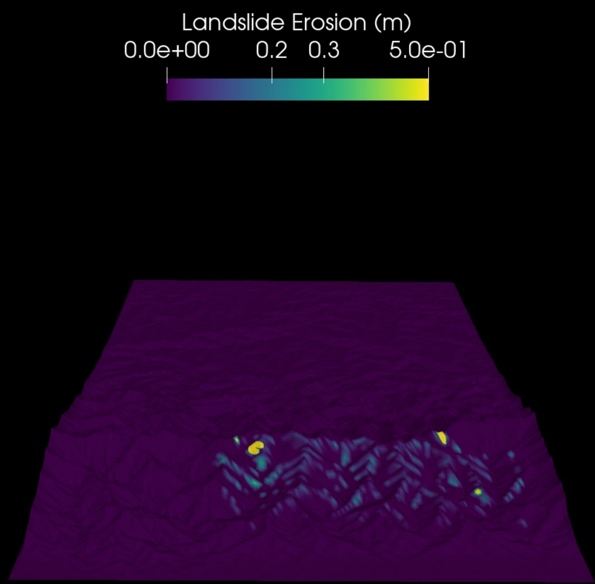
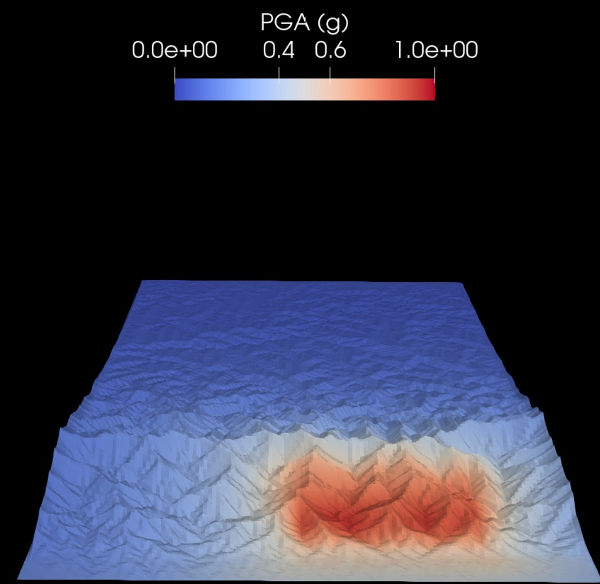
Driving Long-Term Landscape Evolution with Earthquakes





Adam M. Forte

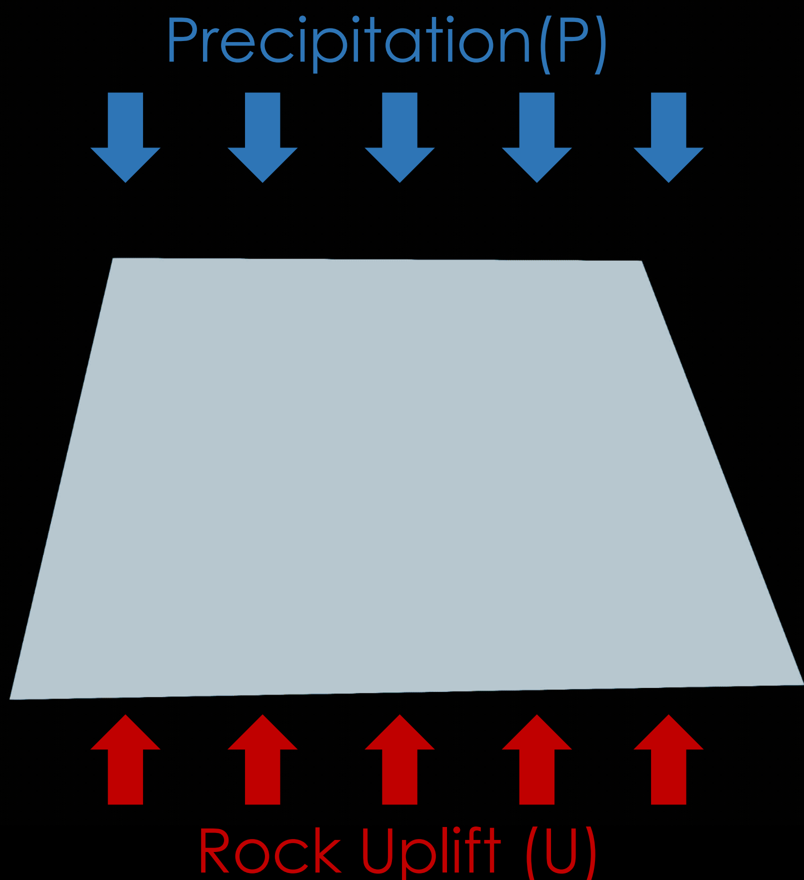
Louisiana State University

Award #2237437

CIRES

Visiting Sabbatical Fellowship

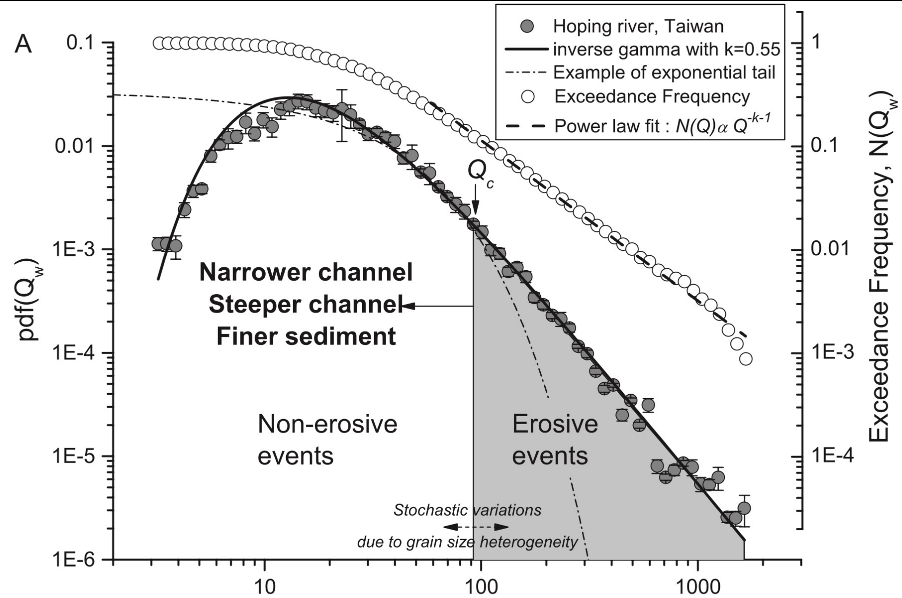
Landscape Evolution and Means



$$\frac{dz}{dt} = U - K(PA)^m S^n$$

- Landscape evolution often considered through the lens of mean or effective forcing.
- For the erosion part of this equation, considering short-term stochasticity can be critical.

Short-Term Stochasticity and Landscape Evolution



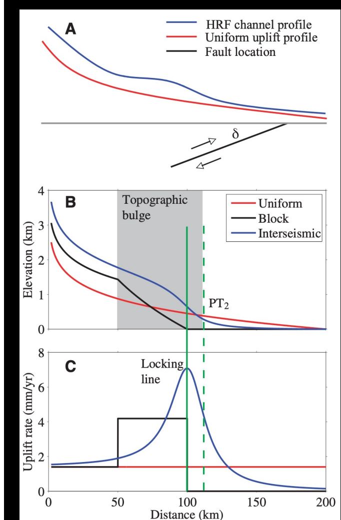
Lague, 2014

- Rivers don't always flow at their mean discharge and not all flows erode.
- Capturing the short-term stochasticity of fluvial erosion makes different predictions for how topography develops.

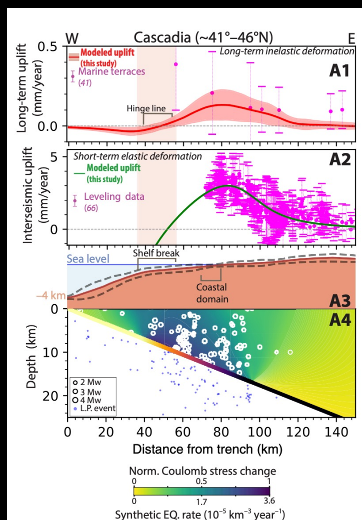
Is considering the effect of short-term stochasticity in rock uplift (i.e., earthquakes) similarly important?

Landscape Evolution and Earthquakes

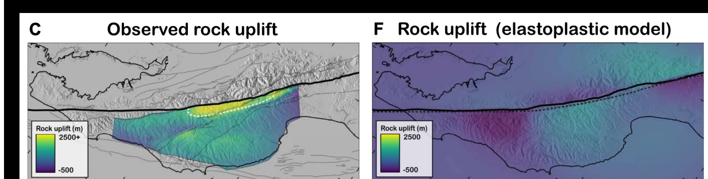
Spatial Patterns of Uplift



Meade, 2010

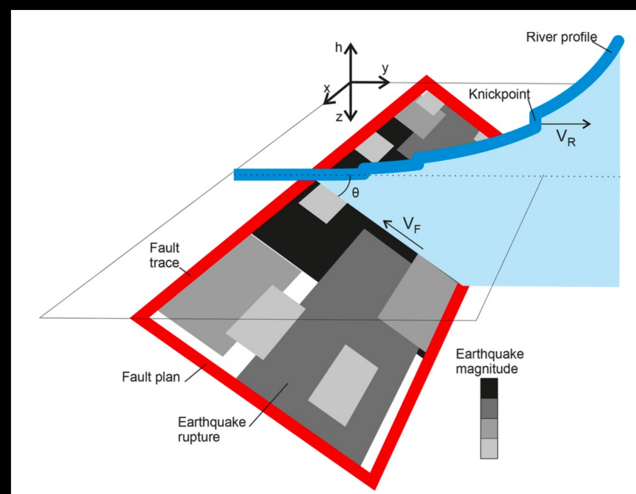


Oryan et al., 2024



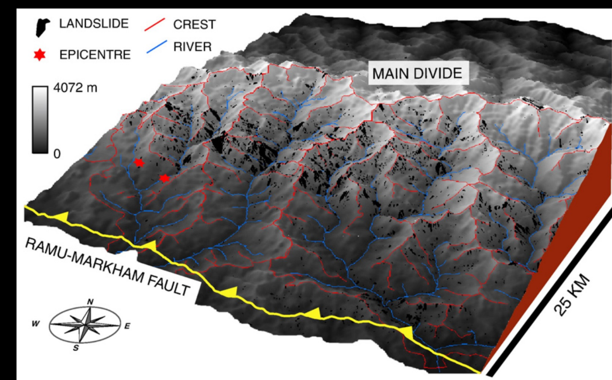
Baden et al., 2022

Numerous Events Over Geologic Time

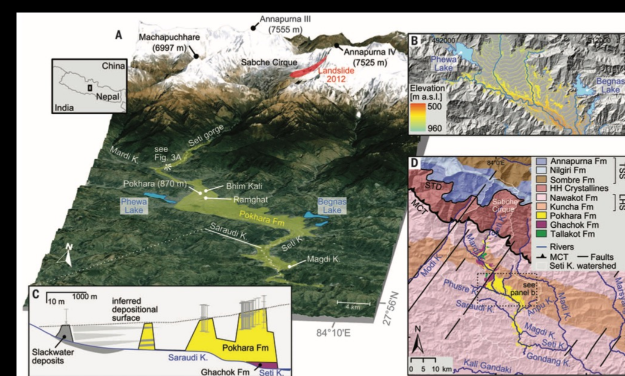


Steer et al., 2019

Individual Events

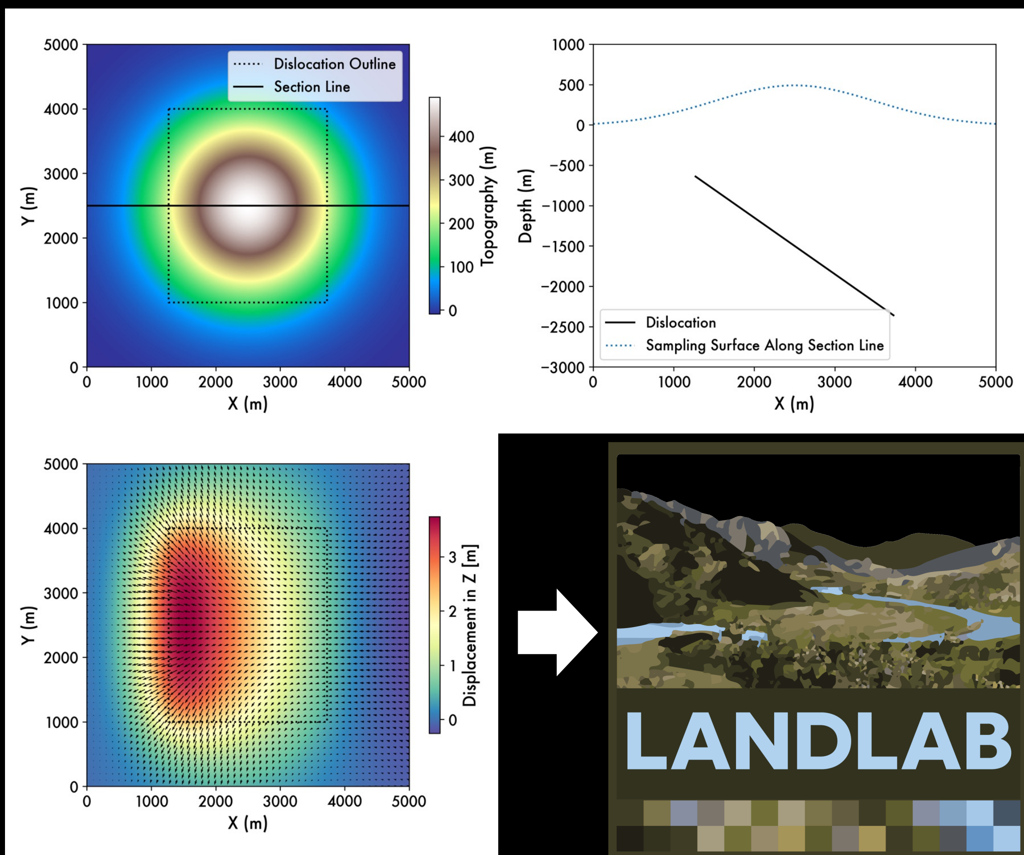


Meunier et al., 2008



Schwanghart et al., 2016

Simulating Landscape Evolution with Earthquakes in Landlab



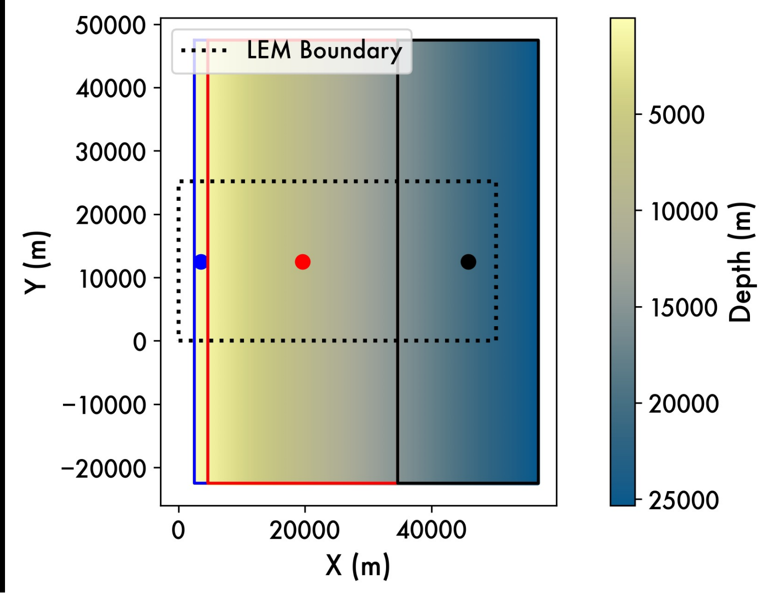
- Individual ruptures and interseismic fault creep both treated as elastic dislocations (Okada, 1992) using okada4py (Jolivet, 2024).

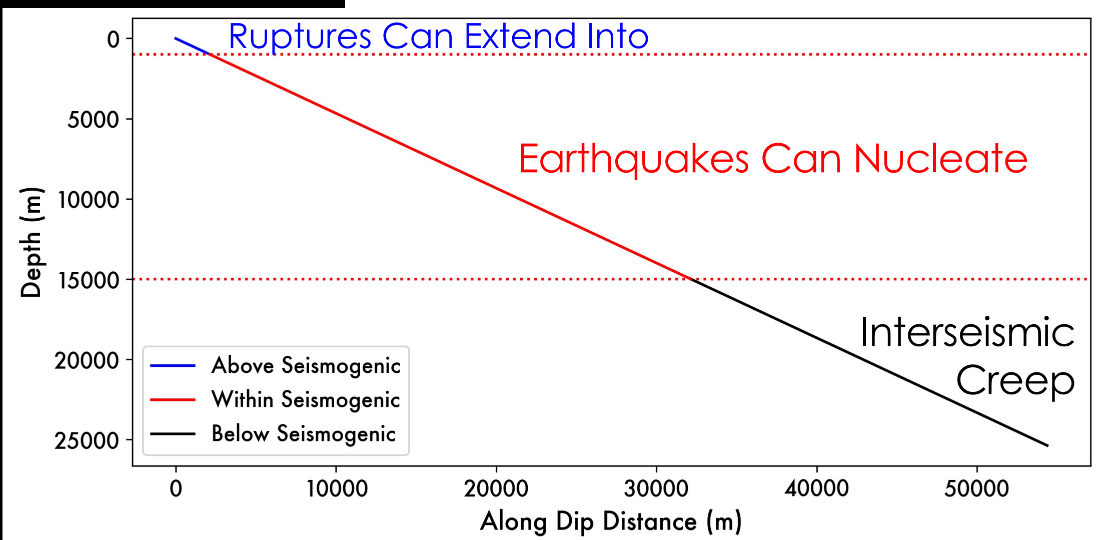
- Developed Landlab components for generating faults, earthquakes, and coseismic landslides.

Landscape Response to Different Seismic Cycles

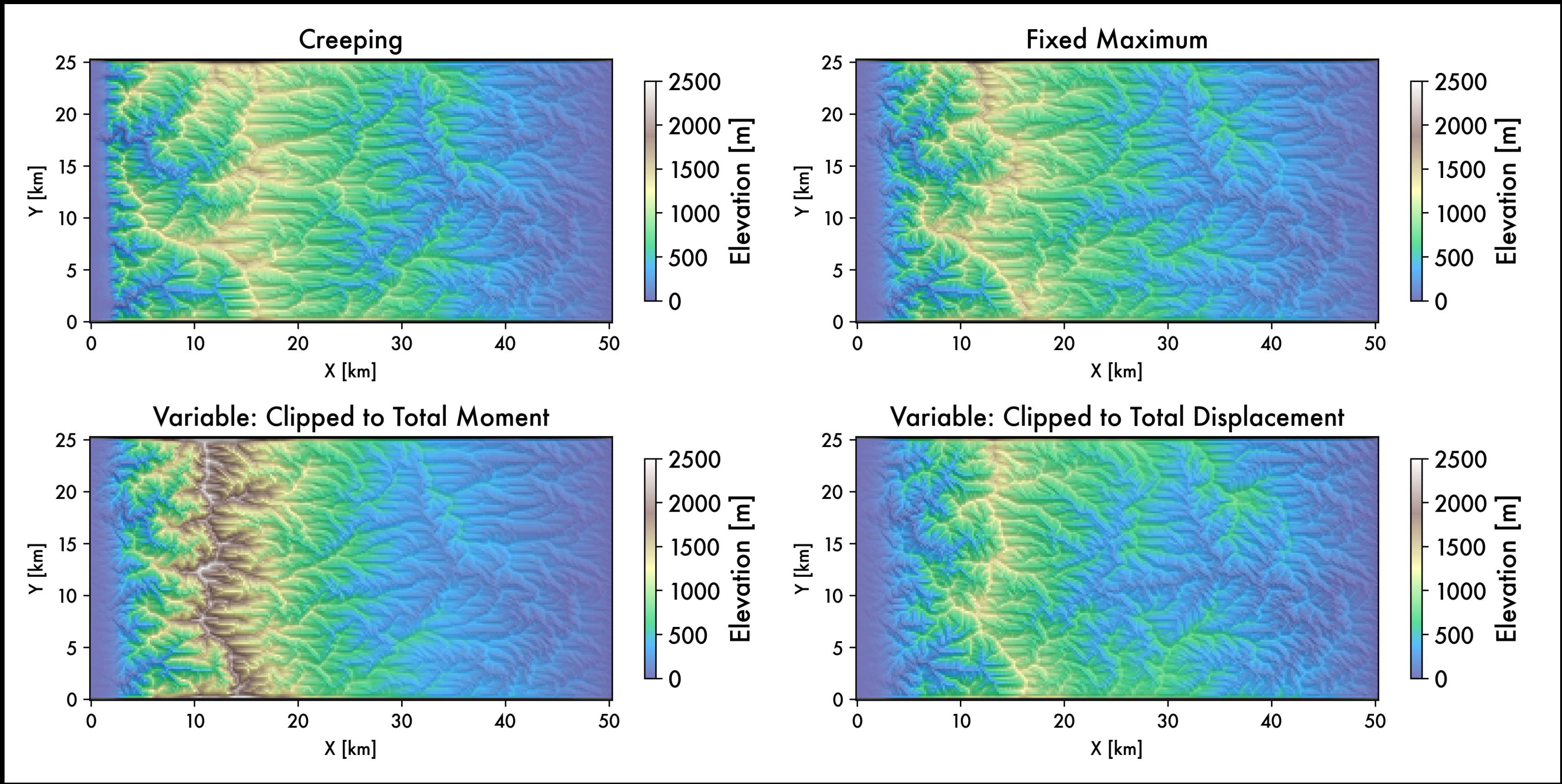
- Simple thrust fault geometry with a 10 mm/yr slip rate for 1.5 million years.

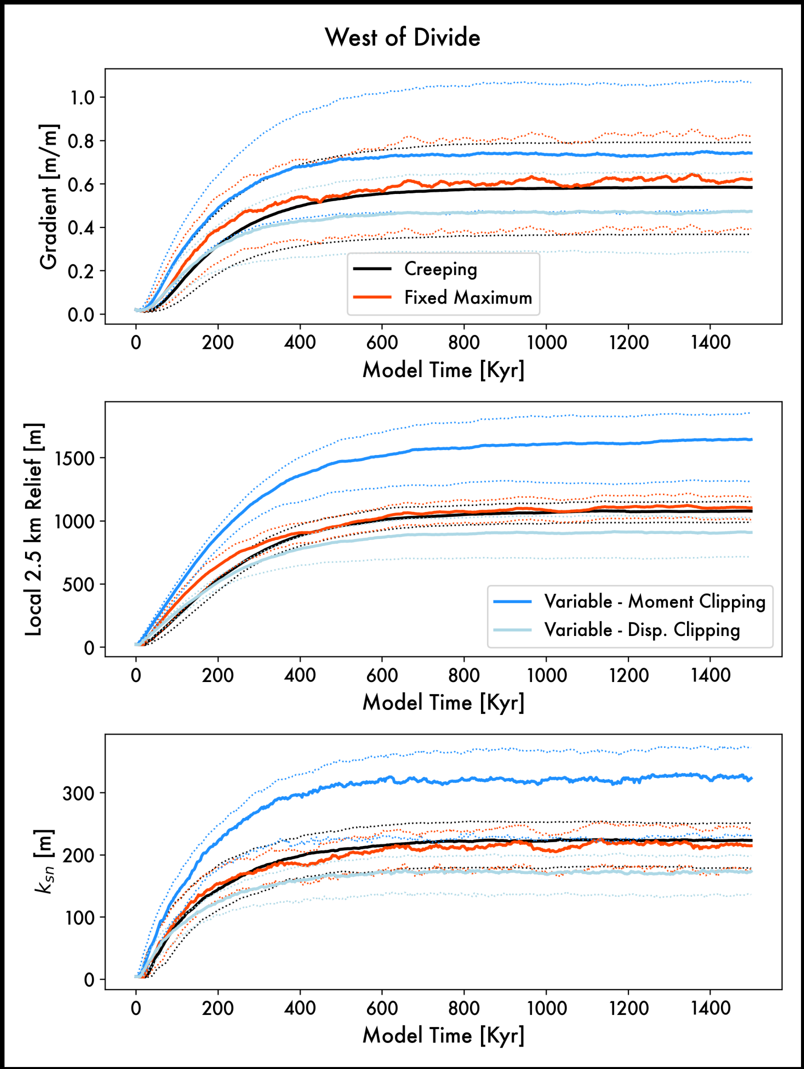
- Four basic scenarios:
  - Whole fault creep
  - Fixed maximum EQs
  - Variable EQs clipped to total moment
  - Variable EQs clipped to total displacement





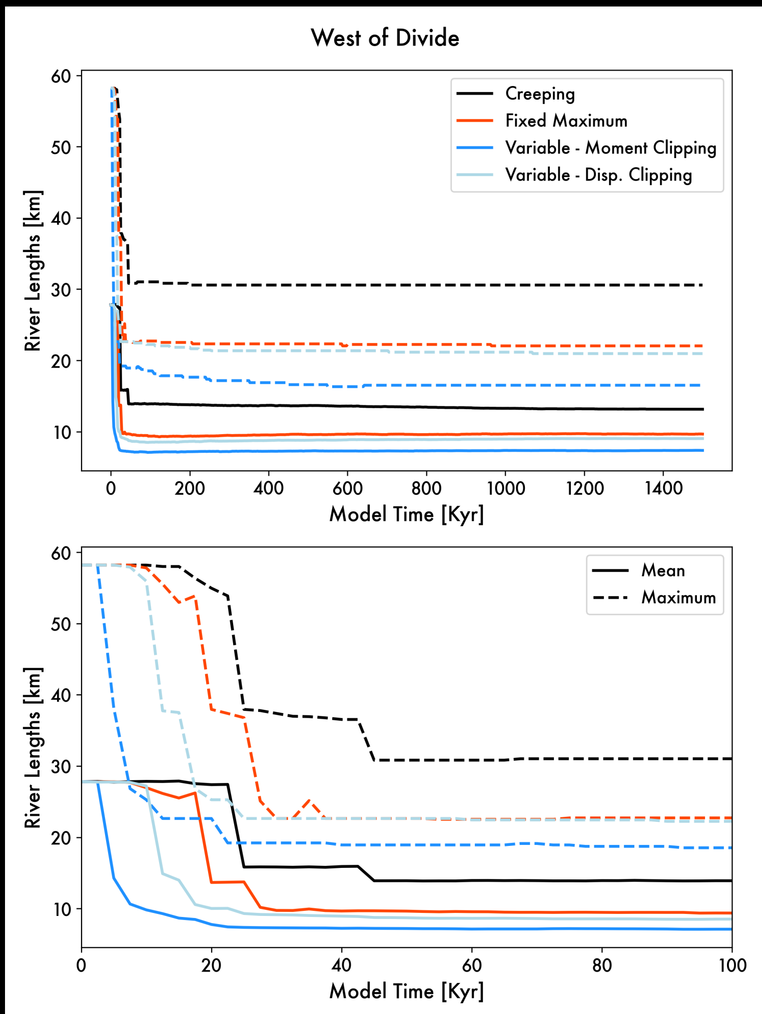
Topography Reflects Differences in Seismic Cycle





Differences in Topographic Metrics

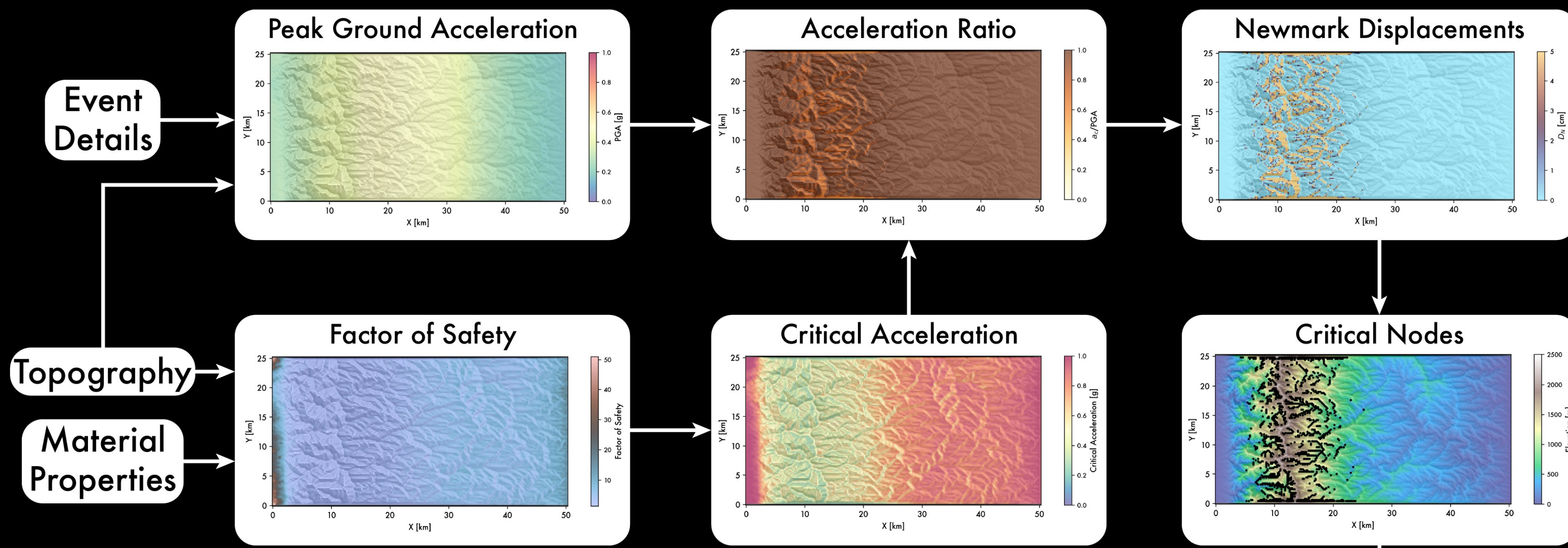
- Landscape wide topographic metrics diverge depending on earthquake style.
- Unsurprisingly, landscapes driven by earthquakes only achieve quasi steady-states.

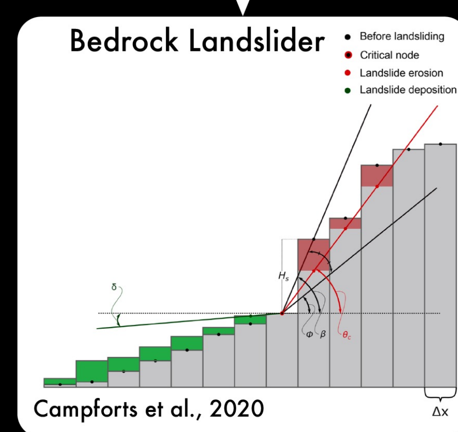


Differences in River Networks

- Inclusion of earthquakes also changes organization of river networks.
- Models with earthquakes tend to have divide shifted toward where the fault would daylight.

PhD student Mehran Basmenji is working on a sensitivity analysis using these models

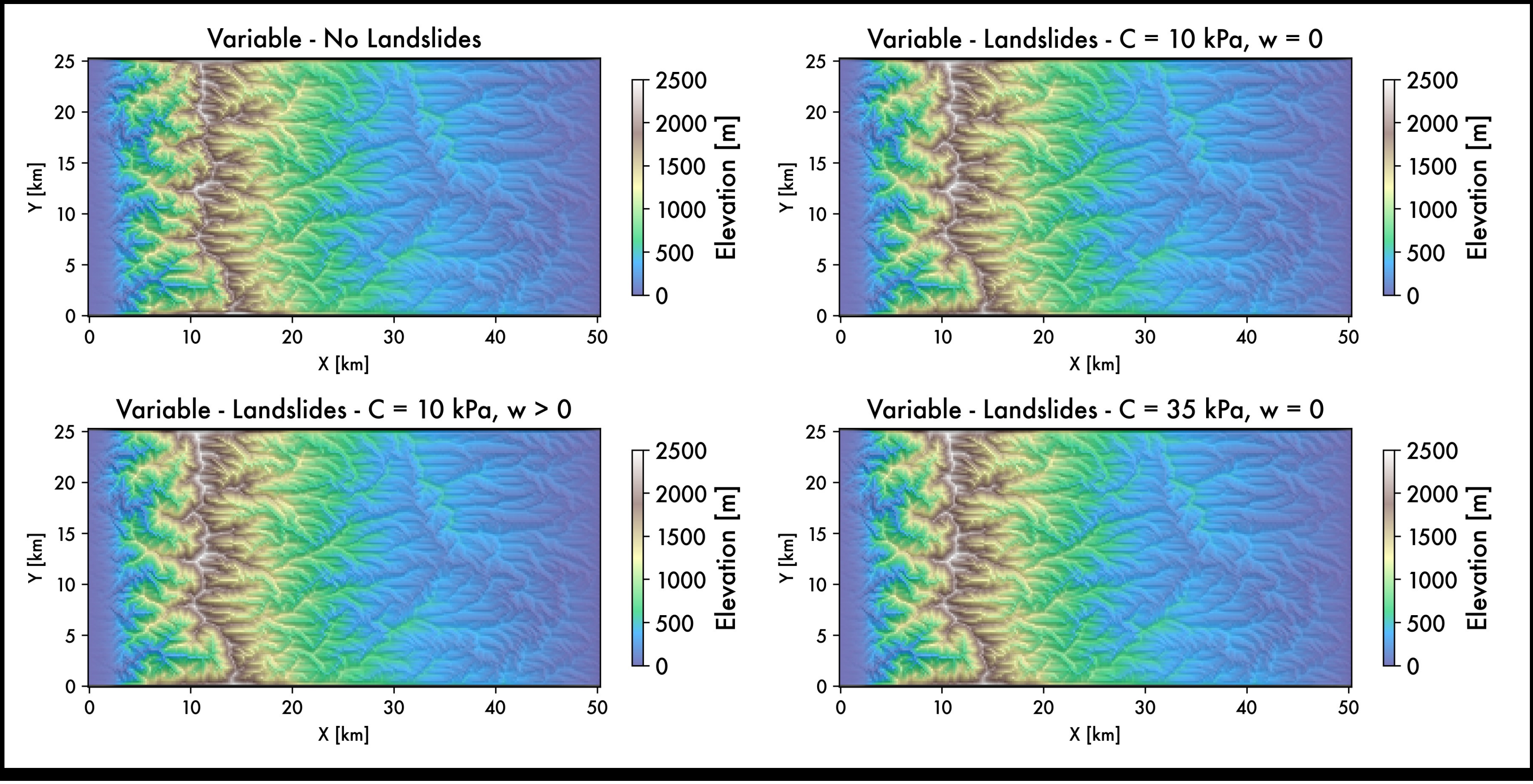




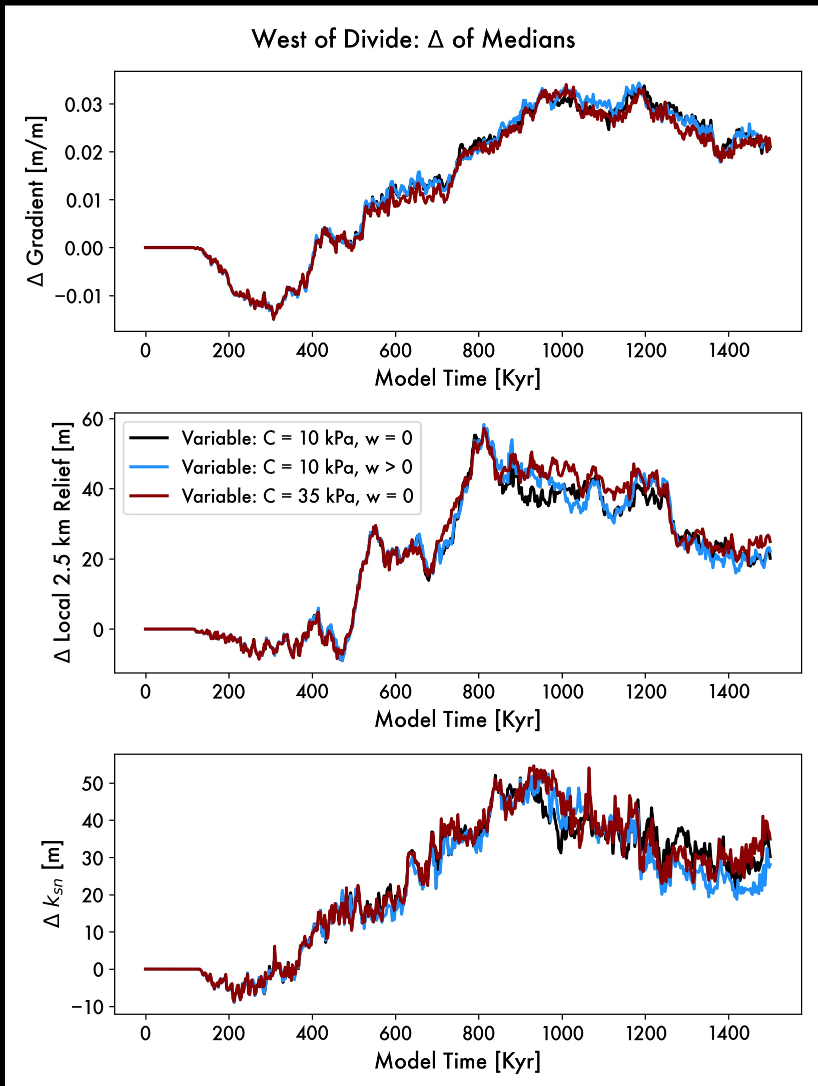
- Adapt approach from hazard analysis to identify locations likely to fail and then pass to existing Landlab components.

- Simulations exploring role of soil cohesion and relative wetness on topographic evolution.

Coseismic Landslides Do Not Change First-Order Landscape Structure

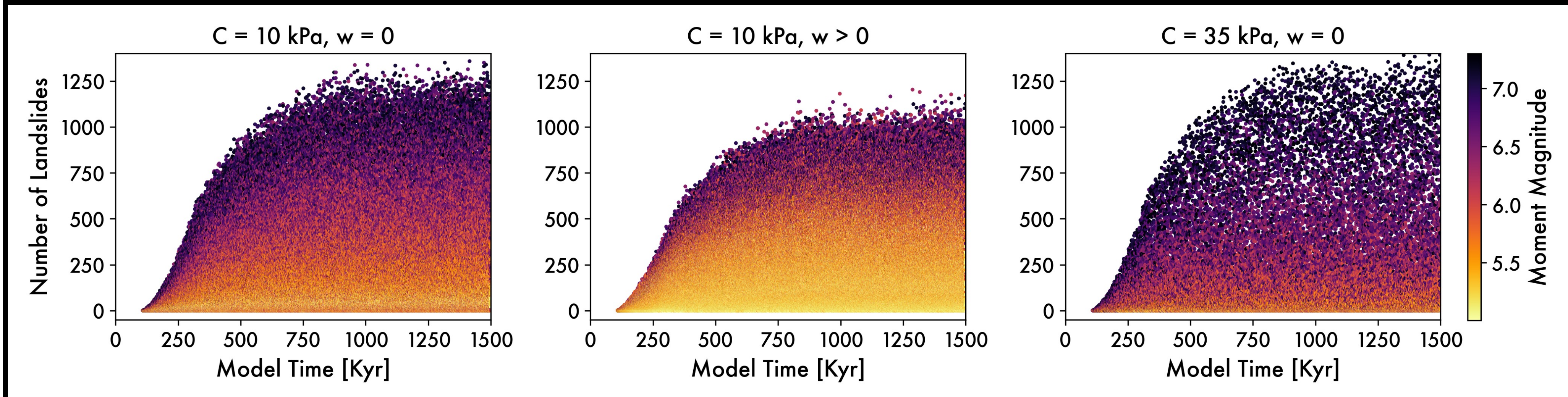


Coseismic Landslides Steepen Landscapes

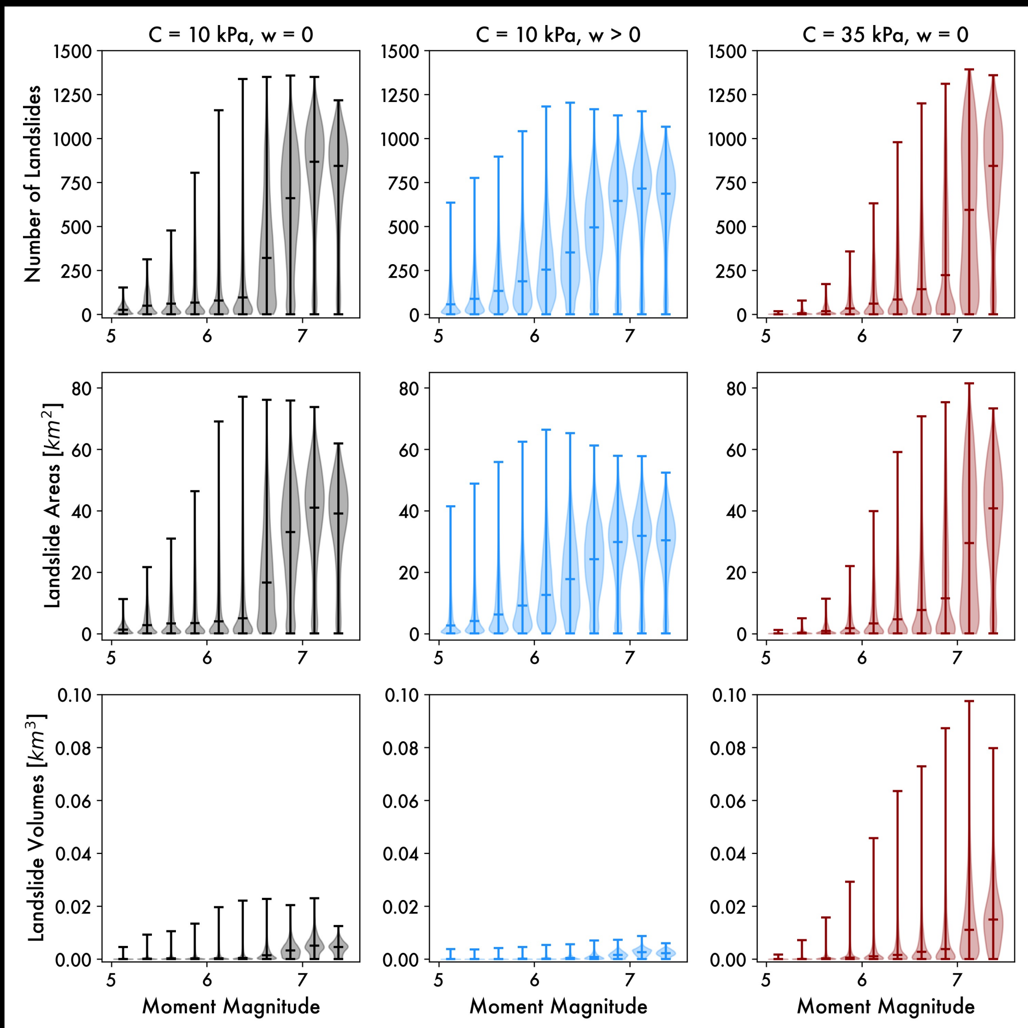


- Models with coseismic landslides are steeper / higher relief than model without landslides.
- Differences in surface properties not strong control on this behavior.

Variability in Landslide Statistics from Differences in Surface Properties



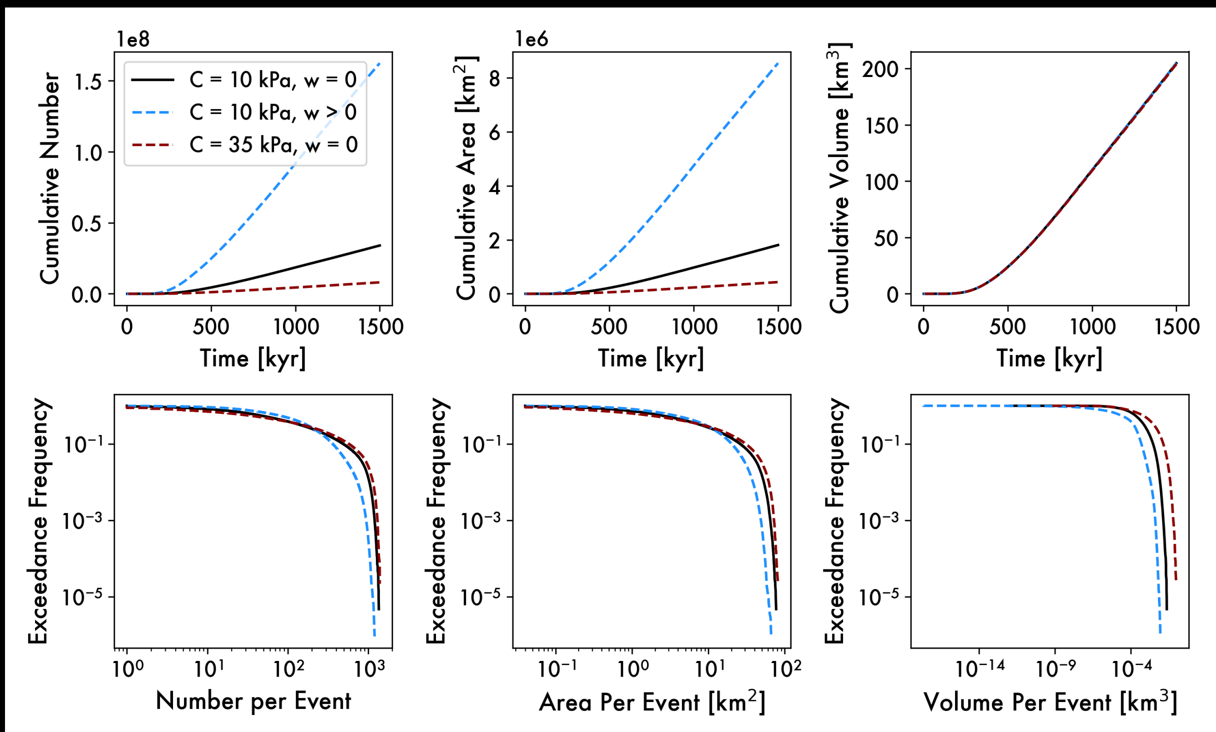
- Soil strength and/or relative wetness change the number of landslides for a given magnitude event.



Distributions of Landslides by Triggering Magnitude

- Wetter soils allow more / larger area landslides to occur at lower magnitudes.
- Stronger soils mean less frequent, but generally larger, landslides, mostly triggered by large magnitude events.

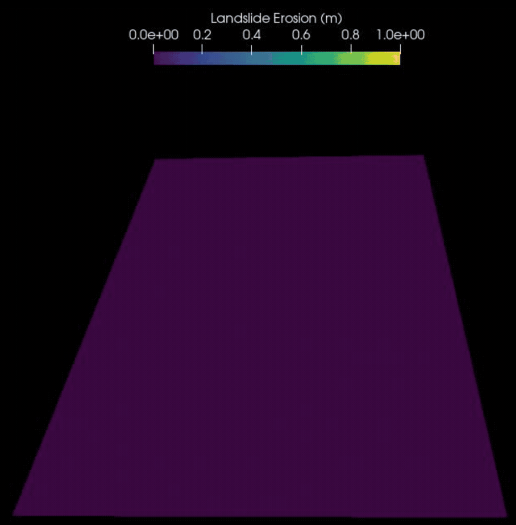
Effective Landslide Sediment Budget Remains Unchanged

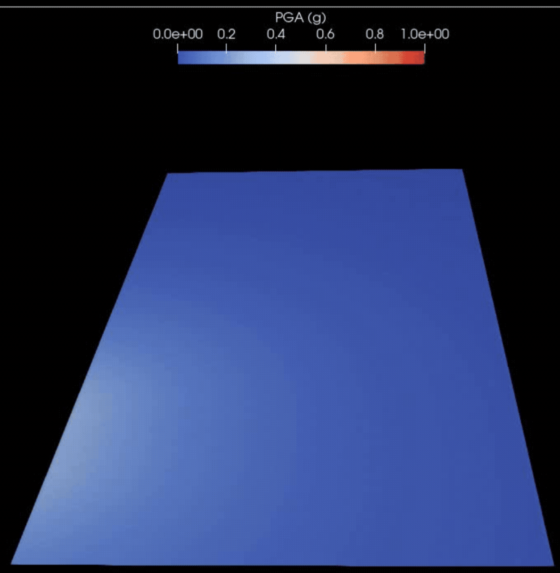


- Detailed statistics of landslides change between different surface conditions.
- However, total landslide volume remains constant across scenarios.

Preliminary Conclusions

- Potential imprint of seismic cycle within topography, but need more testing to understand expectations.
- Coseismic landslides don't necessarily change landscape architecture.
- Simulation of earthquakes driving long-term landscape evolution is useful framework for understanding geologic record of cascading hazards.





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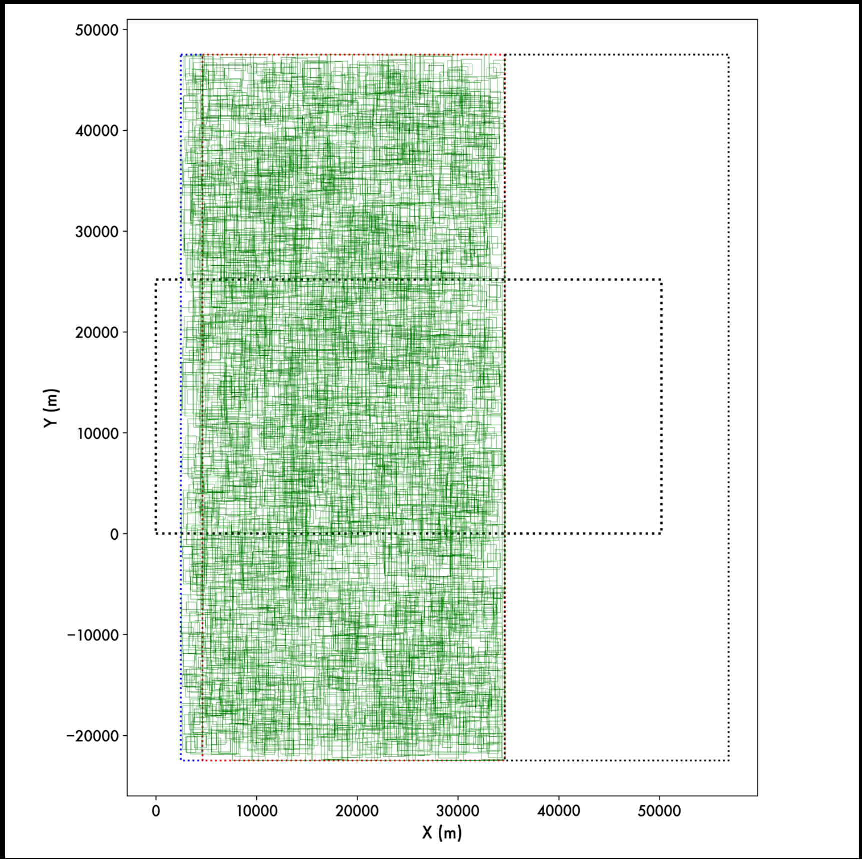
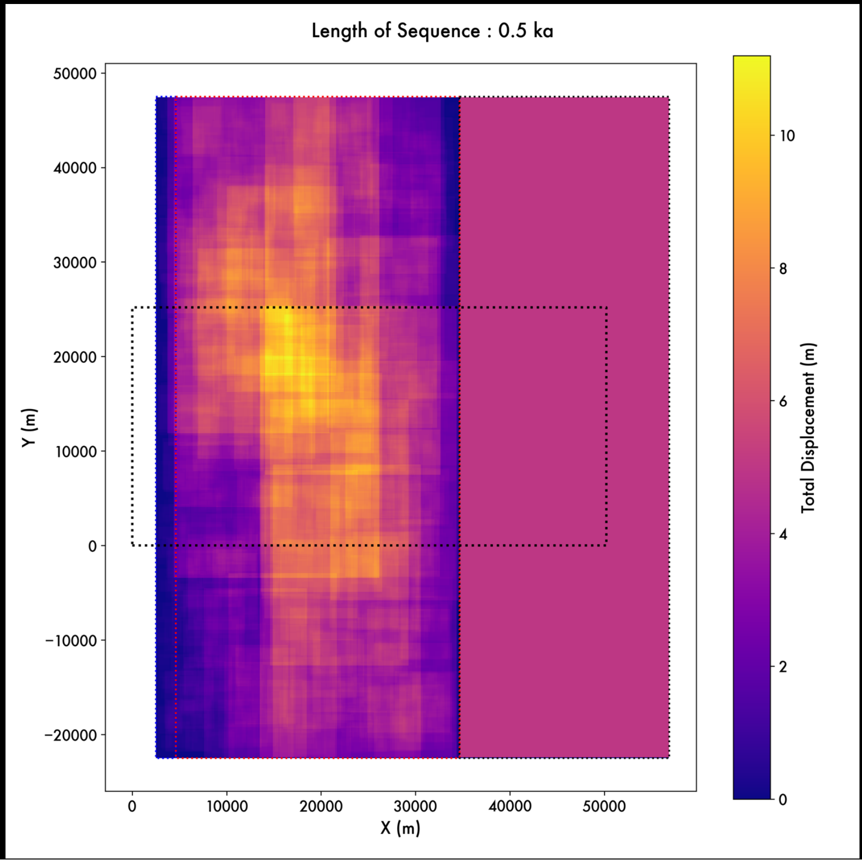
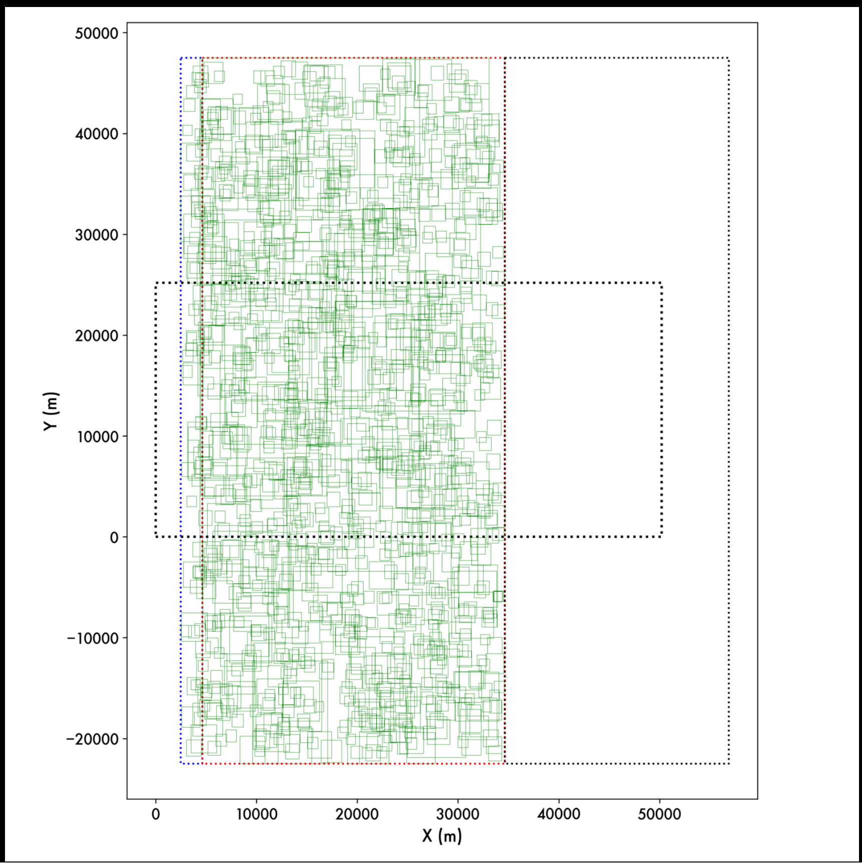
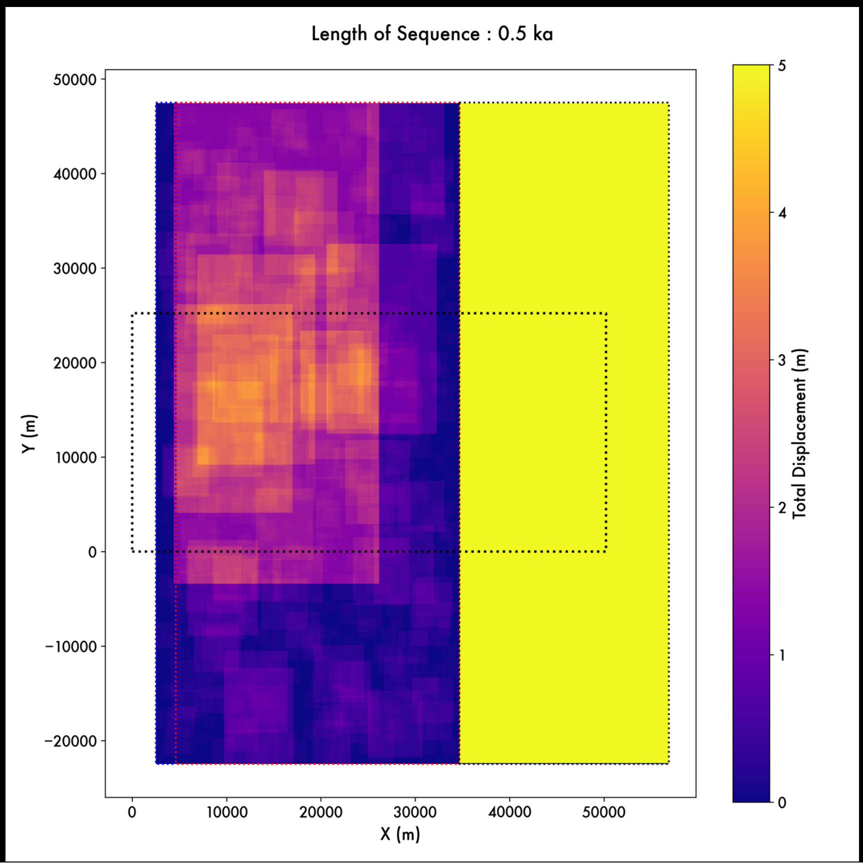
Random Placement of Ruptures on Fault Plane – Cumulative Moment



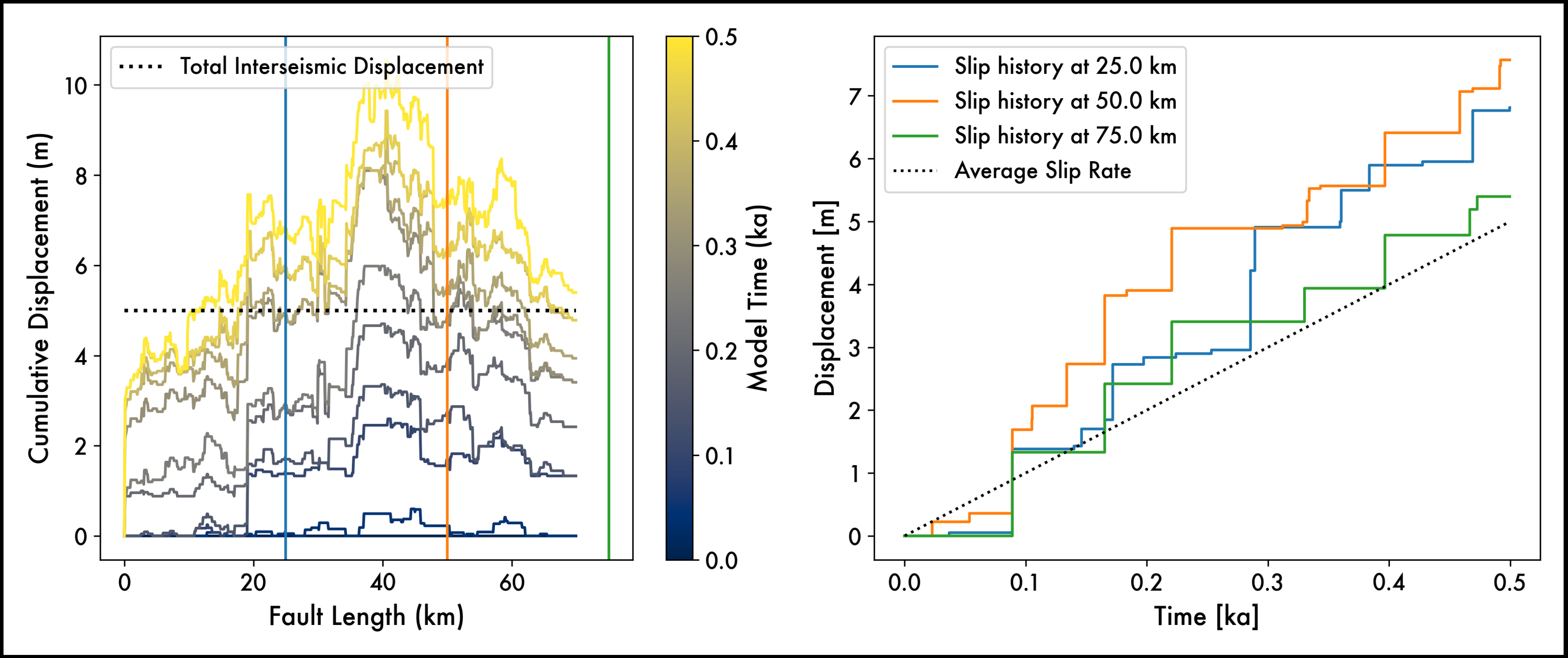


Random Placement of Ruptures on Fault Plane – Displacement



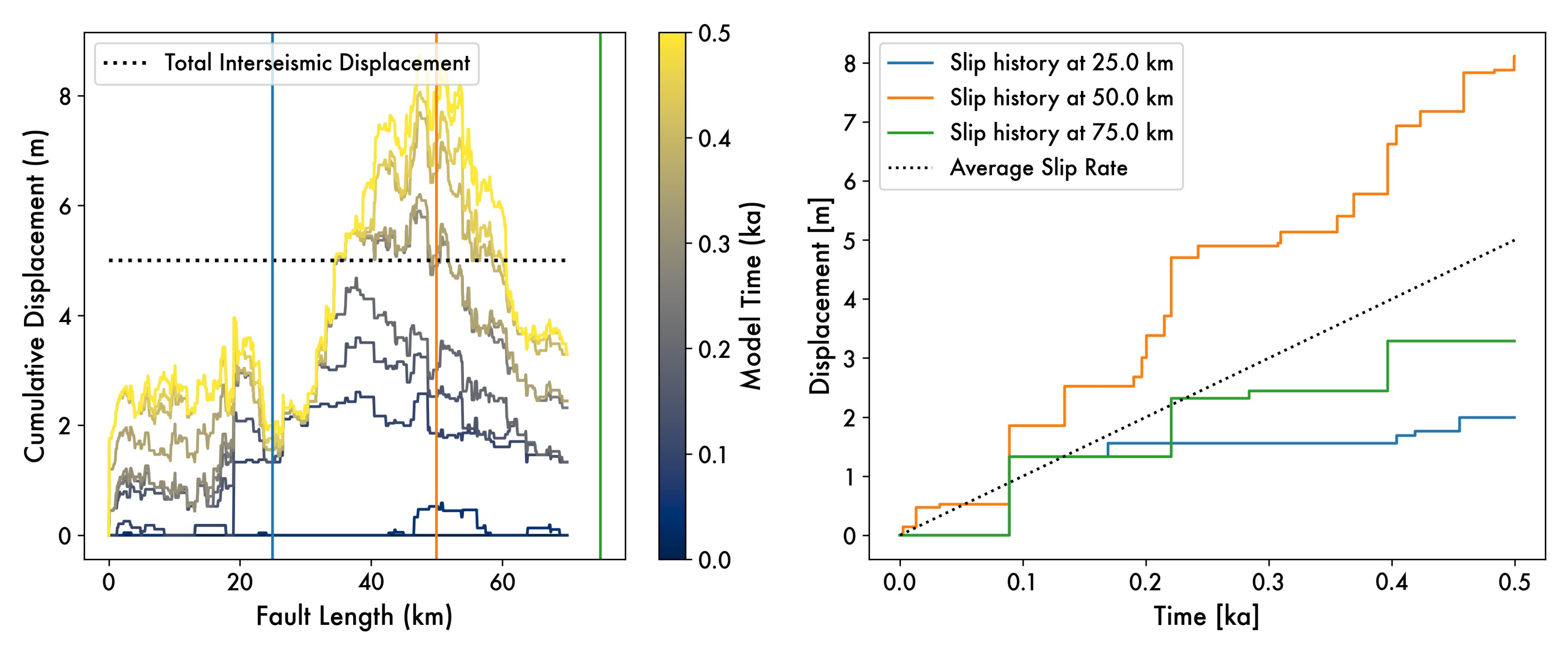


Slip Histories



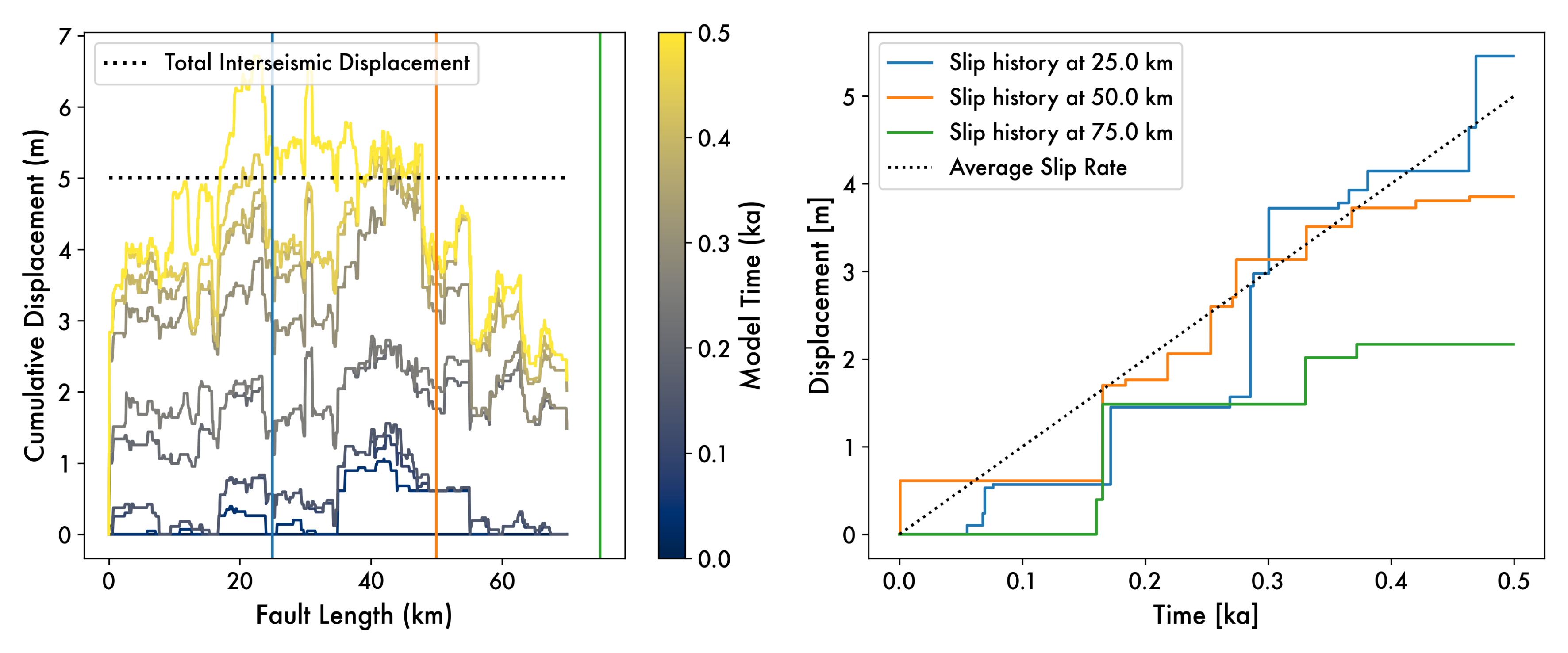
0.5 way through seismogenic zone

Slip Histories



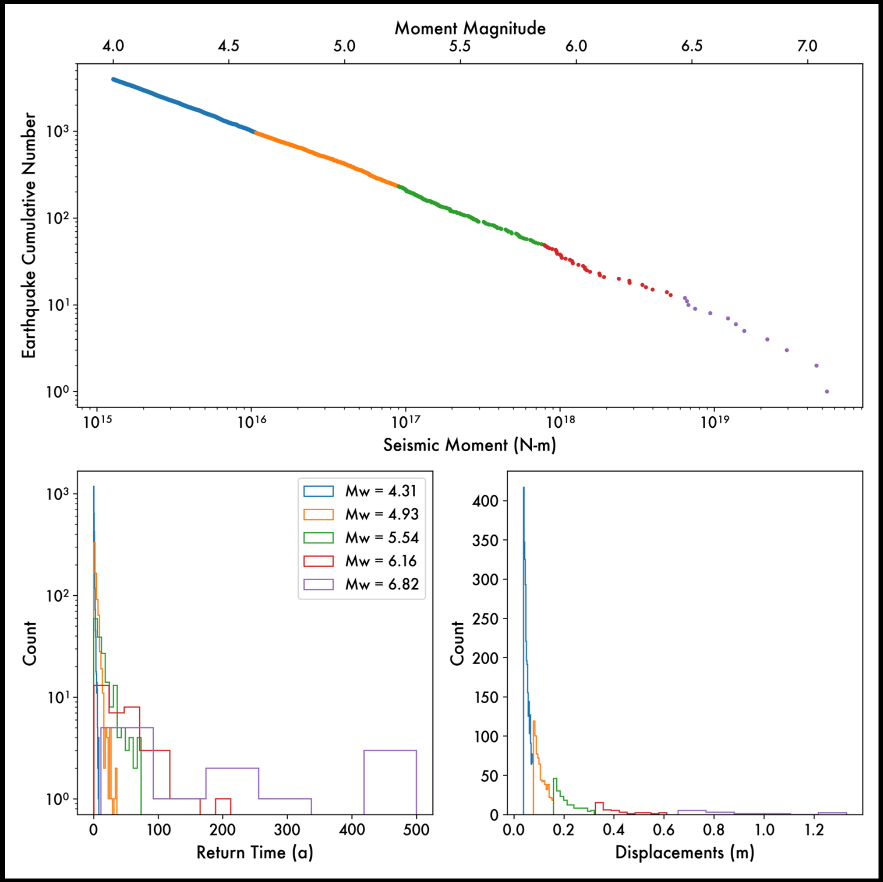
0.25 way through seismogenic zone

Slip Histories



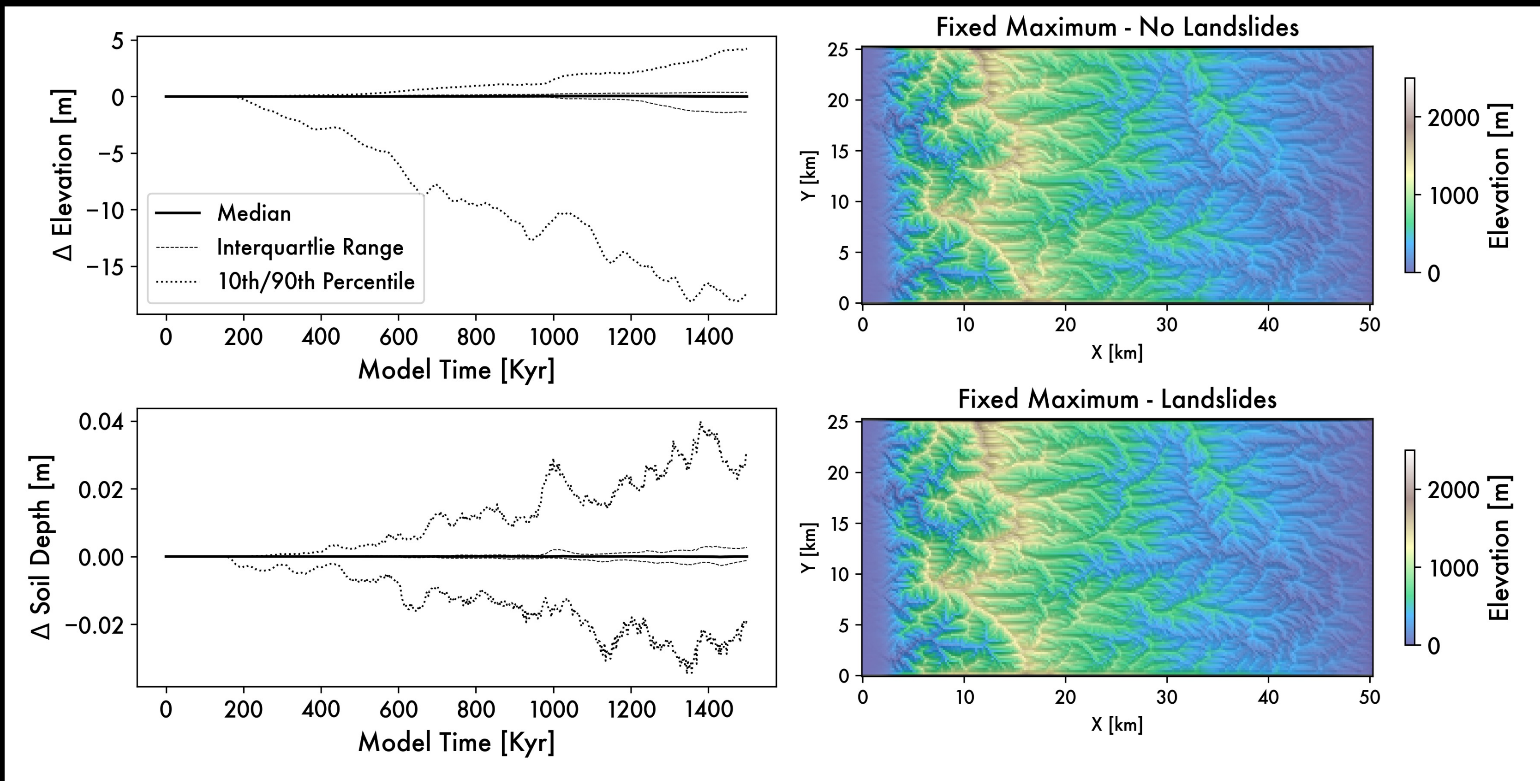
0.75 way through seismogenic zone

Earthquake Catalogs

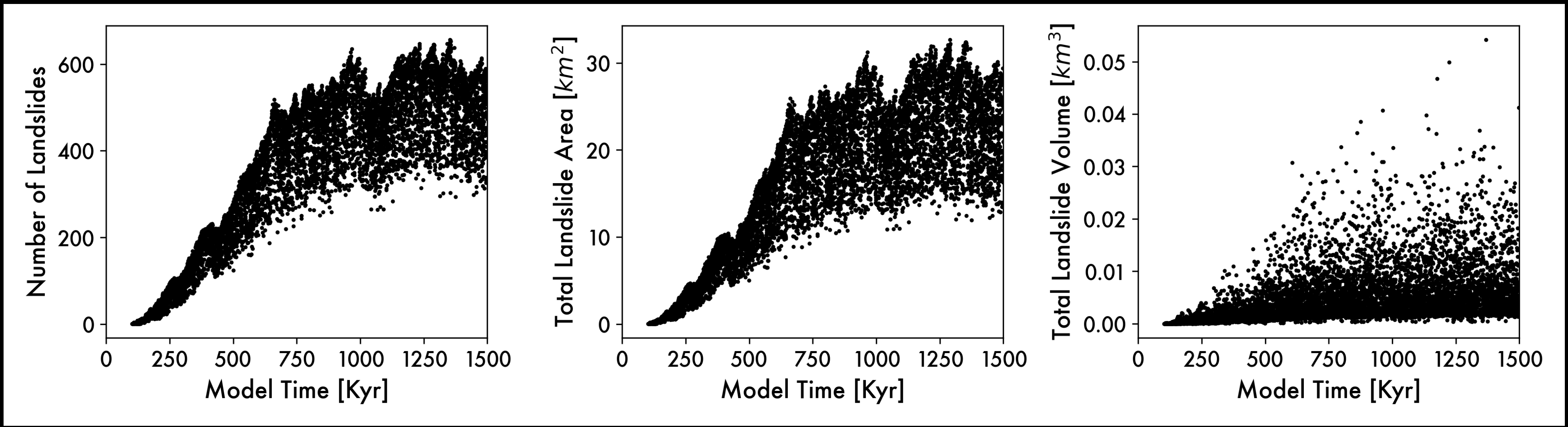


- Generates and draws from semi - realistic earthquake catalogs.
- Minimum magnitude is user controlled parameter, maximum is set by fault / seismogenic zone geometry.

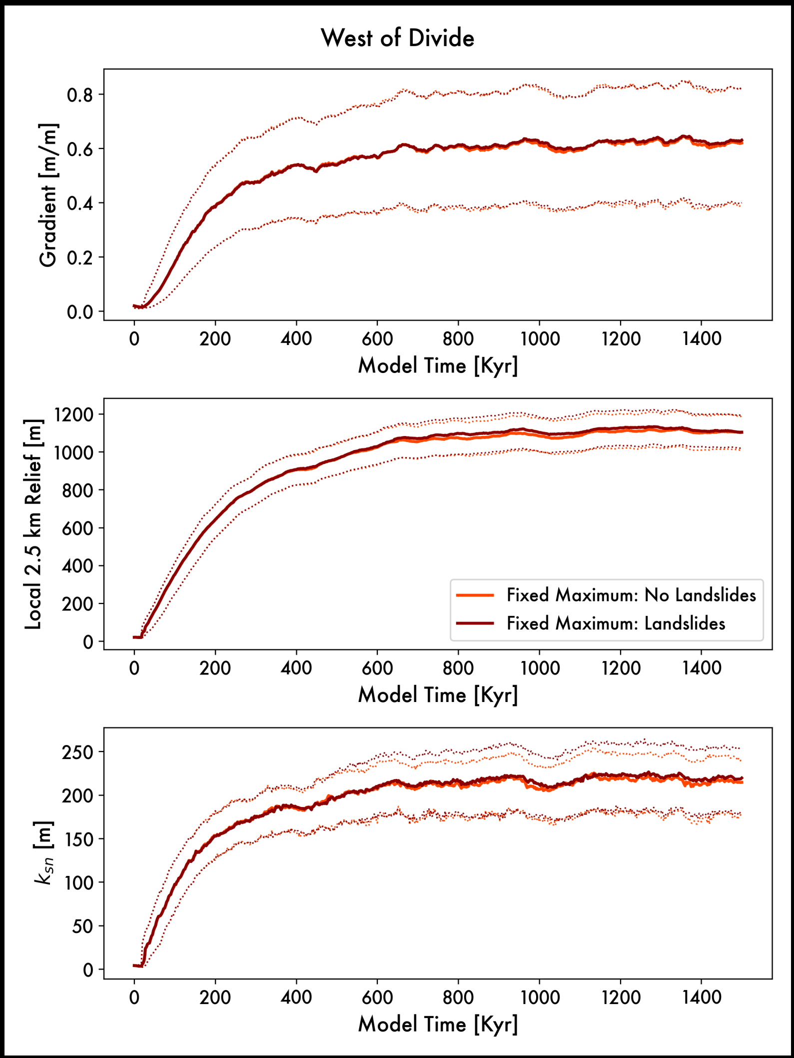
Coseismic Landslides Do Not Change Landscape Structure



Coseismic Landslide Inventory – Fixed Maximum Magnitude Events

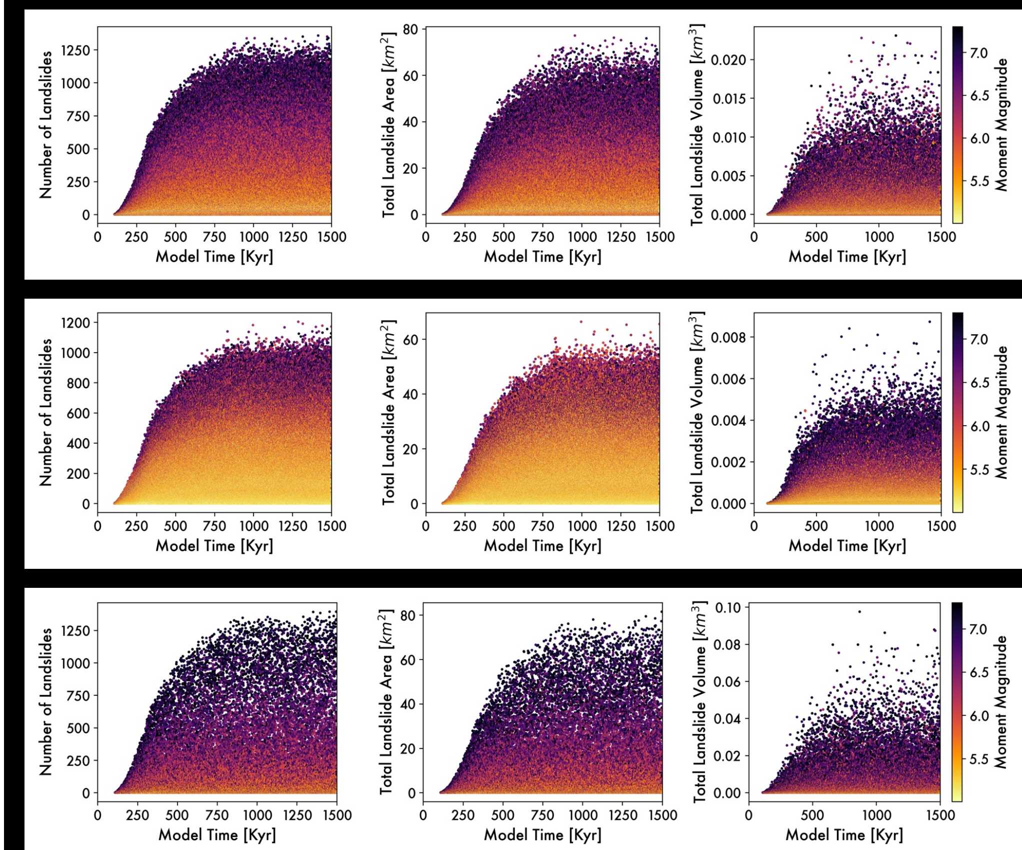


Coseismic Landslides Steepen Landscapes



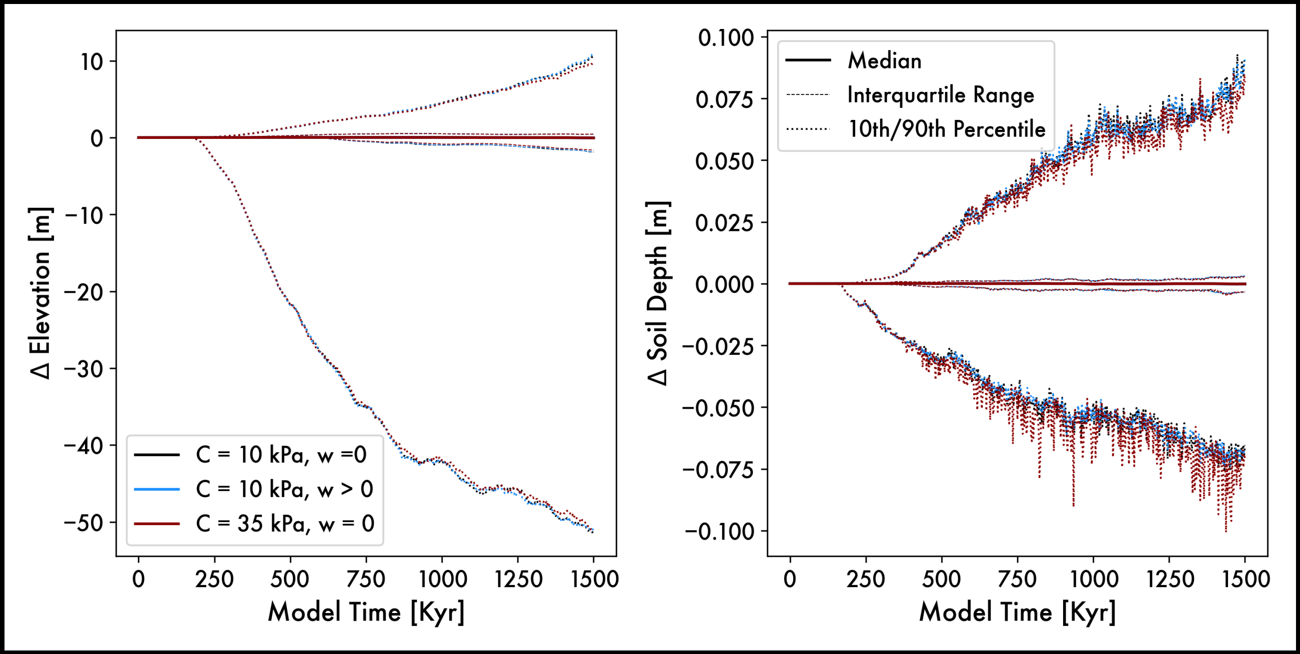
- Presence of coseismic landslides leads to slight steepening of landscape.

Surface Properties Dictate Aspects of Coseismic Landslide Inventories

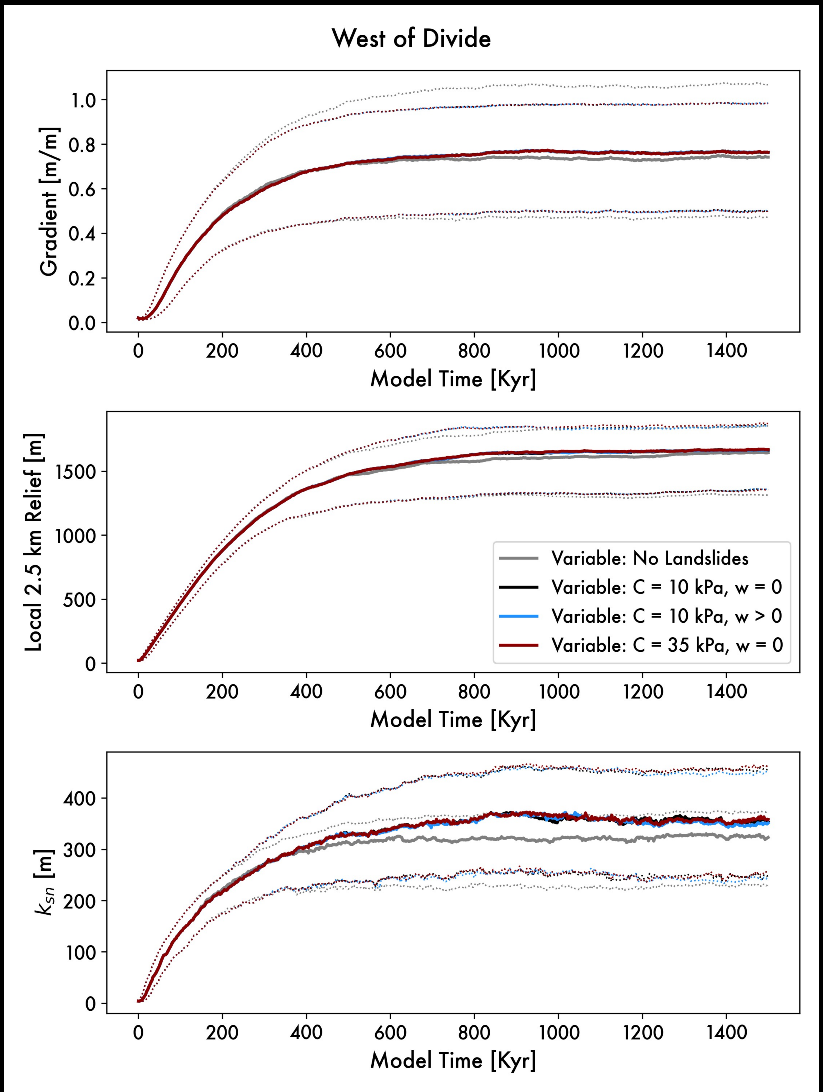


- Landslide statistics reach quasi steady-state.
- Wetter soils lead to more and larger earthquakes at lower magnitudes.
- Stronger soils lead to fewer, but larger landslides, mostly triggered by larger events.

Topographic Differences Are There, But Subtle



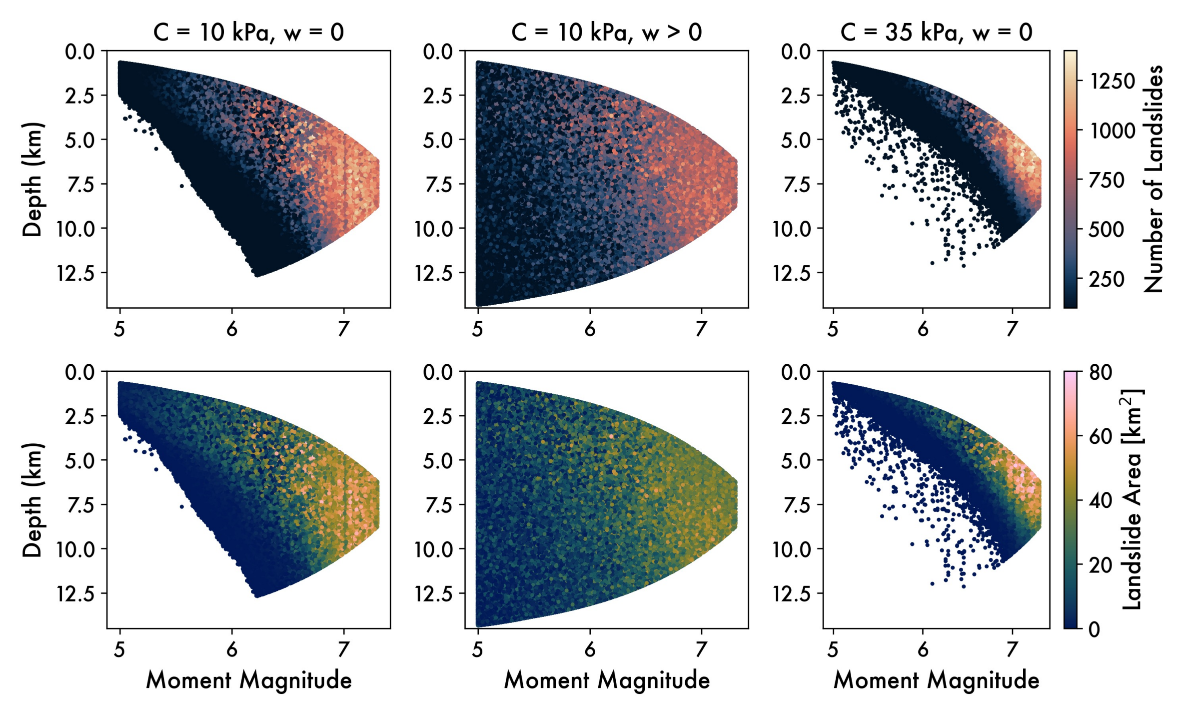
- Comparison between models with and without landslides suggest relatively minor differences in topographic evolution.



Subtle Landscape Metric Changes

- Similar to when only considering maximum magnitude earthquakes, coseismic landslides lead to slight steepening of landscape.

Rupture details influence landslide statistics



- As expected, depth of rupture modulates landslide statistics.
- In landscapes more susceptible to landslides (e.g., wet soils), even deeper events can produce significant landslides.