Rock Weathering and Soil Development

OCN 401 -Biogeochemical Systems

30 August 2012

Reading: Schlesinger, Chapter 4

Outline

- Rock weathering
  - Mechanical erosion
  - Chemical weathering
- Soils and their development
- Weathering rates
- Continental denudation

Rock weathering

- Definition: The breakdown of rocks by chemical and mechanical processes

- Mechanical weathering -- caused by abrasion by water and wind, expansion of water during freezing, plant root expansion, etc.


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www.marlimillerphoto.com


geology.about.com

- Chemical weathering -- caused by the reaction of rocks with acidic or oxidizing substances

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What are the Products of Weathering?

- Mechanical weathering:
  - particles (smaller than starting material)

- Chemical weathering:
  - dissolved material
  - particles
  - gas

What are the Fates of Weathering Products?

- Deposition at the site of weathering
- Erosion, removal, and transport from that site

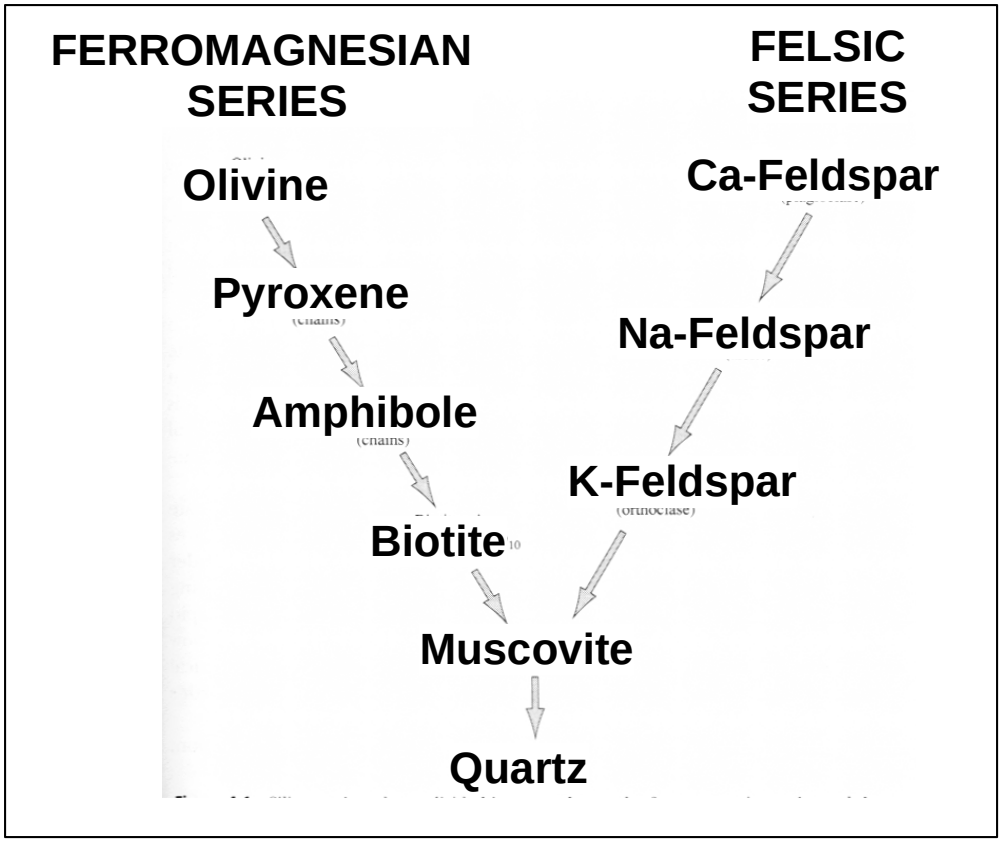
Erosion

- Weathering is the process by which rocks break down; erosion is the removal of that material from the weathering site
- Principal agents of erosion are wind and water
- Natural erosion rates typically <100 t km^{-2} yr^{-1}
- Human activities (especially farming) greatly elevate erosion (often to >>1,000 t km^{-2} yr^{-1})
- Most erosion products are re-deposited somewhere on land, rather than transported to the ocean

What affects chemical weathering?

- Mineralogy

Silicate minerals formed at high temperatures
Rapid weathering



Silicate minerals formed at low temperatures
Slow weathering

What affects chemical weathering?

- Temperature
- Precipitation

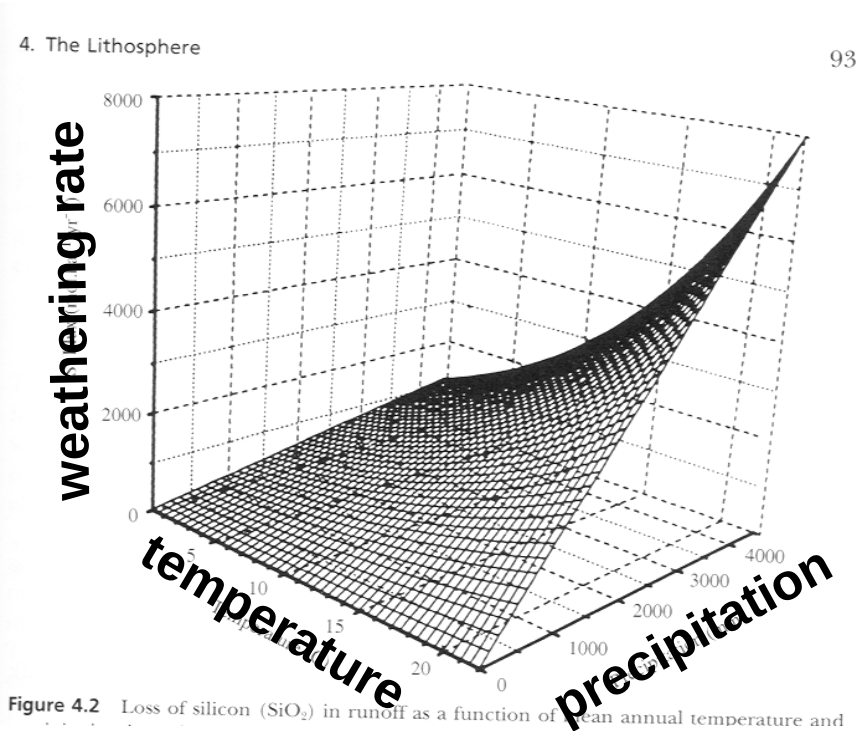


Figure 4.2 Loss of silicon (SiO_2) in runoff as a function of mean annual temperature and

What affects chemical weathering?

- Acids

Weathering of Na-feldspar (albite) to kaolinite:

albite + carbonic acid + water $\rightarrow$

sodium ion + bicarbonate ion + silicic acid + kaolinite

$$2NaAlSi_3O_8 + 2H_2CO_3 + 9H_2O \rightarrow$$

$$2Na^+ + 2HCO_3^- + 4H_4SiO_4 + Al_2Si_2O_5(OH)_4$$

Weathering of limestone:

$$CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^-$$

Principal Acids in Weathering

- Carbonic Acid (H_2CO_3) forms from $CO_2 + H_2O$

- Sources of CO_2 include volcanoes, fossil fuel burning, and oxidation of organic matter (especially in the soil)
  - Wet soil has a higher content of CO_2 and carbonic acid than the atmosphere, so this is a primary location for chemical weathering
  - A major human pollutant

- Nitric Acid (HNO_3) primarily forms during the "nitrification" (or oxidation) of ammonia in soils, and from the atmospheric oxidation of NO_x produced during the combustion of fossil fuels and plant biomass

- Sulfuric Acid (H_2SO_4) primarily forms during the combustion of sulfur-rich coal and as a byproduct of marine algal metabolism

- These are major human pollutants, although both also have natural sources; both are found in "acid rain"

- Although acids mentioned have natural sources, human activities have increased concentrations above natural

- The consequence is that human activities have elevated rates of chemical weathering

Products of Weathering

1. Secondary minerals:
   - Clay minerals (fine-grained silicates, such as kaolinite, illite, montmorillonite, etc.)
   - Oxides of iron (goethite, hematite) and aluminum (gibbsite, boehmite)
   - Phosphate compounds such as $CaHPO_4$, $FePO_4$, and $AlPO_4$
2. Dissolved materials
3. Soil - an aggregate of secondary minerals, particles liberated from parent rocks, and organic matter

Soil is **not** just a collection of inert particles.... Important chemical reactions occur in soils:

- Cation exchange
  - Clay minerals such as montmorillonite substitute one cation (e.g., Mg^{2+}) for another (e.g., Al^{3+})
  - This sets up a negative charge that can make another cation (e.g., Ca^{2+}, K^{+}, NH_4^{+}) dissolved in water stick to the clay

- Soil buffering
  - Reactions such as organic-matter oxidation, or the presence of acid rain, lower soil pH
  - As pH goes down (*i.e.*, H^+ concentration goes up), H^+ displaces cations (especially Ca^{+2}) off the clay particles and into solution
  - This process buffers the pH (makes pH go back up)
  - Formation and dissolution of soil minerals is strongly tied to this pH buffering

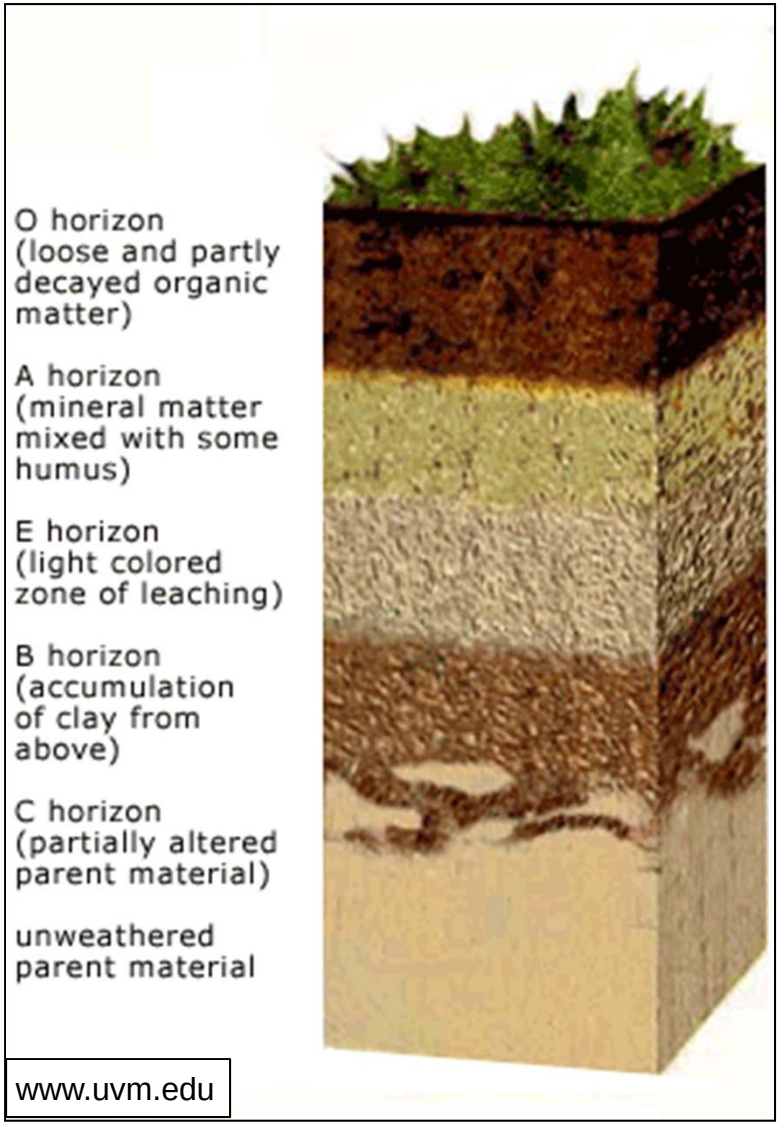
Soil Development

- Rock weathering, water, and organic matter decomposition -- all influence soil development

- Soil consists of layers (called “horizons”) ranging from
  - relatively fresh organic matter at the surface,
  - through a “soup” of organic matter being decomposed by fungi and bacteria and mixed with minerals,
  - to largely mineral material….

  …all sitting on the underlying parent rock

Hypothetical Soil Profile Showing Soil Horizons



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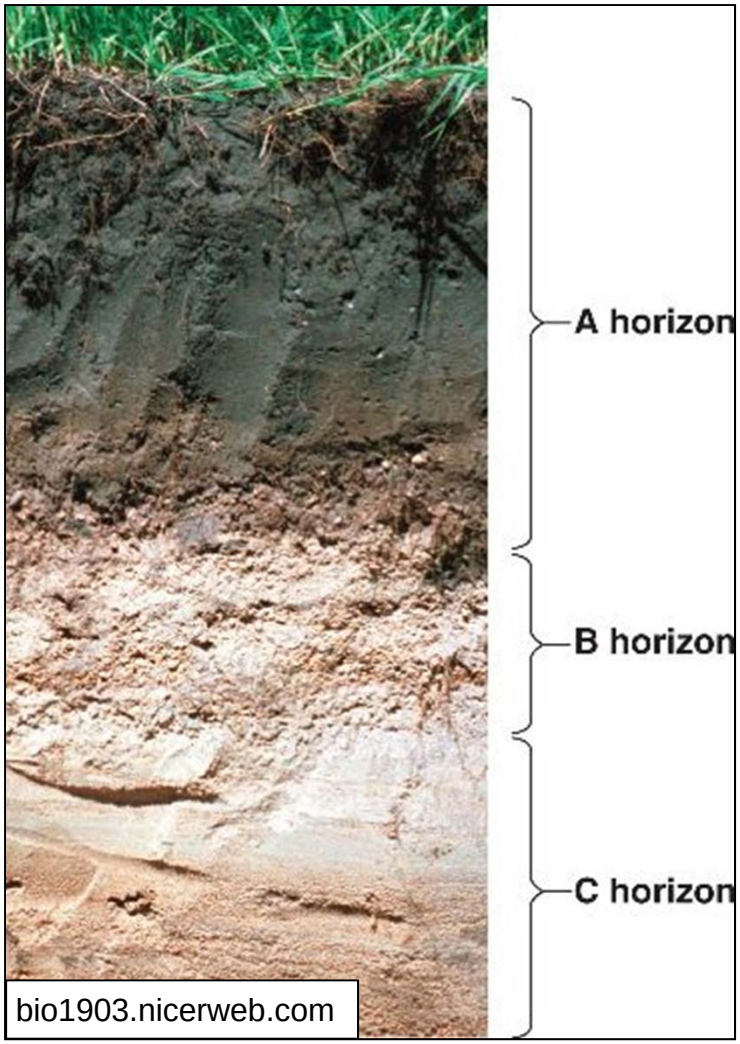

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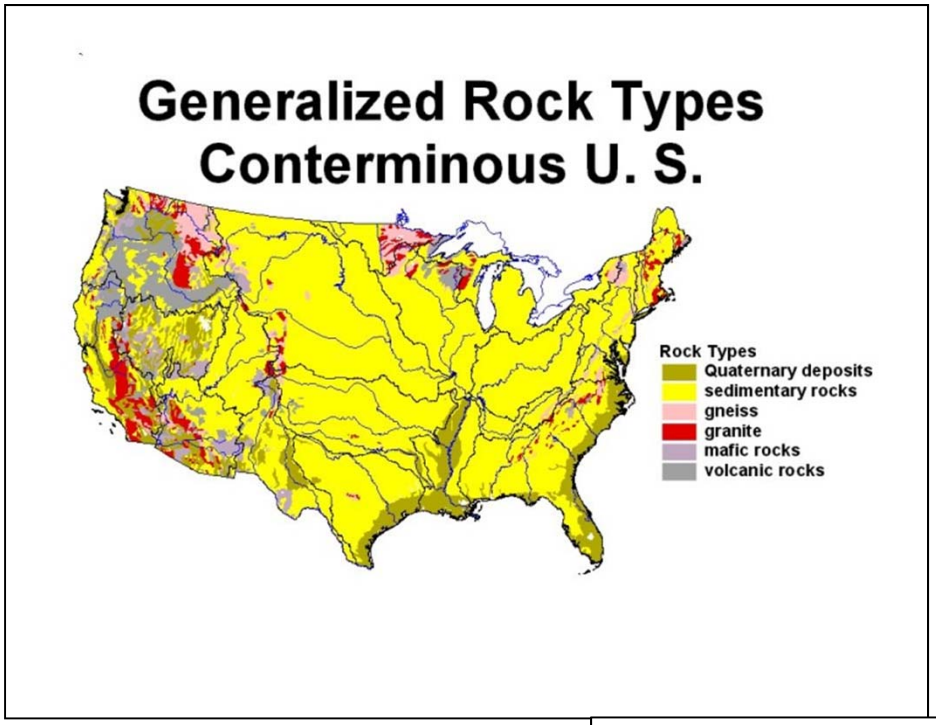
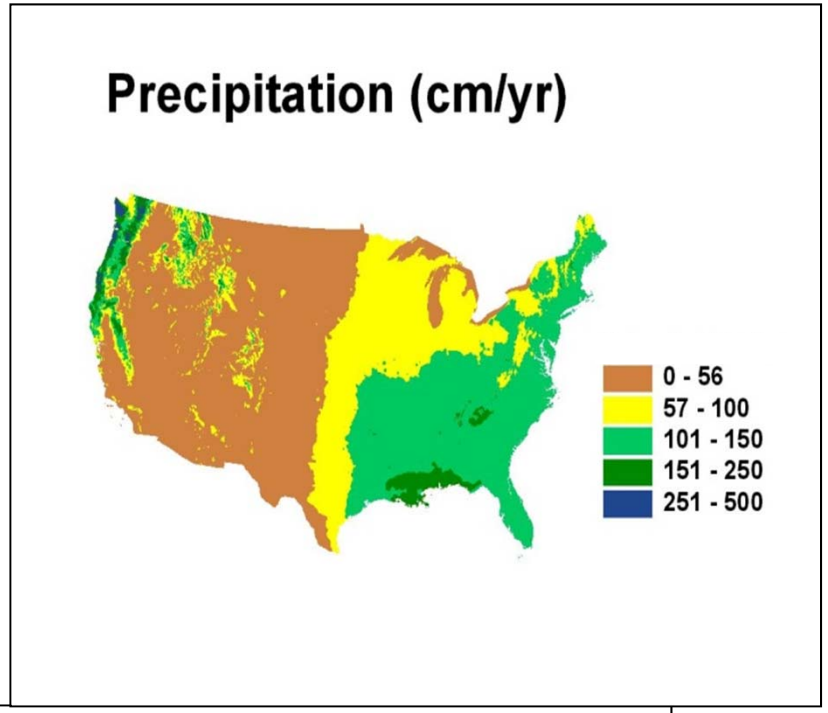
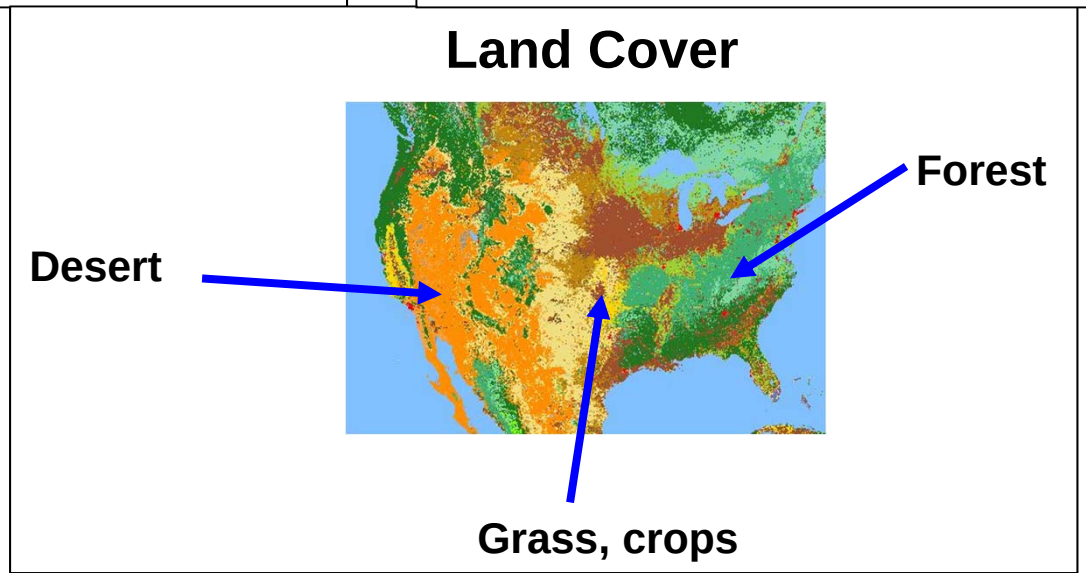
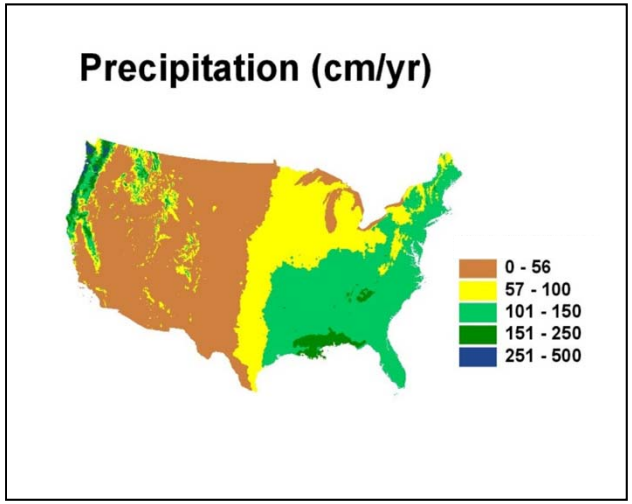
Contributors to Soil Development

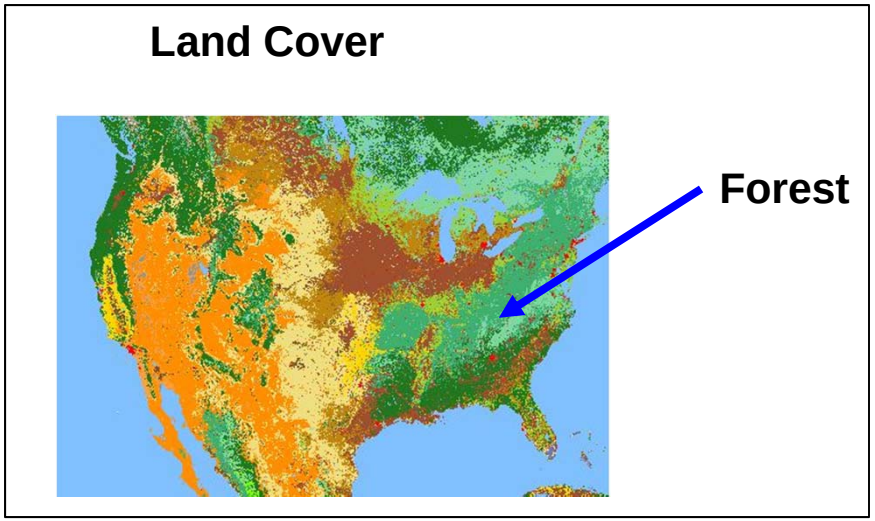




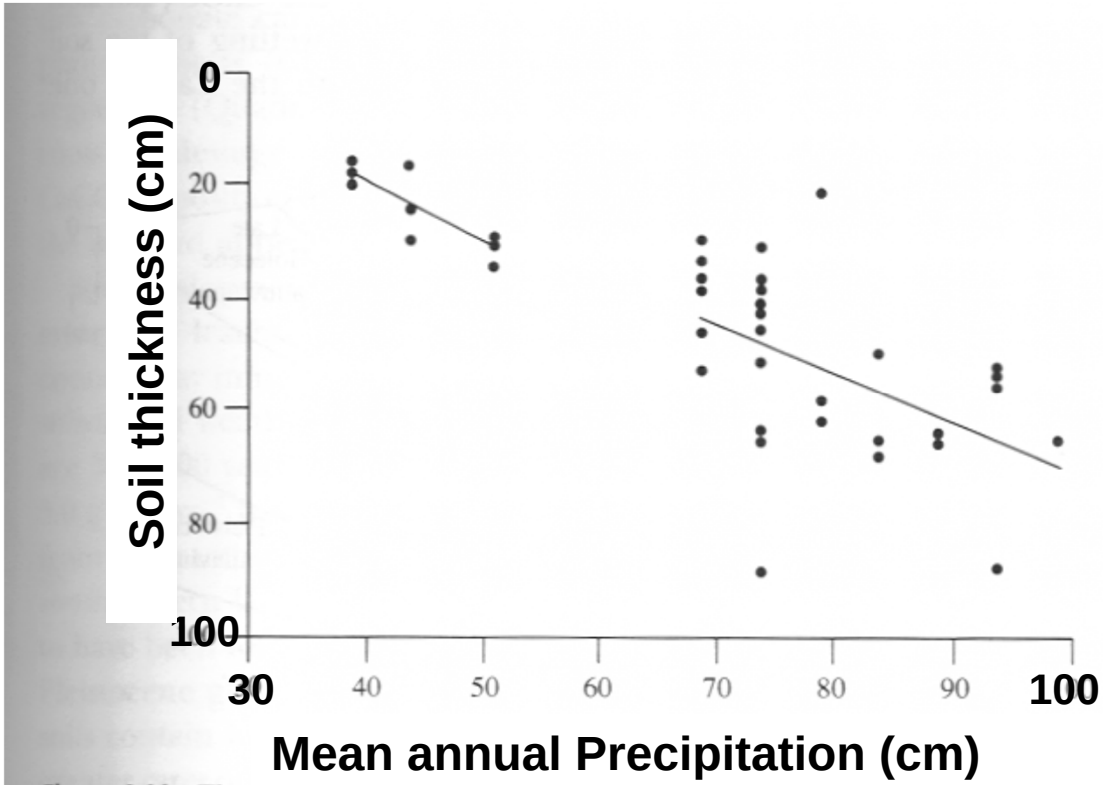


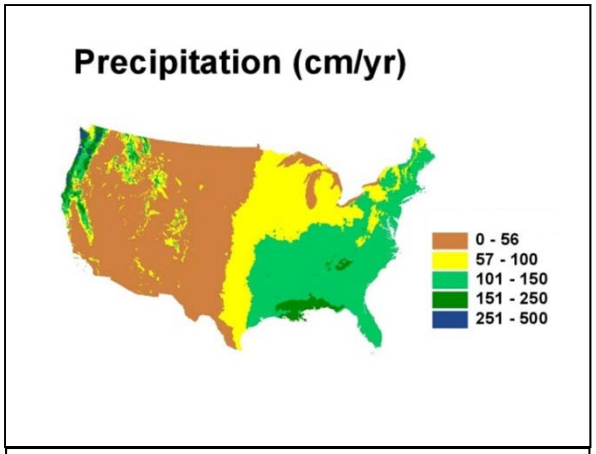
- **Forest soils**
  - Typically form under conditions of abundant organic matter supply and abundant water (at least seasonally)… which promote soil development
  - Typically the profile from rich surface organic matter to the underlying bedrock is well developed
  - *Time* for development (e.g., since last glaciation) is an important consideration

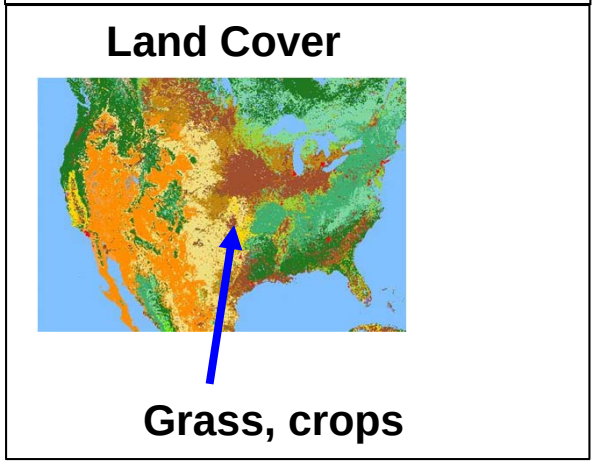




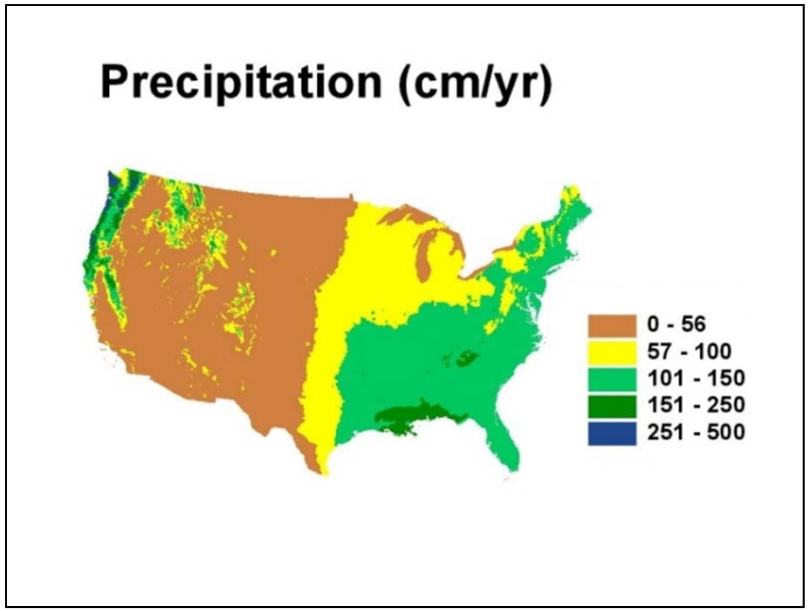
- **Grassland soils**
  - Typically develop under drier conditions than forest soils and with lower organic supply
  - Rate of soil formation influenced by availability of water

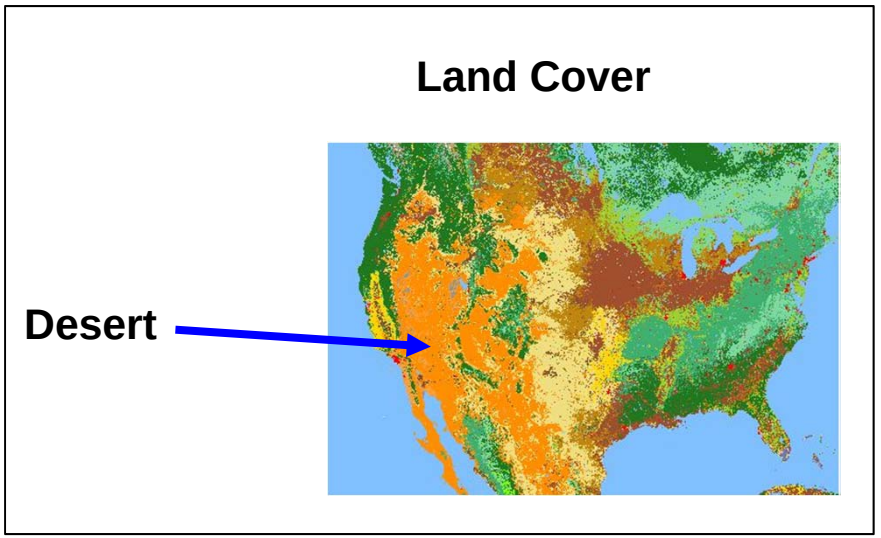




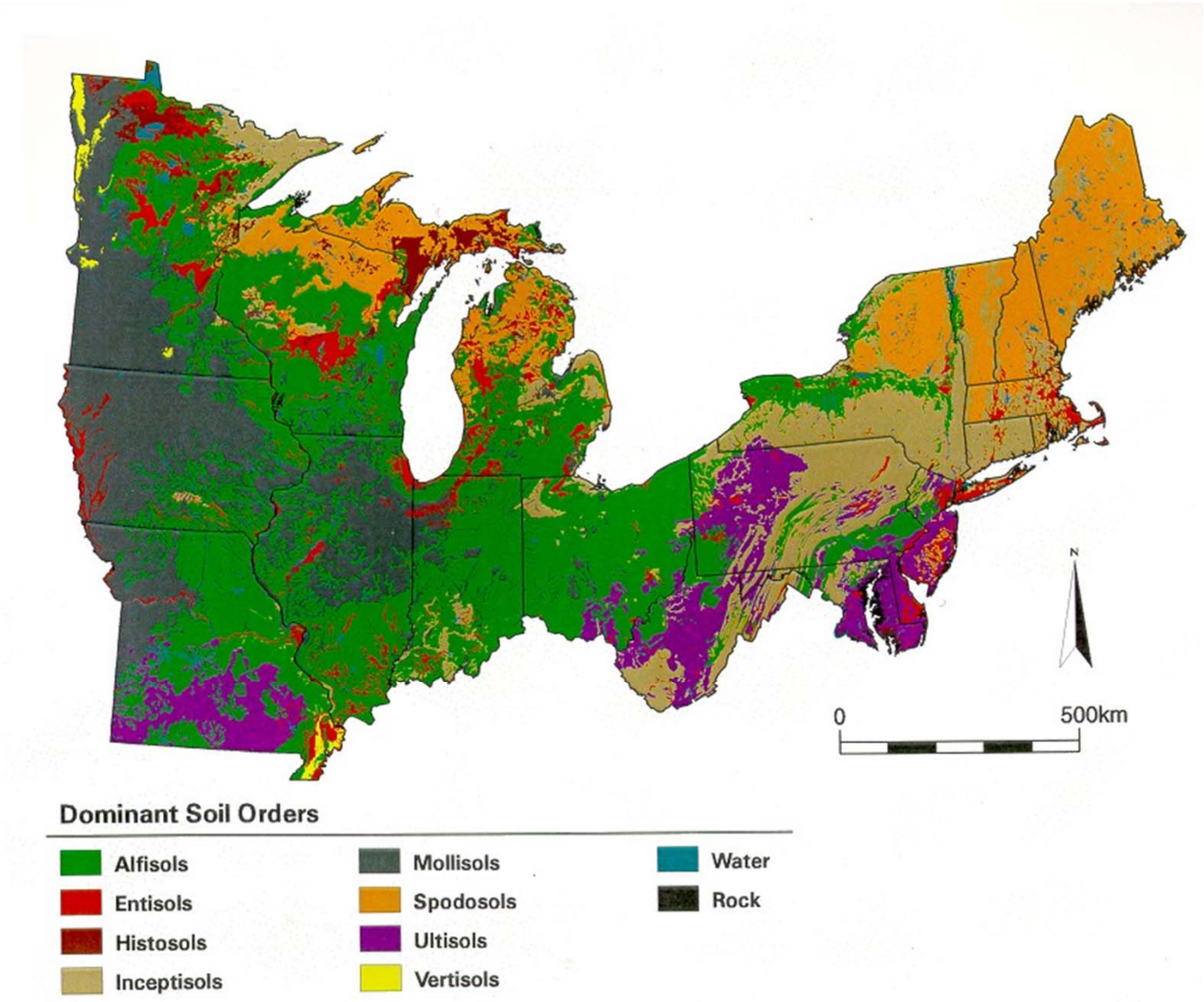


- **Desert soils**
  - Low precipitation and low organic production, so are at the extreme (low) end of soil development rates
  - Typically high in $CaCO_3$ (“caliche”)





Soil Types (Orders) Reflect the Varying Contributors to Soil Formation



The Twelve Soil Orders


Gelisols - soils with permafrost within 2 m of the surface


Histosols - organic soils


Spodosols - acid forest soils with a subsurface accumulation of metal-humus complexes


Andisols - soils formed in volcanic ash


Oxisols - intensely weathered soils of tropical and subtropical environments


Vertisols - clayey soils with high shrink/swell capacity


Aridisols - $CaCO_3$-containing soils of arid environments with subsurface horizon development


Ultisols - strongly leached soils with a subsurface zone of clay accumulation and <35% base saturation


Mollisols - grassland soils with high base status


Alfisols - moderately leached soils with a subsurface zone of clay accumulation and ≥35% base saturation


Inceptisols - soils with weakly developed subsurface horizons


Entisols - soils with little or no morphological development

soils.cals.uidaho.edu

Weathering Rates

- Chemical weathering can be estimated from budgets of dissolved-load export from systems

Watershed	Venezuela	New Hampshire	Maryland	West Africa
Precipitation (cm/yr)	450	130	112	94
vegetation	tropical forest	temperate forest	temperate forest	tropical forest
dissolved transport ($t\ km^{-2}\ yr^{-1}$)	37	8	22	5

Continental Denudation

- Estimated from river transport to ocean
- Contrast these rates with erosion rates of 100 to 1,000 t km^{-2} yr^{-1}

Continent	Area	Chemical Denudation			Mechanical Denudation	
	10^6 km^2	10^9 t/yr	t km^{-2} yr^{-1}		10^9 t/yr	t km^{-2} yr^{-1}
North America	21	0.7	33		1.46	70
South America	20	0.55	28		1.79	90
Asia	47	1.49	32		9.43	201
Africa	30	0.71	24		0.53	18
Europe	11	0.46	42		0.23	21
Australia	10	0.02	2		0.06	6
TOTAL	**139**	**3.9**	**28**		**13.5**	**97**

Lecture Summary

- Weathering and soil development are affected by mineralogy, temperature, water, acids, biota

- Humans are increasing the rates of weathering, soil development, erosion, river transport, and estuarine/delta sedimentation

- Weathering, etc. **increases** immediate availability of essential elements, but **removes** these materials from land for long periods (on human time scales).