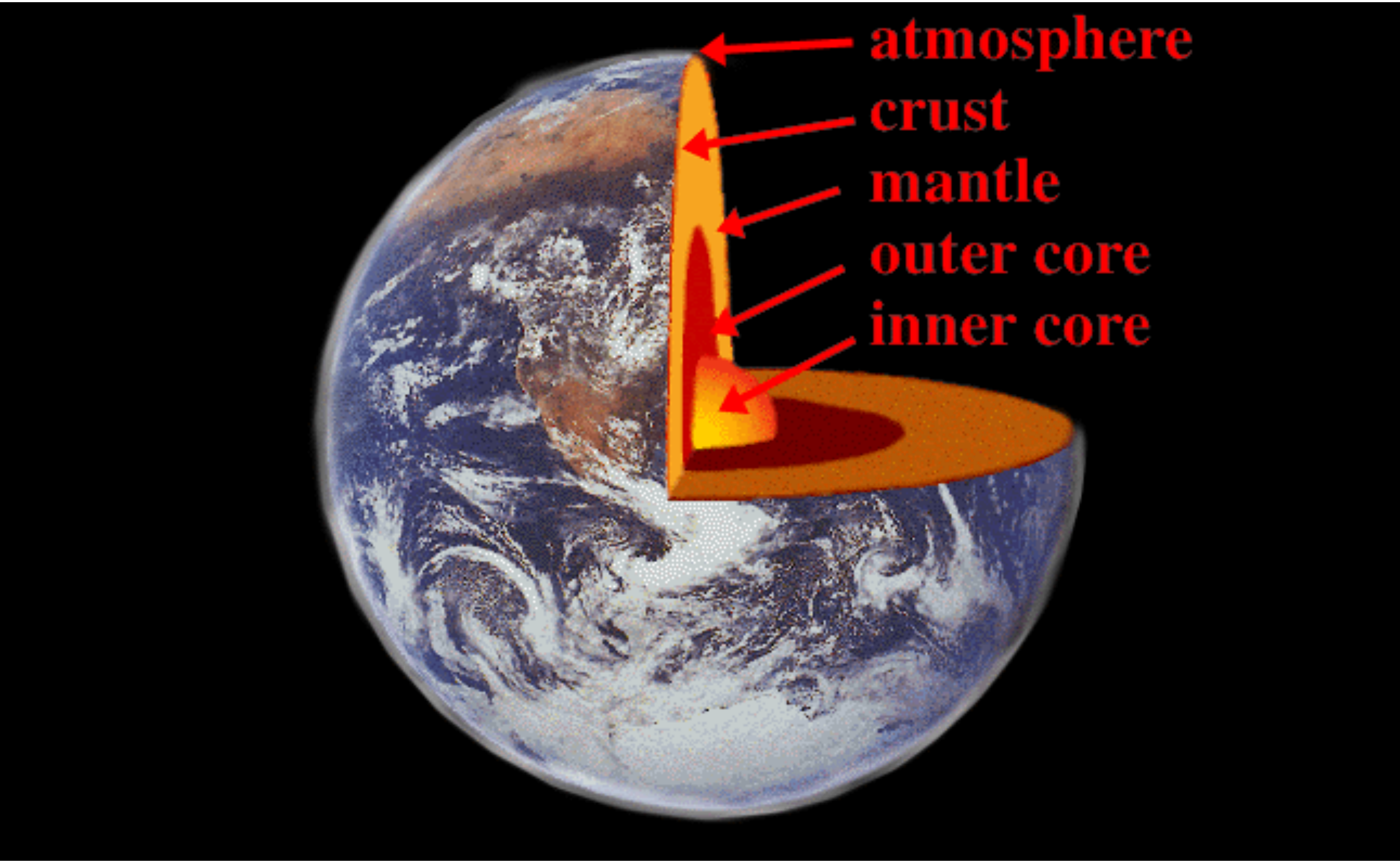
Rock to Regolith

Earth's Critical Zone on Volcanic Ocean Islands

Suzanne P. Anderson, Greg E. Tucker, Robert S. Anderson, Abigail Langston, and Patrick Kelly

National CZO Program | BOULDER CREEK CRITICAL ZONE OBSERVATORY

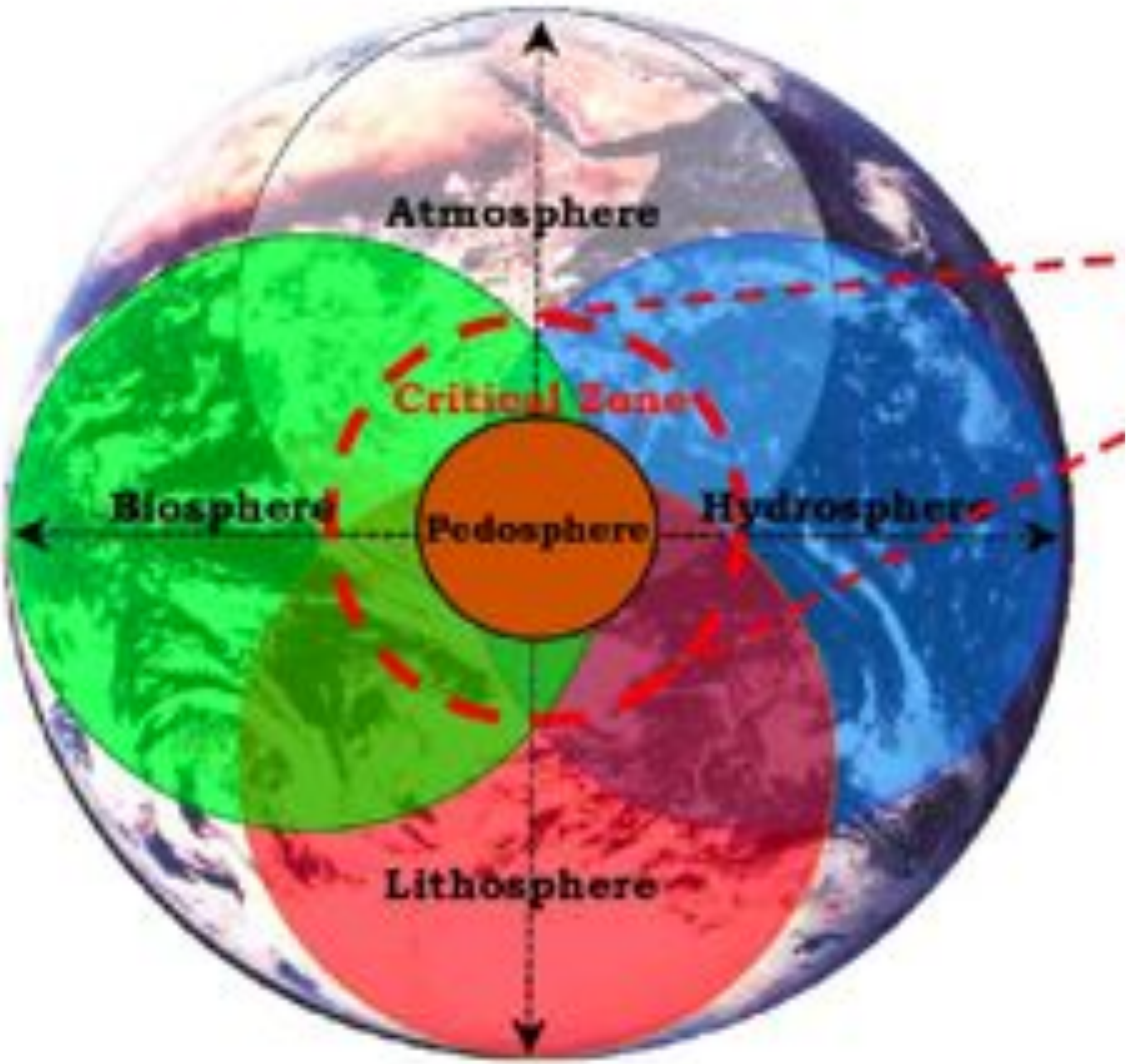
University of Colorado **Boulder**


atmosphere
crust
mantle
outer core
inner core

Soils

Earth's Critical Zone:

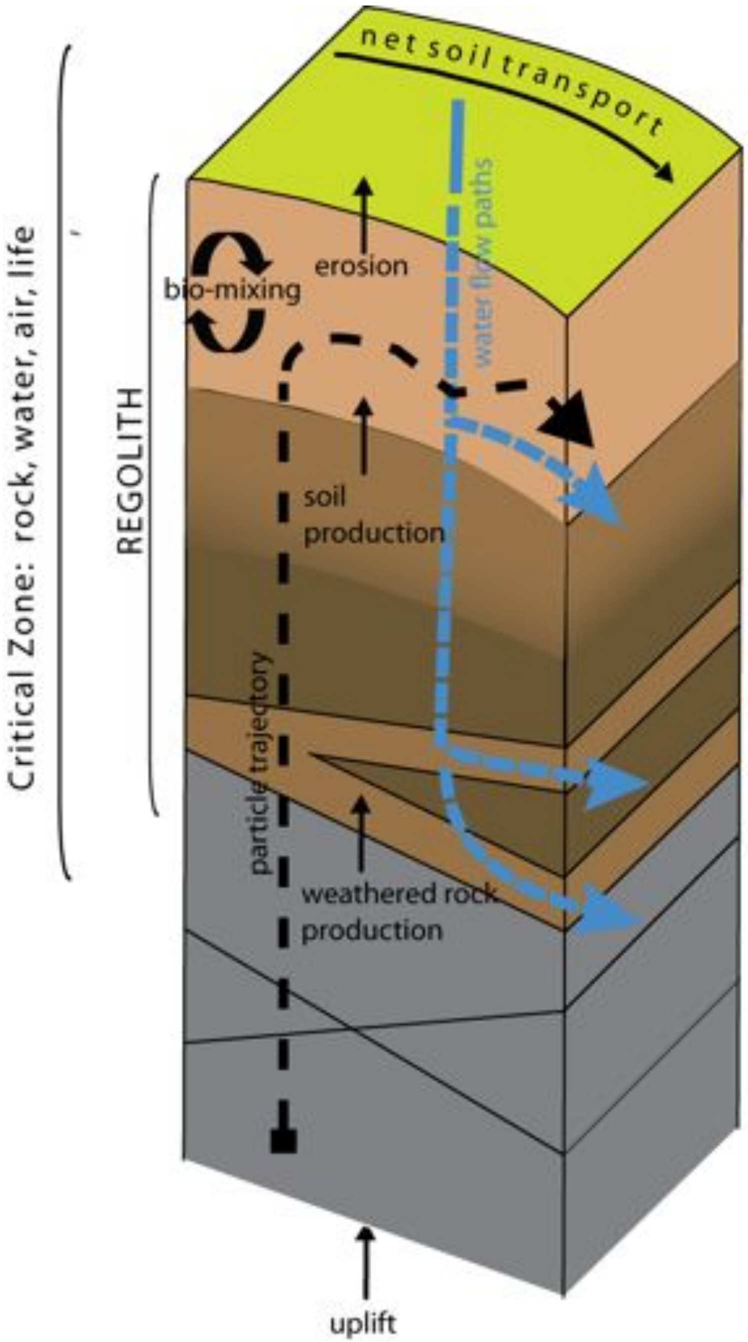
Where Rock meets Water, Air, and Life



Wilding and Lin, 2007, Geoderma

Critical Zone = Earth's surface, where interactions between the "spheres" are important

Critical Zone = interdisciplinary mindset to approach problems of interest (soil formation, landscape evolution, hydrologic function, ecosystem processes…)



Mobile regolith

Weathered rock

Unweathered
rock

Modified from
Anderson et al. (2007) *Elements*

Soil mantled Osborn Mt, WY

Bedrock-dominated
Green Lakes Valley, CO

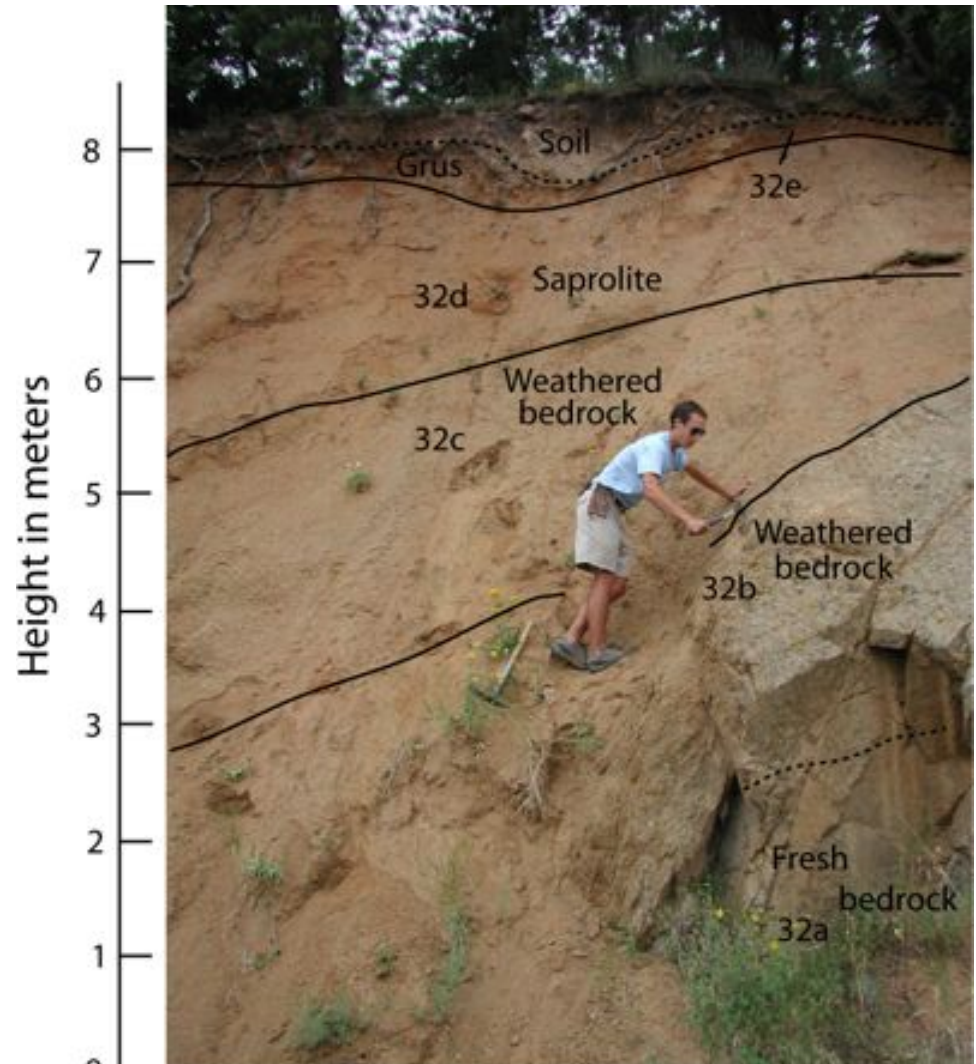
How does rock become soil?

Oregon Cascades

Weathering and Mobile regolith production

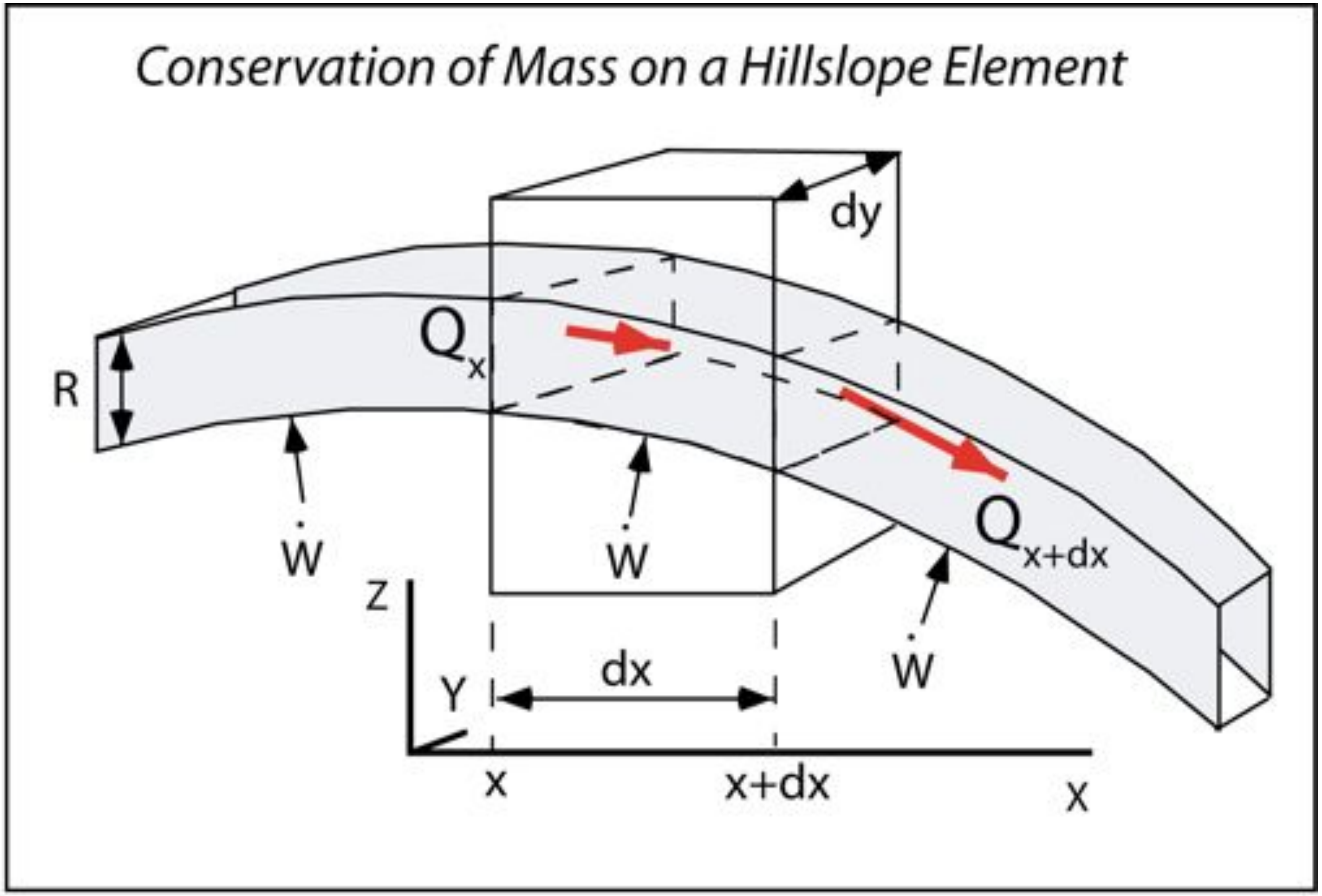
- Rock weathering can be thought of as accumulation of damage
- Processes are sensitive to:
  - Climate
  - Rock type
- Climate/tectonic legacy imprinted in mobile regolith and CZ architecture

Image courtesy David Dethier



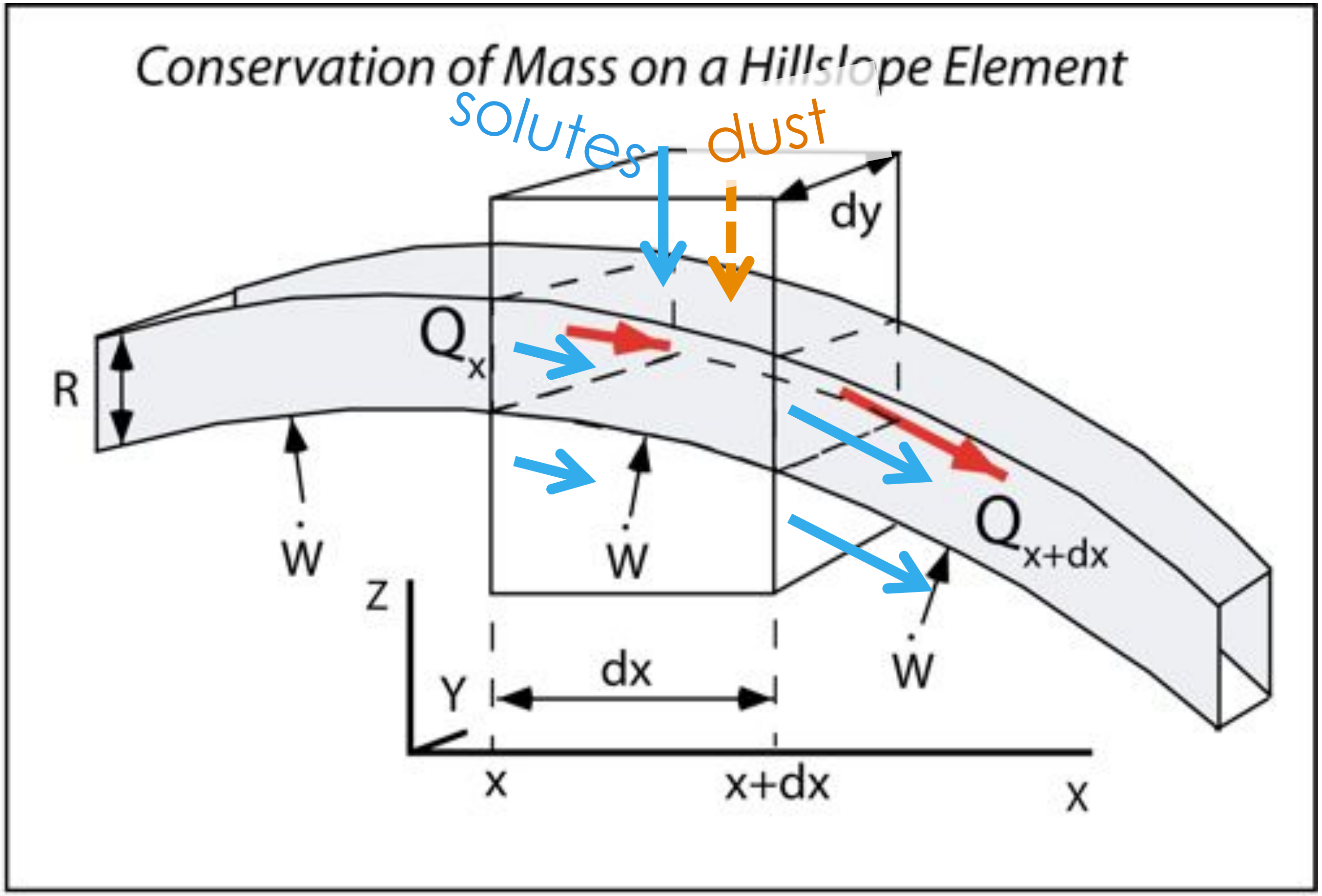
Altered Boulder Creek granodiorite; contacts appear to dip to left and toward road

The simple view of landscape evolution



We need rules for w and for Q

The slightly less simple view of landscape evolution



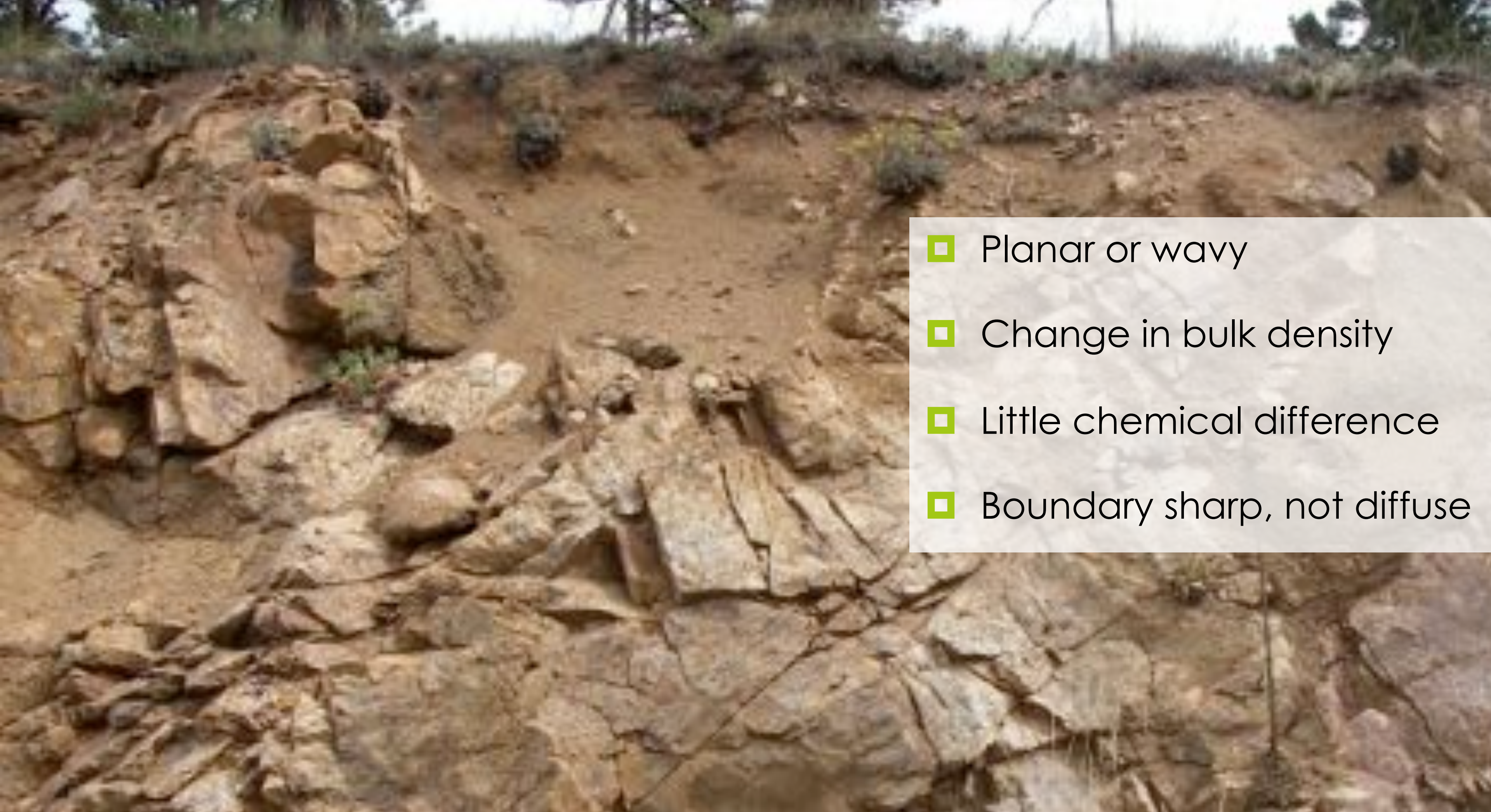
Consider

dissolved fluxes $Q_{dissolved}$

dust fluxes Q_{dust}

Questions

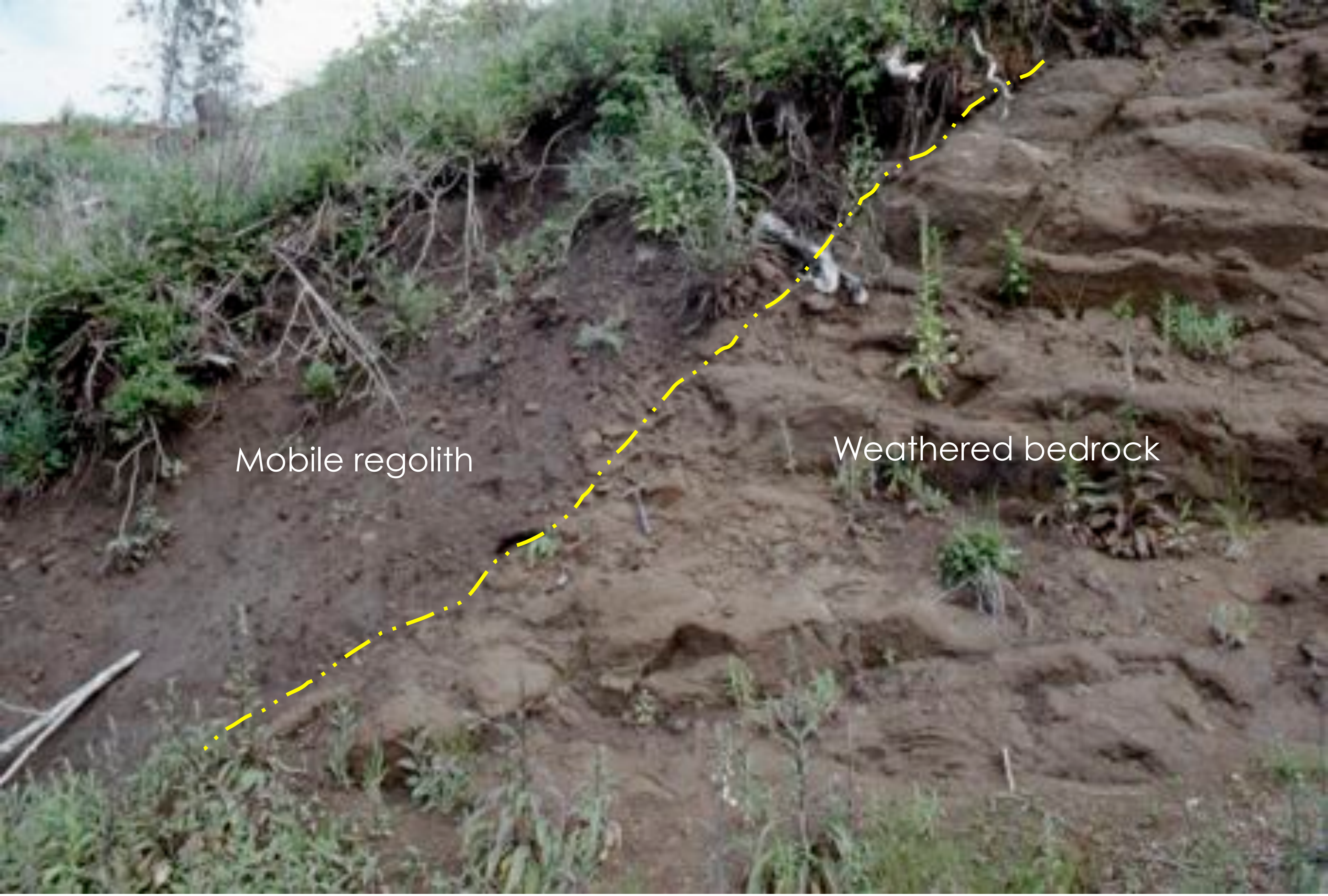
- What controls rate of production of mobile regolith in a landscape? (the w question)
- What governs the efficiency of regolith transport? (the Q question)
- What processes drive evolution of CZ layers?
- How do these rates vary with climate? (role of legacy)
- How can we use Volcanic Ocean Islands (VOI) to add to our understanding?

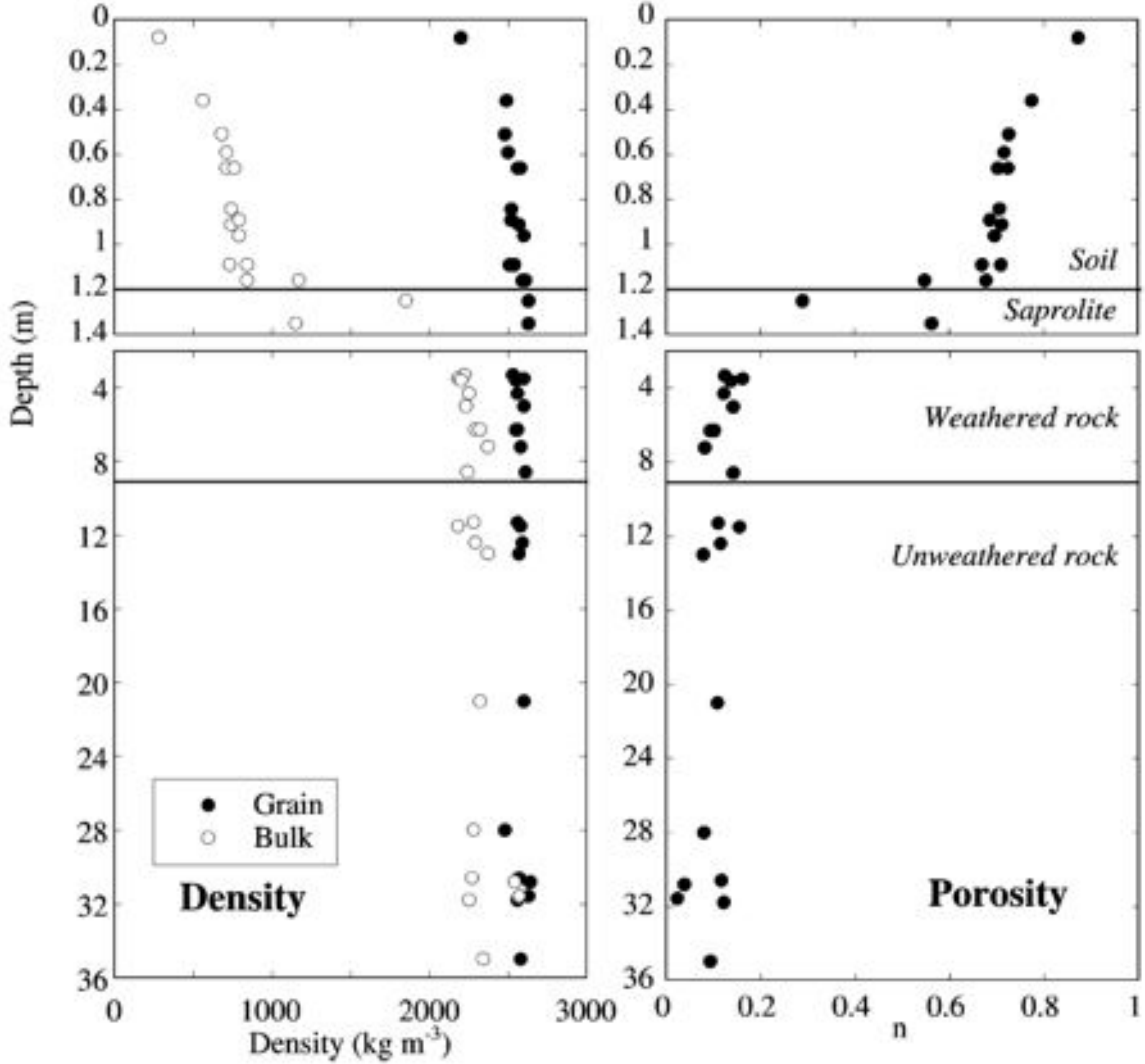


- Planar or wavy
- Change in bulk density
- Little chemical difference
- Boundary sharp, not diffuse

Rock-mobile regolith interface

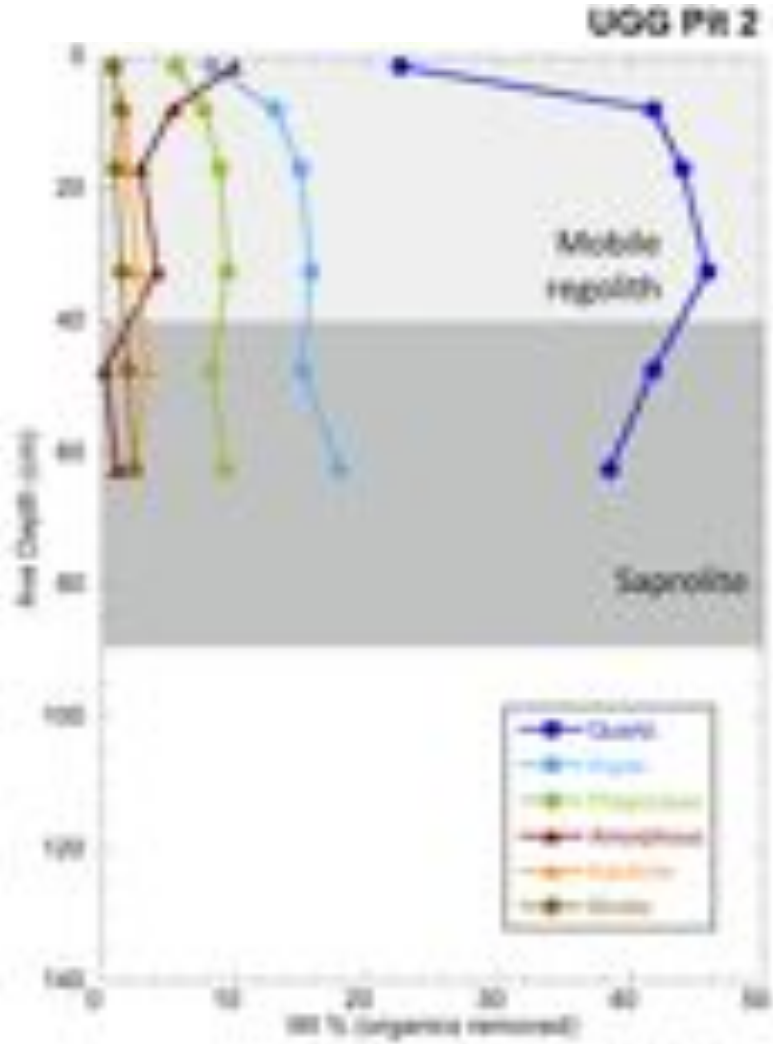
Common characteristics


Mobile regolith
Weathered bedrock



Oregon Coast Range; sandstone

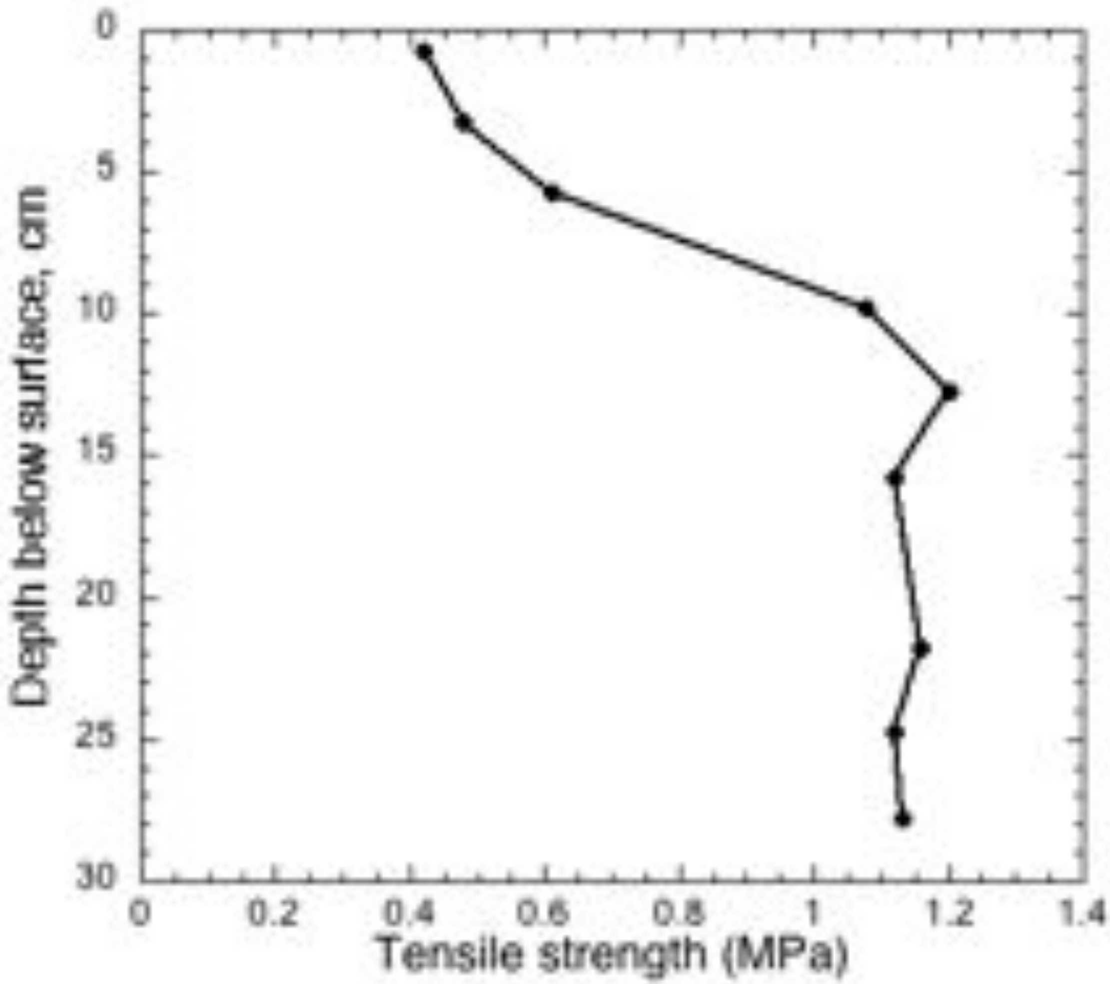
Anderson et al., (2002) *GSA Bull*



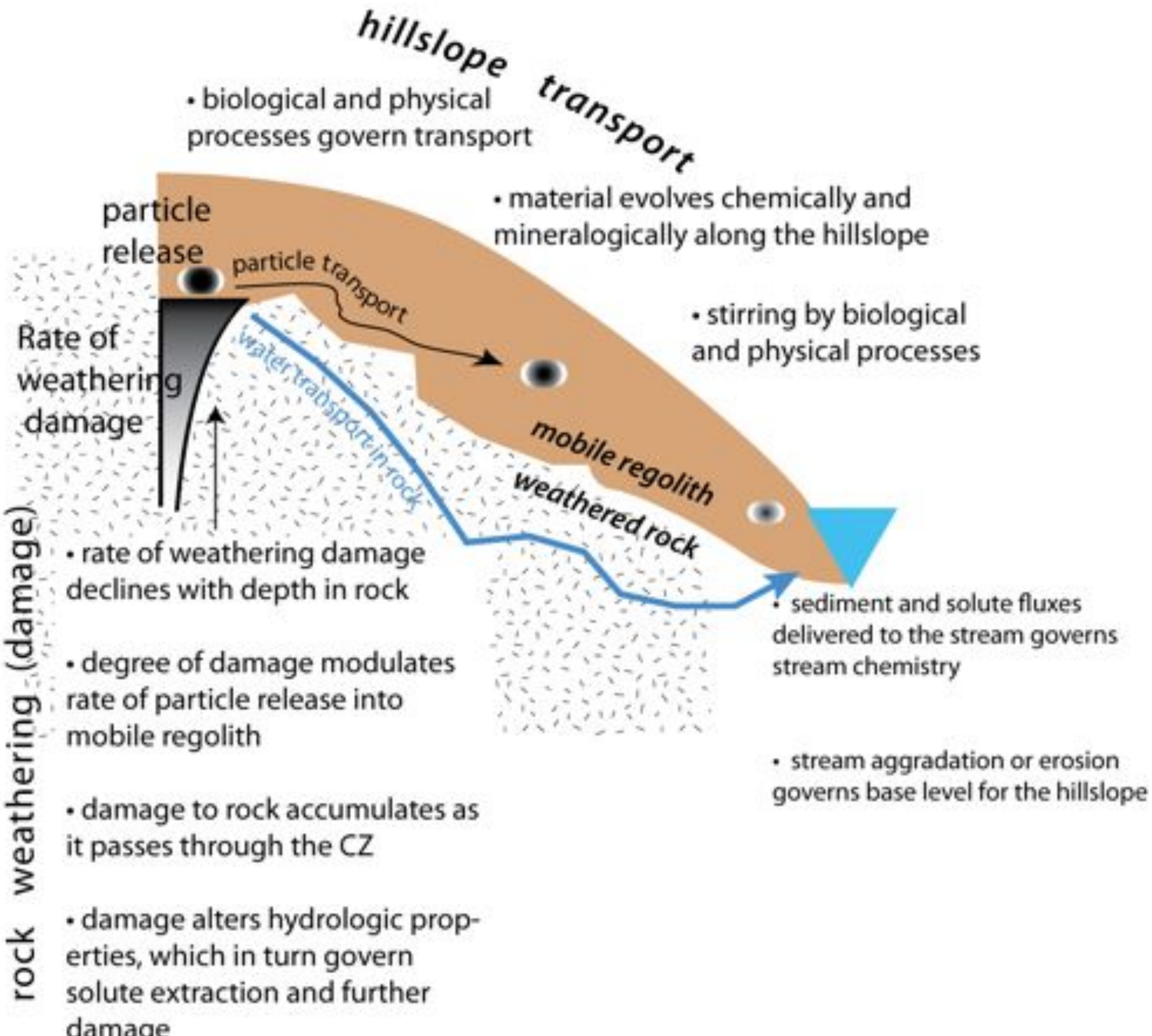
Front Range, Colorado; Precambrian gneiss

Rock strength

First results: Brazilian splitting tensile strength test, Gordon Gulch core



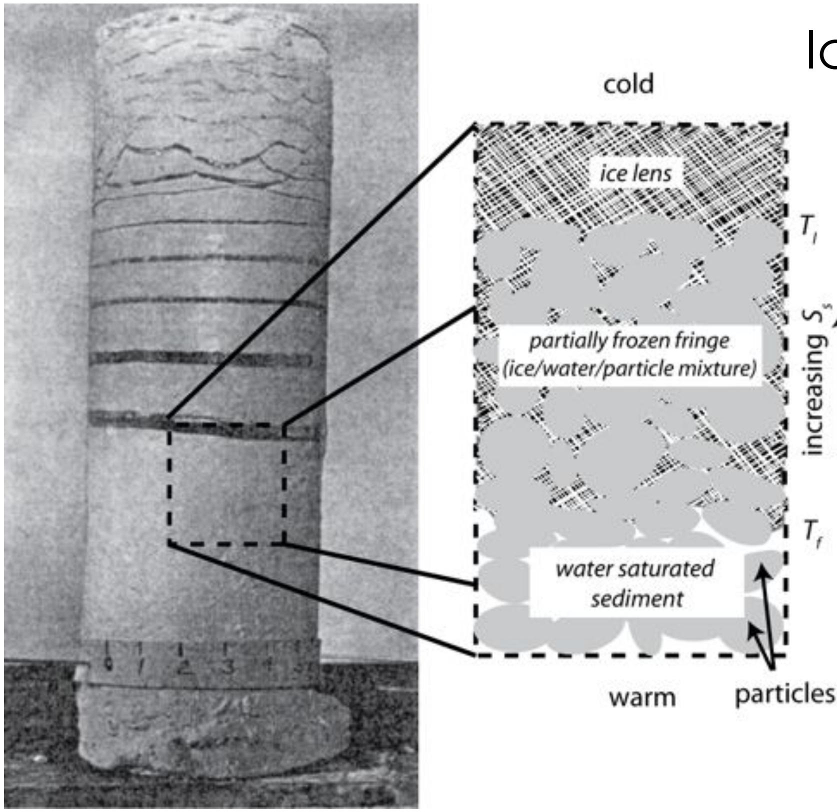
Emerging view: Reactor on a slope



Ice lens growth

Water freezing in soil and rocks

Ice lenses in soils



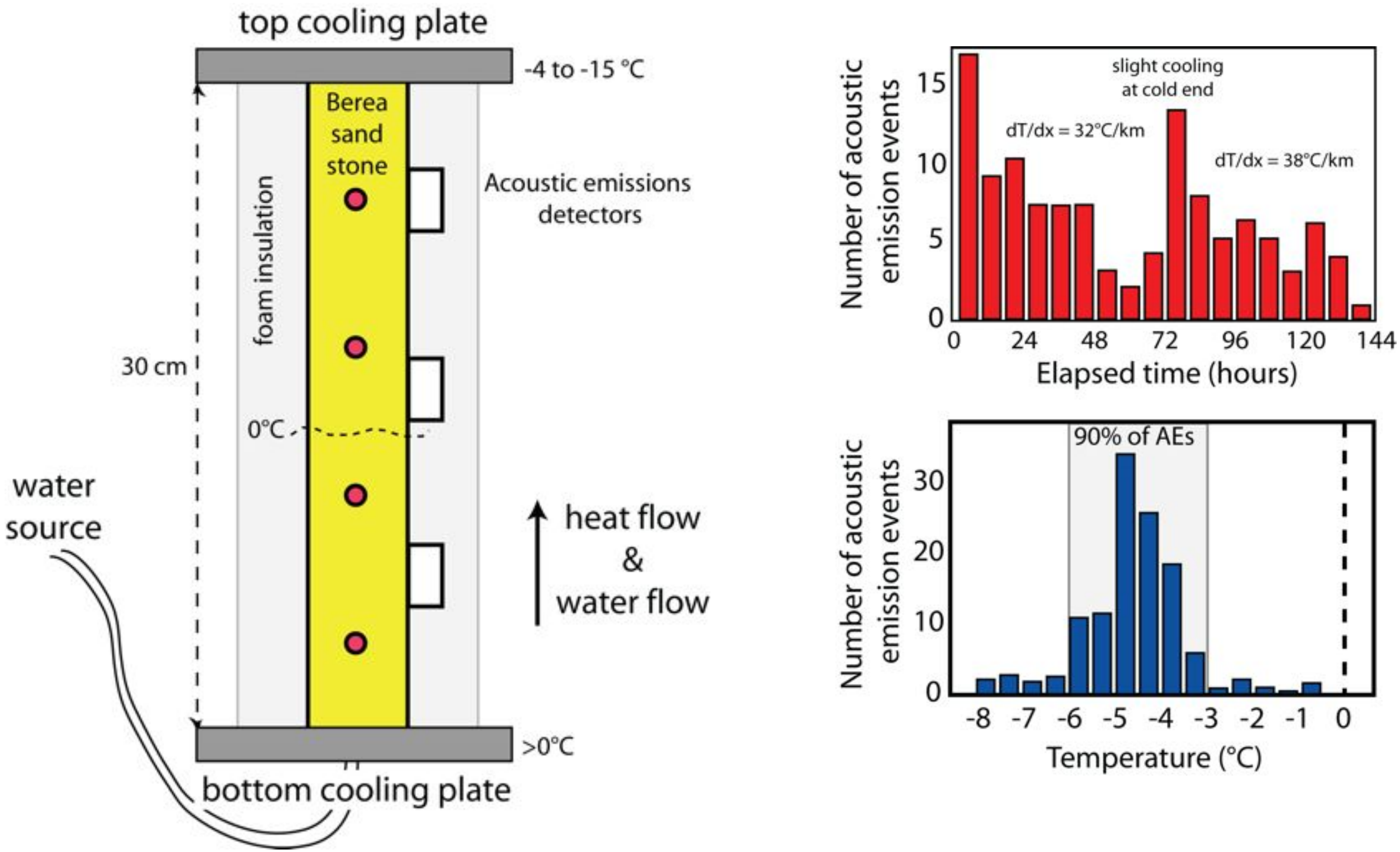
Taber (1930) *J. Geology*
Rempel (2007) *JGR*

Ice lenses in rock

Murton et al. (2006) *Science*

Figure 7 Chalkland periglacial features in southern England. (A) Br
Sussex. (B) South Downs scarp (~130 m high) west of Devil's Dyke, nea
scarp and the dipslope. This figure is available in colour online at ww

Matsuoka & Murton (2008) *Permafrost and Periglacial Processes*

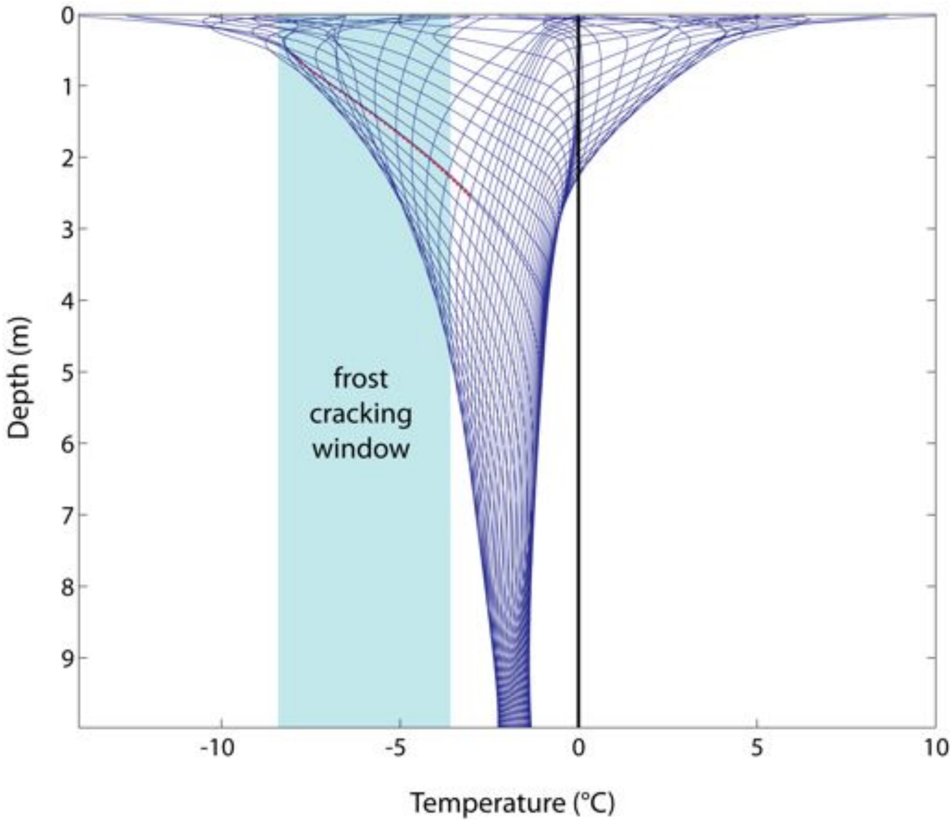


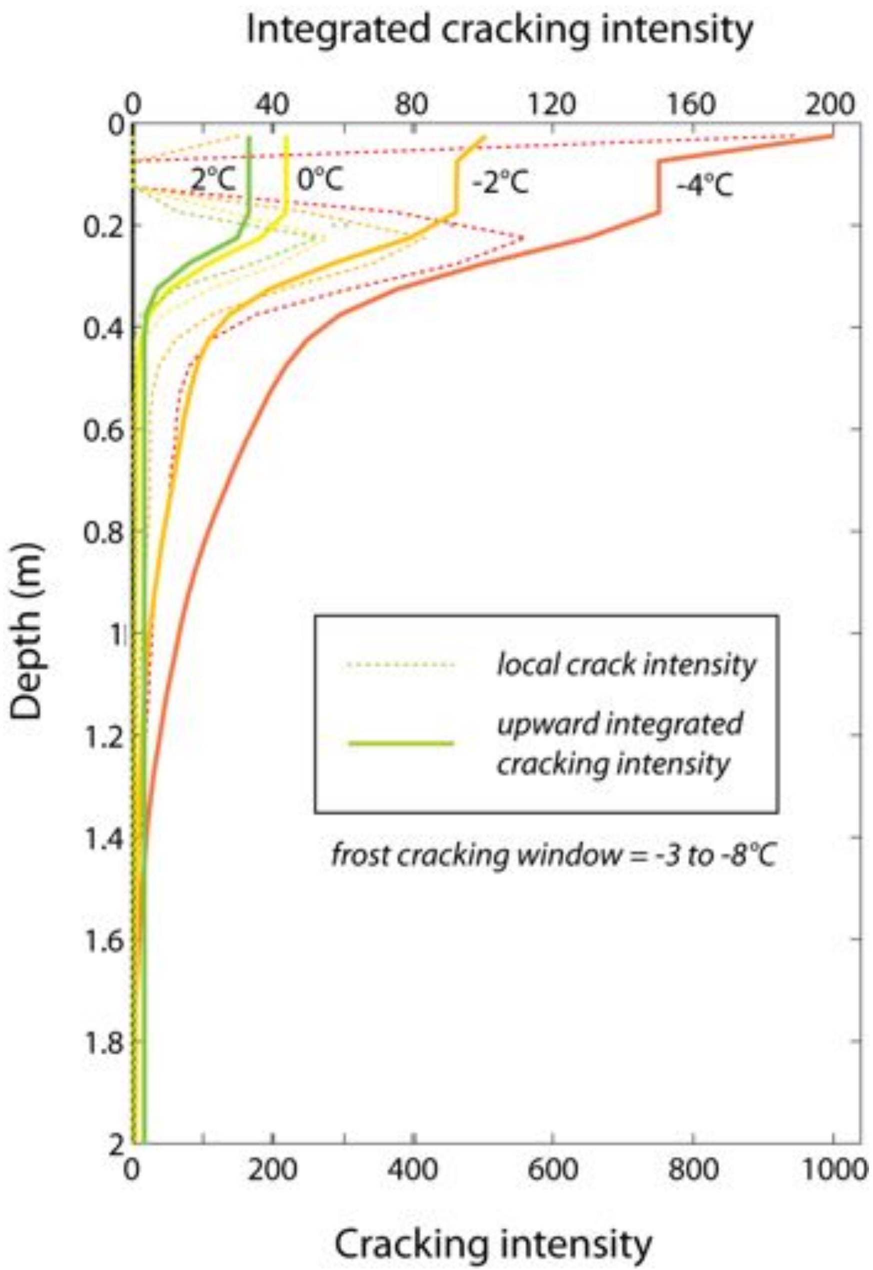
Experiments show that duration of sub-freezing temperatures controls extent of frost cracking of rock

Walder Hallet and Stubbs

Frost cracking (damage) model

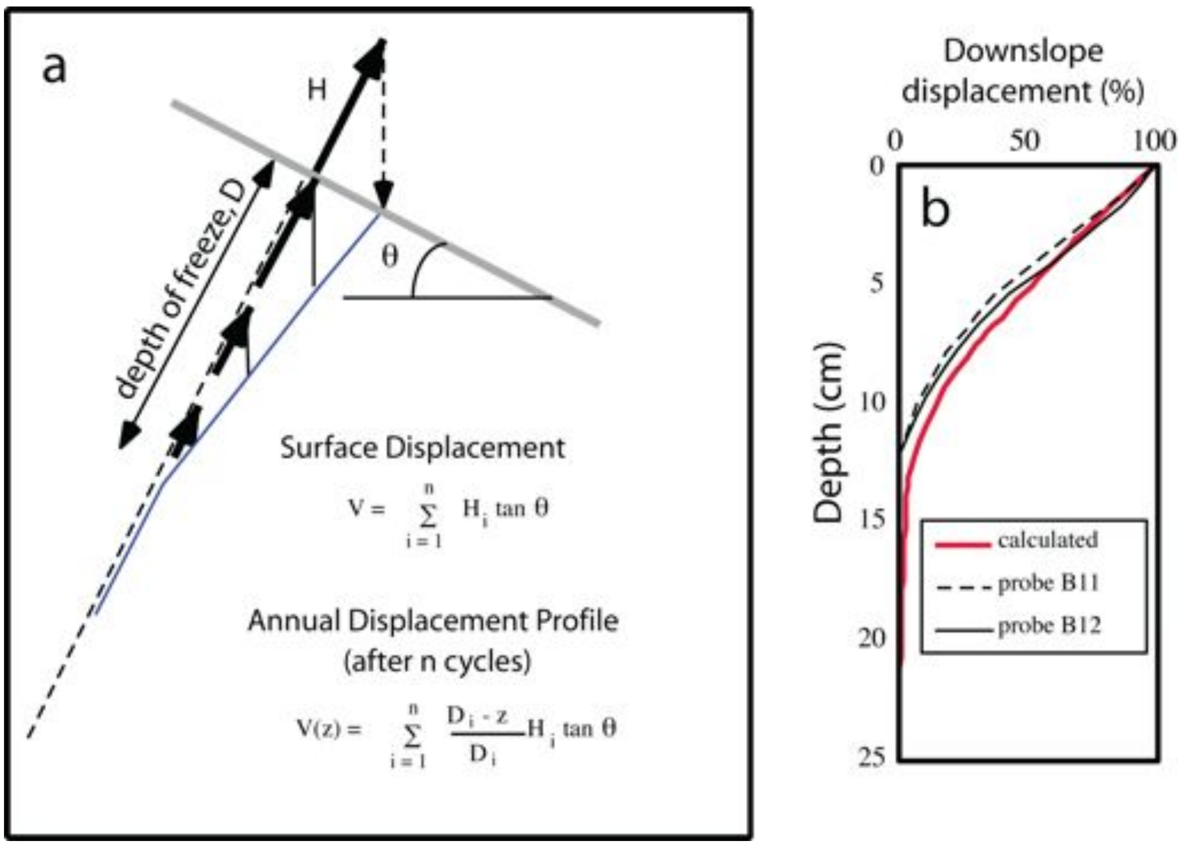
- Thermal model (conduction, stalled by latent heat)
- Access to water (marriage with a vadose zone code)
- Fracture mechanics of the rock
- Integration of damage (crack growth) as the rock mass is exhumed toward mobile regolith interface





- Crack intensity strongly dependent on MAT
- Expected cracking increases monotonically towards surface

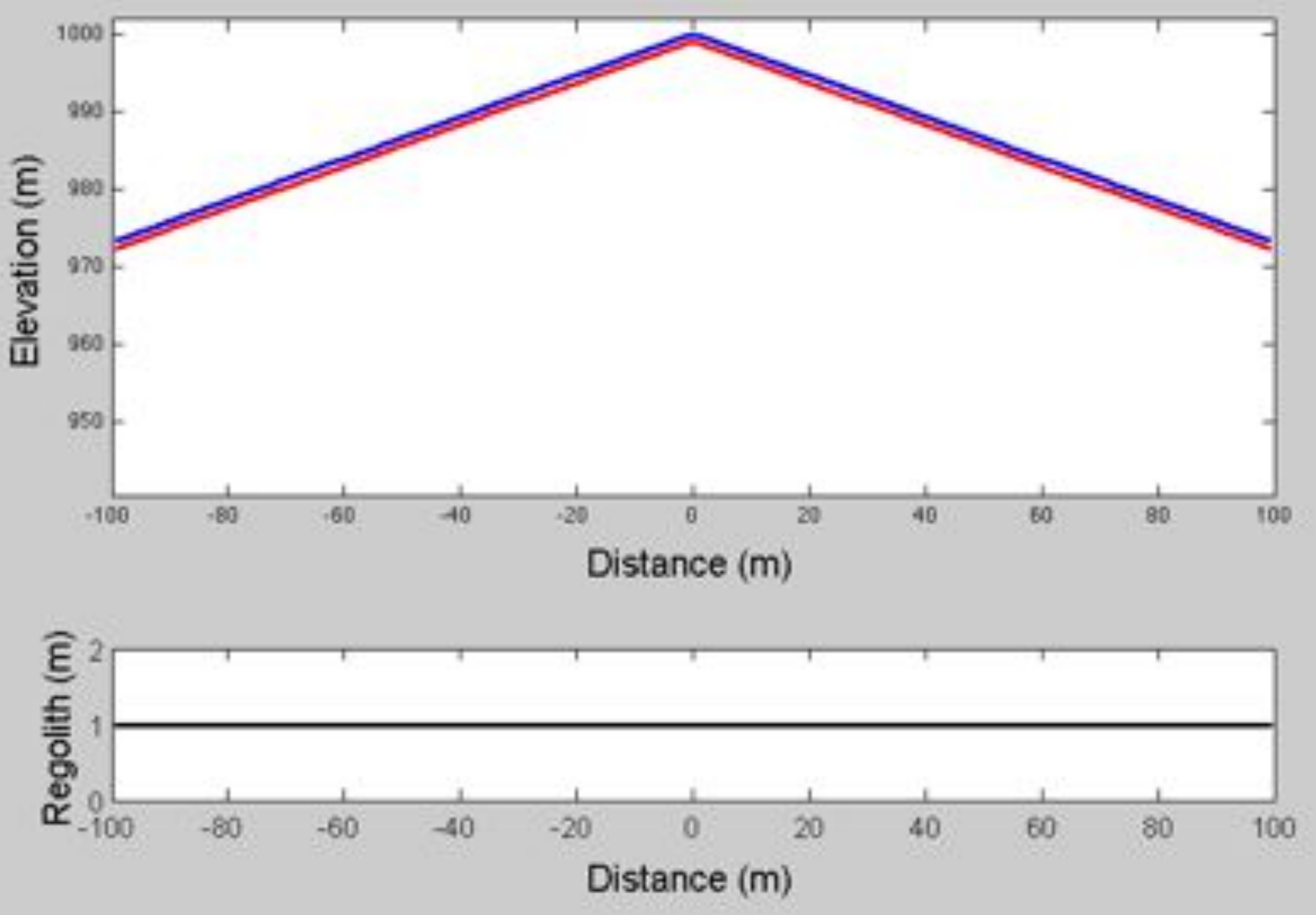
Frost creep transport



Model parts

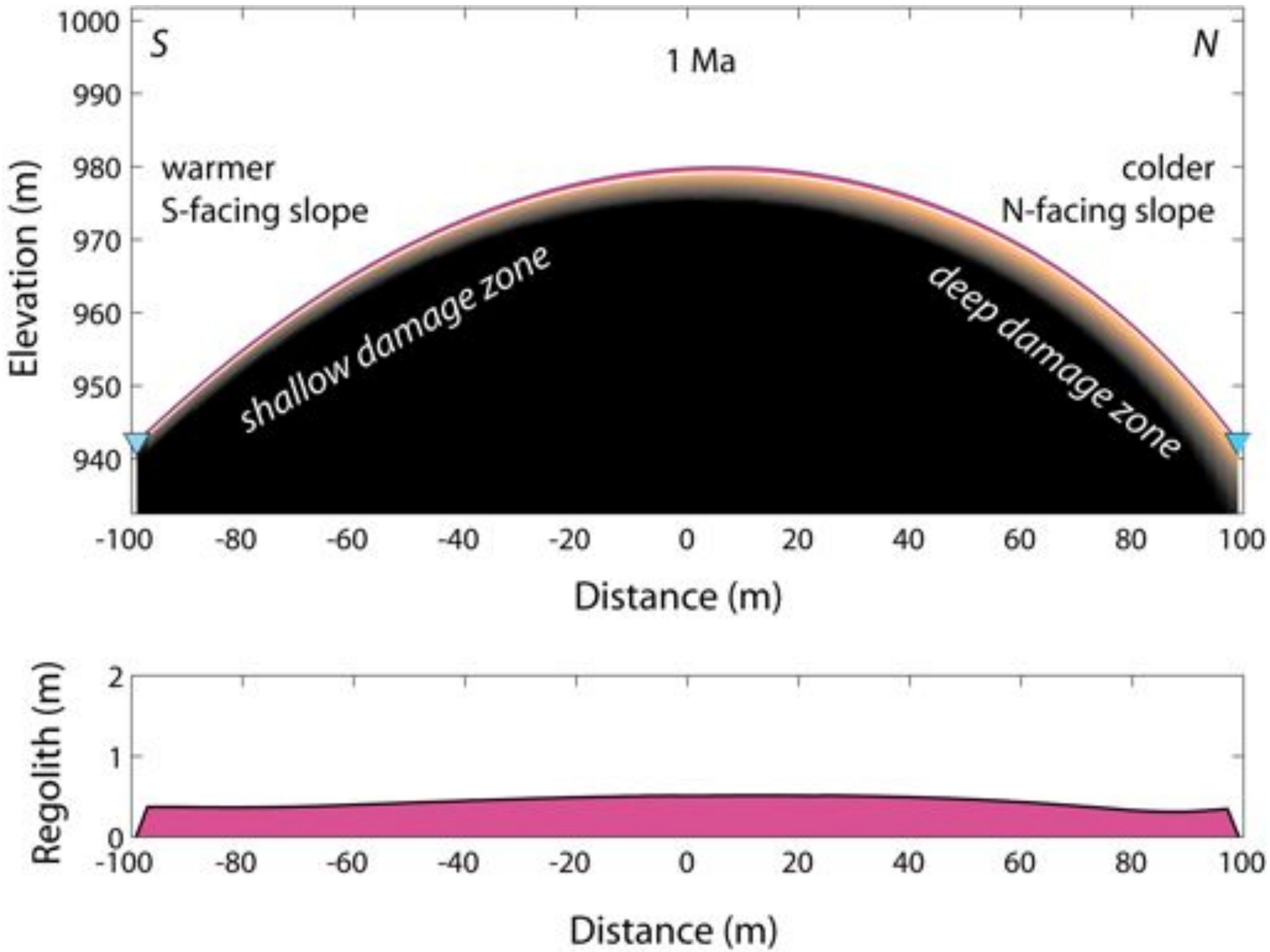
- Frequency and depth of freezing event (f, D)
- Strain per event (β)
- Slope

$$Q = -\frac{1}{2}\rho f \beta D^2 \frac{\partial z}{\partial x}$$



Model with frost processes, oscillating climate

Frost-cracking damage model over 1 Ma



Trees

30-40% of biomass is below ground

Trees as crowbars and transport agents---affecting Q and w

Tree fall

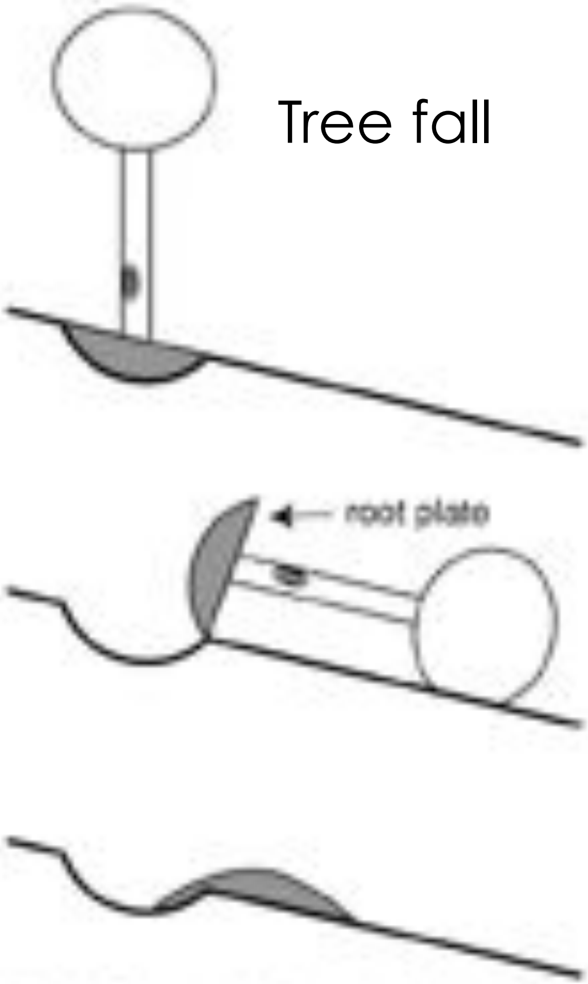


Figure 3 Illustration of the creation of pit and mound topography when a tree topples over.

Root growth & decay

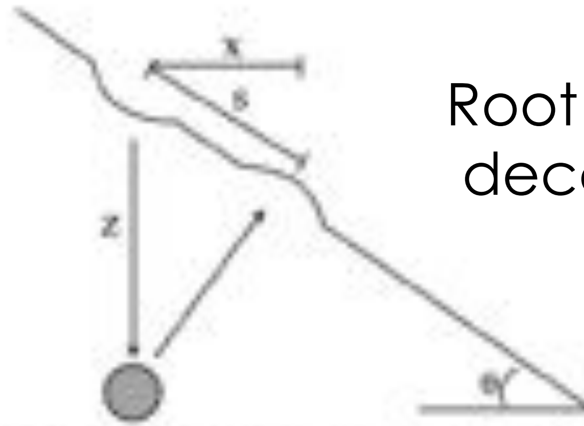
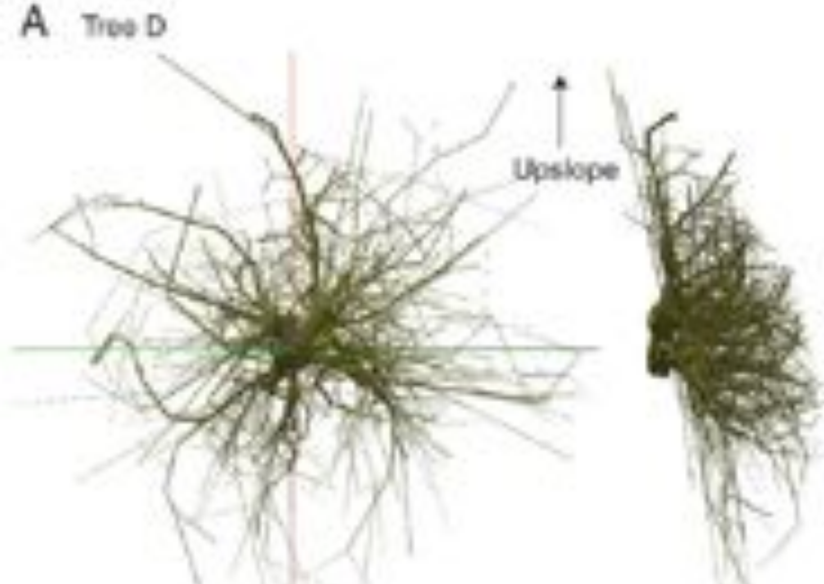


Figure 1 Illustration of geometrical relationships in the calculation of the horizontal distance of soil transport in the process of root growth and decay. The grey circle represents a cross-sectional view of a root. During root growth, soil is pushed in a direction normal to the soil surface. After the root dies, the soil collapses vertically into the root hole.

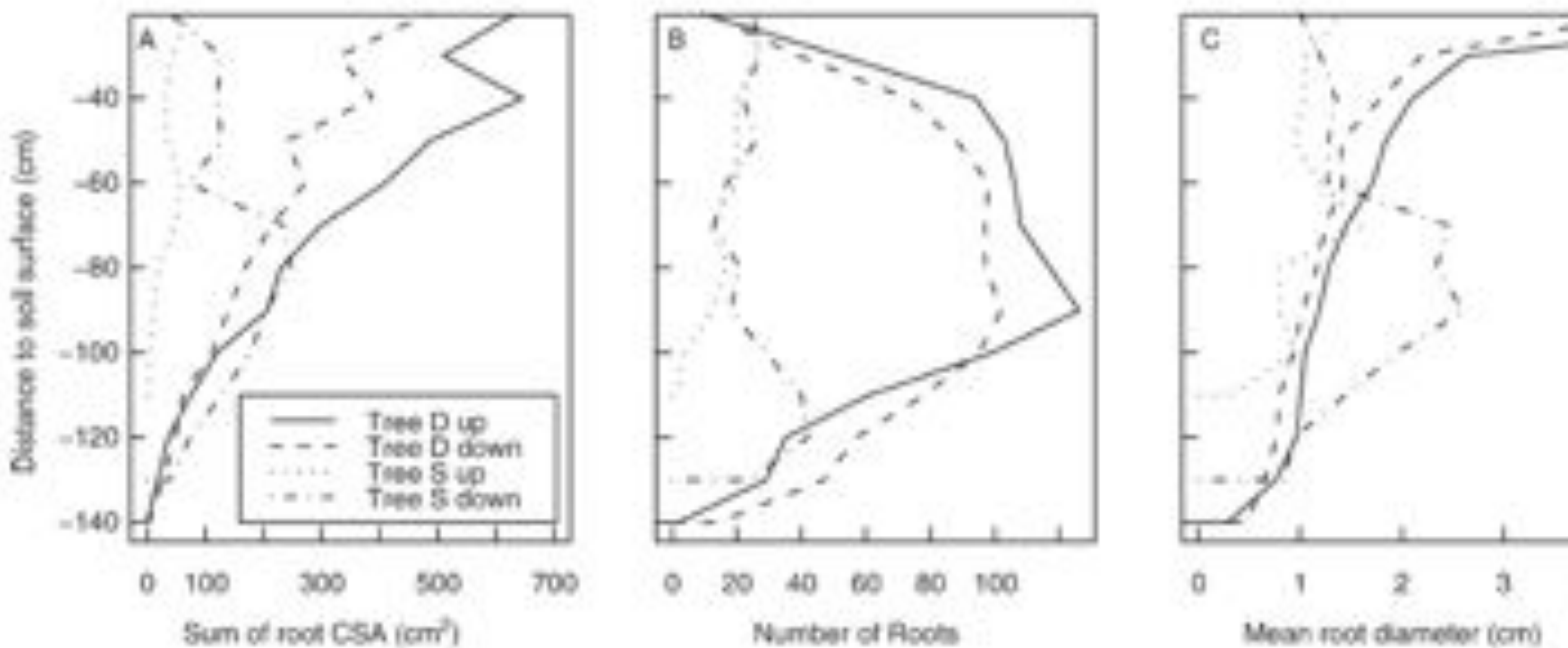
$$Q = -\left[\frac{\rho f V(z)}{t}\right]\frac{\partial z}{\partial x}$$

Gabet et al. (2003) *Ann. Rev. Earth Planet. Sci.*



Danjon et al. (*Ann. Botany*)

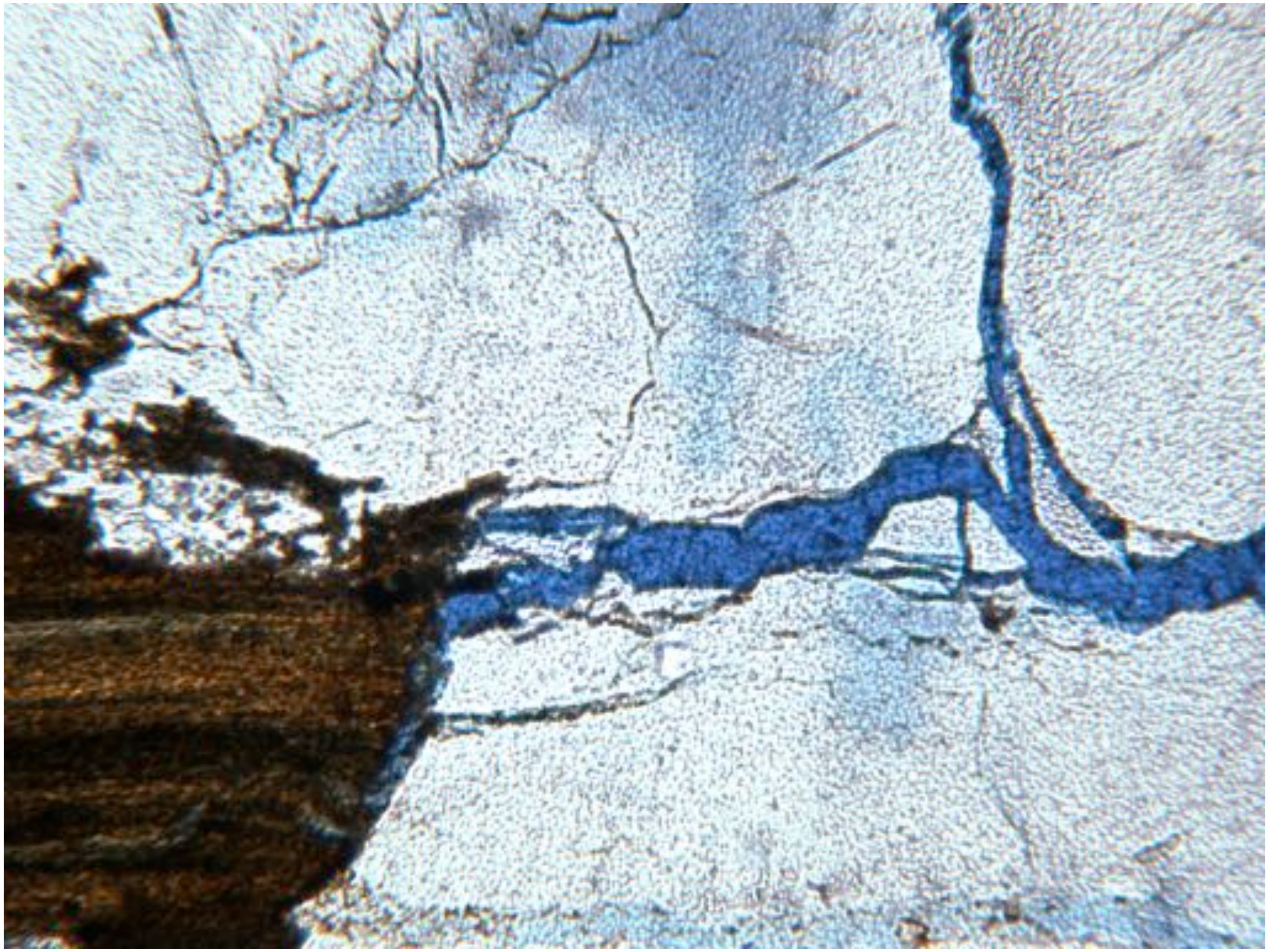
Characterize -root depths
-root size
-number of roots



Spheroidal weathering

Fracturing driven by chemical alteration

Granite outcrop, Puerto Rico (Sue Brantley photo)

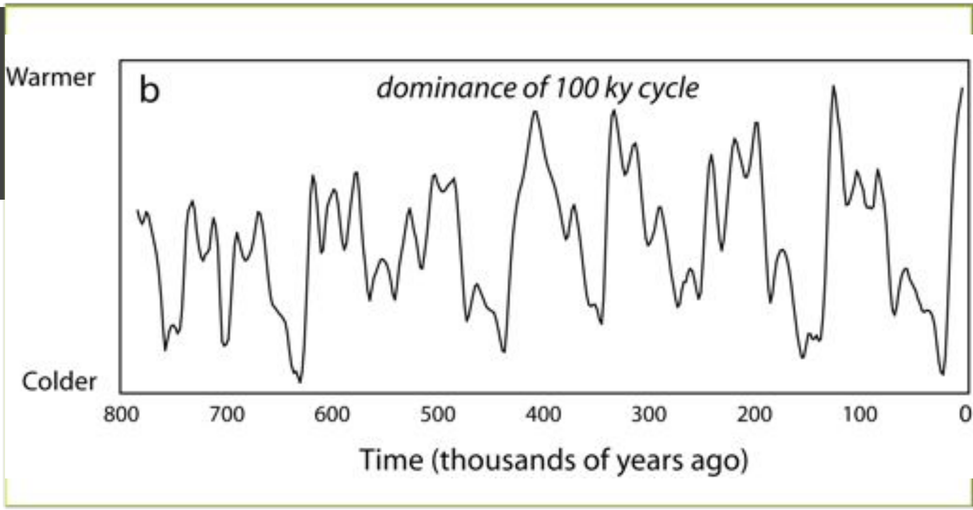


Oxidation of iron and precipitation of ferric oxides:

- positive ΔV
- elastic strain energy
- fracturing
- controlled by O_2 diffusion

Thin section, granite cobble, Bull Lake moraine, Boulder Creek, CO

Time scales



Climate change: 10-100ka oscillations
roughly 10 ka of recent conditions

Mobile regolith residence time: H/w
500mm/10-20 mm/kyr = 25-50 kyr

Landscape change: $L^2/\kappa = (100\text{m})^2/0.01\text{m}^2/\text{yr} = 1$ Ma

It is therefore likely that in many settings a strong legacy of past climate exists on hillslopes

And the shape of the landscape will certainly not change on climate timescales, but will likely achieve a shape that is consistent with some average late Quaternary condition

Volcanic ocean islands

Photo from Jerome Gaillardet

Chemical denudation rates

Chemical denudation rates basalt > granites

<u>Globally</u>:

30-35% of CO_2 consumption from basalt (from <5% of land area)

Of this, about 1/4 from volcanic ocean islands

(Dessert et al., 2003, *Chemical Geology*)

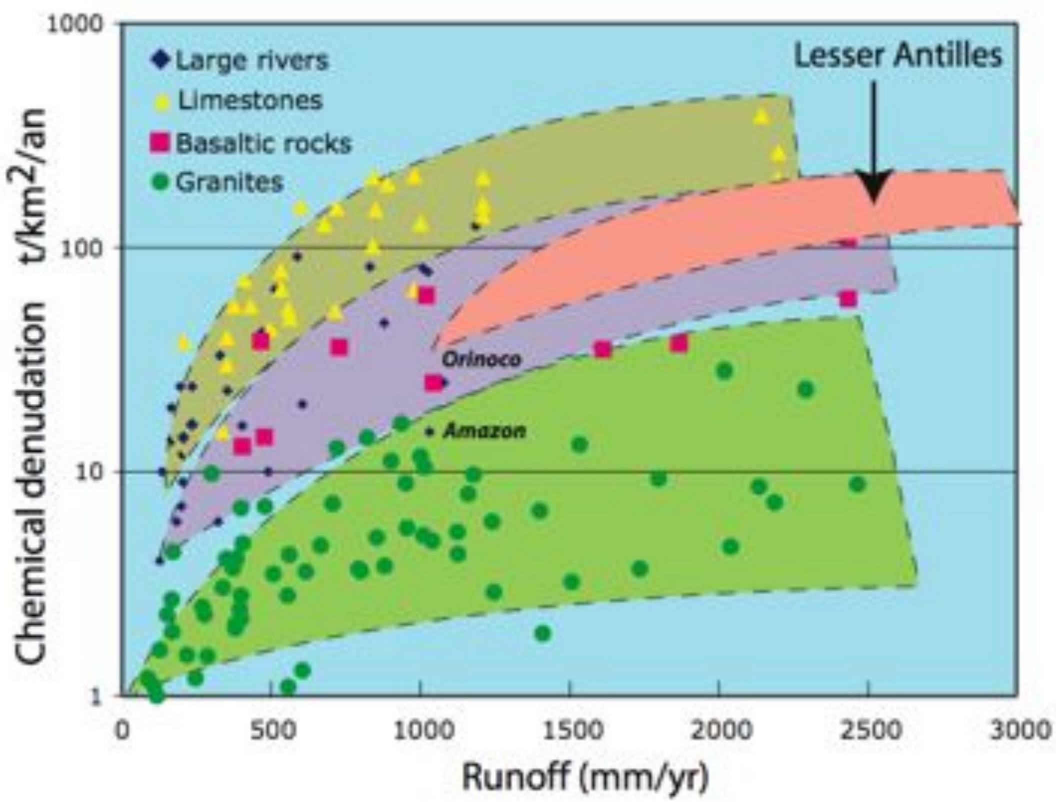
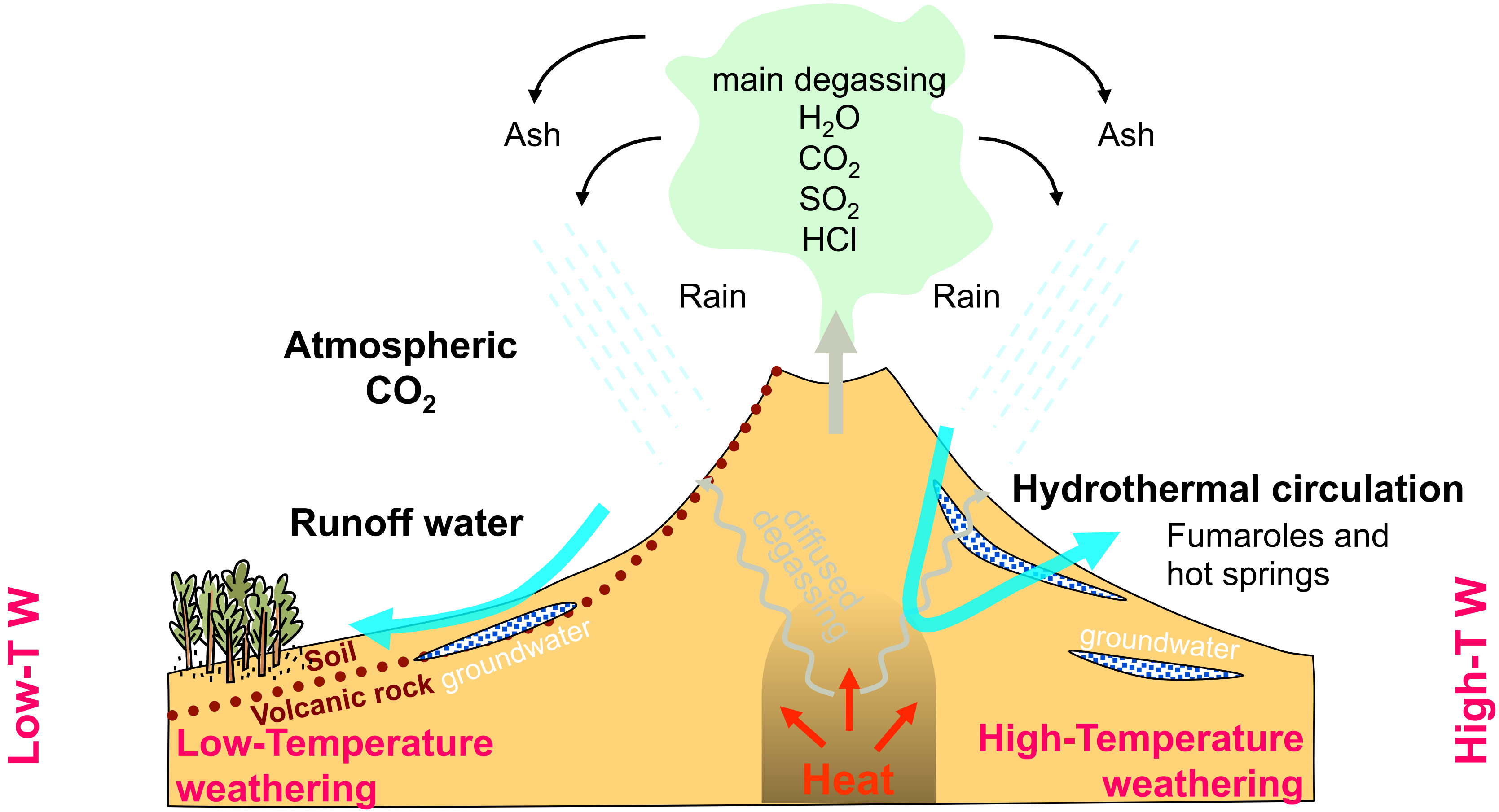


Figure courtesy Jerome Gaillardet



Source of acidity: atmospheric CO_2, ash leaching, sulfide oxidation

Source of acidity: volcanic gazes, ash leaching, sulfide oxidation

Dessert et al., 2009, *Geochim. Cosmochim. Acta*

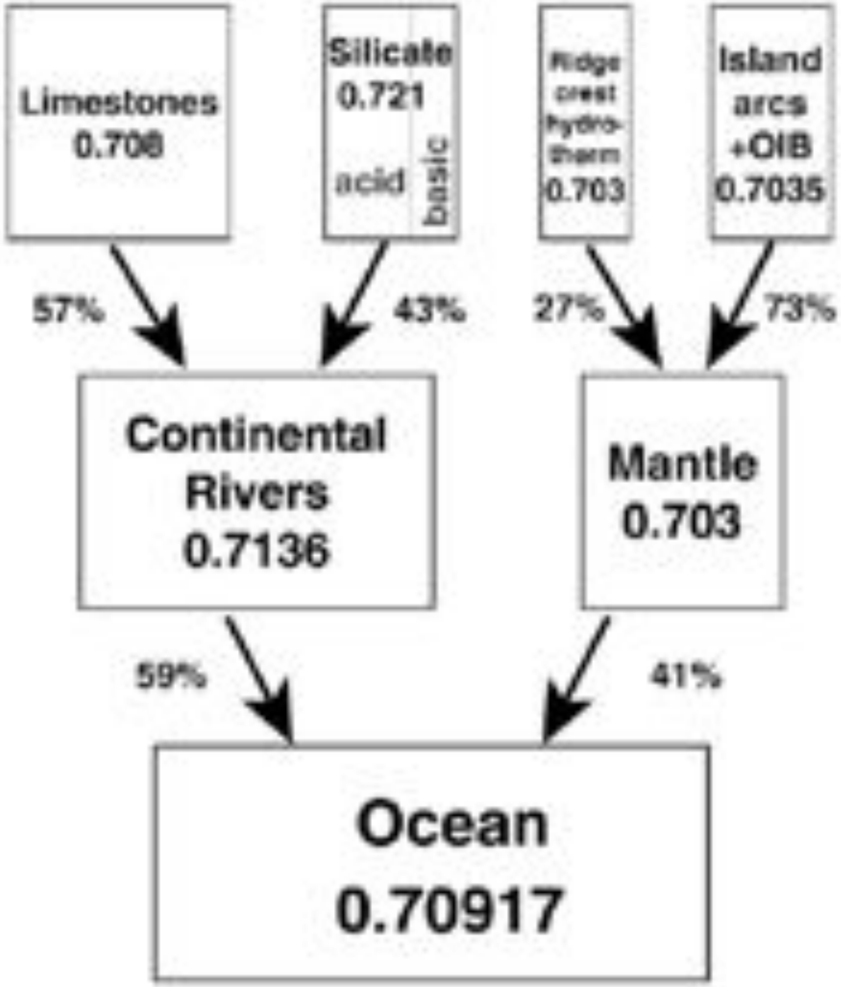
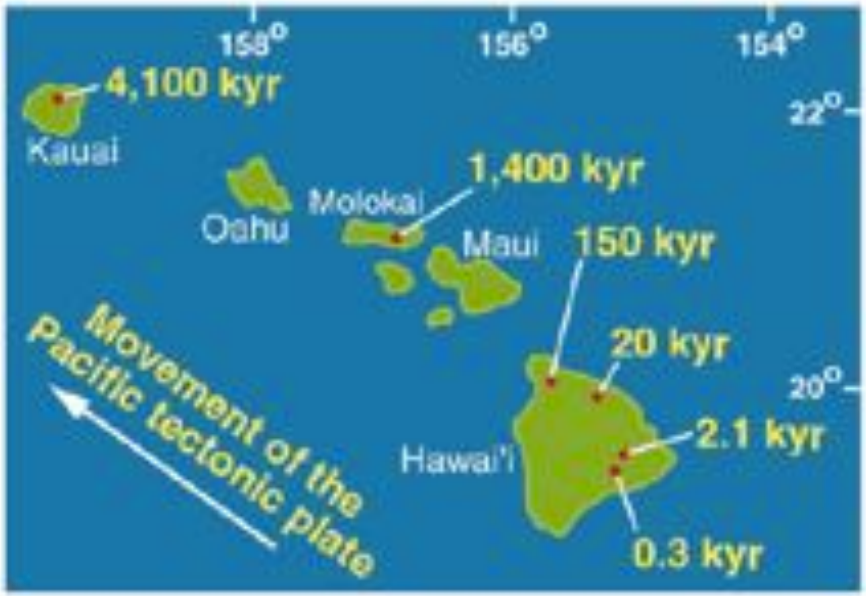
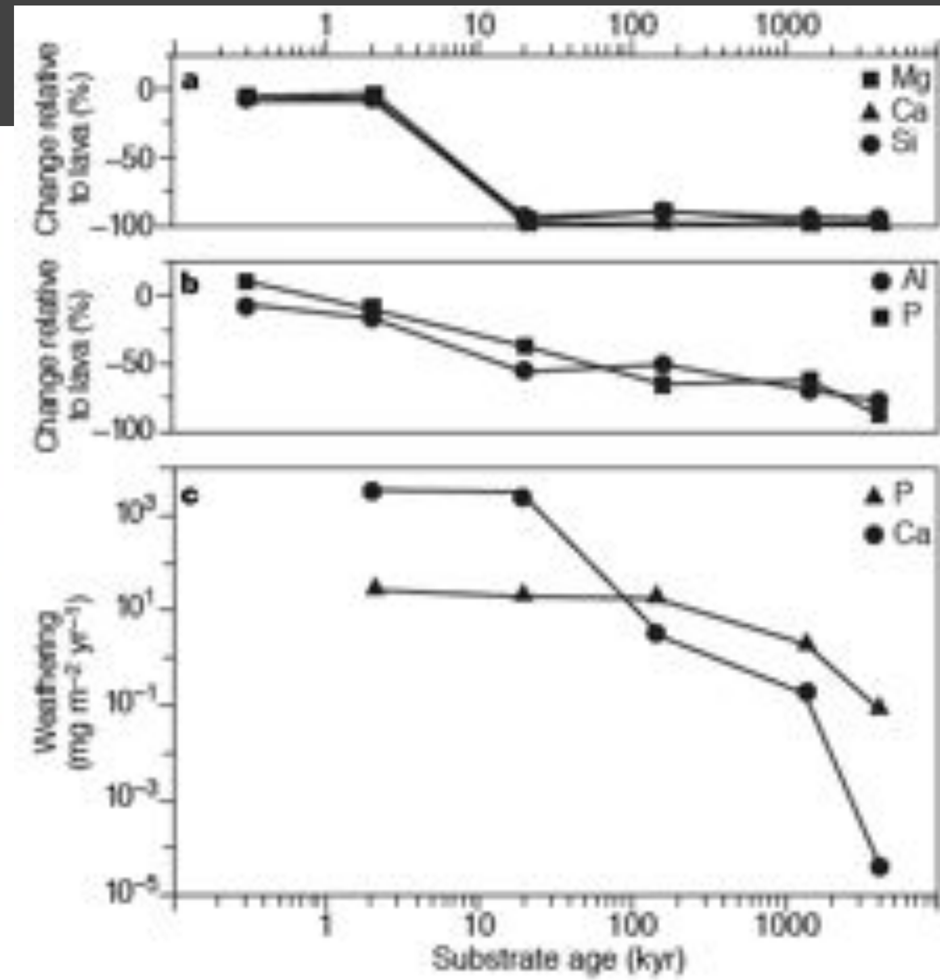


Fig. 1. Strontium isotope oceanic budget. 59% of the oceanic strontium is derived from continental weathering (both of silicate and carbonate rocks). For the remaining 41% of Sr from mantle sources, only 27% can be attributed to ridge-crest hydrothermalism. The missing 73% originates from island arc and OIB weathering (surface and underground), an important source of riverine material towards the oceans (Rad et al., 2007), which has been missed by previous studies.

Allegre et al., (2010) *EPSL*

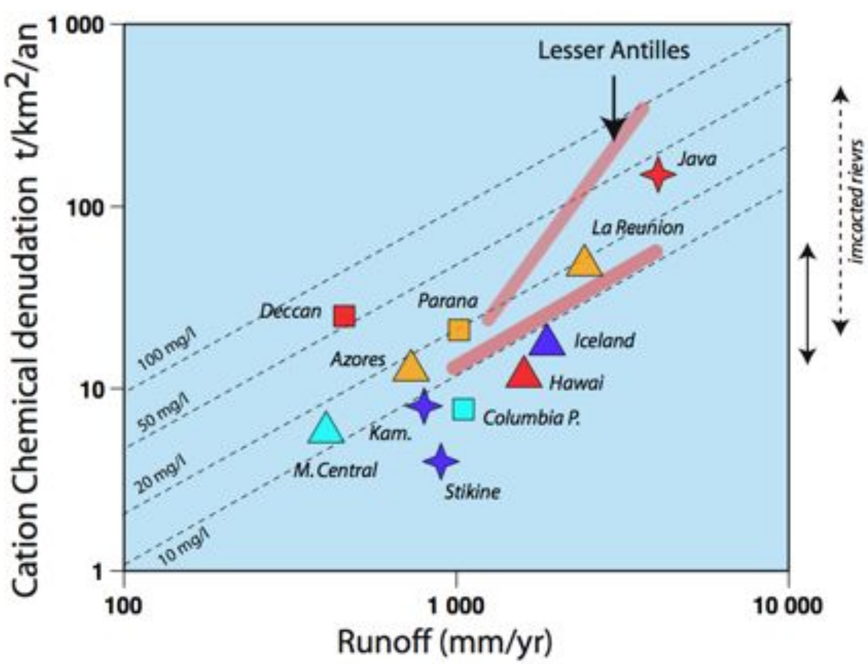
Nutrients

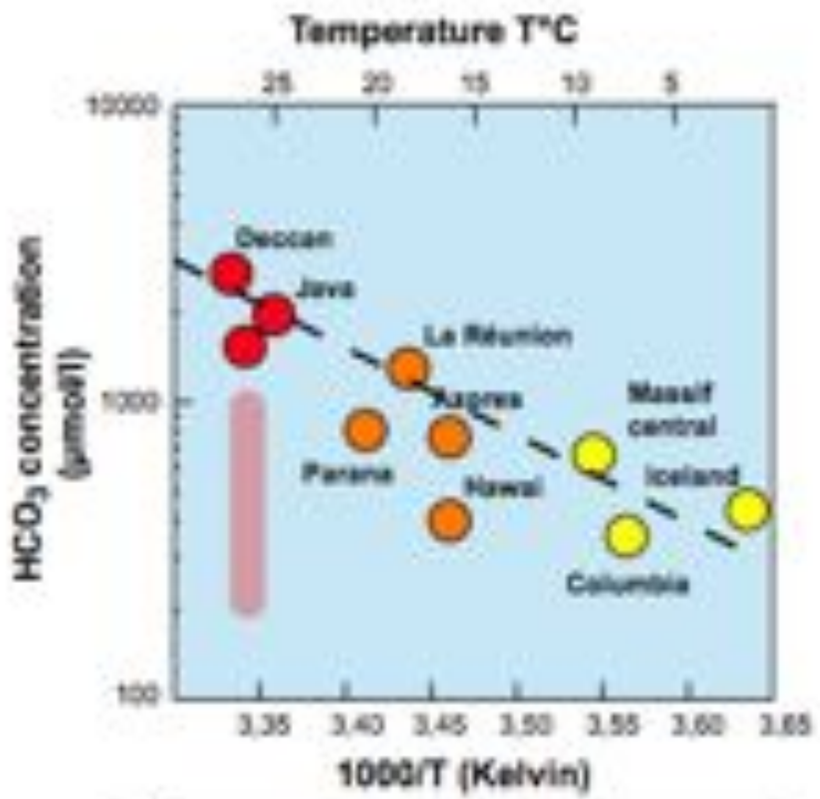




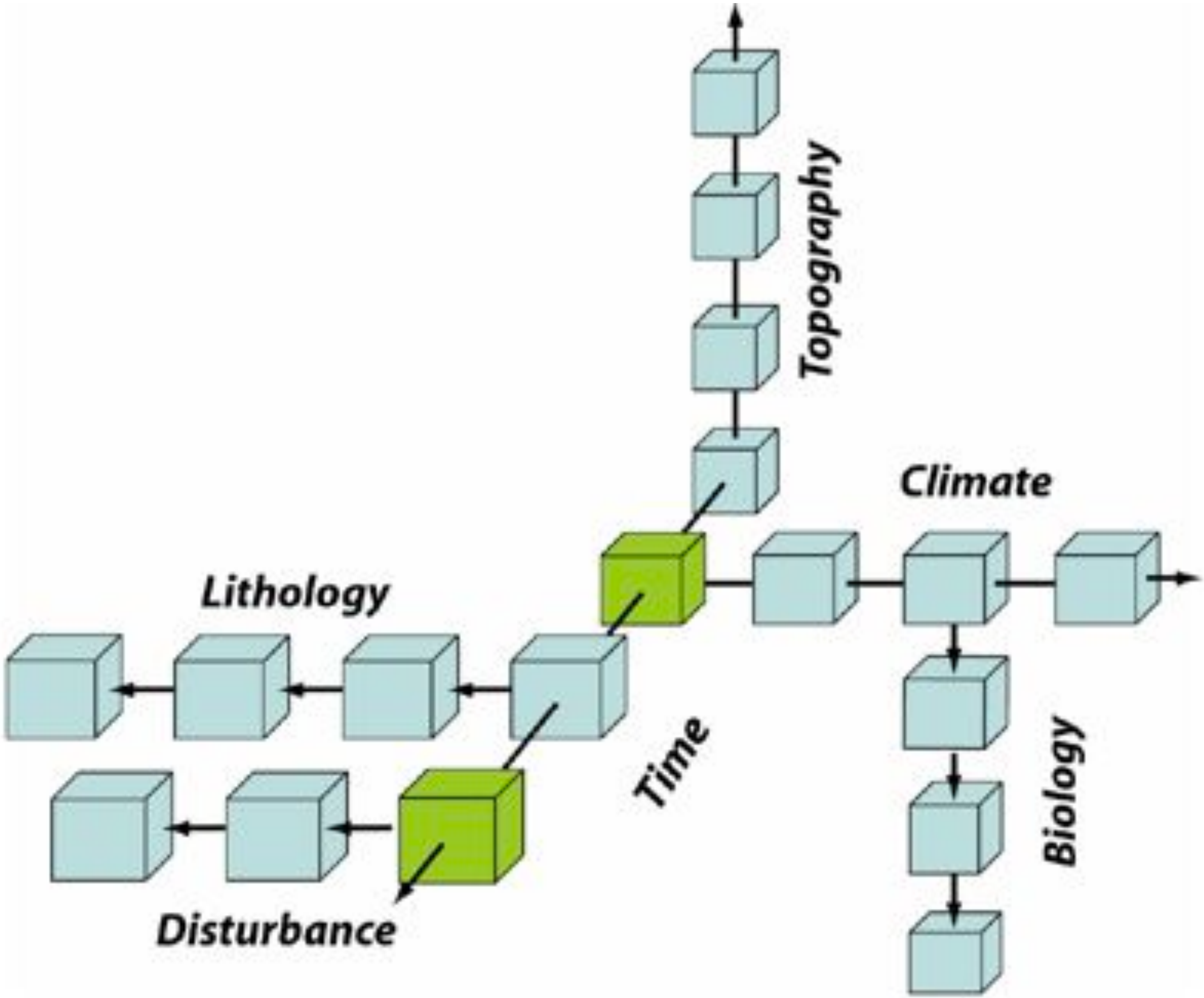
Chadwick et al., 1999, *Nature*

Environmental gradients





Dessert et al., 2003 (by way of J. Gaillardet)

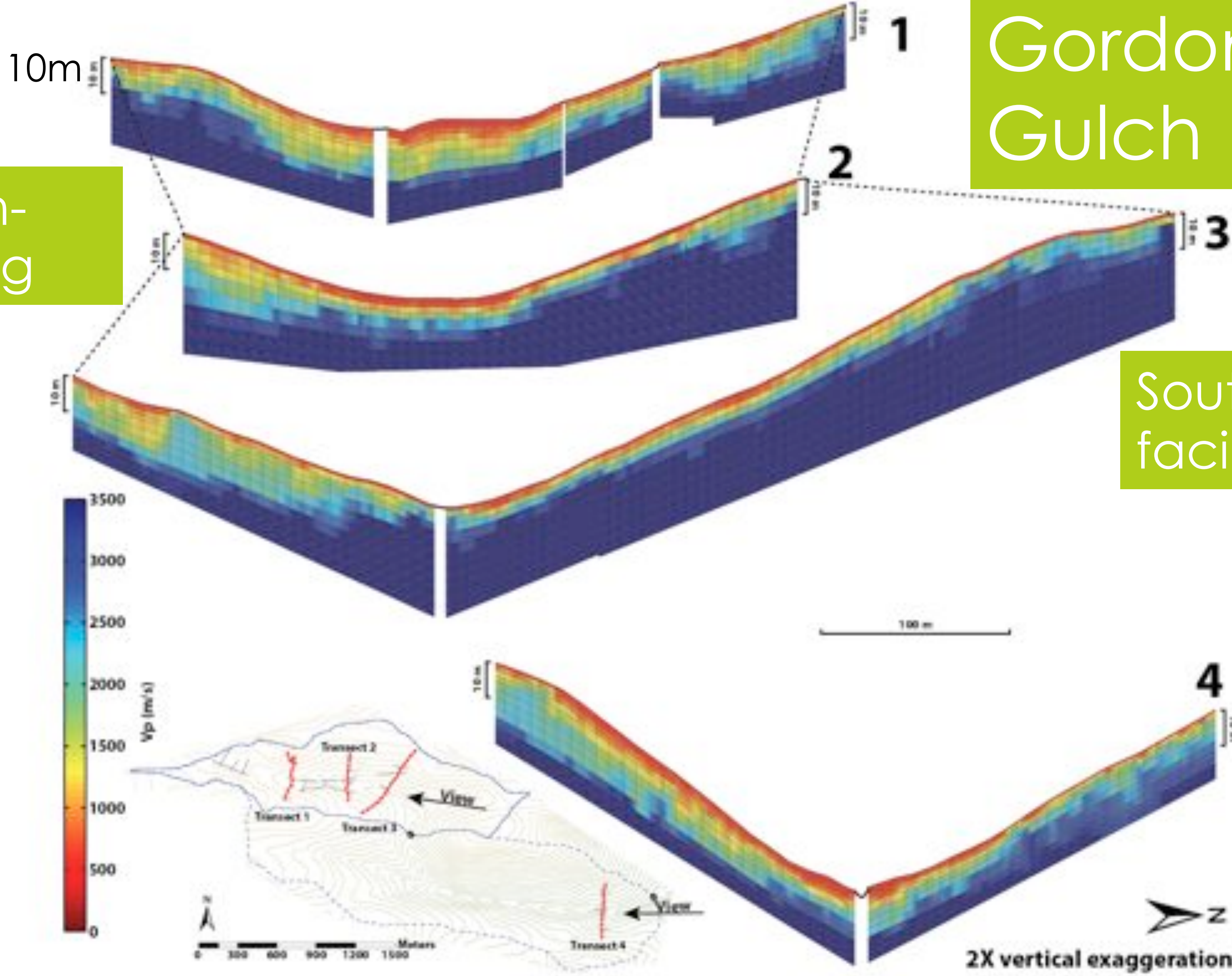


Topography
Climate
Lithology
Time
Biology
Disturbance

Gordon Gulch

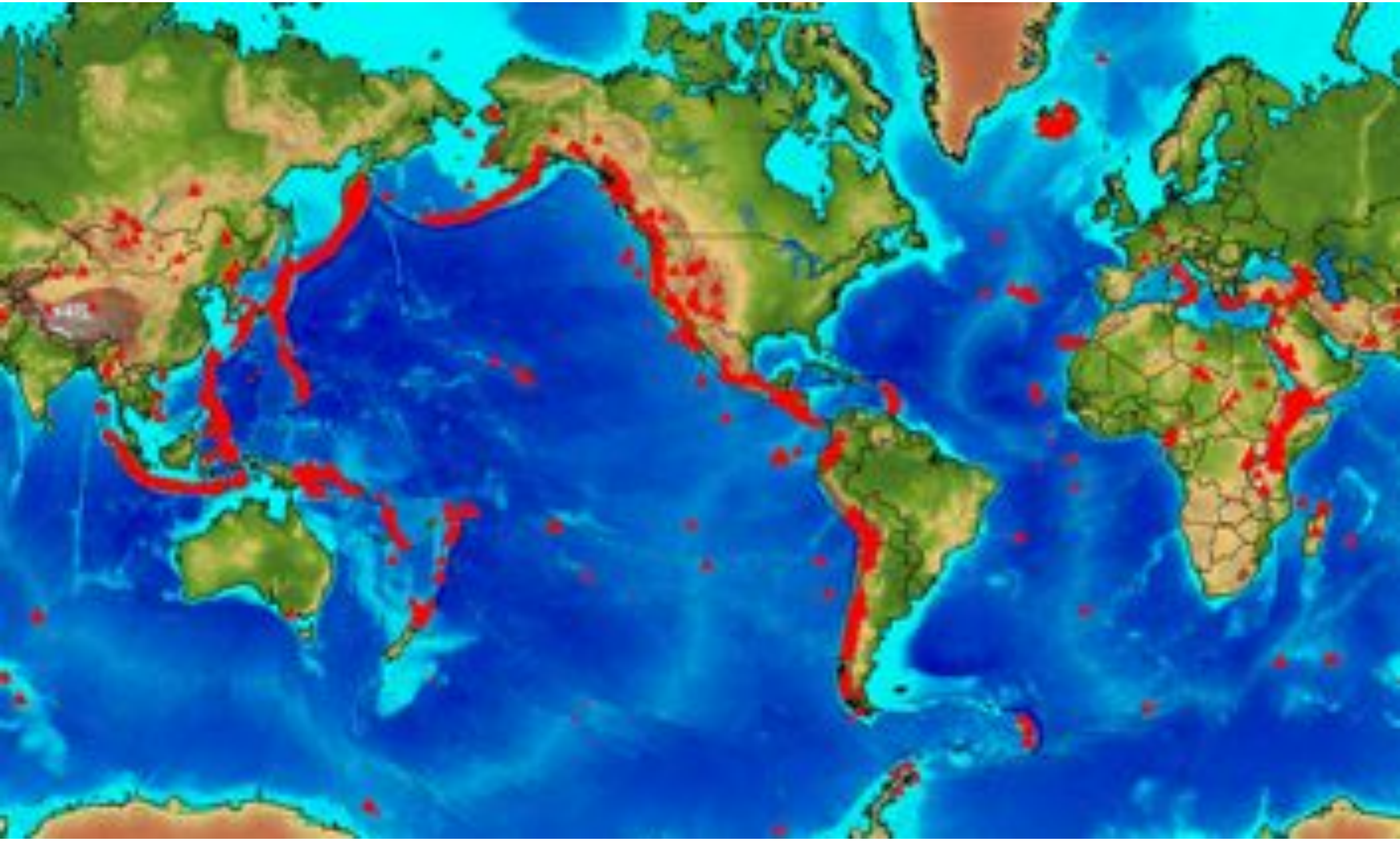
North-facing

South-facing



Shallow seismic refraction (15 km)

Kevin Befus, MS 2010



Conclusions

- We can think of the CZ as a reactor on a slope. Rock accumulates "damage" as it weathers, is released into the mobile layer conveyor belt.
- Climate is important control on rates of weathering and transport.
- Long time scales for hillslope response mean that landscapes and their soils bear legacy of past climates.
- Volcanic ocean islands offer opportunities to explore processes across time, climates, and perhaps other gradients.