A Novel Near-Surface Geophysics Approach to Constrain Material Porosity and Moisture within Critical Zone Structure in Central Puerto Rico

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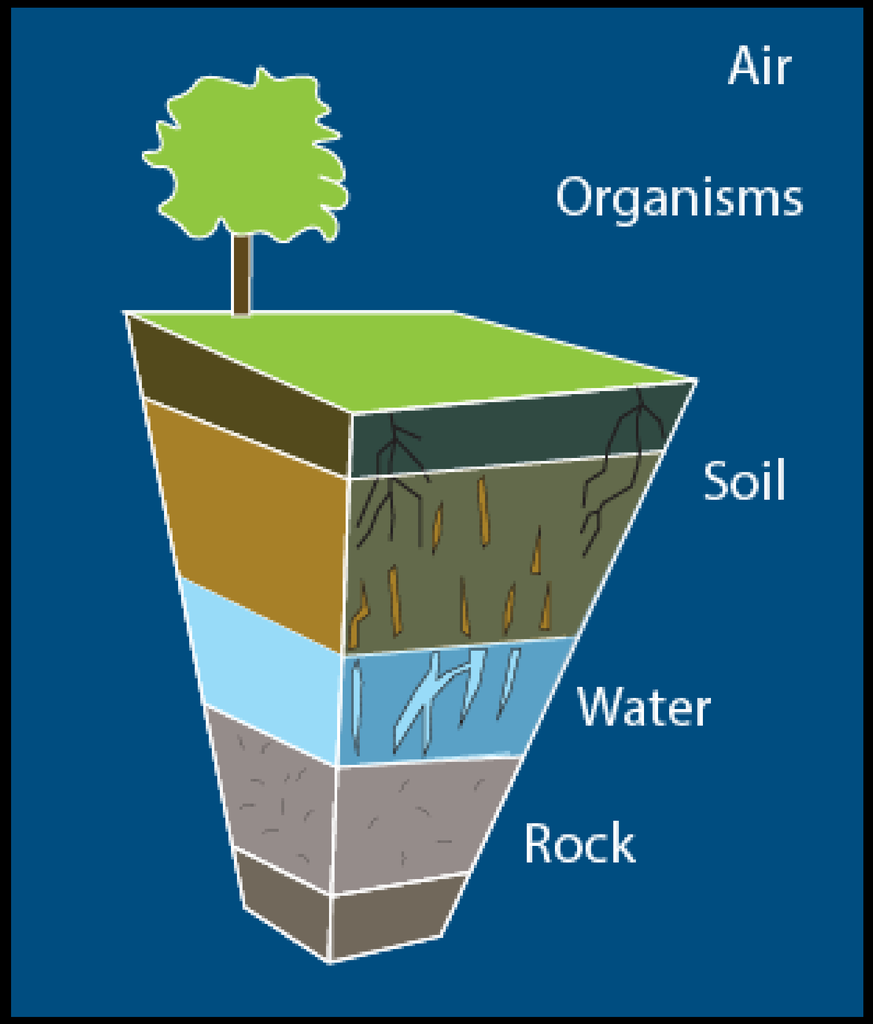
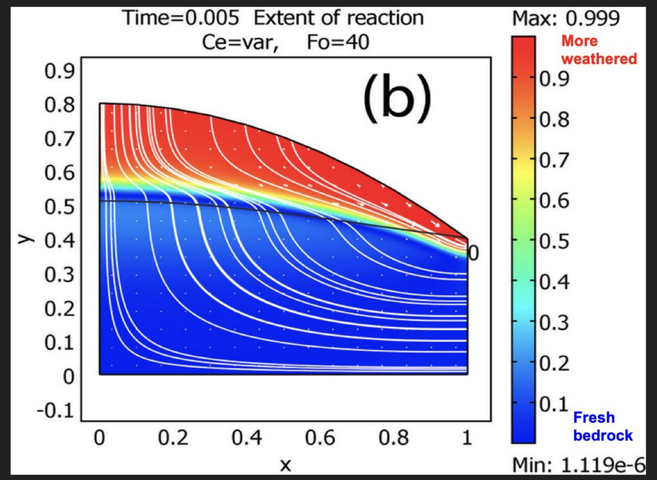
1. University of Maryland, College Park
2. U.S. Geological Survey
3. Now at University of Texas, Austin

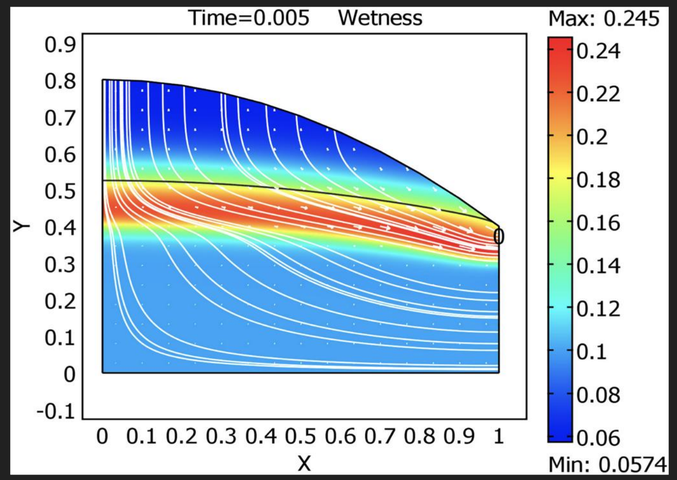
Critical Zone and Subsurface Flow



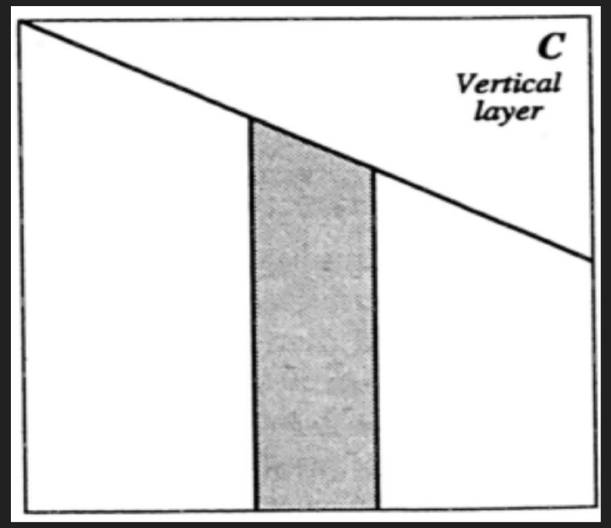
- Critical Zone (CZ): Depth from bedrock or groundwater table to surface
- Can be linked to natural hazard (e.g. landslides)
- Heterogeneity in subsurface during CZ development may impact subsurface flow and therefore local pore-fluid pressure
- What does that actually look like beyond numerical models?

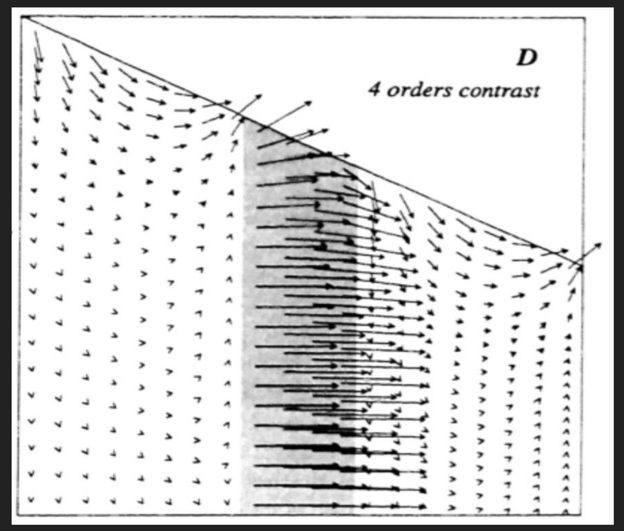
Critical Zone and Subsurface Flow





Lebedeva and Brantley (2020)





Reid and Iverson (1992)

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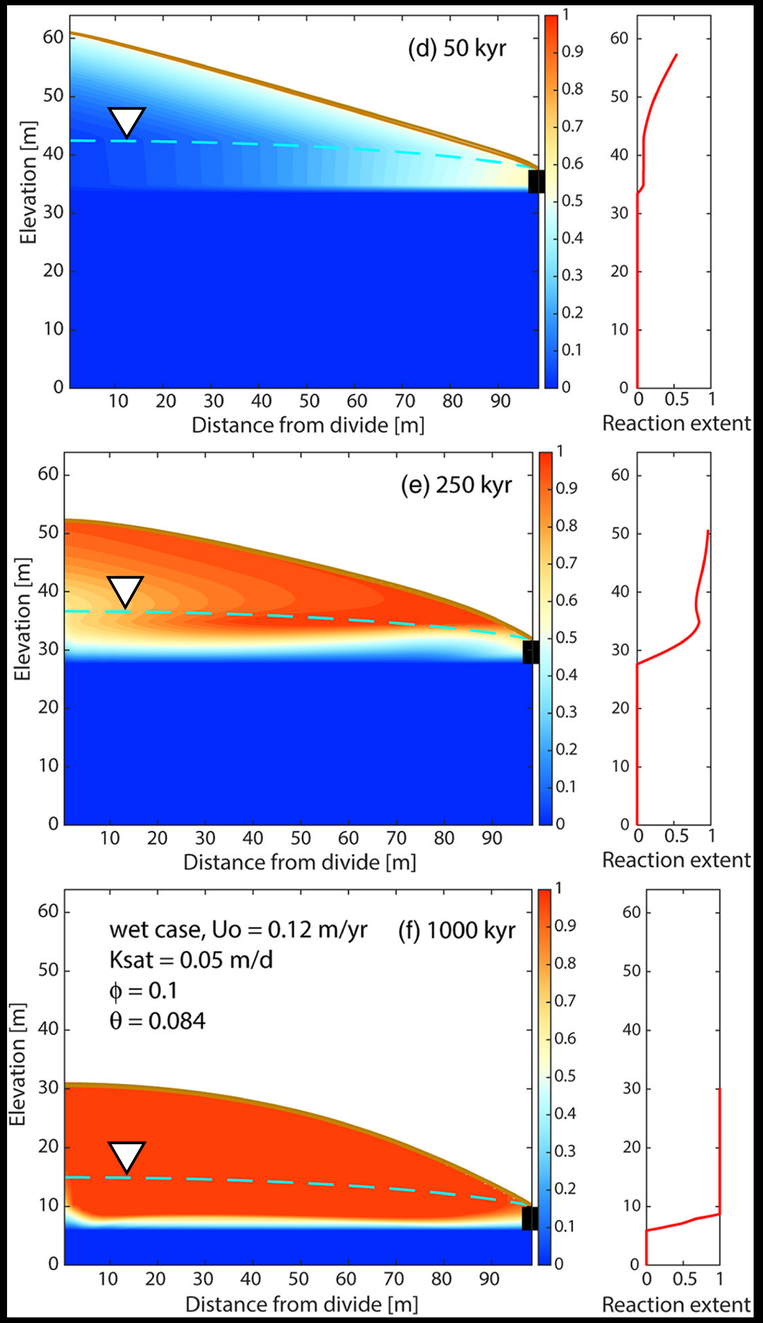
Implications of changing CZ on landslides?



Anderson et al., 2018, *Hydrological Processes*

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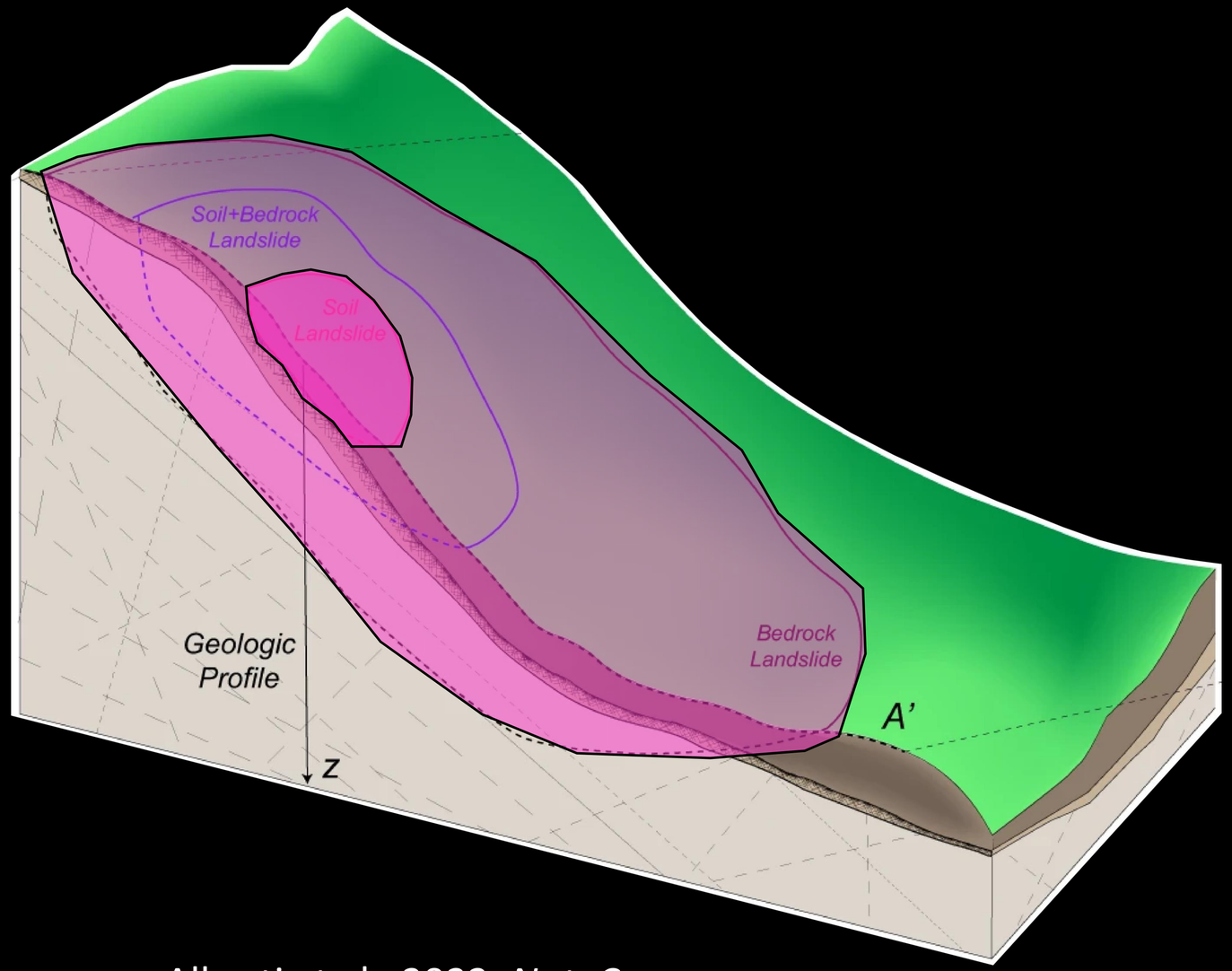
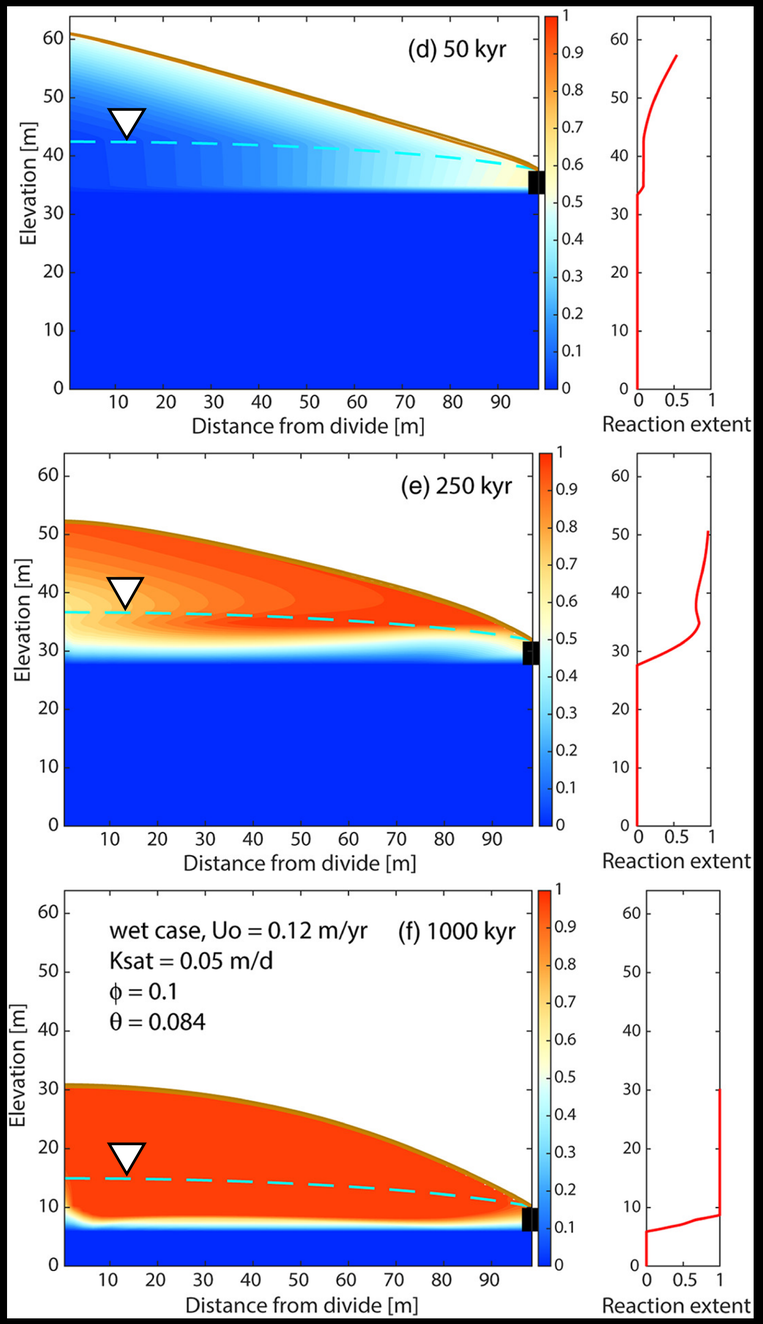


Alberti et al., 2022, *Nat. Comm.*



Anderson et al., 2018, *Hydrological Processes*

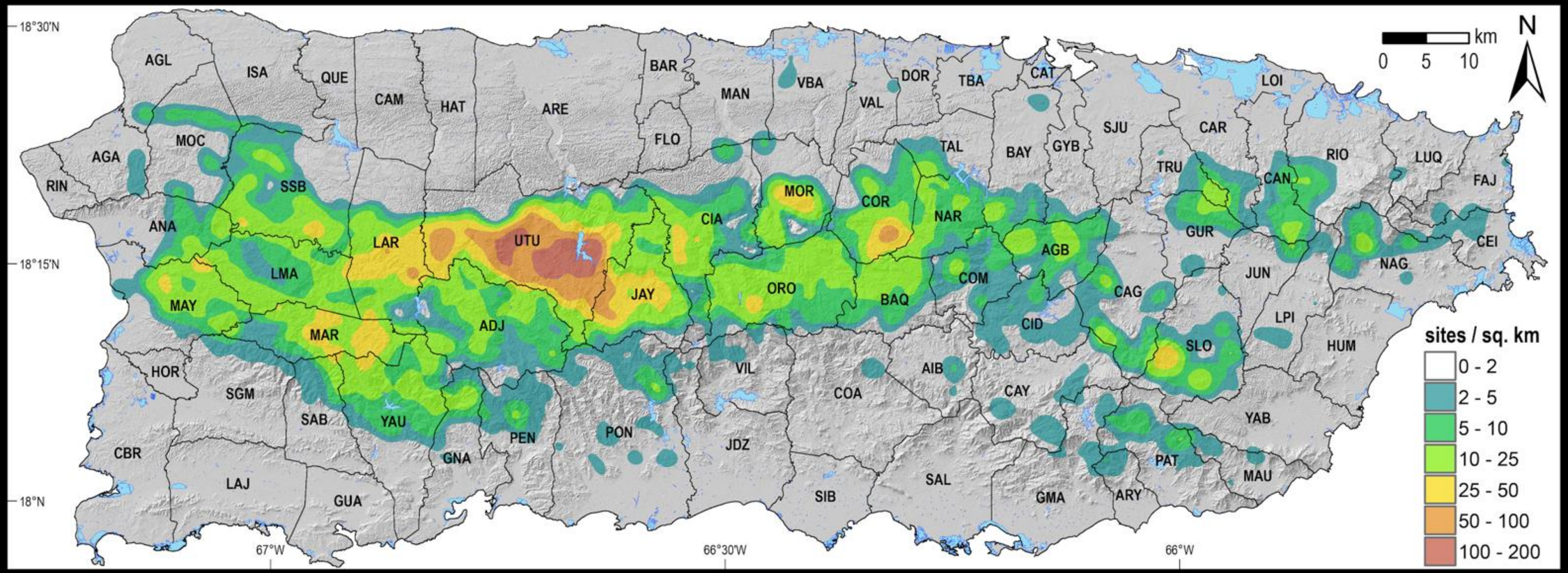
Study site: Utuado, Puerto Rico

Puerto Rico

- ~8700 km^2 area, tropical climate
- Over 3 m residents, and ~1 m within interior (Martinuzzi et al., 2007; Schulz, pers. Comm)

Hurricane Maria

- High Category 4 storm
- 3,000 – 5,000 deaths (Killshore et al., *NEJM*, 2018)

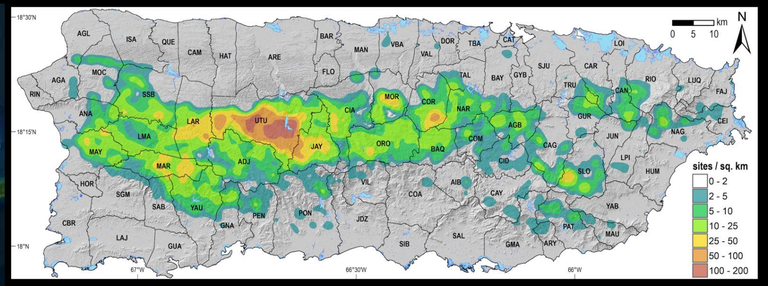


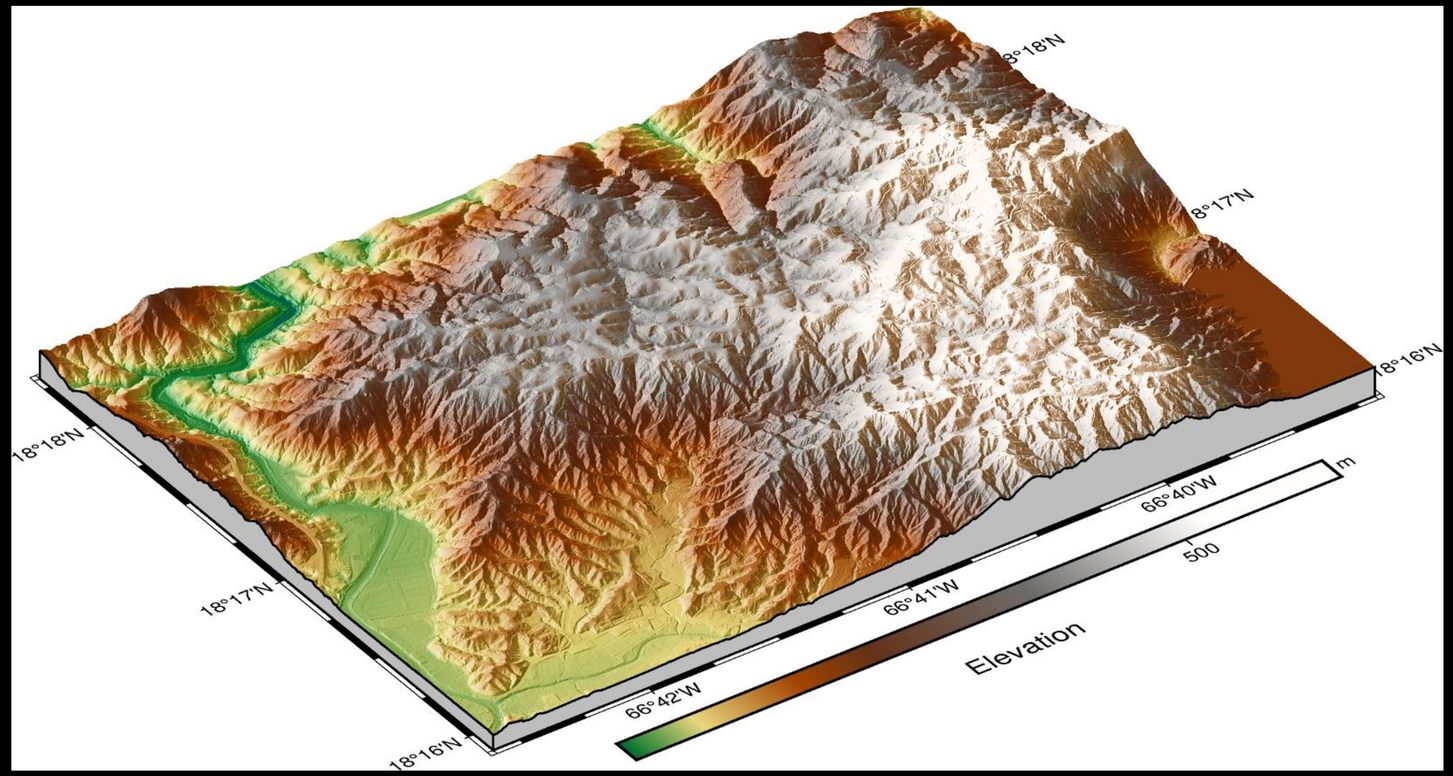
Bessette-Kirton et al., 2019, *GSA Today*

Photo: Erin Bessette-Kirton (USGS)

USGS
science for a changing world

Study site: Utuado, Puerto Rico





- 2017 Hurricane Maria
  - > 70k landslides
  - Observe different shallow landslides across topography
- Steep hillslopes are right below the plateau

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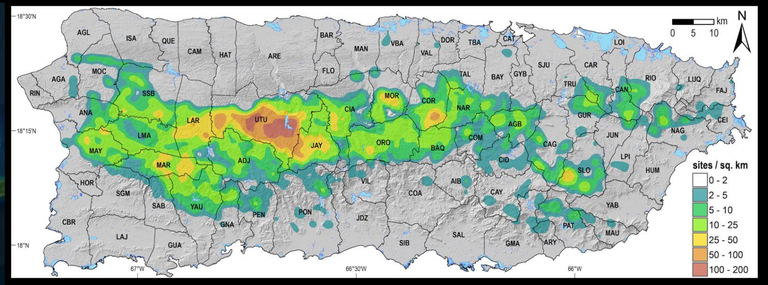
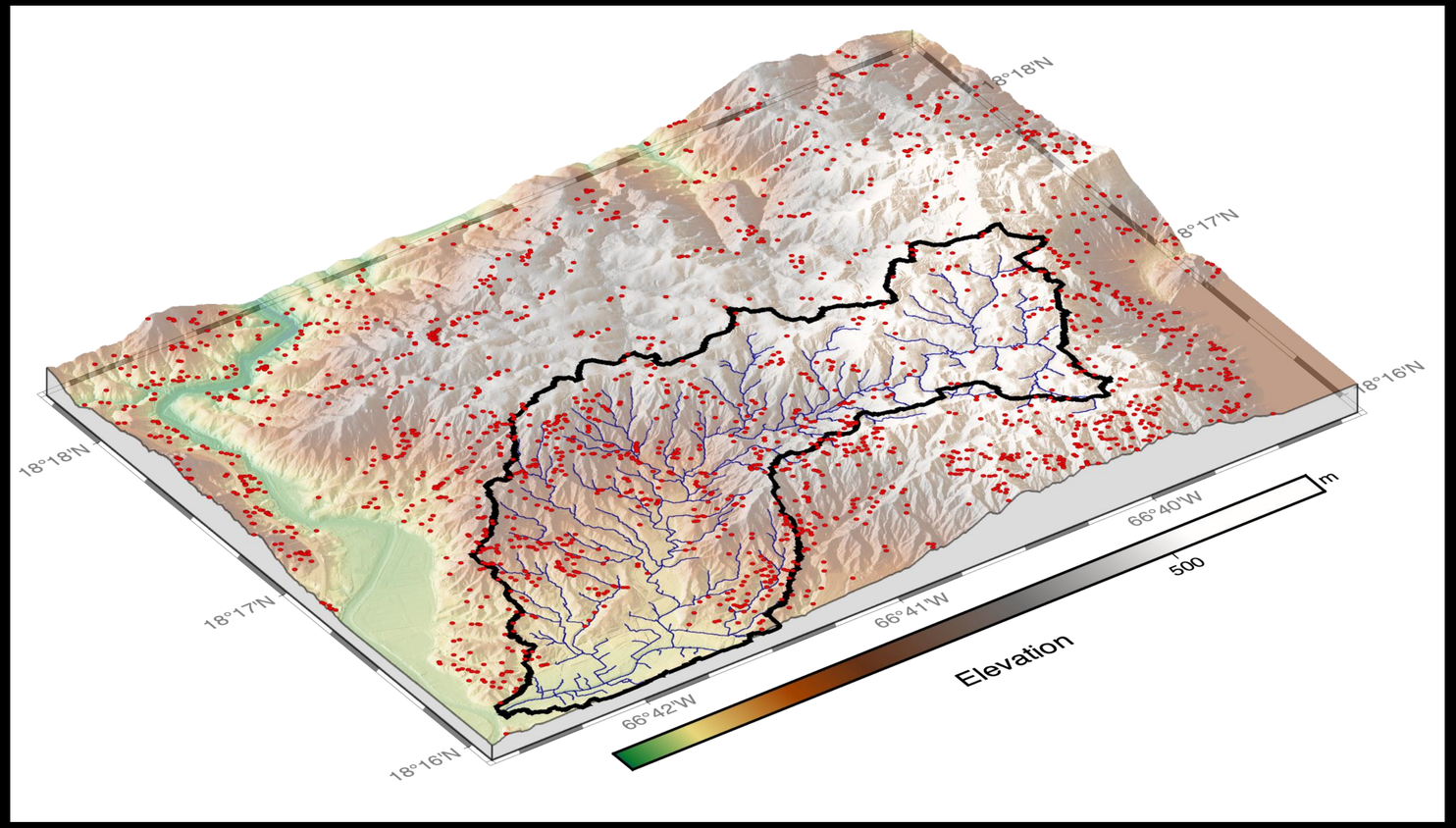


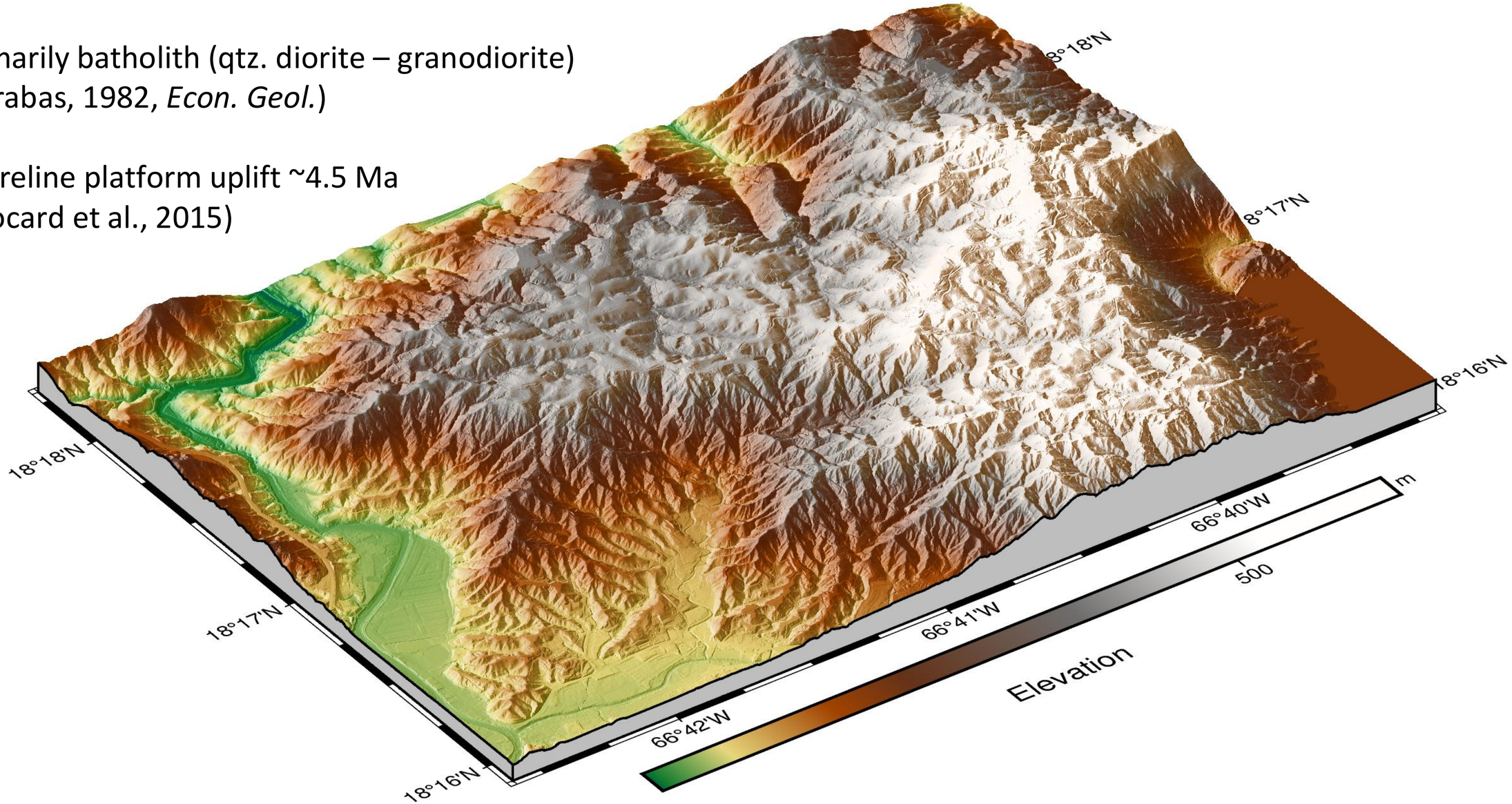


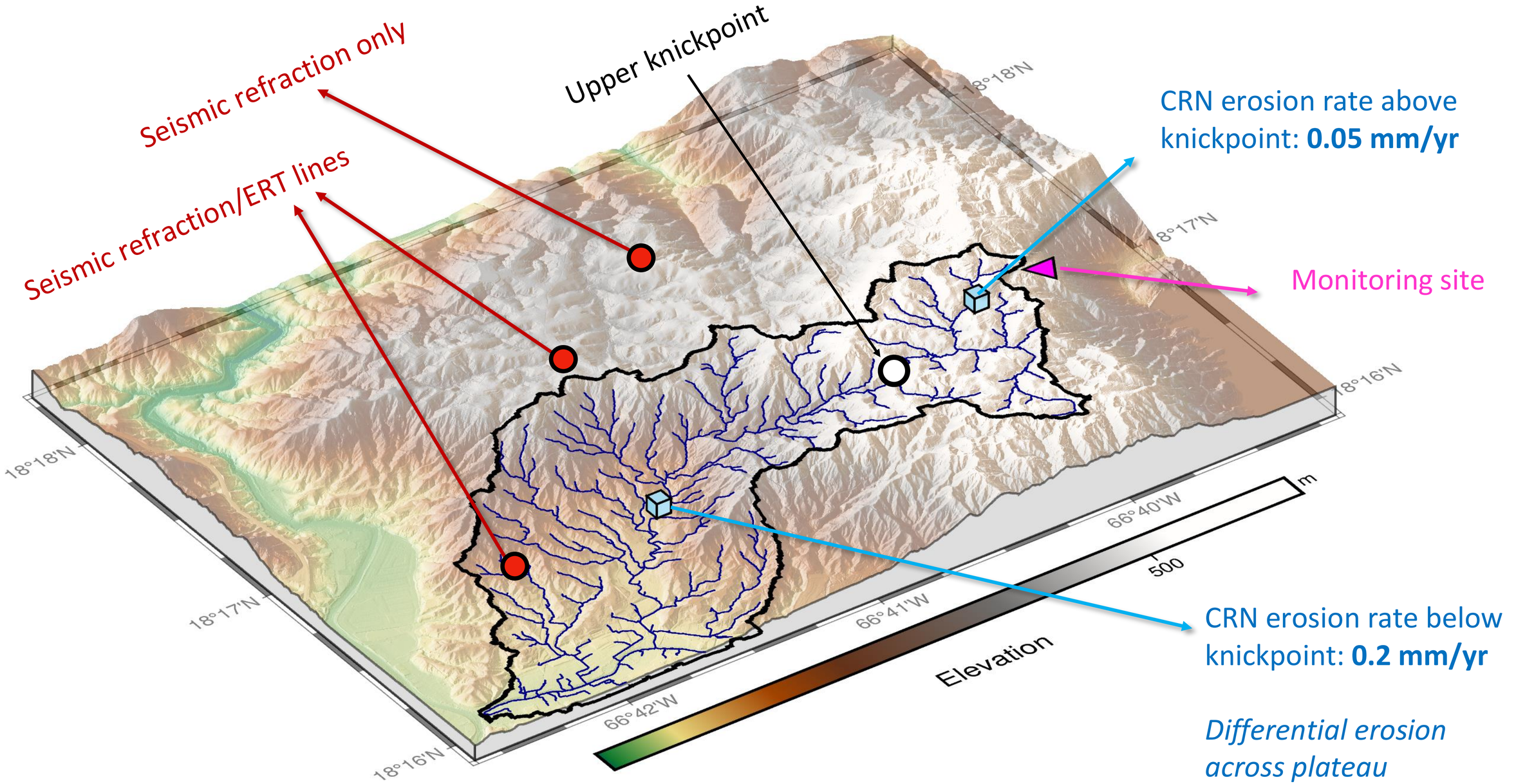
- 2017 Hurricane Maria
  - > 70k landslides
  - Observe different shallow landslides across topography
- Steep hillslopes are right below the plateau
- What controls the size and type of landslides?
- How does weathering gradient impact both deep and shallow landslide styles?

Utuado Plateau

Primarily batholith (qtz. diorite – granodiorite)
(Barabas, 1982, *Econ. Geol.*)

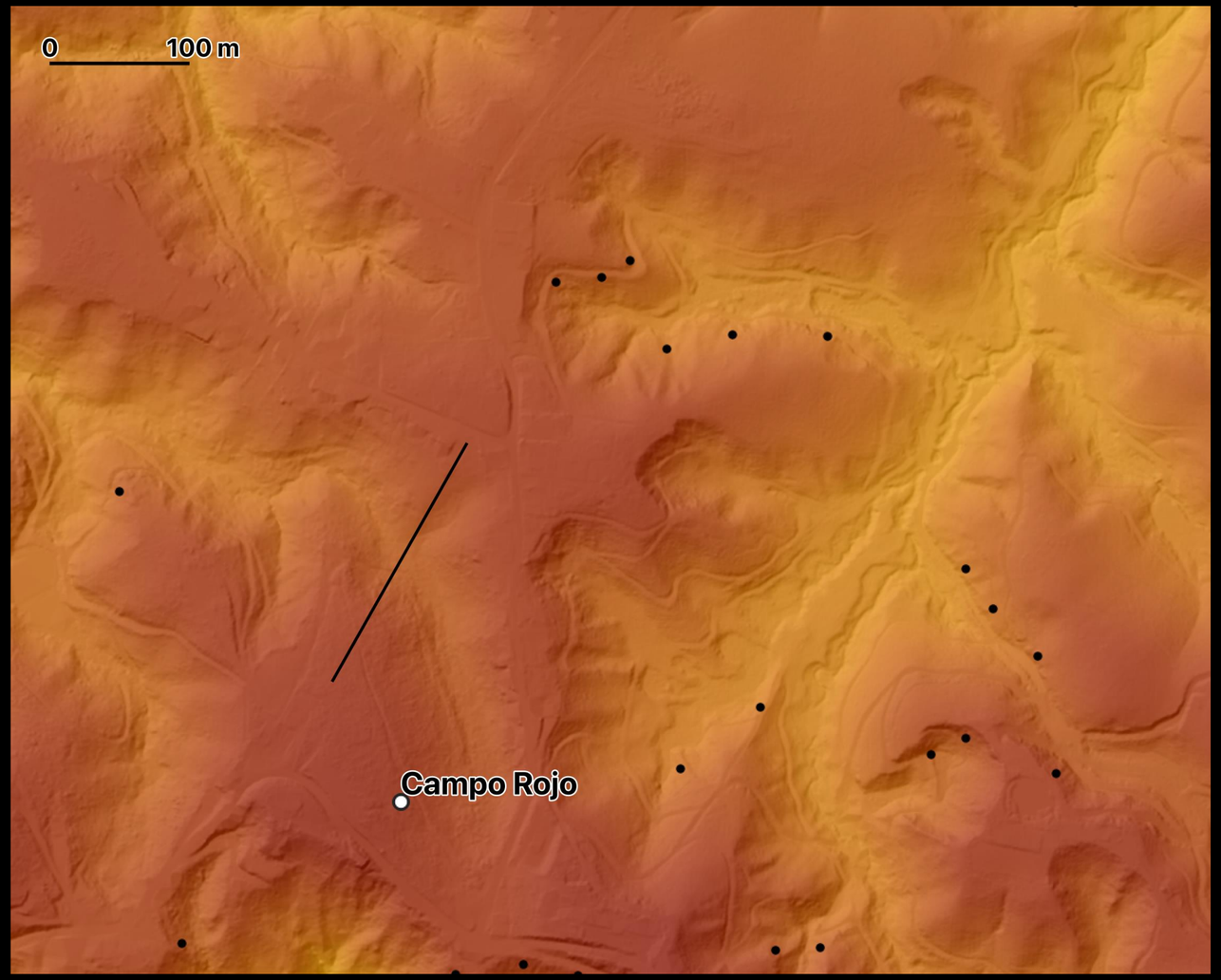
Shoreline platform uplift ~4.5 Ma
(Brocard et al., 2015)



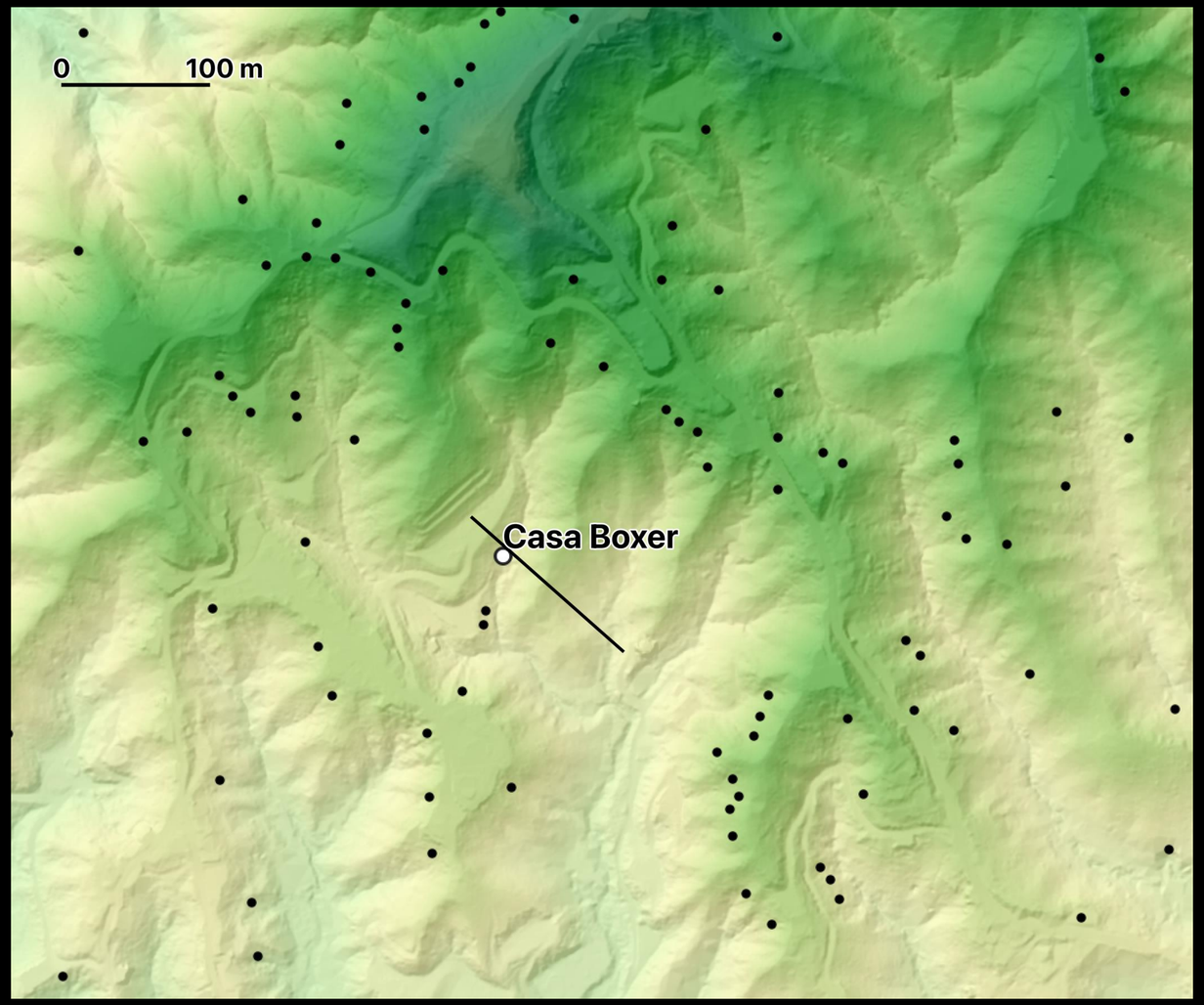

Seismic refraction only
Seismic refraction/ERT lines
Upper knickpoint
CRN erosion rate above knickpoint: **0.05 mm/yr**
Monitoring site
CRN erosion rate below knickpoint: **0.2 mm/yr**
Differential erosion across plateau
18°18'N
18°17'N
18°16'N
66°42'W
66°41'W
66°40'W
Elevation
500
m

Topography between the two sites

Plateau

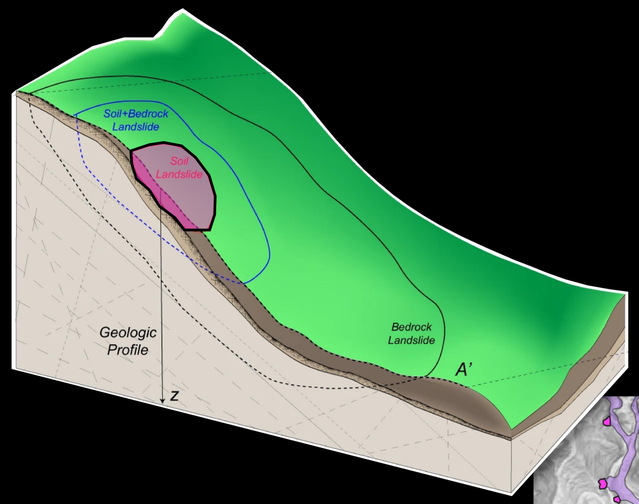


Escarpment



Shallow landslide characterization

Most landslides are shallow during Maria

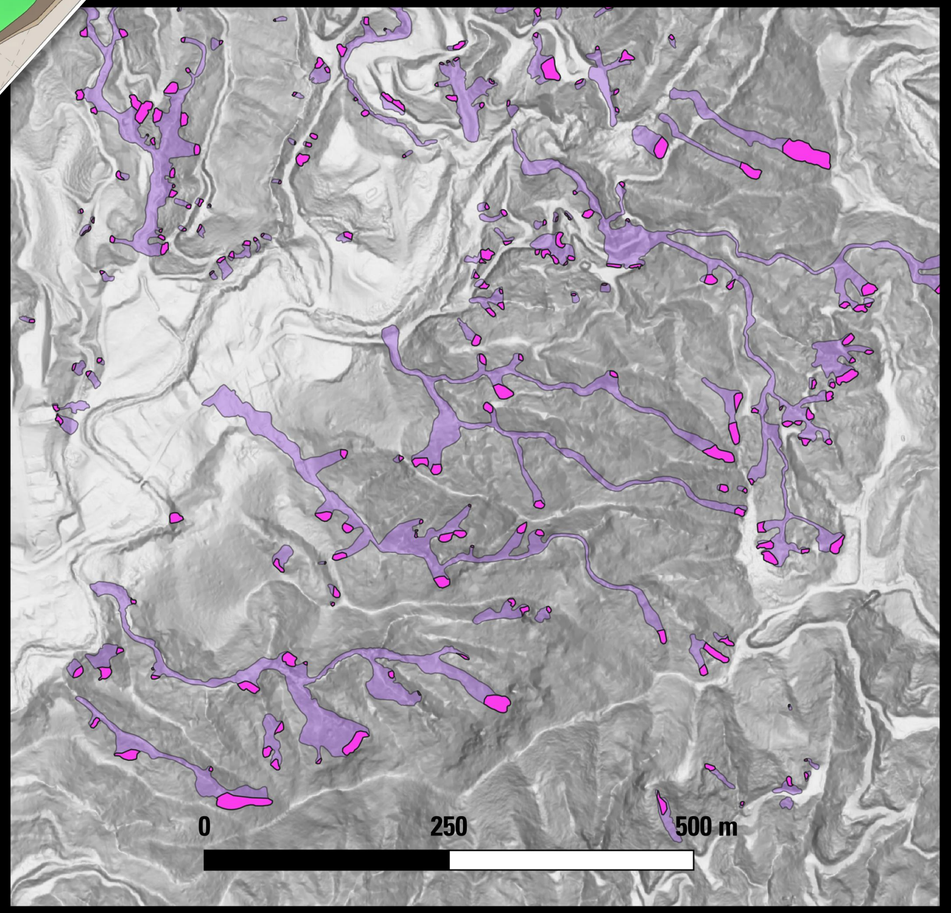


Source area mapping (Einbund et al., 2021, *USGS Data Release*)

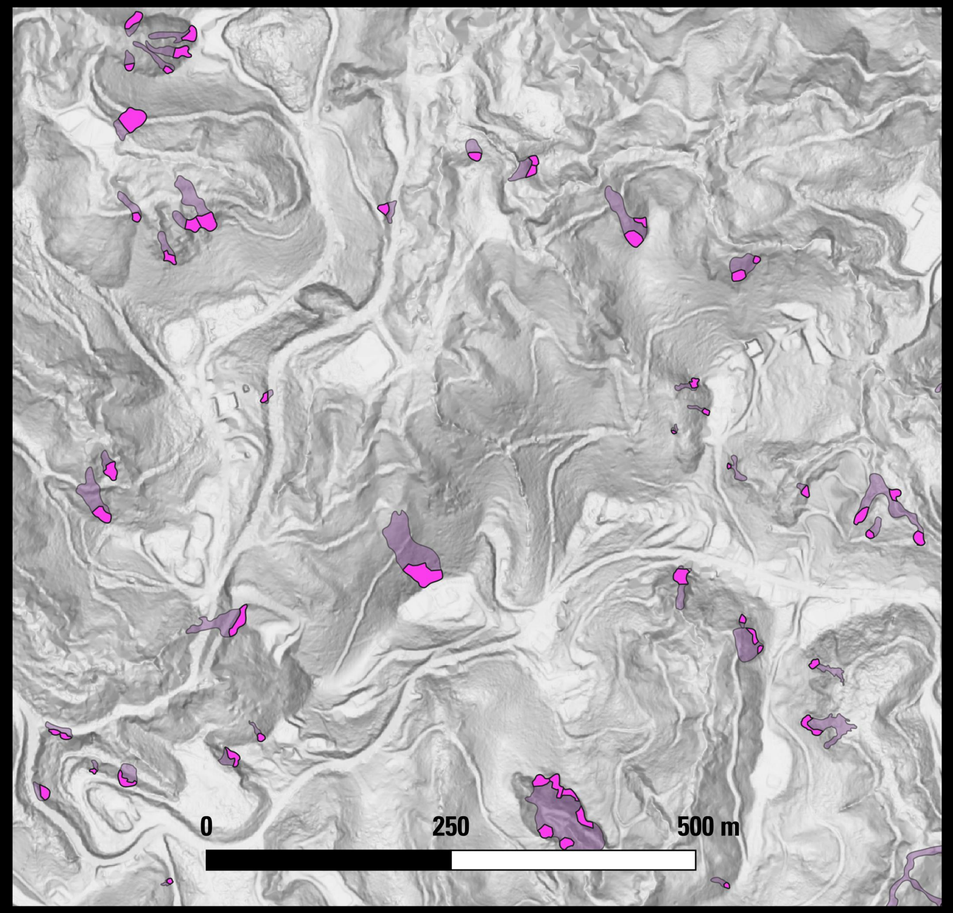
Mapping through imagery + lidar differencing (volumes, depths)

Source area similarities despite mobility differences

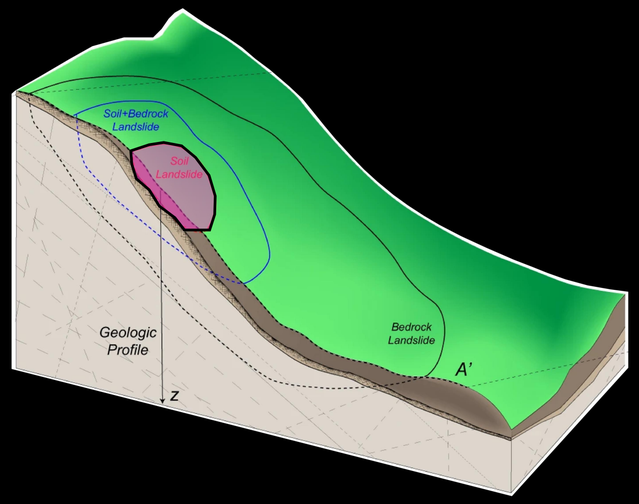
Escarpment



Plateau



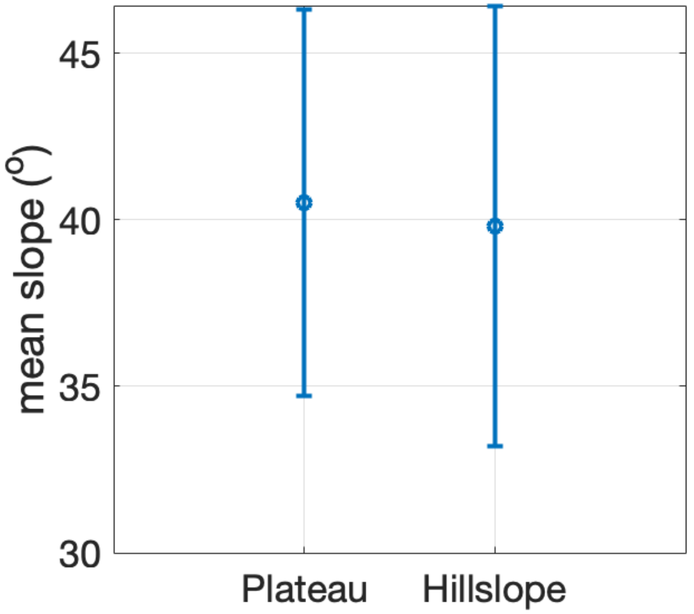
Perkins et al., in review



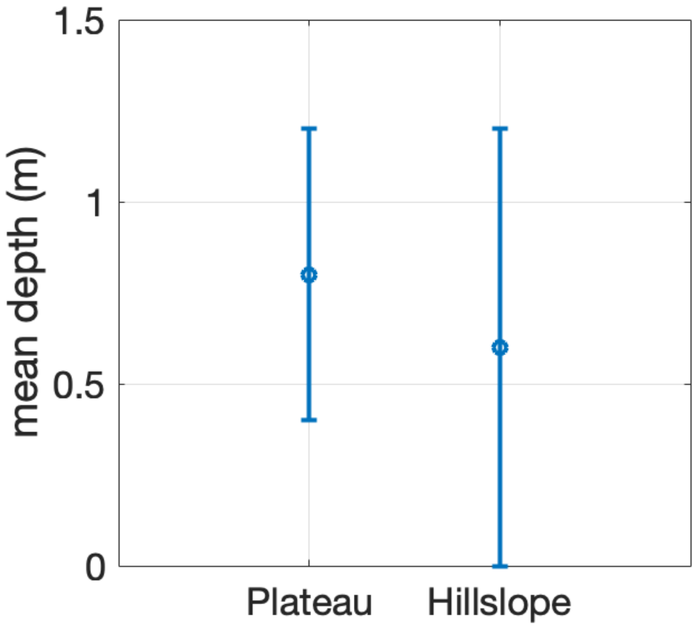
Shallow landslide characterization

Most landslides are shallow during Maria

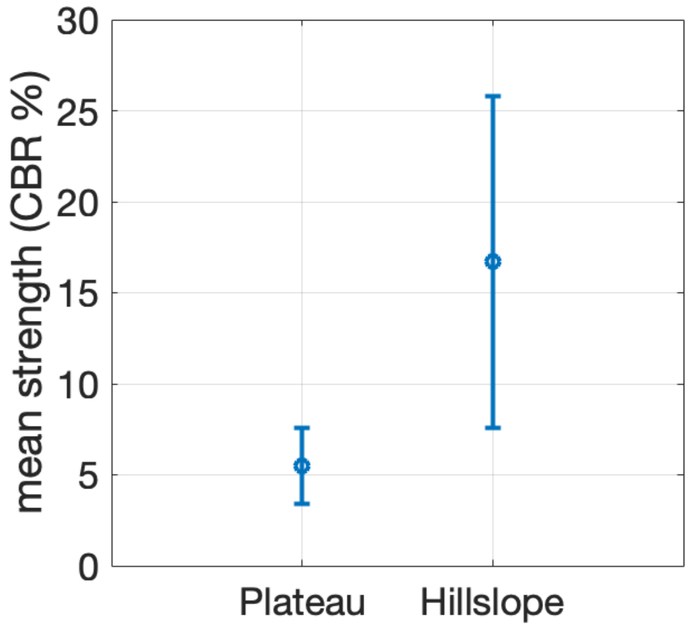
Slope



Landslide thickness



Material strength



***Increase* in landslide concentration below plateau despite significant strength increase!**

Geophysics

Near-surface geophysics (surveyed in spring 2022)

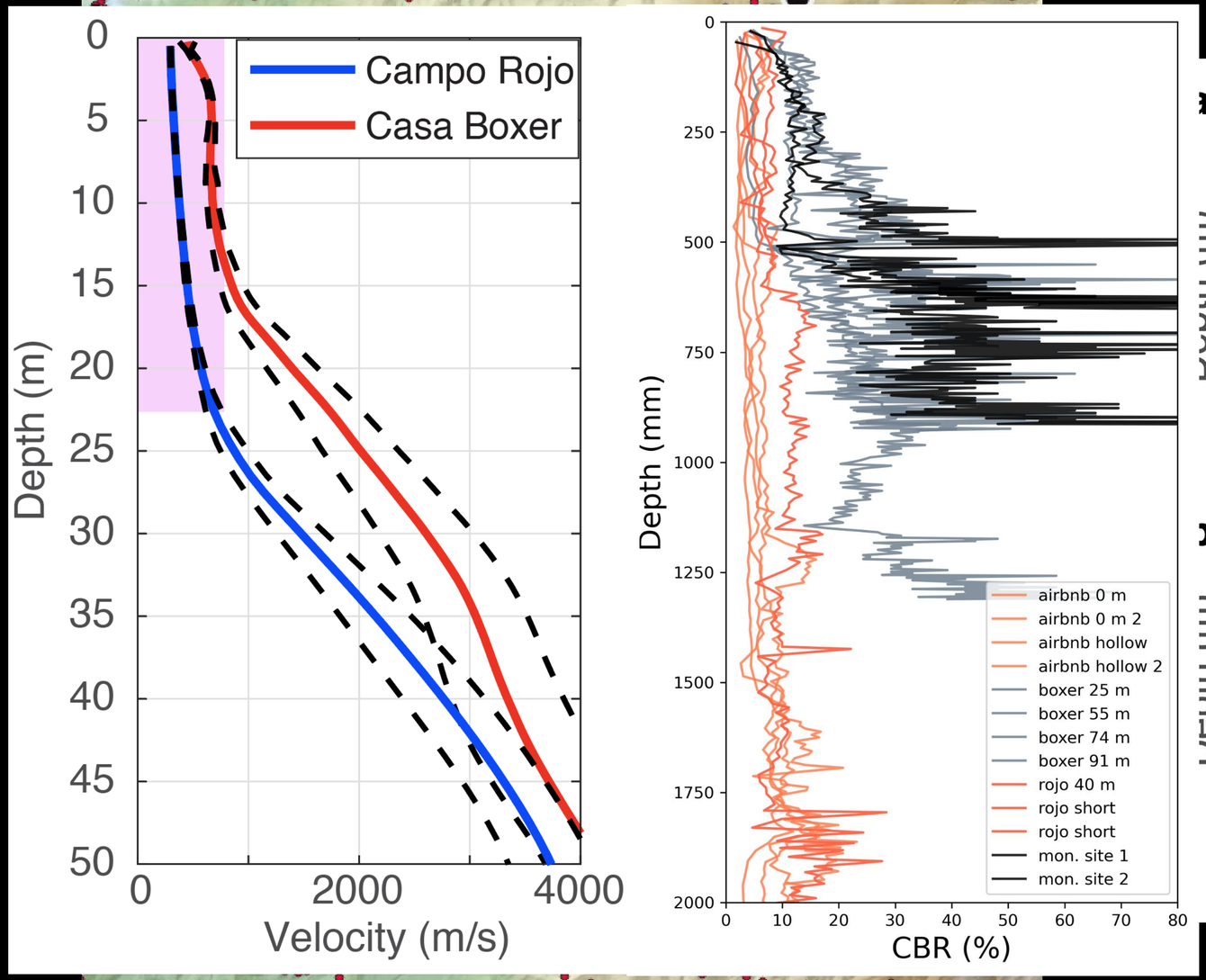
- Seismic refraction (SR)
- Electrical resistivity (ER)
- Bayesian framework for individual inversions
- Joint Bayesian inversion can potentially retrieve porosity and moisture distribution in the subsurface

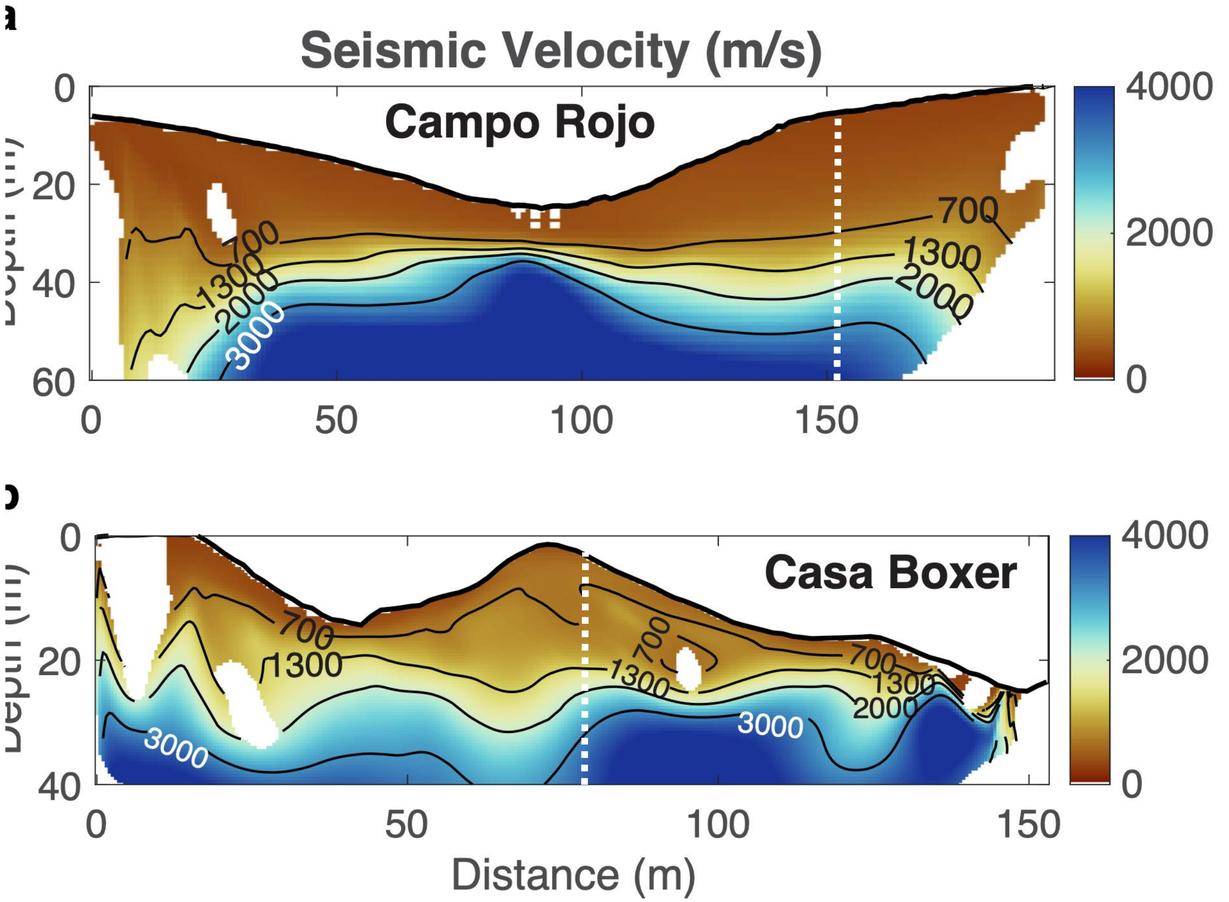
Seismic Refraction

Bill Schulz (USGS)

Electrical Resistivity

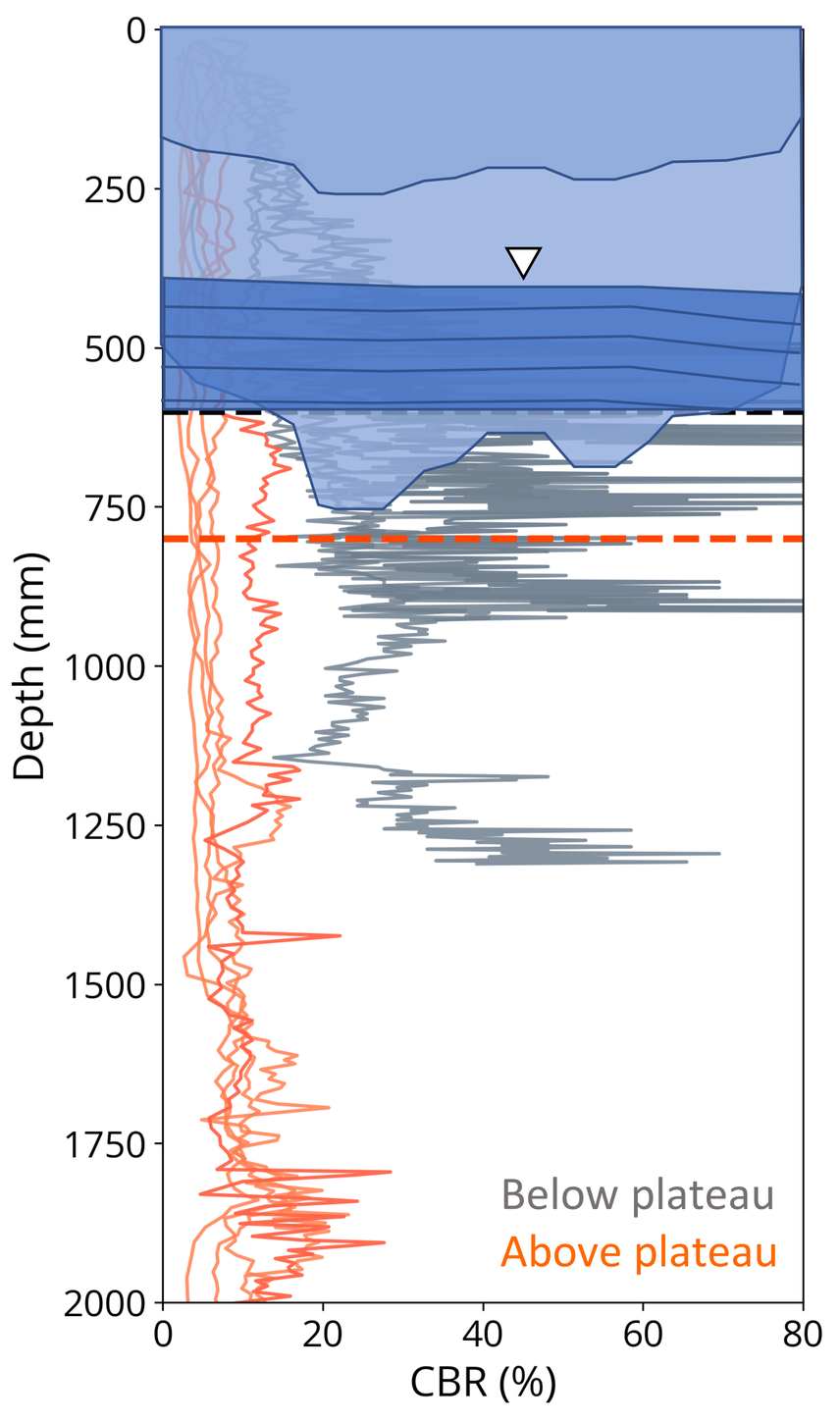
Seismic Refraction





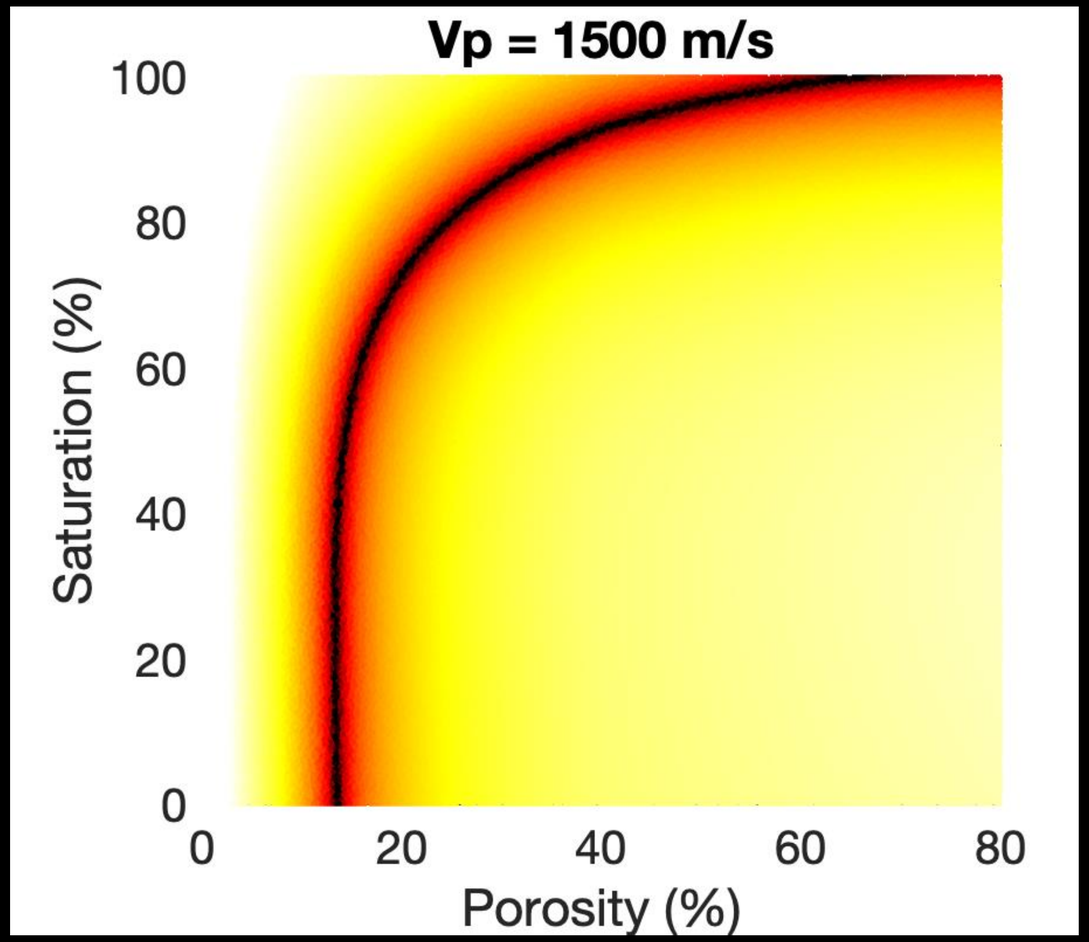
Huang et al., in review


Mason Einbund (USGS)


0
250
500
750
1000
1250
1500
1750
2000
Depth (mm)
0
20
40
60
80
CBR (%)
Below plateau
Above plateau

Rock Physics Model (Seismic Velocity)

Predicting Porosity and Saturation from P-wave velocity

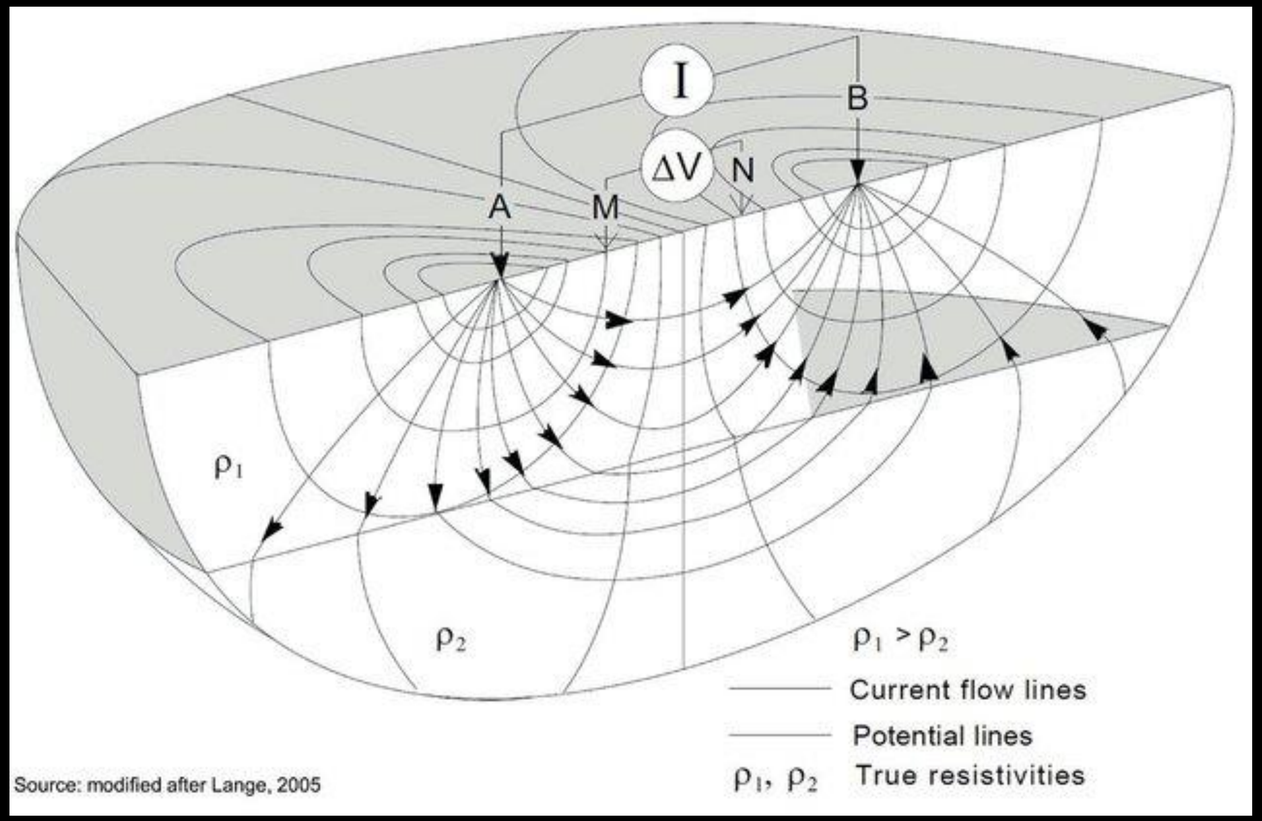


- Vp is a function of elastic moduli (e.g. bulk modulus and shear modulus) and density
- Both elastic moduli and density vary by porosity of the material and fluid content
- Here porosity includes open space in material
- Apply the Hertz-Mindlin theory to estimate bulk and shear moduli
- Assume we know the mineral composition

Geophysics Method: Electrical Resistivity

Electrical resistivity is sensitive to:

- Moisture content
- Mineralogy of subsurface



Ohm's law:

$$V = IR$$

V = voltage
I = current
R = resistance

$$R = \rho \frac{L}{A}$$

p = resistivity
L = length
A = cross-sectional area

Input: Electrical current (I)

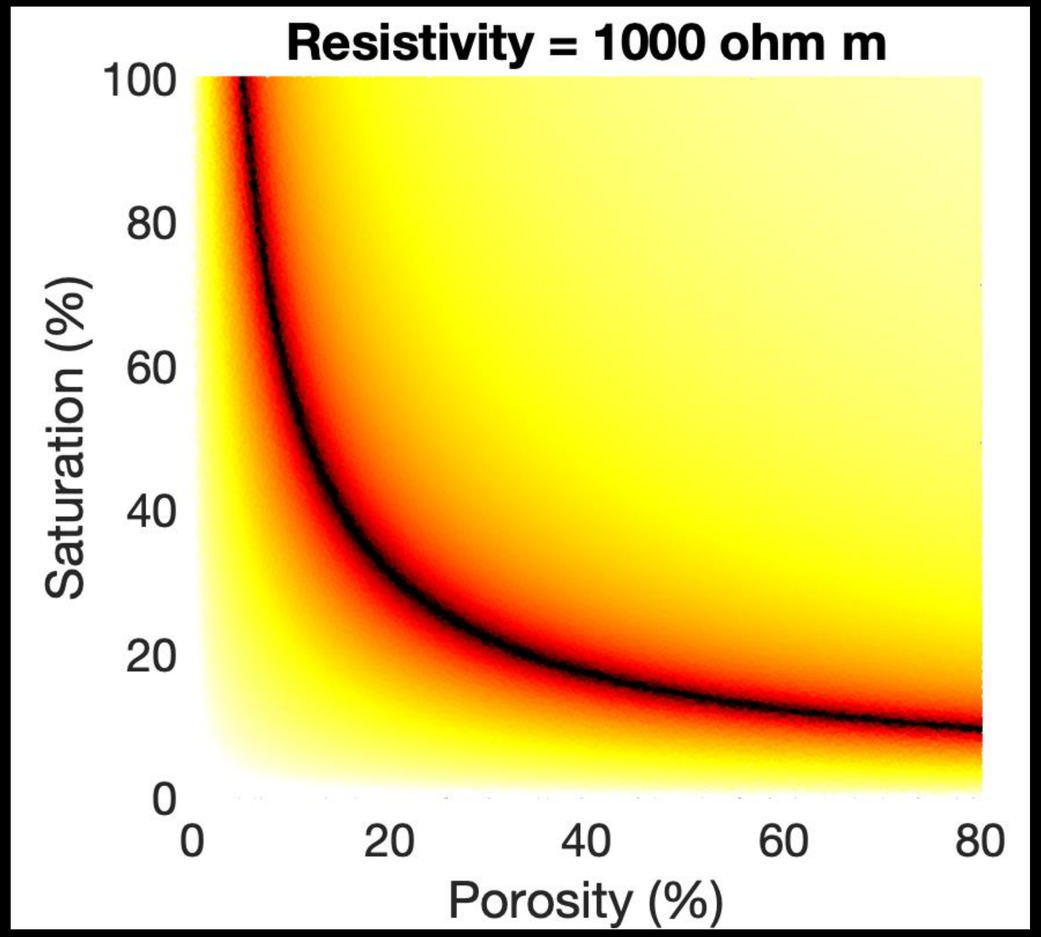
Measurement: Differential electrical potential (*ΔV*)

Unknown: Resistivity in space (*ρ*)

Archie’s Law (Electrical Resistivity)

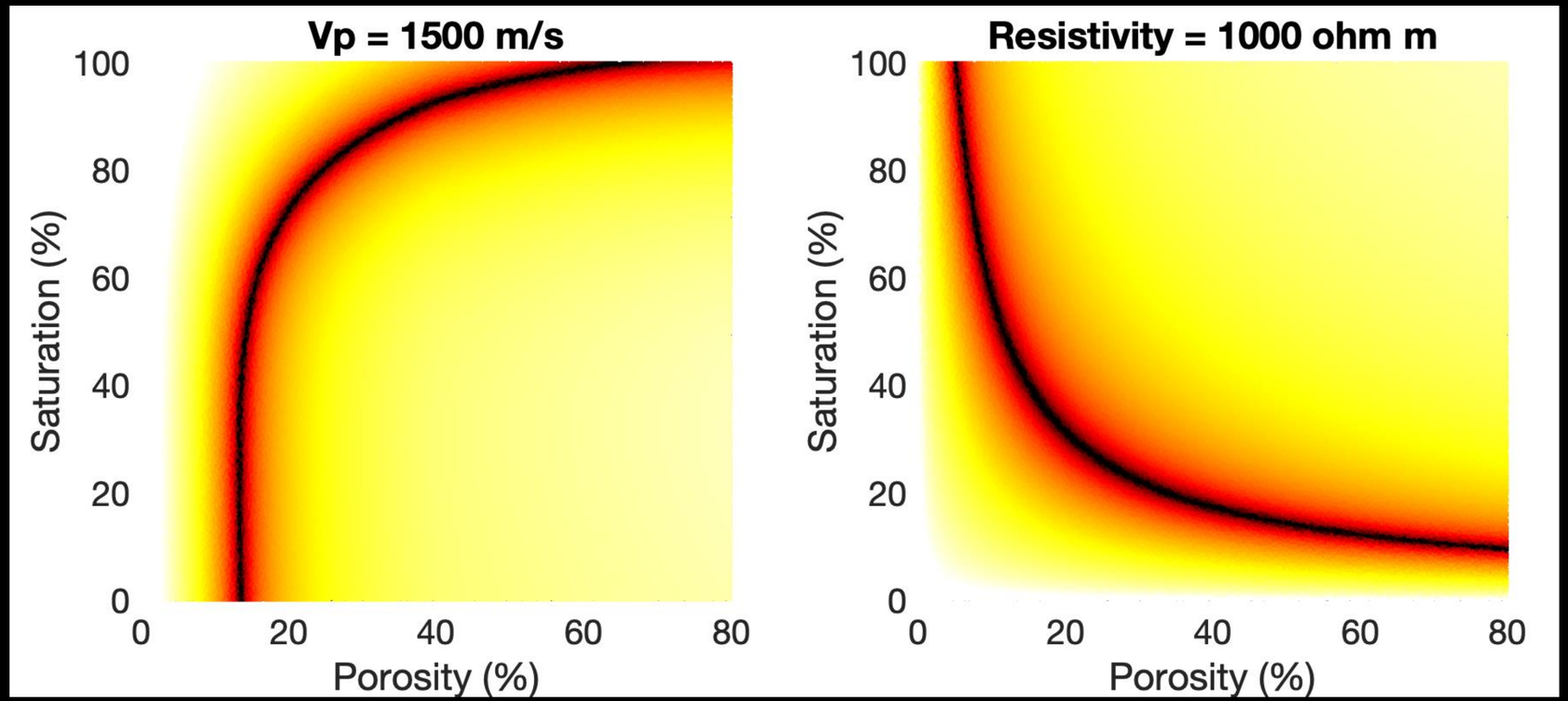
Predicting Porosity and Saturation from Geophysics

- Electrical resistivity is sensitive to both porosity and water content
- Low porosity bedrock implies high resistivity
- High water content implies low resistivity
- Archie’s Law relates porosity and water saturation
- Tradeoff between porosity and water saturation

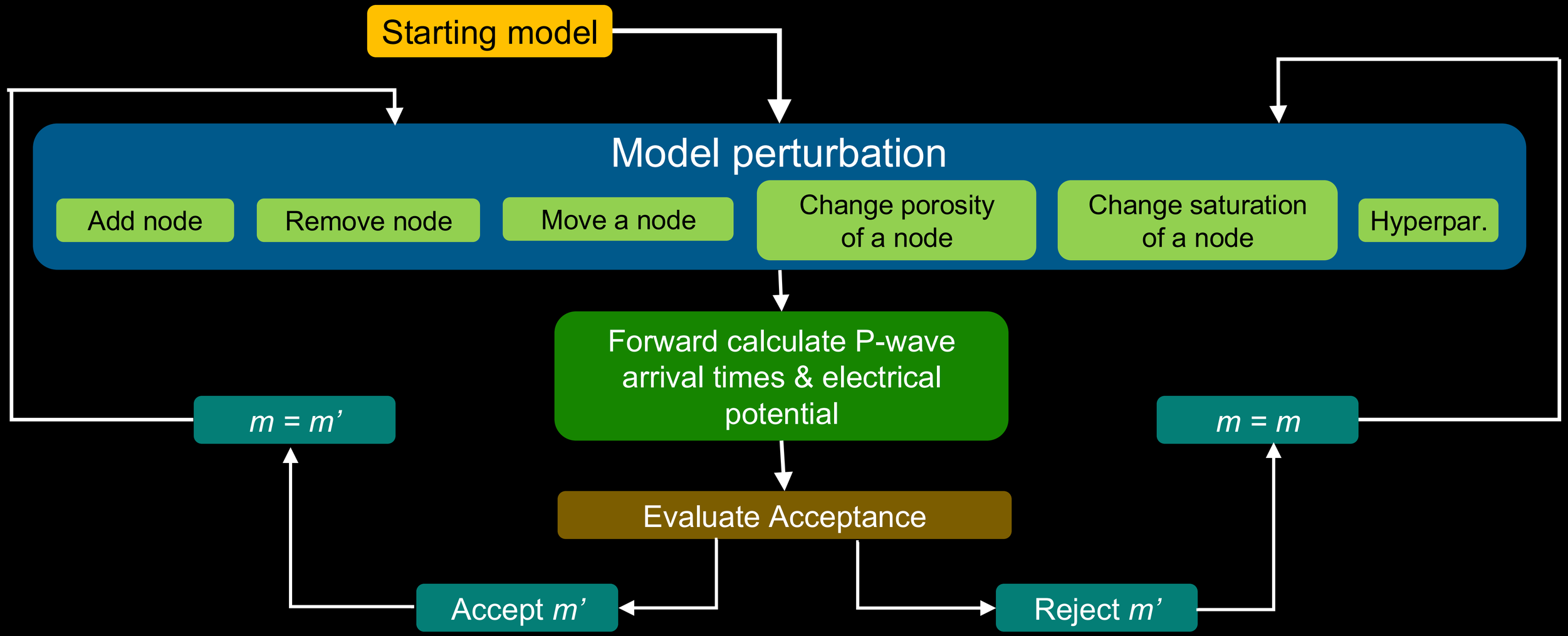


Rock Physics Model and Archie's Law

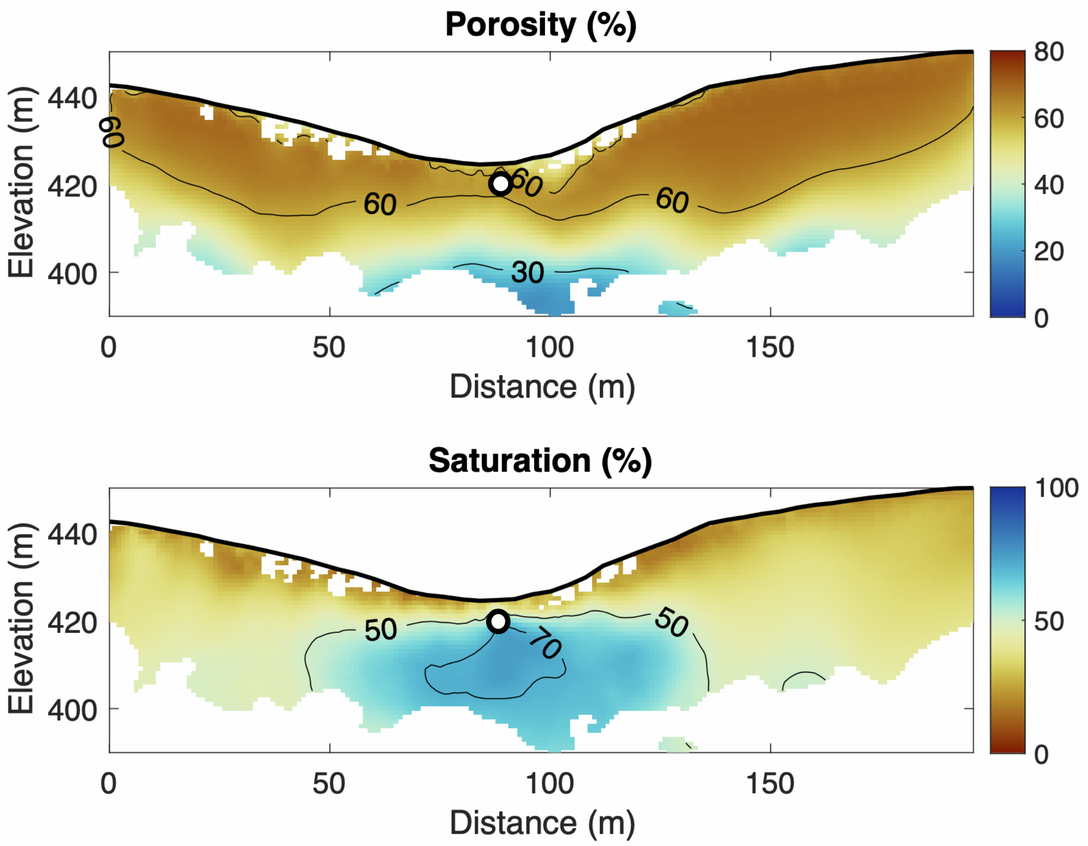
Predicting Porosity and Saturation from Geophysics

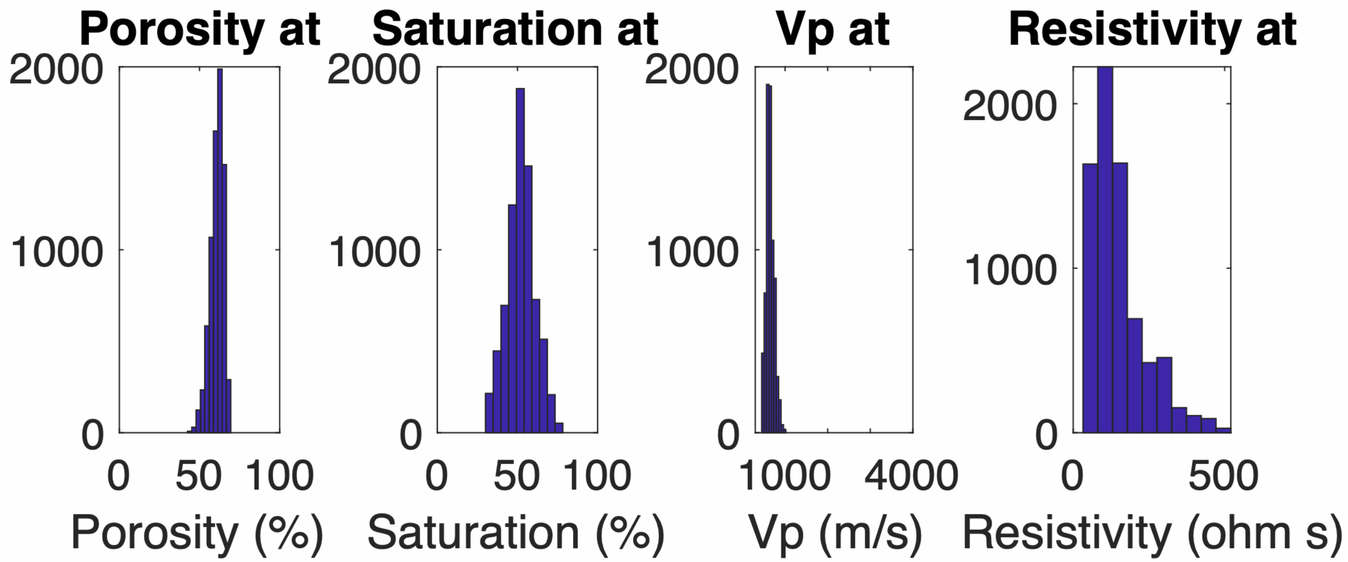


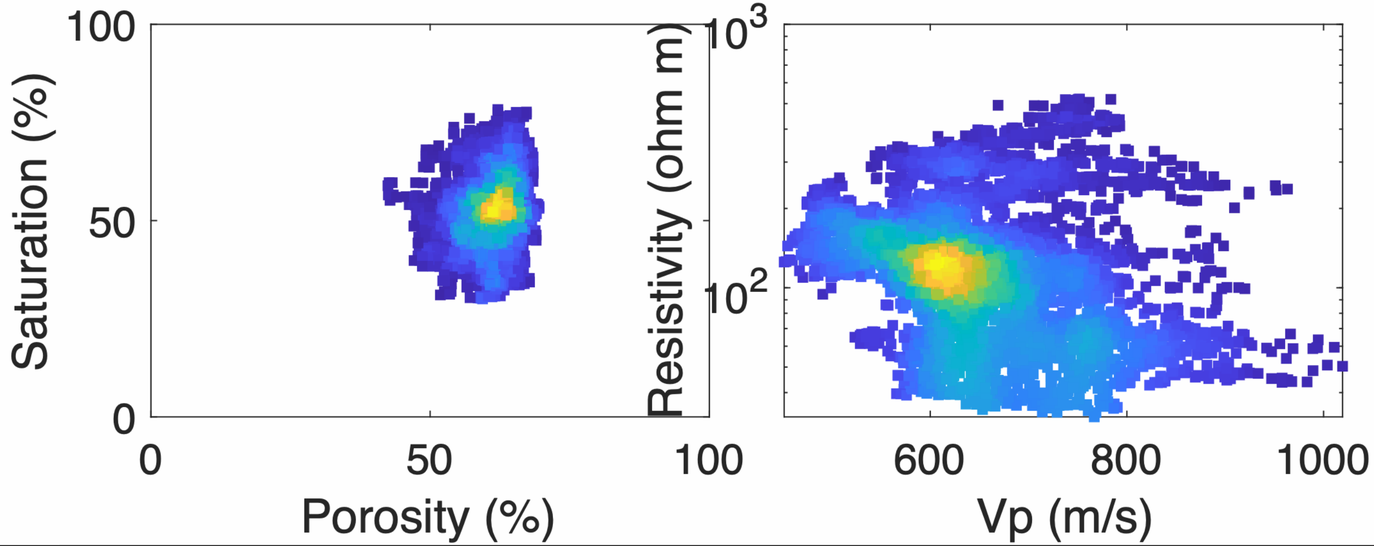
Transdimensional Hierarchical Bayesian Reverse-Jump Markov Chain Monte-Carlo Inversion (THB rj-MCMC) Framework



Joint inversion result (on plateau)



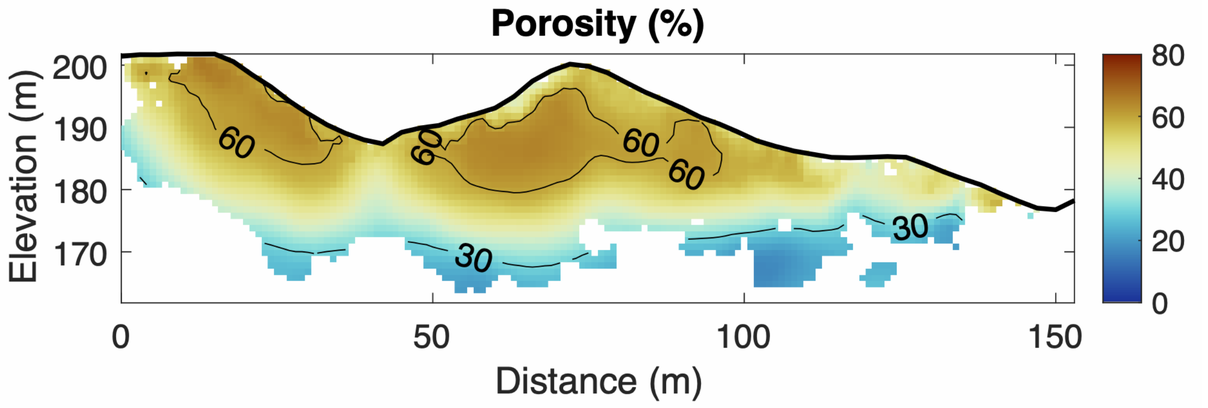


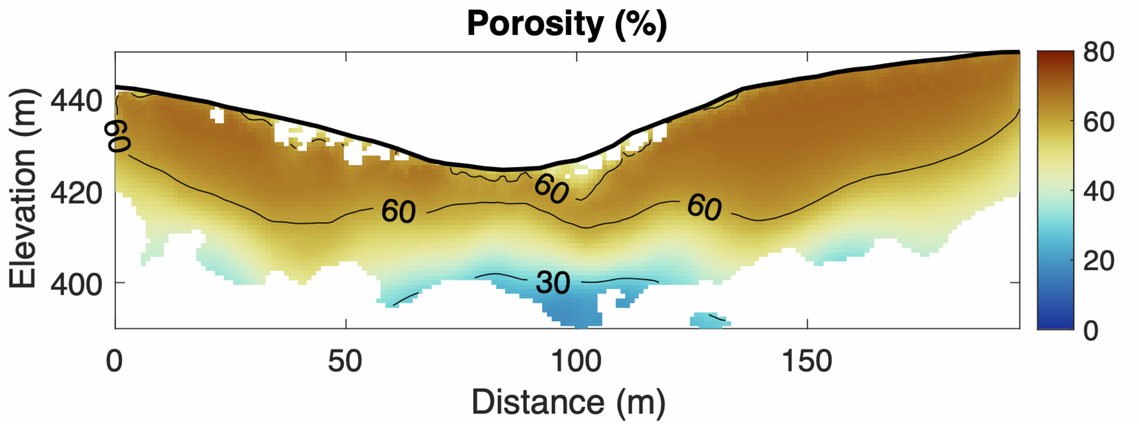


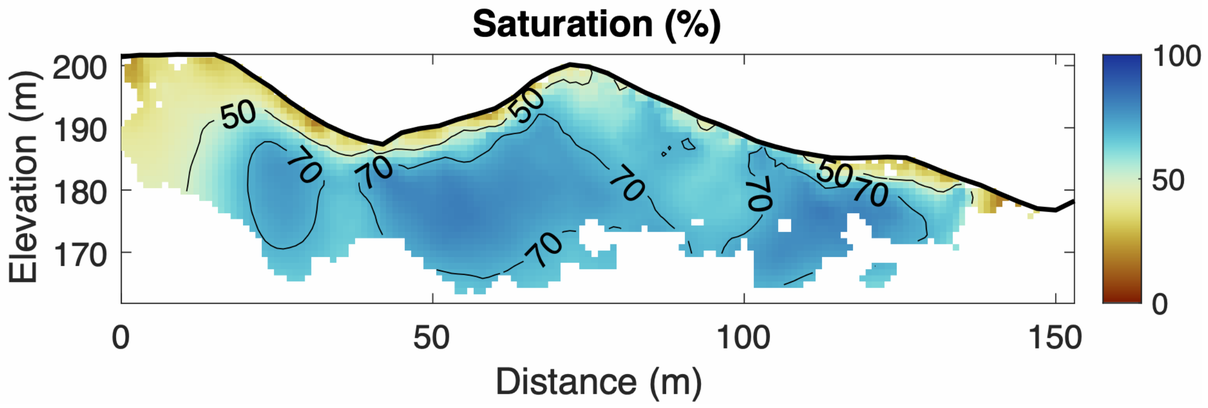
Constraining porosity and saturation

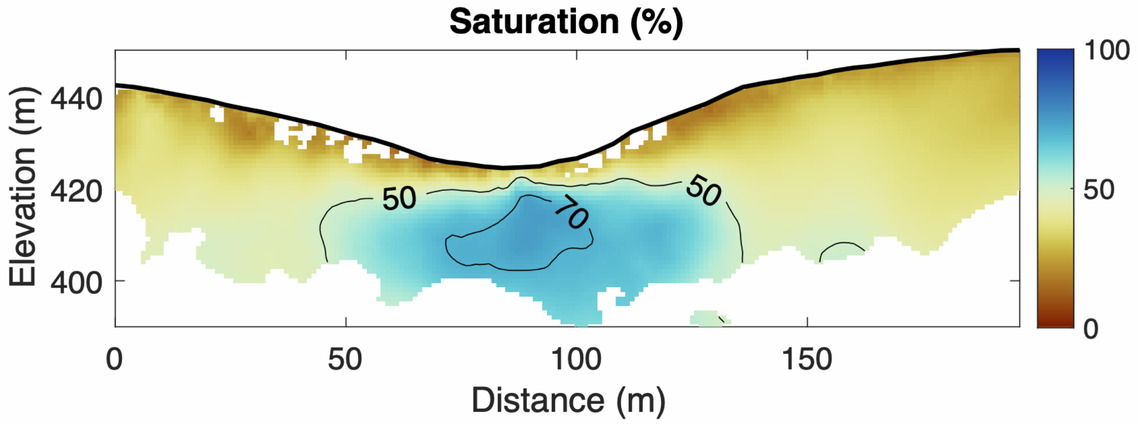
Escarpment (casa boxer)

Plateau top (campo rojo)





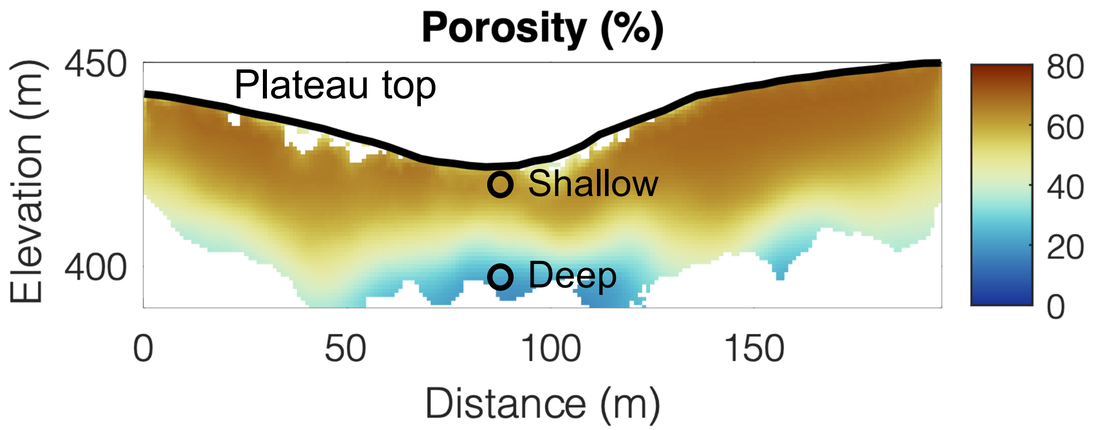


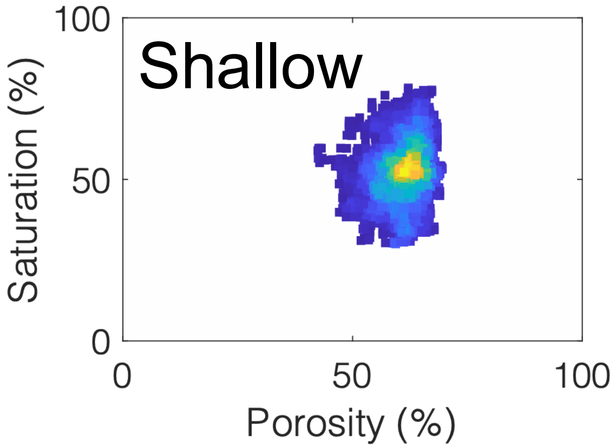


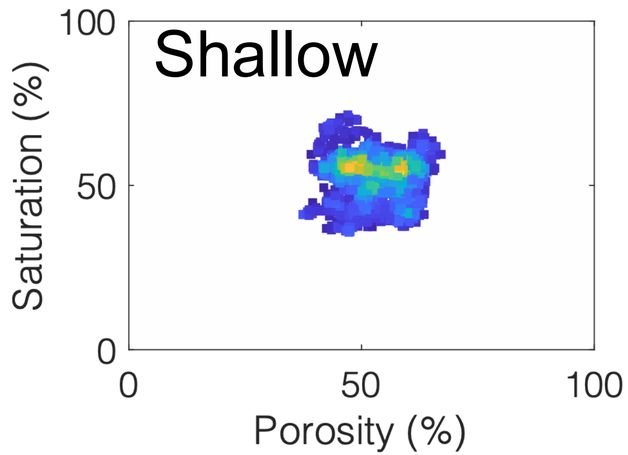
Probability density distribution of porosity and saturation distribution

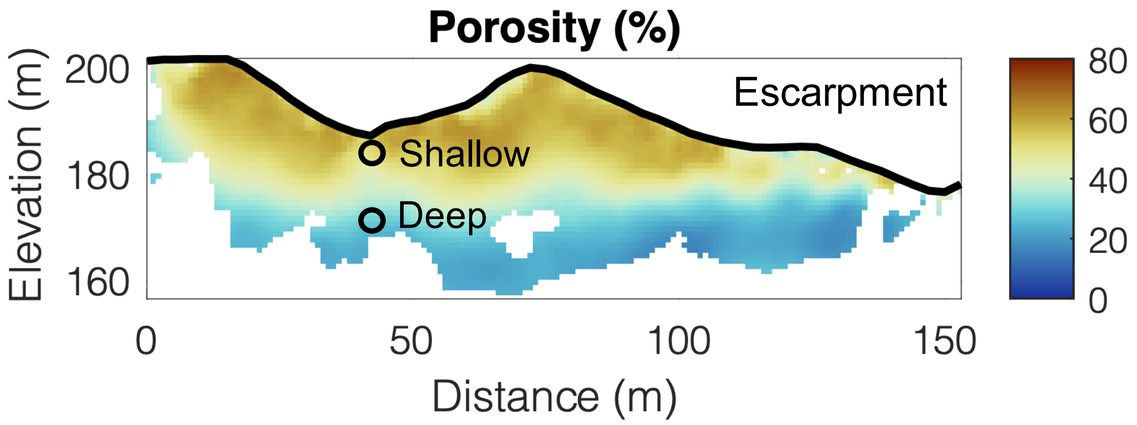
Plateau top

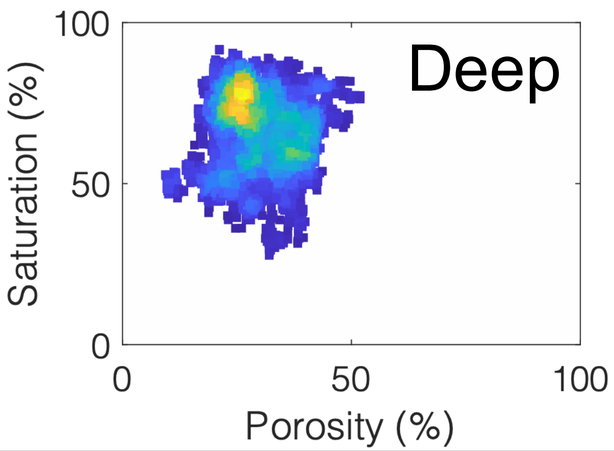
Escarpment

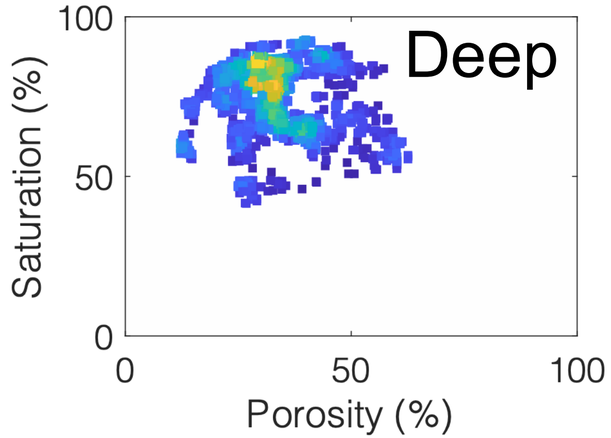








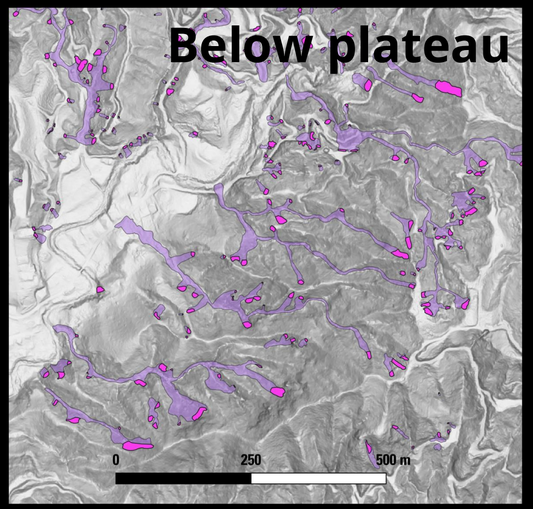


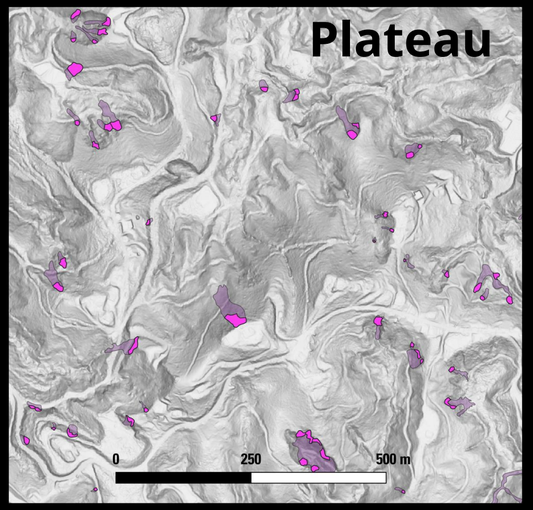


Landslide population above and below the knickpoints

Why are there fewer landslides on the plateau during Maria?

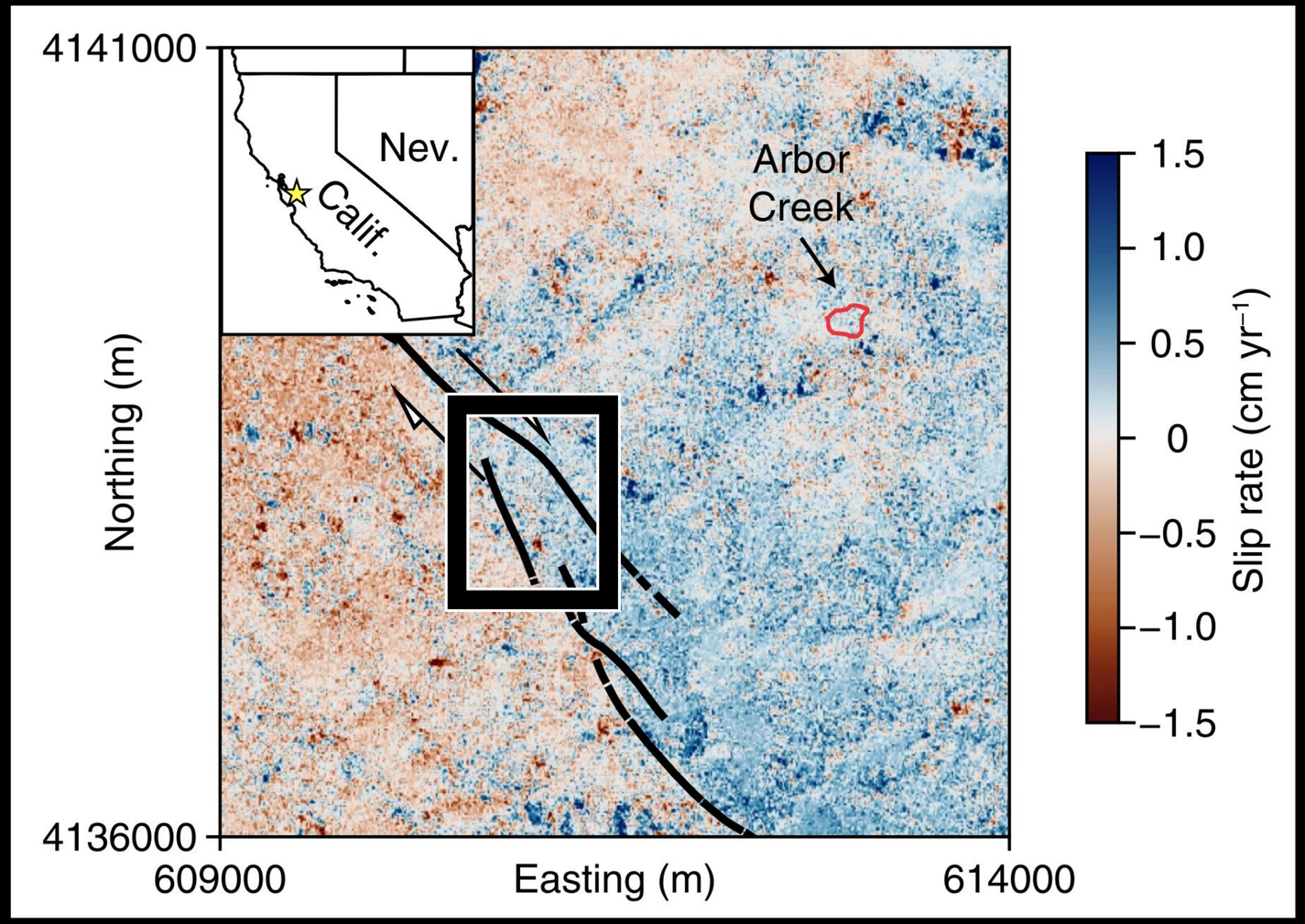
- Porosity:
  - Plateau top: much higher porosity
  - Escarpment: rapid increase of strength on the escarpment
- Saturation:
  - Plateau top: drier; might take longer time to wet up
  - Escarpment: much higher saturation; faster to reach full saturation (despite a higher saprolite strength)
- Rainfall intensity: 20 mm/day to reach total saturation for soils with > 50% saturation in Utuado (Thomas et al. 2020)
- Reasons for fewer landslides on the plateau?

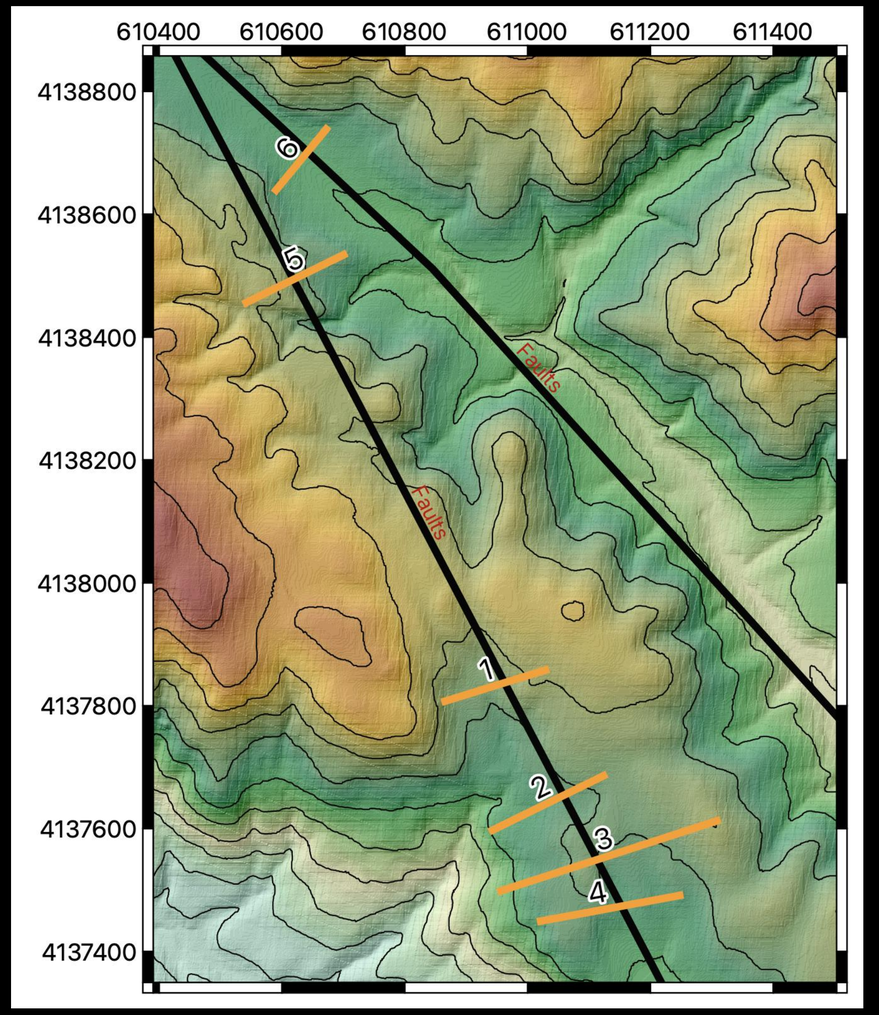




Part 2 - Detecting fault damage zone

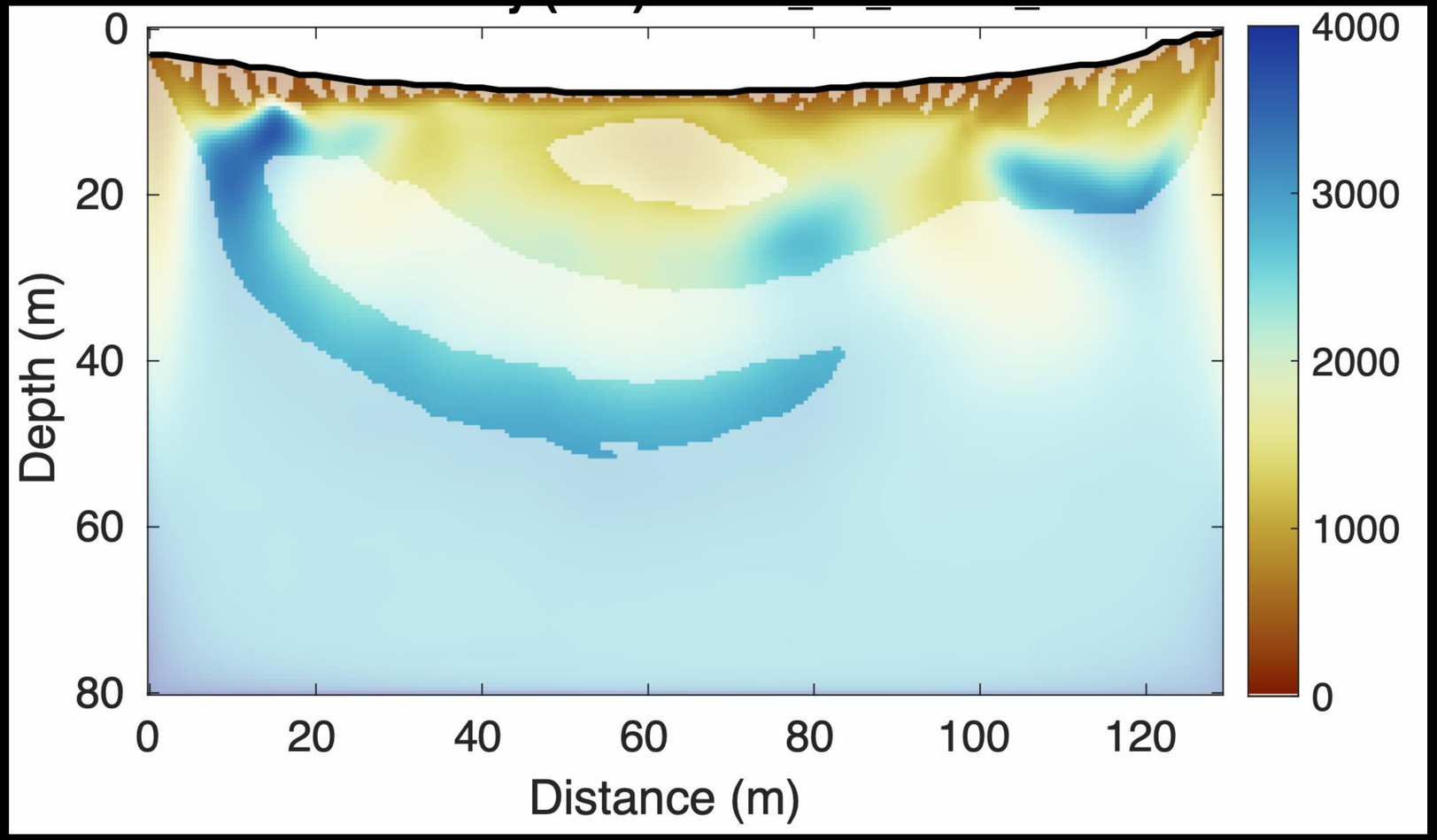
Calaveras Fault



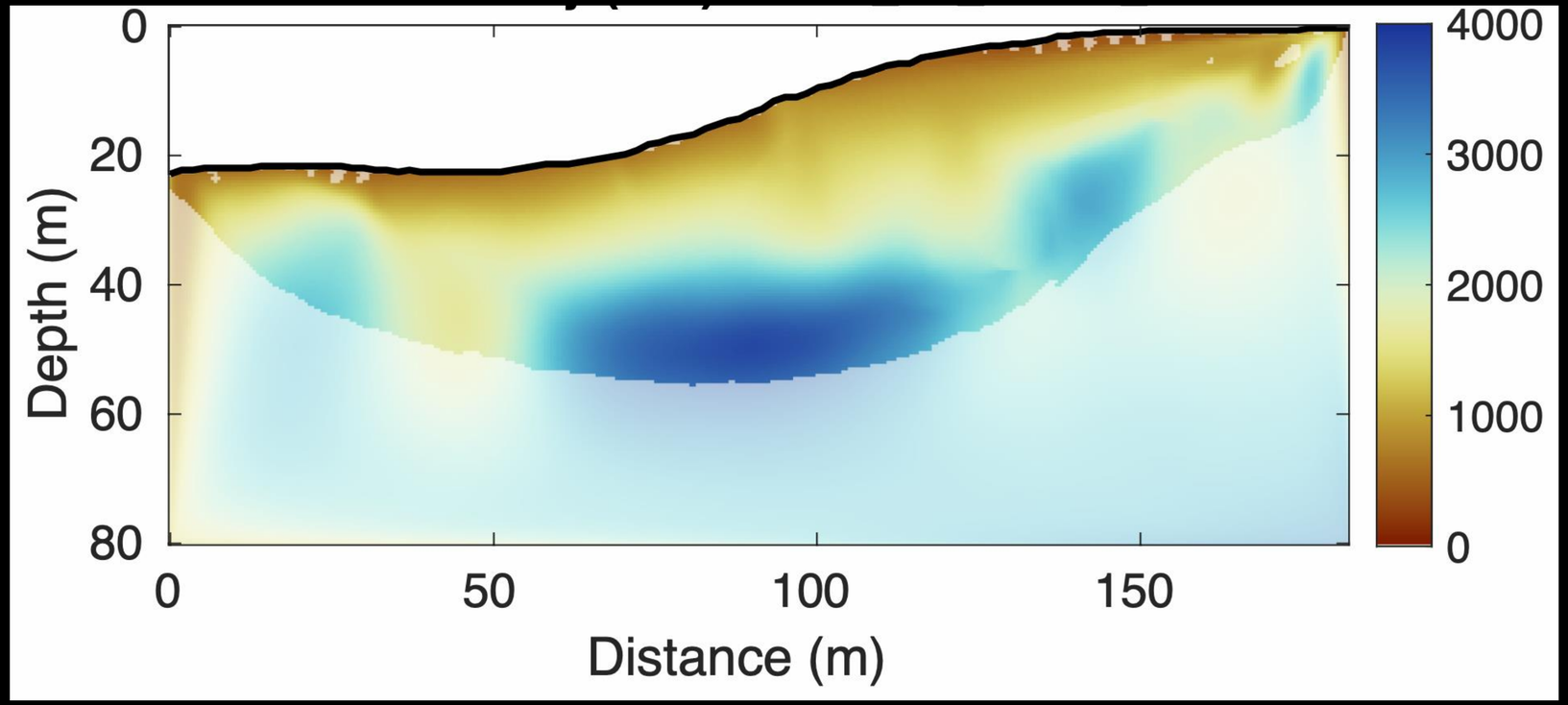


Seismic profile across the ma

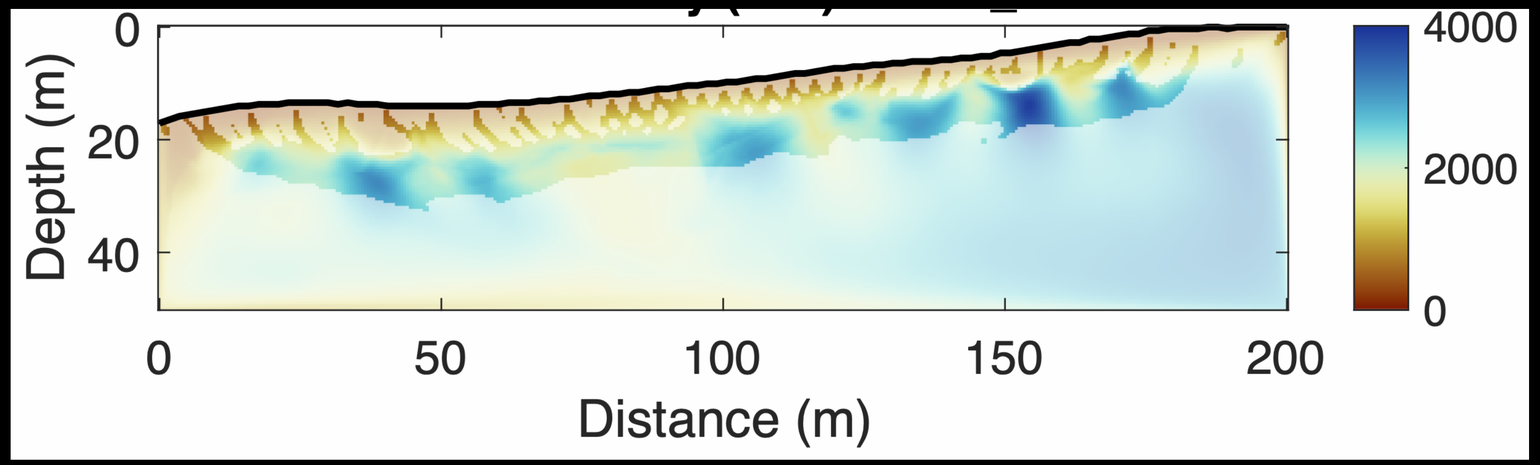
Currently locked or not creeping

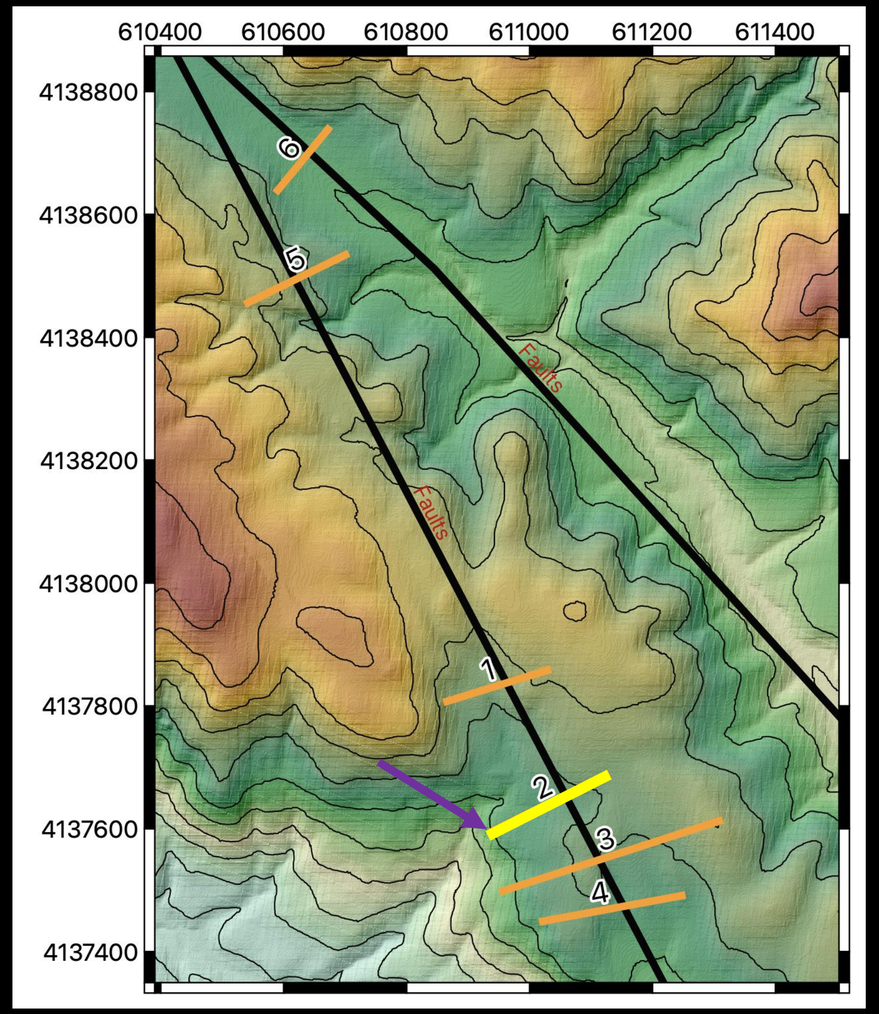


Seismic profile across the cre



Seismic profile across the creeping section





Summary

- The ”creeping” section of the Calaveras fault is a few km SW of the main strand and doesn’t have a clear topographic expression
- There isn’t a clear damage zone along the creeping section. Perhaps the damage zone is not well developed here yet?
- Along the main fault strand that is currently not creeping, a low velocity zone is better developed.
- Using other geophysics methods (ERT, GPR, magnetometer, etc.).
- A joint seismic and resistivity measurements may better evaluate the variation of porosity (and material strength) as well as moisture content.

Thank you!

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