The Role of Rock Solubility on Knickpoint Formation and Landscape Evolution

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Key Points

1. **We used landscape evolution models to simulate how landscapes change in response to soluble rock layers**
2. **Knickpoint generation is traditionally associated with base level fall or changes in erodibility, but can be generated through the inclusion of a soluble rock layer**

Abstract

Landscapes evolve over time in response to changes in climate, tectonics, and other surface processes, proceeding towards a steady state. Within these changes in a given landscape, the layering of rocks with different properties is a factor that must be considered to accurately gauge how a landscape will evolve over time. One rock property that is typically omitted from landscape evolution models (LEMs) is chemical dissolution, despite chemistry data suggesting that dissolution rates of calcite can outpace mechanical erosion rates. However, the effects of dissolution on landscape evolution are poorly understood. Here, we test landscapes' responses to the addition of soluble horizontal rock layers. Utilizing a LEM, we explore landscape response to changes in: (1) widespread erodibility, (2) uplift rate, (3) rock erodibility, and (4) rock solubility. We have observed that in response to the addition of soluble rock layers, the landscape experienced knickpoints that moved through the primary river network over the course of 10^3 to 10^4 years. Knickpoint formation is commonly associated with changes in rock erodibility or base-level fall, but we found that knickpoints also form in response to the addition of soluble rock layers. Last, we discuss preliminary simulations that studies the interaction between soluble rock layers with uplift, climate, and lithologic perturbations, which we plan on studying more thoroughly in the future. Our numerical results can aid in interpreting past geologic settings because we find that knickpoints in landscapes containing soluble rock can form from changes in solubility rather than changes in erodibility or base-level.

Background

- There is a growing understanding that erosion through layered stratigraphy with contrasting lithology can determine the behavior of landscape evolution[1]
- Past research focuses on rock properties such as strength and erodibility[1], but rock solubility is poorly understood

Figure 1: Minnehaha Falls, Minnesota, an example of a real-life knickpoint into carbonate rock.

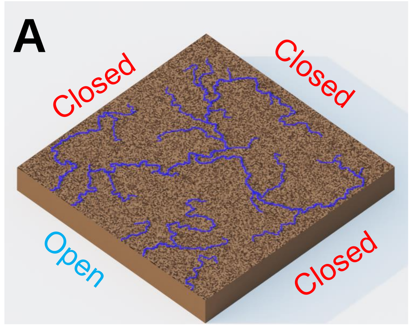
- Rates of chemical erosion via rock dissolution in carbonate rock have been measured to be of similar magnitude to mechanical erosion rates[2]
- Here, we use a landscape evolution model (LEM) to study how landforms change over time in response to changes in uplift, climate, erodibility, as well as rock solubility

Methodology & Model Setup

- We develop a LEM in Landlab[3], a Python-library for numerical modeling Earth surface dynamics and use Landlab's Lithology[4] tool to create rock stratigraphy.
- $\partial\eta/\partial t = U - L - KA^m S^n + D\nabla^2\eta$
  - η – elevation, t – time, U – uplift rate, K – erodibility, A – drainage area, S – slope, m & n – positive exponents, D – diffusion coefficient, L – dissolution rate

Parameter	Definition	Value	Unit
U	Uplift Rate	0.001	m/yr
L	Dissolution Rate	0.0005	m/yr
K_0	Base Erodibility	0.0001	1/yr
D	Hillslope Diffusion Coefficient	0.01	m^2/yr
A_T	Total Drainage Area	25	km^2

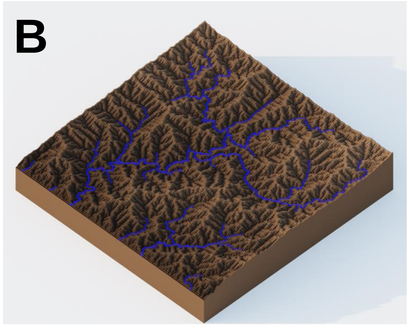
A



Step A

- We create an initial surface seeded with randomized topographic perturbations.

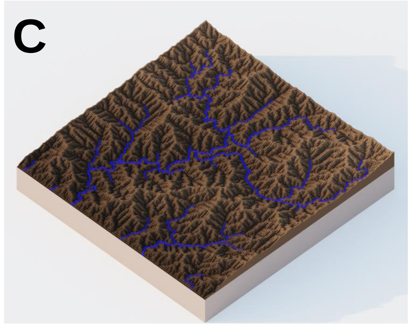
B



Step B

- LEM ran with a single rock type (brown) until the landscape reaches a steady state.

C



Step C

- We then subject the landscape to a horizontal layer of soluble rock (gray), e.g., carbonate rock.

Numerical Results – What Happens when Soluble Rock is Introduced?

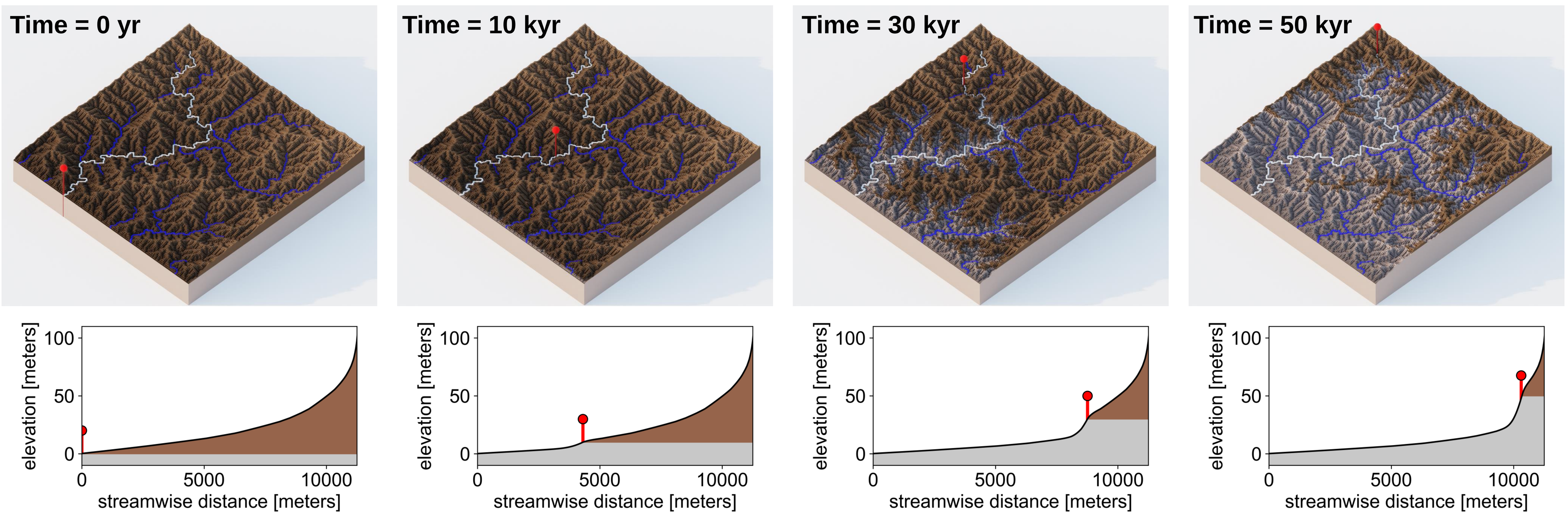


Figure 2: Landscape evolution at 0, 10, 30, and 50 kyrs after soluble rock layer is introduced (gray) below insoluble rock (brown). Top row shows the landscape where the location of the knickpoint is marked by a red pin. The white rivers show the location of the stream profile that is plotted in the row below. The bottom row shows the evolution of the stream topographic profile and the knickpoint migration.

- As the soluble rock layer progresses through the landscape, a knickpoint retreats upstream throughout the landscape (**Figure 2**); after 160 kyrs, the landscape achieves a new steady state with lower slope (**Figure 3**).
- We developed simulations that alter tectonic uplift, climate, and rock erodibility to achieve the same steady state as **Figure 3**.
- The comparison of simulations (**Figure 4**) show that the knickpoint generated via dissolution mechanisms has a unique transient signature in the channel profile.

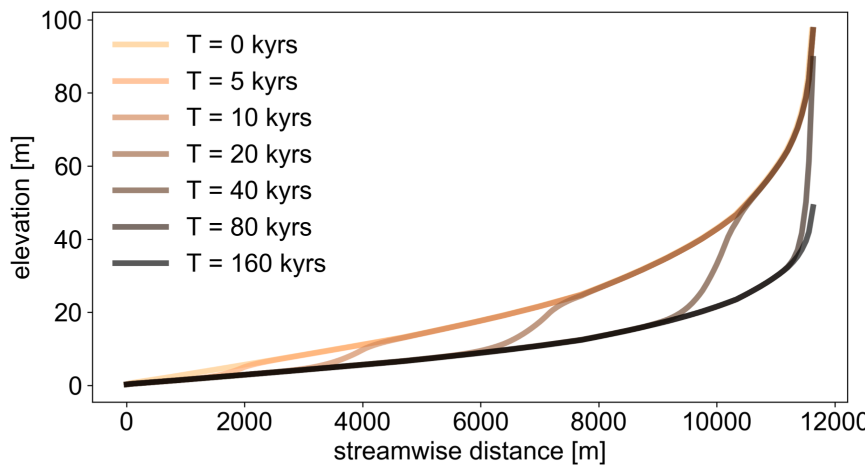


Figure 3: A graph demonstrating knickpoint movement through the landscape over the course of 160 kyrs since a soluble rock layer began progressing through the system.

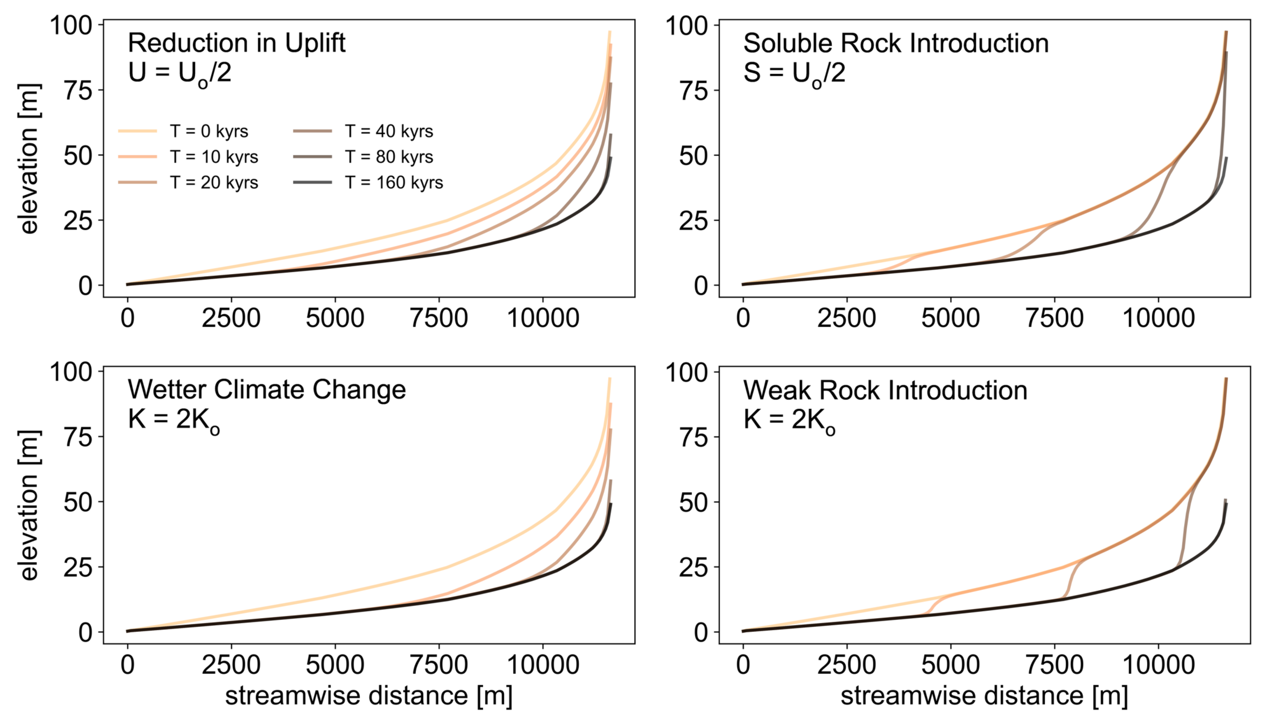


Figure 4: A side-by-side comparison of four modified input factors and how they present as a knickpoint (or lackthereof) moves through a landscape. This accounts for an uplift reduction (top left), soluble rock introduction (top right), change in climate (bottom left) and change in rock type (bottom right).

Discussion & Future Work

- Without base-level fall or changes in rock erodibility, the addition of a soluble rock layer in the landscape promotes knickpoints that are generated purely from dissolution processes.
- From our comparison of landscape perturbations (i.e., change in tectonics, climate, lithology), we find that rock solubility can generate unique knickpoint development.
- In future studies, we will test model behavior of solubility in combination with other perturbations (i.e., changes in climate, tectonics, base-level fall and/or erodibility) and introduce more complex stratigraphic structures.

Acknowledgements

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Key References & Storymap

This QR code links to this project's research storymap. Within the storymap are its key references. This storymap was created as a part of the 2023 REU SLAWR.

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