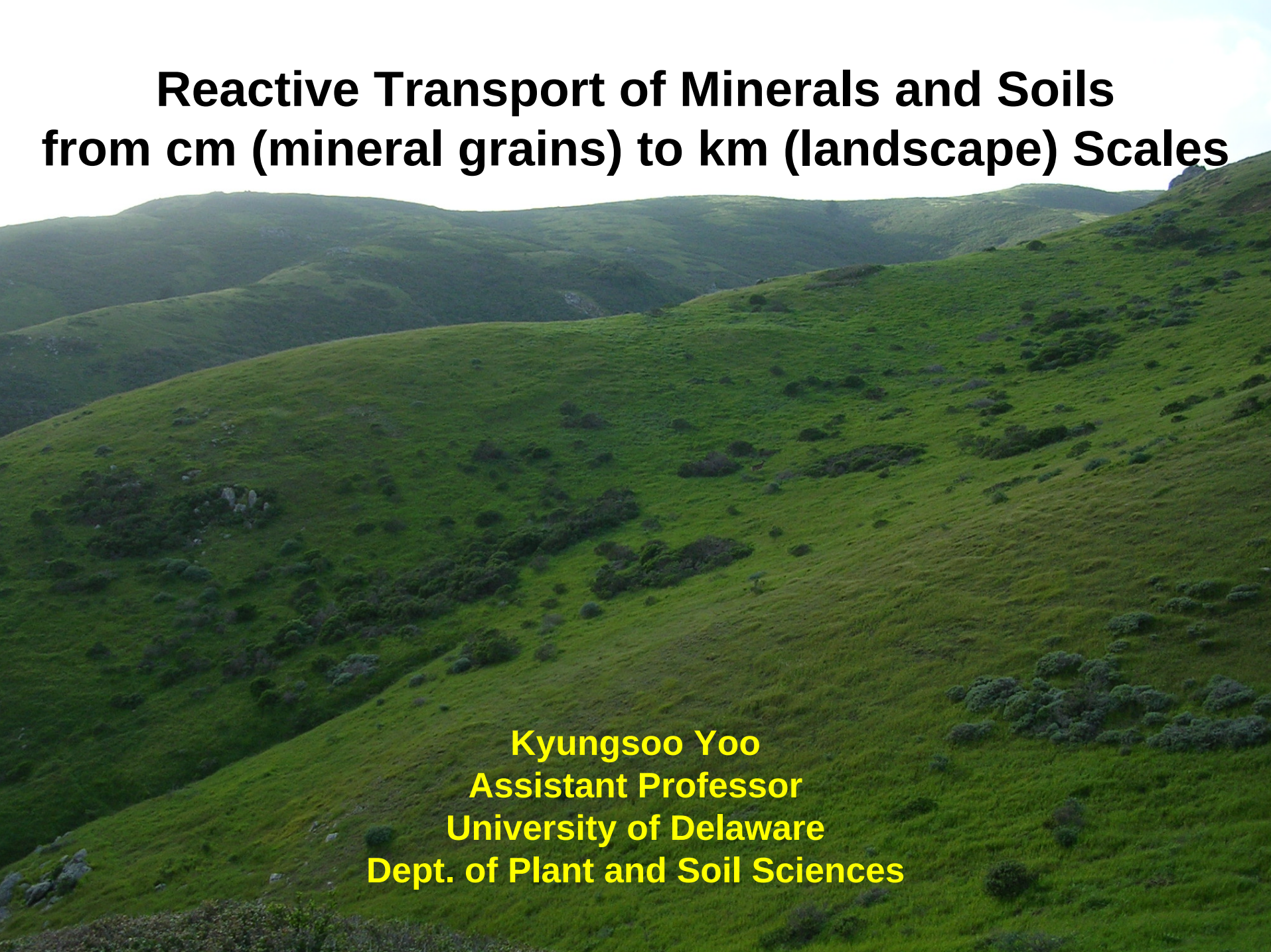
Reactive Transport of Minerals and Soils from cm (mineral grains) to km (landscape) Scales



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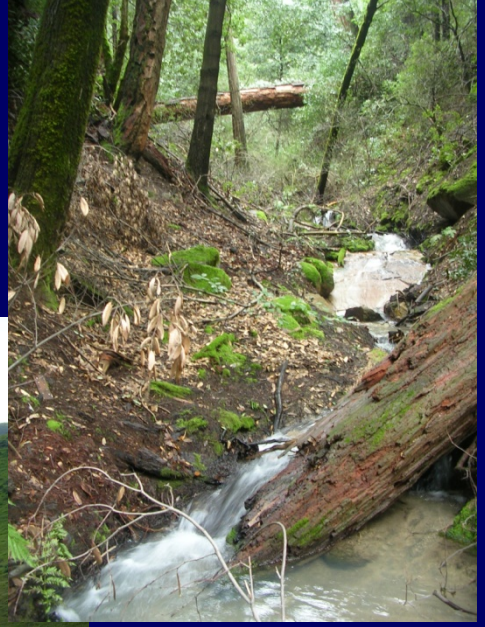
Reactive Transport?

- Reactive Transport of Water: Water moves through static soils while chemically reacting with them.

- Reactive Transport of Minerals and Soils: Minerals and soils vertically and laterally move across biogeochemical gradients.

Scales
in chem. weathering rates

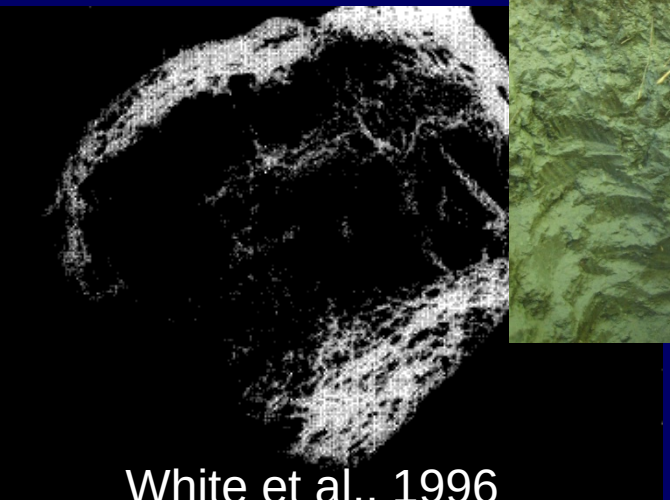
Watershed
(>1 ha)



Hillslope (~1 ha)

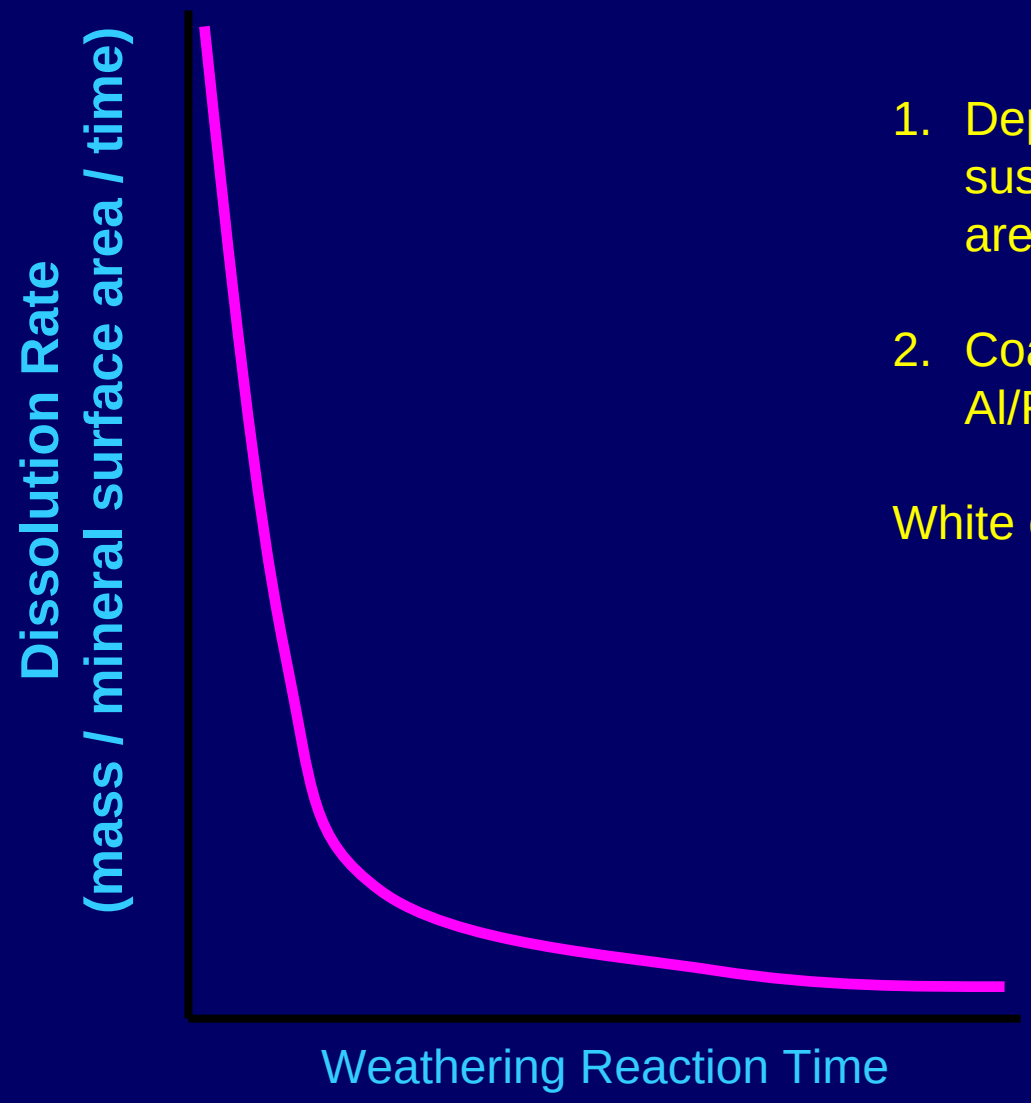
Soil Profile
(~m^2)

Mineral Grain
(<cm)



White et al., 1996

Mineral grain scale



1. Depletion of weathering susceptible mineral surface area.

2. Coating of mineral surface by Al/Fe hydroixdes

White et al., 2002

Long Term Soil Chemical Weathering Rate (W) =Amount of mass loss / Soil Age

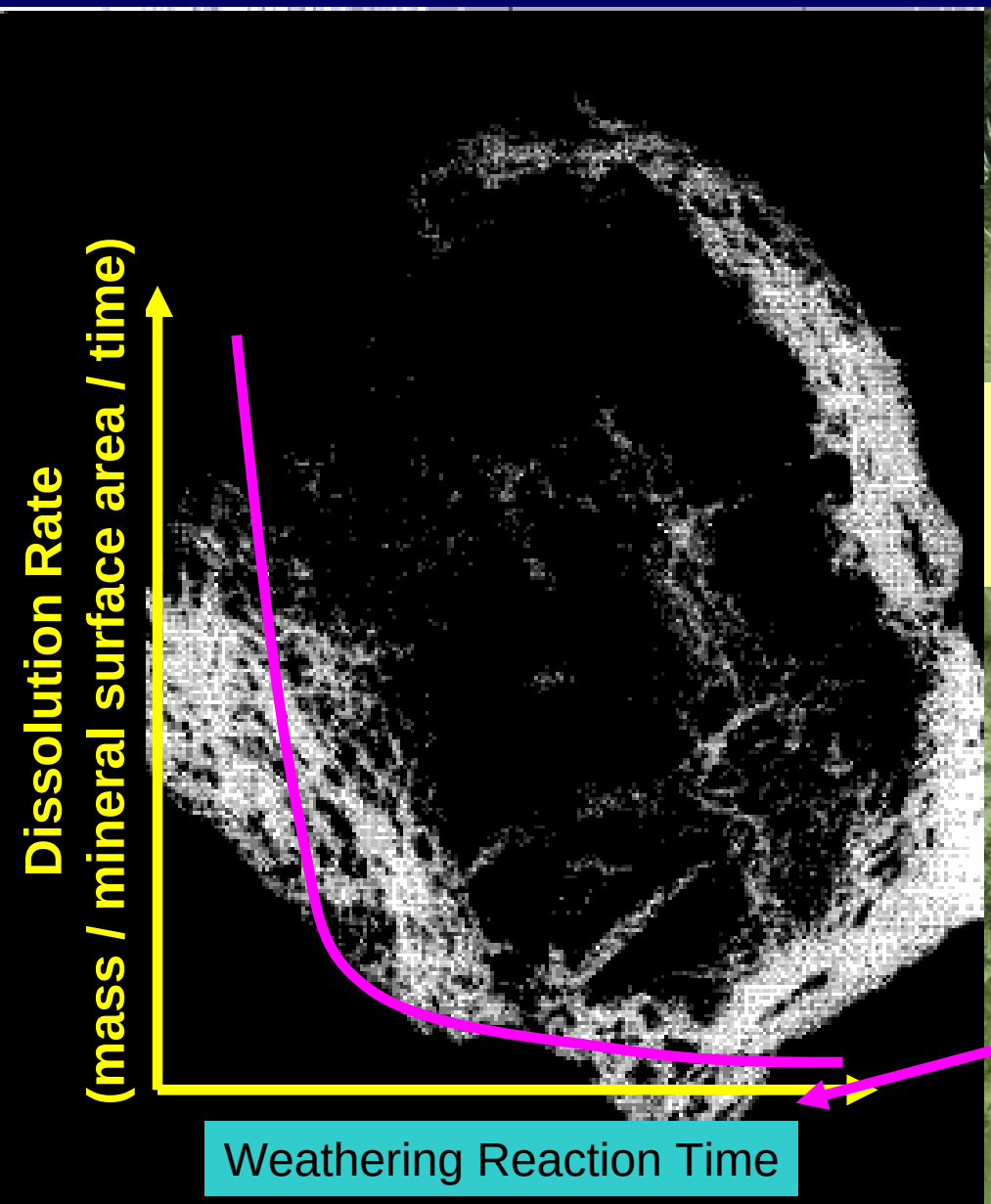
Relative to In-situ underlying geological material

Relative to cessation of erosion or deposition

$$\Delta = \underbrace{\left(\frac{[Zr]_{rock}}{[Zr]_{soil}} - 1\right)}_{Fractional\ \ Mass\ \ Loss} \times Mass\ \ of\ \ Original\ \ \ Material$$

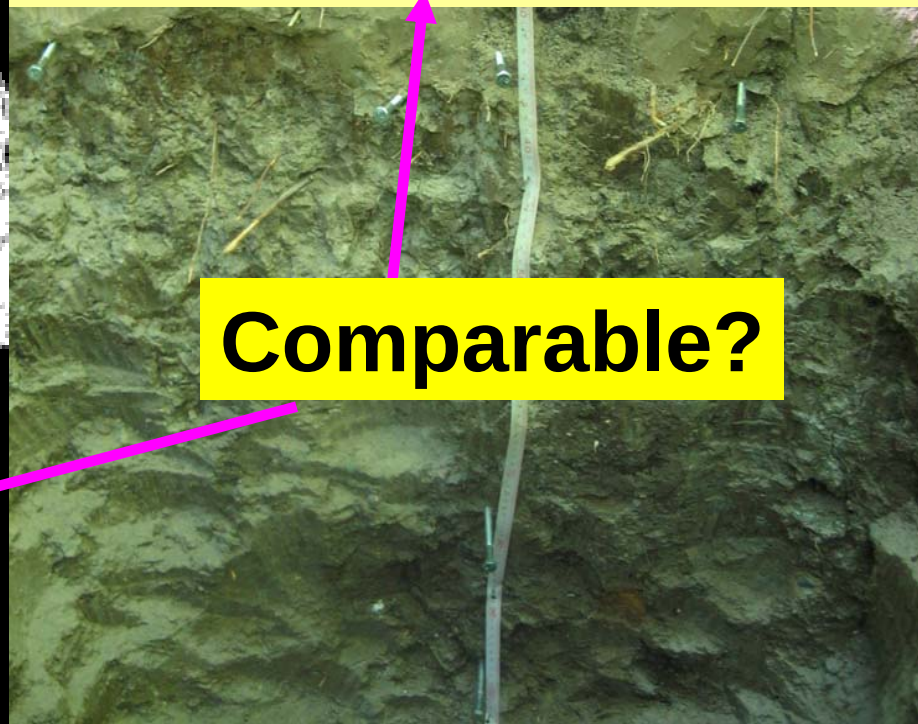
$$W = \frac{\Delta}{Soil\ \ Age}$$ (mass / area /time)

Consistently, lab-based mineral grain scale mineral dissolution rates >> field based rates
However…



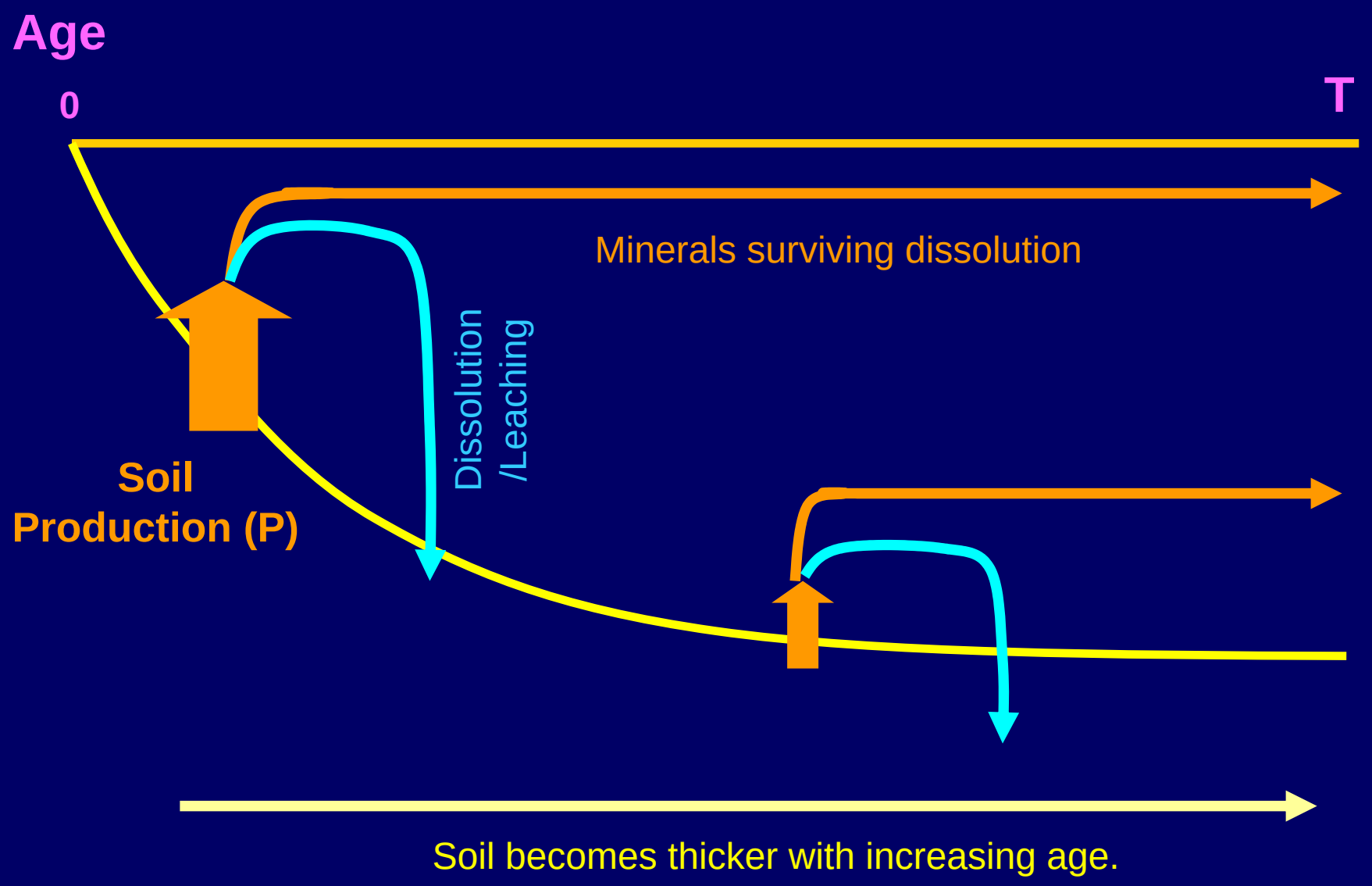
White et al., 1996

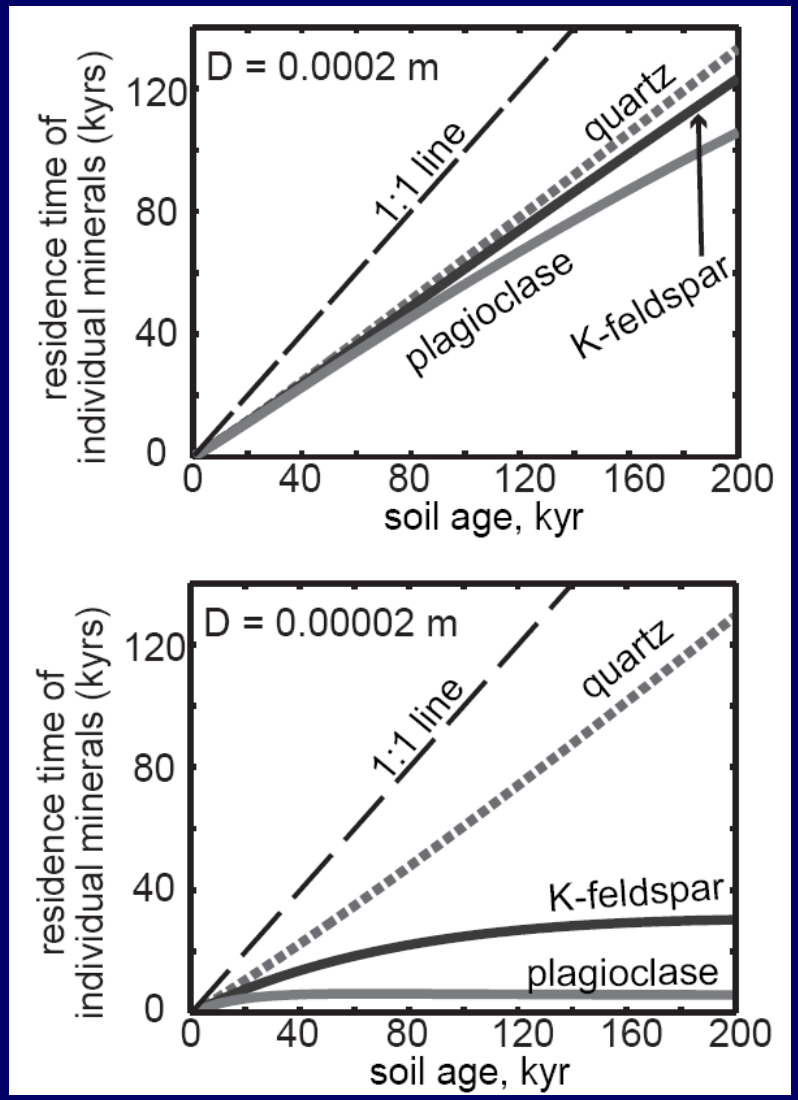
$$W = \frac{\Delta}{Soil \quad Age}$$



Comparable?

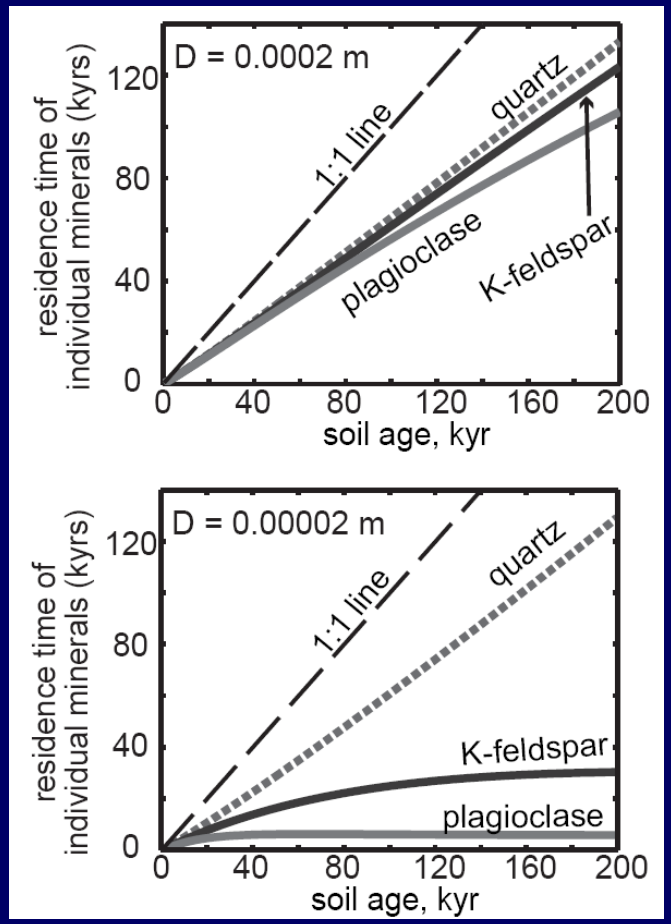
Geochemical soil evolution on stable landforms

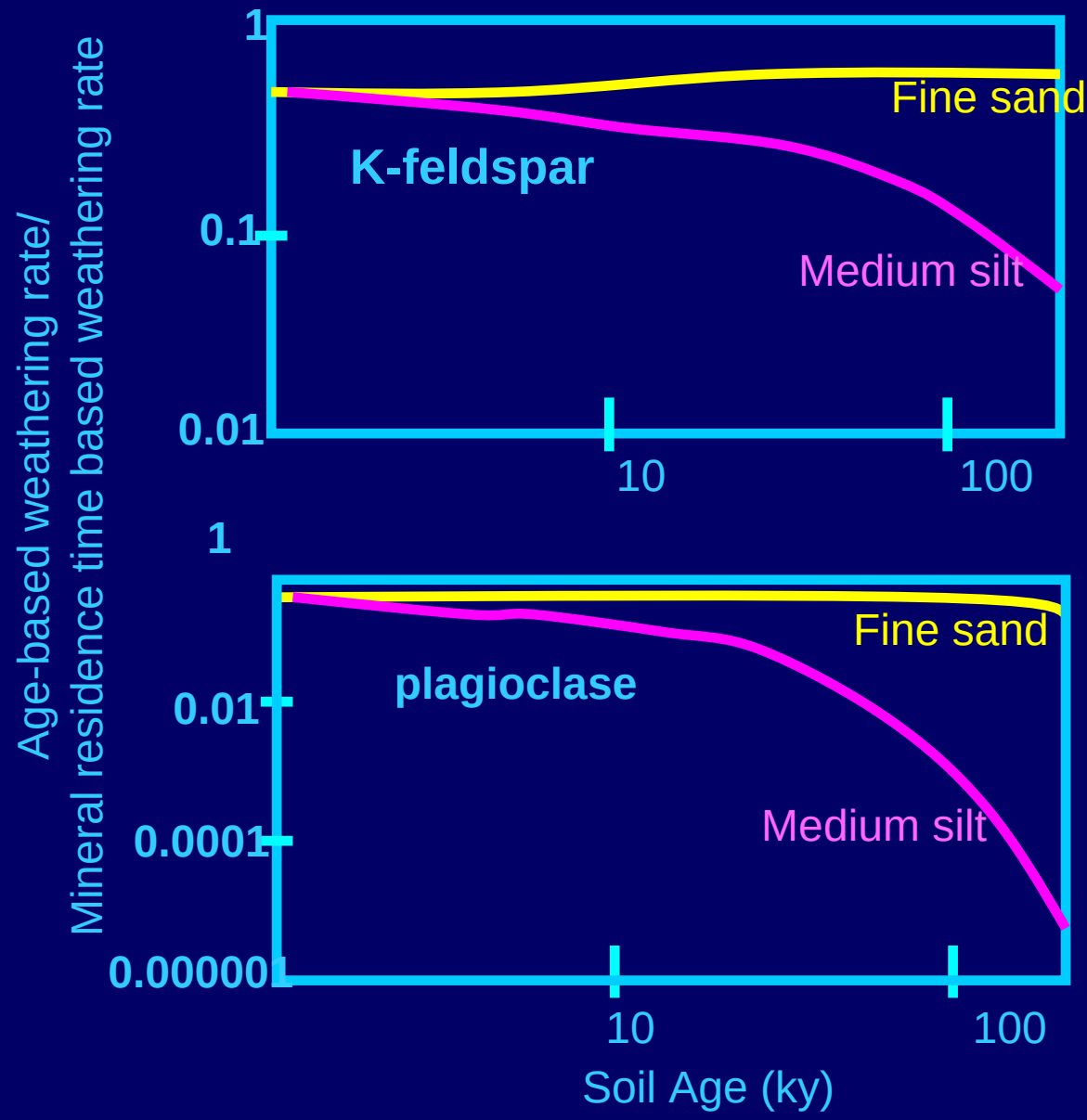




Mineral residence time in soils << Soil ages

(Yoo and Mudd, 2008, Geology)





(Yoo and Mudd, 2008, Geology)

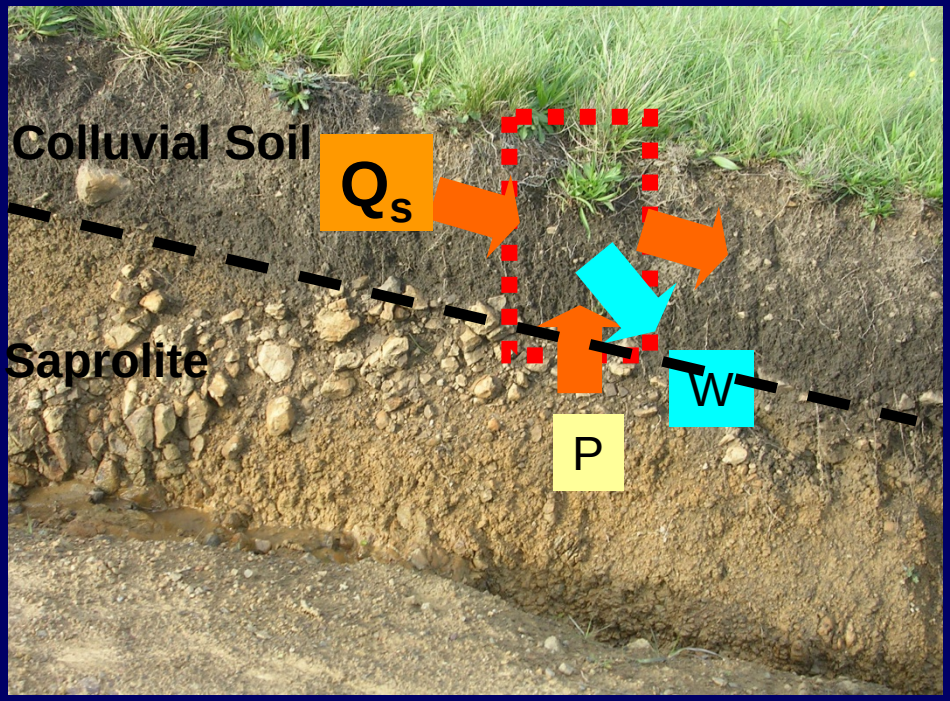
Movement of mineral grains from geological material to soil should be considered in properly scaling up the mineral dissolution rate to soil profile scale weathering rate. **Otherwise, chronosequence based mineral weathering rates are significantly underestimated values.**

Level Soil Chemical Weathering Rate (W)
=Amount of mass loss / Soil Age

Relative to In-situ
underlying geological material
→ **On hillslopes?**

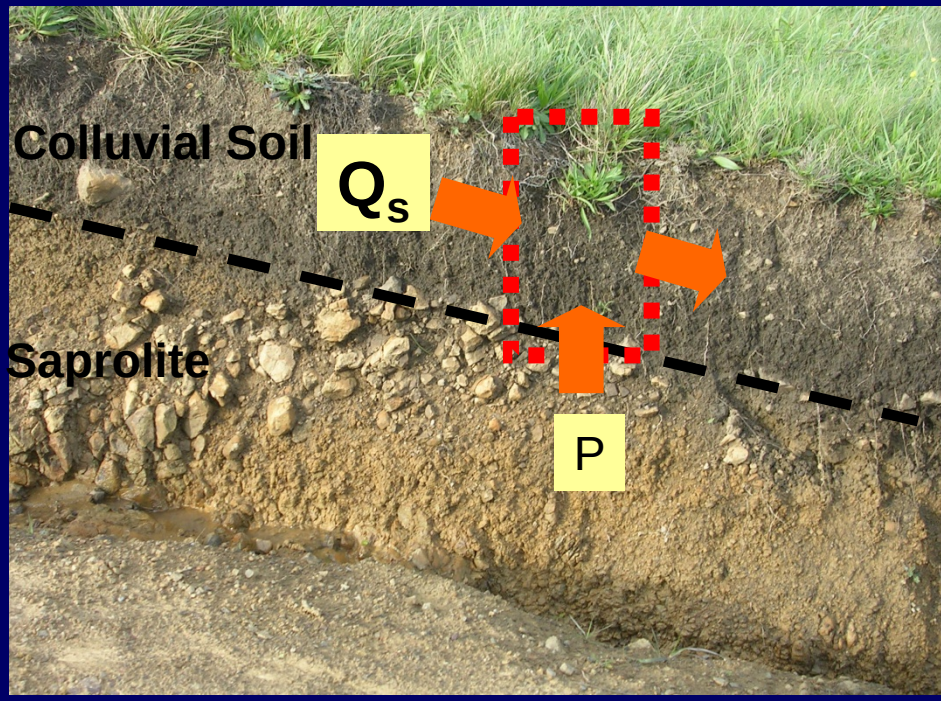
Relative to
cessation of erosion or deposition
→ On Hillslopes?

Mass Balance for Bulk Soil



$$\frac{\partial(\rho_s h_s)}{\partial t} = P - \nabla \cdot \tilde{Q}_s - W$$

Mass Balance for Immobile Element (Zr)



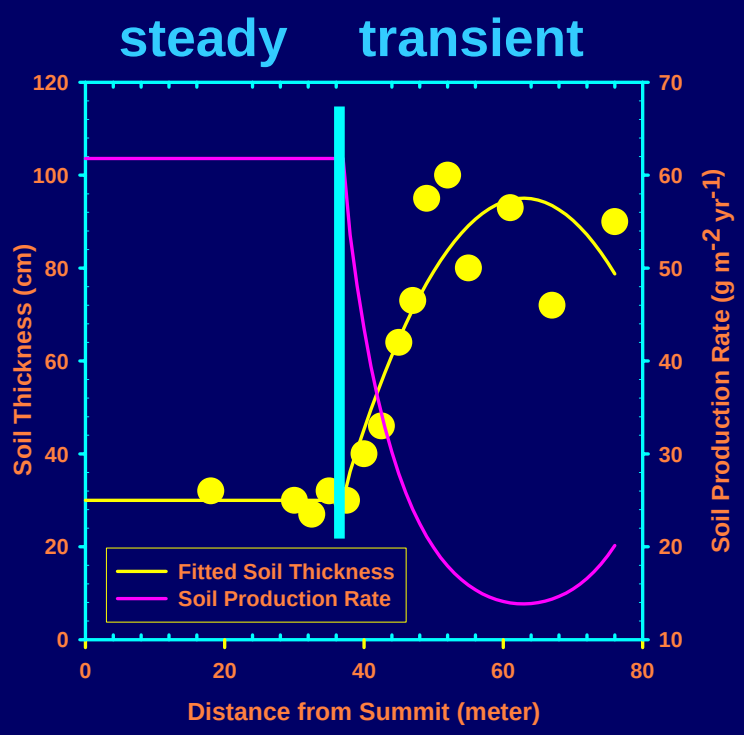
$$\frac{\partial(\rho_s h_s [Zr]_s)}{\partial t} = [Zr]_r P - \nabla \cdot ([Zr]_s \tilde{Q}_s)$$

P: soil mass production rate, Q: colluvial mass flux

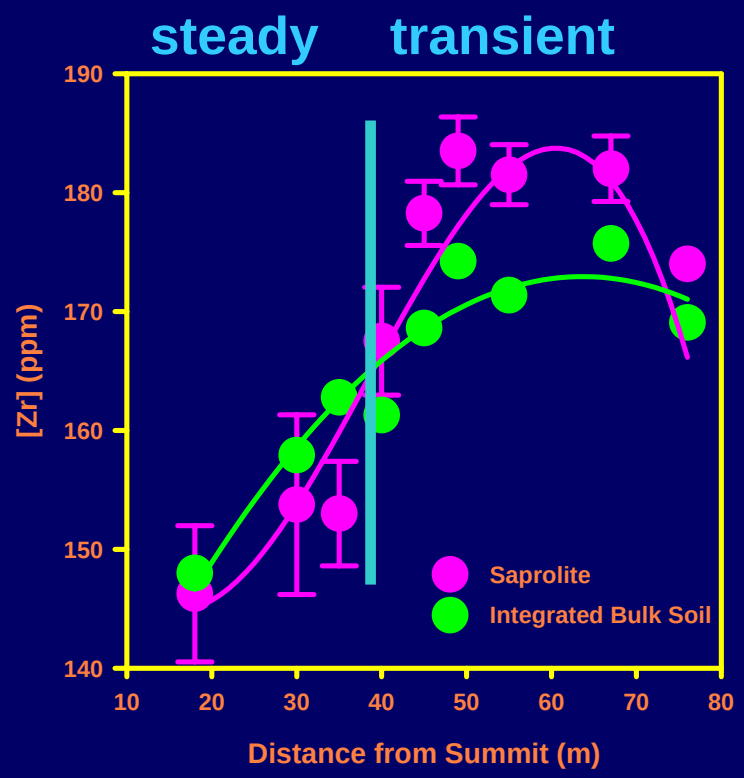
$$W = \left(\frac{[Zr]_{rock}}{[Zr]_{soil}} - 1\right)P - \frac{\nabla [Zr]_{soil}}{[Zr]_{soil}} \cdot \tilde{Q}_s - \rho_s h_s \frac{1}{[Zr]_{soil}} \frac{\partial [Zr]_{soil}}{\partial t}$$

Yoo, Amundson, Heimsath, Dietrich, 2007, JGR, Yoo and Mudd, in press

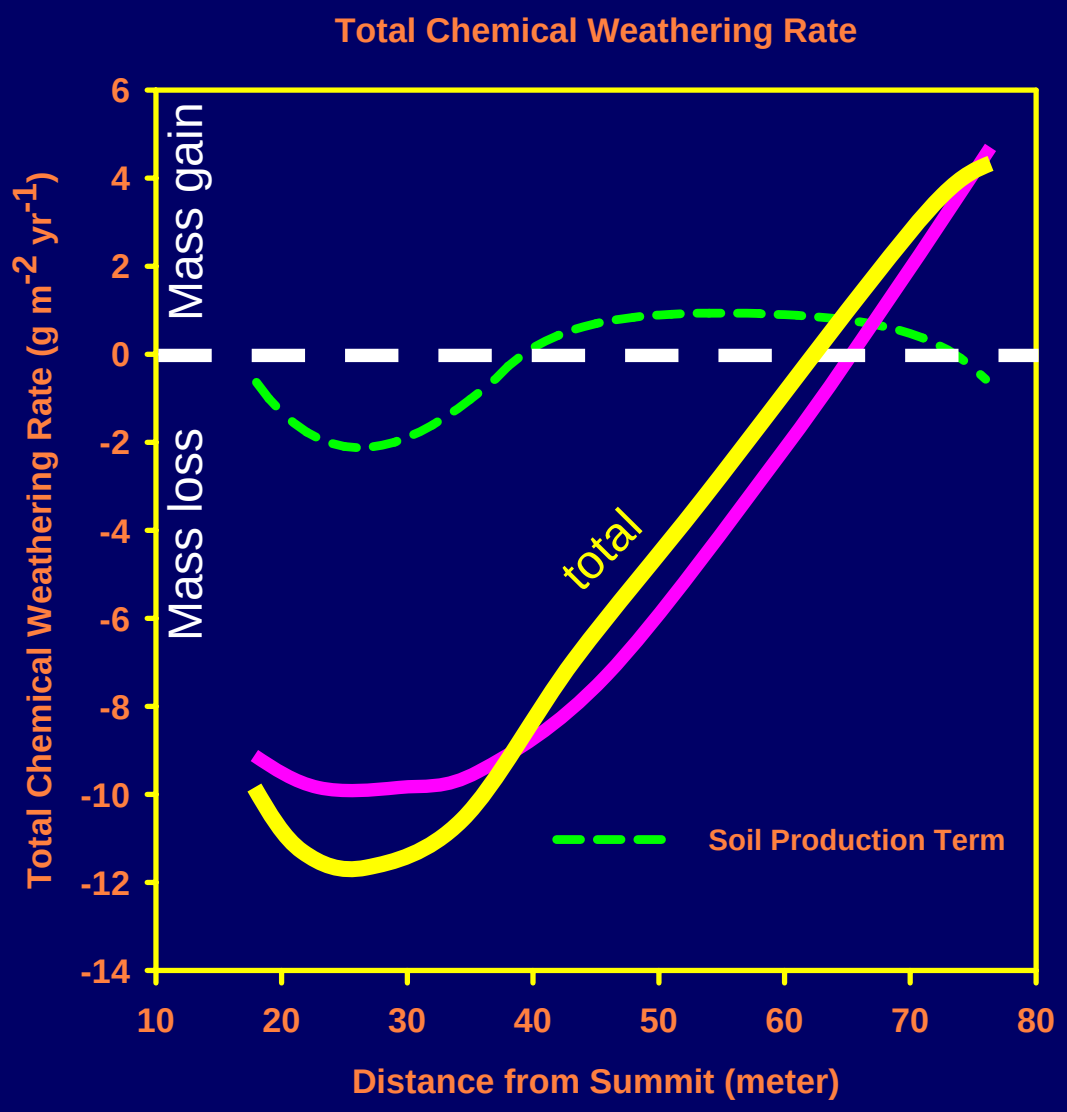
$$W = \left(\frac{[Zr]_{rock}}{[Zr]_{soil}} - 1\right)P - \frac{\nabla[Zr]_{soil}}{[Zr]_{soil}} \cdot \tilde{Q}_s - \rho_s h_s \frac{1}{[Zr]_{soil}} \frac{\partial[Zr]_{soil}}{\partial t}$$



Mudd and Yoo, in review



Yoo, Mudd, Sanderman, Amundson, Blum, in preparation

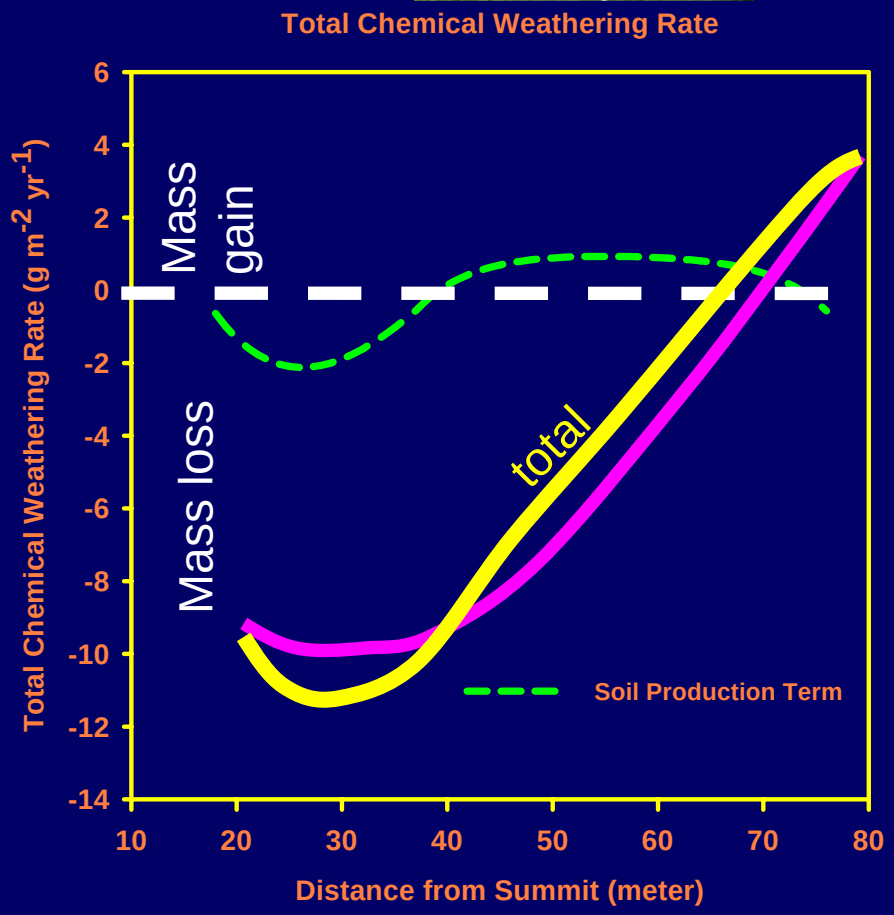


$$W = \left(\frac{[Zr]_{rock}}{[Zr]_{soil}} - 1\right)P$$

$$-\frac{\nabla[Zr]_{soil}}{[Zr]_{soil}} \cdot \tilde{Q}_s$$

Weathering loss rate during lateral sediment transport dominates the total weathering

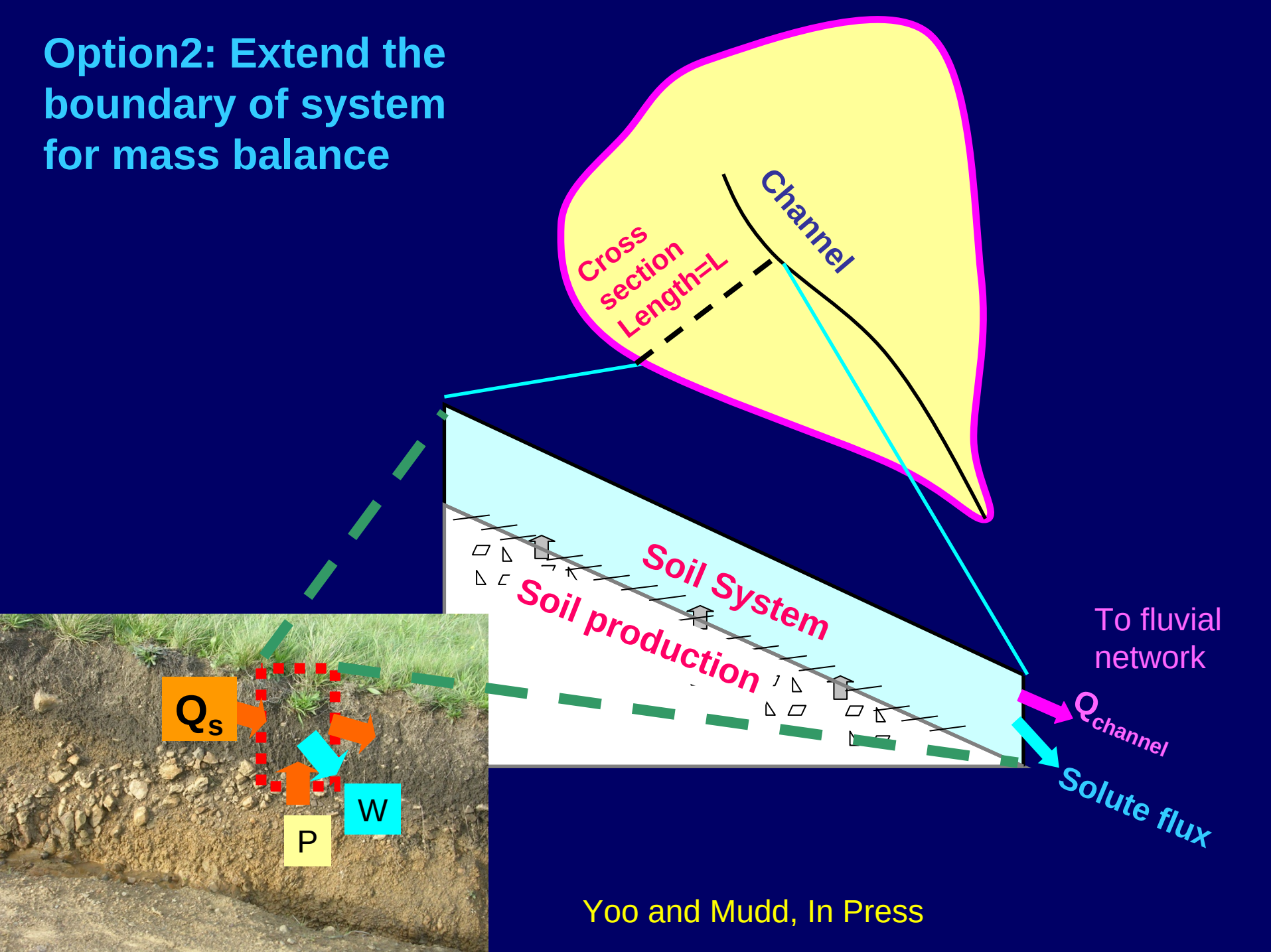
Yoo et al., in preparation



Option1: Simple Space Integration

In the convex slope, soil chemical weathering (dominated by the sediment flux related term) removes ~12 % of the mass input from saprolite to soil.

Option2: Extend the boundary of system for mass balance



Yoo and Mudd, In Press

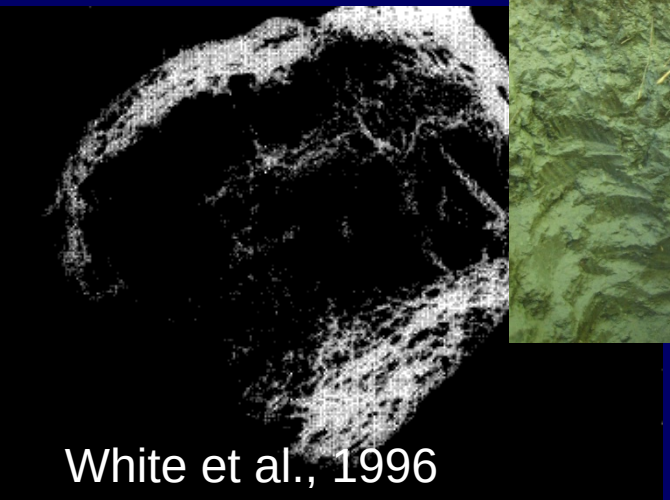
Scaling issues in determining chemical weathering rates emerge partly because of the physical movements of minerals.

Catchment (>1 ha)

Hillslope (~1 ha)

Soil Profile (~m^2)

Dissolution rate = f (reaction time,..)



White et al., 1996

Reactive Transport of Minerals:
Agricultural Sustainability & Global Carbon Cycle

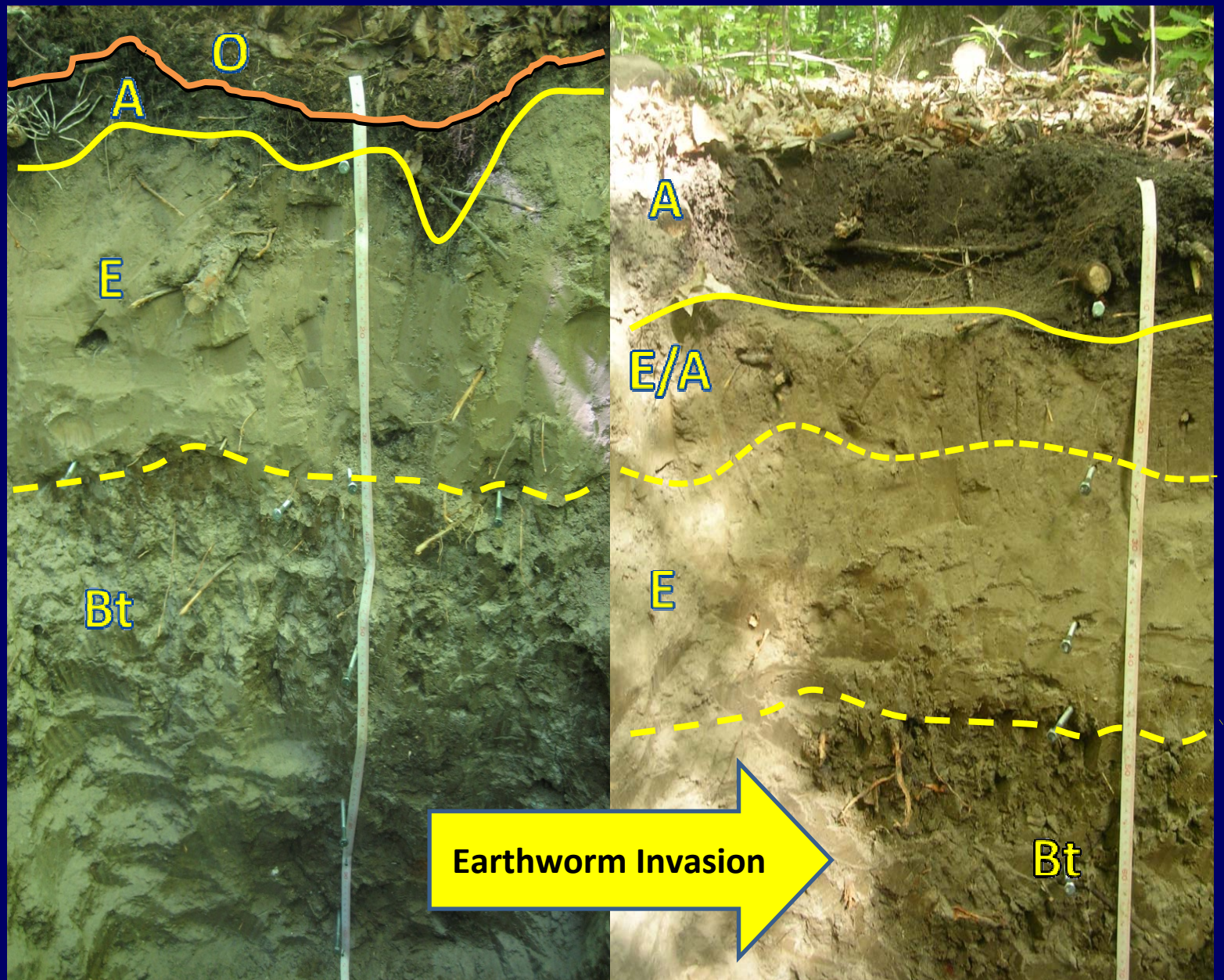
Soil mixing by invasive earthworms (initiating preliminary work)

→moves minerals across bio-geochemical gradient & increases the contact between minerals and organic matter

→ may accelerate inorganic nutrient release from mineral dissolution

→ may accelerate the formation rate of organo-mineral complexes and thus C sequestration.

Earthworm Invasion in Minnesota (Preliminary Field Data)



Reactive Transport of Minerals:
Agricultural Sustainability & Global Carbon Cycle

Soil mixing by tillage (initiating preliminary work)

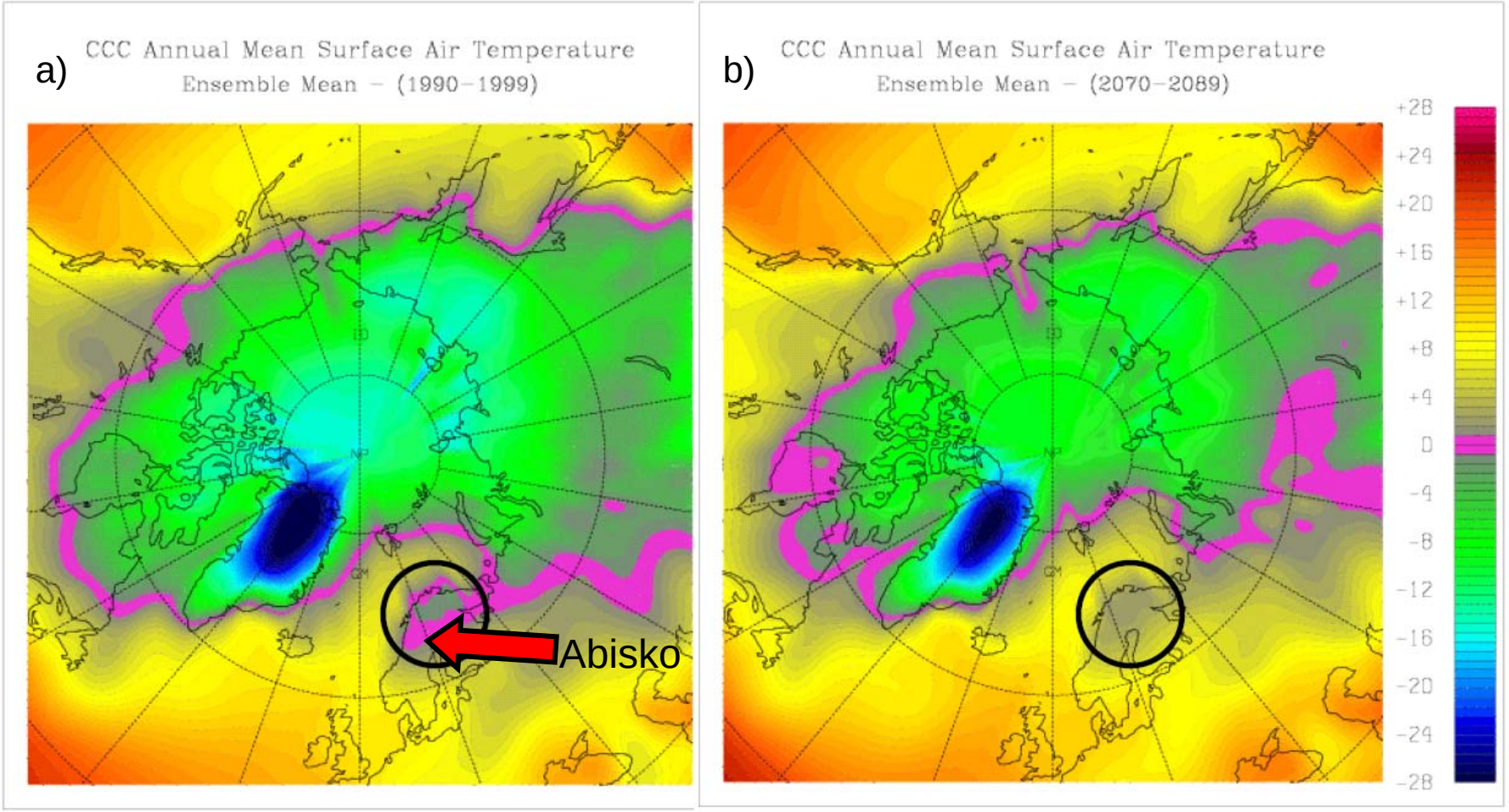
→moves minerals across bio-geochemical gradient & increases the contact between minerals and organic matter

→ may accelerate inorganic nutrient release from mineral dissolution

→ may accelerate the formation rate of organo-mineral complexes and thus C sequestration.

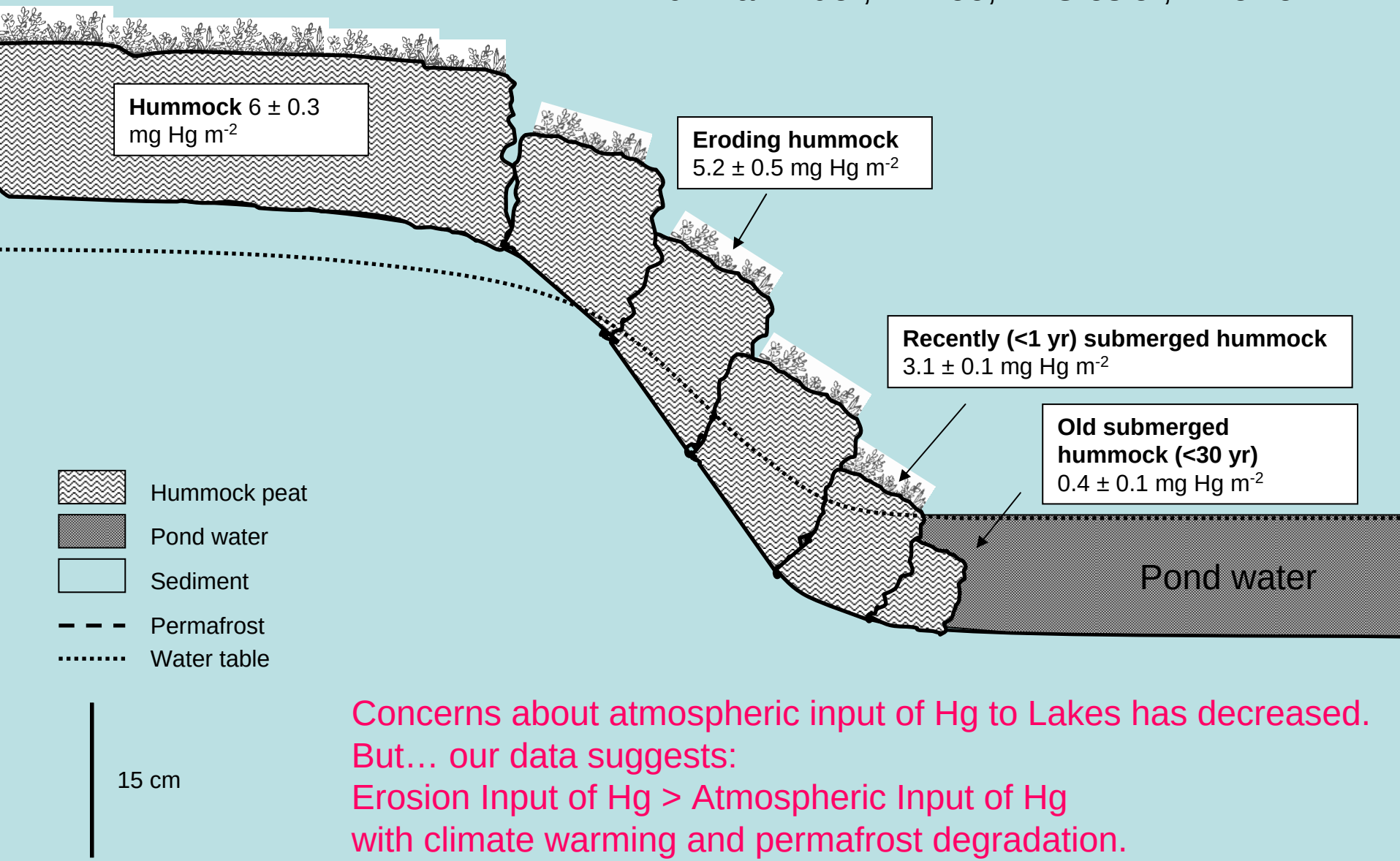
→ Complexation between Al/Fe and Organic matter (Ji, Yoo, Aufdenkampe, in prep)

Projected Permafrost Boundary based on 0 °C isotherm from Canadian Climate Centre (CCC) GCM



Permafrost melting → Accelerated Erosion → Fate of heavy metals in permafrost?

J. Klaminder, K. Yoo, R. Giesler, in review



Concerns about atmospheric input of Hg to Lakes has decreased.
But… our data suggests:
Erosion Input of Hg > Atmospheric Input of Hg
with climate warming and permafrost degradation.

Reactive Transport?

- Reactive Transport of Minerals and Soils: Minerals and soils vertically and laterally move across biogeochemical gradients.

- Useful concept to mechanically and quantitatively couple soil formation to process geomorphology and ecology across diverse scales.

- Useful concept to address agricultural sustainability and carbon cycle in agricultural settings.

- Useful concept to address the fates of contaminants.