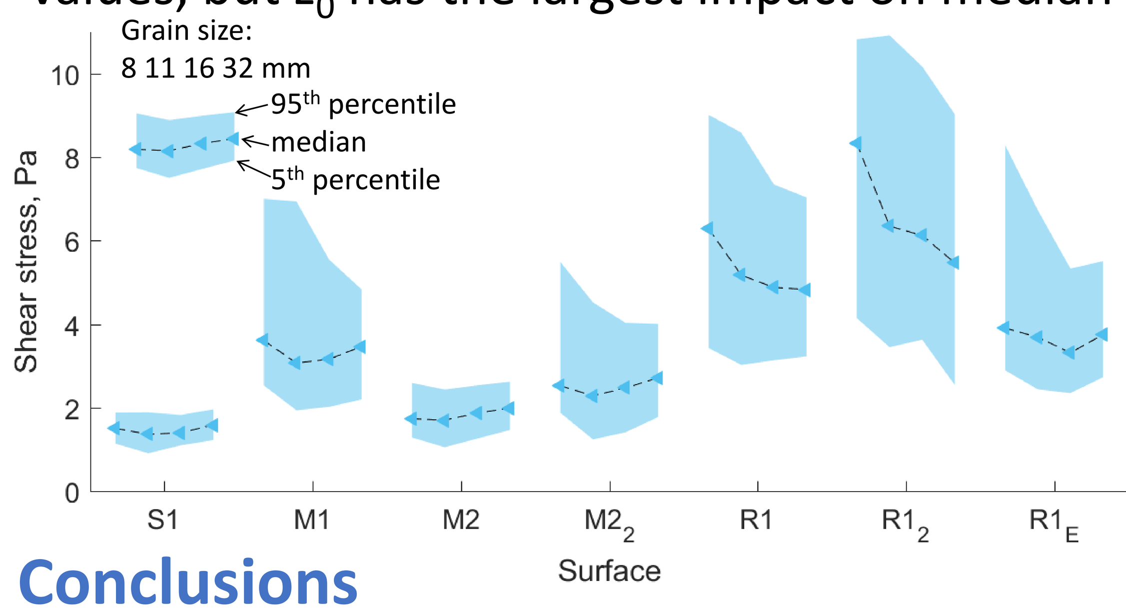

Fig. 12: predictions of τ_c from the Kirchner entrainment model, incorporating measured variability in pivot angles, grain exposure and z_0.

Conclusions

- 3D printing can bring the field into the lab.
- Overall, σ_z is a reasonable predictor for mean grain pivot angle, but the spatial scale and direction of roughness matter.
- There is a surprising lack of correlation between pivot angle and σ_z at the scale of individual grains.
- The influence of surface topography on flow, as well as on pivot angles, is important for determining critical shear stresses.

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