Introduction to Soils and Pedology

• Coined in mid 19th Century by French scientist

• Derived from Greek: pedon=ground, logia = discourse

• “The study, in situ, of the biogeochemical processes that form and distribute soils”

• An observational, vs. an experimental, science - *nature is the laboratory*

• Origins attributed to two centers: Russia (Dokuchaev) and Berkeley (Hilgard)
 Definition of Soils

- Many definitions
- Soil is part of a continuum of materials at earth’s surface
  - Soil vs. non-soil at bottom and top
  - Different soils laterally

- Need to divide continuum into systems, or discrete segments, for study

- Hans Jenny (1930’s) conceptualized soils as physical systems amenable and susceptible to physical variables (STATE FACTORS)
Ecological functions of soil

• Supports plant growth
• Recycles nutrients and waste
• Controls the flow and purity of water
• Provides habitat for soil organisms
• Functions as a building material/base
Role of Pedology in Scientific and Societal Problems

- **Carbon and nitrogen cycles**
  - Are soils part of an unidentified sink for \( \text{CO}_2 \)?
  - What is the effect of agricultural on soil C (and atm \( \text{CO}_2 \))?  
  - Will soils store excess N from human activity?

- **Chemistry of natural waters**
  - How do soils release elements with time and space?

- **Earth history**
  - ‘Paleosols’ and evolution of land plants, atmospheric \( \text{CO}_2 \) records, human evolution
  - Soils and archaeology

- **Biodiversity**
  - Is soil diversity analogous to, and complementary to, biodiversity
  - Microorganisms in soil represent unknown biodiversity resources
Soils as a Physical System

• System is open to surroundings (exchange energy and matter)

System Properties = f (initial state, external surrounding, time)

• “Soil is those portion’s of the earth’s crust whose properties vary with soil forming factors”
What Determines Soil Type

- Climate
- Vegetation
- Topography
- Time
- Parent Material
- Human Activities
Soil Composition

- Minerals
- Organic matter
- Water
- Air
The four components of soil:

- Air: 20–30%
- Water: 20–30%
- Mineral: 45%
- Organic: 5%
Mineral component

- Makes up less than 50% of a “soil”
- Varies in chemical composition
- Contains particles of several size ranges (small to really really small)
- Depends on the underlying geology/bedrock
Organic matter

- Small constituent by weight, but huge influence on soil properties
- Made up of partially decomposed plant & animal residues + organic compounds synthesized by soil microbes
- A TRANSITORY component of soils
Functions of Organic Matter

1. **Stabilizes** soil structure, making soil easily managed

2. Increases the amount of **water** a soil can hold (and availability of the water)

3. Major source of plant **nutrients**

4. Main **food/energy** for soil organisms
Soil Water

1. Held to varying degrees depending on amount of water and pore size

2. Not all soil water is available to plants
Soil Air

1. High spatial variability
2. High temporal variability
3. High moisture content (Rh ≈ 100%)
4. High CO$_2$ content
5. Low O$_2$ content
Conditioning Variables

  \[ S = f_{(c,l,o,r,p,t...)} \]
- Climate
- Vegetation
- Relief
- Time
- Parent Material
Soil Starts with Weathering

**Chemical Alteration**
- Solution & Leaching
- Biological Action
- Hydration

**Mechanical**
- Impact
- Wedging: Frost, Plant Roots, Salt Crystal Growth, Expansion of Hydrated Minerals
Transfers

Leaching from Surface
- K, Mg, Na
- Ca
- Si
- Al, Fe

Accumulation beneath Surface
- Al, Fe in Humid Climates
- Ca in Arid Climates
Characterization of Soils

- Morphological
- Physical
- Chemical
- Hydrological
Soil Morphology

• Major terms and concepts:

  - Soil profile: 2d vertical exposure of soil vs. depth (pedon is 3D)

  - Soil horizons: roughly horizontal bands of soil that form from soil forming processes
Field Pedon Description

0-18 A Sbk 5 YR 3/4
18-33 Bw1 Sbk 7.5 YR 3/4
33-47 Bw2 Sbk 7.5 YR 3/4
47-67 BC1 Sbk 10 YR 3/4
67-84 BC2 Sbk 10 YR 3/4
## Field Pedon Description

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Color (Moist)</th>
<th>Texture</th>
<th>Clay (%)</th>
<th>Gravel (%)</th>
<th>Structure</th>
<th>Effervescence</th>
<th>pH</th>
</tr>
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<tbody>
<tr>
<td>6-4</td>
<td>Oi</td>
<td></td>
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<tr>
<td>4-0</td>
<td>Oe</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-18</td>
<td>A</td>
<td>5 YR 3/4</td>
<td>sl</td>
<td>13</td>
<td>&gt;50</td>
<td>2 m sbk</td>
<td>eo</td>
<td>5.1</td>
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<tr>
<td>18-33</td>
<td>Bw1</td>
<td>7.5 YR 3/4</td>
<td>sl</td>
<td>12</td>
<td>&gt;50</td>
<td>2 c sbk</td>
<td>eo</td>
<td>5.1</td>
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<tr>
<td>33-47</td>
<td>Bw2</td>
<td>7.5 YR 3/4</td>
<td>sl</td>
<td>8</td>
<td>&gt;50</td>
<td>2 m gr</td>
<td>eo</td>
<td>5.4</td>
</tr>
<tr>
<td>47-67</td>
<td>BC1</td>
<td>10 YR 3/4</td>
<td>sl</td>
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<td>&gt;50</td>
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<td>eo</td>
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<td>10 YR 3/4</td>
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<td>&gt;50</td>
<td>2 f sbk</td>
<td>eo</td>
<td>5.5</td>
</tr>
</tbody>
</table>
Morphological Properties of Soils

• Major terms and concepts:
  - Soil profile: 2d vertical exposure of soil vs. depth (pedon)
  - Soil horizons: roughly horizontal bands of soil that form from soil forming processes
Key Processes of Soil Formation

- Additions
  - Organic C
  - Dust
- Removals
  - CO2
  - Weathering products
- Transfers
  - Clay
  - Organic matter
  - Carbonate
- Transformations
  - Plants to SOM
  - Primary silicates to secondary silicates, carbonates

CO2 flux
OM additions, OM transformations, weathering
Clay transfers
Clay and carbonate transfers
Leaching
Soil Horizon Nomenclature

• Based on interpretation of dominant soil forming processes affecting that horizons
  - Names based on presumed changes relative to parent material (t=0)
• Universal with some variance

• Originated by Russians in 19th Century
The “Master” horizons

• O surface horizon made of organic matter
• A surface horizon, mineral soil high in organic matter
• subsurf. horizon light in color due to leaching, site of Eluviation processes
• E subsurf horizon, site of illuviation processes
• B least weathered (and deepest) of all the soil horizons
• C bedrock
• R bedrock
A horizons

B horizons

C horizons (parent material)
Subscripts: Processes occurring in these Horizons

**O horizon**
- \(O_i\) identifiable (recognizable) material
- \(O_e\) Intermediate (even balance?)
- \(O_a\) highly decomposed (almost all gone)

**A horizon**
- \(A_p\) plowed surface
- \(A_b\) buried surface
More Subscripts

B horizons

• \( t \) clay accumulations (terra cotta)
• \( g \) “gleying” (very wet climates)
• \( k \) karbonates (dry zones– really spelled with a “c”)
• \( s \) sesquioxide accumulations (think iron, aluminum, red/yellow)
• \( h \) humus (high organic content)
• \( w \) “weak” development, distinctive colorations
• \( o \) residual oxides – red color, “tropical soils”
• \( ss \) “slickensides” of clay
Rules for naming

- **C horizon**
  - r (highly weathered rock) “saprolite”
  - k (carbonates)

- **Subscript Rules**
  - rarely use more than three
  - t (almost) always first

Examples:

Btg, Cr, Bw, Ap, . . .
Transition horizons and subdivisions within master horizons

- Oi: Organic, slightly decomposed
- Oe: Organic, moderately decomposed
- Oa: Organic, highly decomposed
- A: Mineral, mixed with humus, dark colored
- E: Horizon of maximum eluviation of silicate clays, Fe, Al oxides, etc.
- EB: Transition to B, more like E than B
- BE: Transition to E, more like B than E
- B: Most clearly expressed portion of B horizon
- BC: Transition to C, more like B than C
- C: Zone of least weathering

Solum

Bedrock
## Master Horizon Subdivisions

<table>
<thead>
<tr>
<th>Lower Case Modifiers of Master Horizons</th>
<th>Definitions (relative to soil parent material)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Highly decomposed organic matter (O horizon).</td>
</tr>
<tr>
<td>b</td>
<td>Buried soil horizon</td>
</tr>
<tr>
<td>c</td>
<td>Concretions or nodules of rion, aluminum, manganese or titanium.</td>
</tr>
<tr>
<td>d</td>
<td>Non-cemented, root restricting natural or human made (plow layers, etc.) root restrictive layers.</td>
</tr>
<tr>
<td>e</td>
<td>Intermediate decomposition of organic matter (O horizon).</td>
</tr>
<tr>
<td>f</td>
<td>Indication of presence of permafrost</td>
</tr>
<tr>
<td>g</td>
<td>Strong gleying present in form of reduction or loss of Fe and resulting color changes.</td>
</tr>
<tr>
<td>h</td>
<td>Accumulation of illuvial complexes of organic matter which coat sand and silt particles.</td>
</tr>
<tr>
<td>i</td>
<td>Slightly decomposed organic matter (O horizon).</td>
</tr>
<tr>
<td>j</td>
<td>Presence of jarosite (iron sulfate mineral) due to oxidation of pyrite in previously reduced soils.</td>
</tr>
<tr>
<td>k</td>
<td>Accumulation of calcium carbonate due to pedogenic processes.</td>
</tr>
<tr>
<td>m</td>
<td>Nearly continuously cemented horizons (by various pedogenic minerals)</td>
</tr>
<tr>
<td>n</td>
<td>Accumulation of exchangeable sodium</td>
</tr>
<tr>
<td>o</td>
<td>Residual accumulation of oxides due to long-term chemical weathering.</td>
</tr>
<tr>
<td>p</td>
<td>Horizon altered by human related activities</td>
</tr>
<tr>
<td>q</td>
<td>Accumulation of silica (as opal)</td>
</tr>
<tr>
<td>r</td>
<td>Partially weathered bedrock</td>
</tr>
<tr>
<td>s</td>
<td>Illuvial accumulation of sesquioxides</td>
</tr>
<tr>
<td>ss</td>
<td>Presence of features (called slickensides) caused by expansion and contraction of high clay soils</td>
</tr>
<tr>
<td>t</td>
<td>Accumulation of silicate clay by weathering and/or illuviation</td>
</tr>
<tr>
<td>v</td>
<td>Presence of plinthite (iron rich, reddish soil material)</td>
</tr>
<tr>
<td>w</td>
<td>Indicates initial development of oxidized (or other) colors and/or soil structure</td>
</tr>
<tr>
<td>x</td>
<td>Indicates horizon of high firmness and brittleness</td>
</tr>
<tr>
<td>y</td>
<td>Accumulation of gypsum</td>
</tr>
<tr>
<td>z</td>
<td>Accumulation of salts more soluble than gypsum (e.g. Na₂CO₃, etc.)</td>
</tr>
</tbody>
</table>
Soil Profile Description Data Forms

**FIELD SHEET FOR RECORDING SOIL CHARACTERISTICS**

Soil Type: Auberry coarse sandy loam

Location: 1/4 mi W New Auberry on N Fork Rd. (Map No. Sec. 105 225', Mod.)

Geographical Landscape: rolling upland

Elevation: 2150 ft

Slope: 0%

Aspect: NE

Drainage: well

Soil: Deep

Water: Alkaline none

Mode of Formation: primary (residual)

Parent Material: Tonalite (Gneissic granite)

Climate: Subhumid wet, Thermal

MAP: 25" MAT: 57°F

Natural Cover: Grasses, forbs, blue oak, red oak

Soil Region: VII

Profile Group: D

Genetically Related Soil Series: Abwood, Sierra

<table>
<thead>
<tr>
<th>PROFILE SKETCH</th>
<th>COLOR</th>
<th>TEXTURE</th>
<th>STRUCTURE</th>
<th>CONSISTENCY</th>
<th>REACTION</th>
<th>WISC: Resins, Pores, Clay Films, Cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>20%</td>
<td>5%</td>
<td>5% (Creeks) 5% (Clays)</td>
</tr>
<tr>
<td>B</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>20%</td>
<td>5%</td>
<td>5% (Creeks) 5% (Clays)</td>
</tr>
<tr>
<td>C</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>20%</td>
<td>5%</td>
<td>5% (Creeks) 5% (Clays)</td>
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<td>D</td>
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<td>E</td>
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<td>10%</td>
<td>20%</td>
<td>5%</td>
<td>5% (Creeks) 5% (Clays)</td>
</tr>
</tbody>
</table>

Natural Land Division: E3

Soil Rating (Storrie index): 67 x 90 x 95 = 46

Soil Grade: 3

Land Use Capability Unit: ZE-1 (18)

Present Use: Rangeland

Suitability: Irrigated Crops: fair (pasture) Range: fair grass-appearing

Non-Irrigated Crops: fair (cane, barley) Timber not suited

Soil Management: Forage responds to N and P, legumes respond to S

Remarks: Erosion hazard moderate - avoid overgrazing
Soil Color

• **Hue:** *Dominant spectral color*
  - Reflects pm/age/climate
  - Unoxidized silicate rocks are yellowish, soil formation forms FeO that is red

• **Value:** *Relative lightness or darkness*
  - Reflects OM content

• **Chroma:** *Brightness (oxidation)*
  - Reflects age/degree of Fe oxidation
Soil Value Related to Organic Carbon Content

![Graph showing the relationship between soil organic carbon content and Munsell color value for different soil types: Mollisol (dry) and (moist), and Alfisol (dry) and (moist). The graph shows a positive correlation with different symbols representing each soil type.]
Soil Structure

• Aggregation of mineral grains and OM into multi-particle structures
  - Soil structure exists at scales from micron to cm scale
  - We are concerned about field-scale observable structure (macro)

• Key controls on ‘macro’ structure
  - Clay content (clay shrinking and swelling align soil particles into plates (very near surface), blocks (common near surface) or prisms (deeper in soil)
  - Organic matter (polysaccrides) important for near surface particle aggregation (granular)
  - Clay + Na⁺ very important for formation of columnar structure.
## Types of Soil Structure

### Commonly A horizons

- Crumb: Aggregates are small, porous, and weakly held together. Usually found in surface soil or A horizon.

- Granular: Aggregates are small, non-porous, and are strongly held together. Usually found in subsurface or A horizon of desert soils.

- Platy: Aggregates are flat or plate-like, with horizontal dimensions greater than the vertical. Usually found in subsurface or B horizon of loamy soil.

- Angular blocky or cube-like: Aggregates have sides that are nearly right angles, tend to overlap. Usually more permeable than blocky type. Usually found in subsoil or B horizon.

- Subangular blocky or nut-like: Aggregates have sides forming obtuse angles, corners are rounded. Usually more permeable than blocky type. Usually found in subsoil or B horizon.

- Prismatic: Without rounded caps. Prism-like with the vertical axis greater than the horizontal. Usually found in subsoil or B horizon.

- Columnar: With rounded caps. Usually found in subsoil or B horizon.

### Commonly B horizons

- Structure lacking: Soil particles exist as individuals such as sand and do not form aggregates. Usually found in subsoil or C horizon.

- Massive: Soil material clings together in large uniform masses, as in loam. Usually found in subsoil or C horizon.
Structure near surface

‘Clods” : lack of soil structure

Granular Structure: OM interaction with mineral grains
Subsurface Structure

- **Platey Structure:** near surface due to shrinking/swelling or compaction

- **Prismatic Structure:** subsurface in moderate clay content with seasonal water
Subsurface Structure

*Columnar:* combination of clay and Na⁺
Soil Texture

• Relative proportion of sand, silt, and clay
  - Sand: 0.05 to 2 mm
  - Silt: 0.002 to 0.05 mm
  - Clay: < 0.002 mm (2 microns)

• Particle distribution determined by sedimentation

• Textural classes (textural triangle) based on long-term practical experience
  - Reflects large influence of clay on soil characteristics
  - Clay (to be discussed later) has impact on water, physical processes, etc.
**Review of Description Sheet**

**Factors of Soil Formation:**

- **Soil Type:** Auberry coarse sandy loam
- **Location:** 1/2 mi W New Auberry on N Fort Rd (N40°47'44" W116°23'25"
- **Geographical Landscape:** Rolling upland
- **Elevation:** 2150 ft, Slope 9.7%, Aspect NNE, Erosion none
- **Groundwater:** Deep, Drainage well, Alkali none
- **Mode of Formation:** Primary or residual
- **Parent Material:** Tonalite (Sierran Granite)
- **Climate:** Subhumid Warm-Thermal
- **Natural Cover:** Grasses, forbs, blue oak, chamise, borrego
- **Profile Group:** VII
- **Genetically Related Soil Series:** Abuanhee, Sierra

**FIELD SHEET FOR RECORDING SOIL CHARACTERISTICS**

<table>
<thead>
<tr>
<th>PROFILE</th>
<th>COLOR</th>
<th>TEXTURE</th>
<th>STRUCTURE</th>
<th>CONSISTENCE</th>
<th>REACTION</th>
<th>MISC: Roots, Peres, Clay films, Congelations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10F5-8</td>
<td>D</td>
<td>Cohesive</td>
<td>26% Metric</td>
<td>62</td>
<td>35 (coarse) 56 (coarse)</td>
</tr>
<tr>
<td>Bb</td>
<td>10YR 5</td>
<td>B</td>
<td>Cohesive</td>
<td>45% Metric</td>
<td>60</td>
<td>16 (coarse) 18 (coarse)</td>
</tr>
<tr>
<td>Bc</td>
<td>10YR 5</td>
<td>B</td>
<td>Cohesive</td>
<td>45% Metric</td>
<td>60</td>
<td>16 (coarse) 18 (coarse)</td>
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<tr>
<td>C</td>
<td>10YR 5</td>
<td>B</td>
<td>Cohesive</td>
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<td>B</td>
<td>Cohesive</td>
<td>45% Metric</td>
<td>60</td>
<td>16 (coarse) 18 (coarse)</td>
</tr>
</tbody>
</table>

- **Natural Land Division:** E3
- **Soil Rating (Soil Index):** 67x90x90x95 = 146
- **Soil Grade:** 3
- **Land Use Capability Unit:** TL 2 18
- **Present Use:** Rangeland
- **Suitability:** Irrigated crops fair (pasture), Range fair (woody-species)
- **Non-Irrigated crops:** Fair (hay, barley), Timber not suited
- **Soil Management:** Forage responds to N, and P, legumes respond to S
- **Remarks:** Erosion hazard moderate, avoid overgrazing

**Practical or mgt concerns**
Soil Physical Properties

• **Soil Texture** - provides general information regarding the amounts of sand, silt and clay

• **Bulk Density** - mass of dry soil per unit bulk volume, including the air space (pores)

• **Depth to Bedrock** - influences the depth to which roots may penetrate the soil
Physical properties (continued)

• **Aggregate Stability** - determines soil structure and is very important to hydrological properties and aeration.

• **Soil Color** - measured in terms of hue, value and chroma, reflects organic matter content and oxidizing or reducing soil conditions.
Physical properties (continued)

- **Aggregate Stability** - determines soil structure and is very important to hydrological properties and aeration.
- **Soil Color** - measured in terms of hue, value and chroma, reflects organic matter content and oxidizing or reducing soil conditions.
Soil Chemical Properties

- **Organic Matter Content** - provides a generalized indication of the relative fertility status of the soil; promotes greater water retention, aeration, fertility

- **Soil pH** - an index of the relative acidity or alkalinity of the soil; often considered a master variable in determining the nutrient availability of a soils
Chemical Properties (Continued)

- **Soil Salinity Range** - an index of salt content; salts in large quantities may inhibit the plant’s ability to extract water and nutrients from the soil
- **Cation Exchange Capacity** - relative measure of the soil’s potential to retain added nutrients; soils with high CEC have a greater nutrient retention potential than soils with a low CEC
Soil Hydrological Properties

- **Drainage** - provides an estimate of the amount of water that remains in soil after wetting.
- **Plant available water content** - an index that relates to the amount of soil water available for plant use immediately after wetting.
- **Soil infiltration rate** - rate at which water enters the soil surface; is highly dependent on soil physical properties such as soil texture.
Hydrological Properties (Continued)

• **Permeability** - the ability of the soil to transmit water through and below the rooting zone

• **Water table depth** - provides a generalized estimate of the depth to standing water over a small geographic area
Soil Colloids

• “Organic and inorganic matter with very small particle size and a correspondingly large surface area per unit mass” (“Soil bank”)

• Four categories:
  - Crystalline silicate clays (phyllosilicates)
  - Noncrystalline silicate clays
  - Iron and aluminum oxide clays
  - Organic matter (humus)
“Clay” is ...

- A particle size class (<0.002 mm)

- A mineral type with specific properties and characteristics (secondary mineral)
Relative Size Comparison of Soil Particles

Sand
.05 to 2mm
feels gritty

Silt
.002 to .05 mm
feels smooth

Clay
less than .002 mm
feels sticky

“Big” → smaller → really small

Sand → silt → clay
Fundamentals of clay mineralogy

- 2 basic building blocks: the silica (Si) tetrahedron and the aluminum (Al) octahedron
- These building blocks form sheets: “silicate layer clays”
Shape of silicon tetrahedron and aluminum octahedron
Isomorphous substitution

**Equal shape/size (ionic radii)**

- The replacement of one ion for another of similar size within the crystalline structure of the clay

- This changes the total charge and location of the charge on the mineral (greatly affecting the properties of the clay)
Isomorphic Substitution in tetrahedral sheet

\[(+4) \times 2 = +8\]
\[-(-2) \times 4 = -8\]
\[Si_2O_4\] (neutral)

\[SiAlO_4\] (net negative charge)

\[(+4) + (+3) = +7\]

Tetrahedral sheet
Isomorphic Substitution in octahedral sheet

\[(\text{OH})_2\text{Al}_2\text{O}_2 \rightarrow (\text{OH})_2\text{AlMgO}_2\]

(-1) x 2 = -2  \hspace{1cm} (-2) x 2 = -4  \hspace{1cm} (-2) + (-4) = -6

(+3) x 2 = +6  \hspace{1cm} (+3) + (+2) = +5  \hspace{1cm} \text{neutral, net negative charge}

Octahedral sheet
Ionic Radii of elements in silicate clays
- Tetrahedral & Octahedral sheets

Note that Al, Fe, O, and OH can fit in either.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Radius, nm(^a)</th>
<th>Found in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si(^{4+})</td>
<td>0.042</td>
<td></td>
</tr>
<tr>
<td>Al(^{3+})</td>
<td>0.051</td>
<td>Tetrahedral sheet</td>
</tr>
<tr>
<td>Fe(^{3+})</td>
<td>0.064</td>
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</tr>
<tr>
<td>Mg(^{2+})</td>
<td>0.066</td>
<td>Octahedral sheet</td>
</tr>
<tr>
<td>Zn(^{2+})</td>
<td>0.074</td>
<td></td>
</tr>
<tr>
<td>Fe(^{2+})</td>
<td>0.070</td>
<td>Octahedral sheet</td>
</tr>
<tr>
<td>Na(^{+})</td>
<td>0.097</td>
<td>Exchange sites</td>
</tr>
<tr>
<td>Ca(^{2+})</td>
<td>0.099</td>
<td></td>
</tr>
<tr>
<td>K(^{+})</td>
<td>0.133</td>
<td></td>
</tr>
<tr>
<td>O(^{2-})</td>
<td>0.140</td>
<td>Both sheets</td>
</tr>
<tr>
<td>OH(^{-})</td>
<td>0.155</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)1 nm = 10\(^{-9}\) m.
Types of clay minerals

• Based on numbers and combinations of structural units (tetrahedral and octahedral sheets)
• Number of cations in octahedral sheet
• Size and location of layer charge (due to isomorphic substitution)
• Absence or presence of interlayer cations
• Two general categories: 1:1, 2:1
Clay minerals

**1:1 clays**
(One tetrahedral sheet for each octahedral sheet)

- Kaolinite
- Nacrite
- Dickite
- Halloysite
- Etc.

**2:1 clays**
(Two tetrahedral sheets for each octahedral sheet)

- Montmorillonite, beidellite, saponite, etc.
- Illite, muscovite, biotite, etc.
- Tri- or di-vermiculite
- Cookeite, chamosite ETC

*Weird-o, not truly 2:1*
Visual comparison of common silicate clays

1:1 clays

- Tetrahedral sheet
- Octahedral sheet
- Tetrahedral sheet
- Octahedral sheet

- Water molecules, Mg^{2+} and other ions

Kaolinite

1:1

Kaolinite (1:1) Nonexpanding (no swelling)

2:1 clays

- Tetrahedral sheet
- Octahedral sheet
- Tetrahedral sheet
- Octahedral sheet

- Water molecules, miscellaneous cations

Smectite

Expanding (max. swelling)

Vermiculite

Expanding (some swelling)

Fine-grained mica

Nonexpanding (min. swelling)

Chlorite

Nonexpanding (min. swelling)
1:1 Silicate Clays

- Layers composed of one tetrahedral sheet bound to one octahedral sheet
- Kaolinite: one of the most widespread clay minerals in soils; most abundant in warm moist climates
- Stable at low pH, the most weathered of the silicate clays
- Synthesized under equal concentrations of $\text{Al}^{3+}$ and $\text{Si}^{4+}$
Kaolinite

• A 1:1 clay
• Little or no isomorphous substitution
• “nutrient poor”
• No shrink-swell (stable because of H-bonding between adjacent layers)
• A product of acid weathering (low pH, common in soils of the SE USA)
Structure of Kaolinite

NO ISOMORPHOUS SUBSTITUTION!!!

Sheets of silicon tetrahedra and aluminum octahedra linked by shared oxygen atoms.
Kaolinite under low pH

\[ \text{Al—OH} + \text{H}^+ \leftrightarrow \text{Al—OH}_2^+ \]

No charge \hspace{2cm} \text{positive charge}
Visual comparison of common silicate clays

1:1 clays
- Tetrahedral sheet
- Octahedral sheet
- Tetrahedral sheet
- Octahedral sheet

Kaolinite (1:1)
- Nonexpanding (no swelling)

2:1 clays
- Tetrahedral sheet
- Octahedral sheet
- Tetrahedral sheet
- Octahedral sheet

Water molecules, Mg²⁺ and other ions

Smectite
- Expanding (max. swelling)

Vermiculite
- Expanding (some swelling)

Fine-grained mica
- Nonexpanding (min. swelling)

Chlorite
- Nonexpanding (min. swelling)
2:1 Silicate Clays

- Two silica tetrahedral sheets linked to one aluminum octahedral sheet
- Three key groups:
  - Smectites (e.g., montmorillonite)
  - Vermiculites
  - Micas (e.g., illite)
- And one weirdo (the chlorites)
Clay minerals

1:1 clays
(one tetrahedral sheet for each)

- Kaolinite, nacrite, dickite, halloysite, etc.

2:1 clays
(two tetrahedral sheets for each)

- Smectite
  - Montmorillonite, beidellite, saponite, etc.

- Micas
  - Illite, muscovite, biotite, etc.

- Vermiculite
  - Tri-or divermiculite
- Chlorites
  - Cookeite, chamosite ETC

Pyrophyllite

Weirdo, not truly 2:1

only one with no substitution
Visual comparison of common silicate clays

1:1 clays
- Tetrahedral sheet
- Octahedral sheet

2:1 clays
- Tetrahedral sheet
- Octahedral sheet
- Water molecules, Mg$^{2+}$ and other ions
- K$^+$

Kaolinite (1:1)
- Nonexpanding (no swelling)

Smectite
- Expanding (max. swelling)

Fine-grained mica
- Vermiculite
- Expanding (some swelling)

Chlorite
- Nonexpanding (min. swelling)
Smectite (2:1, Montmorillonite)

- Layer charge originates from the substitution of $\text{Mg}^{2+}$ for $\text{Al}^{3+}$ in the octahedral sheet
- Unstable (weathers to something else) under low pH and high moisture
- Most swelling of all clays
- “Nutrient rich”
Structure of basic Smectite (Montmorillonite):

Structure of montmorillonite (a smectite): it is built of two sheets of silicon tetrahedra and one sheet of aluminum octahedra, linked by shared oxygen atoms.
Structure of basic Smectite
(Montmorillonite)

Causes cations to move into the interlayer space, where they can be replaced by other cations.

Isomorphous substitution in the octahedral sheet.

\[ \text{INTERLAYER } \text{Ca} + \text{Mg} + \text{H}_2\text{O} \]

\[ = \text{Mg} \text{ (this slide only)} \]
Visual comparison of common silicate clays

1:1 clays
- Tetrahedral sheet
- Octahedral sheet
- Kaolinite (1:1)
- Nonexpanding (no swelling)

2:1 clays
- Tetrahedral sheet
- Octahedral sheet
- Water molecules, miscellaneous cations
- Smectite
- Vermiculite
- Expanding (max swelling)

Fine-grained mica
- Nonexpanding
- Chlorite
- Nonexpanding (min. swelling)
Vermiculites (2:1)

- Alteration product of micas (rock form)
- Formed from loss of $K^+$
- Interlayer $K^+$ of mica replaced with $Mg^{2+}$
- Limited shrink-swell ...
  - High layer charges: Isomorphic substitution in BOTH tetrahedral & octahedral sheets
  - “nutrient rich!” (the most)
  - Stable under moderate to low soil pH, high Mg, Fe
  - Common in midwestern US
Structure of Vermiculite

Lots of charge imbalance, both sheets:

High nutrient supply capacity

= Al (this slide only!)

= Mg (this slide only!)
Visual comparison of common silicate clays

**1:1 clays**
- Tetrahedral sheet
- Octahedral sheet
- Kaolinite (1:1)
- Nonexpanding (no swelling)

**2:1 clays**
- Tetrahedral sheet
- Octahedral sheet
- Water molecules, Mg\(^{2+}\) and other ions
- Smectite
  - Expanding (max. swelling)
- Vermiculite
  - Expanding (some swelling)
- Fine-grained mica
- Nonexpanding (min. swelling)
- Chlorite
  - Nonexpanding (min. swelling)
(2:1, Fine-grained Mica: Illite)

- $\text{Al}^{3+}$ substitution for $\text{Si}^{4+}$ on the tetrahedral sheet
- Strong surface charge
- "fairly nutrient poor"
- Non-swelling, only moderately plastic
- Stable under moderate to low pH, common in midwestern US
Structure of Illite
Structure of Illite

1. Isomorphous substitution is in the tetrahedral sheets

2. K+ comes into the interlayer space to satisfy the charge and "locks up" the structure
Visual comparison of common silicate clays

**1:1 clays**
- Kaolinite
- Nonexpanding (no swelling)

**2:1 clays**
- Tetrahedral sheet
- Octahedral sheet
- Water molecules, Mg$^{2+}$ and other ions
- K$^+$
- Fine-grained mica
- Nonexpanding (min. swelling)

**Chlorite**
- Nonexpanding (min. swelling)
Chlorites (2:1:1)

- Hydroxy sheet in the interlayer space
- Restricted swelling
- “Nutrient poor”
- Common in sedimentary rocks and the soils derived from them
- Isomorphic substitution in both tetrahedral and octahedral sheets
Structure of Chlorite

1. Iron-rich
2. “locked” structure
3. Low nutrient supply capacity

\[ \text{Mg-Al hydroxy sheet} \]

\[ \text{Mg-Al hydroxy sheet} \]

\[ \text{Mg-Al hydroxy sheet} \]

- \( \text{Al} \)
- \( \text{Fe} \)
- \( \text{Mg} \)
Visual comparison of common silicate clays

1:1 clays

- Tetrahedral sheet
- Octahedral sheet
- Tetrahedral sheet
- Octahedral sheet
- Water molecules, miscellaneous cations

Kaolinite (1:1)
Nonexpanding (no swelling)

2:1 clays

- Tetrahedral sheet
- Octahedral sheet
- Tetrahedral sheet
- Octahedral sheet
- Water molecules, Mg²⁺ and other ions

Smectite
Expanding (max. swelling)

Vermiculite
Expanding (some swelling)

Fine-grained mica
Nonexpanding (min. swelling)

Chlorite
Nonexpanding (min. swelling)

2:1 clays

- Tetrahedral sheet
- Octahedral sheet
- Tetrahedral sheet
- Octahedral sheet
- Hydroxide sheet

K⁺
## Comparison of common silicate clays

<table>
<thead>
<tr>
<th>Property</th>
<th>Kaolinite</th>
<th>Smectite</th>
<th>Fine-grained mica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swelling</td>
<td>Low</td>
<td>High</td>
<td>Low to none</td>
</tr>
<tr>
<td>Bonding</td>
<td>Hydrogen (strong)</td>
<td>Van der Waal’s (weak)</td>
<td>Potassium ions (strong)</td>
</tr>
<tr>
<td>Net negative charge (CEC)</td>
<td>Low: 2-5 cmol(_c/)kg</td>
<td>High: 80-120 cmol(_c/)kg</td>
<td>Mod: 15-40 cmol(_c/)kg</td>
</tr>
<tr>
<td>Charge location</td>
<td>Edges only - NO isomorphic substitution</td>
<td>Octahedral sheets</td>
<td>Tetrahedral sheets</td>
</tr>
<tr>
<td>General class</td>
<td>1:1 (TO)</td>
<td>2:1 (TOT)</td>
<td>2:1 (TOT)</td>
</tr>
</tbody>
</table>
Total Elemental Analyses

Sample Preparation

- Typical methods of sample preparation include extraction, dissolution, or acidification and should result in a solution free of particulates. Typical acid matrices include 10% HCl (1 volume of concentrated HCl in 10 volumes of solution), 25% HNO3, and 1% HNO3.
- Samples be at least 10ml in volume, but can generally get by with 5ml samples.

Analyses

- ICP, Inductively Coupled Plasma
- ICAP-OES, Inductively Coupled Plasma Optical Emission Spectrometer
- Provides total elemental analysis of acidic solutions of soil extracts
Total Elemental Analyses

Methods

- A nebulized mist is injected from a liquid into the center of an argon plasma. A plasma is created from a flow of gas within a high energy field which ionizes the gas and causes intense heating. Temperatures inside an ICP plasma reach 10000 K.

- The intense heat causes the dissociation of most chemical compounds, and the energy that the component atoms absorb causes them to undergo excitation and ionization energy transitions. The transitions produce spectral emissions characteristic of the elements being excited.

- The spectra produced by the plasma is broken down into individual spectral lines by the ICP's spectrometer, and the ICP's computer translates the spectral lines into concentrations for a specified suite of elements.

Interpreting Results

- Data values are expressed on an atomic weight basis (not as molecular species) and are reported in ppm.

- To convert elemental values to other forms you need to factor in the atomic weight of the element as a fraction of the molecular weight of the species in question.
Elemental Weathering

Valency

Increasing resistance to hydrolysis

Coordination number

Paton et al., 1995
Mass Balance

Goal

- To interpret the effects of weathering and pedogenesis quantitatively
- To merge pedologic and hydrochemical environments by assessing elemental and mineralogical gains and losses from the soil system
Mass Balance

What is mass balance?

- A physical and chemical model and mathematical tool used to quantify net gains and losses of material/mass in and out of soil horizons (mass transfers) during pedogenesis.

- Comparison of bulk density, volume, and chemical composition between soil horizons and their respective parent material.
Mass Balance

What does mass balance do?

- Accounts for the fate of elements during weathering
- Accounts for mineral neoformation
- Accounts for leaching

\[ \Delta z \begin{align*} V_p & \text{ (or } V_w \text{)} \end{align*} \]
Mass Balance

Conservation of Mass

\[
\frac{V_p \rho_p C_{j,p}}{100} + m_{j,flux} = \frac{V_w \rho_w C_{j,w}}{100}
\]

- The volume, density and concentration of the parent material (+) or (-) what has been added or removed contributes to the volume, density, and concentration of that element in the soil.

- The units combine to give the mass of element j in grams. So…the mass of the element in the soil is a product of the new volume (original volume (+) or (-) what has been removed), BD, and concentration.
Mass Balance

Strain

- To observe strain based on the volume change due to weathering:

\[ \varepsilon_{i,w} = \frac{V_w - V_p}{V_p} = \frac{V_w}{V_p} - 1 \]

- This is strain or volume change determined by use of an immobile element like Ti or Zr due to weathering

- Don’t assume isovolumetric weathering (an initial volume may dilate or collapse during soil evolution)

  - So…the volume change relative to an immobile element determined by the density and concentration loss of a mobile element

\[ \varepsilon_{i,w} = \frac{\rho_p C_{i,p}}{\rho_w C_{i,w}} - 1 \]
Mass Balance

Strain

“a change in bulk density that is not compensated by an inversely proportional change in the concentration of the immobile element”
(Chadwick et al., 1990)

- Collapse- negative strain due to mineral dissolution and element mobility
- Dilation- positive strain due to elemental additions
Mass Balance

Mass Gains and Losses

- Open System Mass-Transport Function: Mass Fractions Relative to the mass of element in parent material

\[ \tau_{j,w} = \frac{100 m_{j,flux}}{V_p C_{j,p} \rho_p} = \frac{\rho_w C_{j,w}}{\rho_p C_{j,p}} (\varepsilon_{i,w} + 1) - 1 \]

- Density, concentration and volume change are considered

- -1.0 = 100% of mass of element originally in parent material was extracted during weathering.
- 0.00 = element has been immobile
Mass Balance Theory

Increasing Soil Age (Ky)

- Collapse & Gain
- Dilation & Gain
- Collapse & Loss
- Dilation & Loss

Loss/Gain (%)

Volume Change (%)

Averaged over the top 1 m

- % Na
- % Ca
- % Mg
- % O.C.
Mass Balance

Limitations

1. External sources are often unidentifiable
2. Determining accurate parent material is critical
   - In soils derived from sedimentary parent materials, the least weathered soil horizon is considered the parent material
3. Bulk density is difficult to determine for some textures (ie. gravelly)
Pedology: A Platform for Regional and Global Biogeochemical Studies

1) Why soils and pedology research matter.
   - Pedological Rules
   - Pedology and biogeochemistry (Amundson, 2004)

2) Regional Biogeochemical Research
   - C storage and variability in grassland systems
Soils reflect and at the same time affect the environment

- Soils of any region reflect climatological, geological, biological, and topographical conditions.

- Soil properties that regulate water, gas exchange and nutrient status and influence plant growth have important affects on the environment.
Pedological Rules

• There is a pressing need to identify the extent to which we can extrapolate beyond individual study sites and model systems.

• Pedological rules are “general principles that underpin and create patterns” within and among ecosystems and strengthen our ability to generalize biogeochemistry more broadly (regionally and globally).

• Our investigations should allow us to probe the limits of these rules and potentially identify key contingent factors that may alter their manifestation.
Elemental Distribution of Soil Versus the Earth’s Crust (Amundson, 2004)
Elemental Distribution of Vegetation Versus the Earth’s Crust (Amundson, 2004)
Scientific Approach

• Utilize environmental gradients to establish the range and variability in soil properties, processes and behavior that constrain regional and global biogeochemical models.

• State Factor Analyses (Jenny, 1941, 1980; Vitousek, 2004)

• Integrate geochemical, biochemical and mass balance approaches with traditional pedological measurements.
Carbon Storage and Variability in Grassland Systems

Environmental Gradients

- Toposequences (Aguilar et al, 1988; Kelly et al, 1988)

- Lithosequences (Aguilar et al, 1988)

- Climosequences (Honeycutt et al, 1987; Kelly, 1989)
summit
shoulder
backslope
footslope
toeslope

native
cultivated
Topographic Gradient

Summit    Shoulder    Backslope    Footslope

- nd sis
- nd ss
- nd shale
- chey wells
- goodland
- oberlin
- hockley

OC (g cm$^{-2}$ m$^{-1}$)
Parent Material Gradient
OC (g cm\(^{-2}\) m\(^{-1}\))

<table>
<thead>
<tr>
<th>OC (g cm(^{-2}) m(^{-1}))</th>
<th>0.0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
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<tbody>
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<td>sandstone</td>
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<td>siltstone</td>
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<td>shale</td>
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<td>60</td>
<td>60</td>
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</tr>
</tbody>
</table>
Topographic Gradient

Parent Material Gradient

Moisture Gradient

Summit  Shoulder  Backslope  Footslope
Climosequence
OC (g cm\(^{-2}\) m\(^{-1}\))

Mean Annual Precipitation (cm)

- 34.4 cm MAP
- 46.2 cm MAP
- 50.2 cm MAP
- 57.5 cm MAP
- 65 cm MAP
- 88.4 cm MAP
Pedological Rules

• Grassland ecosystems vary systematically in C storage as a function of landscape position, bioclimatic and Edaphic conditions.

• The relationship between conditioning variables and soil properties provide a potential avenue for extrapolating beyond site level and constraining regional studies.
Pedology & Biogeochemical Research

- Earth Sciences are now at the forefront of research addressing biogeochemical questions at regional and global scales.

- Identify pedological processes that operate consistently, or at least change predictability, across similar ecosystems within and between regions?

- There is a pressing need to identify those pedological processes that are predictive (quantifiable) rather than descriptive.

- Once established and tested the “Pedological Rules” can be utilized to help quantify the range and variability of biogeochemical responses to key drivers (climatic extremes and land use).