Experimental evidence for fluvial bedrock incision by suspended sediment

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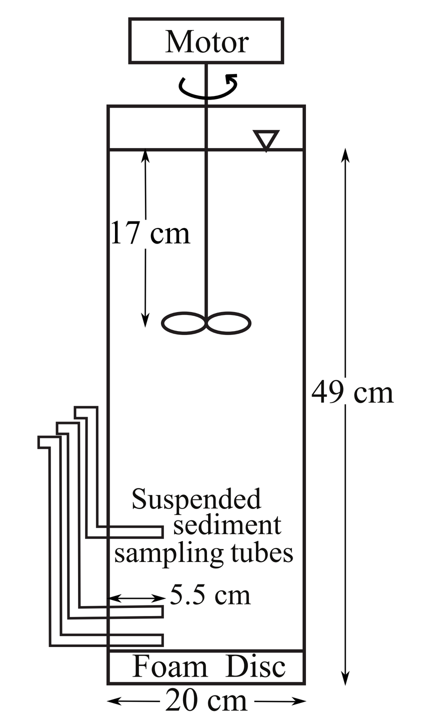
Motivation

Suspended sediment often makes up the majority of the total sediment load in fluvial systems, yet predicting the relative influence of suspended versus bed load on bedrock erosion rates is difficult due to a paucity of data and contrasting river incision theories. We performed controlled abrasion mill experiments with both suspended and bed load sediment to systematically explore the role of suspended sediment in fluvial bedrock incision.

Abrasion mills simulate fluvial erosion



(Modified from Sklar and Dietrich, 2001)

Experiments verify foam replicates bedrock

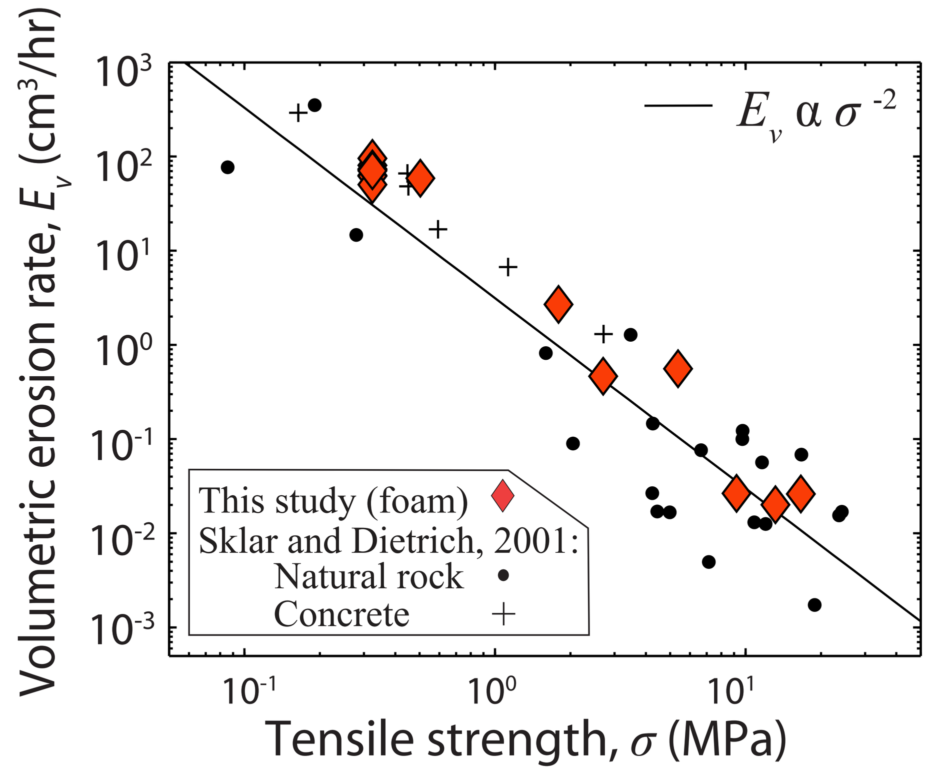
We used low-density, polyurethane foam as a bedrock substitute because:

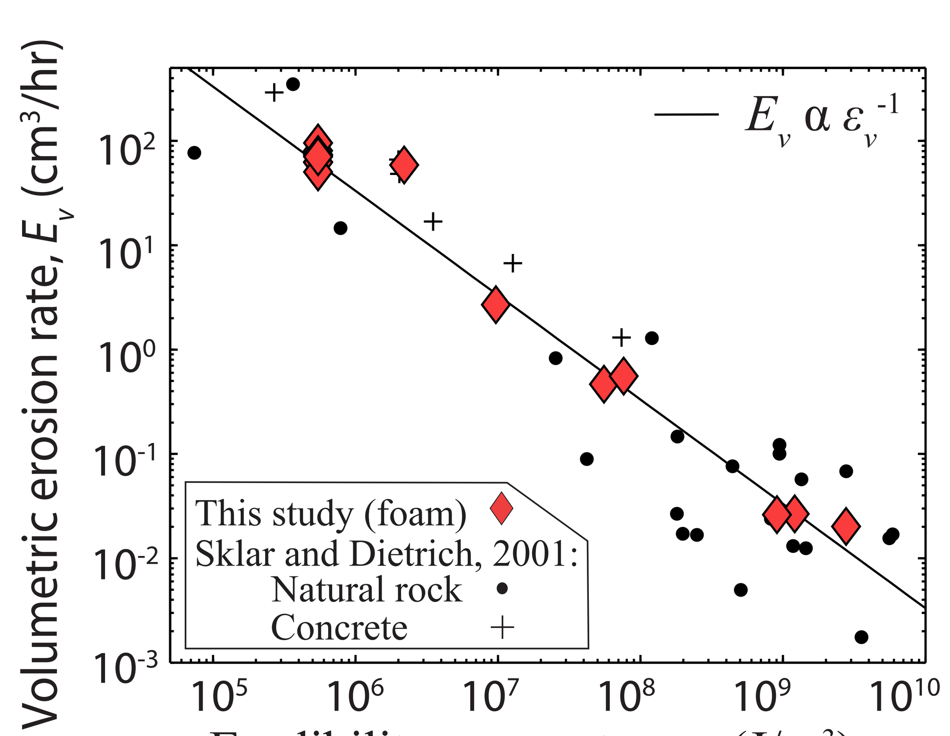
1. Foam is homogenous
2. Foam erodes faster than natural rock
3. Foam requires no curing time

Experimental parameters:

- Grain size: 7 mm
- Sediment supply: 150 g
- Fluid shear stress: 22 Pa
- Foam density: 0.06 - 0.96 g/cm³
- Foam tensile strength: 0.3 - 17 MPa

Foam erosion rates match those of natural rock and concrete:





Theoretical Scaling:
(after Sklar and Dietrich, 2004)

$$E_v \propto \varepsilon_v^{-1} = \frac{2Y}{k_v \sigma^2}$$

E_v: Volumetric rock erosion rate
ε_v: Erodibility parameter (energy required to erode a unit volume of rock).
Y: Young's modulus
σ: Tensile strength
k_v: Dimensionless constant

Key Findings

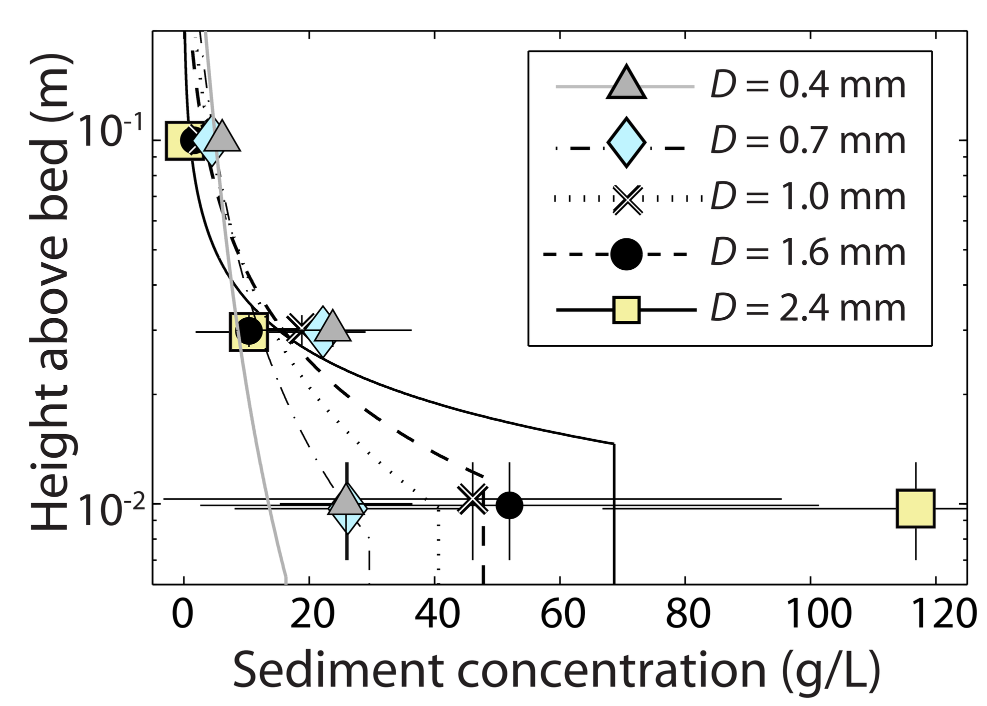
1. Polyurethane foam acts as a bedrock analog allowing for increased erosion rates.
2. Suspended sediment can fluvially erode, with erosion rate a function of grain size, sediment load, and viscous dampening of particle impacts.
3. During large floods in natural rivers, erosion by suspended bed material may outpace bed load erosion by up to a factor of ~4.

Experiments comparing suspended and bed load erosion

Experimental parameters:

- Grain size, D: 0.43 - 44 mm
- Sediment supply: 70 g
- Foam tensile strength: 0.32 MPa
- Foam density: 0.06 g/cm³
- Fluid shear stress: 22 Pa

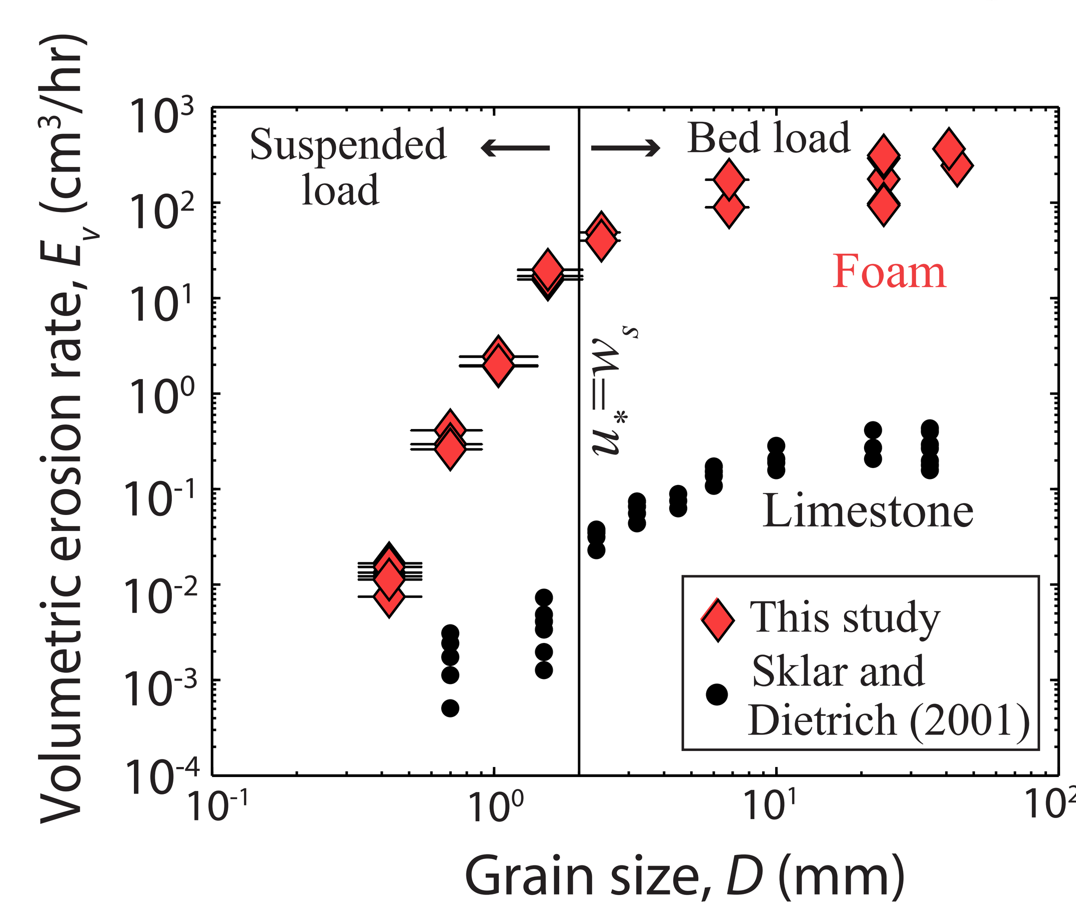
Sediment concentration profiles approximately match theoretical predictions (Rouse, 1937) :



$$c = c_b \left[\frac{(1/z) - (1/H)}{(1/H_b) - (1/H)} \right]^{\frac{w_s}{\beta \kappa u_*}}$$

c: Sediment concentration
c_b: Near bed sediment concentration
z: Height above bed
H: Flow depth
H_b: Bed load layer thickness
w_s: Particle settling velocity
β: Dimensionless constant
κ: von Karmen's constant
u_*: Shear velocity

Suspended sediment erodes and erosion rates decrease with grain size:



Conclusions

1. Suspended sediment is capable of fluvially eroding bedrock.
2. Suspension erosion rates in our experiments were smaller than by bed load due to:
   - Reduced near-bed sediment concentration because part of the load was dispersed higher in the water column.
   - Slower settling and impact velocities due to finer sediment within the suspension regime.
   - Viscous damping of impacts for fine sediment below the Stokes numbers of ~75.
3. For natural rivers:
   - Suspension of coarse bed material in large floods allows suspension erosion to outpace bed load erosion.
   - For small floods or low sloping channels, suspended sediment erosion will have a reduced role because of comparatively low impact energies and viscously damped collisions for small particles in suspension.

Comparison to theory and previous experiments

Existing mechanistic theories:

Sklar and Dietrich (2004): Erosion proportional to bed load impact velocity, assumes suspended sediment does not erode.

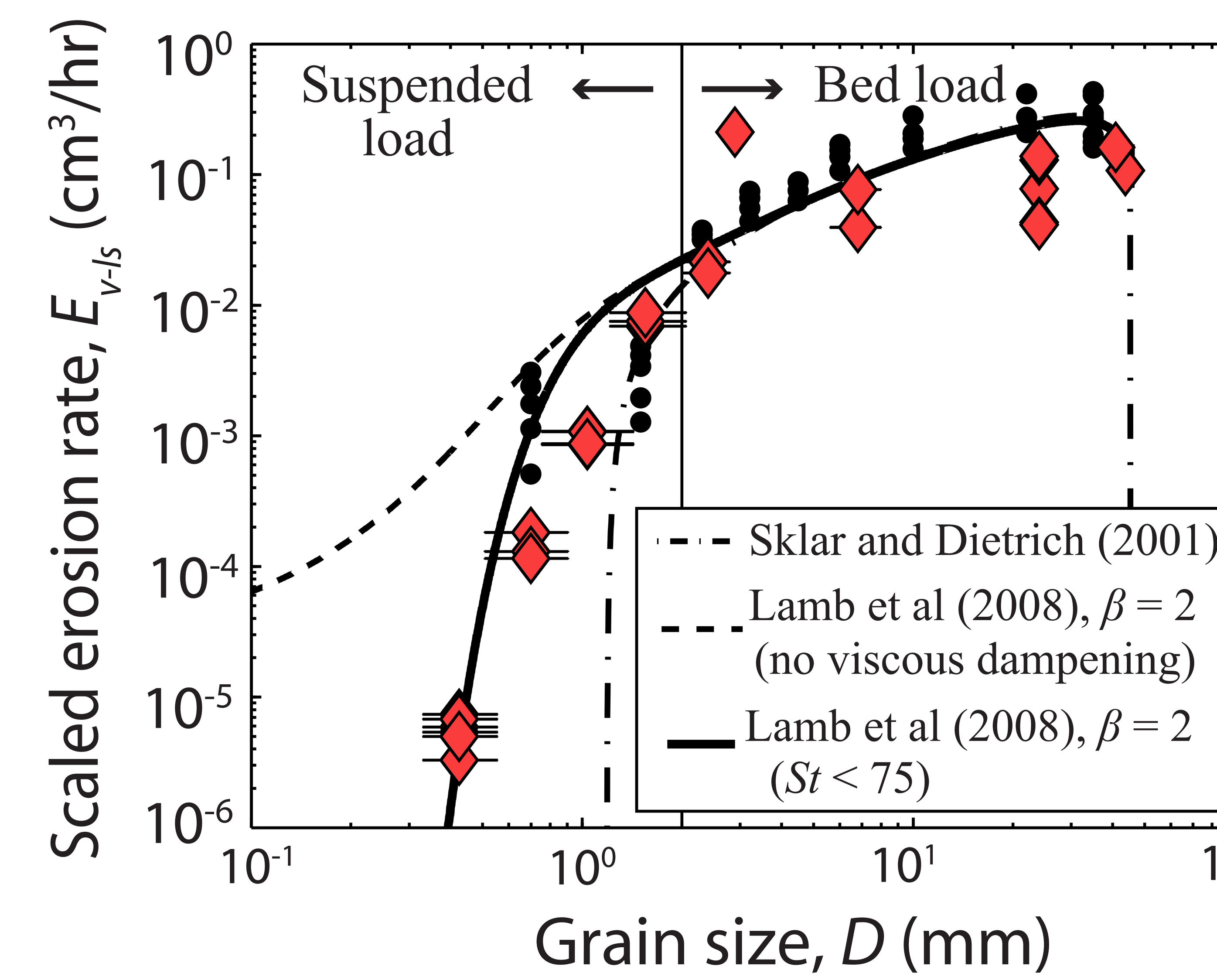
Lamb *et al* (2008): Erosion rate proportional to near bed sediment concentration and particle impact velocity, allows for erosion by suspended sediment.

Comparing erosion of foam (this study) to limestone (Sklar and Dietrich, 2001) requires a conversion factor:

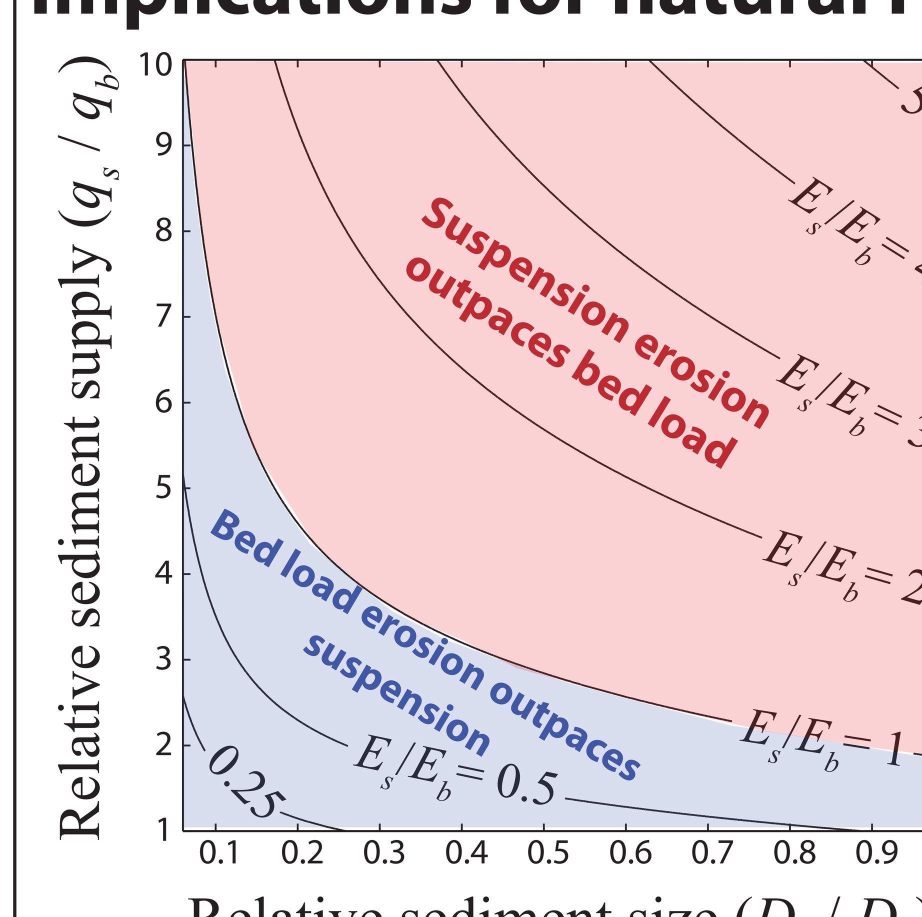
$$E_{v-ls} = E_v \left(\frac{\varepsilon_v}{\varepsilon_{v-ls}} \right)$$

E_{v-ls}: Expected limestone volumetric rock erosion rate
ε_v: Foam erodibility parameter
ε_{v-ls}: Limestone erodibility parameter

Measured erosion rates agree with suspension erosion theory when viscous damping of particle impacts is accounted for:



Implications for natural rivers



Scaling to August 2000 flood of LiWu River, Taiwan (2240 m³/s discharge, 20 yr recurrence interval)

E_s: Suspended load erosion
E_b: Bed load erosion
D_s: Suspended load grain size (varied in model from 1.2 to 120 mm)
D_b: Bed load grain size (set to LiWu River D_{50} = 42 mm)
q_s: Supply of suspended load
q_b: Supply of bed load

References

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Rouse, H.R., 1937, Modern conceptions of the mechanics of turbulence: *Trans. Am. Soc. Civ. Eng.*, v. 102, p. 463-543.

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