Imaging Critical Zone Processes

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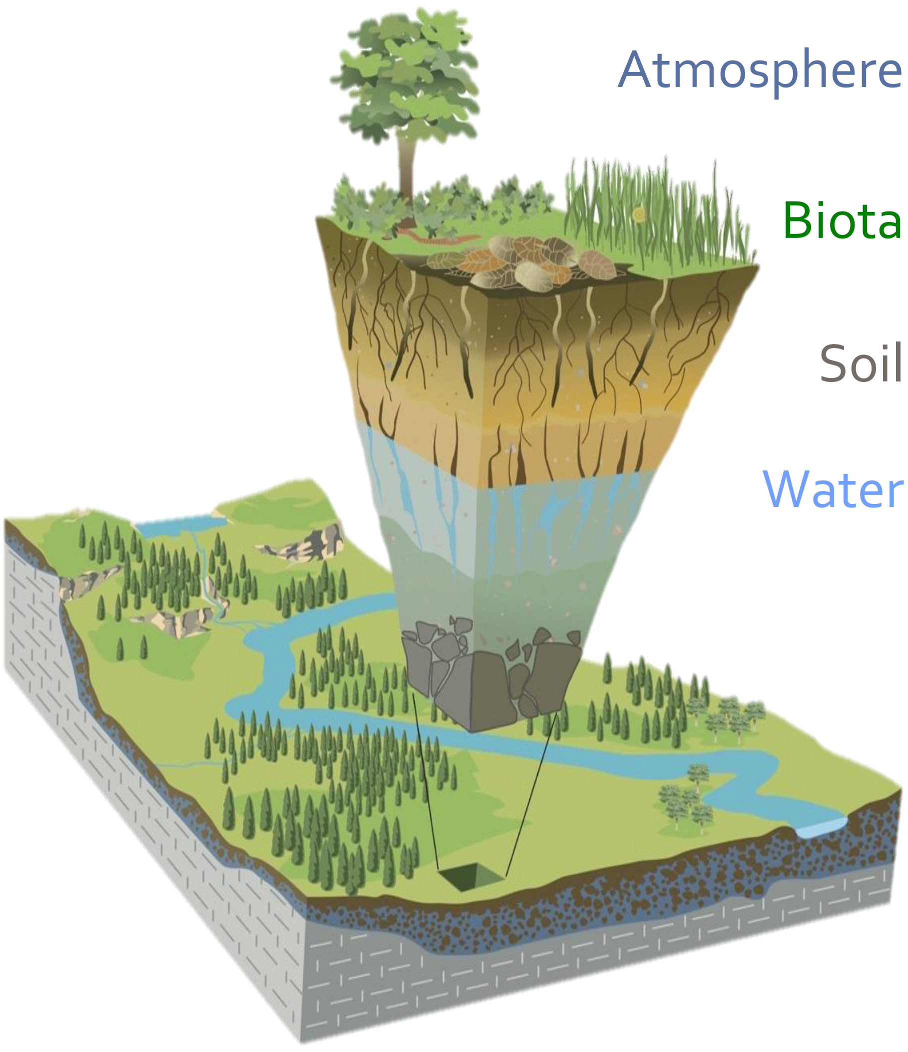
Key critical zone processes

1. Delivery of water/energy to the subsurface
2. Transformation of rock into soil
3. Links between vegetation and hydrology
4. Controls on terrestrial carbon
5. Changes in CZ services with disturbance

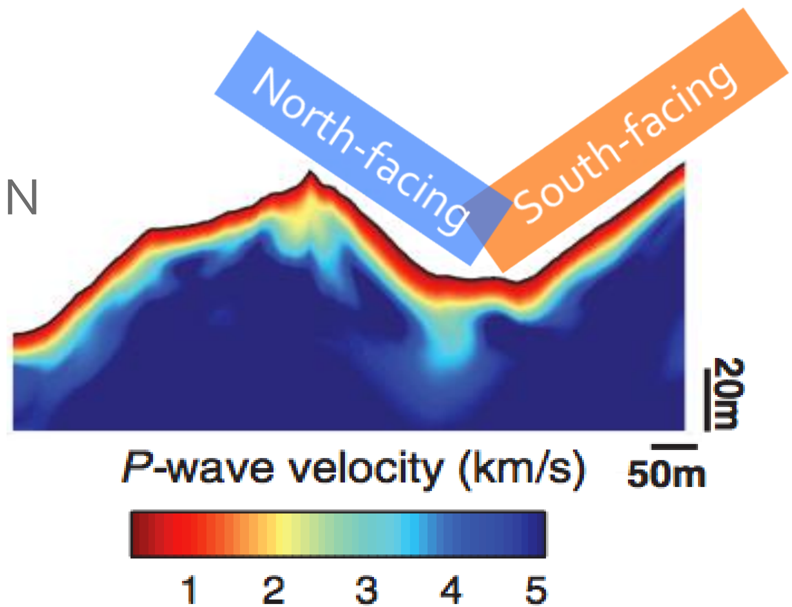
[Sullivan et al., 2017, New Opportunities for Critical Zone Science]



[Chorover et al., 2007, *Elements*]

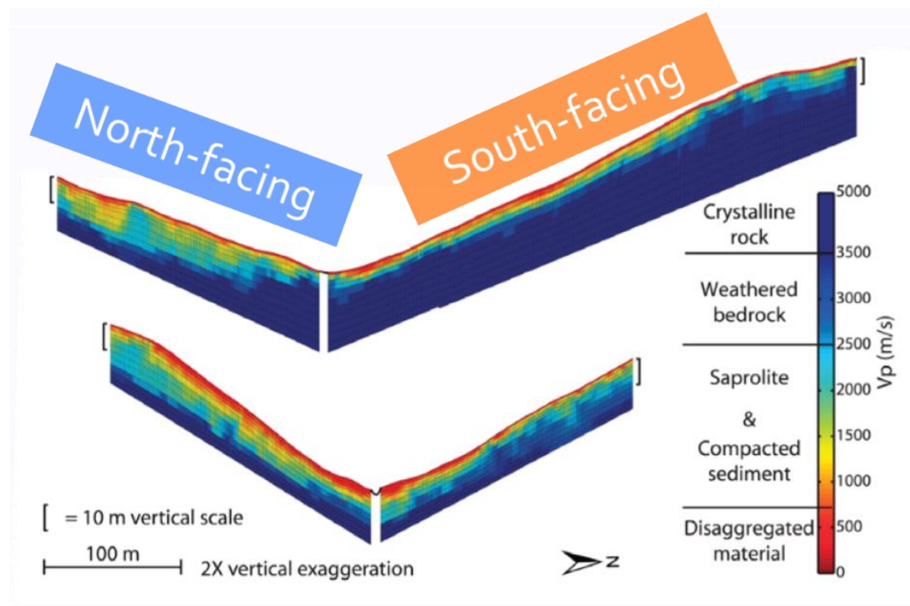
Geophysical observations provide a "macroscope" into subsurface

- Minimally: a better way to interpolate
- Better: a way to explore CZ controls, processes



[St. Clair et al., 2015, *Science*]

Little difference in regolith thickness with slope aspect



[Befus et al., 2011, *VZJ*]

Thicker regolith on N-facing slopes

A lot has happened since 2015

AGU PUBLICATIONS

Reviews of Geophysics

REVIEW ARTICLE

10.1002/2014RG000465

Multiscale geophysical imaging of the critical zone

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Key Points:
- Geophysics as a tool for imaging of critical zone processes
- Can image deep critical zone where direct measurements are limited
- Examples of recent successes and opportunities for the future

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Abstract Details of Earth's shallow subsurface—a key component of the critical zone (CZ)—are largely obscured because making direct observations with sufficient density to capture natural characteristic spatial variability in physical properties is difficult. Yet this inaccessible region of the CZ is fundamental to processes that support ecosystems, society, and the environment. Geophysical methods provide a means for remotely examining CZ form and function over length scales that span centimeters to kilometers. Here we present a review highlighting the application of geophysical methods to CZ science research questions. In particular, we consider the application of geophysical methods to map the geometry of structural features such as regolith thickness, lithological boundaries, permafrost extent, snow thickness, or shallow root zones. Combined with knowledge of structure, we discuss how geophysical observations are used to understand CZ processes. Fluxes between snow, surface water, and groundwater affect weathering, groundwater resources, and chemical and nutrient exports to rivers. The exchange of gas between soil and the atmosphere

What CZ scientists would like

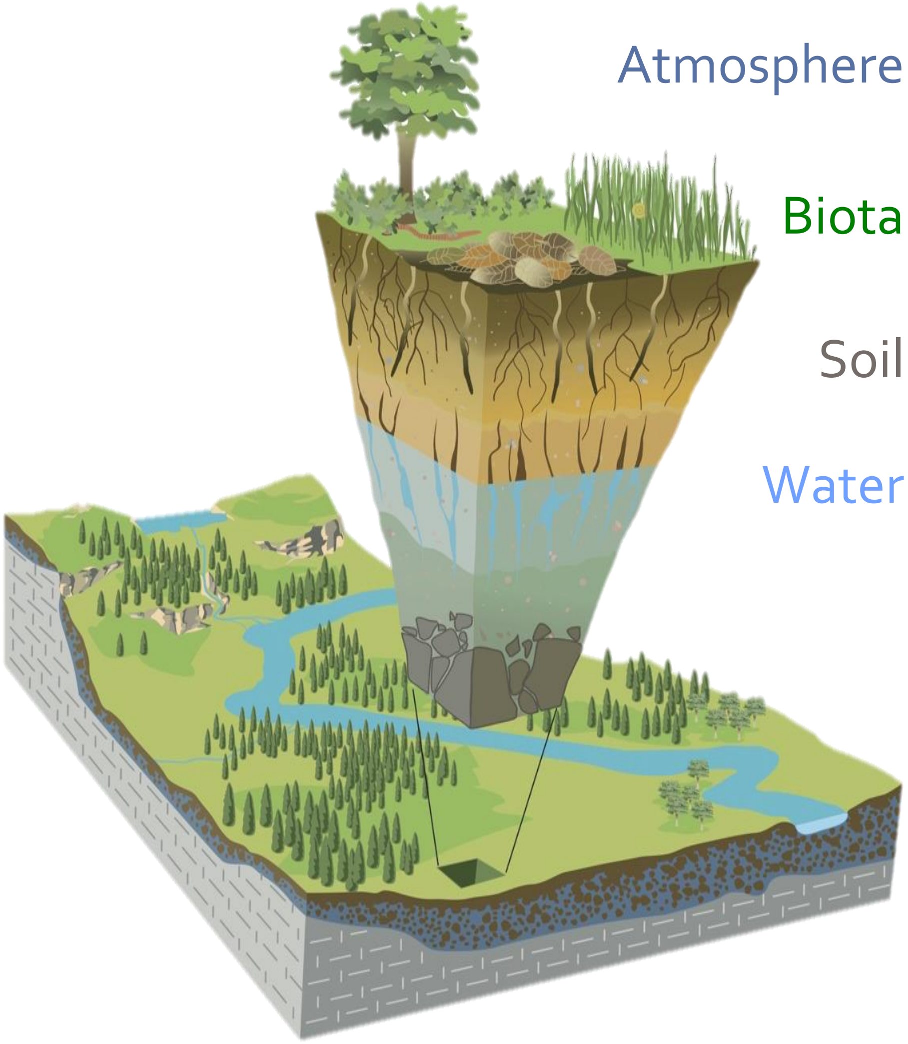
Macroscopic distributions of:

- Porosity
- Bulk density
- Chemical/mineralogical composition
- Mineral surface area
- Root distributions
- Subsurface “connectivity”
- …

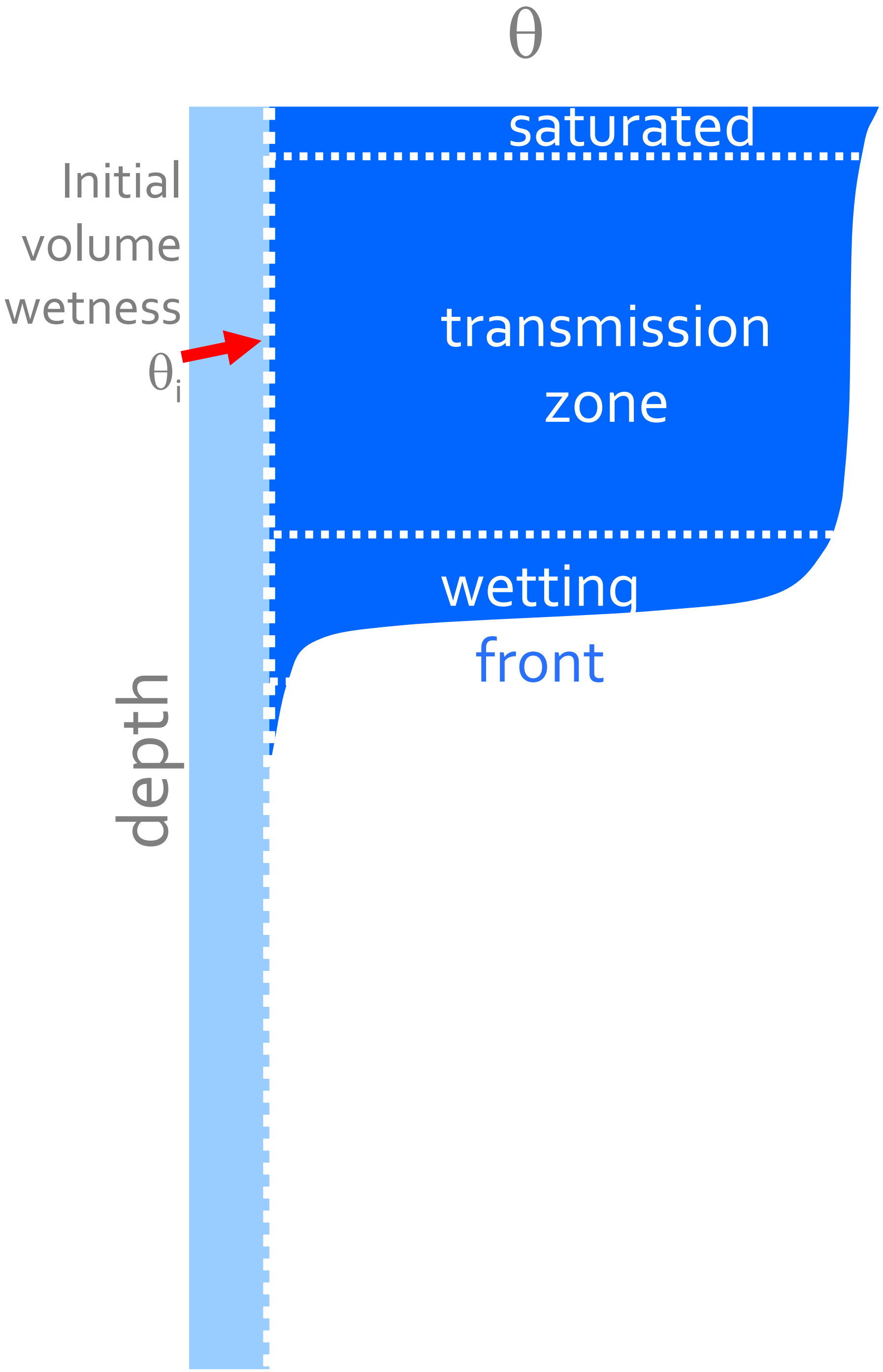
Key critical zone processes

1. Delivery of water/energy to the subsurface
2. Transformation of rock into soil
3. Links between vegetation and hydrology
4. Controls on terrestrial carbon
5. Changes in CZ services with disturbance

[Sullivan et al., 2017, New Opportunities for Critical Zone Science]



[Chorover et al., 2007, *Elements*]

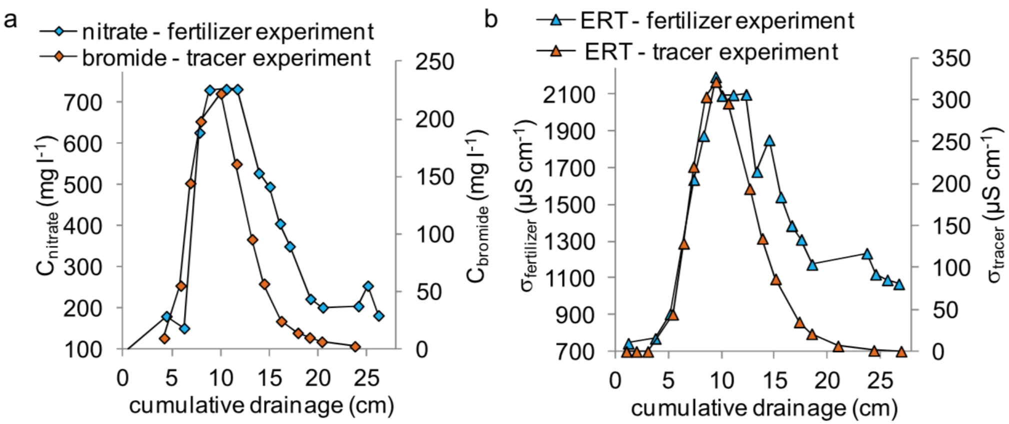


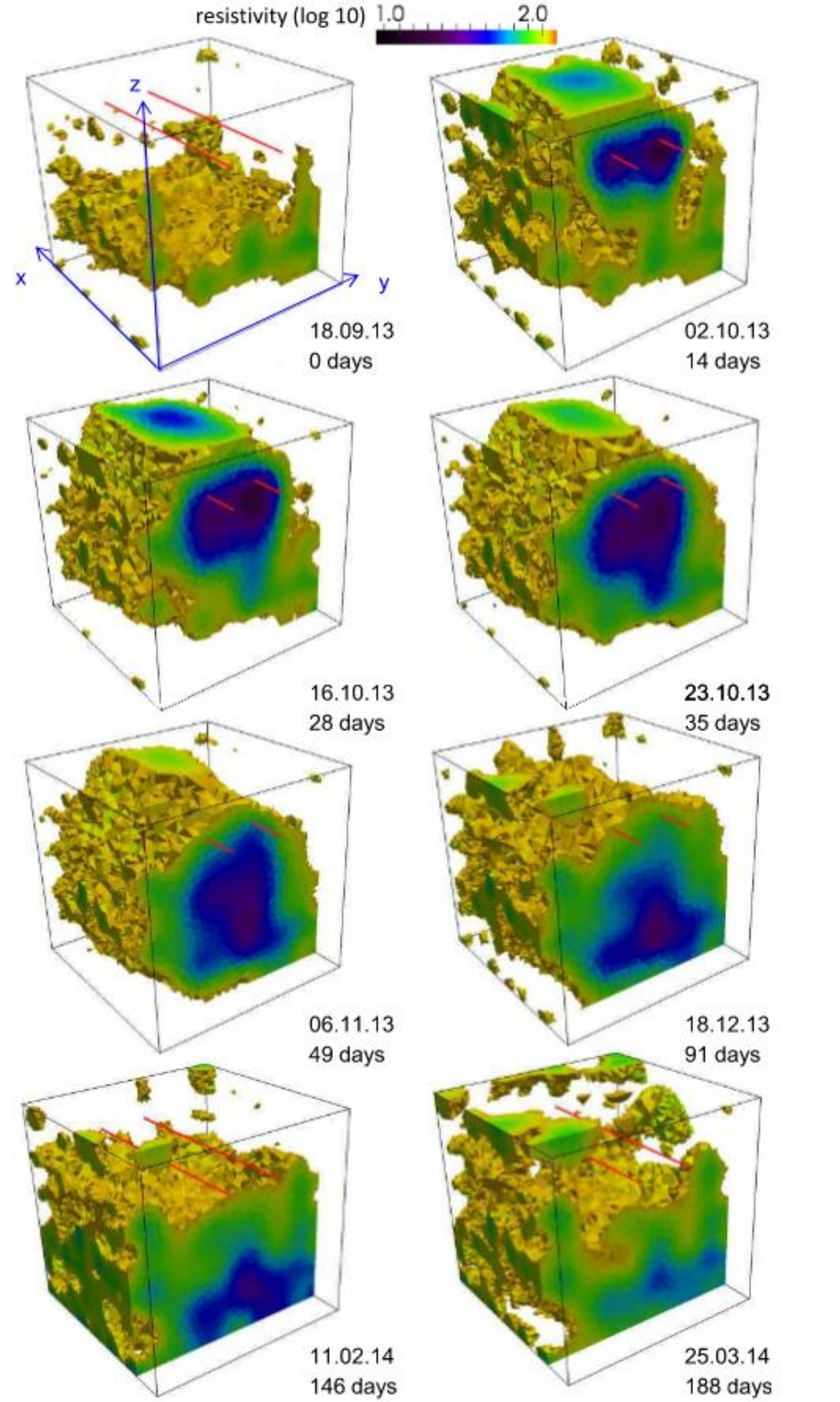
1) Delivery of water into the subsurface*

- Controls a variety of ecosystem services
- Moisture is generally an easy geophysical target
  - Δ electrical resistivity
  - Δ dielectric permittivity
  - Δ seismic velocity

*more from Sander Huisman soon

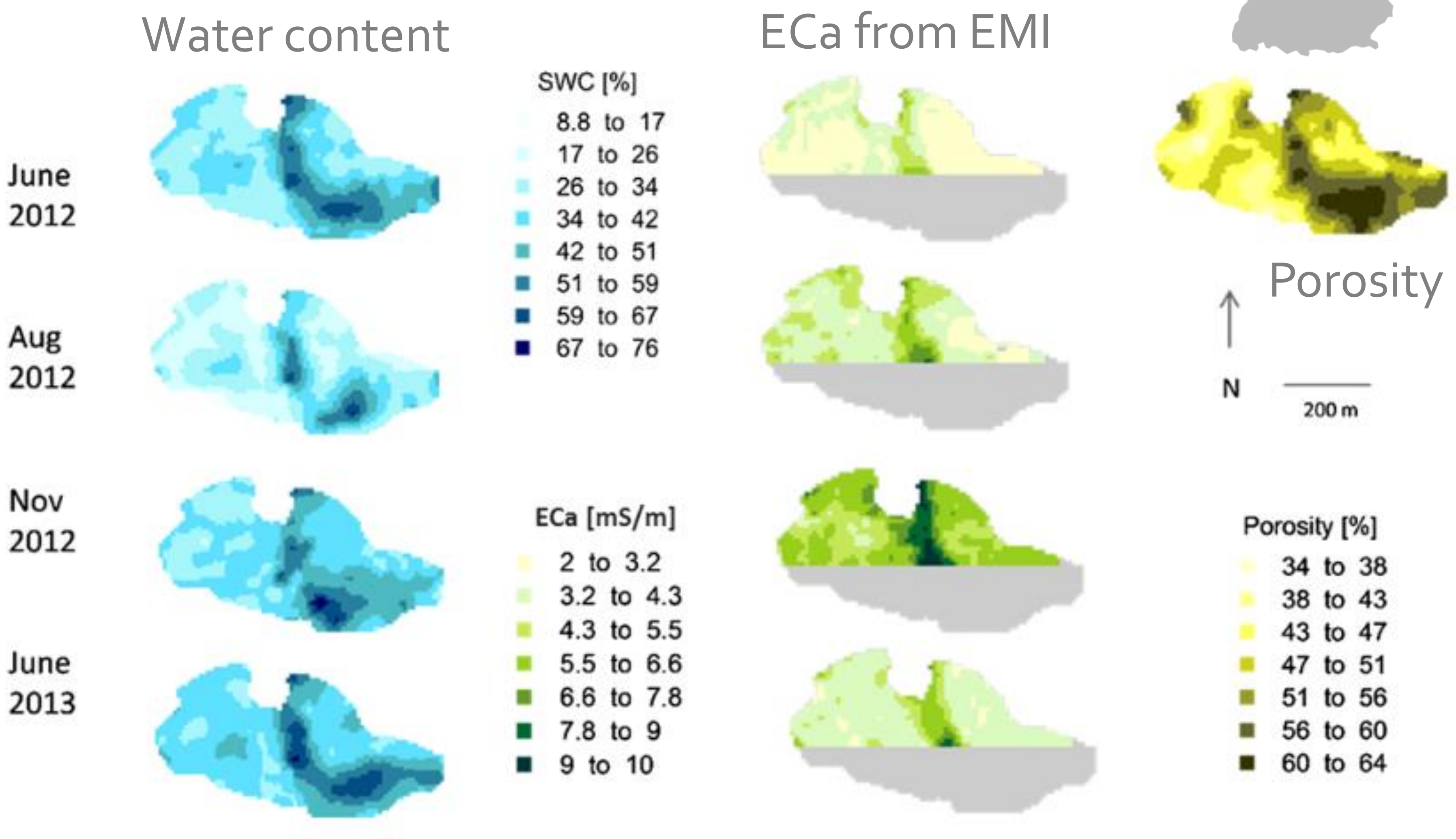
Moving beyond simple conservative tracers





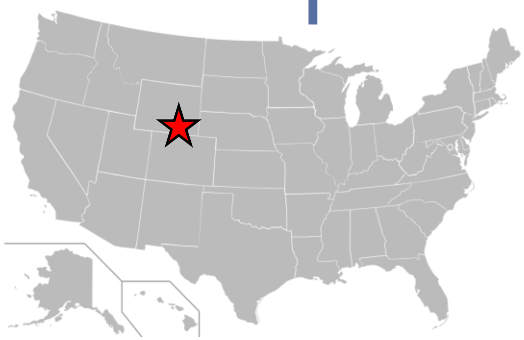
[Wehrer et al., 2016, *WRR*]

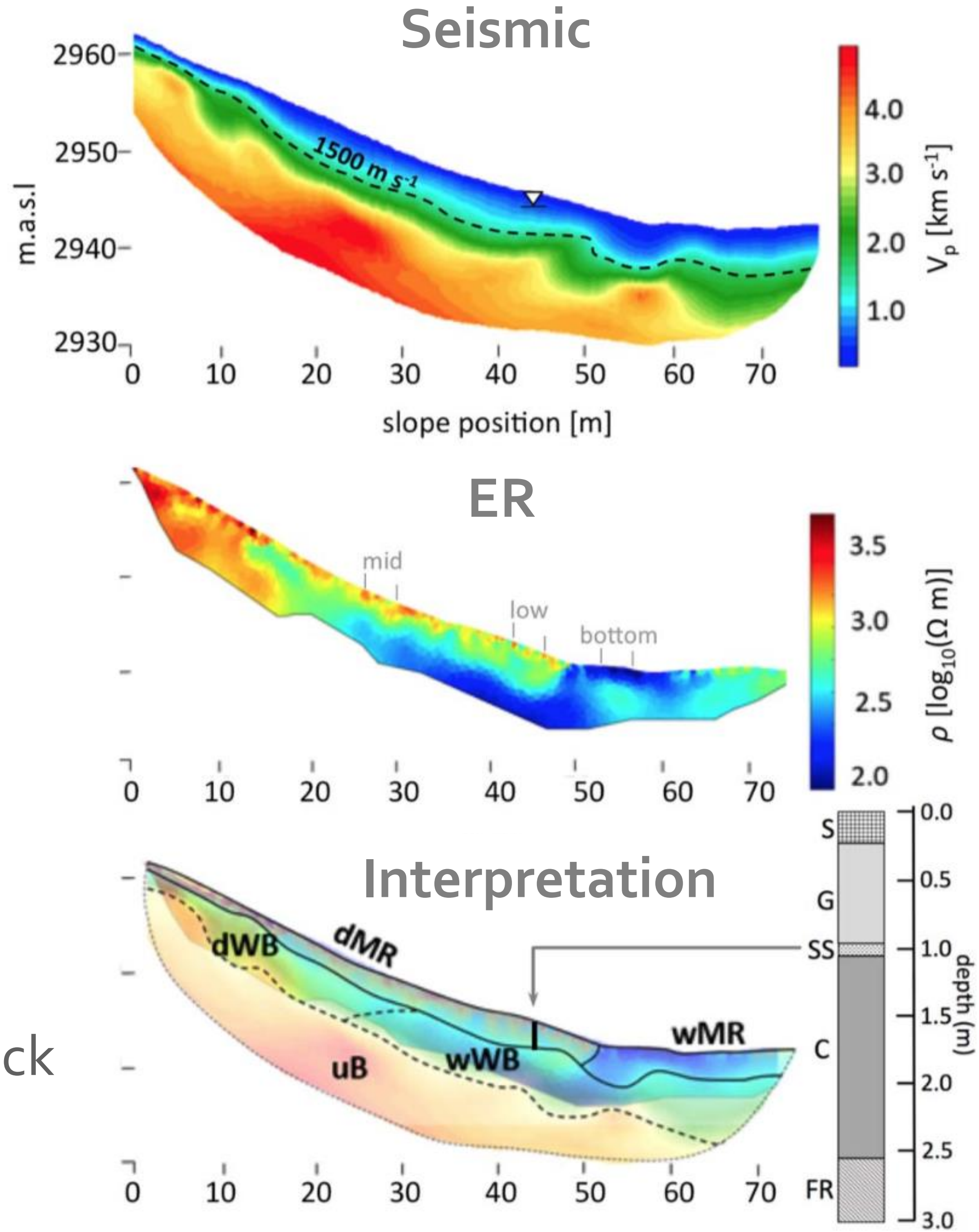
Importance of the right rock physics relations



[Altdorff et al., 2017, *EES*]

What are controls on water movement through a hillslope?



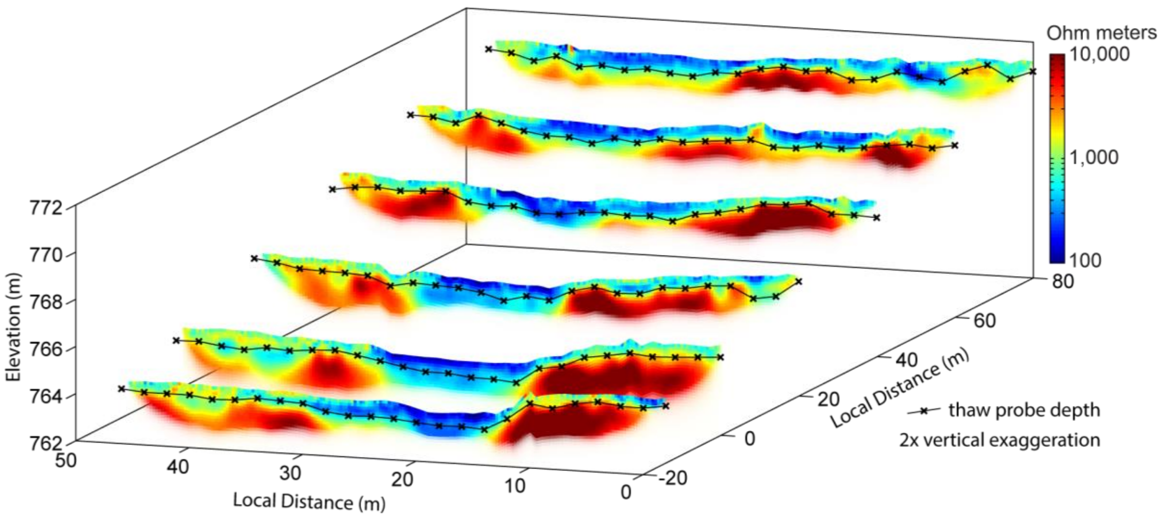


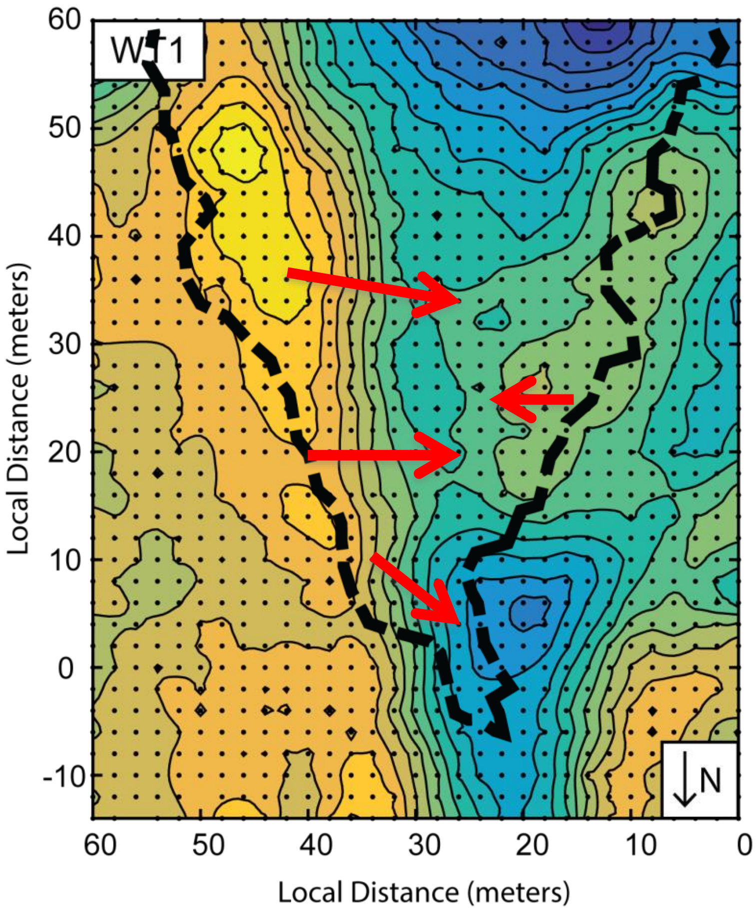
- MR: mobile regolith
- WB: weathered bedrock
- B: bedrock

[Thayer et al., 2018, *WRR*]

Water tracks in the Arctic

Mapping flowpaths in permafrost



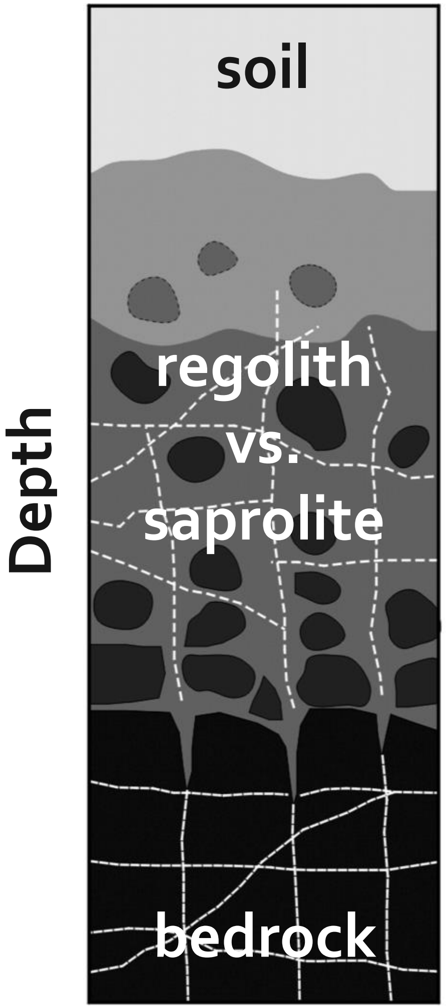


[Voytek et al., 2016, *Geophysics*]

Issues to think about

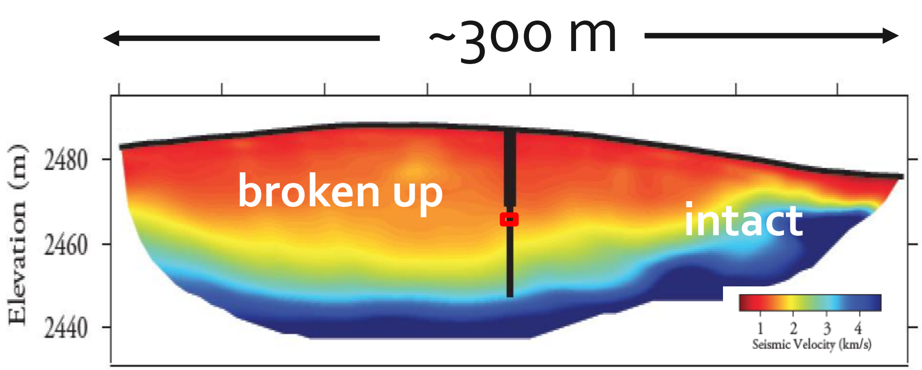
- Testing conceptual models of hydrologic, geochemical processes
- Imaging seasonally changing flow paths
- Developing rock physics relations between geophysics and other key properties

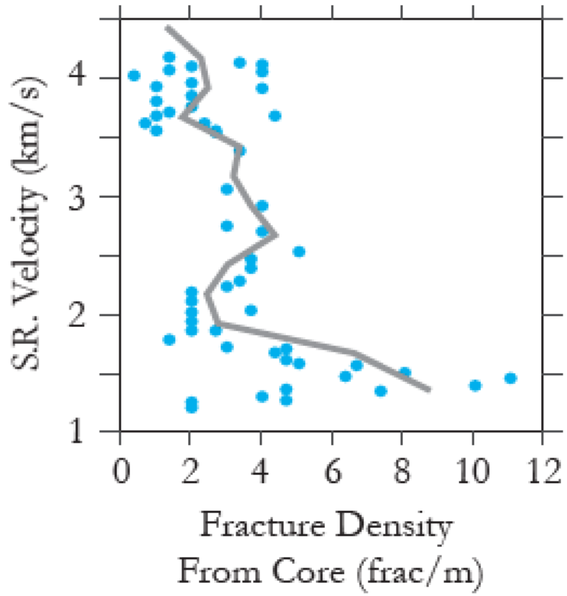
2) Transformation of rock into soil

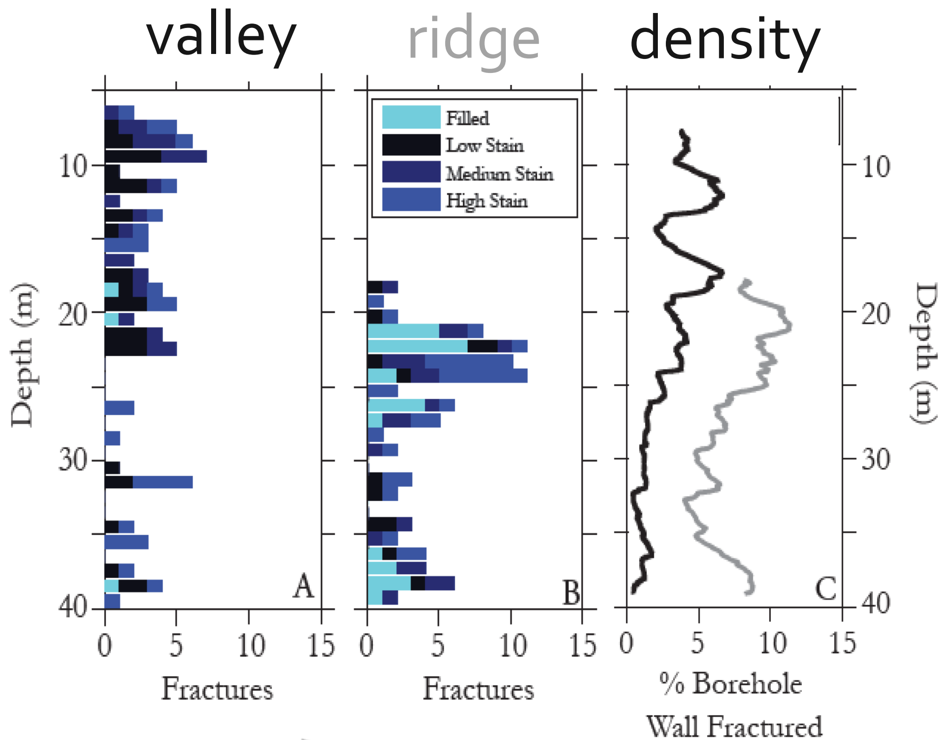


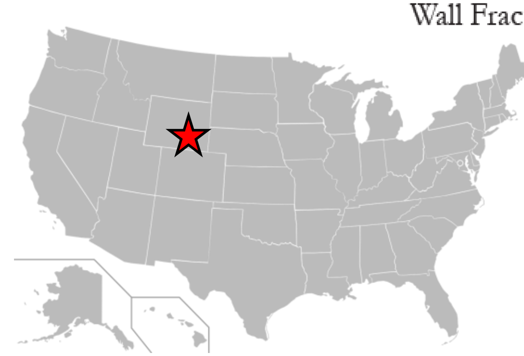
- Weathering of rock at the bedrock-saprolite interface is key to critical zone processes
- Weathered material: prone to landslides, impacting landscape evolution; provides the medium for plant growth
- A good geophysical target

How does weathering vary over a landscape?







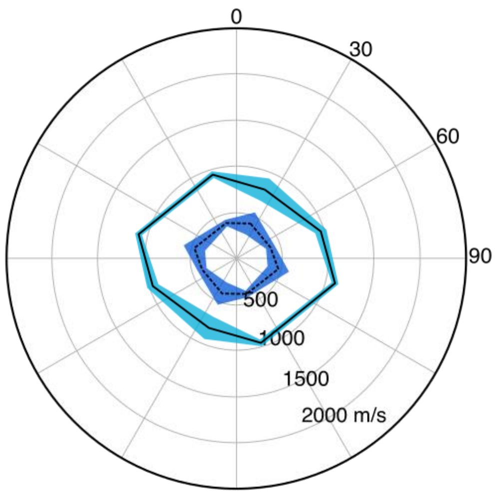


[Hayes et al., in prep]

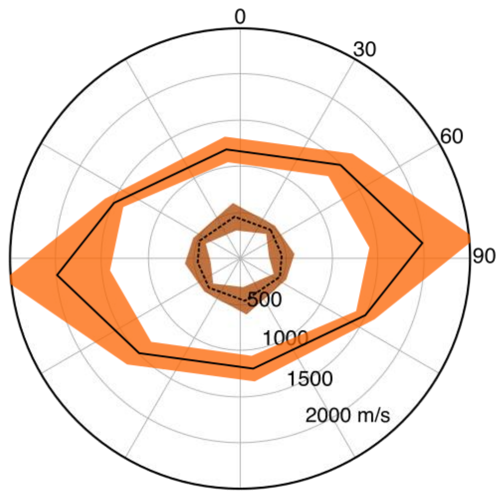
Seismic anisotropy & fracturing

- Soil layer is isotropic; ~500 m/s on N- and S-facing hillslopes

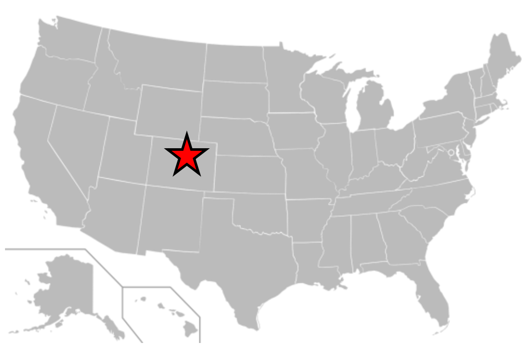
North-facing



South-facing

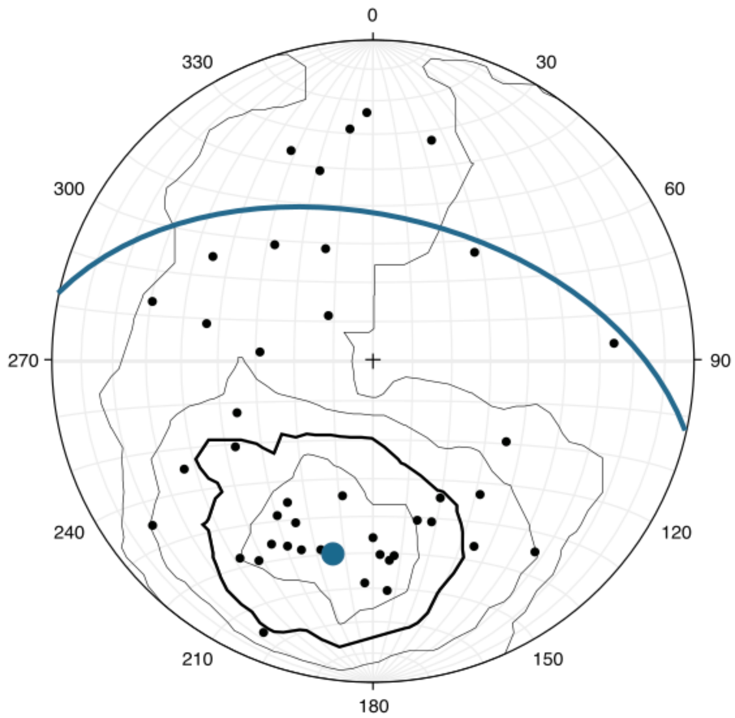


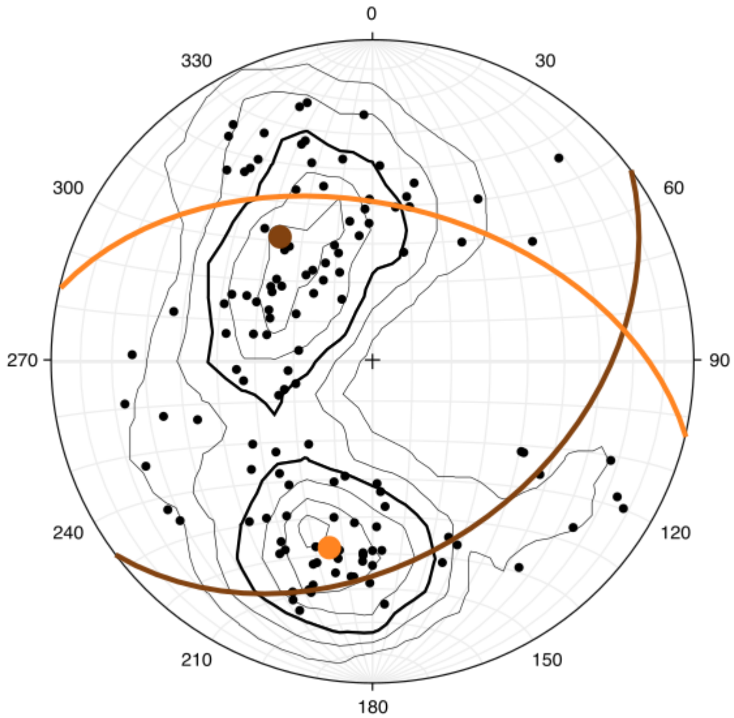
- North-facing regolith:
  - less pronounced anisotropy
  - velocities from ~800-1500 m/s
- South-facing regolith:
  - more pronounced anisotropy
  - velocities from ~1000-2000 m/s



[Pommer et al., in prep]

Fracture orientation is similar on both aspects





North-facing

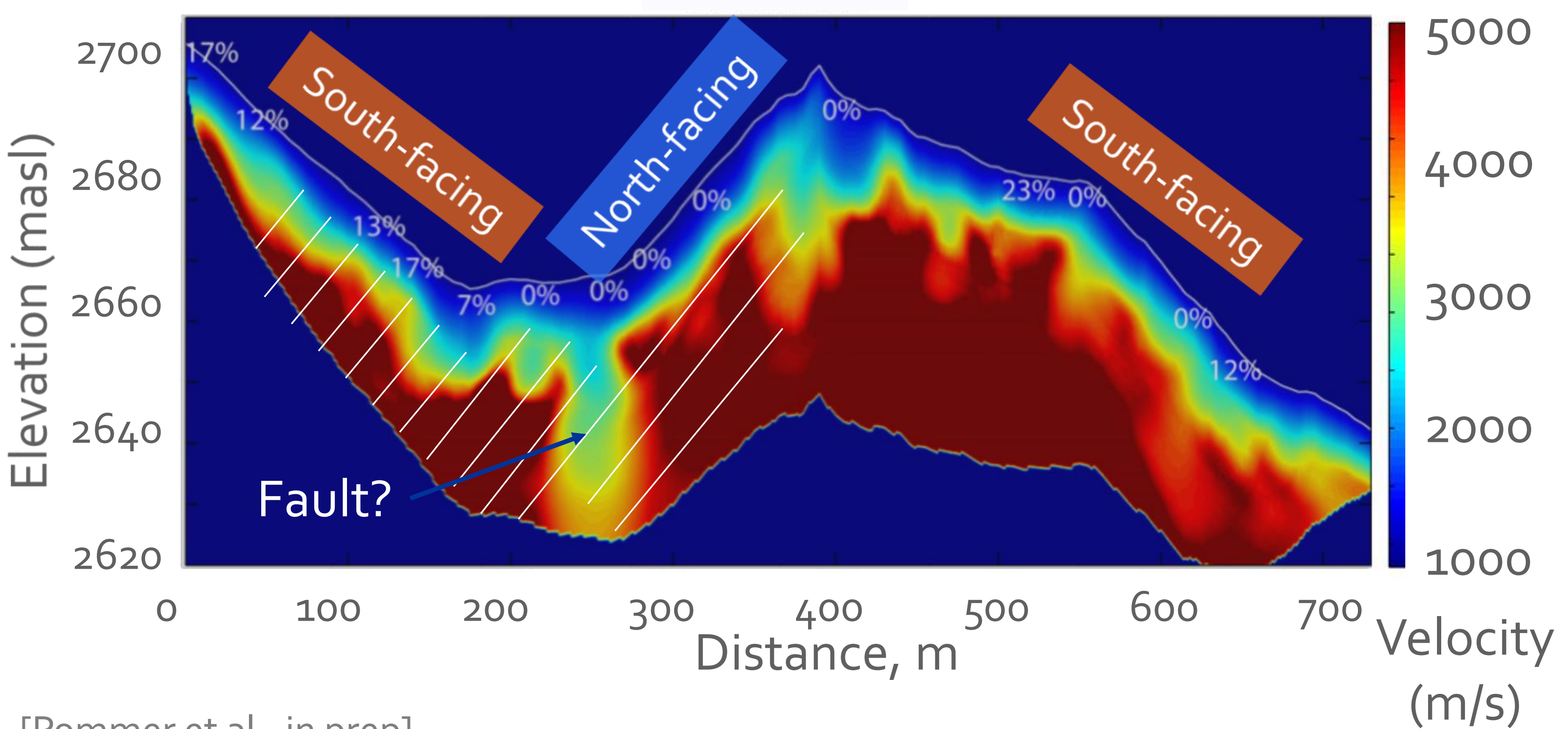
South-facing

No. boreholes	2	5	
Total fractures	42	138	
Mean strike/dip of significant clusters	282°/52°N	054°/40°S	283°/51°N

[Pommer et al., in prep]

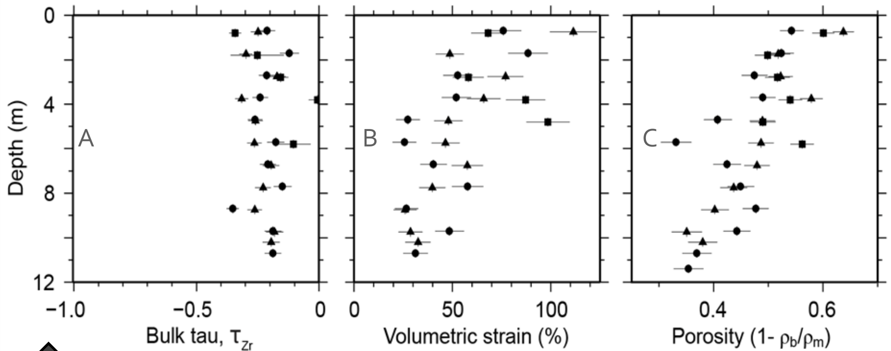
Importance of foliation

S- facing slopes are more deeply weathered, is this because of foliation alignment with topography?

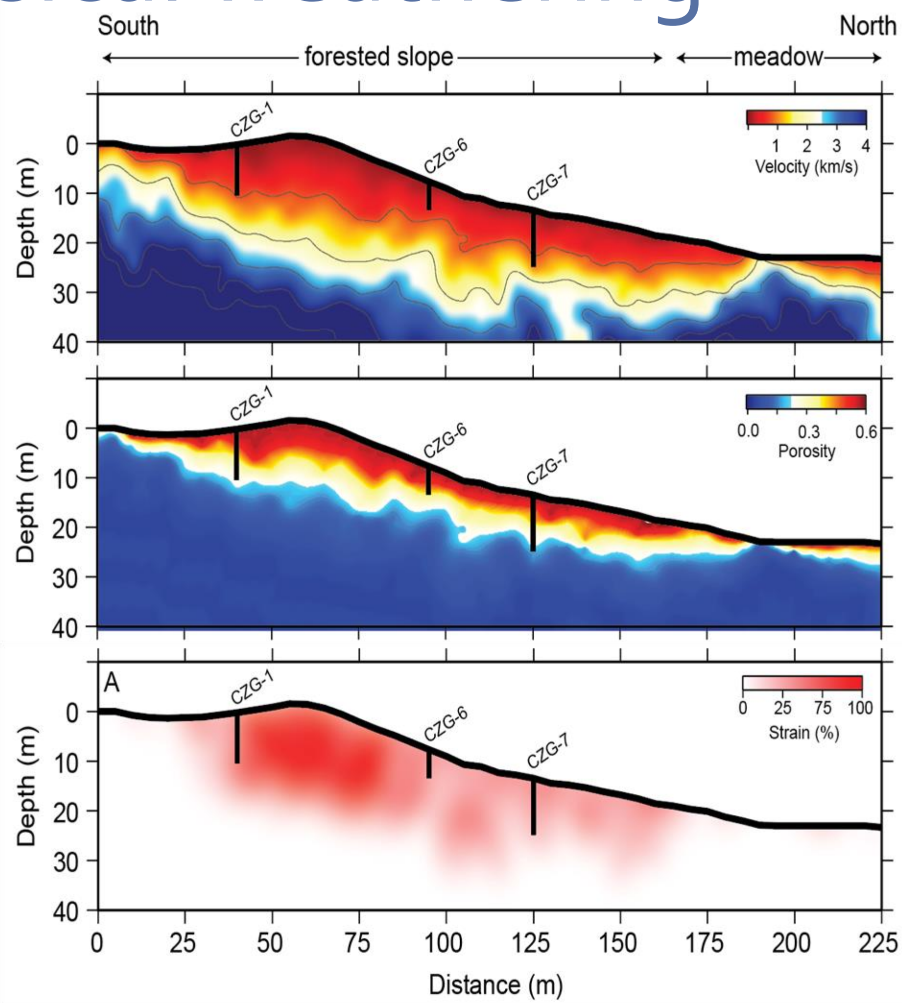


[Pommer et al., in prep]

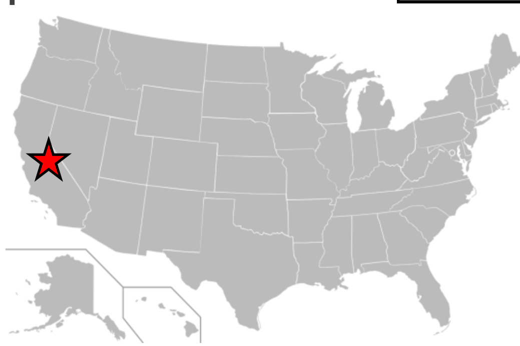
Chemical vs. physical weathering



Mass loss can't describe porosity; strain can



Estimate porosity from seismic refraction velocities; transform to strain



$$\phi_w = 1 - \frac{\tau_b + 1}{\varepsilon + 1}$$

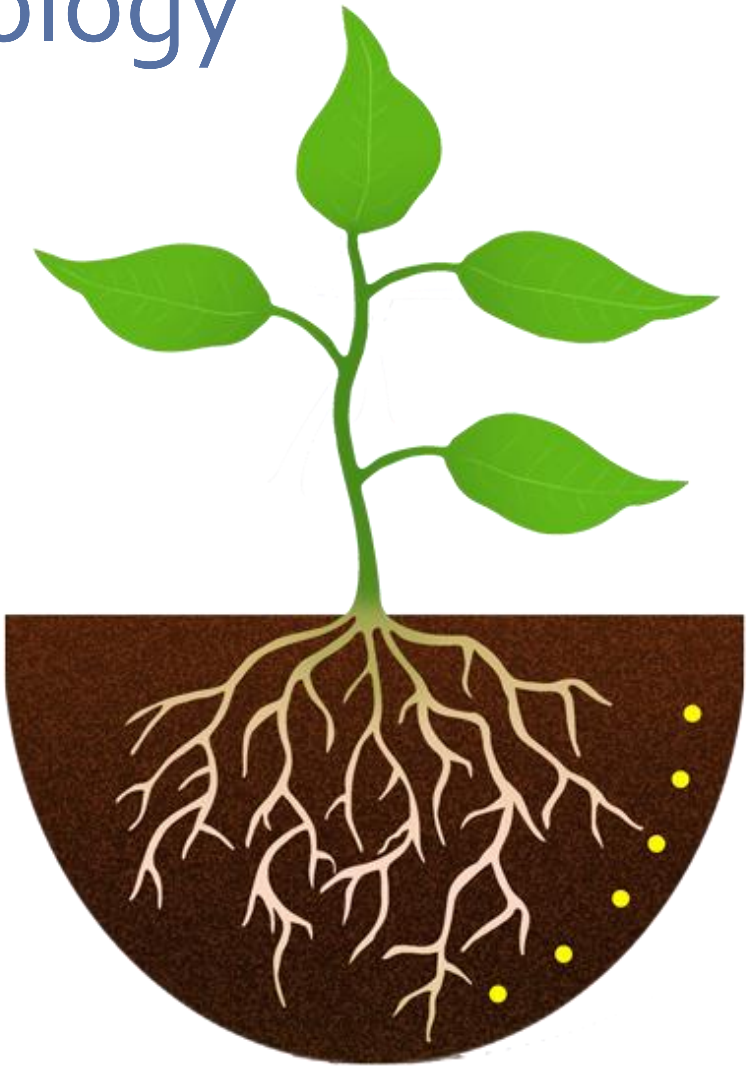
[Hayes et al., in review, *Science Advances*]

Issues to think about

- How to parse physical and chemical weathering?
- What are the controls of regional stress, freeze-thaw processes, physical and chemical heterogeneity on the measured weathering signal?
- Trees!

3) Links between vegetation and hydrology

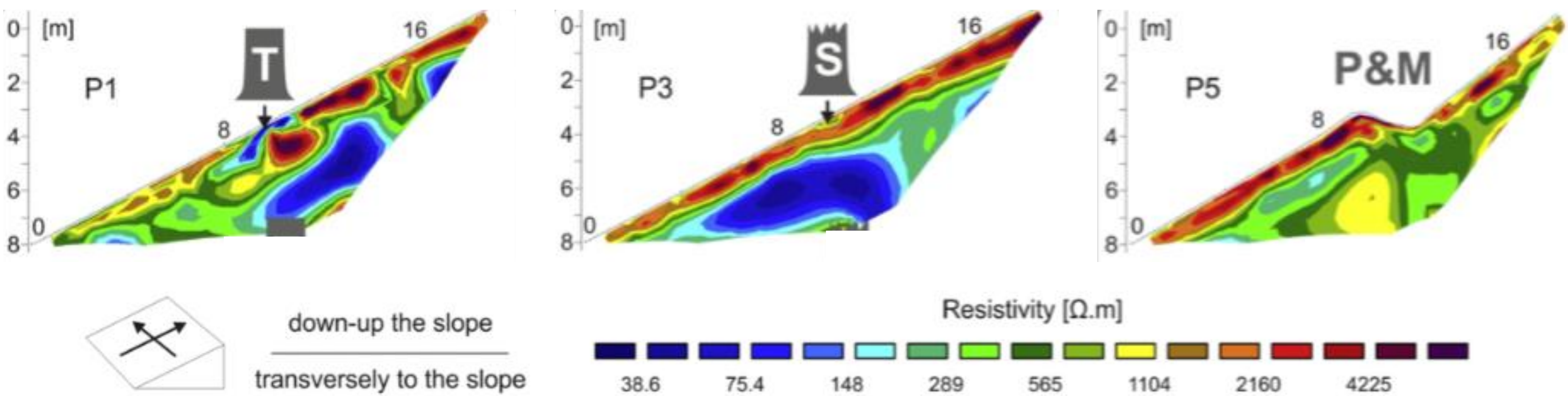
- Geophysics has primarily been used to explore changing moisture content
- What are sensitivities to biogeochemical changes?



Regolith under trees

- Tree roots add complexity
- Large contrast in resistivity under living trees disappears when they die

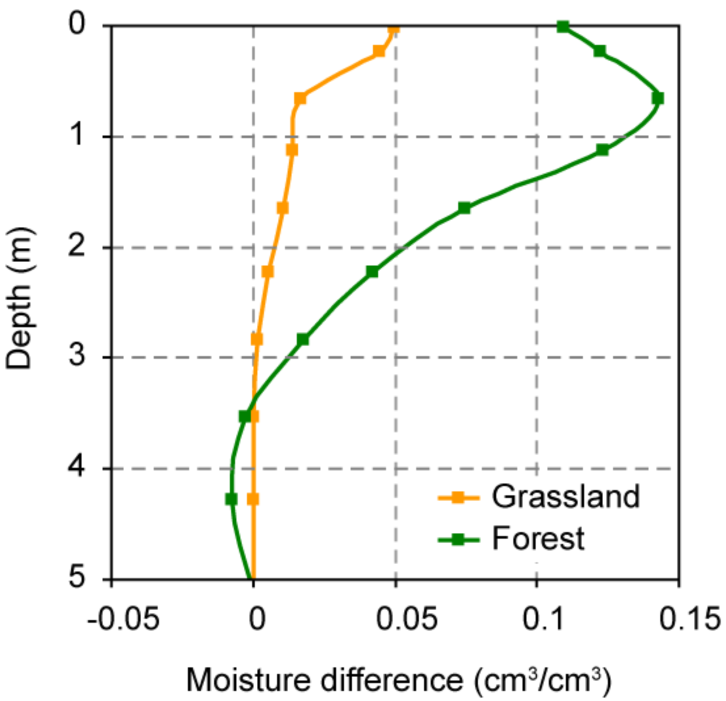
under tree | under stump | pit-and-mound

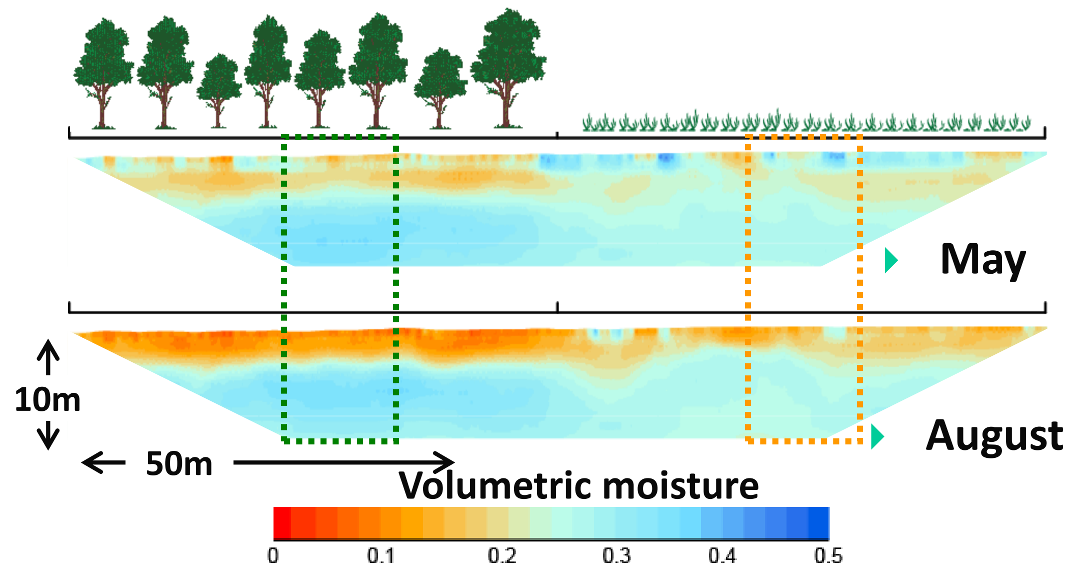


[Pawlik & Kasprzak, 2018, *Geomorphology*]

Early work on rooting depths

Time-lapse ER for soil moisture dynamics reveals rooting depth differences of forest and grassland.





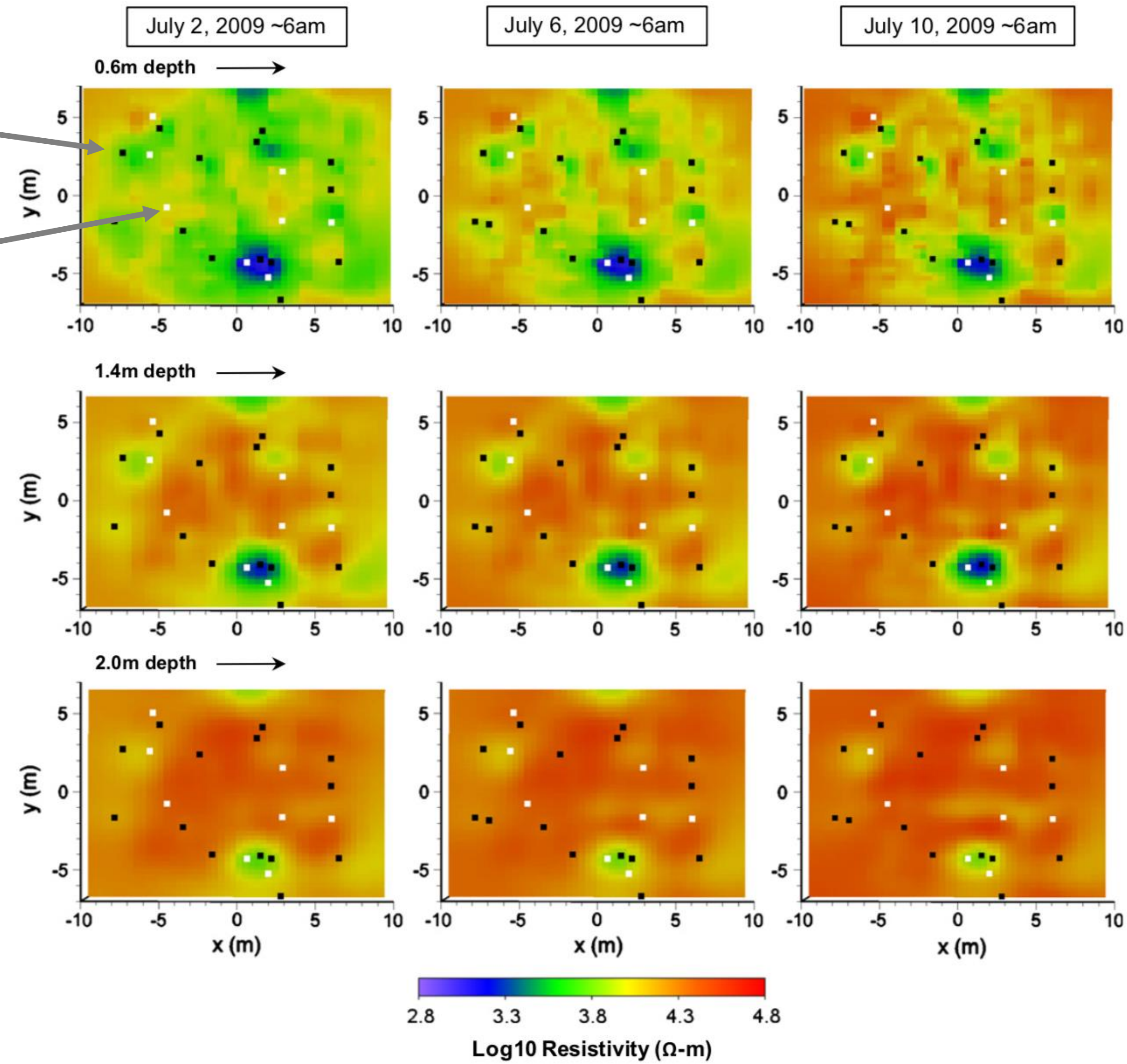
Data enabled improved root parameterization in global climate and landscape hydrology models.

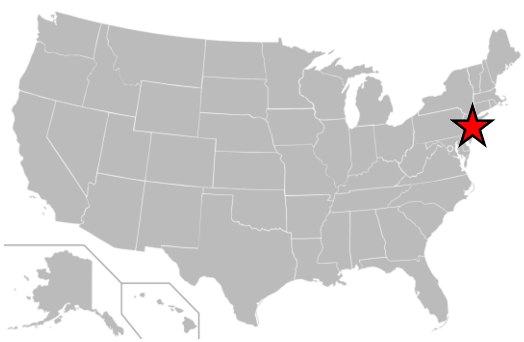
[Jayawickreme et al., 2008, *GRL*]

Imaging hydraulic redistribution

trees

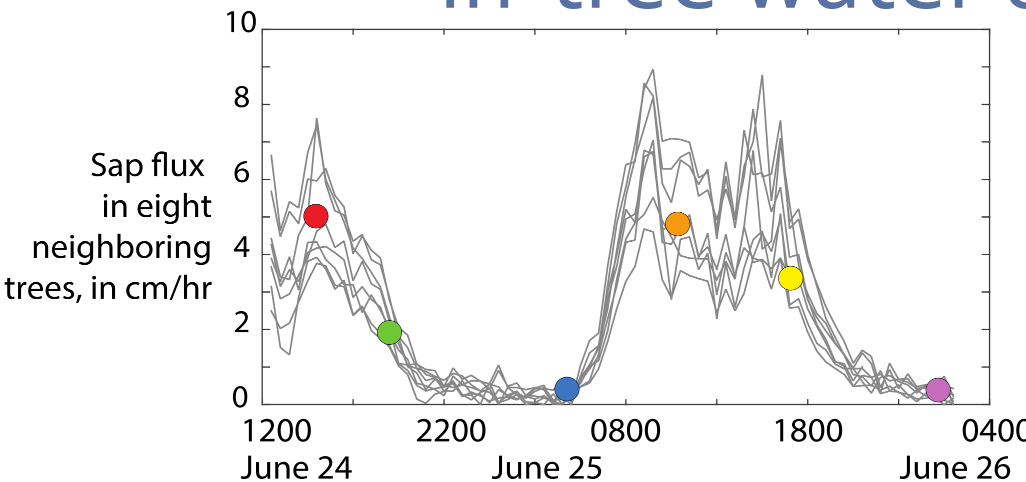
soil borings

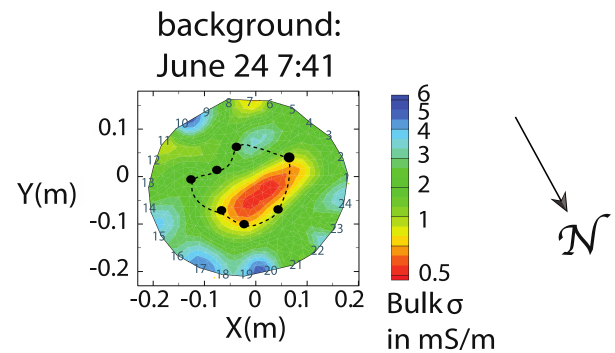


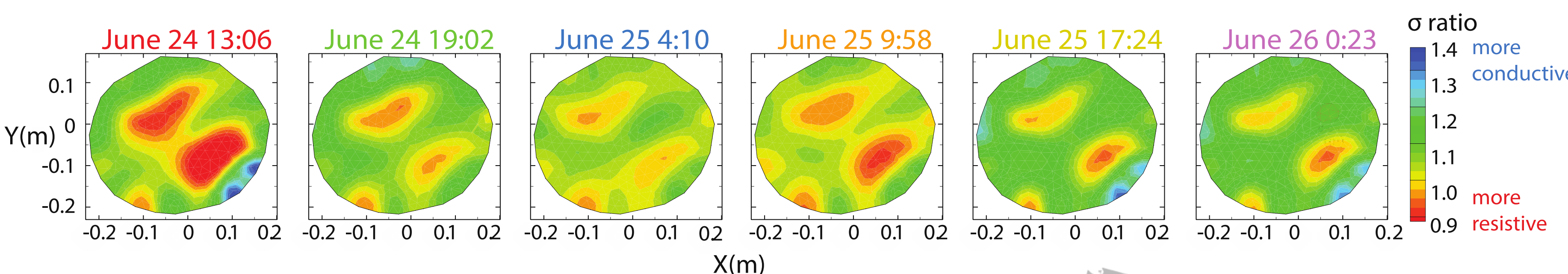


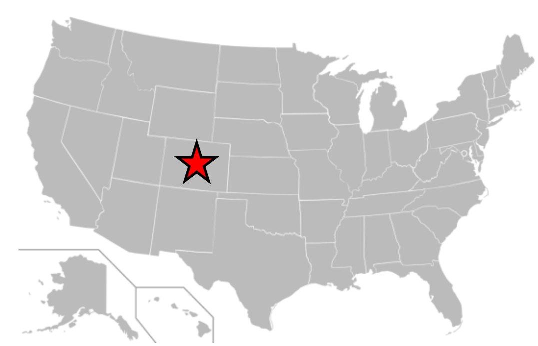
[Robinson et al., 2012, *JoH*]

Can the subsurface be linked to in-tree water use?



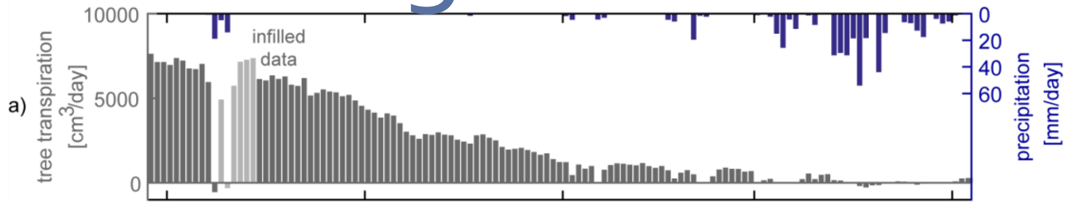






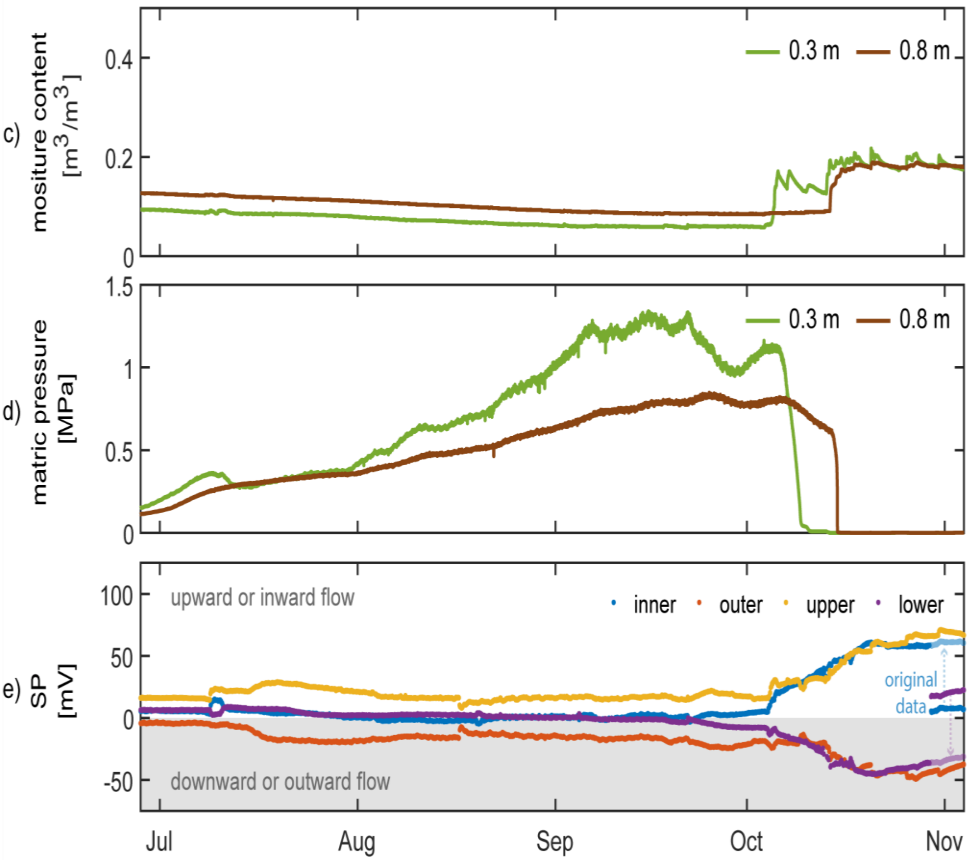
[Mares et al., 2016, *JoH*]

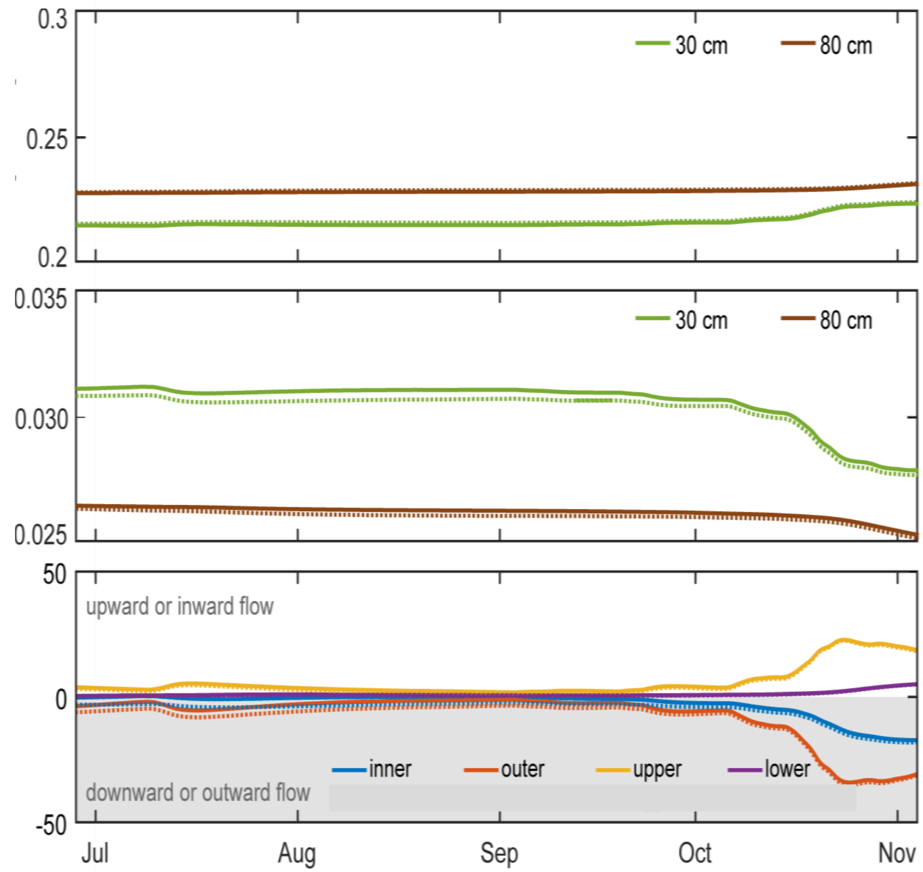
Can we predict connections through time?



Measured

Modeled





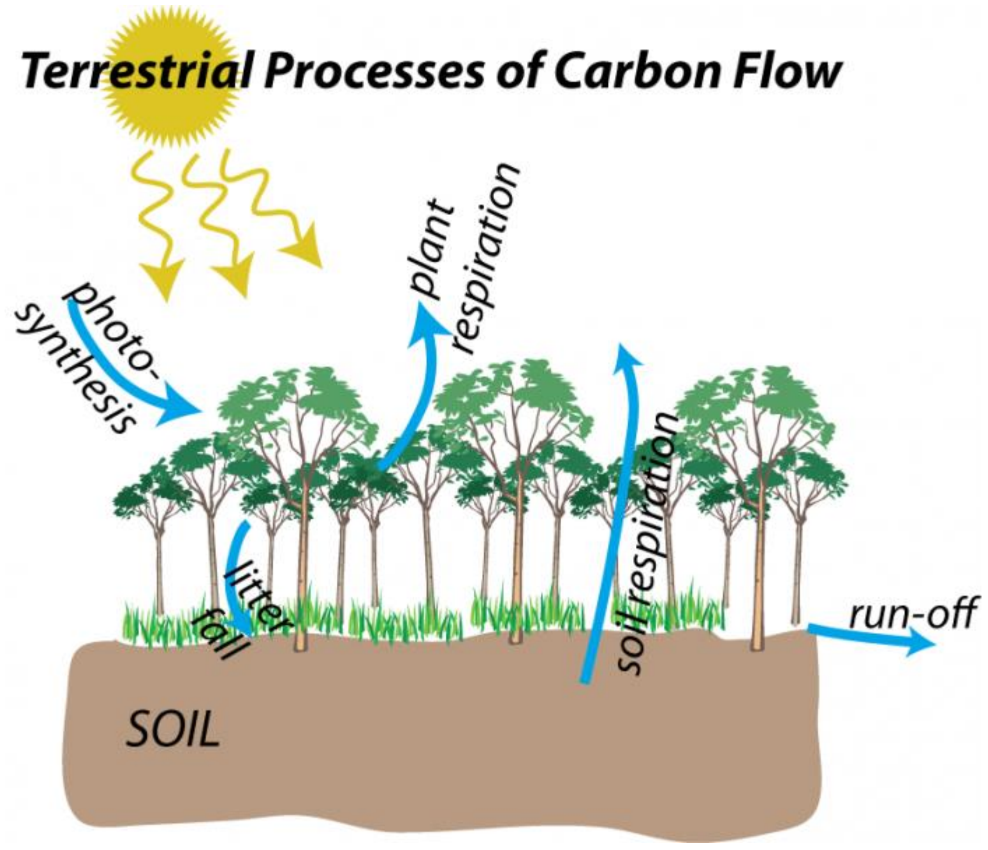
[Voytek et al., in revision, *HP*]

Issues to think about

- What is the geophysical signature of root behavior, associated fungi?
- How species dependent are results?
- How do we scale plant-plot measurements up to watersheds? Can we image the "wood wide web"?
- How do we make reasonable models of large-scale hydrology that incorporate plant physiology in meaningful ways?

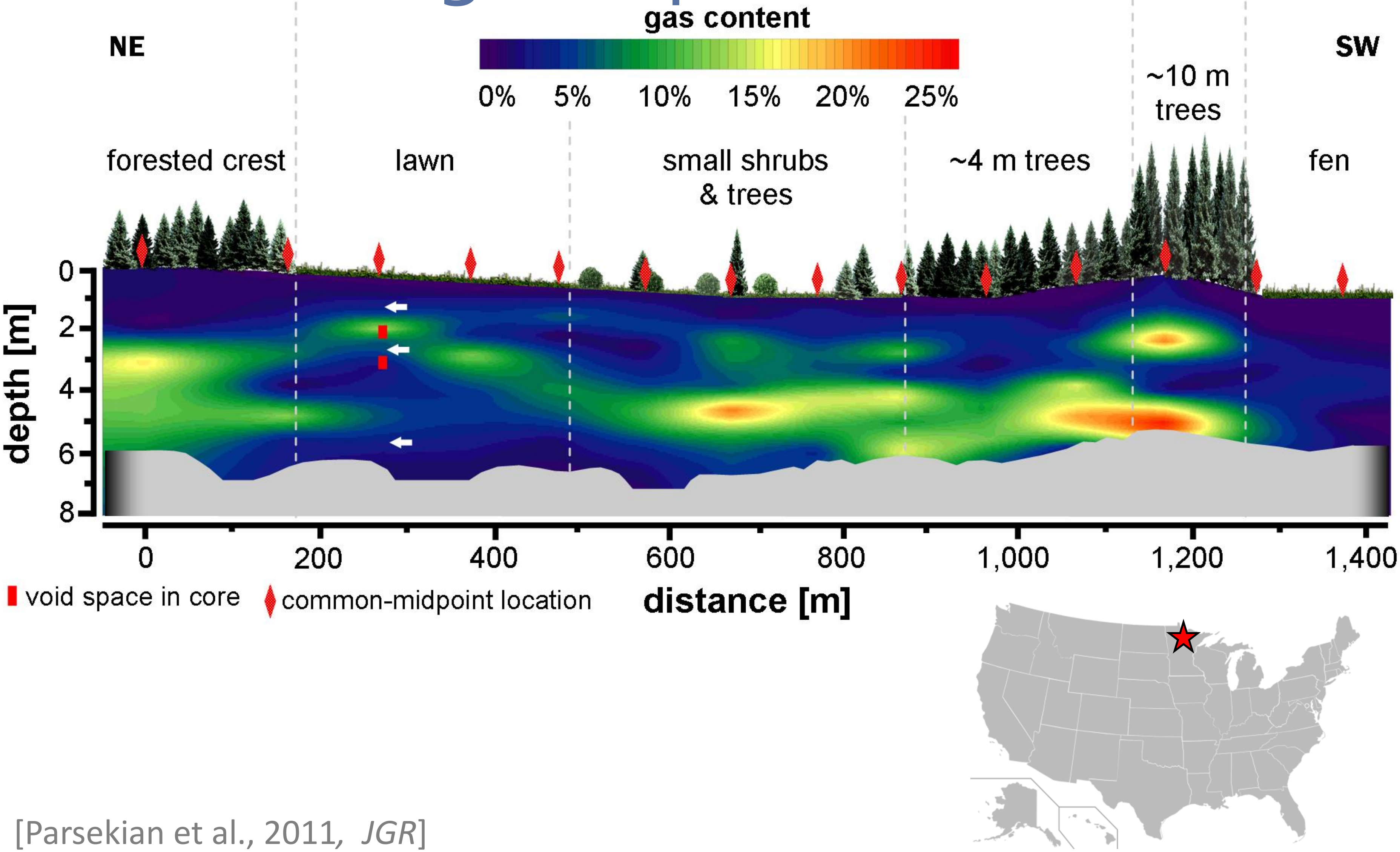
4) Controls on terrestrial carbon

- Assessment of stocks needed to quantify carbon cycling, role in a changing climate
- Can image gases, structural constraints on carbon stores, transport



[www.e-education.psu.edu]

Distribution of free-phase gas in peatland



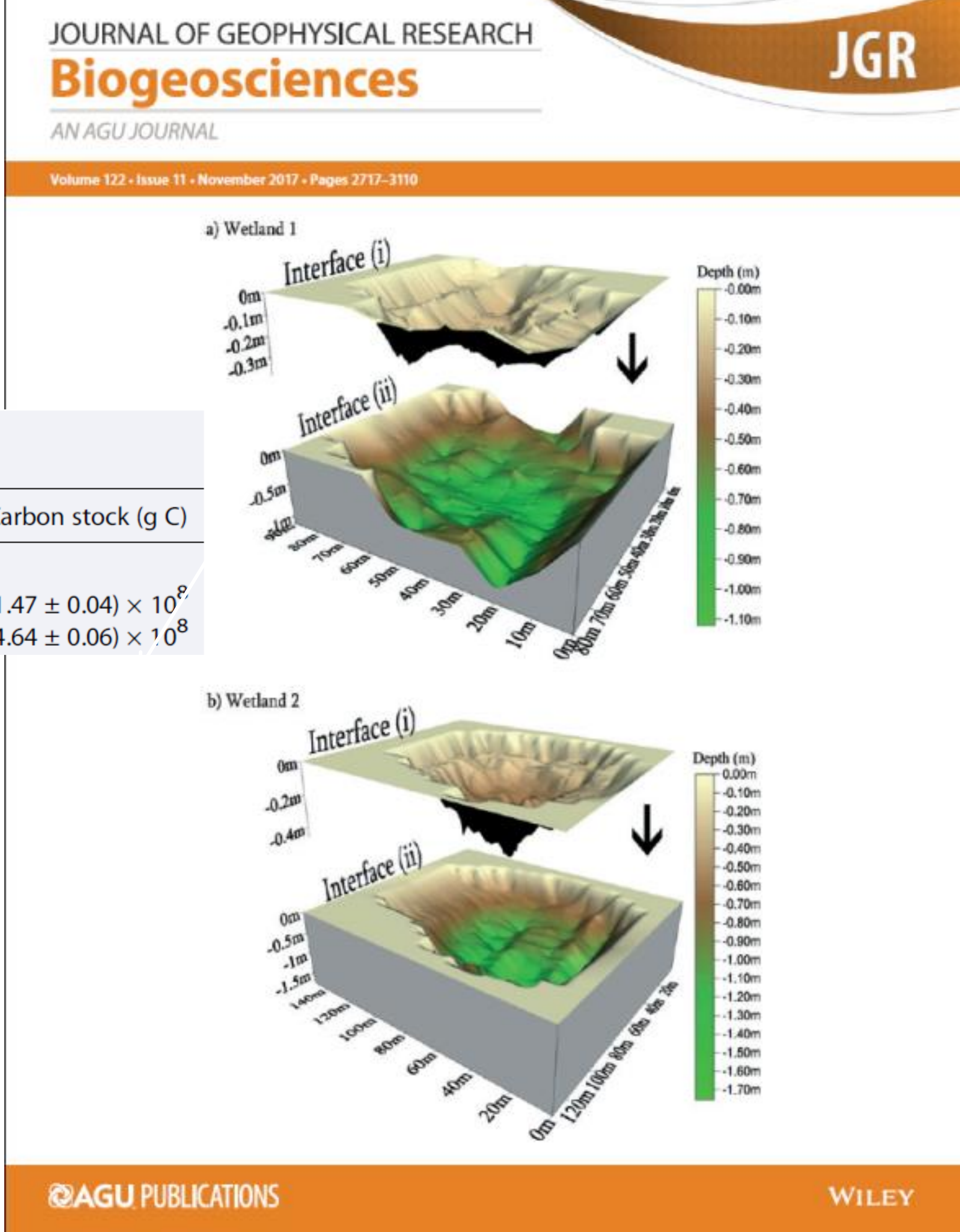
[Parsekian et al., 2011, *JGR*]

Prediction of C stocks in wetlands

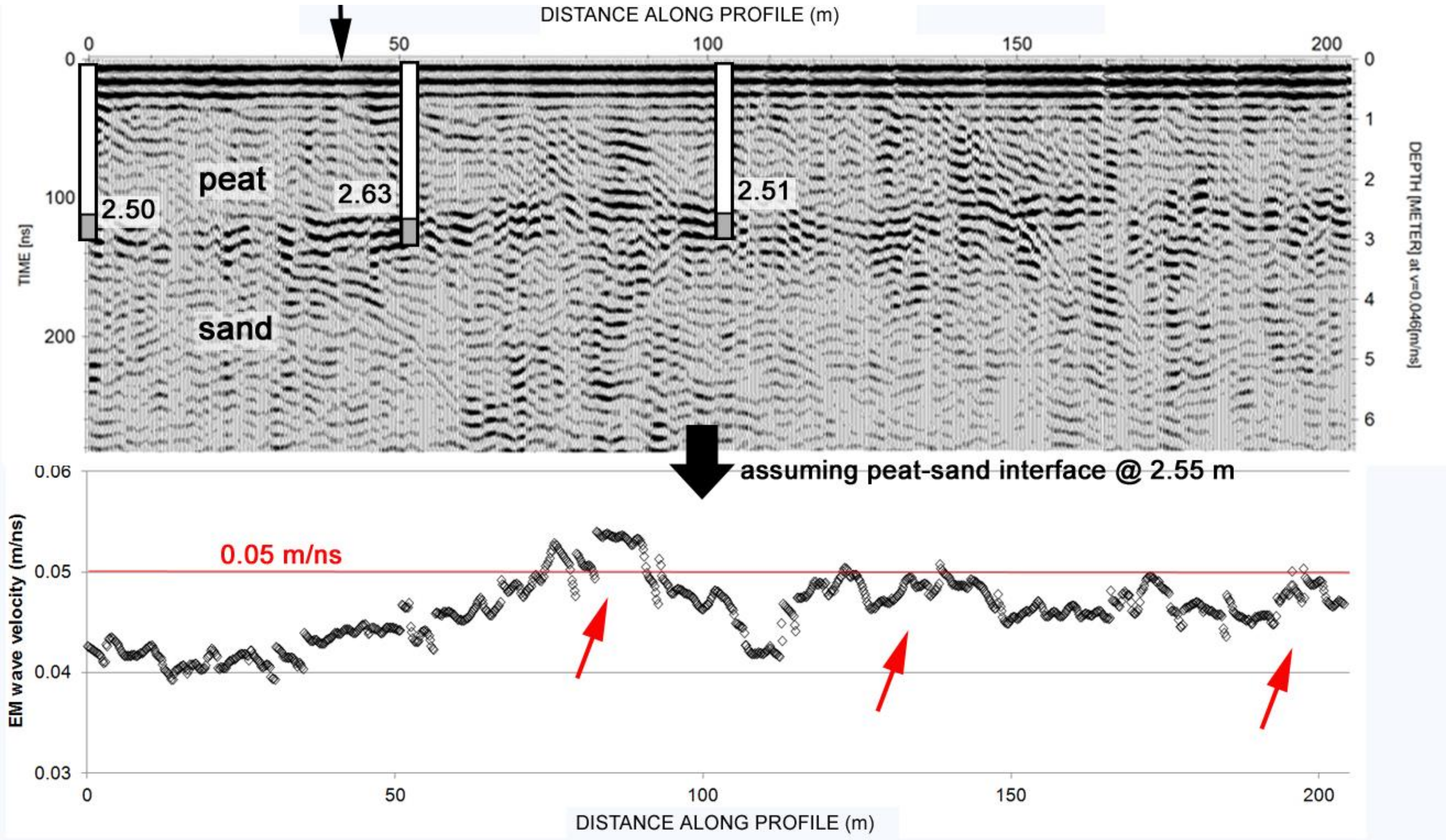
Table 1
Carbon Volume and Stock Estimates

Depression	Surface area (m^2)	Carbon volume (m^3)	Carbon stock (g C)
		Full grid	
1	9,106	3,165	$(1.47 \pm 0.04) \times 10^8$
2	15,776	9,996	$(4.64 \pm 0.06) \times 10^8$

[McClellan et al., 2017, *JGR-B*]



Burning of peats—C + disturbance



- Marked lateral changes in EM wave velocity likely related to heterogeneities of burned peat with depth
- Can we infer changes in peat thickness if constrained?

[Comas et al., in prep]

Issues to think about

- What observing networks are needed to make quantitative estimates of carbon cycle status, dynamics, and evolution?
- What information, if any, can geophysics provide on carbon fate, form or reactivity?

Opportunities in CZ geophysics

- Many open questions about how to use these data quantitatively (or even qualitatively)
- Methods can be used to:
  - Test conceptual models of hydrologic processes
  - Image large-scale geometry of geologic units, permafrost, catchment-scale geomorphic events
- Needs:
  - Thinking/collaboration across disciplinary boundaries
  - Developing rock physics relations between geophysics and physical, chemical, biological properties of interest
  - Moving to larger scales, time lapse imaging
  - …

- Altdorff et al., 2017, *EES.* Potential of catchment-wide soil water content prediction using electromagnetic induction in a forest ecosystem.
- Befus et al., 2011, *VZJ. S*eismic constraints on critical zone architecture, Boulder Creek watershed, Front Range, Colorado.
- Chorover et al., 2007, *Elements.* Soil biogeochemical processes within the critical zone.
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- Hayes et al., in prep. Characterizing the distribution of fractures in the deep critical zone with geophysics and drilling.
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- McClellan et al., 2017. *JGR-B.* Estimating belowground carbon stocks in isolated wetlands of the Northern Everglades Watershed, central Florida using ground penetrating radar and aerial imagery.
- Nyquist et al., 2018, *VZJ*. Testing the fill-and-spill model of subsurface lateral flow using ground-penetrating radar and dye tracing.
- Parsekian et al., 2011, *JGR.* Geophysical evidence for the lateral distribution of free phase gas at the peat basin scale in a large northern peatland.
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- Pommer et al., in prep. An exploration of critical zone weathering on opposing montane hillslopes.
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- Voytek et al., 2016, *Geophysics.* Identifying hydrologic flowpaths on arctic hillslopes using electrical resistivity and self potential.
- Voytek et al., in review, *HP.* Propagation of diel transpiration signals in the subsurface observed using the self-potential method.