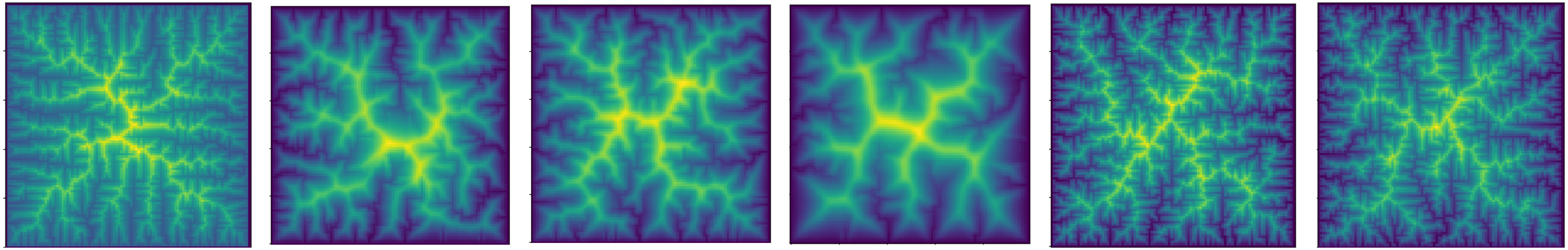
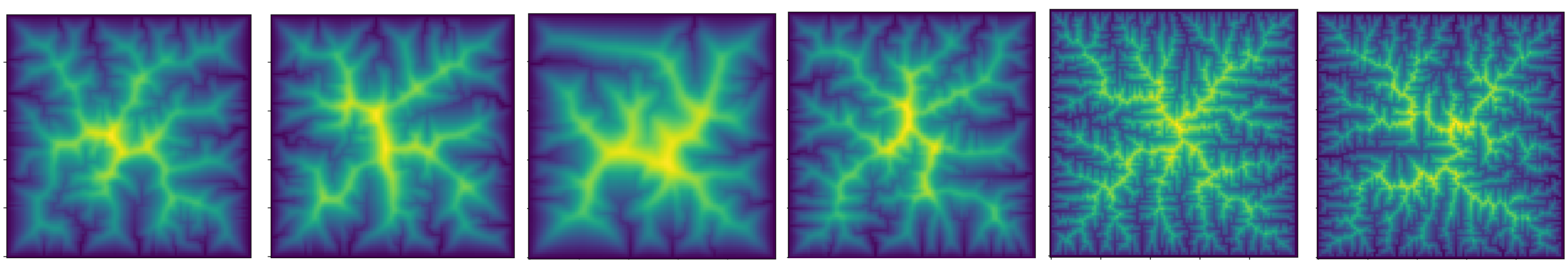


Testing Landscape Evolution Models

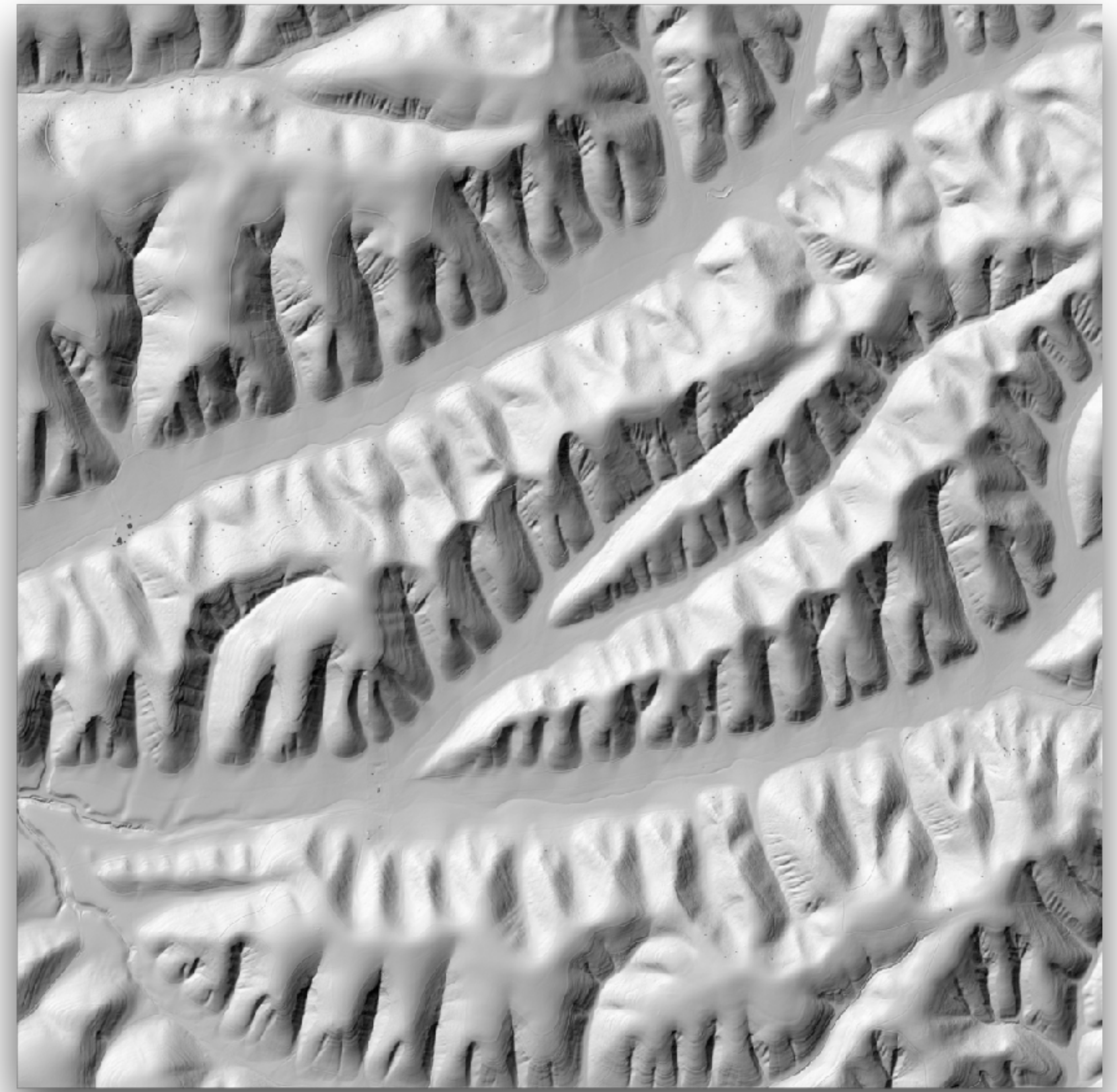
Katy Barnhart

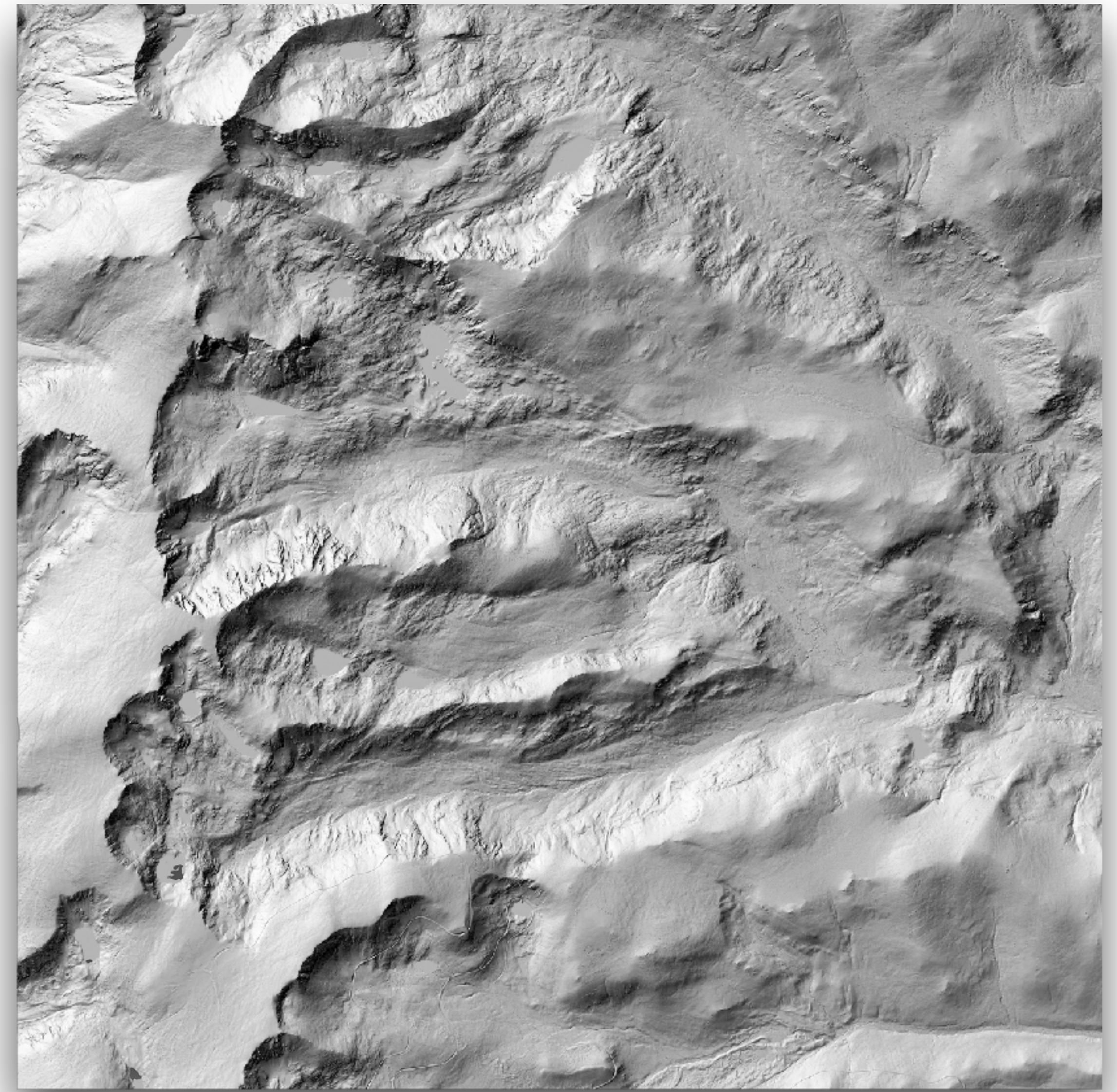
CIRES and Dept. Geological Sciences, University of Colorado

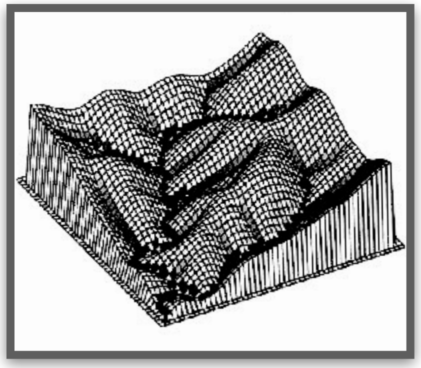


Coupling of Tectonic and Surface Processes—April 25th, 2018

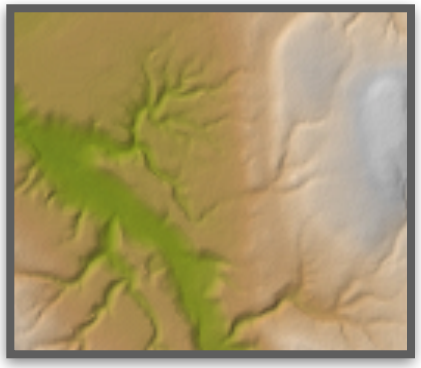
Can these landscapes be inverted for geomorphic and tectonic process?



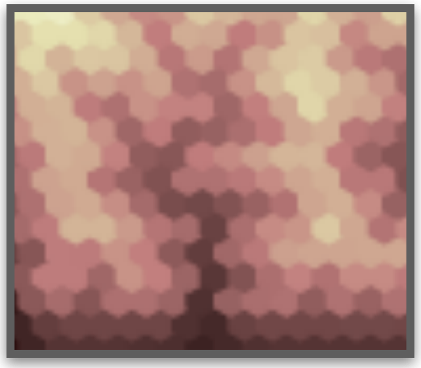




Overview of development and use of Landscape Evolution Models

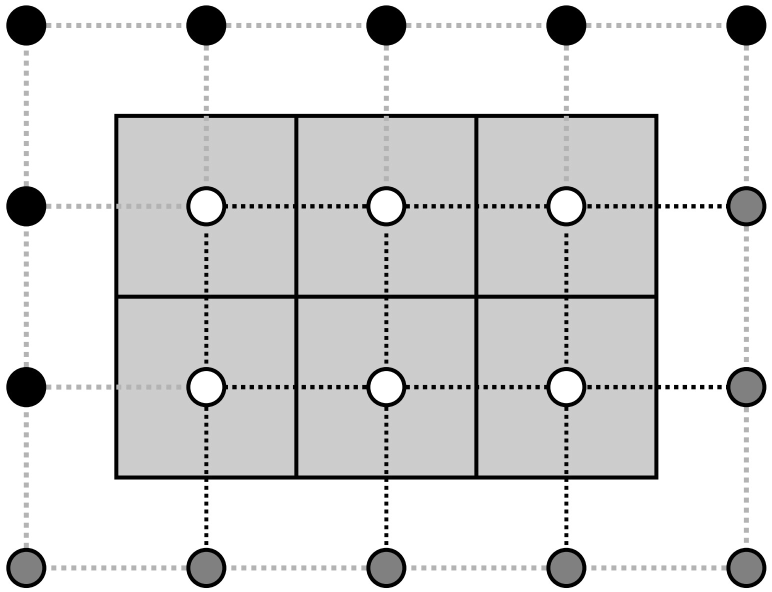


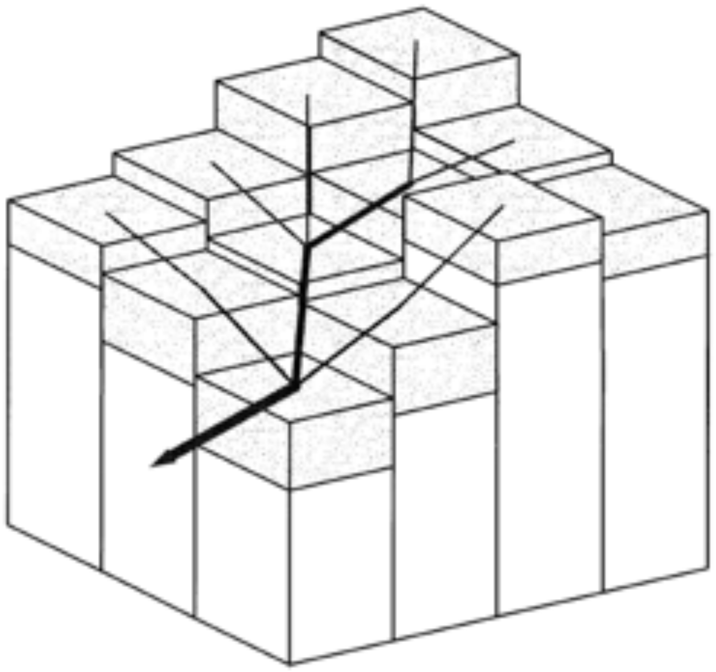
Testing alternative models in a natural experiment of postglacial landscape evolution



Inferring geomorphic and tectonic parameters in a synthetic experiment

Parts of most LEMS





- Representation of topography (raster grid, irregular mesh)
- Method to create and route water
- Diffusion-like erosion and transport
- Channel erosion (and sometimes transport) depends on **slope** and **drainage area**
- Representations of other geomorphic processes

Types of questions

Evolution of specific field areas

Testable predictions

Consequences of current theories

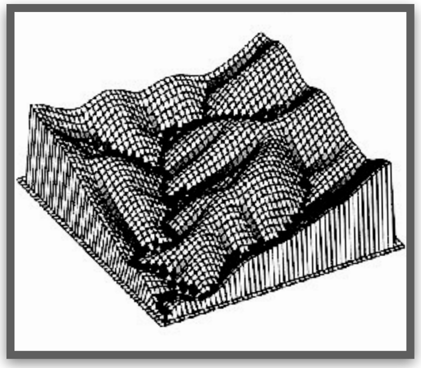
Hypothetical scenarios.

Challenges

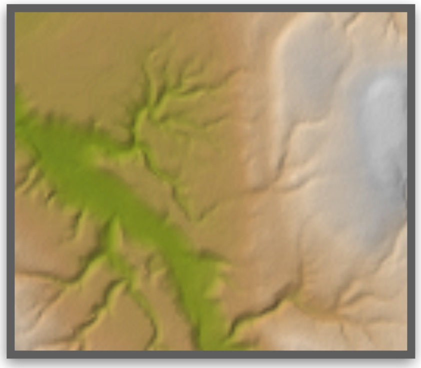
Geomorphic transport laws

Full coupling with geodynamics and climate

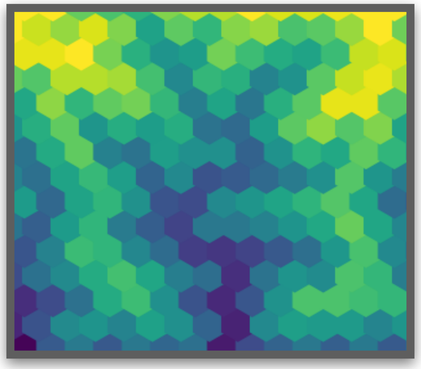
Comparing models and data



Overview of development and use of Landscape Evolution Models

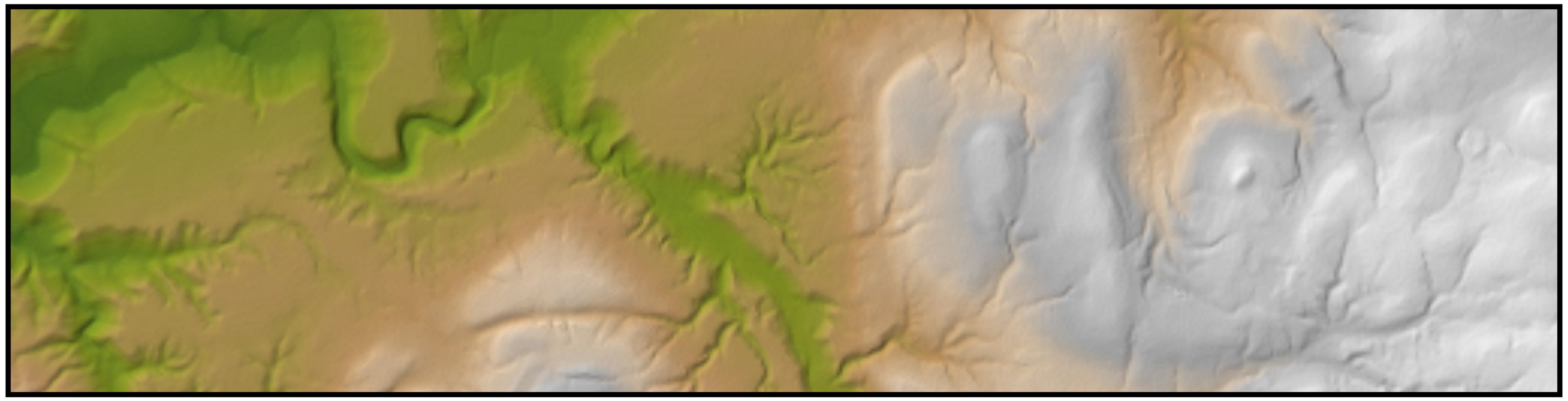


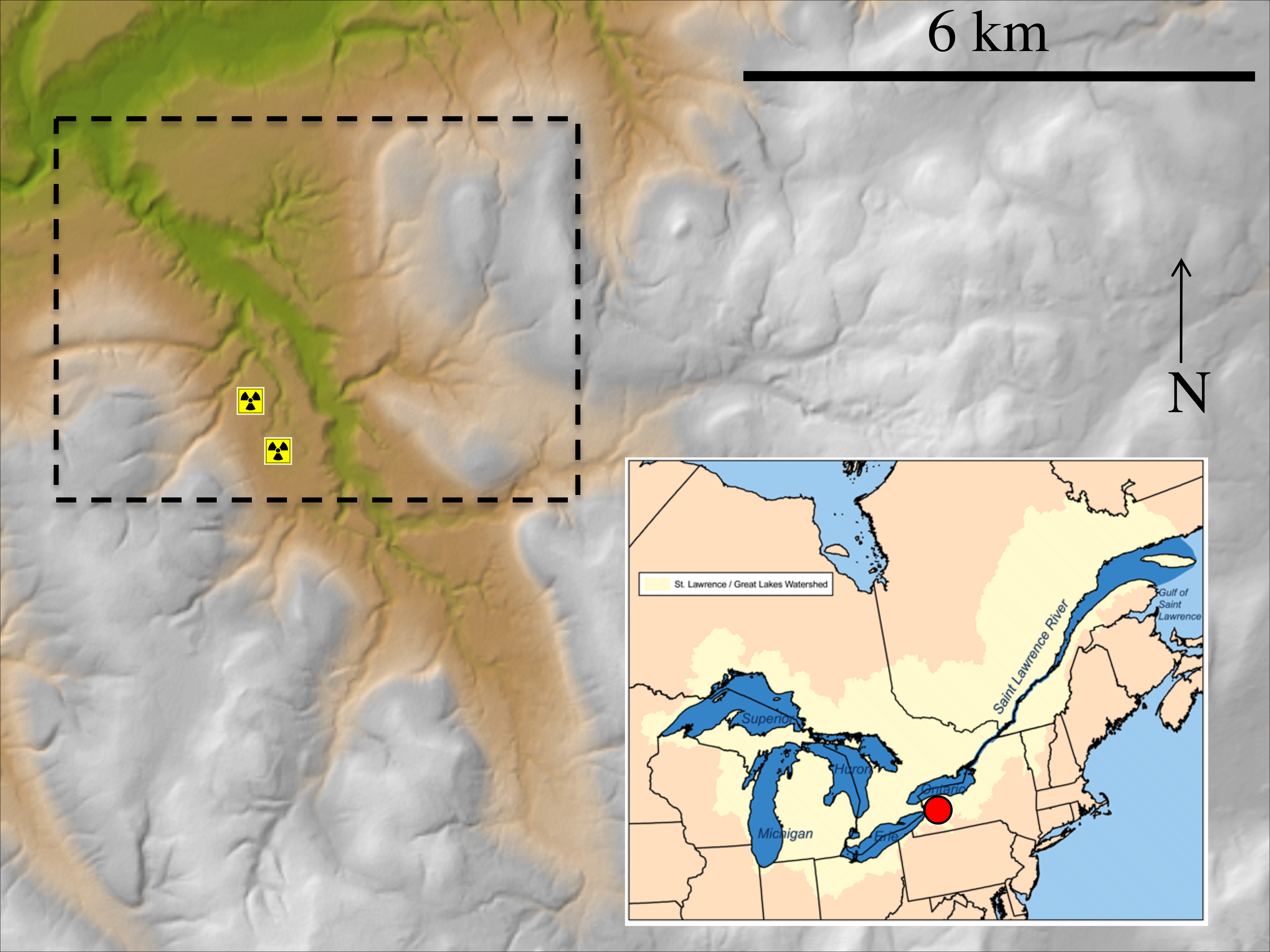
Testing alternative models in a natural experiment of postglacial landscape evolution

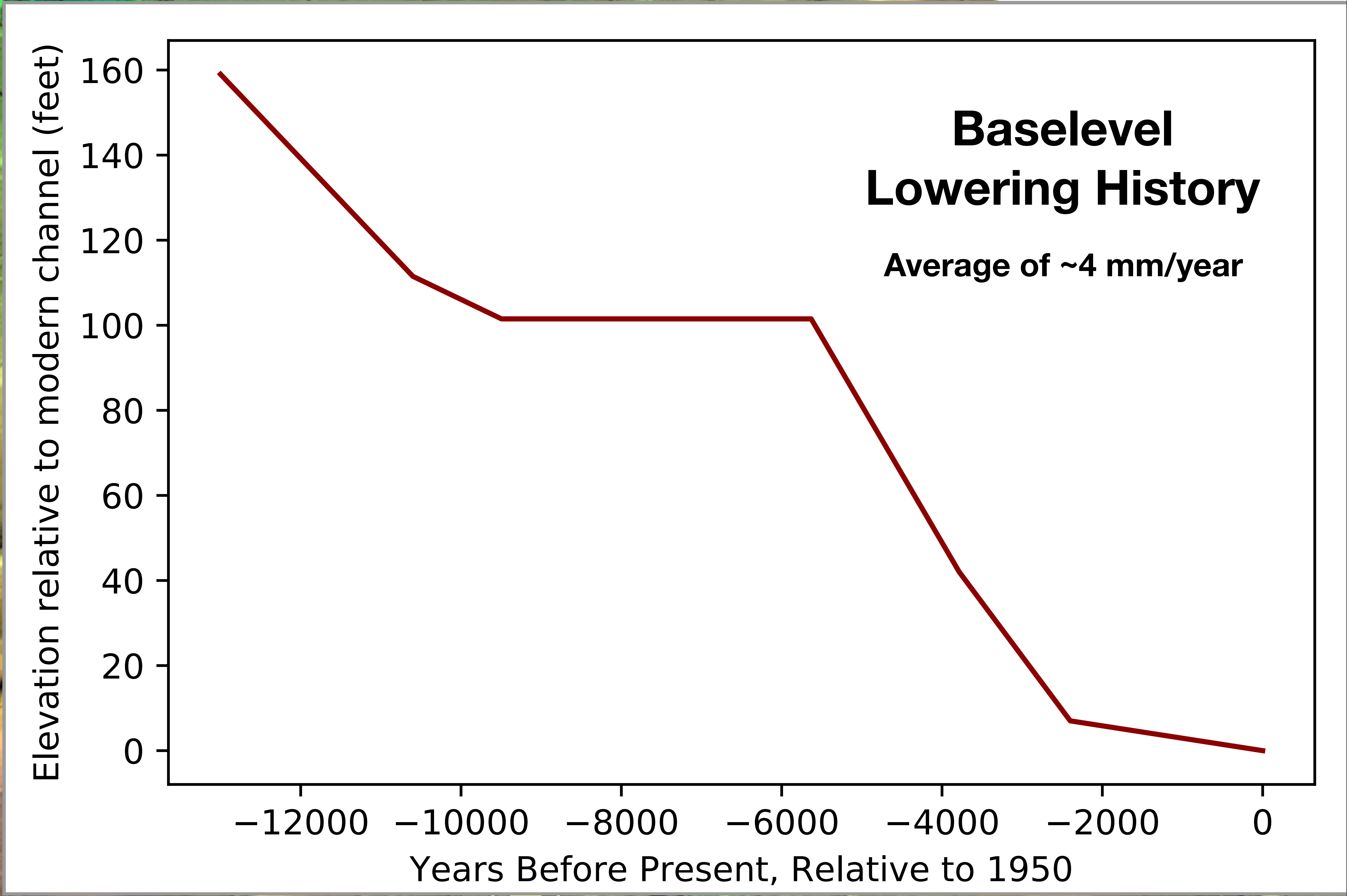


Inferring geomorphic and tectonic parameters in a synthetic experiment

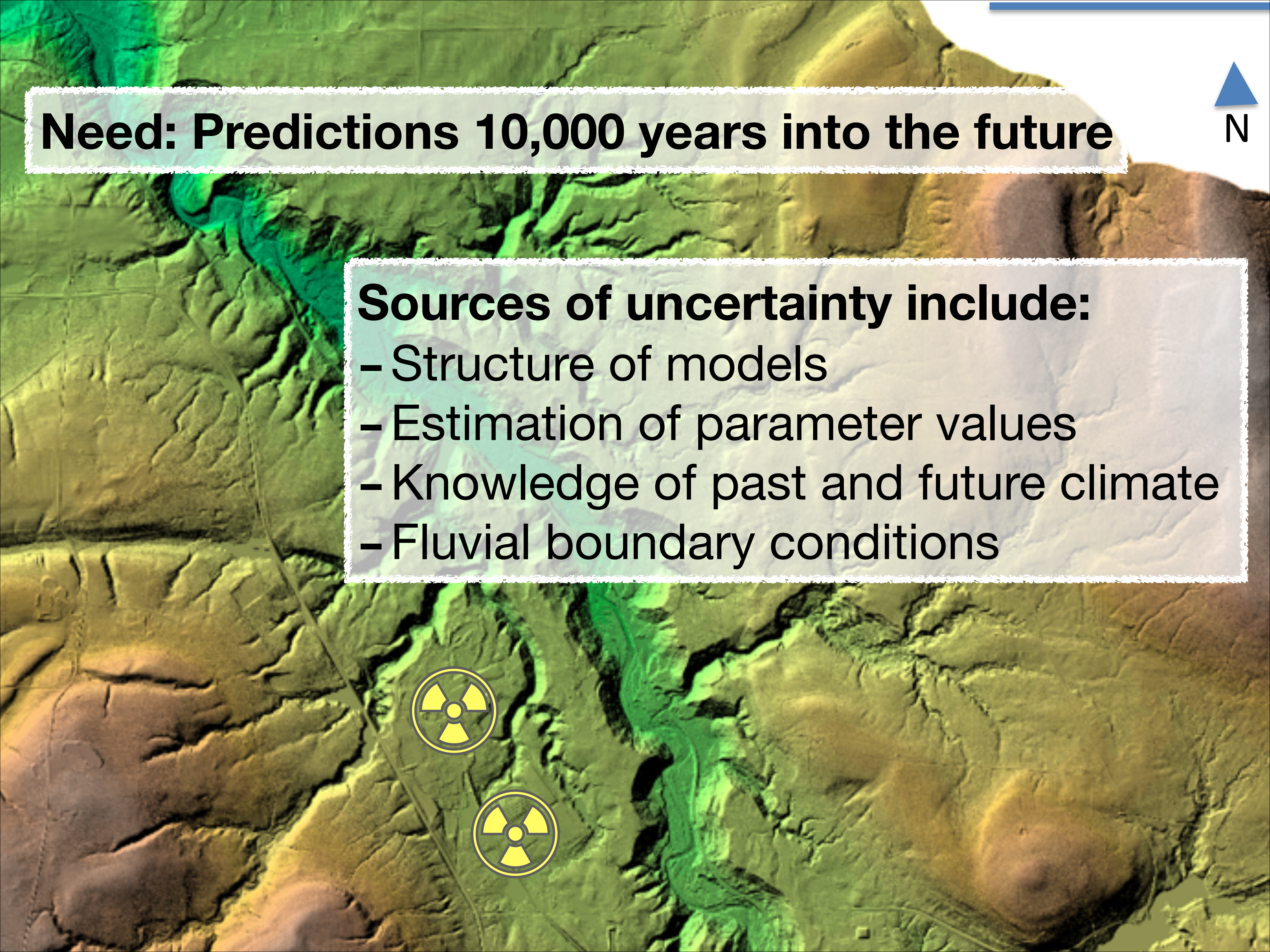
How much complexity is needed?

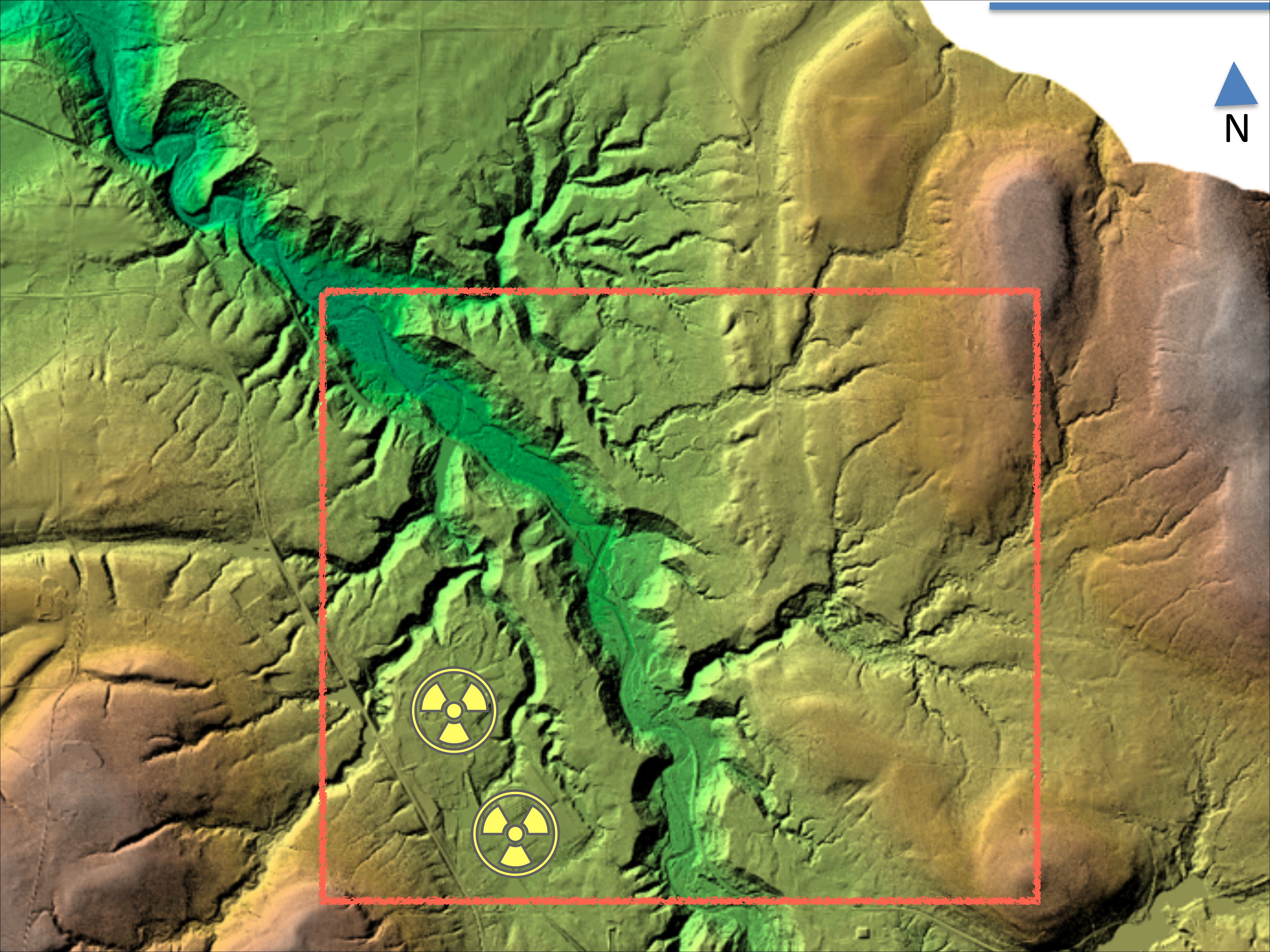



6 km
N
St. Lawrence / Great Lakes Watershed
Gulf of Saint Lawrence
Saint Lawrence River
Superior
Huron
Michigan
Ontario
Erie

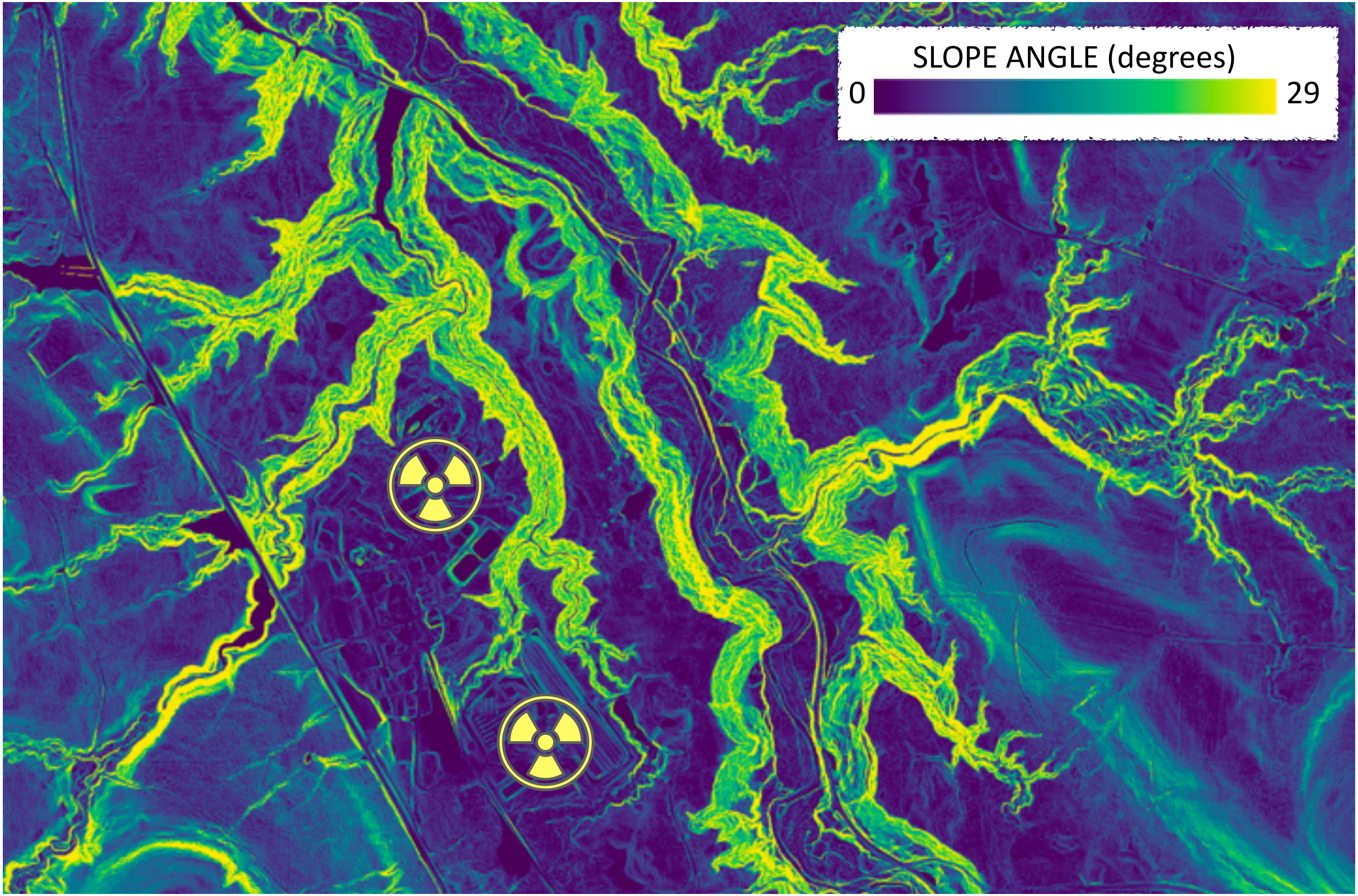


Baselevel
Lowering History
Average of ~4 mm/year
Elevation relative to modern channel (feet)
160
140
120
100
80
60
40
20
0
−12000
−10000
−8000
−6000
−4000
−2000
0
Years Before Present, Relative to 1950

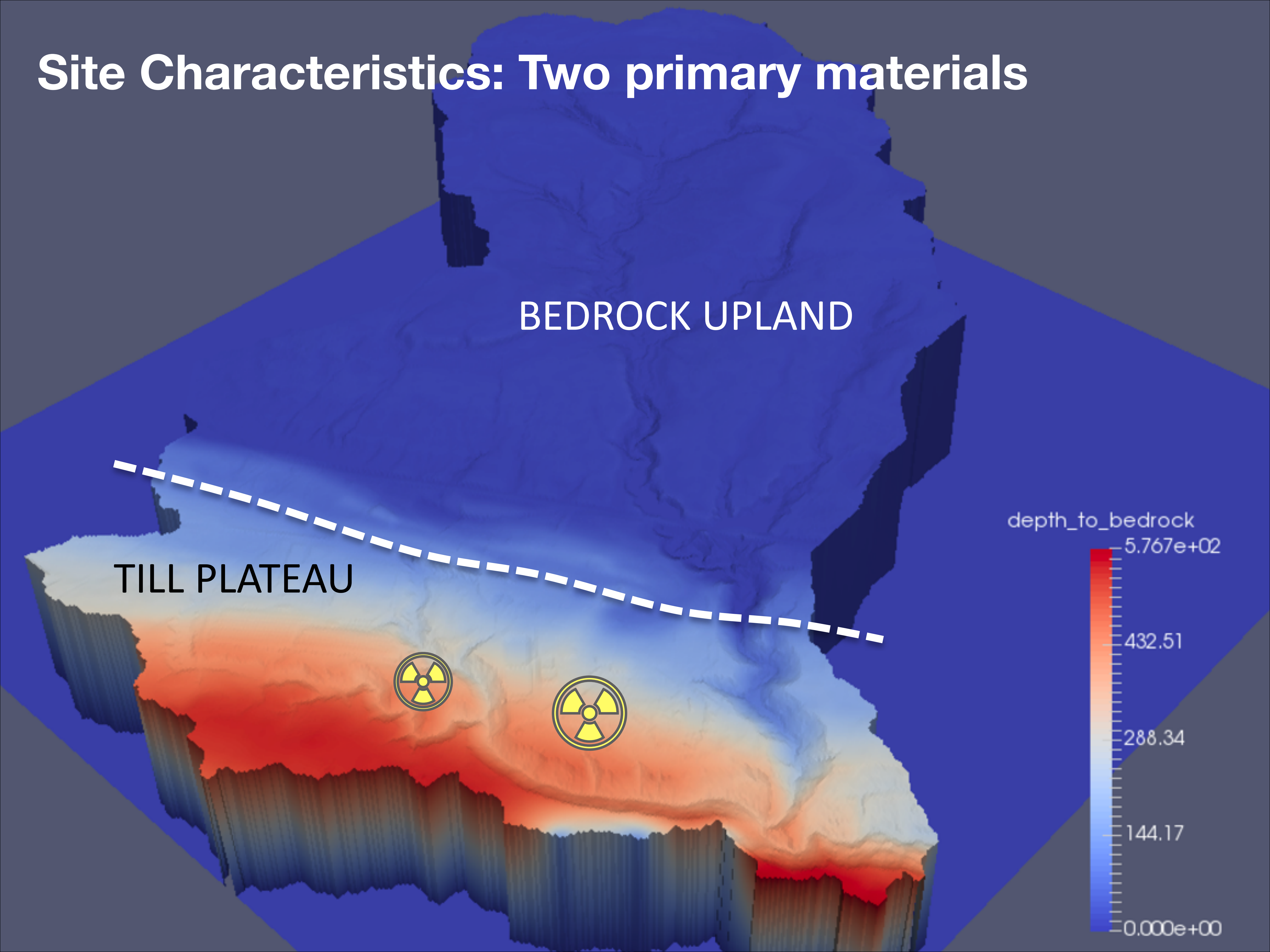

Need: Predictions 10,000 years into the future
N
Sources of uncertainty include:
– Structure of models
– Estimation of parameter values
– Knowledge of past and future climate
– Fluvial boundary conditions


N

Site Characteristics: Steep channel-side slopes



Site Characteristics: Two primary materials



Approach

12 Elements of Complexity

The BASIC model

$$\frac{\partial \eta}{\partial t} = -KA^{1/2}S + D\nabla^2\eta$$

η = land elevation
t = time
A = drainage area
S = steepest-descent gradient
K, D = parameters

Hillslope Processes

- **Linear**/Nonlinear

Hydrology and Climate

- **Deterministic**/Stochastic
- **Uniform runoff**/Variable Source Area
- Time variable climate (Yes/**No**)

Channel Processes

- **Fixed**/Variable area exponent
- Erosion Threshold (Yes/**No**)
- **Stream power**/Shear Stress
- **Constant**/Depth dependent threshold
- **Detachment limited** vs Hybrid Transport and Detachment limited
- Fraction of fines (Yes/**No**)

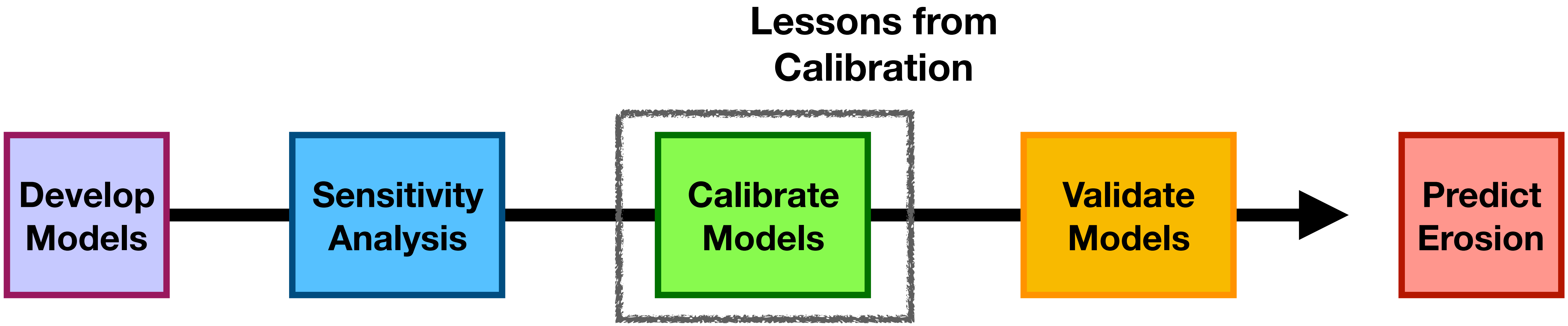
Materials

- Differentiate between soil/ alluvium and rock (Yes/**No**)
- Distinguish between shale bedrock and glacial till (Yes/**No**)

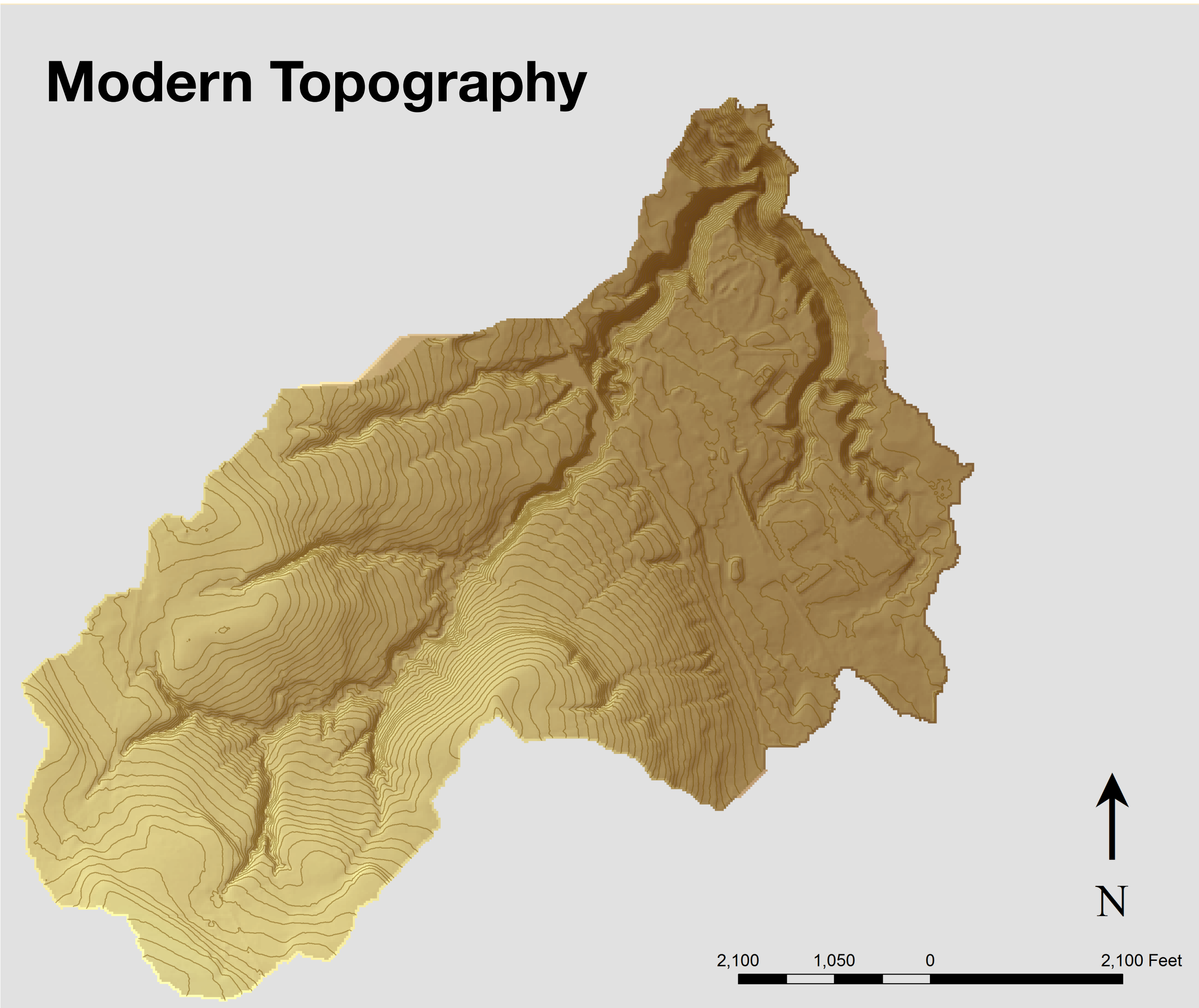
12 - 1 element models
66 - 2 element
220 - 3 element models

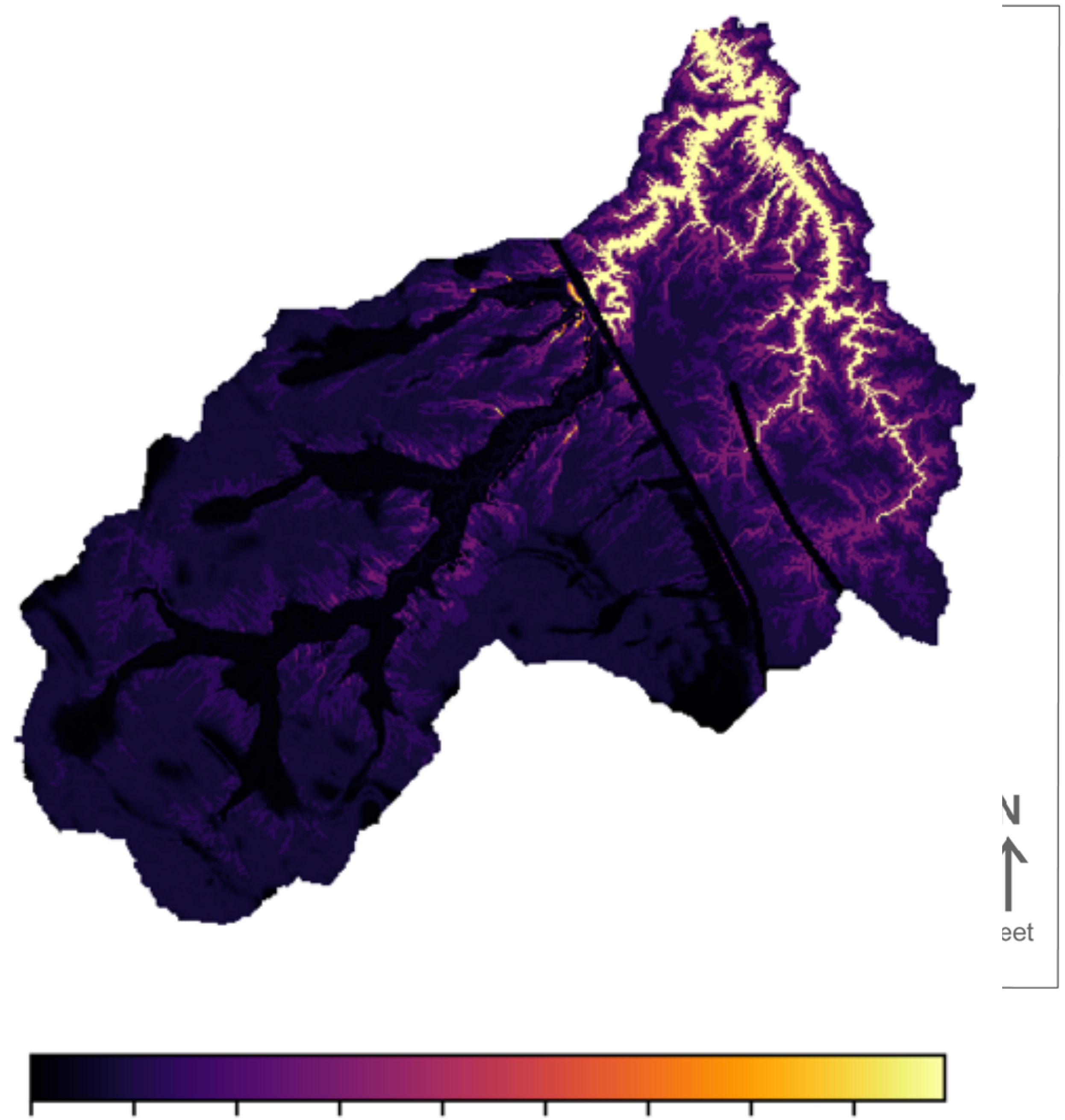
37 Alternative Models

Approach


Lessons from
Calibration
Develop
Models
Sensitivity
Analysis
Calibrate
Models
Validate
Models
Predict
Erosion

Model Data Comparison





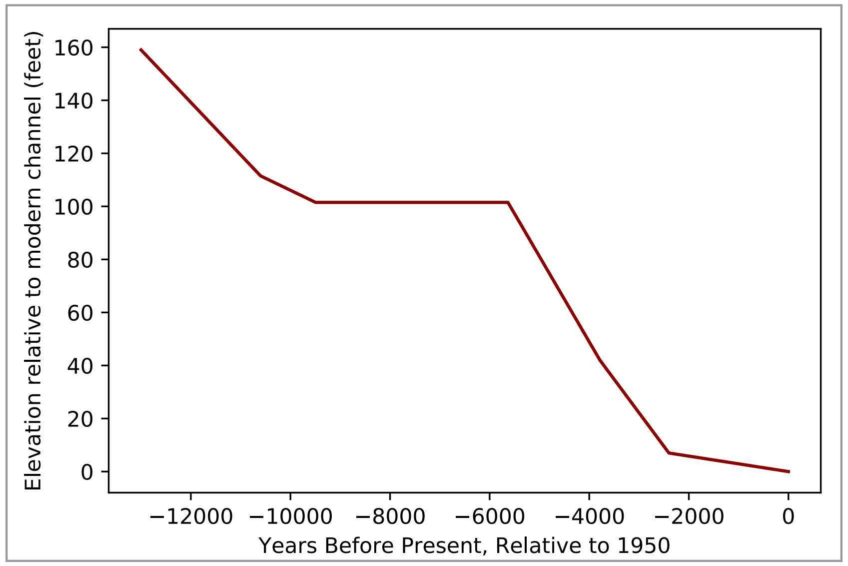
Low Weight **High Weight**

Is this a good natural experiment?

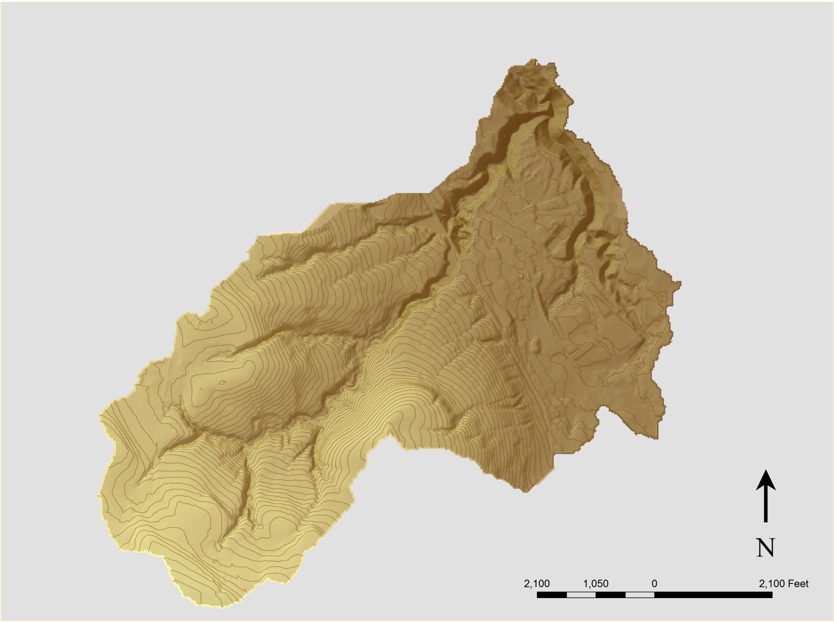
A natural experiment in landscape evolution is a case study of landform development in which only one element varies significantly, and for which the driving forces, initial conditions, and/or boundary conditions are well constrained.

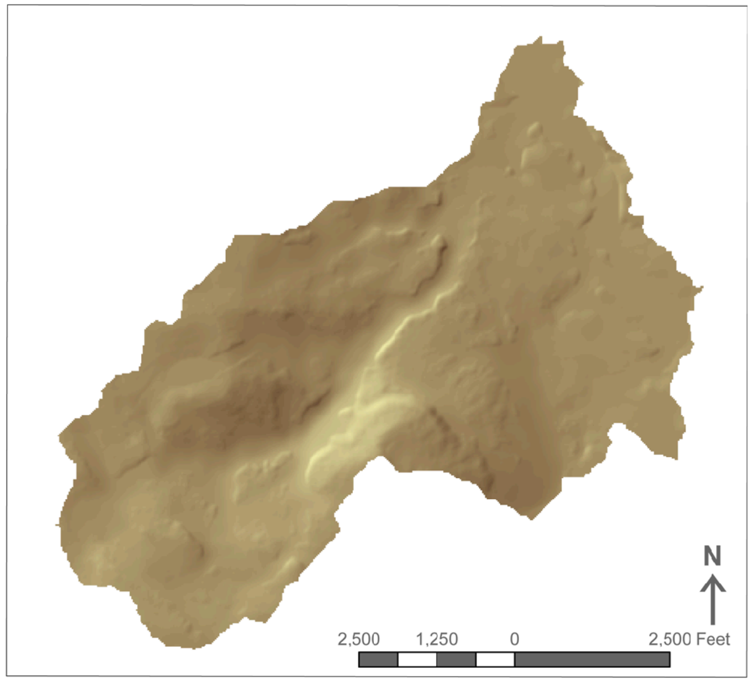
- Tucker Earth Surf. Process. Landforms 34, 1450–1460 (2009)

Boundary conditions are constrained

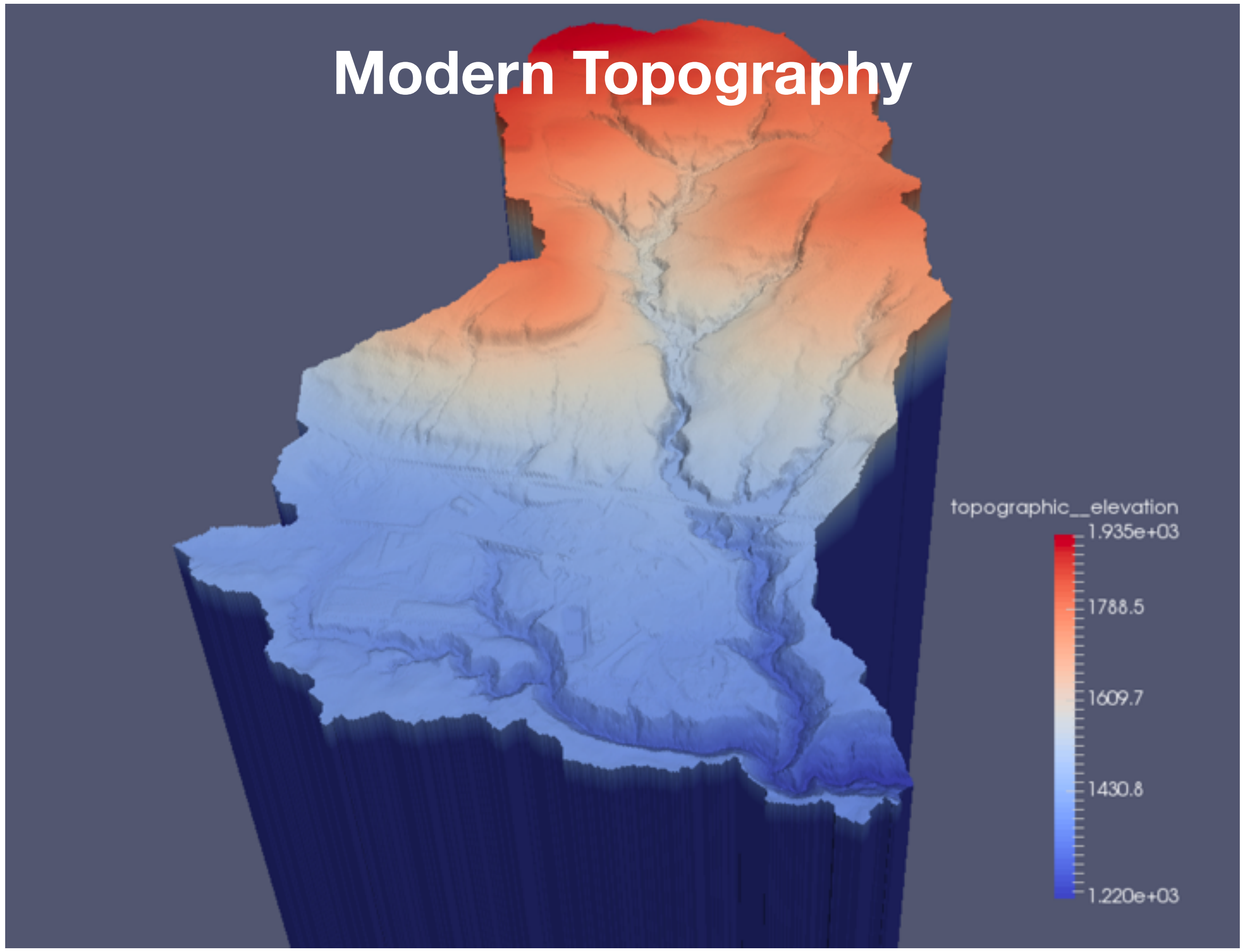


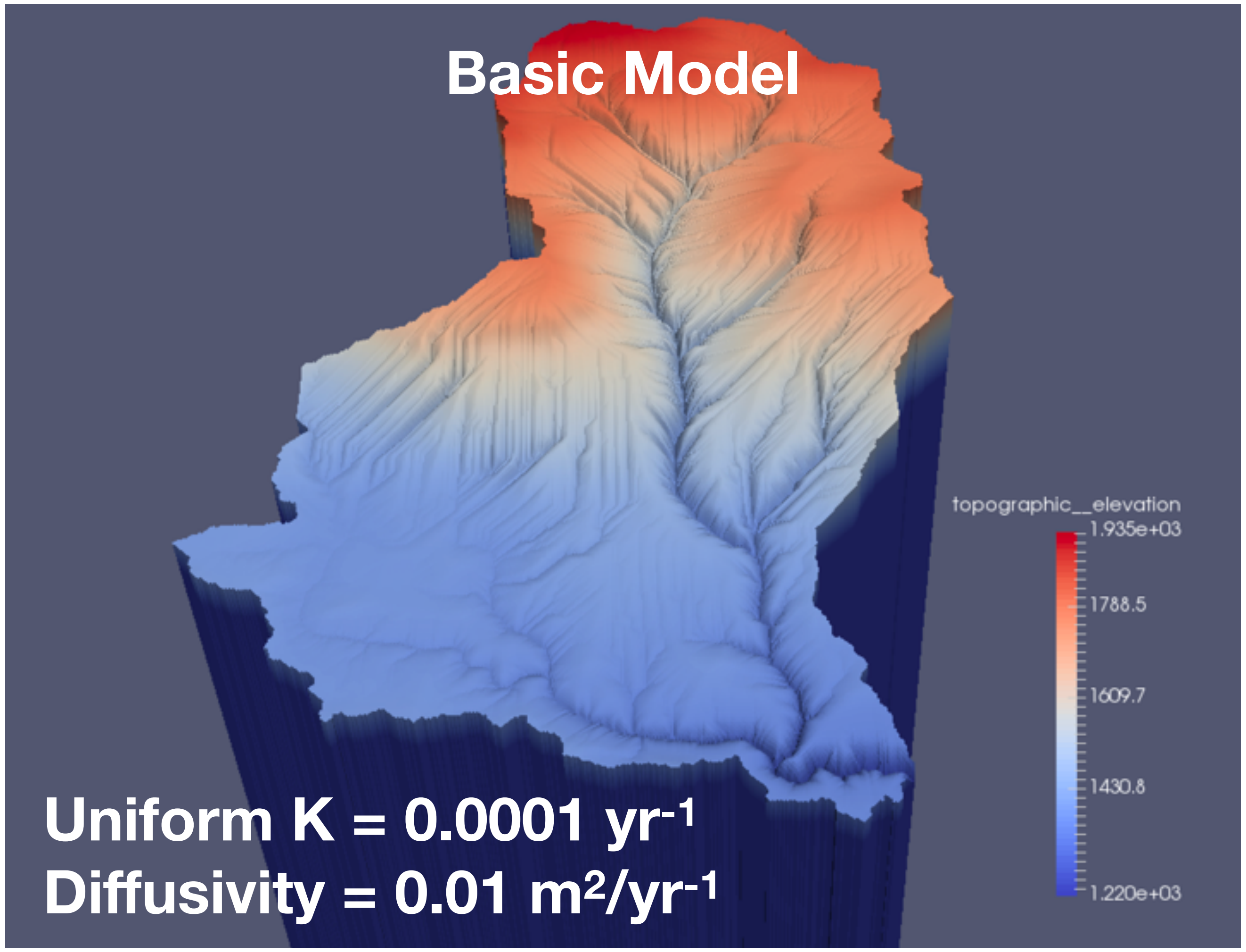
Initial conditions are constrained





- No Intermediate Benchmarks


Modern Topography
topographic__elevation
1.935e+03
1788.5
1609.7
1430.8
1.220e+03


Basic Model
Uniform K = 0.0001 yr-1
Diffusivity = 0.01 m2/yr-1
topographic__elevation
1.935e+03
1788.5
1609.7
1430.8
1.220e+03

What does calibration tell us?

How much complexity is *enough?*

A more complicated model should best a simpler model.
If only because it has more degrees of freedom.

Is it better?

Yes!

*** after accounting for number of parameters**

The element of complexity added to the ability of the model to match the data (*as defined by the objective function)*

NO!

Do the calibrated parameter values indicate that the calibration is trying to recover the simpler option through parameter choice? Then the new element of complexity does not add anything.

Hillslope Processes

- **Linear**/Nonlinear

Hydrology and Climate

- **Deterministic**/Stochastic
- **Uniform runoff**/Variable Source Area
- Time variable climate (Yes/**No**)

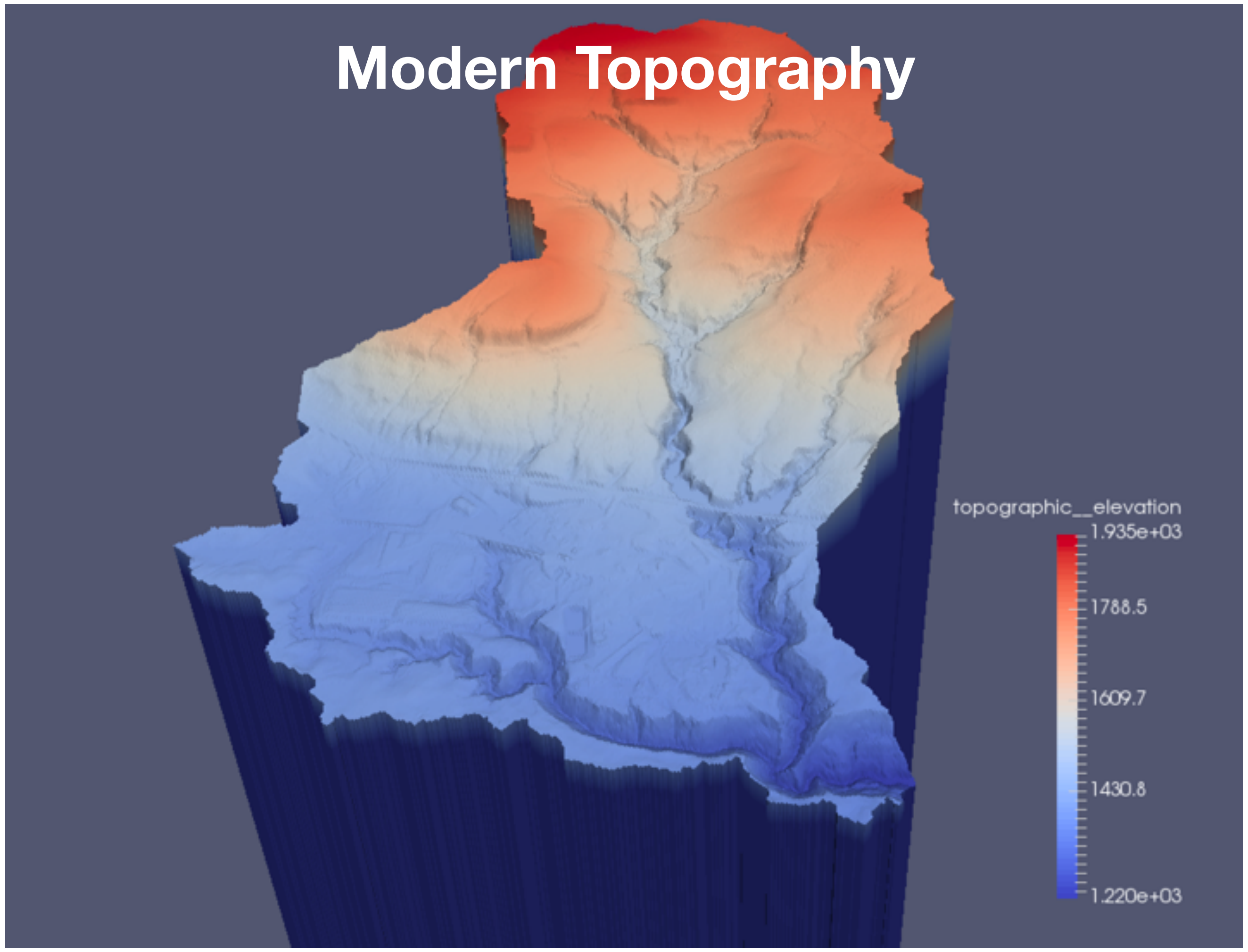
Channel Processes

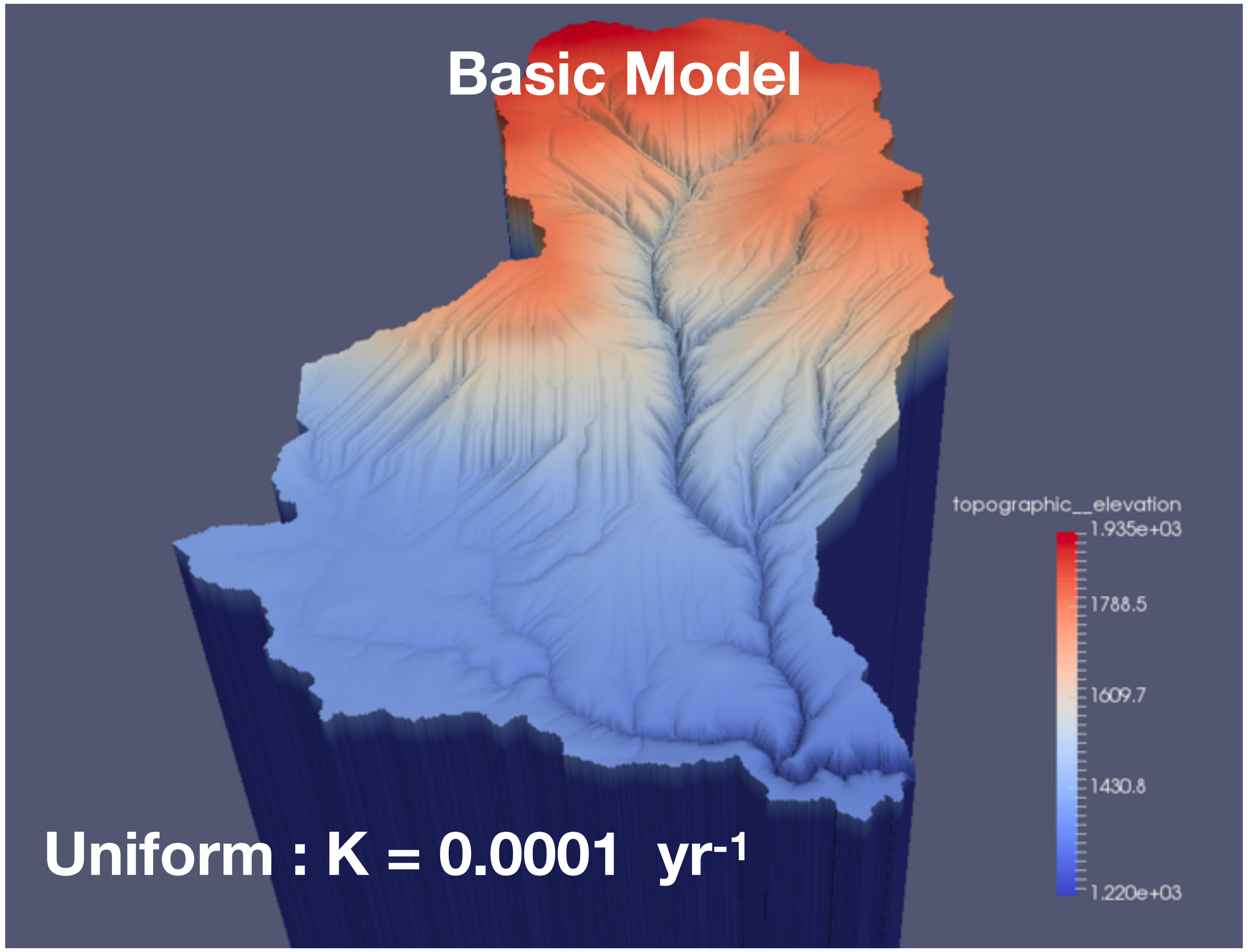
- **Fixed**/Variable area exponent
- Erosion Threshold (Yes/**No**)
- **Stream power**/Shear Stress
- **Constant**/Depth dependent threshold
- **Detachment limited** vs Hybrid Transport and Detachment limited
- Fraction of fines (Yes/**No**)

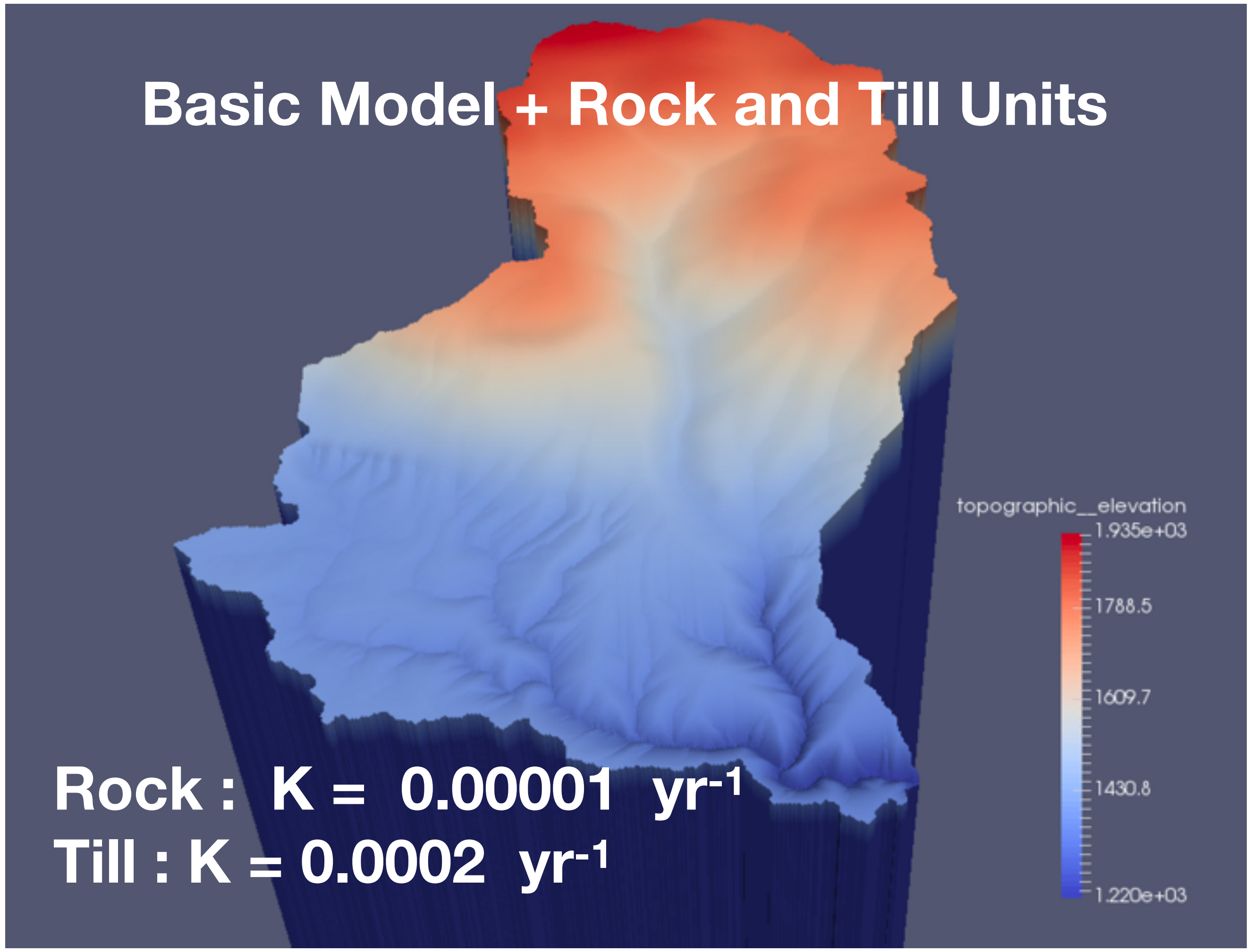
Materials

- Differentiate between soil/ alluvium and rock (Yes/**No**)
- Distinguish between shale bedrock and glacial till (Yes/**No**)

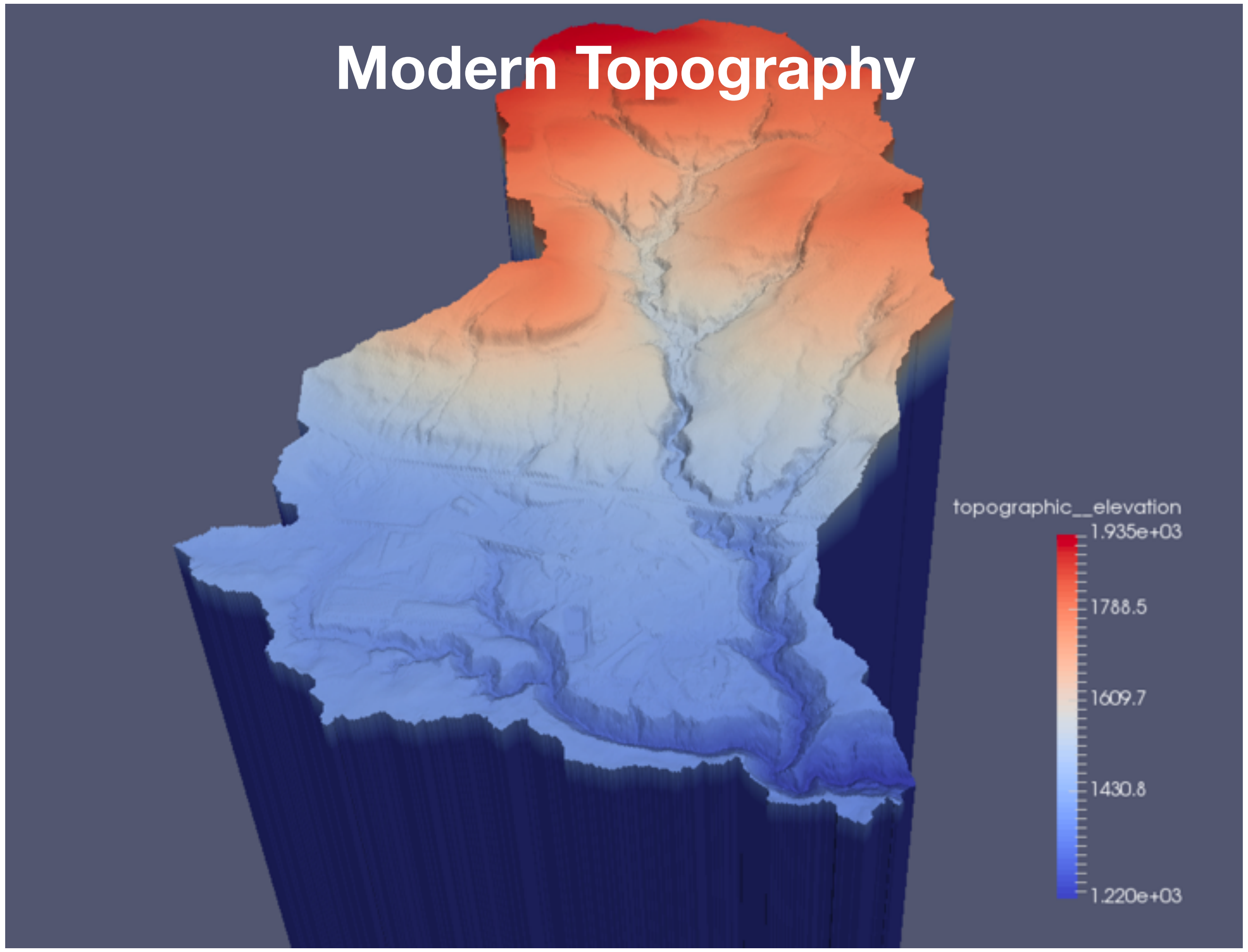
Biggest Improvement:
Differentiate between rock and till

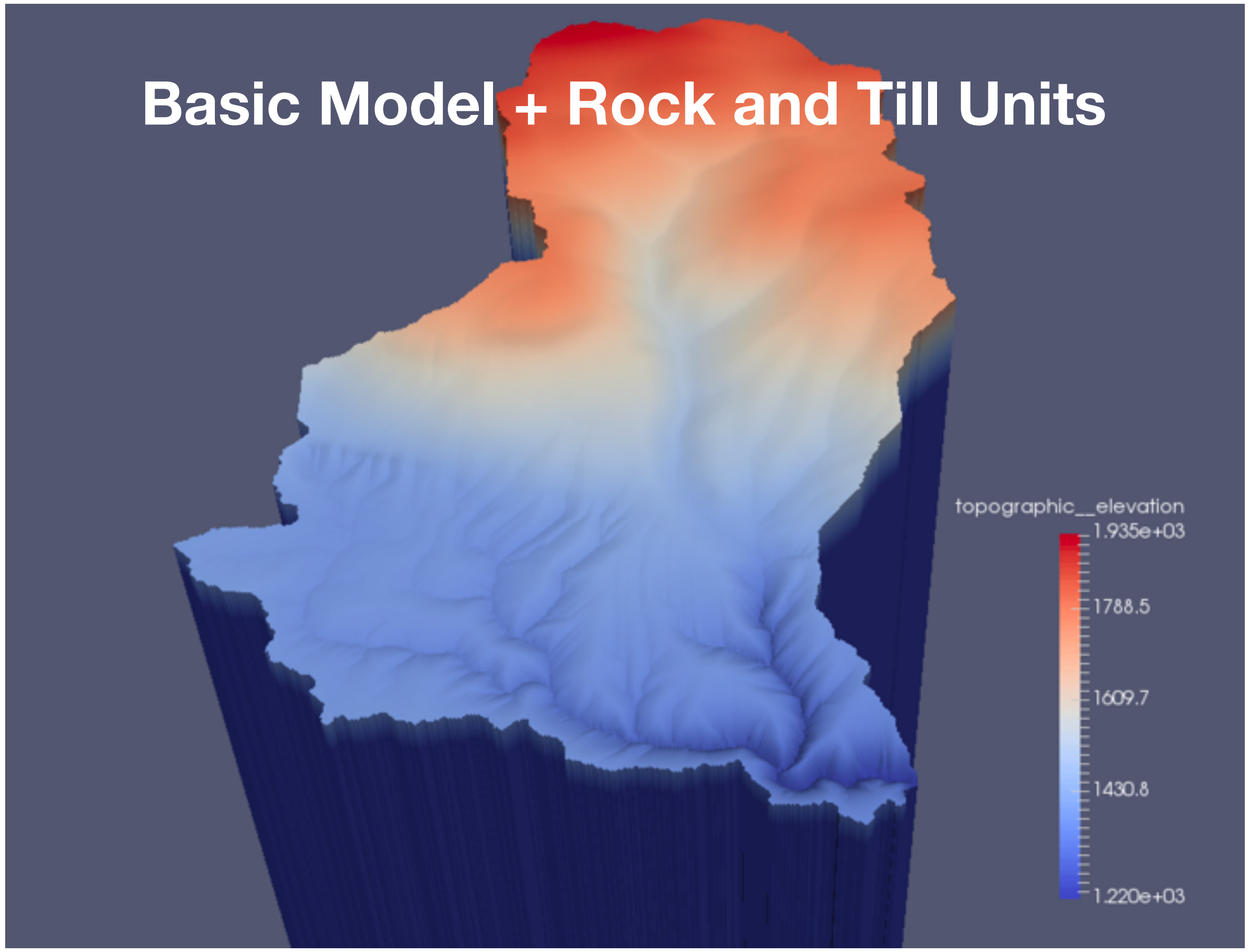


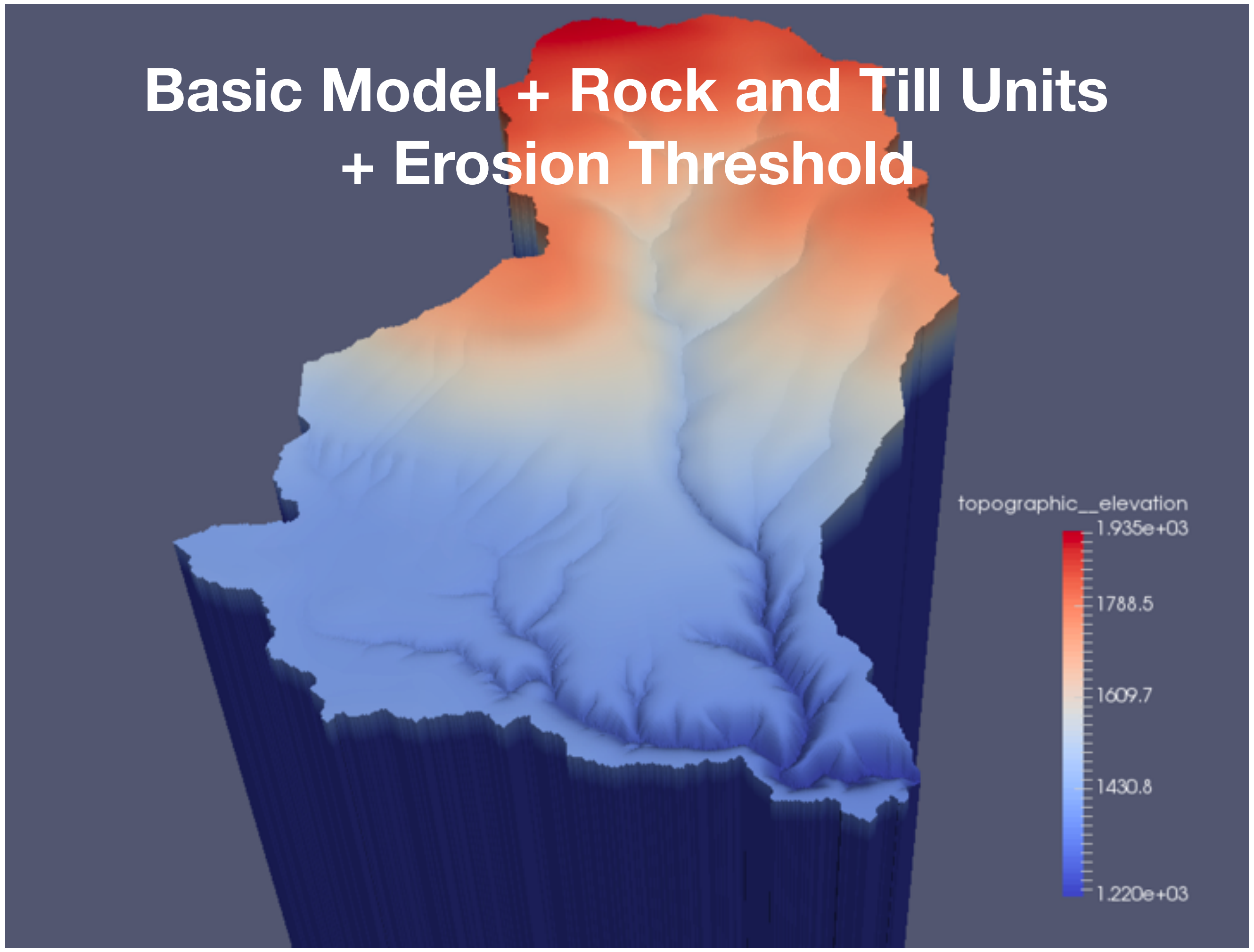




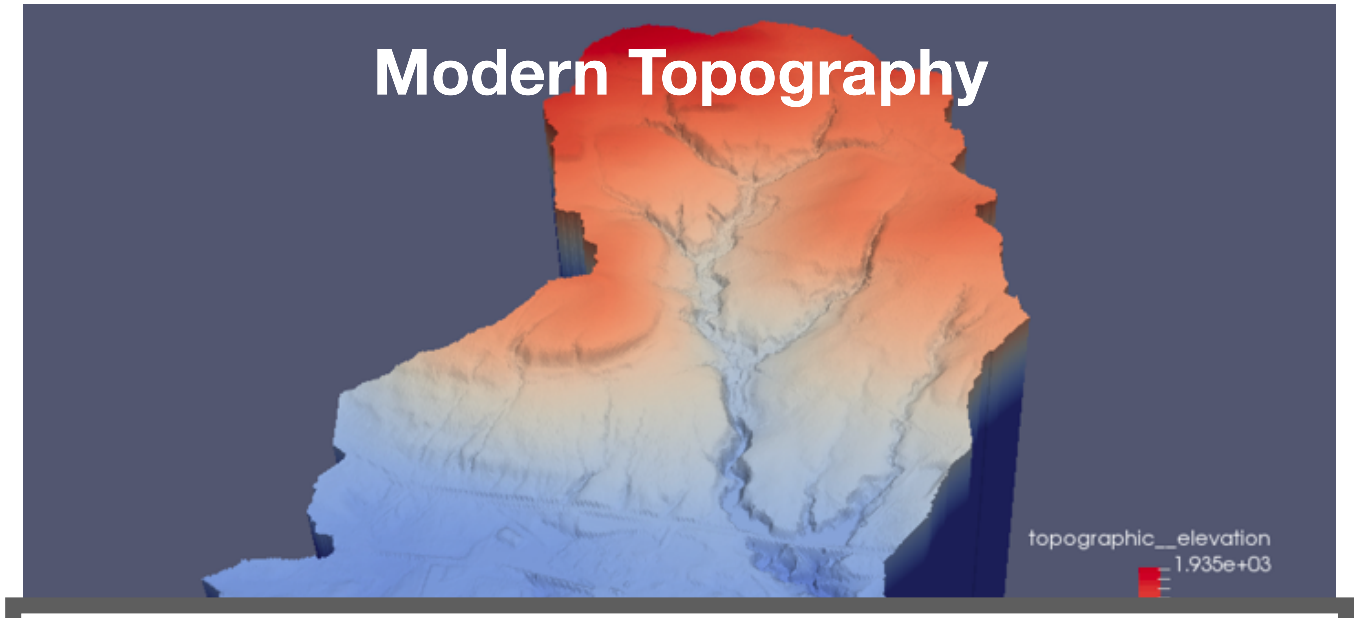
Second Biggest Improvement: Add a fluvial erosion threshold







Third Biggest Improvement: Add non-linear hillslope transport



Channel Erosion

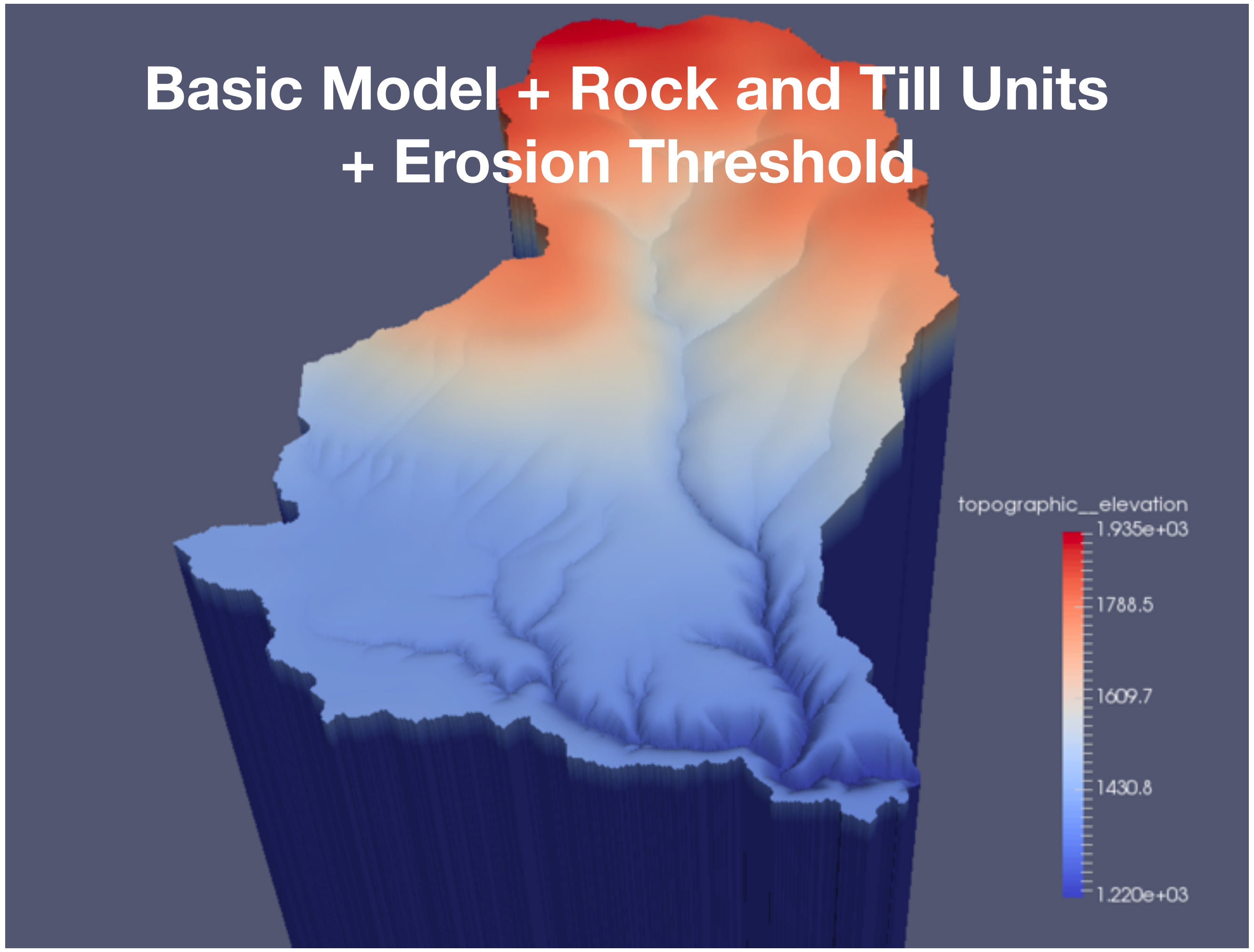
till: $E = 0.00086\,A^{1/2}\,S - 0.06$ m/yr

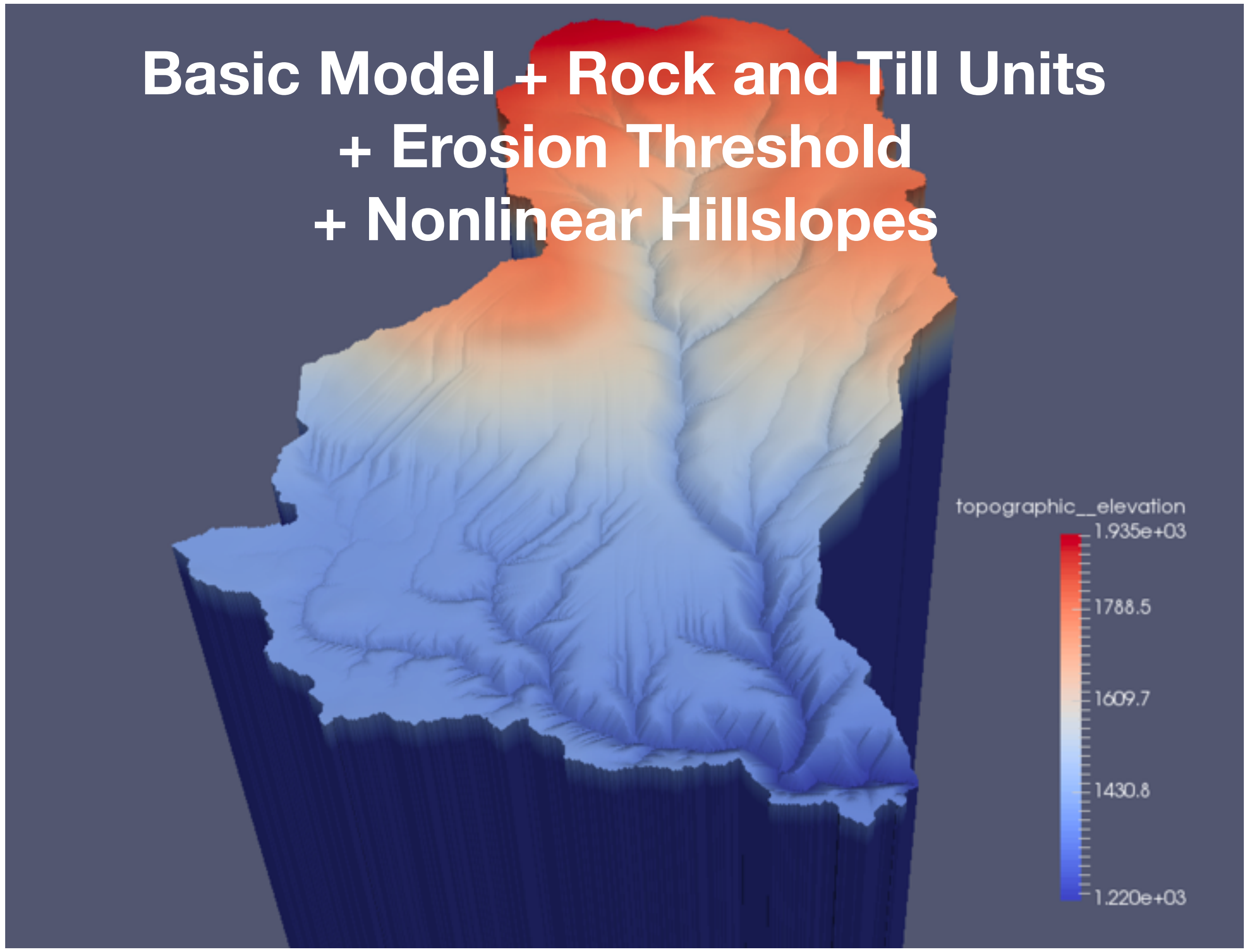
rock: $E = 0.001\,A^{1/2}\,S - 1.56$ m/yr

Hillslope Transport

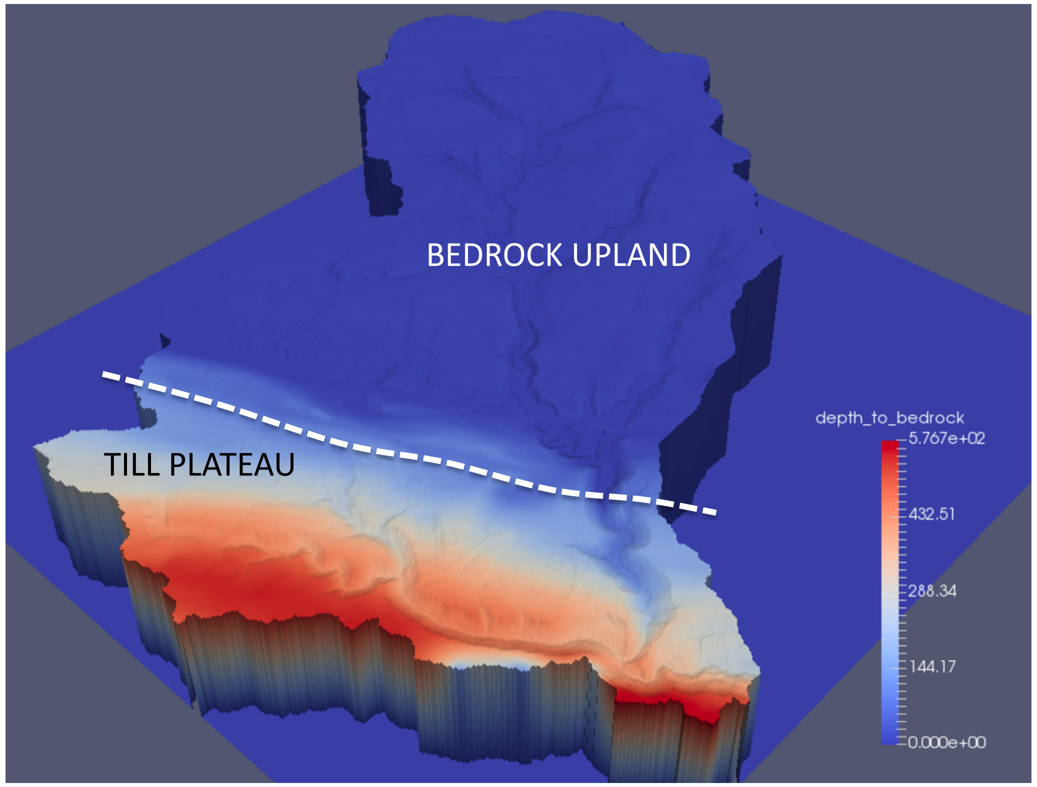
$D = 0.005$ m²/yr

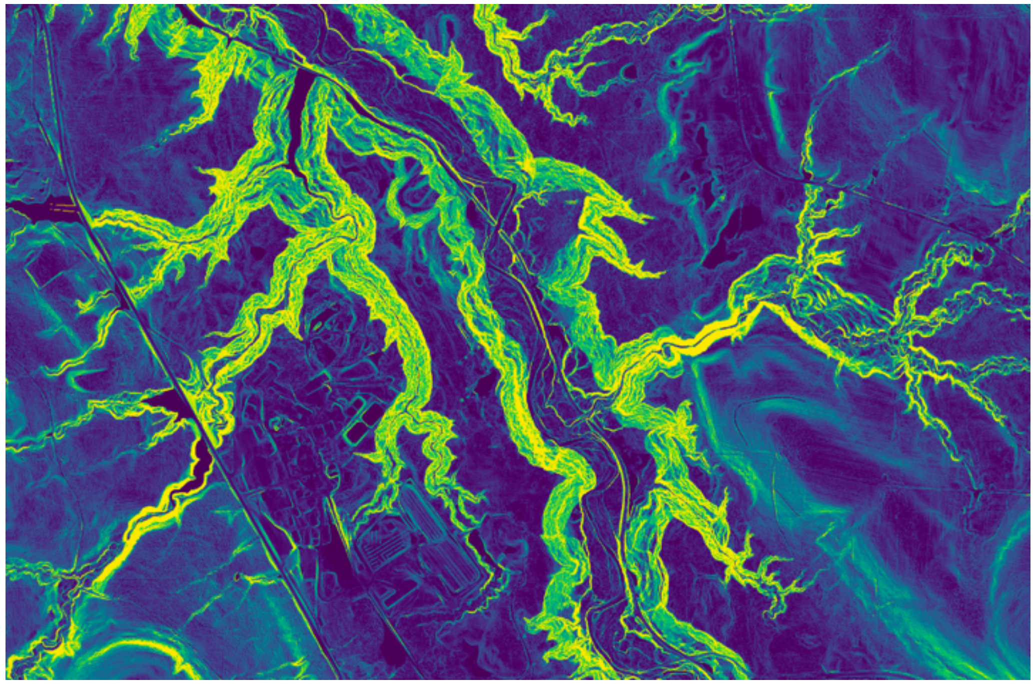
$S_c = 0.38$ (20.6°)





What did we learn from calibration?



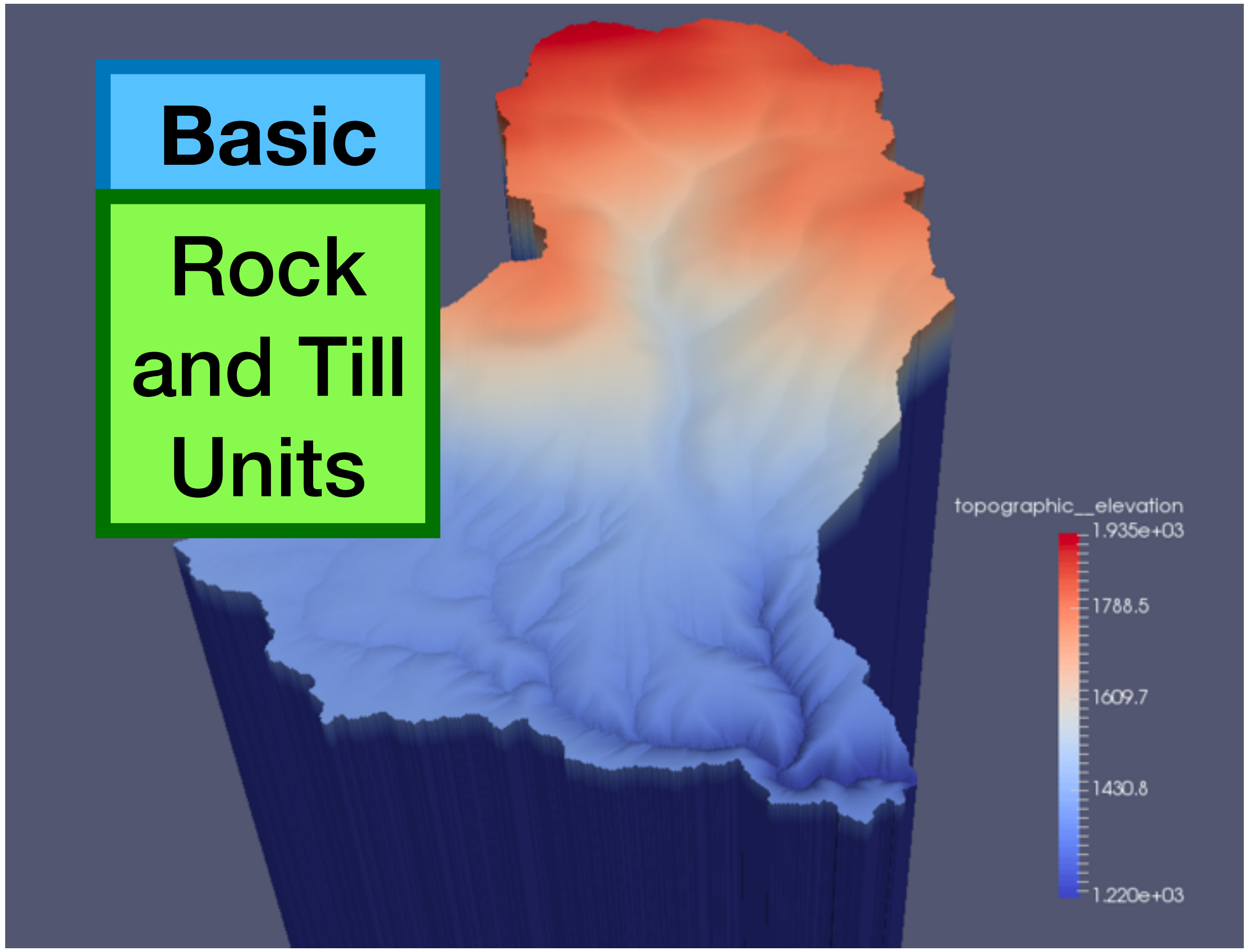


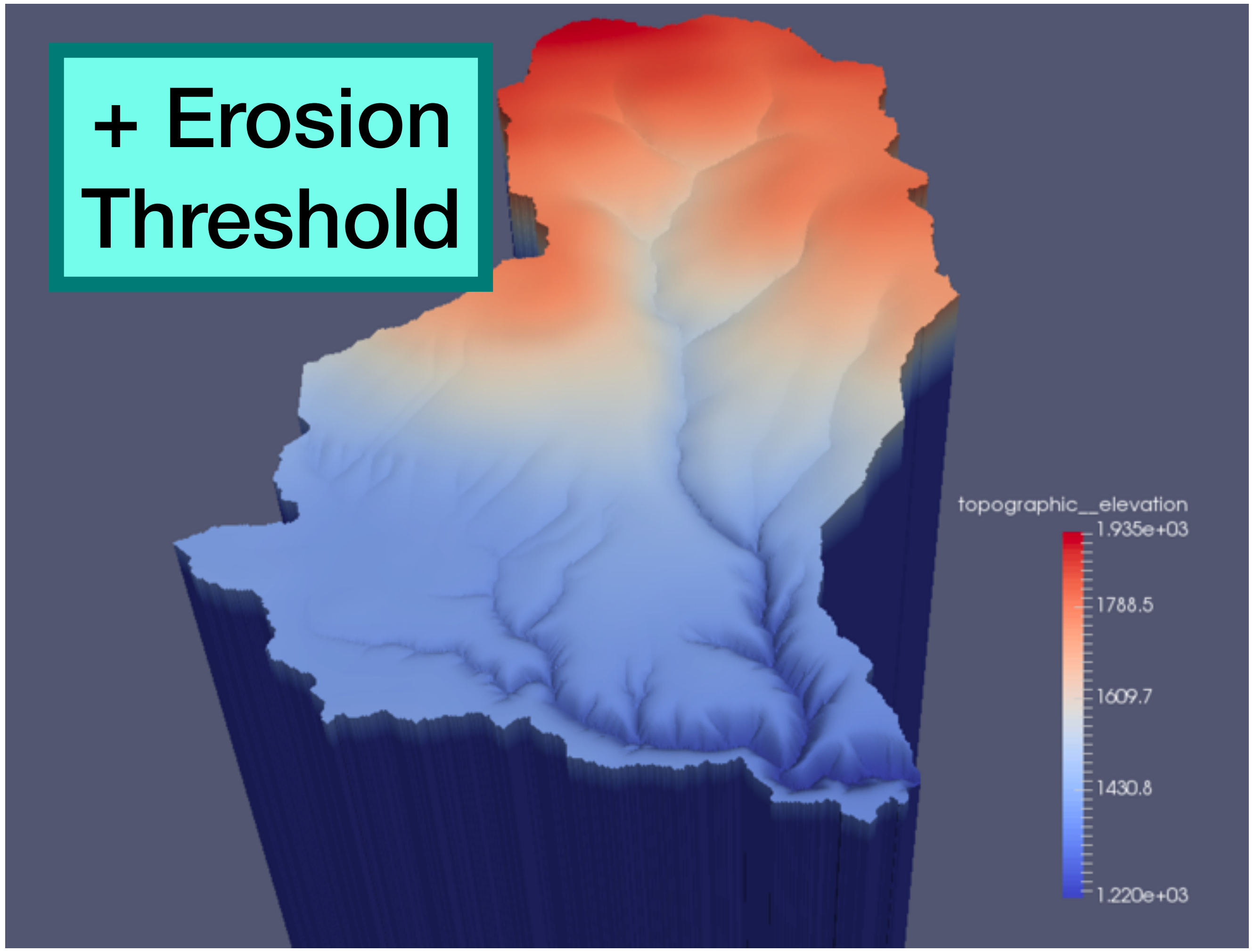
1. Lithology

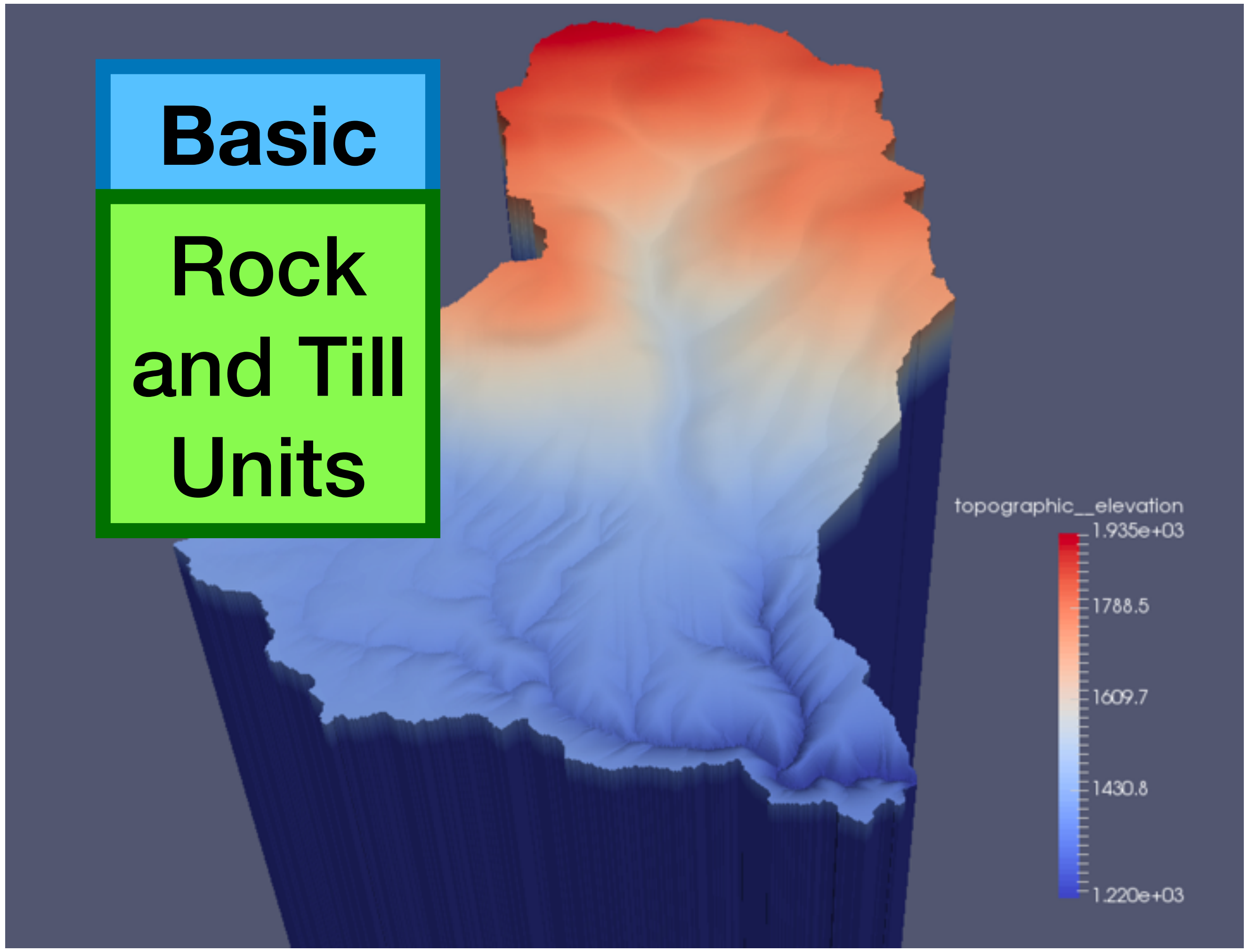
2. Erosion threshold

3. Non linear hillslopes

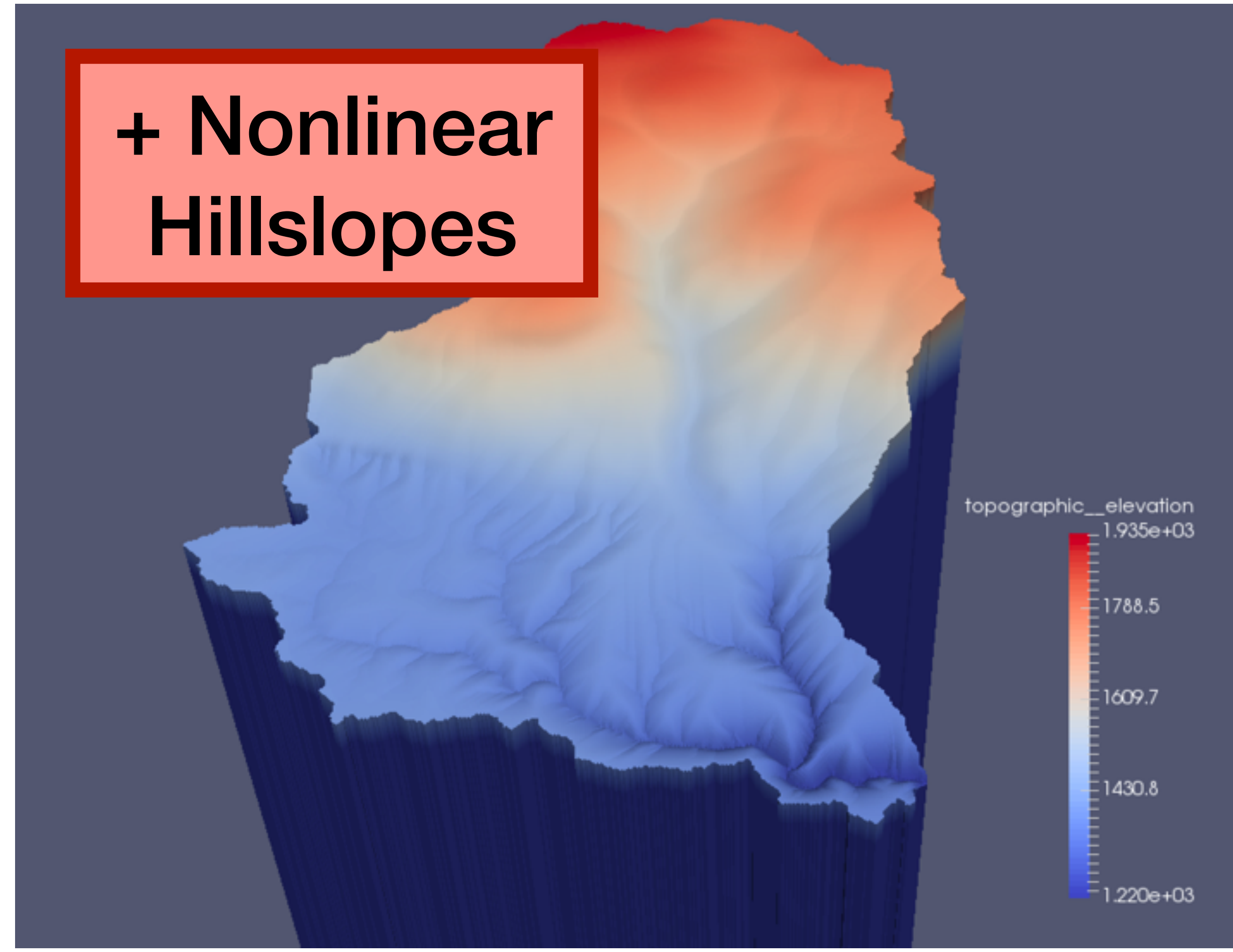
Are these improvements linearly independent?


Basic
Rock and Till Units
topographic__elevation
1.935e+03
1788.5
1609.7
1430.8
1.220e+03

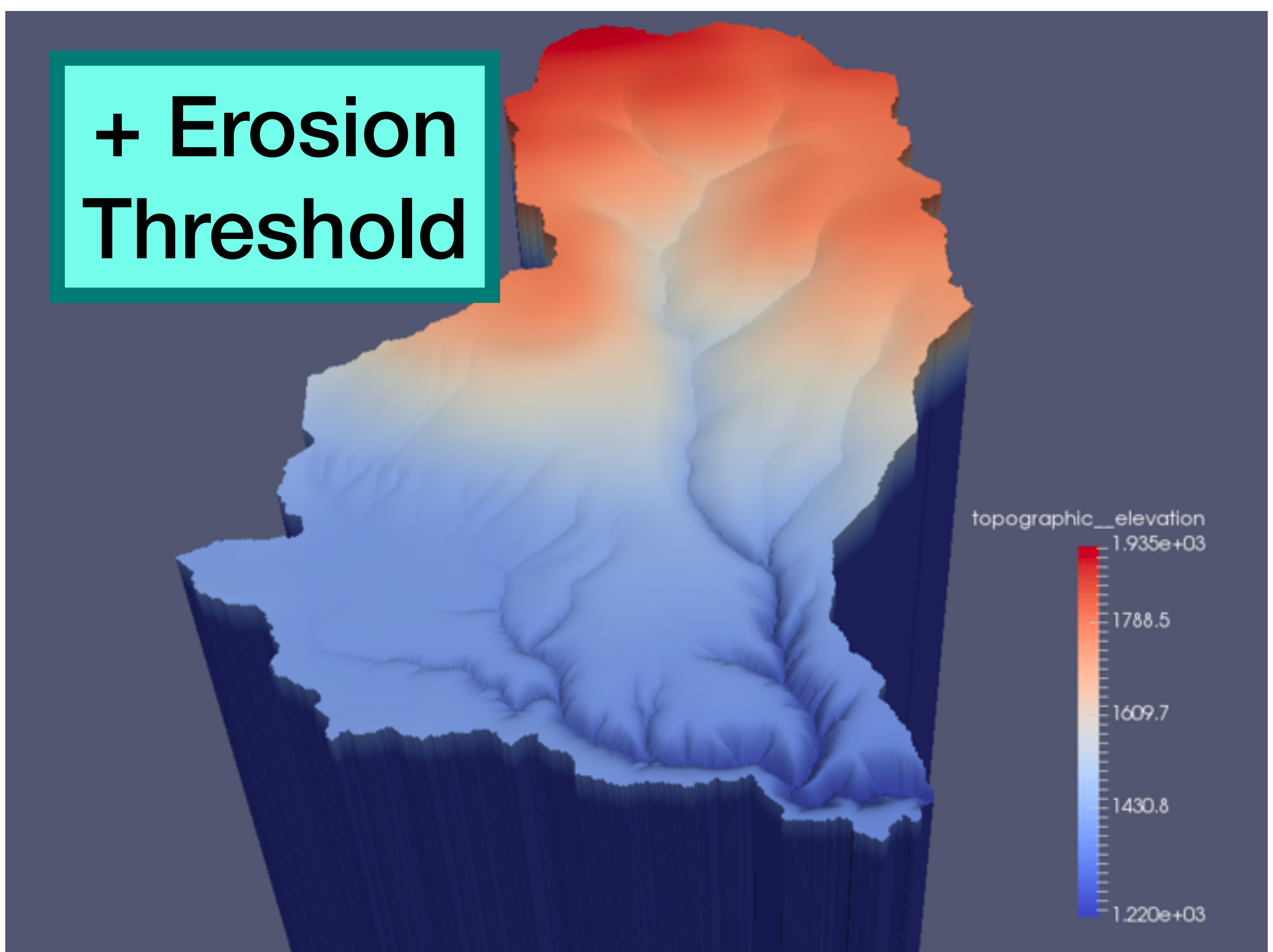

+ Erosion Threshold
topographic__elevation
1.935e+03
1788.5
1609.7
1430.8
1.220e+03



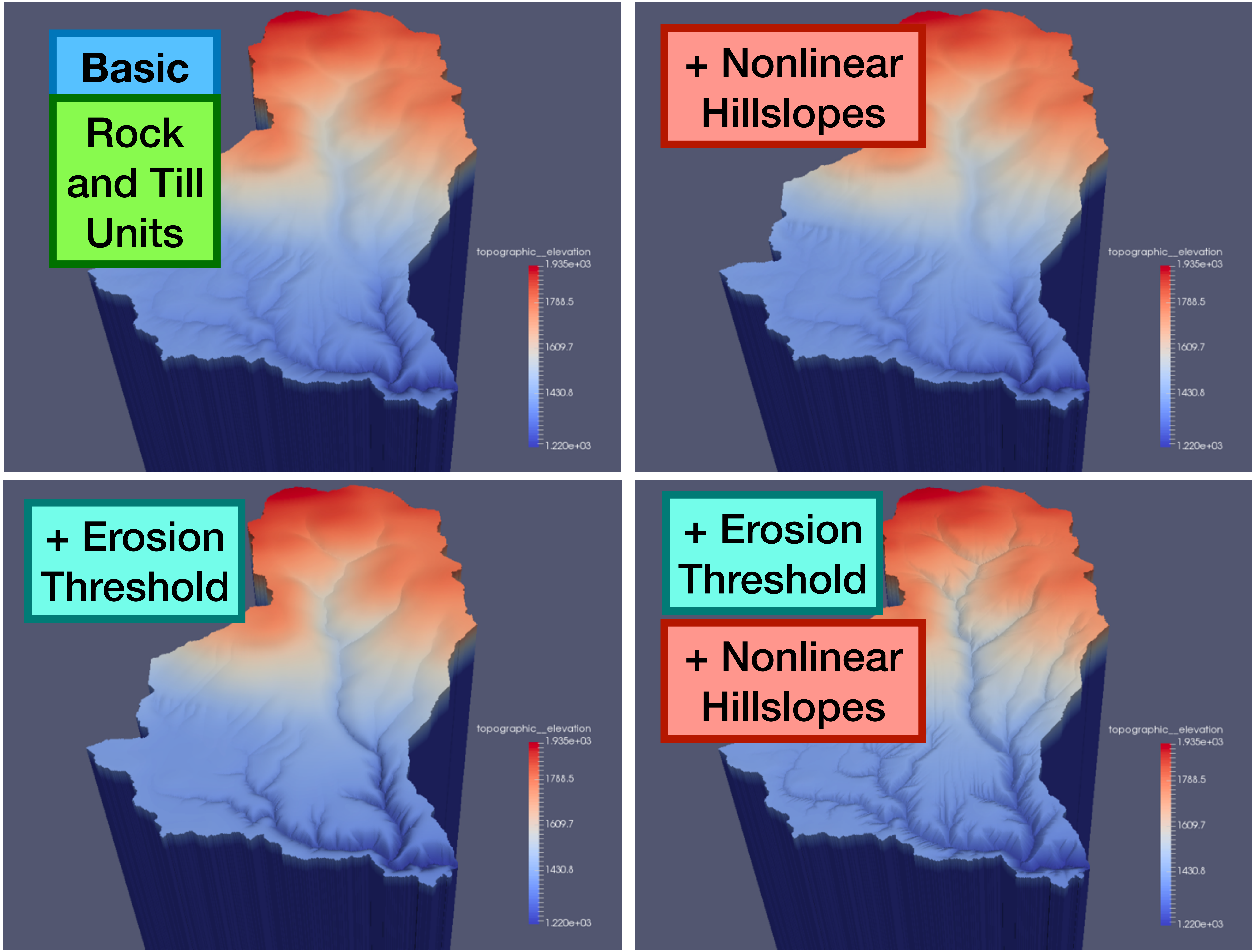
Basic
Rock and Till Units
topographic__elevation
1.935e+03
1788.5
1609.7
1430.8
1.220e+03



+ Nonlinear Hillslopes
topographic__elevation
1.935e+03
1788.5
1609.7
1430.8
1.220e+03

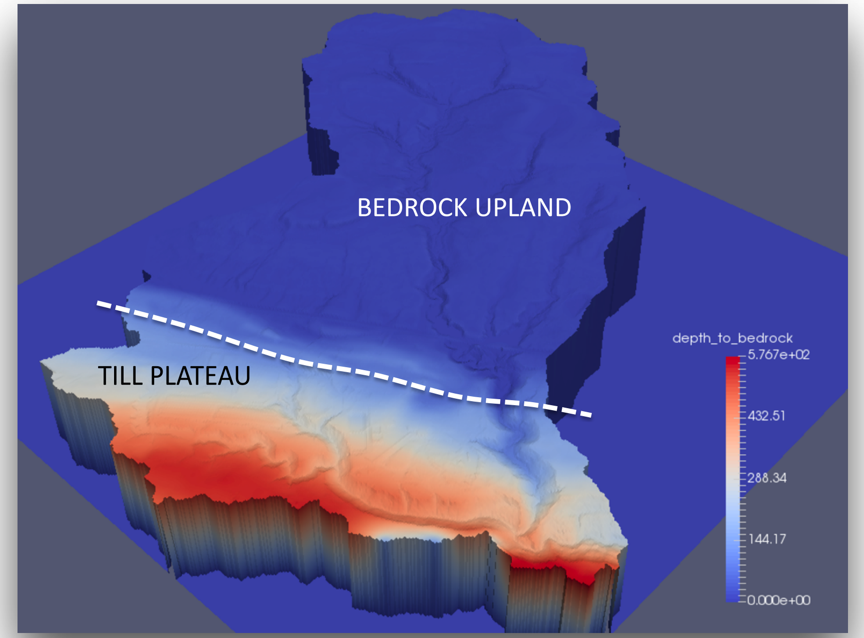


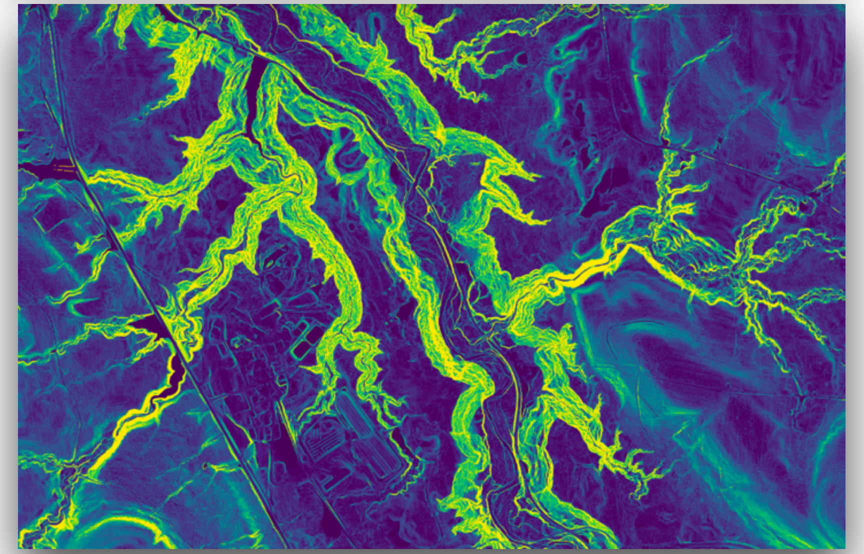
+ Erosion Threshold
topographic__elevation
1.935e+03
1788.5
1609.7
1430.8
1.220e+03

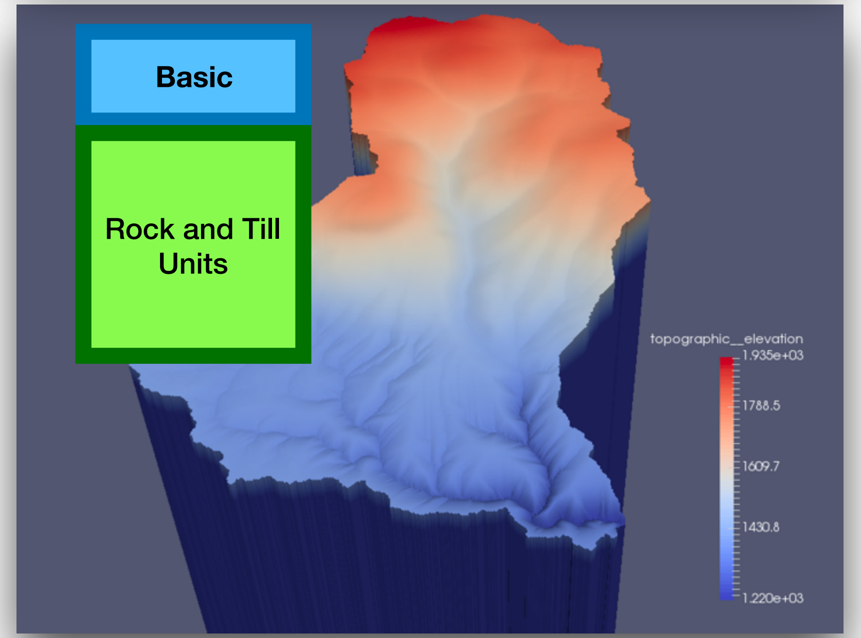

Basic
Rock and Till Units
+ Nonlinear Hillslopes
+ Erosion Threshold
+ Erosion Threshold
+ Nonlinear Hillslopes
topographic__elevation
1.935e+03
1788.5
1609.7
1430.8
1.220e+03

Are these improvements linearly independent?

NO!

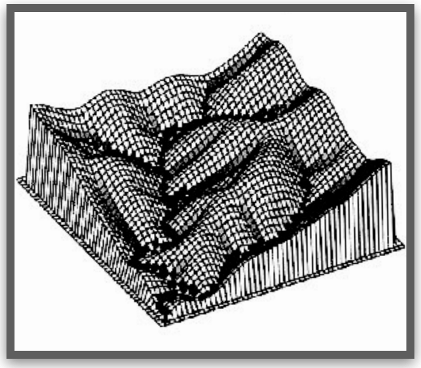




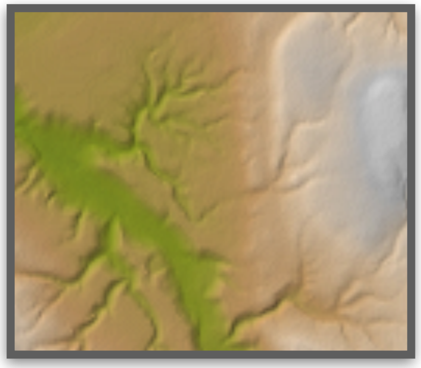


Synthesis

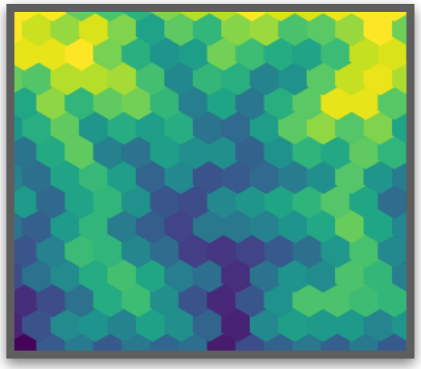
- We can identify what elements of complexity add to model performance with numerical inversion.
- Effects are not linearly independent.
- Results are conditioned on the objective function.



Overview of development and use of Landscape Evolution Models

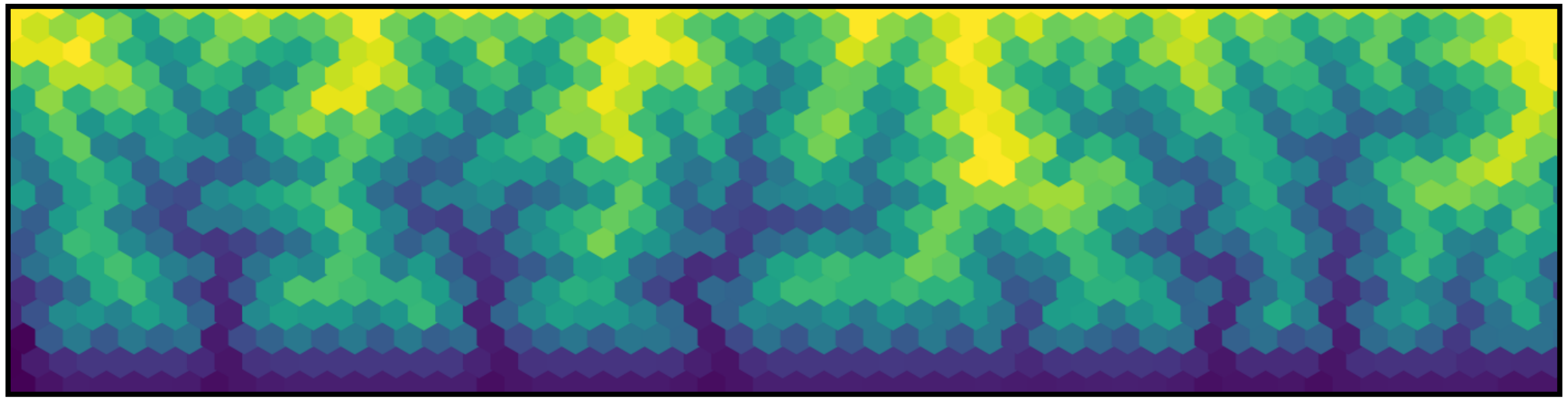


Testing alternative models in a natural experiment of postglacial landscape evolution



Inferring geomorphic and tectonic parameters in a synthetic experiment

What are the limits to inverting topography?



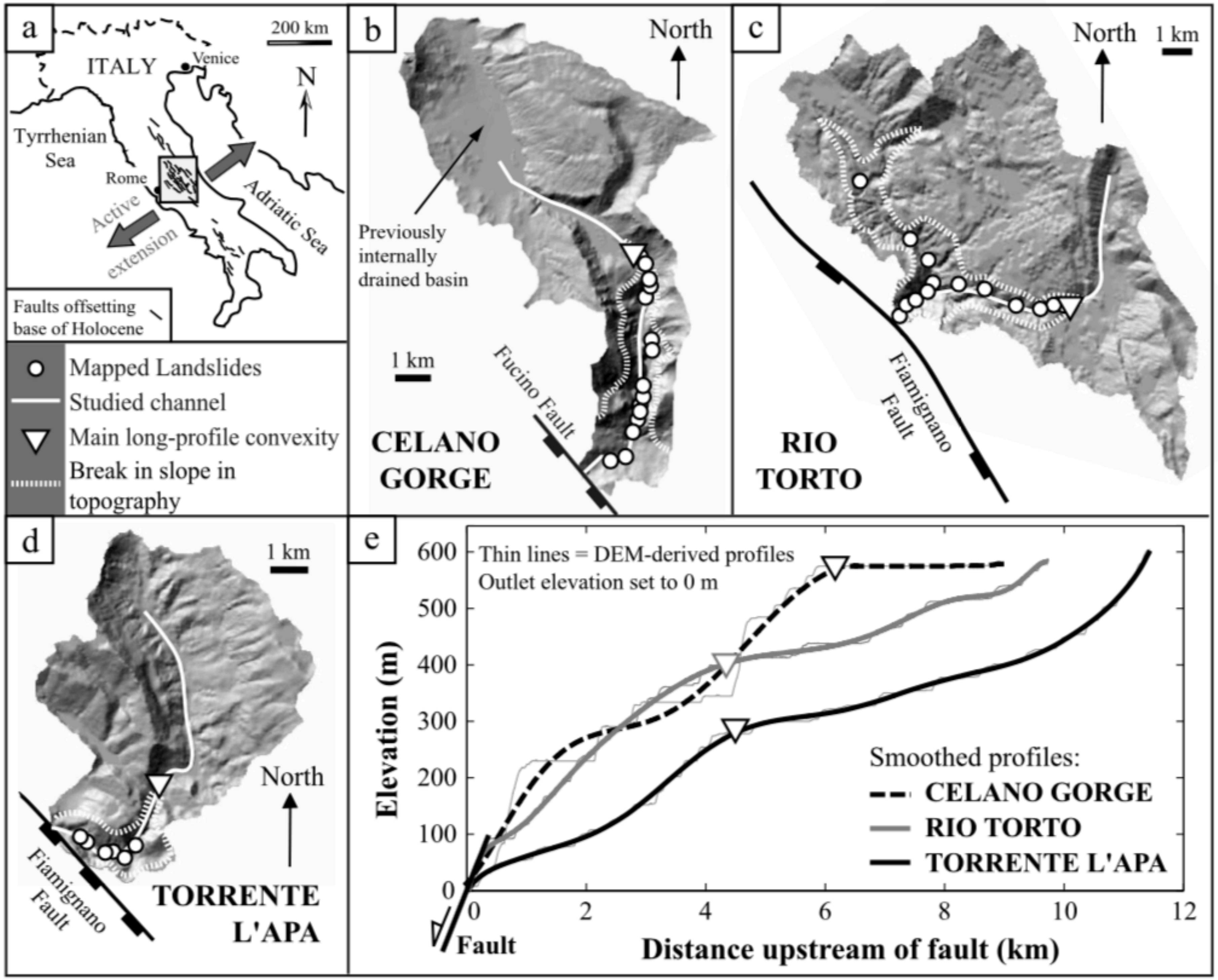


Figure 1. (a) Location map; box shows location of the central Apennines. Shaded topography of the (b) Celano Gorge, (c) Rio Torto, and (d) Torrente l'Apa catchments; mapped landslides, main long-profile convexities along the studied channels, and break in slope in topography delineating steepened landscape are shown. (e) River profiles extracted from the 20 m resolution DEM. Modified after *Whittaker et al.* [2010].

Geomorphic Parameters

- Material strength
- Diffusivity
- Transport length
- Process representation

Tectonic Parameters

- Timing of faulting
- Rate of faulting
- Viscosity of mantle
- Strength of lithosphere

Basic Approach

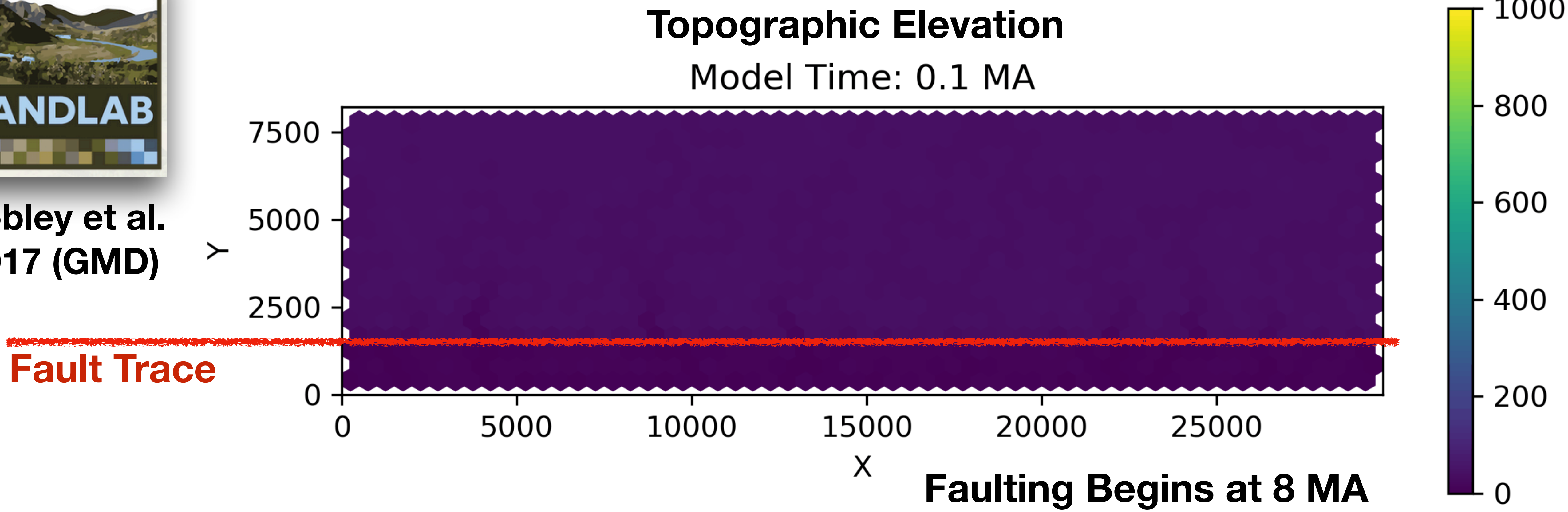
- Create a **synthetic truth** that is a *known model with known parameter values*.

- See if we can recover the true parameter values given a plausible set of parameter ranges.

    - Take away information and/or add noise.

    - How does our ability to recover the **synthetic truth** degrade?

Hobley et al. 2017 (GMD)



- Hexagonal Grid
- Process Components
  - **S**tream **P**ower with **A**lluvium **C**onservation and **E**ntrainment (SPACE, Shobe et al. 2018)
  - Exponentially decaying production of transportable material
- Model runs for 8 MA, then vertical faulting begins

Two Parameters:

Fd : Faulting Duration

0 ⟷ **4 MA**

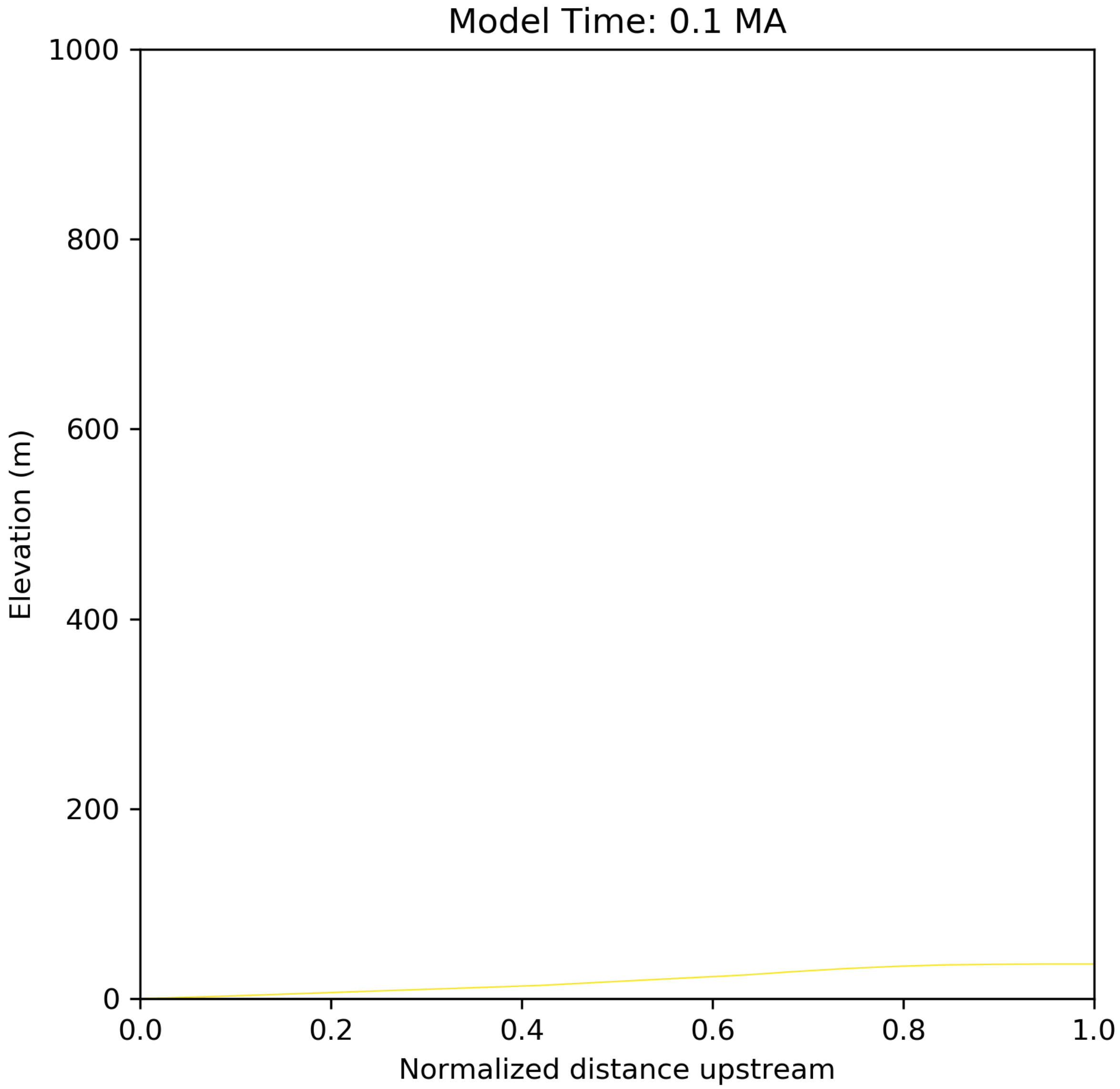
Highly Transient — **Reached new steady state**

Pp : Process Parameter

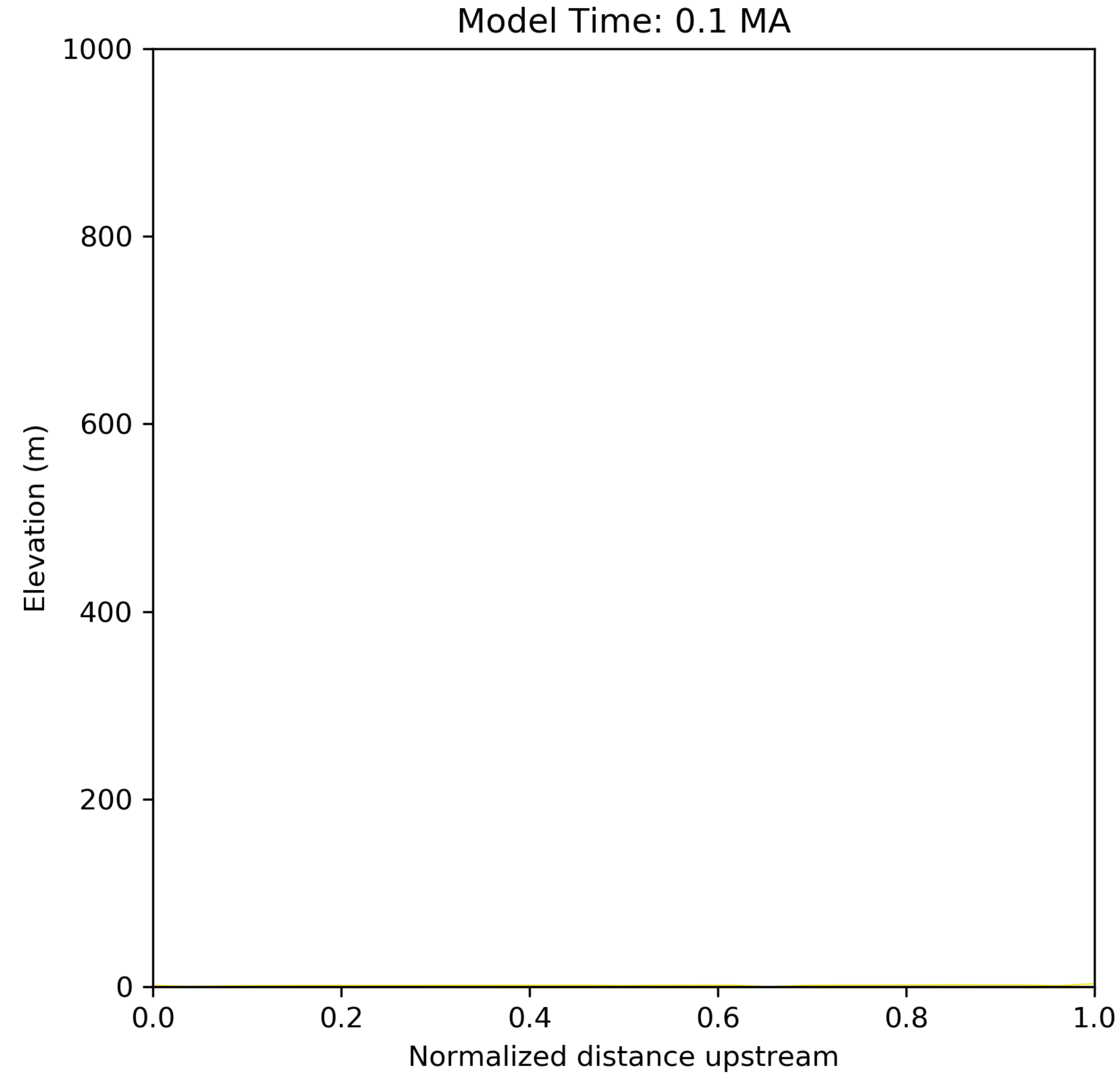
0 ⟷ **1**

Transport Limited — **Detachment Limited**

Transport Limited (Pp = 0)

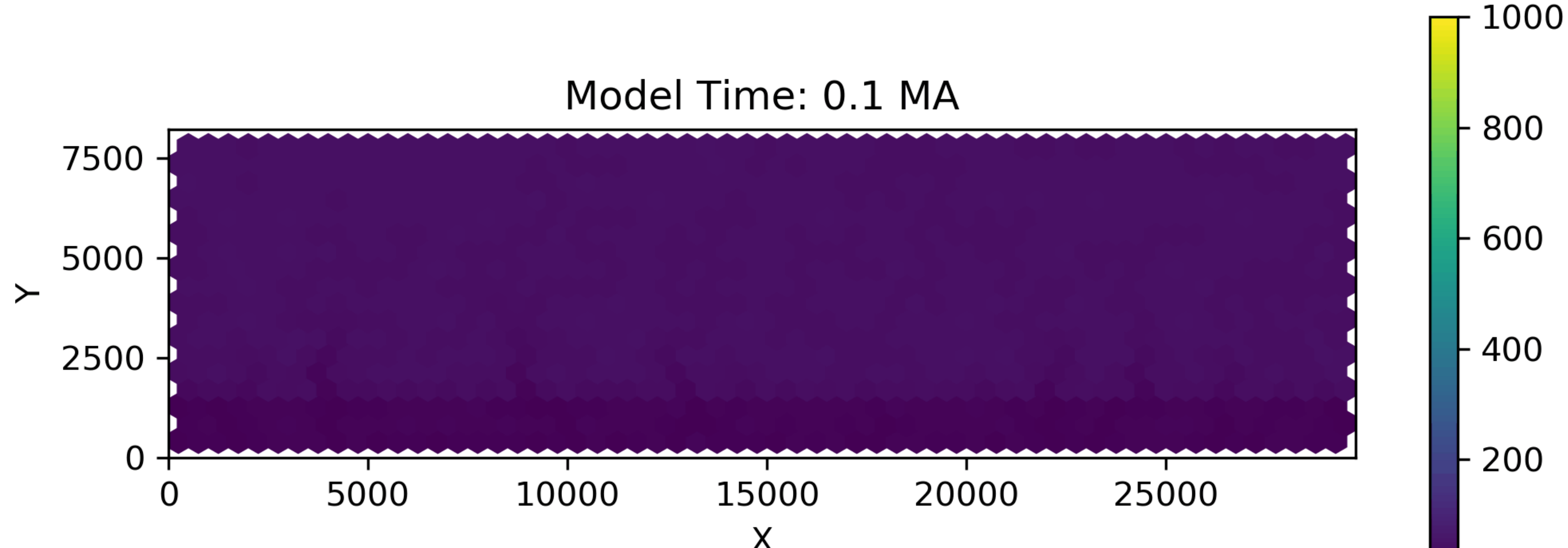


Detachment Limited (Pp = 1)



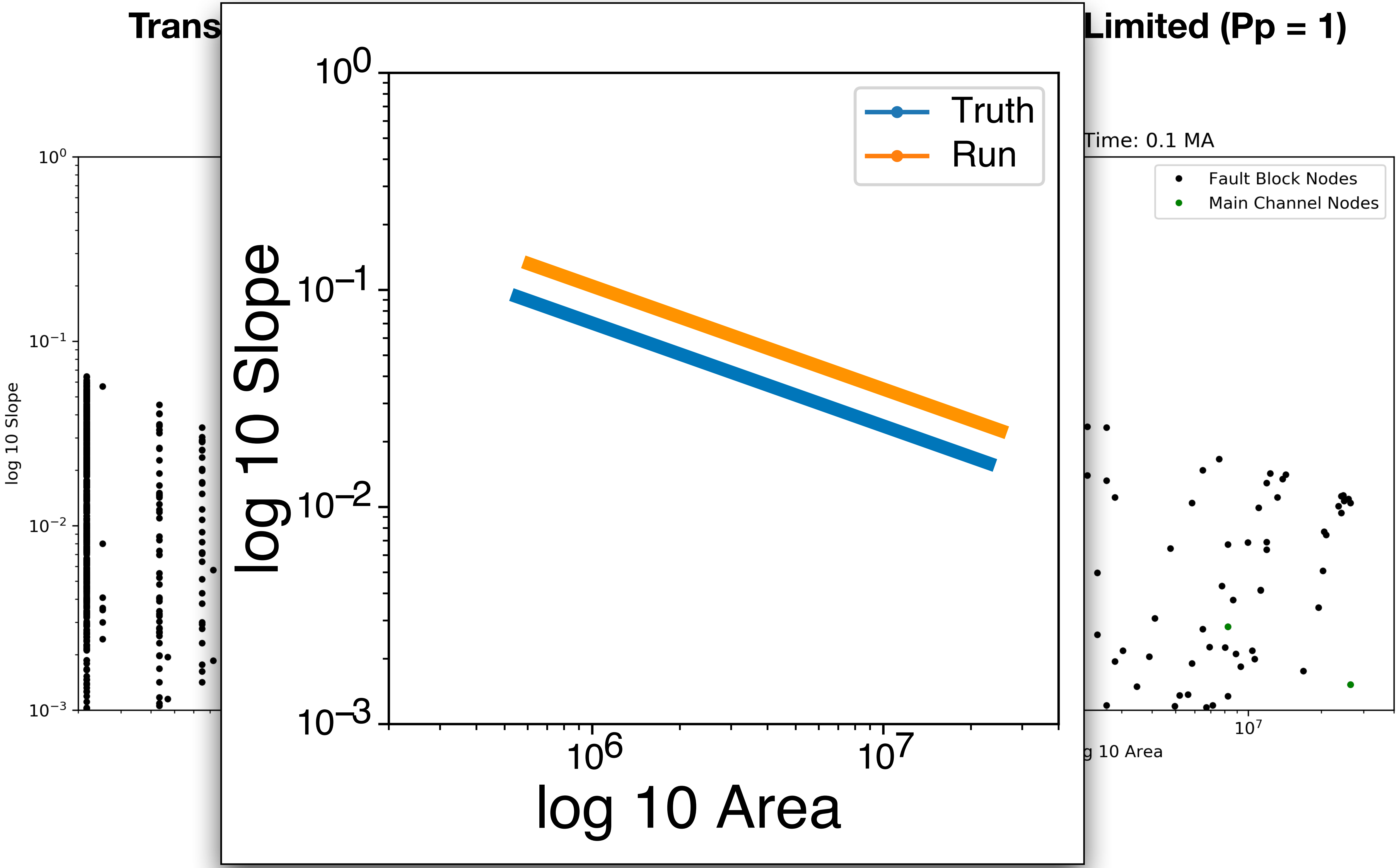
Faulting Begins at 8 MA

Each line shows the profile of the largest channel at 0.1 MA time slices.

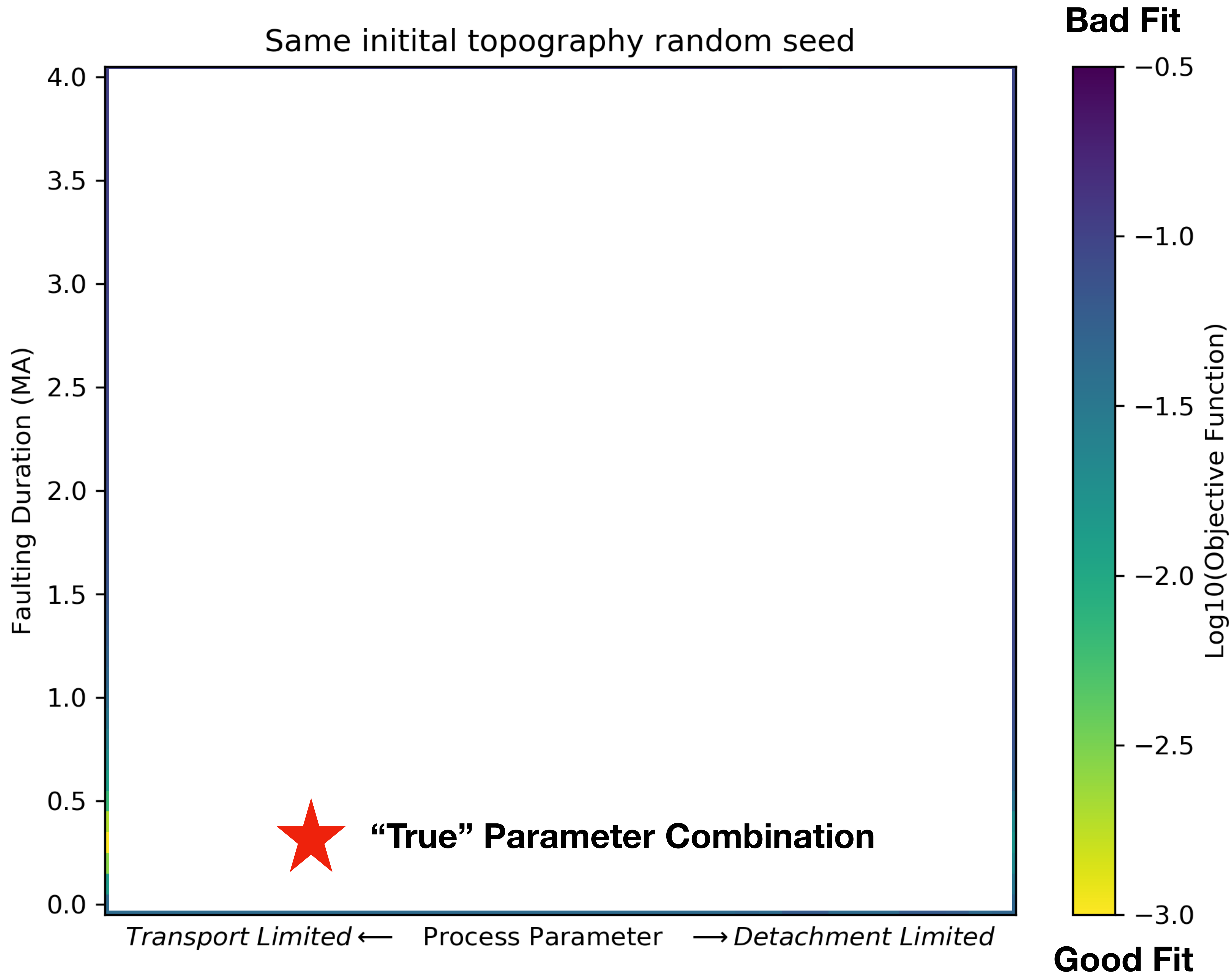


K_{rock} and K_{sed} set so that the equilibrium slope area curves are equivalent

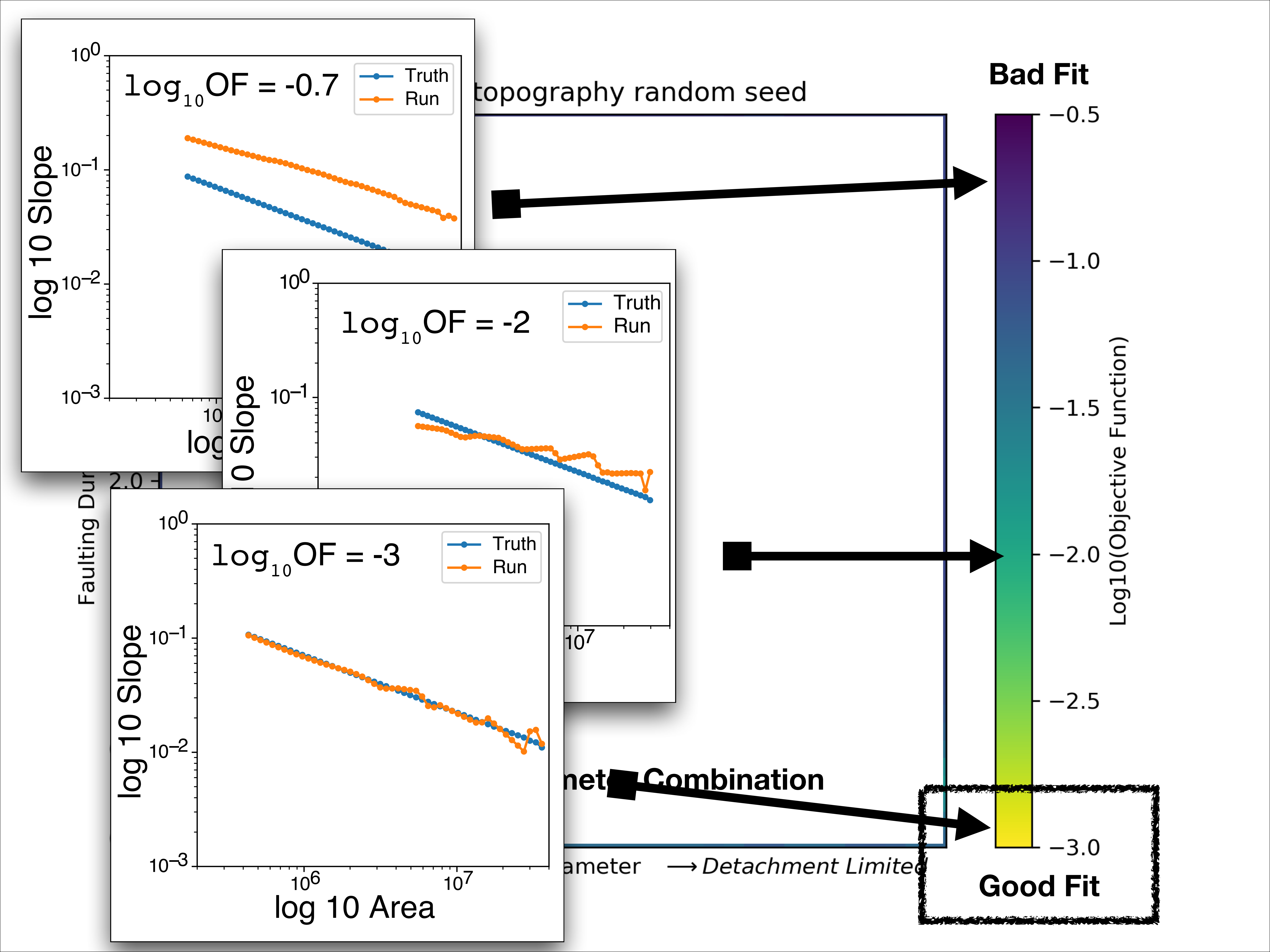
Trans... Limited (Pp = 1)



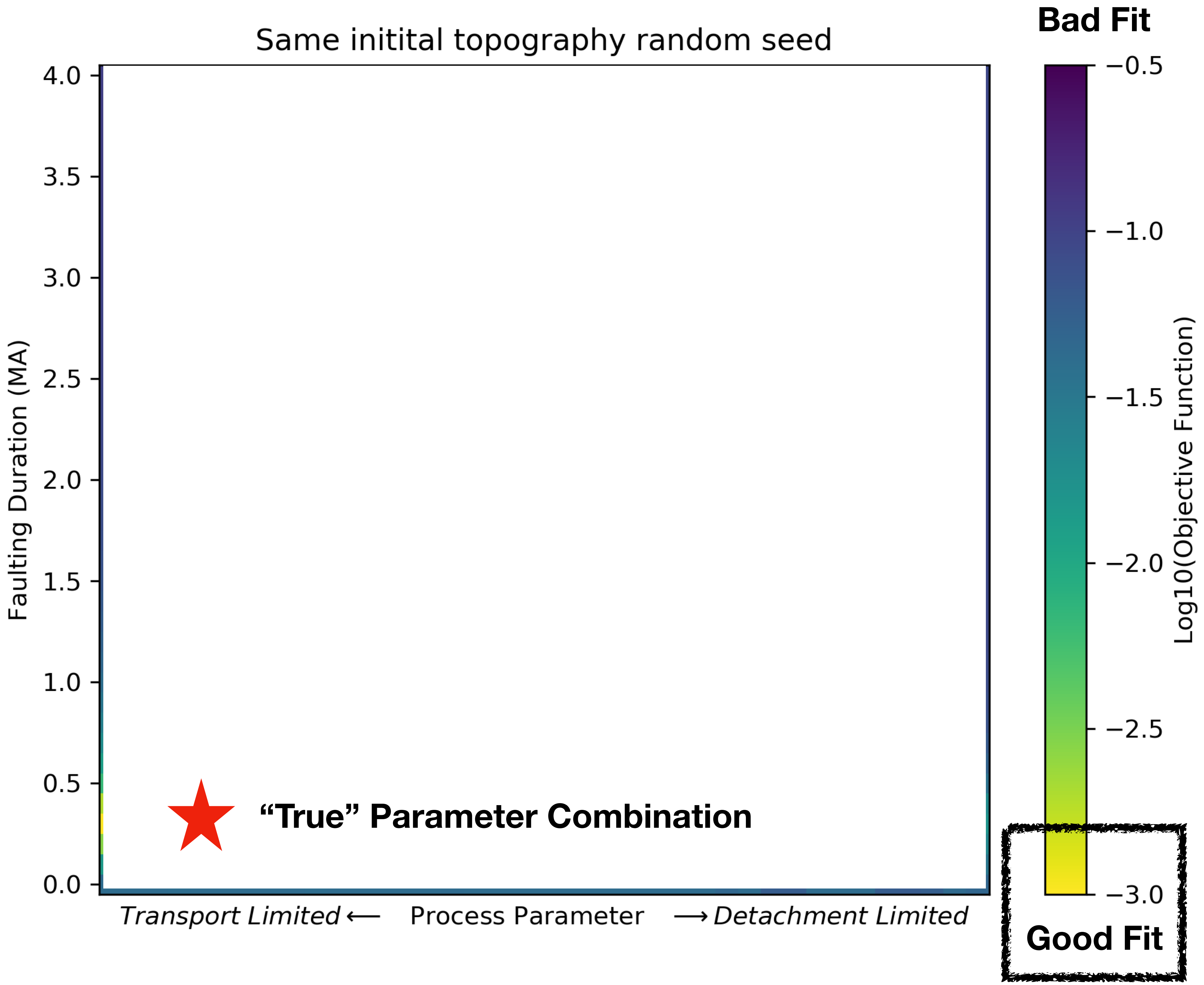
Faulting Begins at 8 MA



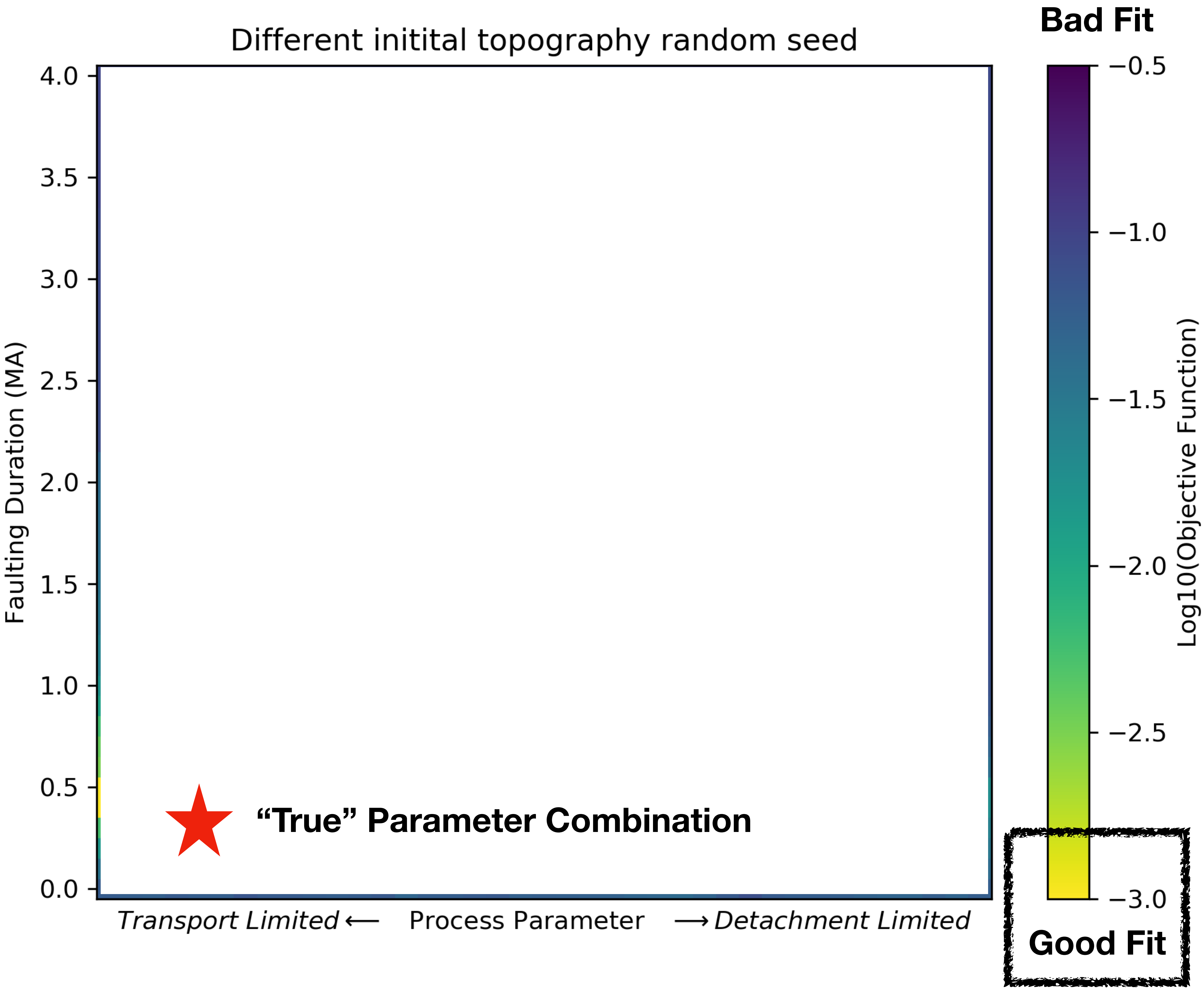
Same initital topography random seed
Bad Fit
Good Fit
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Faulting Duration (MA)
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
Log10(Objective Function)
“True” Parameter Combination
Transport Limited ⟵ Process Parameter ⟶ Detachment Limited



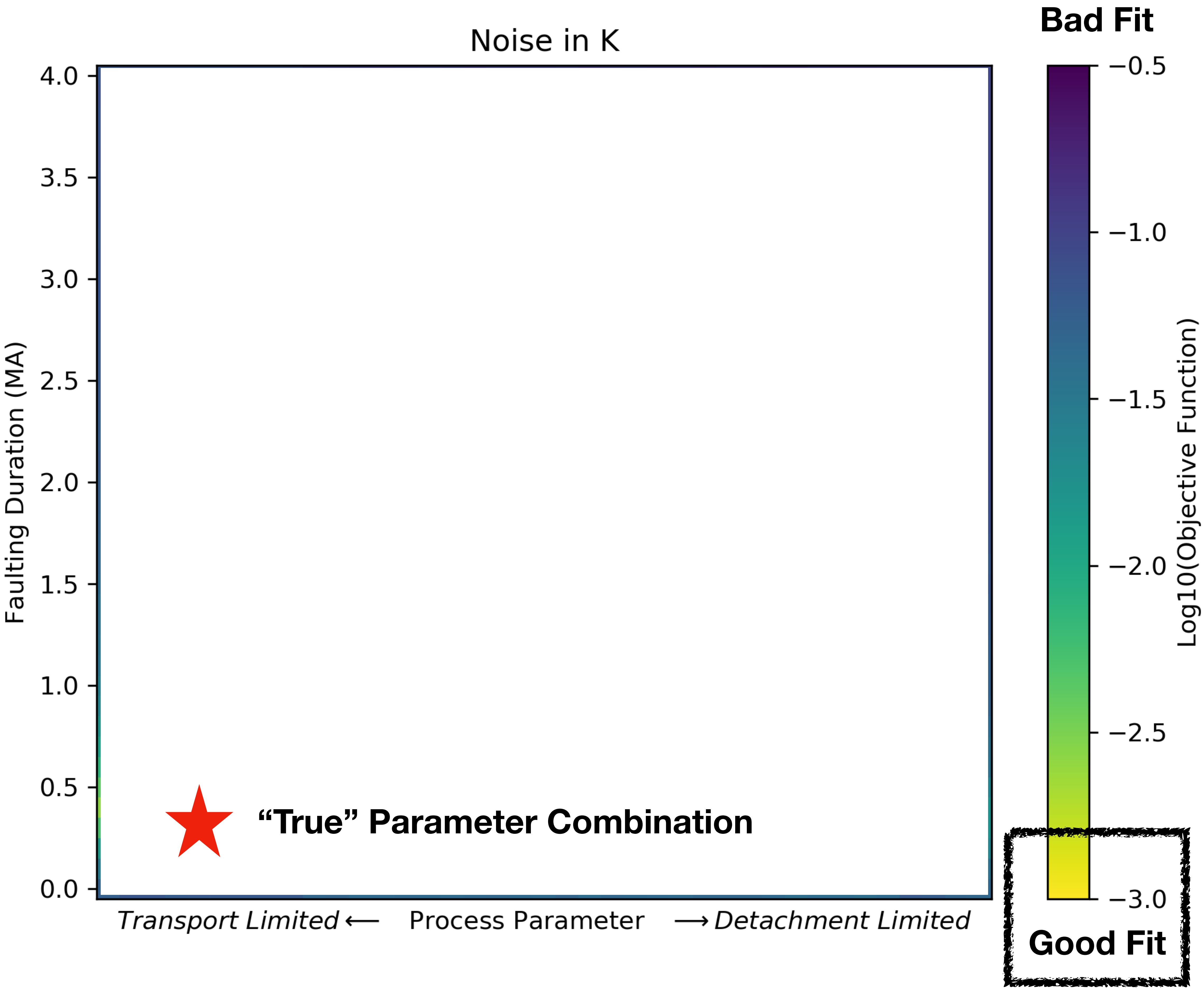
Bad Fit
Good Fit
Log10(Objective Function)
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
topography random seed
Combination
Faulting Du
Detachment Limited
log10OF = -0.7
log10OF = -2
log10OF = -3
Truth
Run
log 10 Slope
log 10 Area



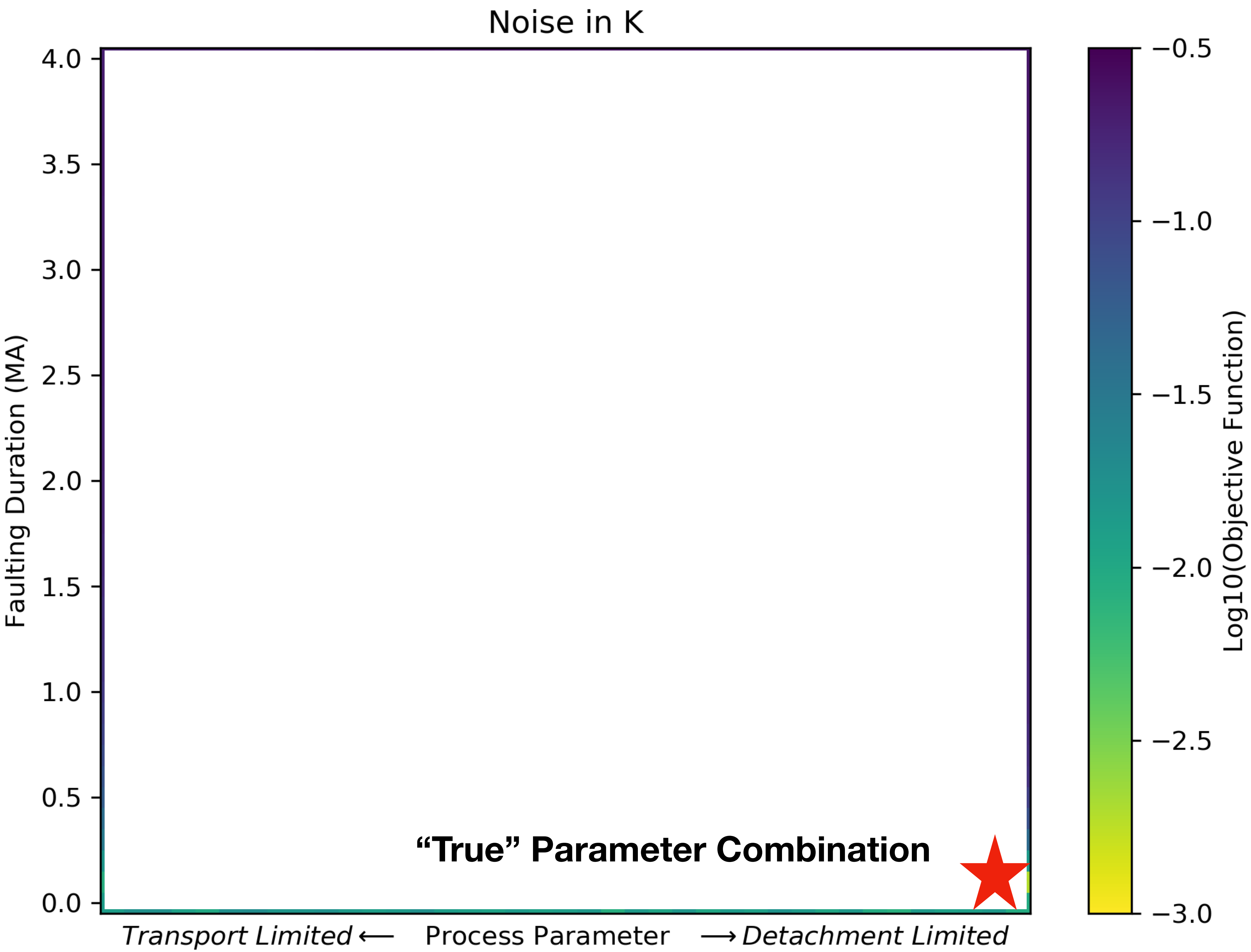
Same initital topography random seed
Faulting Duration (MA)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
“True” Parameter Combination
Transport Limited ⟵ Process Parameter ⟶ Detachment Limited
Bad Fit
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
Good Fit
Log10(Objective Function)

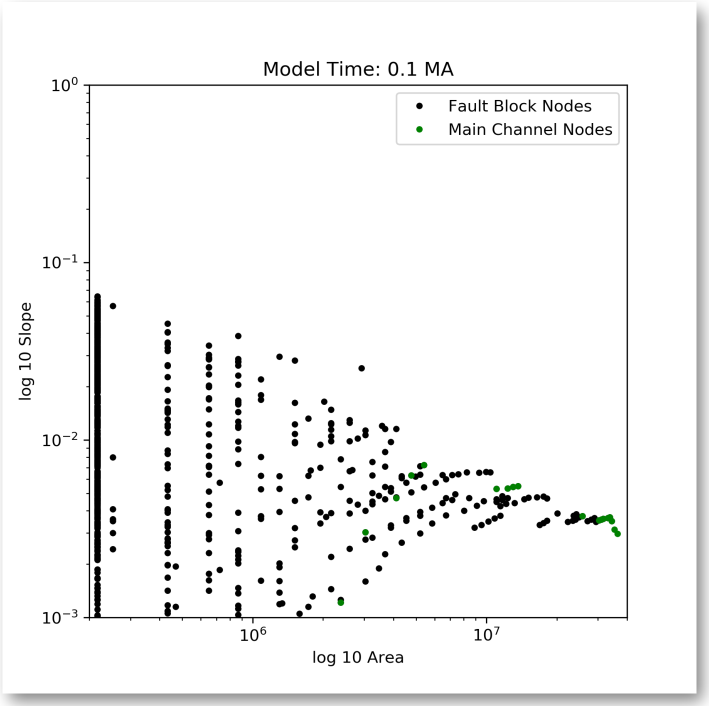


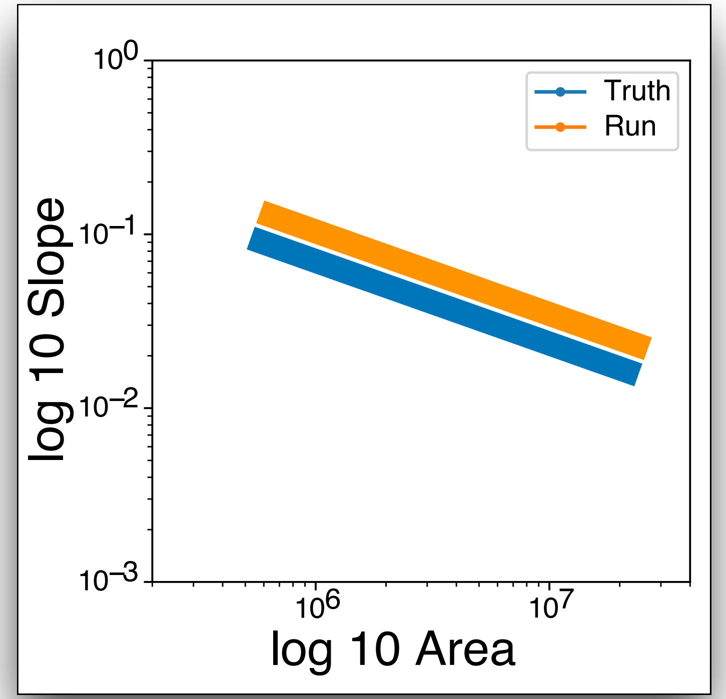
Different initital topography random seed
Faulting Duration (MA)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
"True" Parameter Combination
Transport Limited ⟵ Process Parameter ⟶ Detachment Limited
Bad Fit
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
Log10(Objective Function)
Good Fit

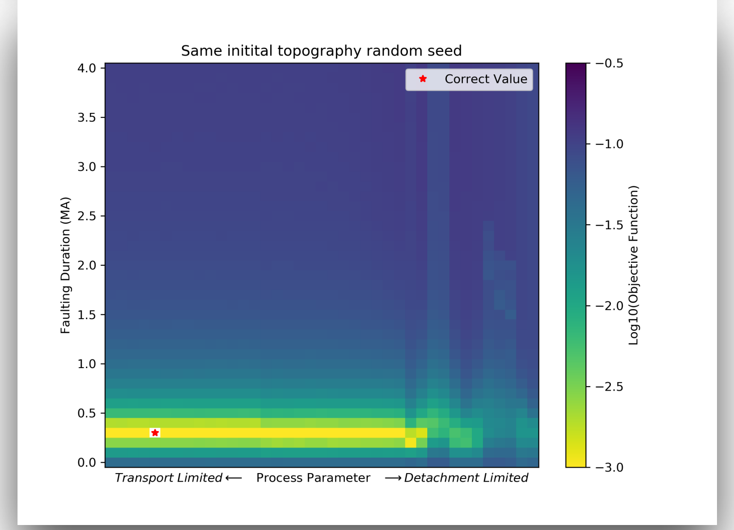


Bad Fit
Noise in K
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Faulting Duration (MA)
"True" Parameter Combination
Transport Limited ⟵ Process Parameter ⟶ Detachment Limited
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
Log10(Objective Function)
Good Fit


Noise in K
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Faulting Duration (MA)
"True" Parameter Combination
Transport Limited ⟵ Process Parameter ⟶ Detachment Limited
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
Log10(Objective Function)

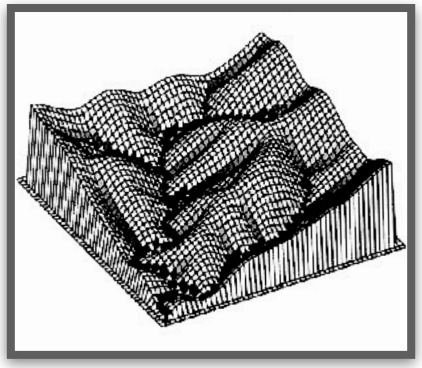




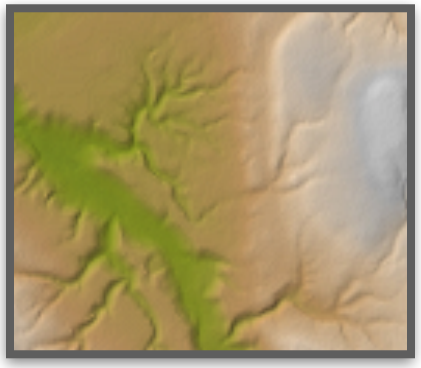


Synthesis

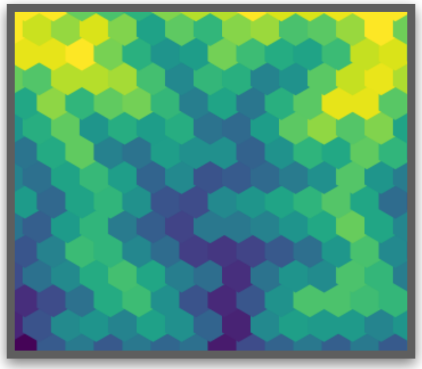
- Synthetic experiments can place constrain on where we can and cant expect inversion to work
- More complex objective functions that include other data (e.g. thermochronology) have been applied and could be tested in this framework.



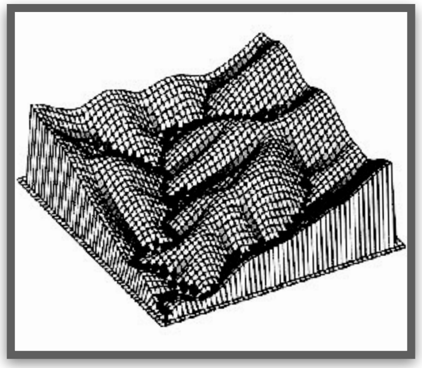
- We can use topography to invert for process.

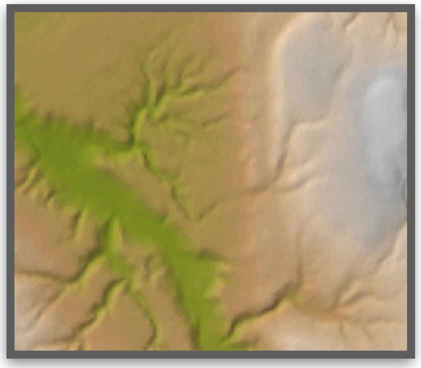


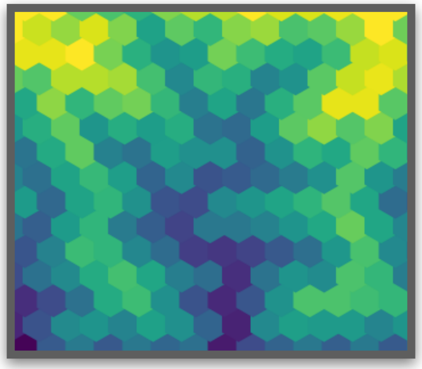
- Additional model elements are not linearly additive.



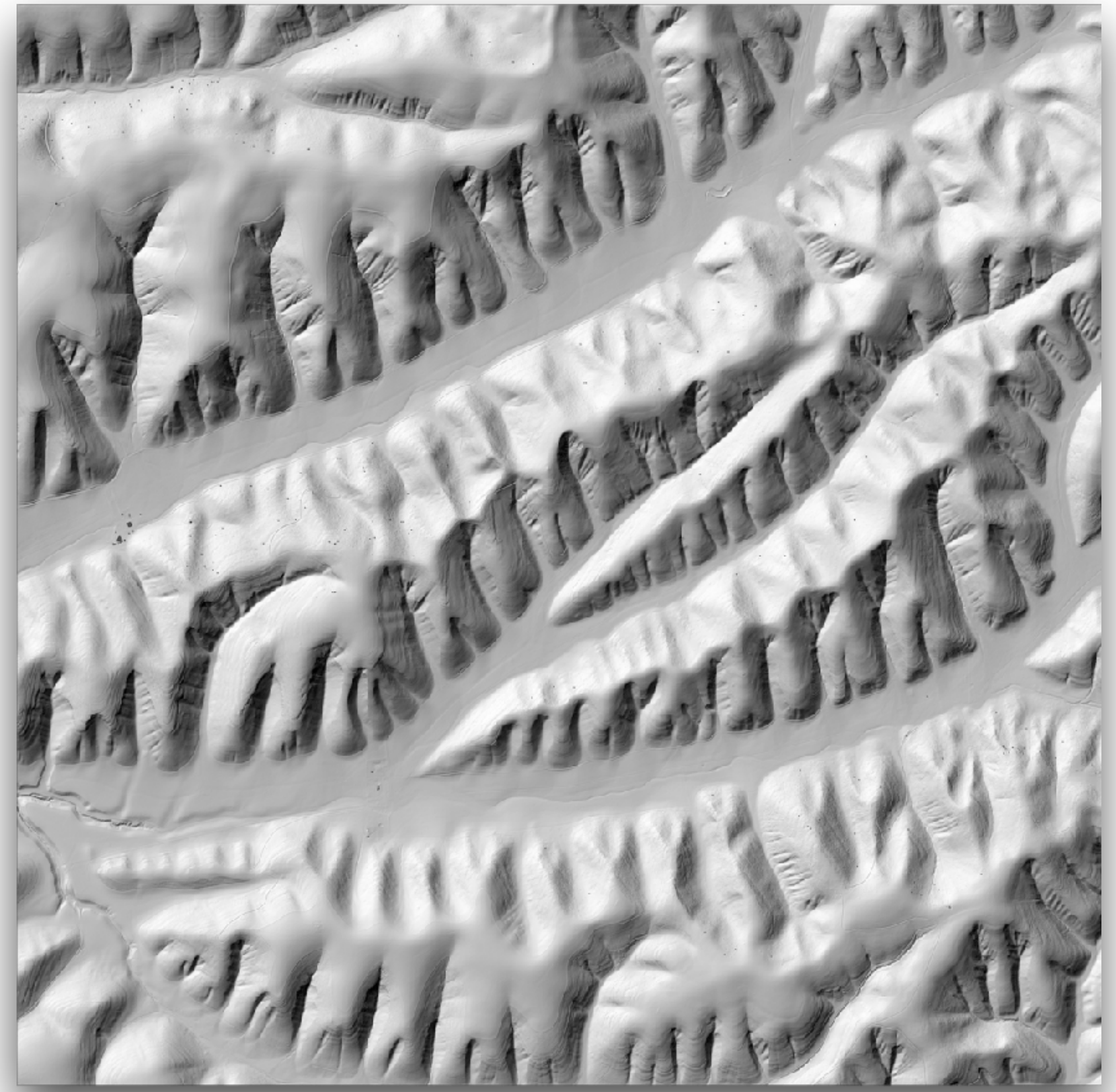
- Synthetic experiments can help us understand the properties of our objective functions.

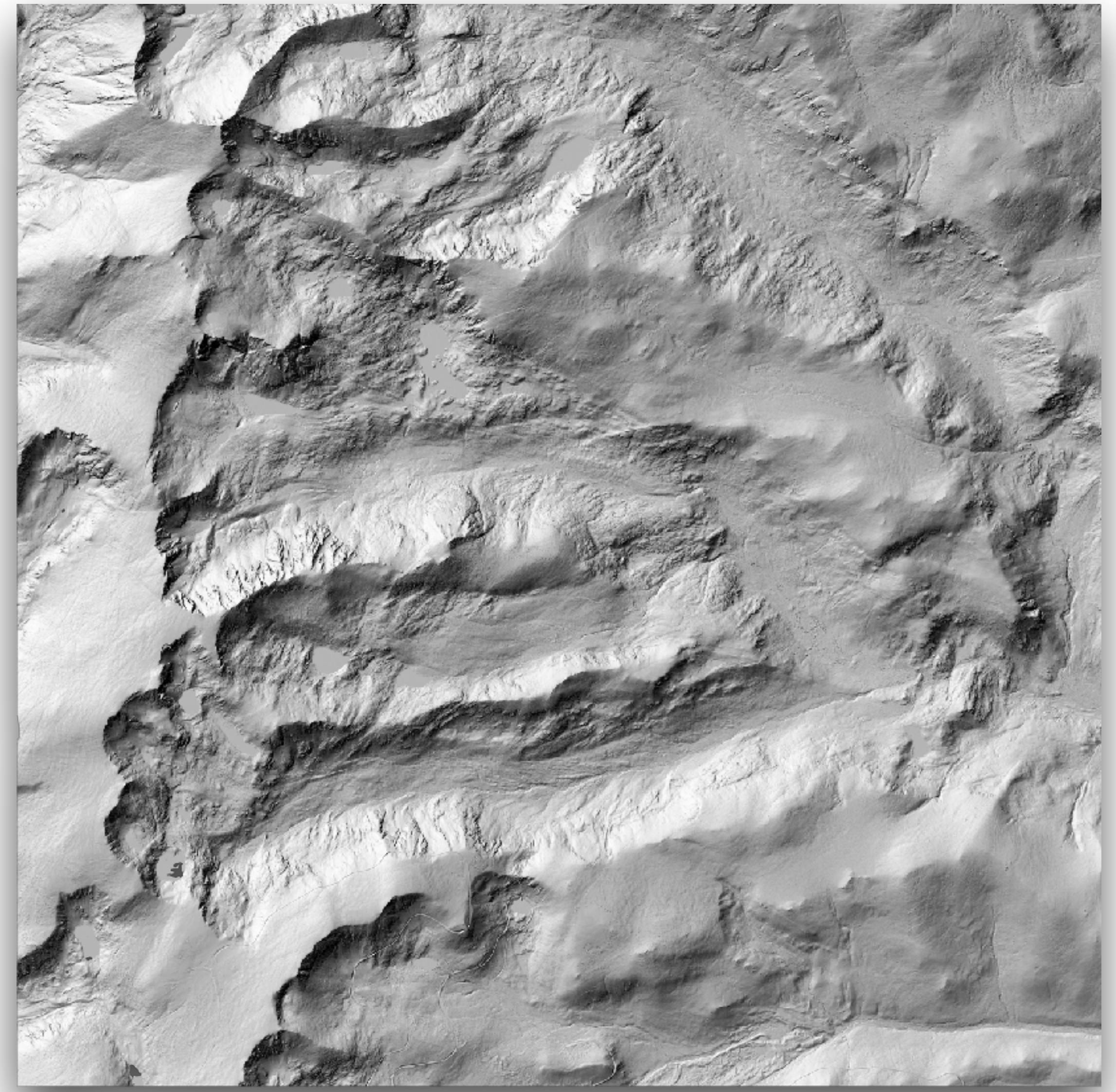






- Steady state vs transient systems
- Categorical properties and choices
- Nonlinear interactions
  (especially in coupled models)





Questions?