Complexity and Innovation: Advancing CZ Science

Susan L. Brantley,

Earth and Environmental Systems Institute, Penn State

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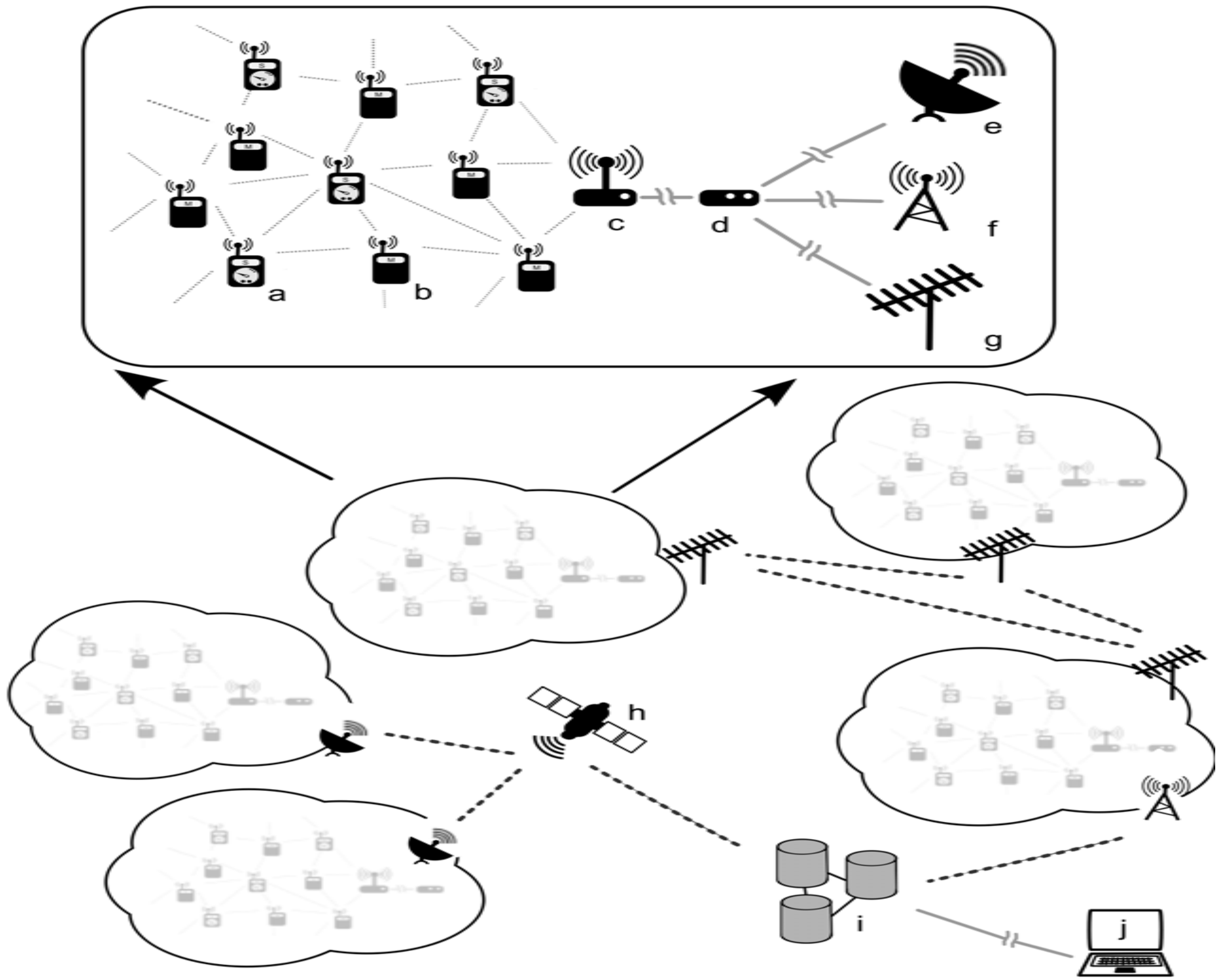
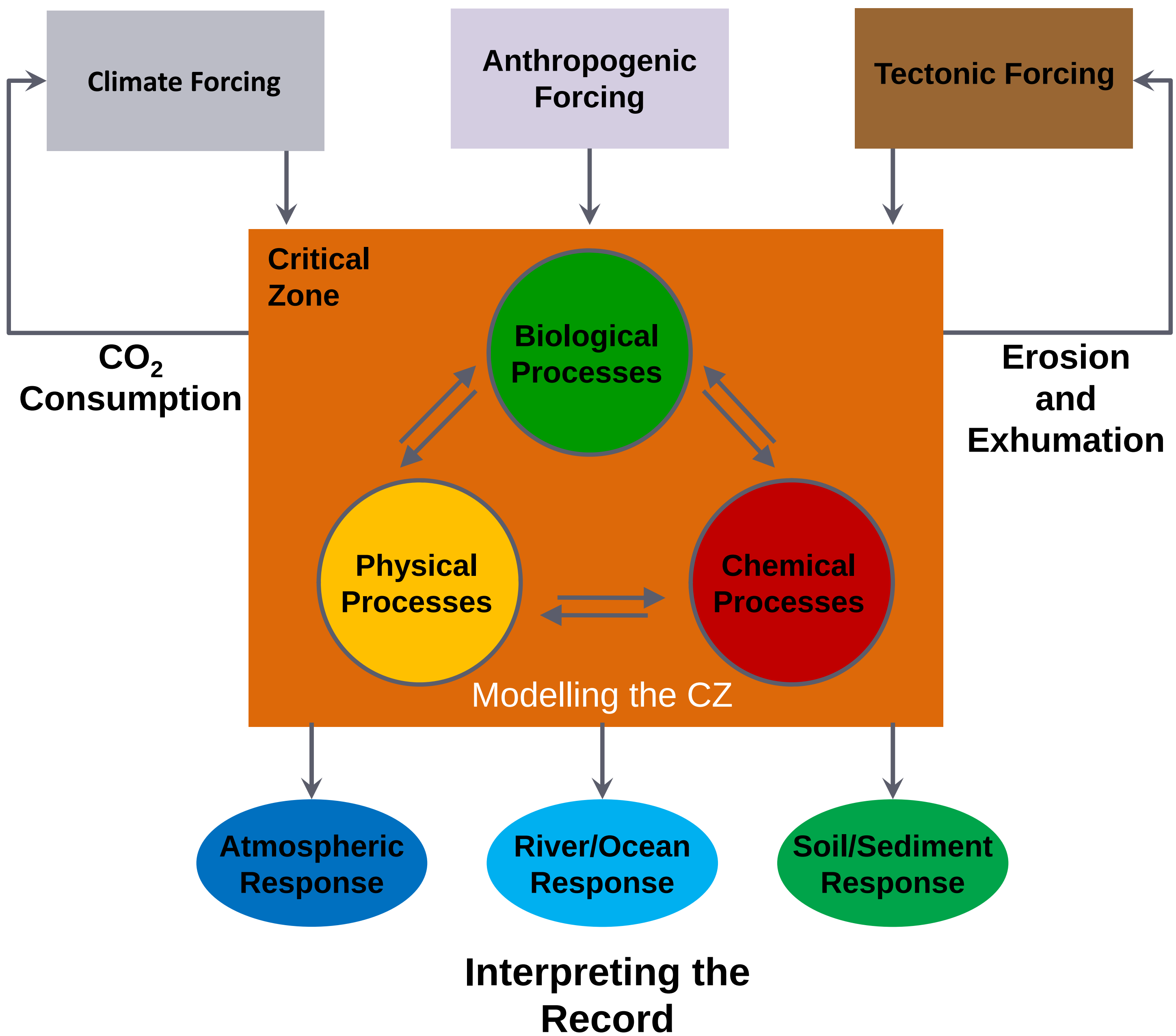
DOE Environmental Systems Science, Potomac Maryland

The "Critical Zone" is the zone extending from the outer limits of the vegetation canopy to the lower limits of groundwater



Critical Zone Observatories are being developed all over the world to develop models to quantify CZ evolution over time …from timescales of the meteorologist to that of the geologist



Meteorologists looking at surface
from above

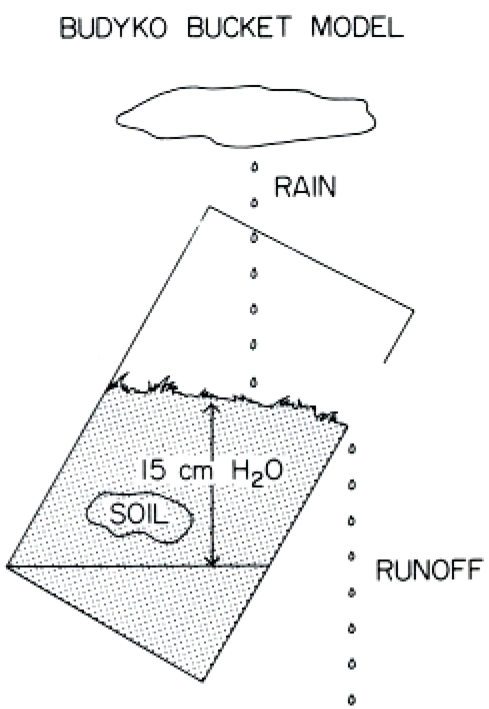
Earth’s surface

Geologists looking at surface from below

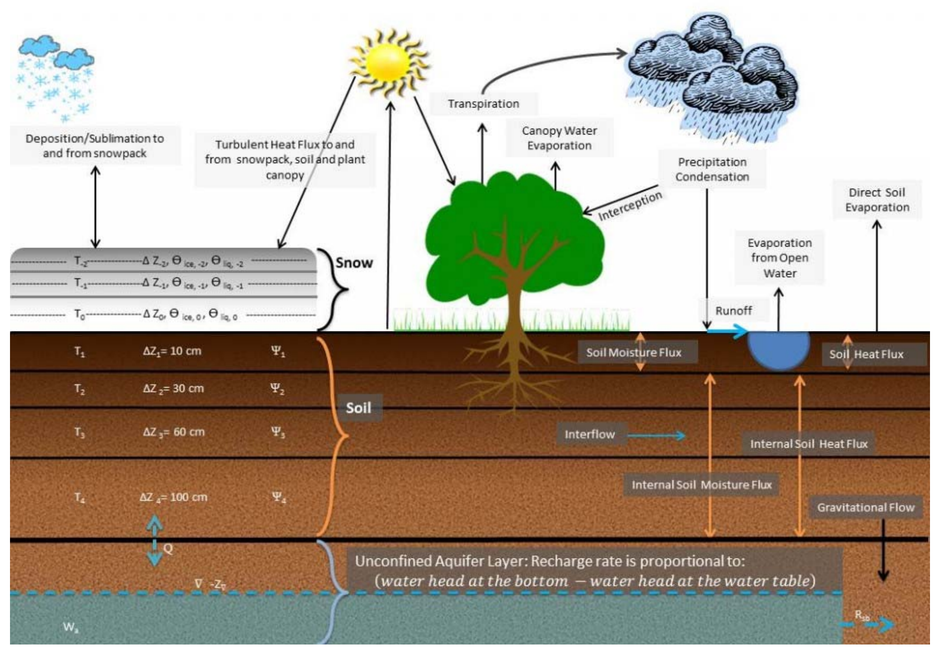
From Frank and Ernest (copyright 2000 by
Ghaves, www.thecomics.com

Land surface parameterizations 1969 to today

- Early GCMs prescribed surface T and wetness
- Early land surface parameterizations by Manabe (1969) were single bucket-type parameterizations which ignored precipitation infiltration-runoff partitioning on soil moisture
- Later LSPs included vegetation effects
- LSPs now include fast upper soil moisture layer, a root zone and subsurface storage region, and varying vertical distributions of moisture through vegetation (of different character such as height, density, etc.)



From Dickinson, http://www.scopenvironment.org/downloadpubs/scope35/chapter05.html



NOAH Land Surface Model, http://www.jsg.utexas.edu/noah-mp/

The big challenge: incorporating heterogeneity of earth's (sub)surface

A major challenge in representing land surface properties in global models of water, energy, and carbon is how to include the heterogeneous distributions of trace gas emissions, vegetation properties, soil properties, and land surface topography.

It would be ideal if LSP parameters could be estimated from land surface physical characteristics alone…[but] past experience indicates that direct relationships among model parameters and land surface characteristics are elusive. (NRC, 1998)

Soils map of the U.S. created from U.N. Food and Agriculture Organizations digital world soil map

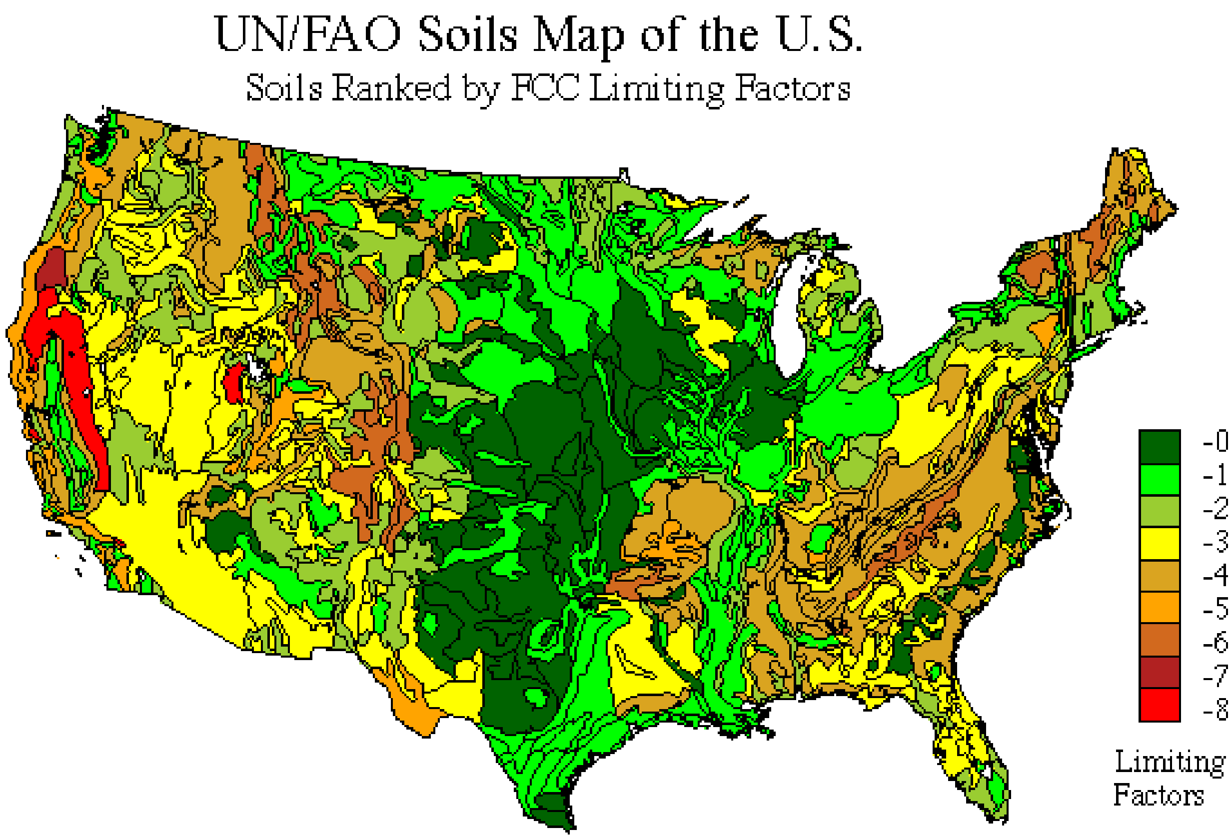
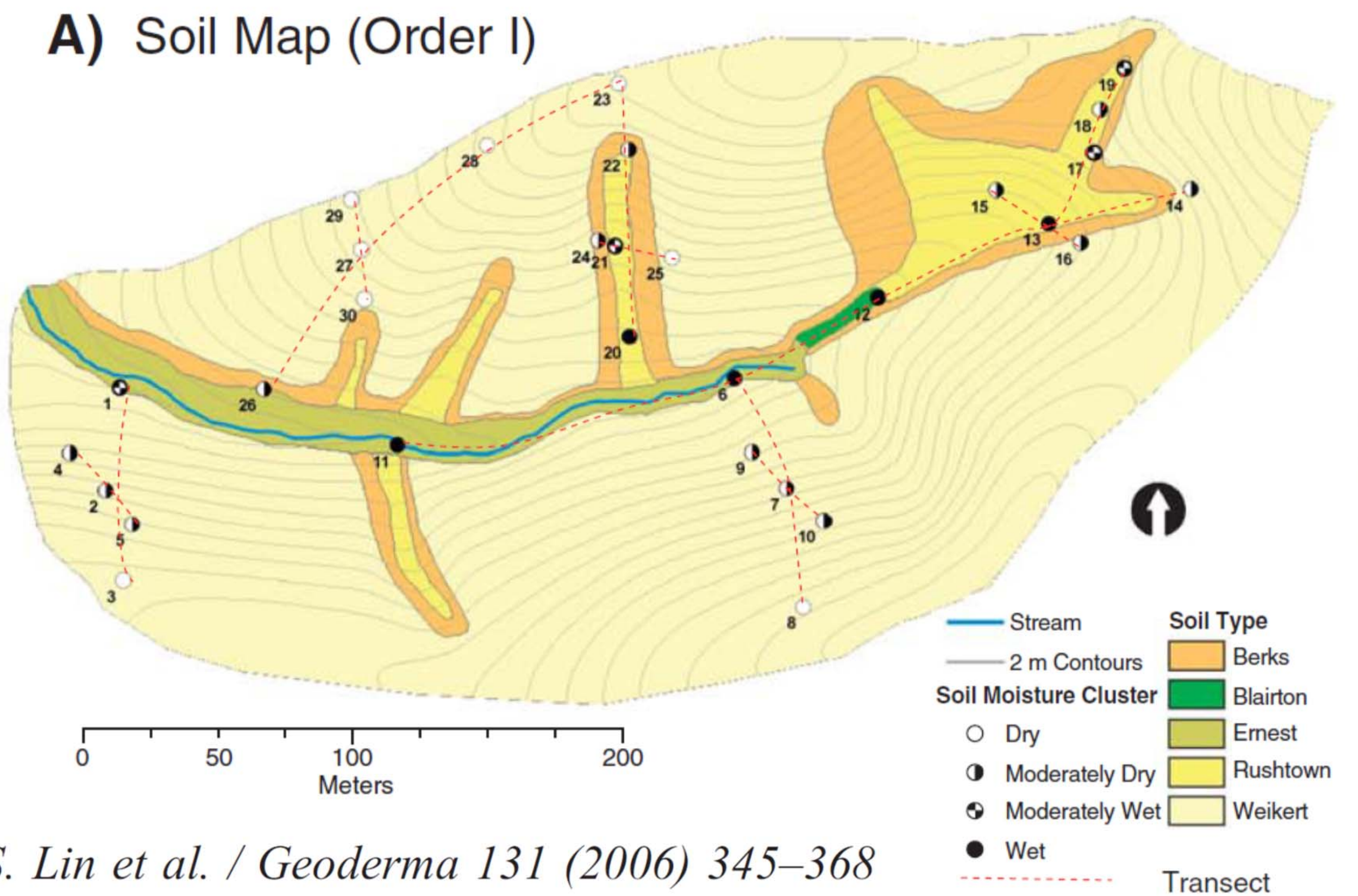


Fig. 3-2. Soils are classified by their number of agronomic limiting factors. Soils with a high number of limiting factors are problematic and require remediation for agricultural production. The best soils for agriculture have no or few limiting factors. Figure and caption reproduced from Imhoff et al., "**Assessing the Impact of Urban Sprawl on Soil Resources in the United States Using Nighttime "City Lights" Satellite Images and Digital Soils Maps**", in Land Use History of North America (LUHNA), http://landcover.usgs.gov/luhna/chap3.php.

Five soil orders on one rock type (shale) in the 0.1 km^2 Shale Hills CZO



H.S. Lin et al. / Geoderma 131 (2006) 345–368

Methane concentrations in Pennsylvania groundwater

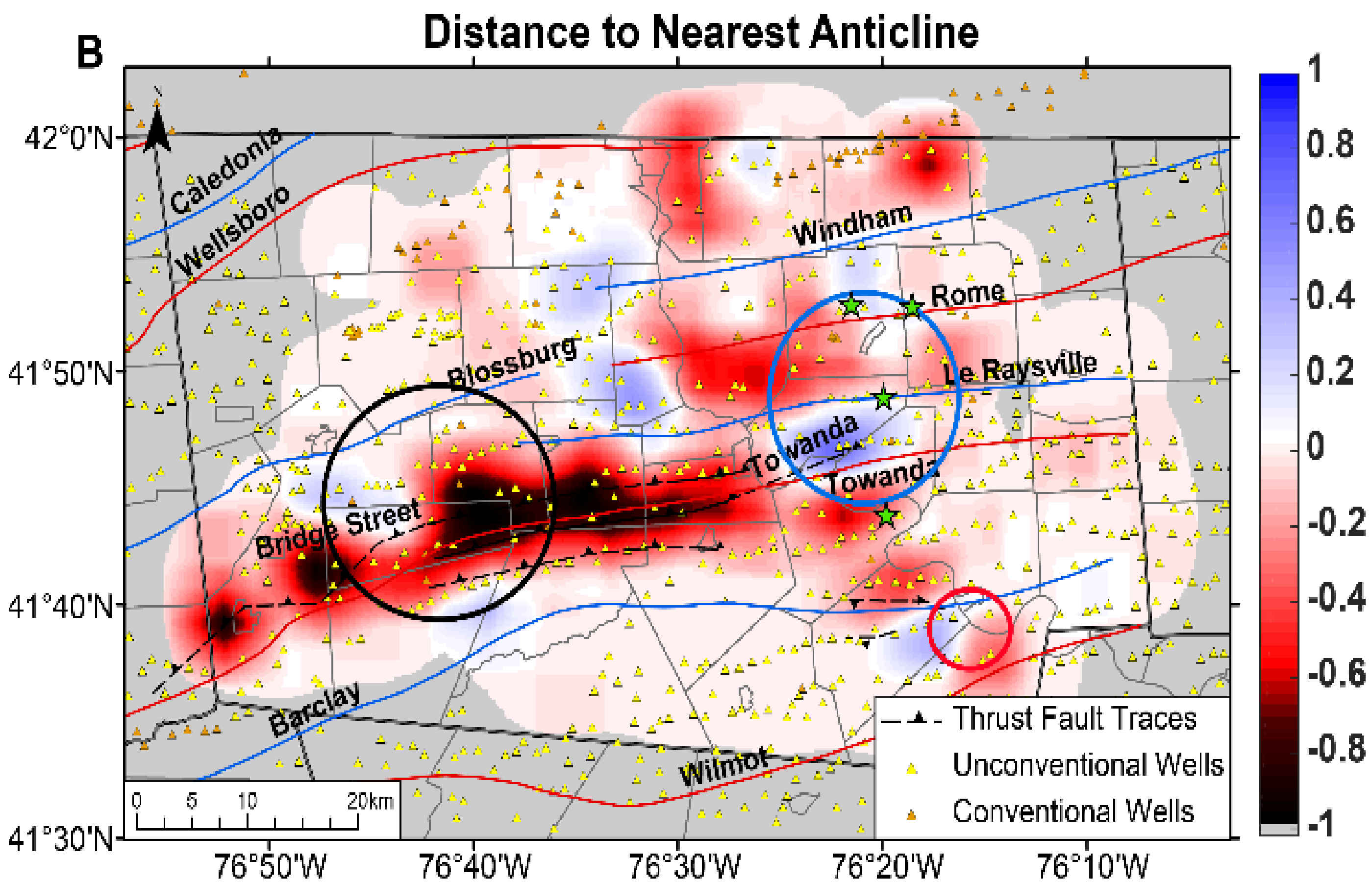
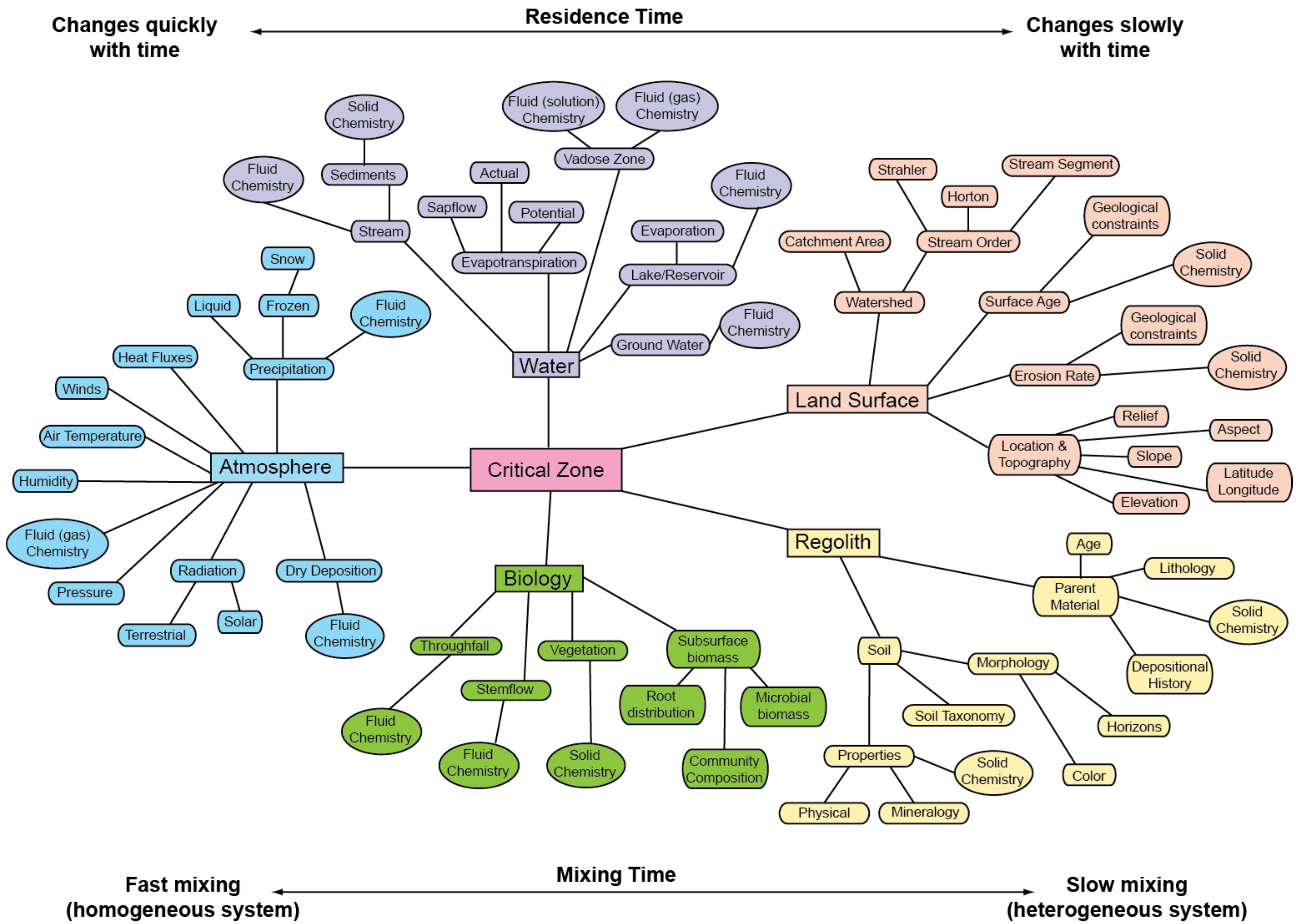


Figure from Tao Wen, J. Li, X. Niu, and S. L. Brantley, EST, in review

Critical Zone Observatory Network: 9 CZOs

Critical zone science spans from timescales of the meteorologist to the geologist

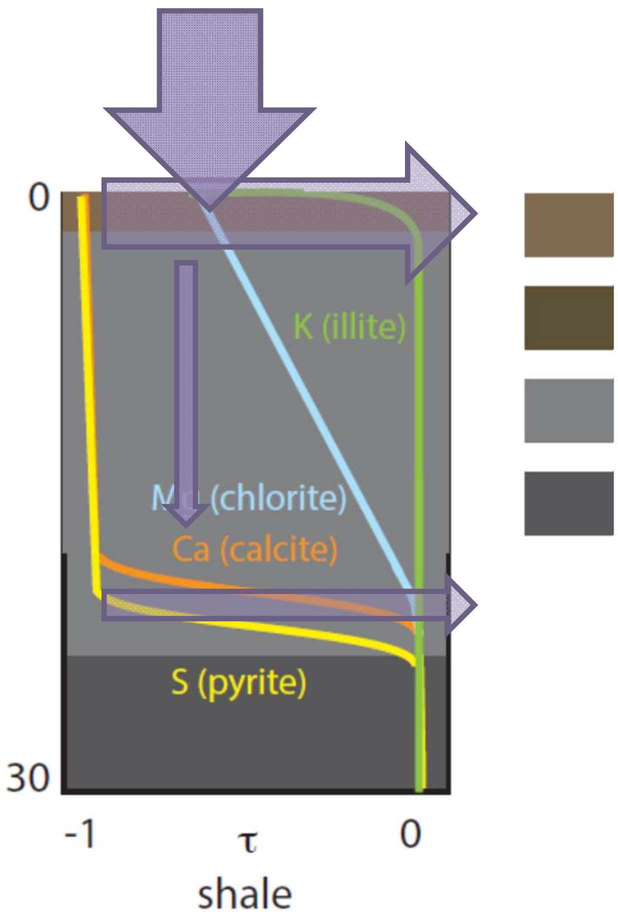
All the data

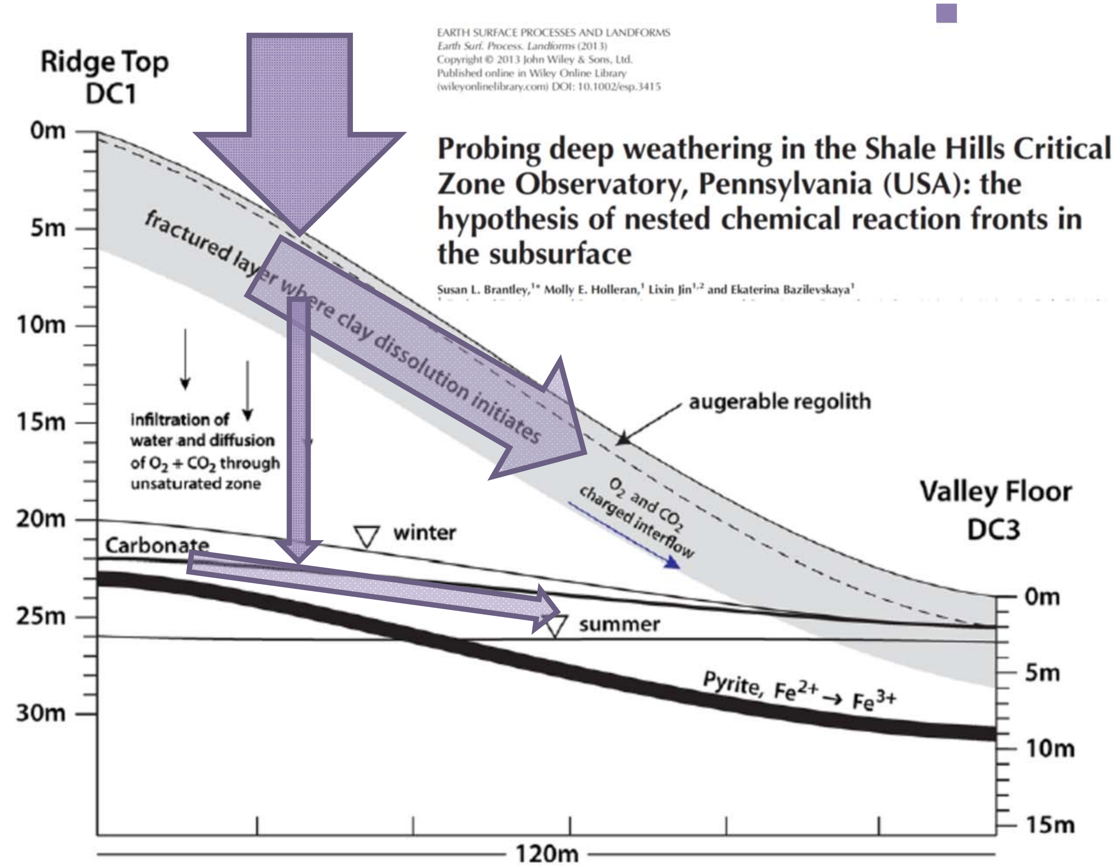


Niu X, Lehnert KA, Williams JZ, Brantley SL. CZChemDB and EarthChem: Advancing management and access of critical zone geochemical data. *Applied Geochemistry* 2011;**26:S108–S111.**

Co-located observations extend understanding from 1D to 2D to 3D

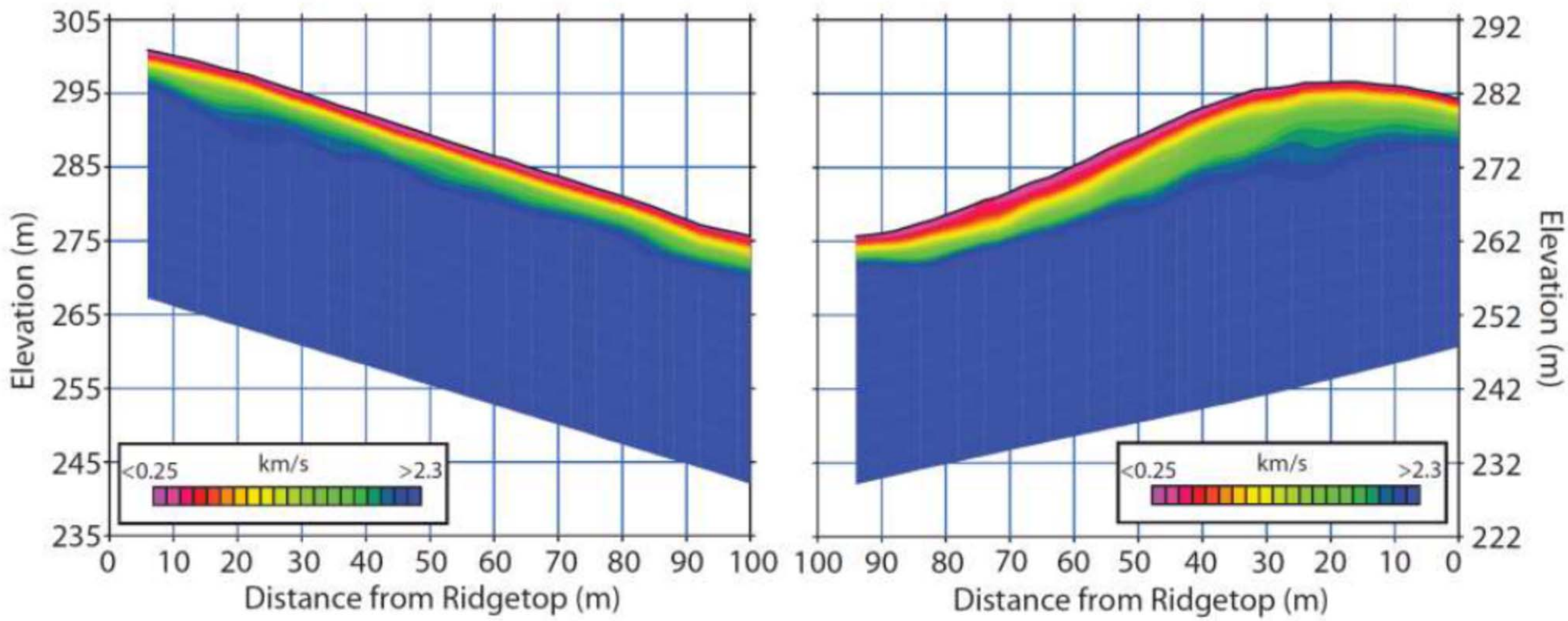
Susquehanna Shale Hills Critical Zone Observatory





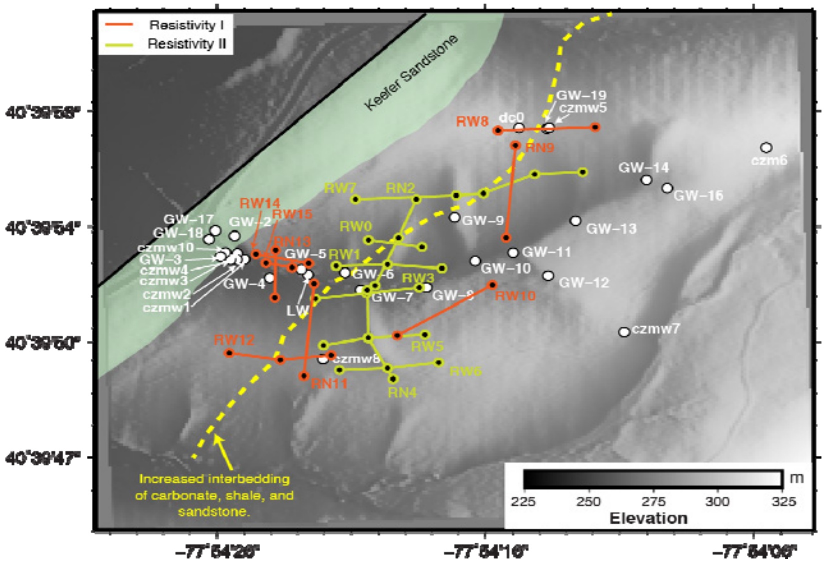
Brantley et al.,
Geomorphology, 2017

Refraction seismic images showing regolith



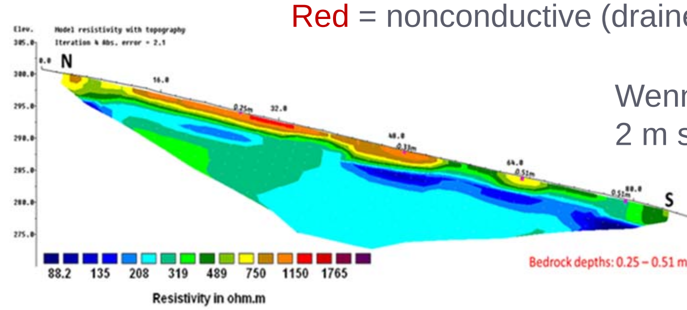
West, N., E. Kirby, B. Clarke, A. Nyblade and S.L. Brantley. 2018, submitted. Climatic preconditioning of the Critical Zone: Elucidating the role of subsurface fractures in the evolution of asymmetric topography. Earth and Planetary Science Letters.

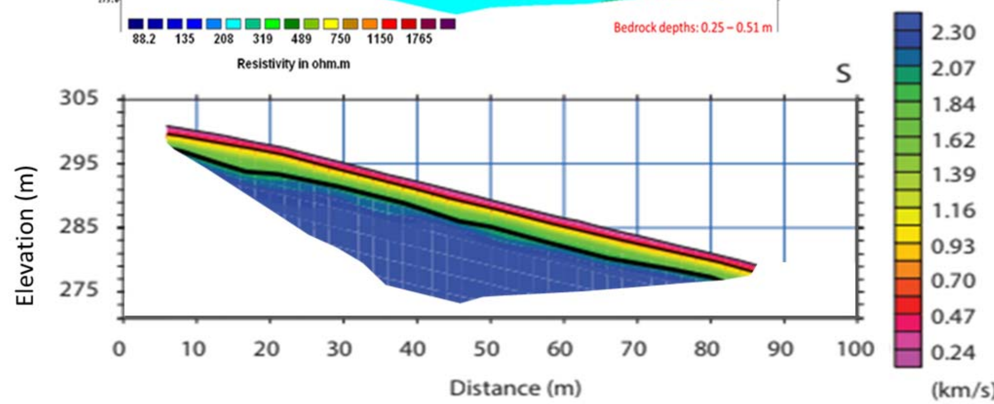
Resistivity Measured by Penn State undergrads Terrance A. Delisser, Robby Miles, with Andy Nyblade



Resistivity profile:
Blue = conductive (saturated) layer
Red = nonconductive (drained) layer

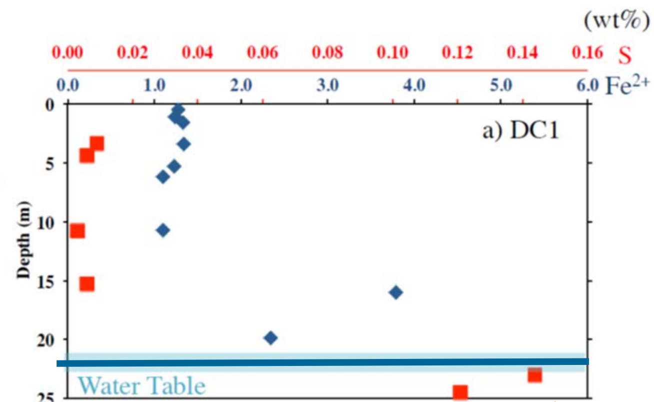
Wenner array, 2 m spacing

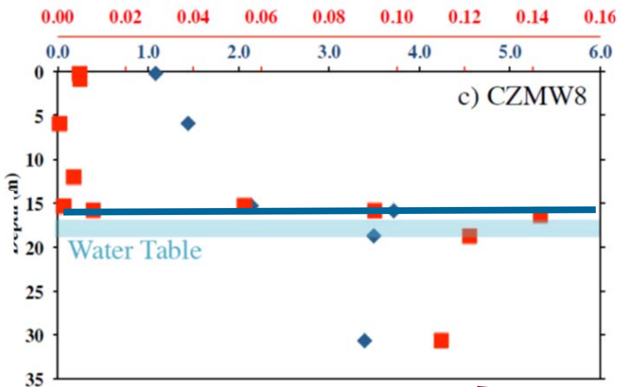


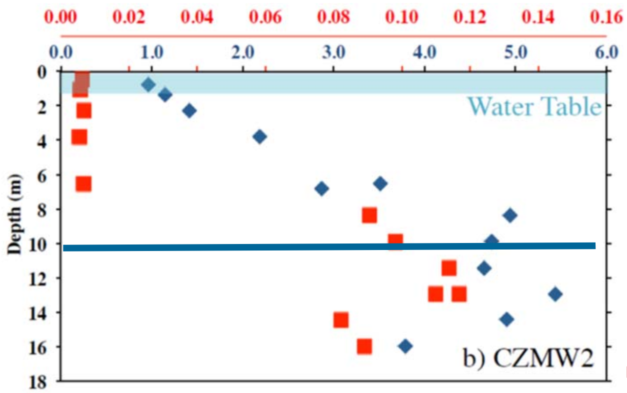


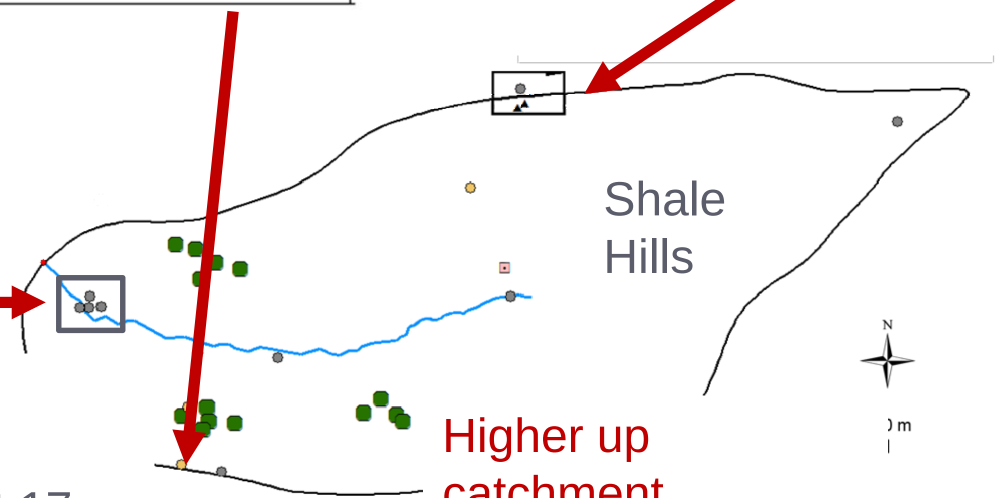
Seismic (Vp) model:
Blue = fast (less fractured);
Red = slow (more fractured and weathered)

What do these fronts look like in 3D? Depth to water table and Fe(II) and S









Valley floor
Water table at 1 m
Redox front at 12 m

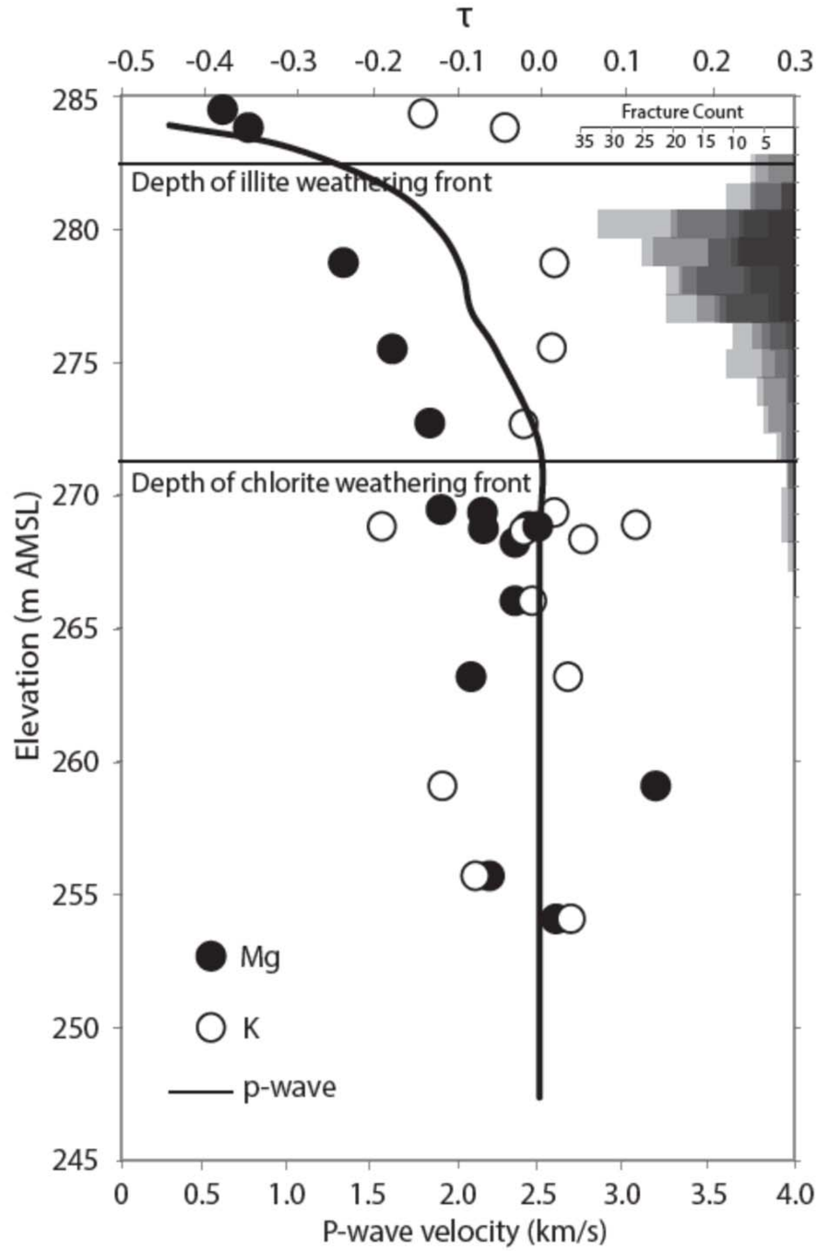
Part way up catchment
Water table at 17 m
Redox front at 18 m

Higher up catchment
Water table at 23 m
Redox front at 23 m

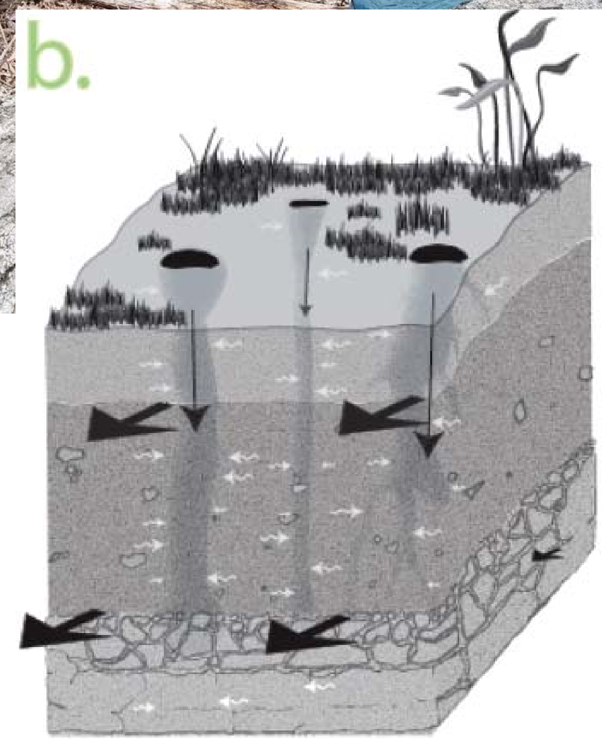
Requiring every scientist to work in the same place forces convergence: scientists begin to realize that terms from different disciplines refer to the same concepts. This leads to better conceptual models

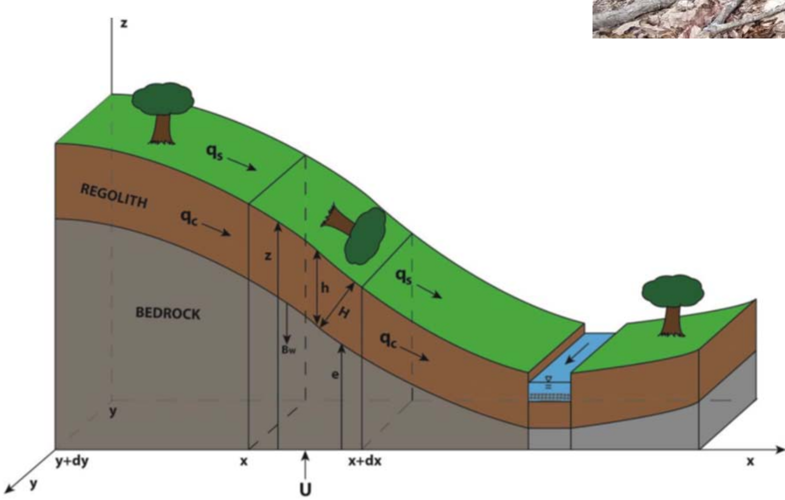
P wave velocity shows same geometry as the chlorite reaction front in the surface and overlaps with fractured zone

West, N., E. Kirby, B. Clarke, A. Nyblade and S.L. Brantley. 2018, submitted. Climatic preconditioning of the Critical Zone: Elucidating the role of subsurface fractures in the evolution of asymmetric topography. Earth and Planetary Science Letters.



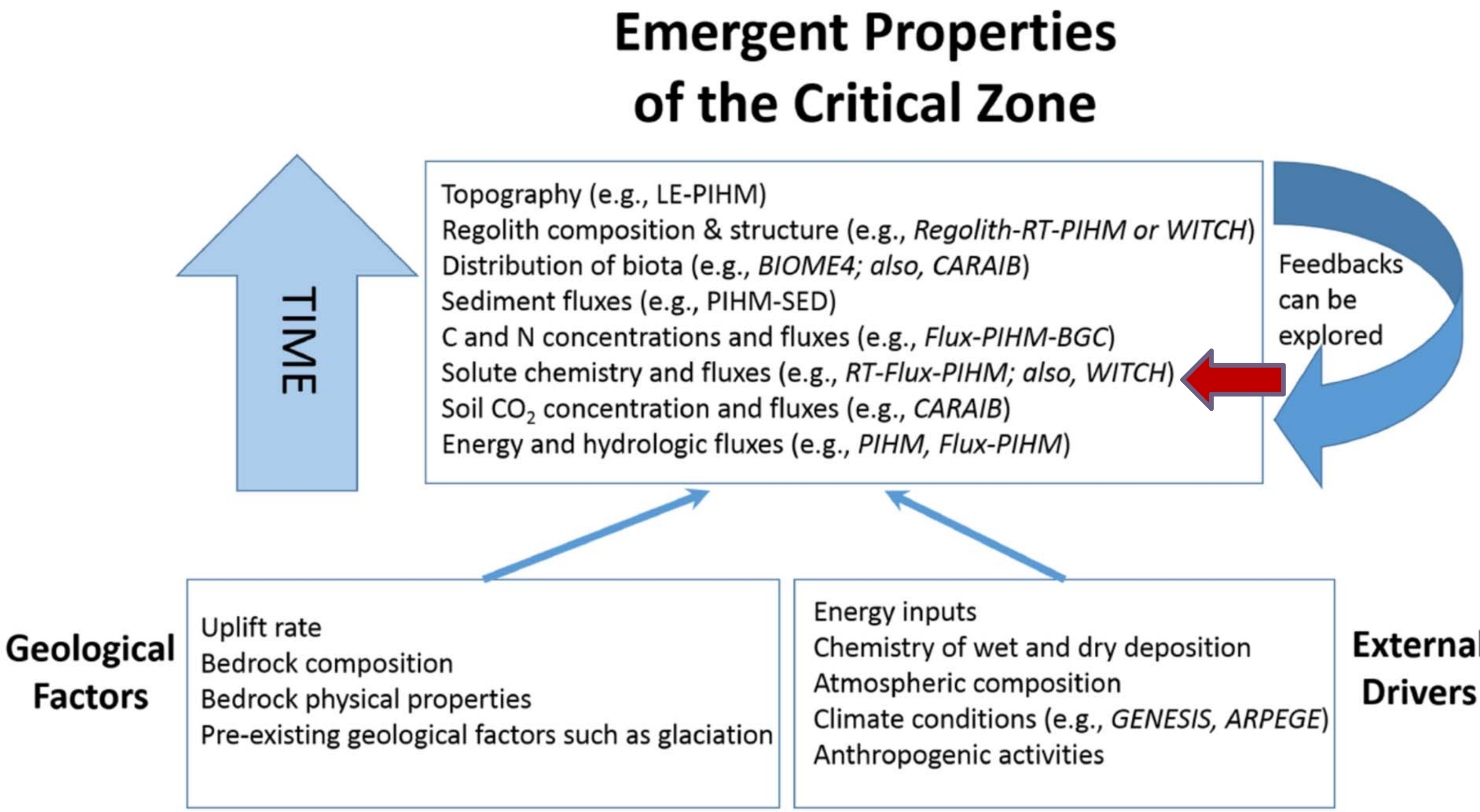
Mobile soil (geomorphologist) = rooting depth (ecologist) = zone of interflow (hydrologist) = upper reaction front (geochemist)





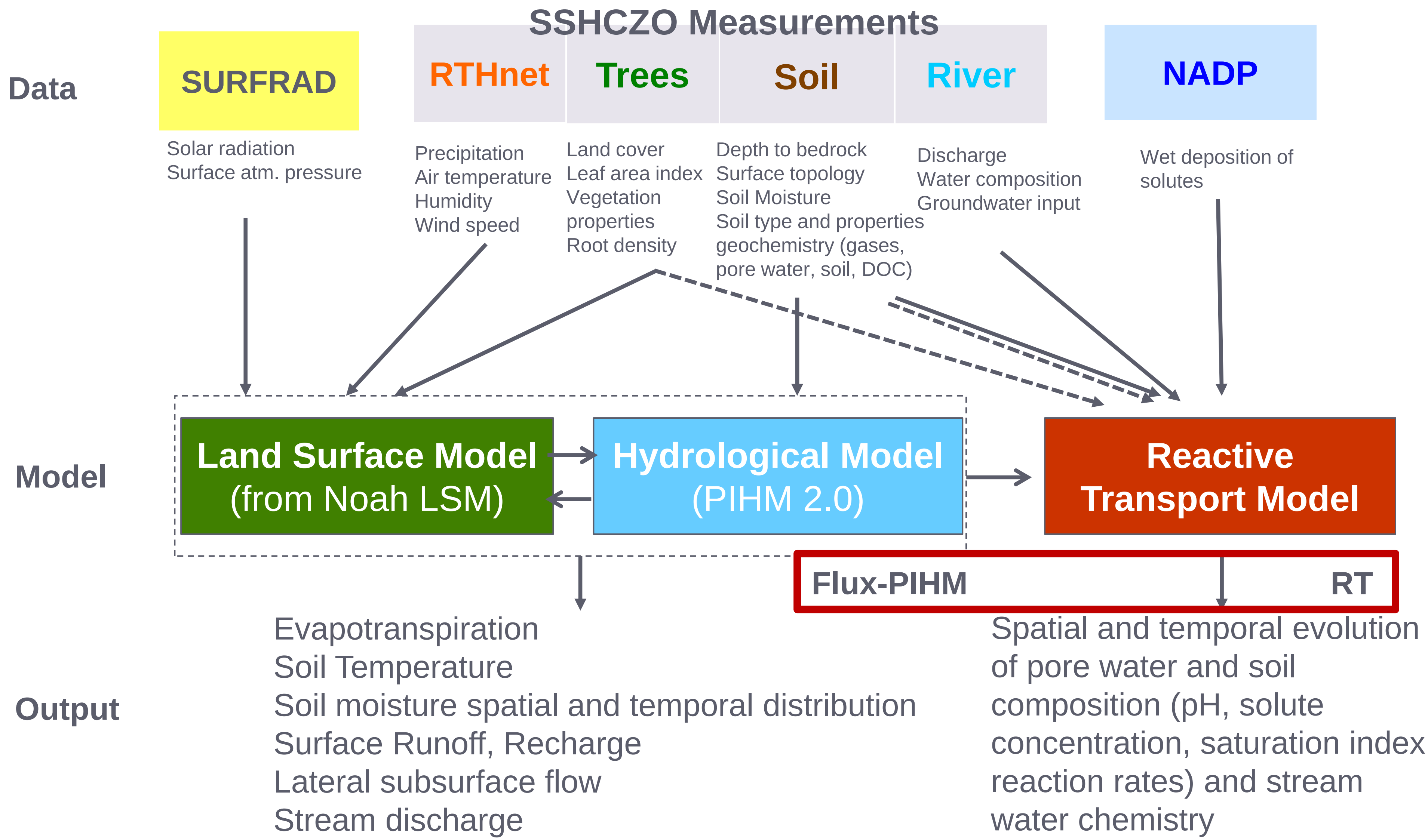
Numerical modeling allows the different disciplinary scientists to communicate across timescales

To understand the CZ requires using a suite of models to interpret CZ dynamics.



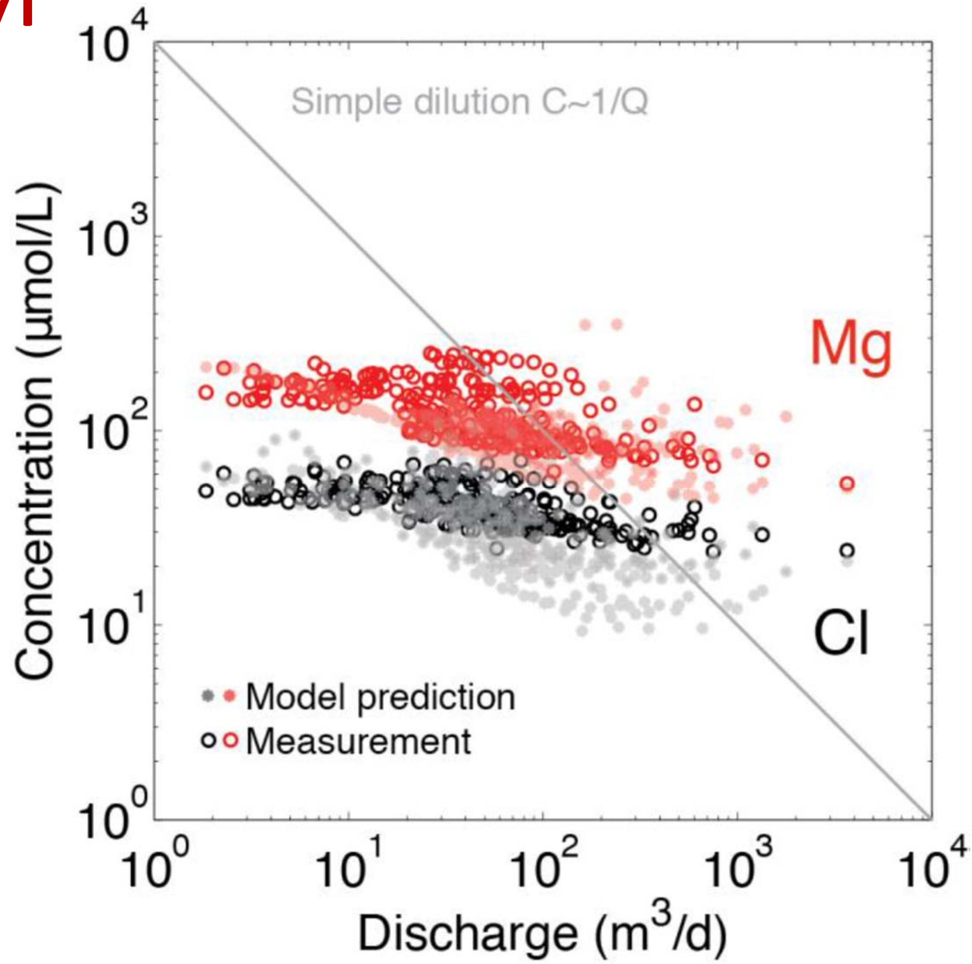
Duffy et al., 2014

An integrated understanding of interactions between energy, water, soil, and biomass at the watershed scale.



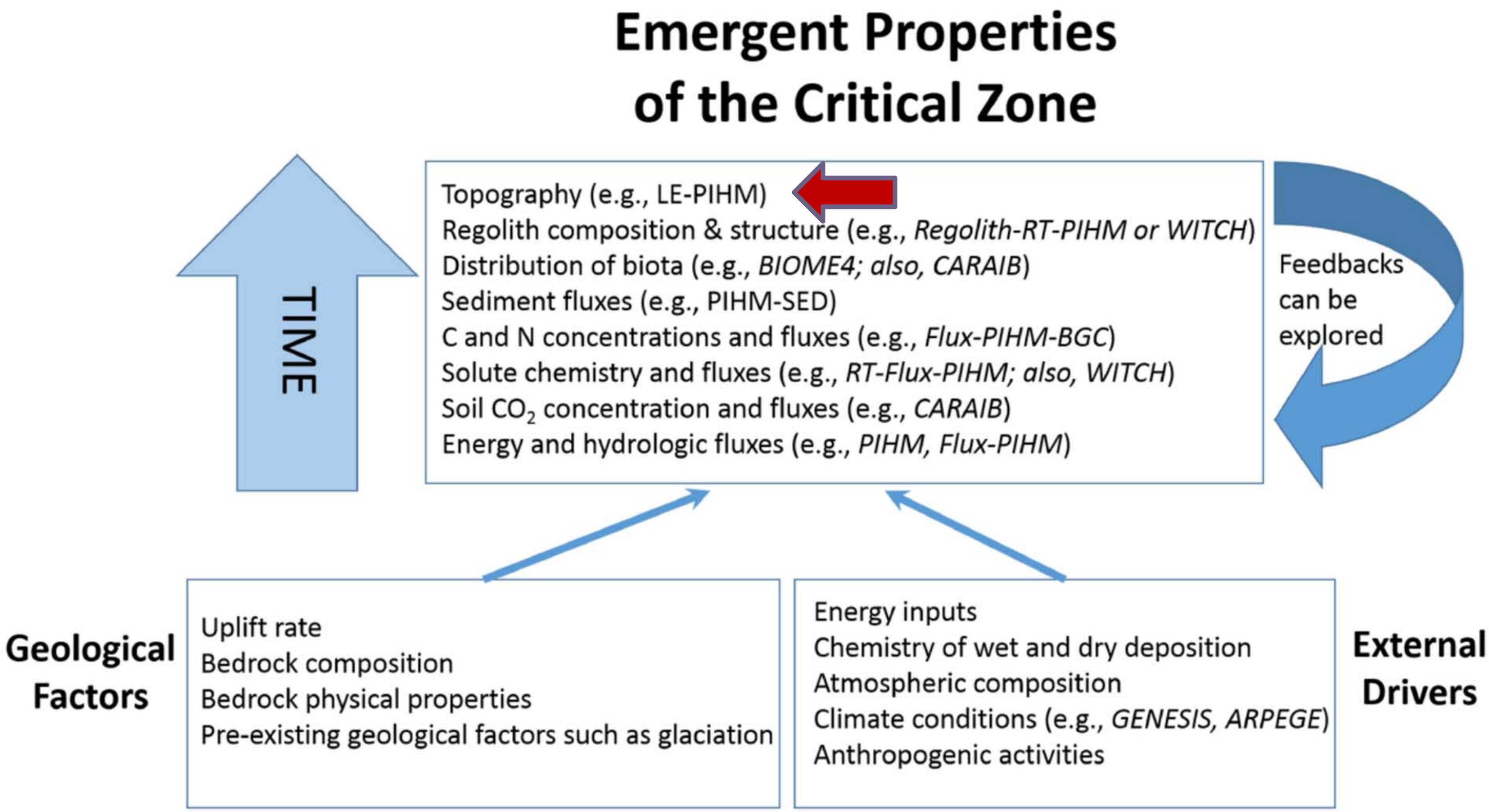
Slide from Pam Sullivan; Models by Li Li, Yuning Shi, Chris Duffy, Chen Bao, Dacheng Xiao (Penn State)

Comparison of concentration-discharge relationship for Mg and Cl between data and RT-Flux-PIHM



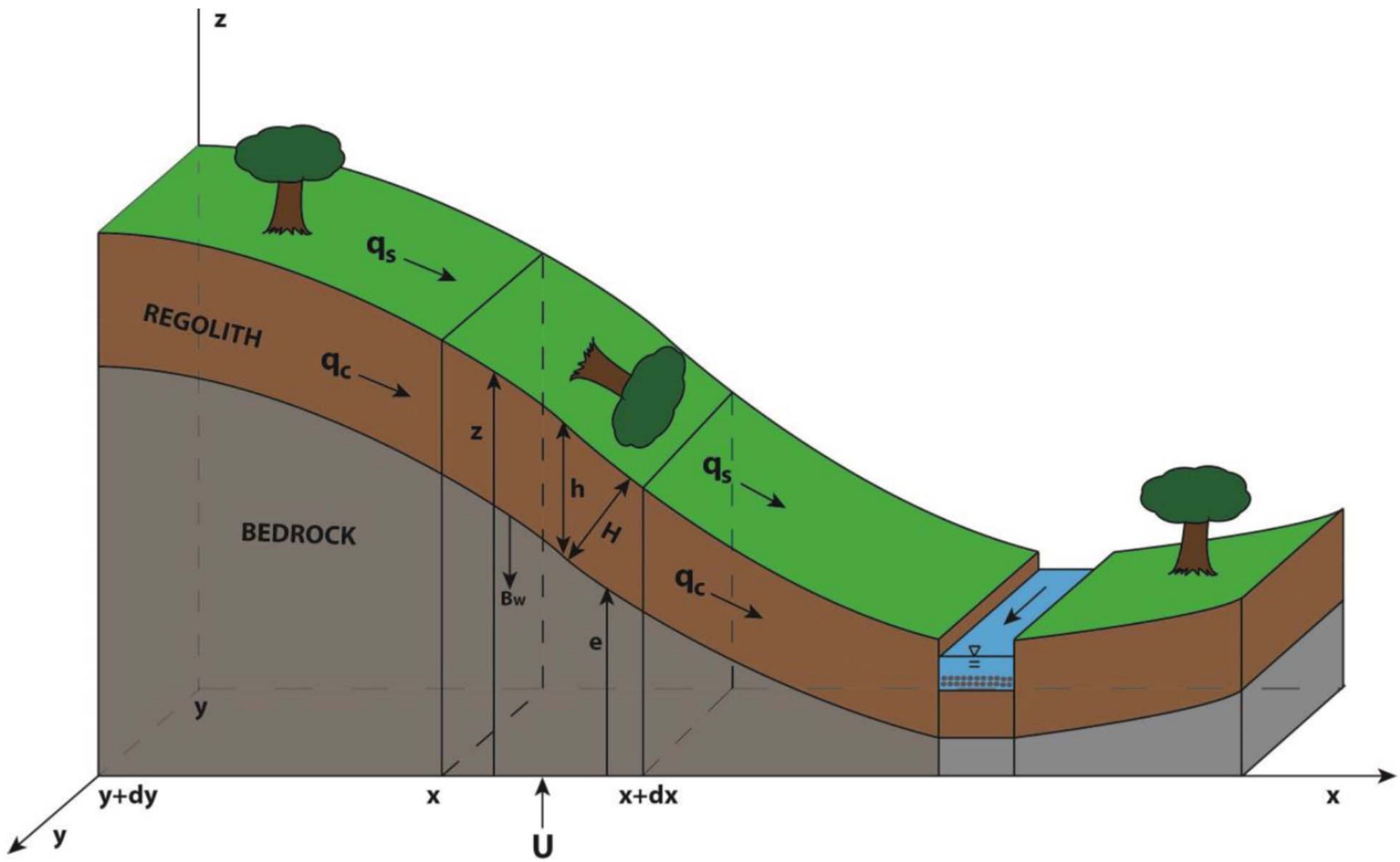
Bao, C. et al.: RT-Flux-PIHM: A coupled hydrological, land surface, and reactive transport model for hydrogeochemical processes at the watershed scale. *Water Resources Research*, **2017**.

To understand the CZ requires using a suite of models to interpret CZ dynamics.

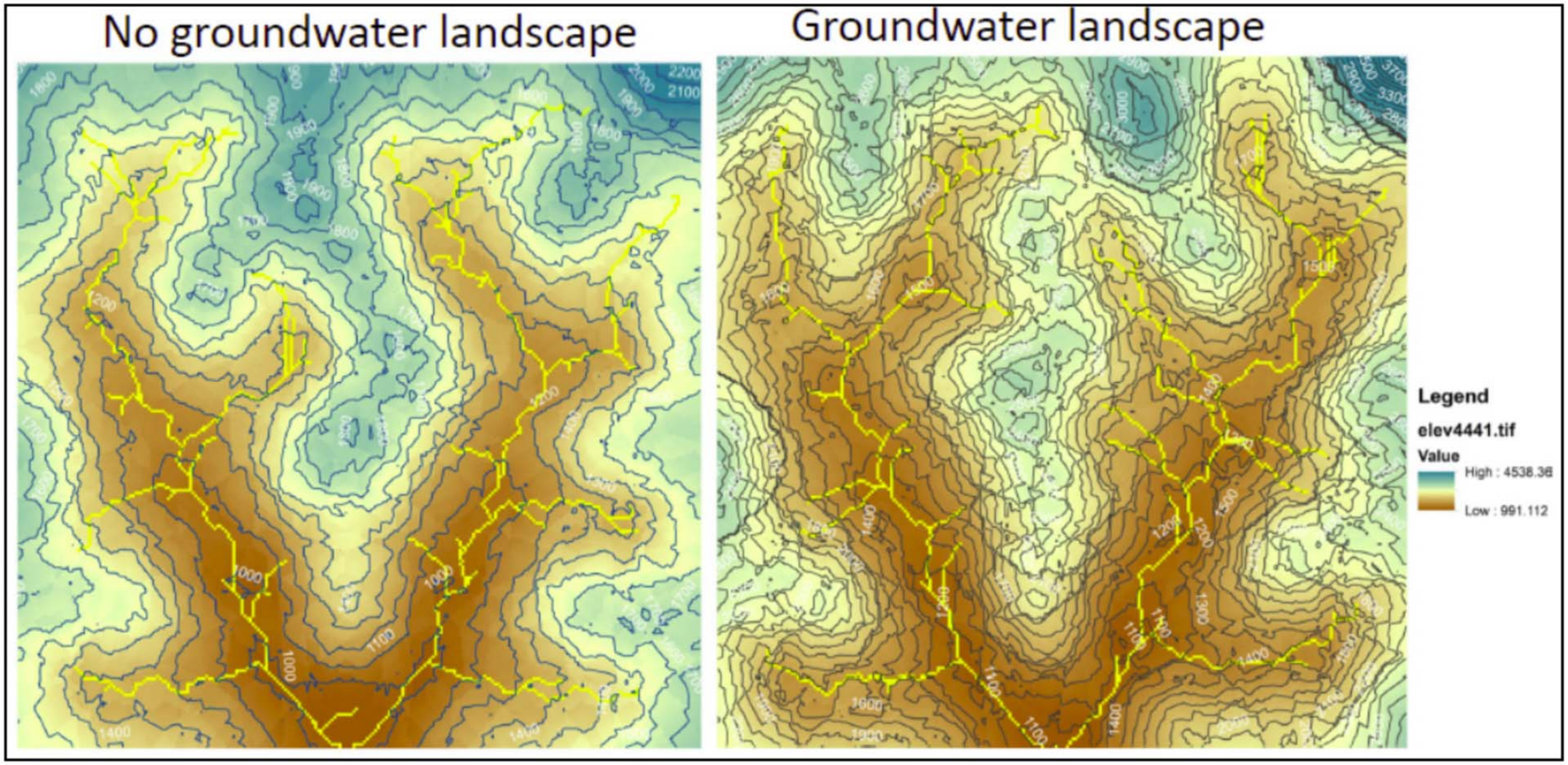


Duffy et al., 2014

LE-PIHM
(Yu Zhang, C. Duffy, R. Slingerland)



Landscape evolution with and without infiltration

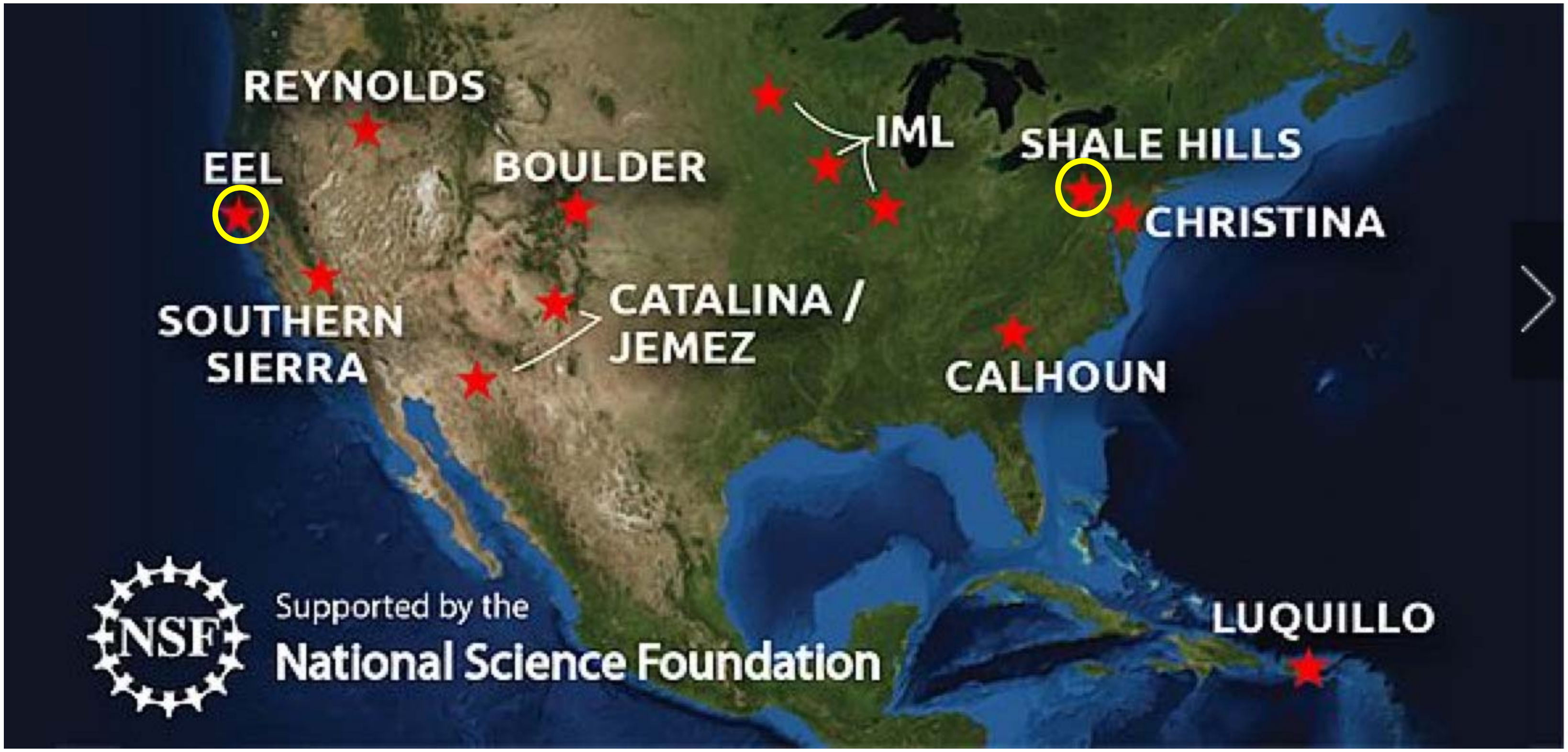


Steeper steady-state landscape results under constant uplift because there is less runoff

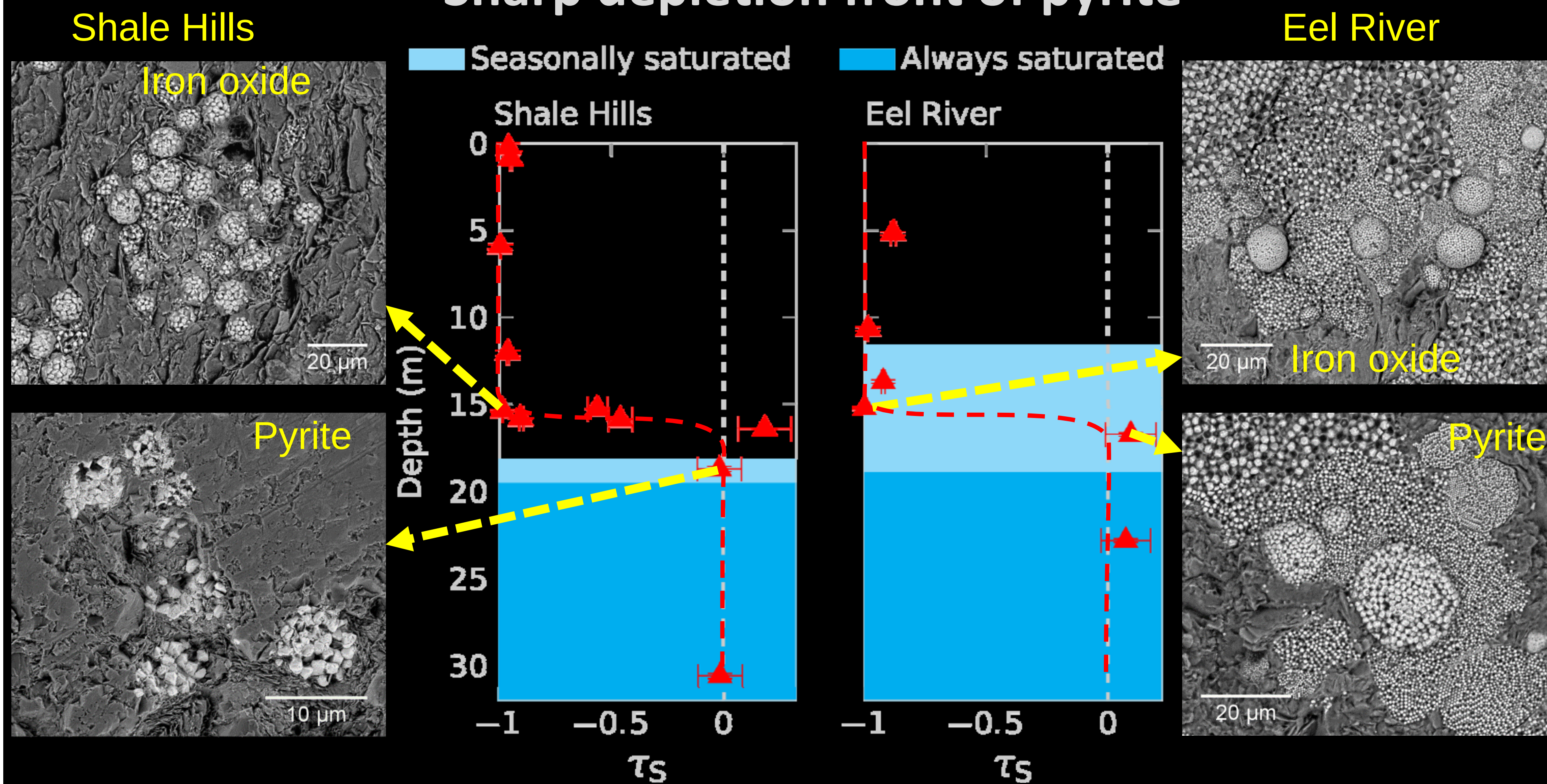
Duffy et al., 2014

Observations of repeated patterns that are observed at multiple observatories drive conceptual models explaining why landscapes are the same and different

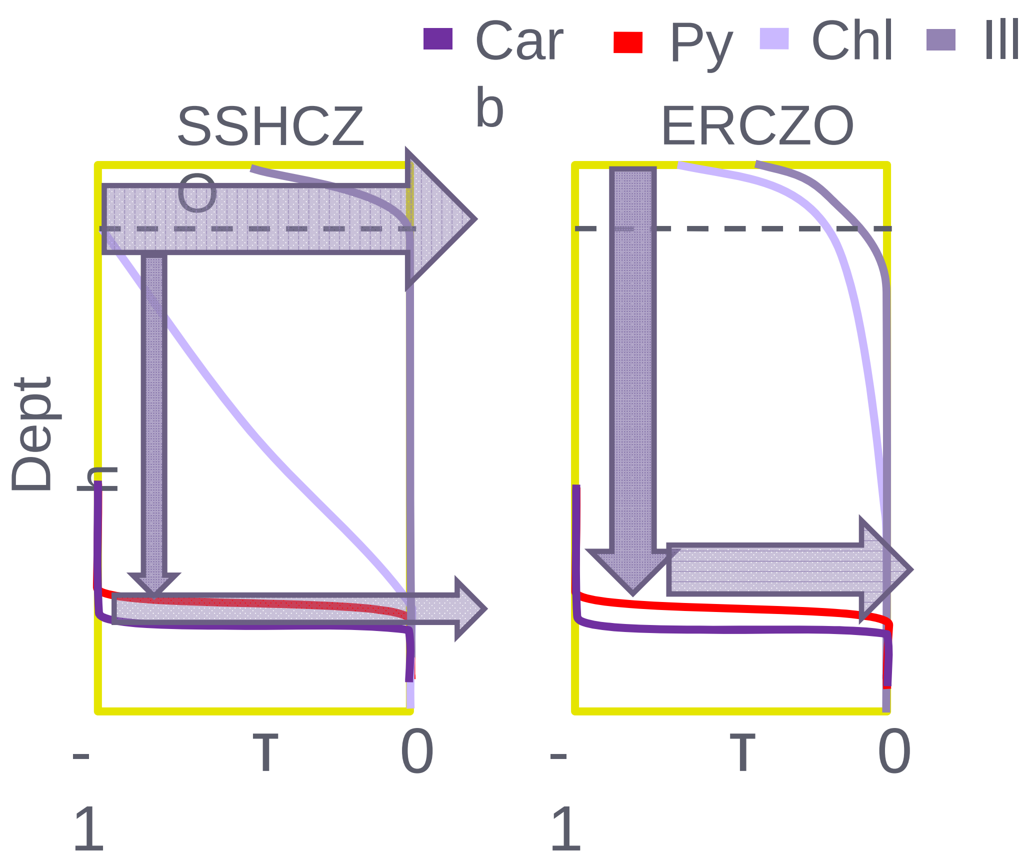
The Critical Zone Observatories



Sharp depletion front of pyrite



Gu, X. 2017. Using Neutron Scattering to Understand Porosity in Crystalline and Sedimentary Rock during Weathering, Ph.D. Dissertation. Pennsylvania State University.



It should be possible to drill boreholes, analyze reaction front locations and geometry, and map broadly generalized long-term directions of water flow.

In addition, the relative partitioning of water flow can be estimated based on the relative solubilities of the minerals: high solubility minerals dissolve at depth, less soluble dissolve toward the surface.

By coupling weathering models with hydrologic models, we eventually will be able to predict the subsurface regolith (i.e., the permeability architecture).

Gu, X. 2017. Using Neutron Scattering to Understand Porosity in Crystalline and Sedimentary Rock during Weathering, Ph.D. Dissertation. Pennsylvania State University.

Towards Improved Land Data Assimilation Systems

Modeling Technique

Incorporate physics-based hydrologic model

Data Assimilation Technique

Fully utilize reanalyses, remotely-sensed and *in situ* data

Automated parameter and state optimization

Improved land surface and hydrologic data assimilation systems

Slide from Yuning Shi (Penn State)

Towards Improved Land Data Assimilation Systems

Modeling Technique

Incorporate physics-based hydrologic model, soil genesis model, and geomorphological evolution model

+

Data Assimilation Technique

Fully utilize reanalyses, remotely-sensed and *in situ* data

Automated parameter and state optimization

→

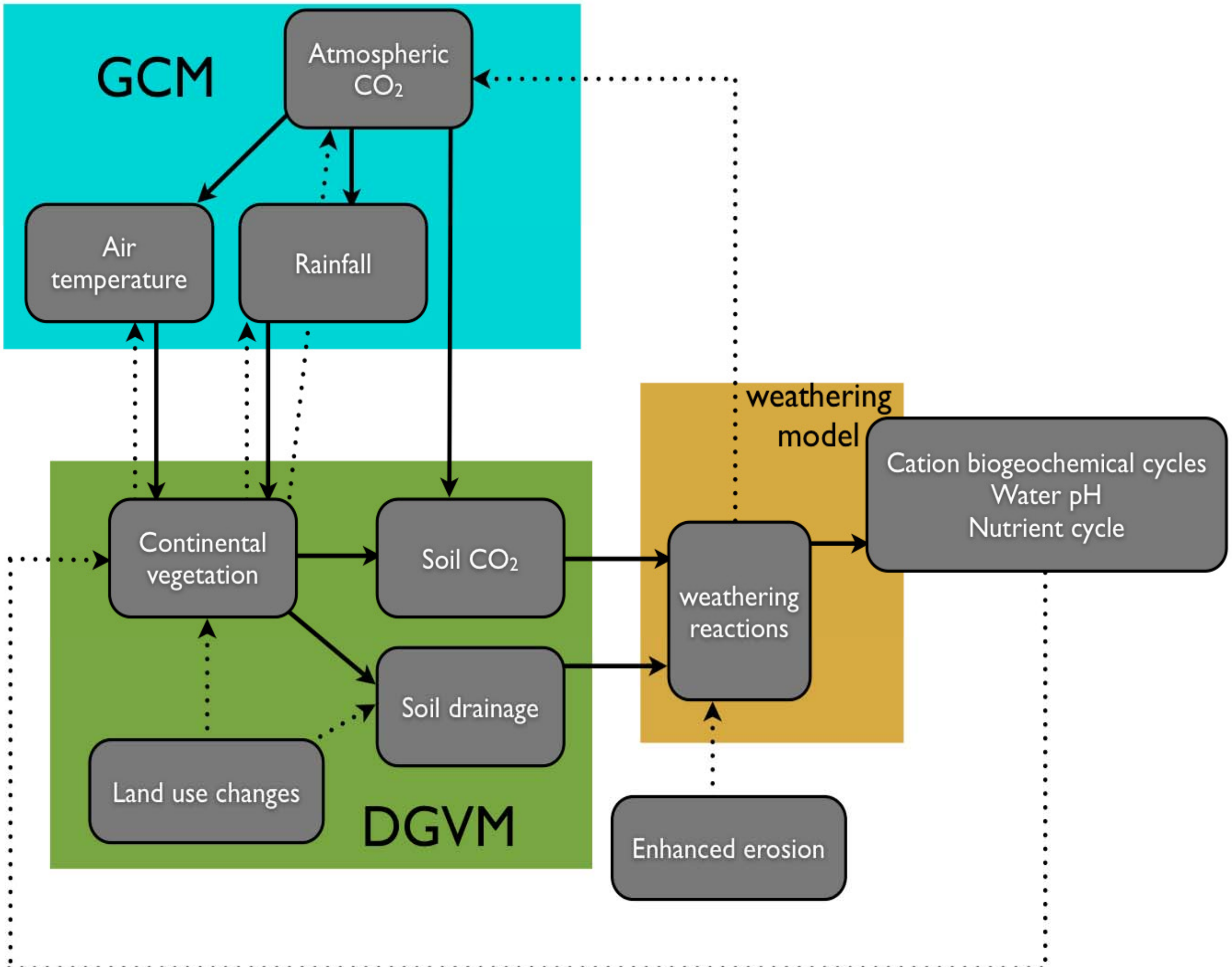
Improved land surface and hydrologic data assimilation systems

Slide from Yuning Shi (Penn State)

Earthcasting future soils

Climate models (GCM for General Circulation Model) in use today include GENESIS and ARPEGE, among others; vegetation models (DGVM for Dynamic Global Vegetation Model) include BIOME and CARAIB among others; weathering models include WITCH, SAFE, CRUNCH, and FLOTRAN among others. The solid arrows stand for processes that are currently included in numerical models. Dashed arrows represent processes and feedbacks that are not yet modeled within our current Earthcasting efforts.

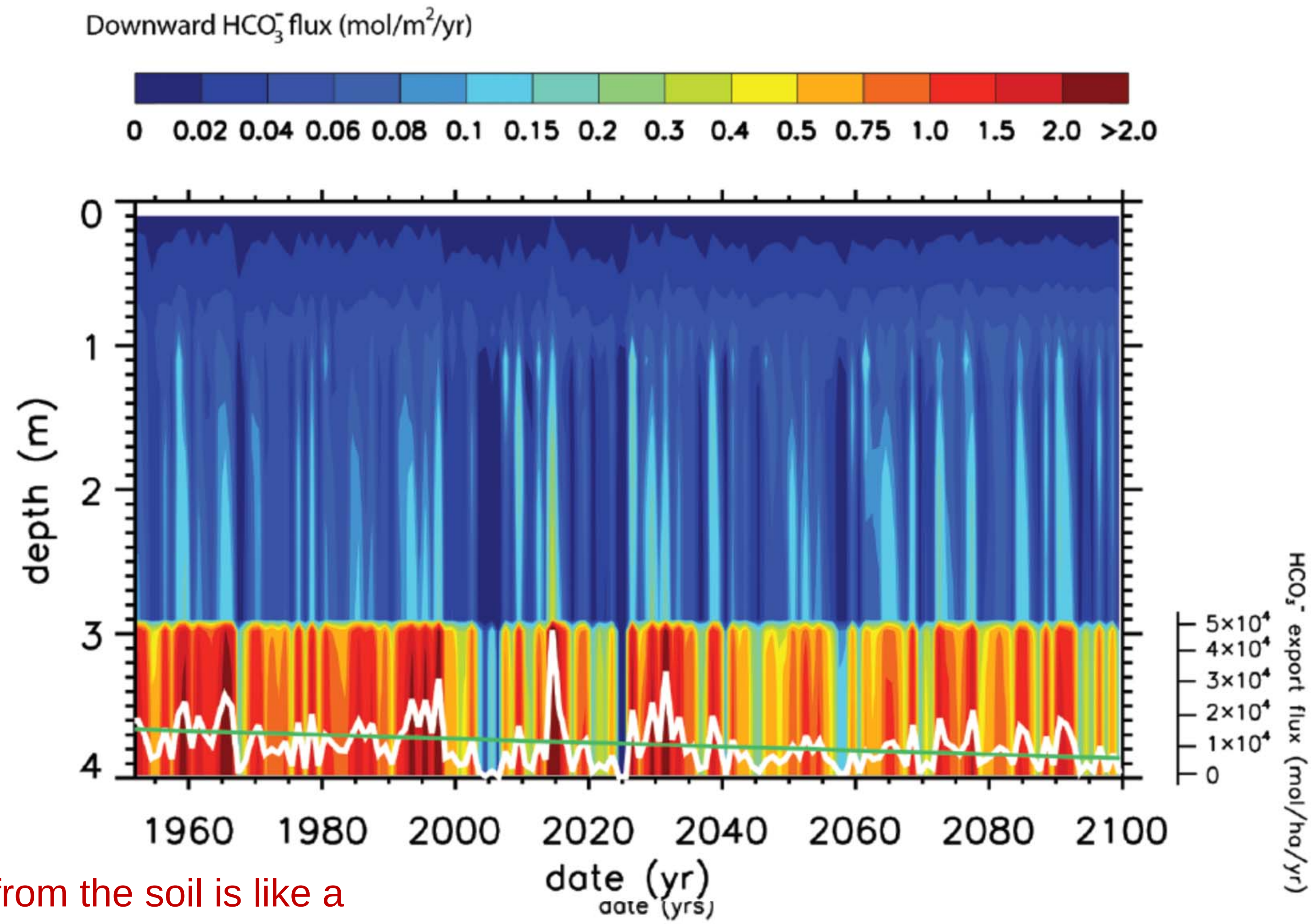
doi: 10.12952/journal.elementa.000019.f002



Godderis and Brantley, Elementa, inaugural issue, 2013

IPCC scenario A1B (CO_2 increases from 315 to 700 ppmv)

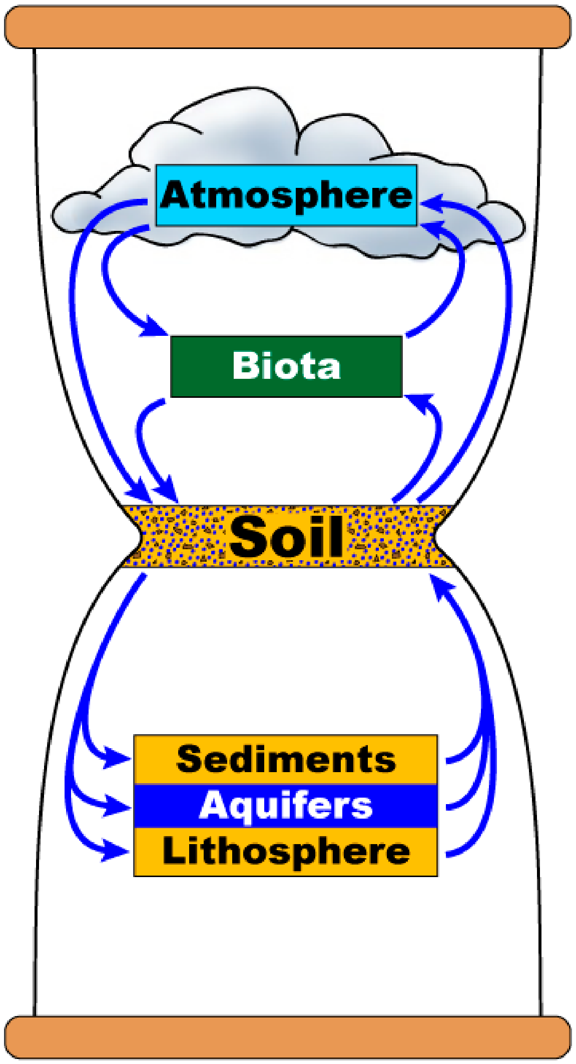
Scenario of very rapid economic growth, a peak in global population followed by decline, accompanied by new and efficient technologies



Loss of carbonate from the soil is like a "terrestrial lysocline" that responds to increasing CO_2 in the atmosphere

Godderis and Brantley, Elementa, inaugural issue, 2013

Conclusions



- We are improving our understanding of the earth surface system and integrating it across disciplines
- Progress is slow because it requires people to work together (this is hard): observatories force scientists to make measurements side by side that can be compared and measured
- We need to stay the course with long-studied sites!
- At the same time, we need to enable more scientists to cross sites looking for patterns to generate better conceptual and numerical models and then to apply the models to multiple sites
- We need to start using data assimilation with output from models of regolith and landform evolution to improve our ability to understand land surface evolution

Acknowledgments

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