Soil Formation, Diversity, and Behavior

Objectives

To gain a general understanding of:

- The 5 soil forming factors and 4 soil forming processes
- Soil diversity
- Soil behavior
Soil = \( f(\text{PM}, \, \text{Cl}, \, \text{O}, \, \text{R}, \, \text{T}) \)

Factors:
PM = parent material (rocks)
Cl = climate (precipitation and temperature)
O = organisms (plants and animals)
R = relief (topography, drainage)
T = time
Stages of Volcanism

- Submarine alkalics
- tholeiite pillows
- shallow-water hyaloclastites

- Ocean floor
- Main tholeiite shield
- Post-shield alkalics

- Erosion, reef building
- Rejuvenation

- Atoll
- Seamount

Explanation:
- Rejuvenation
- Subsidence
- Coral
- Alkalics
- Subaerial flows
- Filled caldera
- Hyaloclastite
- Pillow lava
- Alkalics

Main shield
Volcanic Stages

- Coral: 0.01 - 1 M, 1.7 – 3 M
- Volcanic ash: 3 – 4 M
Geology of Tinian

Source: R.L. Carruth (2003), USGS, Report 03-4178
Oxisols developed on volcanic outcrops
Limestone rock
Volcanic rock
Limestone rock
Volcanic rock

Source: R.L. Carruth (2003), USGS, Report 03-4178
Soil Orders of Saipan

Map made by J. Deenik
Coarse \( \text{SiO}_2\)-rich

Fine Fe/Mg-rich

Source: Singer & Munns (1991)
Chemical composition of some common primary and secondary minerals.

<table>
<thead>
<tr>
<th>Light-colored minerals</th>
<th>Dark-colored minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz SiO₂</td>
<td>Biotite (black mica) K(Mg,Fe)₂AlSi₃O₁₀(OH)₂</td>
</tr>
<tr>
<td>Orthoclase feldspar KAlSi₃O₈</td>
<td>Olivine (Mg,Fe)₂SiO₄</td>
</tr>
<tr>
<td>Anorthoclase feldspar (K,Na)AlSi₃O₈</td>
<td>Hypersthene (Mg,Fe)SiO₃</td>
</tr>
<tr>
<td>Plagioclase feldspar</td>
<td>Pyroxene</td>
</tr>
<tr>
<td>Albite NaAlSi₃O₈</td>
<td>Pigeonite (Mg,Fe)SiO₃</td>
</tr>
<tr>
<td>Anorthite CaAl₂Si₂O₆</td>
<td>Augite Ca(Mg,Fe)Si₂O₆·(Al,Fe)₂O₄</td>
</tr>
<tr>
<td>Nepheline NaAlSiO₄</td>
<td></td>
</tr>
<tr>
<td>Calcite CaCO₃</td>
<td>Magnetite Fe₃O₄</td>
</tr>
<tr>
<td>Gypsum CaSO₄·2H₂O</td>
<td>Hematite Fe₂O₃</td>
</tr>
<tr>
<td>Kaolinite (clay) Al₂Si₂O₅(OH)₄</td>
<td>Ilmenite FeO·TiO₂</td>
</tr>
<tr>
<td>Gibbsite Al(OH)₃</td>
<td>Melilite Ca(Mg,Fe)₂Si₂O₇</td>
</tr>
<tr>
<td>Montmorillonite (Al,Mg)₆Si₄O₁₀·5(OH)₆·12H₂O</td>
<td>Chlorite (Mg,Fe)₆(Al,Fe)₂Si₂O₆(OH)₆</td>
</tr>
<tr>
<td></td>
<td>Limonite Fe₂O₃·nH₂O</td>
</tr>
</tbody>
</table>

Source: Zumberge & Rotford (1983), p.21
Weathering

- **Physical**: disintegration of parent material into smaller and smaller particles (no chemical change)

- **Chemical**: primary minerals in parent material subject to a variety of chemical reactions (hydration, hydrolysis, dissolution, acid reactions, complexation) forming secondary clay minerals (phyllosilicates, Al/Fe oxides)
Goldich Stability Series

Most susceptible to weathering

- Olivine
- Pyroxene
- Amphibole
- Biotite
- Na-rich plagioclase
- K-feldspar
- Muscovite
- Quartz

Least susceptible to weathering

- Ca-rich plagioclase

Least stable
-formed at high temperatures

Most stable
-formed at low temperatures
Rain picks up CO₂ from the atmosphere

Water percolating through the soil picks up more CO₂ from the upper part of the soil profile becoming acidic

A feldspar crystal, loosened from the rock below, slowly alters to clay as it reacts with the acidic water

Water carries away soluble salts and SiO₂ to a stream

\[
\text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{H}_2\text{CO}_3
\]

\[
2\text{KAlSi}_3\text{O}_8 + 2\text{H}^+ + \text{H}_2\text{O} \rightarrow \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 2\text{K}^+ + 4\text{SiO}_2
\]

Feldspar

Kaolinite
Weathering Reactions of Pyroxenes

$$\text{Ca(Mg,Fe)Si}_2\text{O}_6 + \text{H}_2\text{O} + \text{H}^+ = \text{Ca-montmorillonite} + \text{H}_4\text{SiO}_4 + \text{Ca}^{2+} + \text{Fe(OH)}_3$$

$$\left(\frac{1}{2}\text{Ca,Na}\right)(\text{Al,Mg,Fe})_4(\text{Si,Al})_8\text{O}_{20}(\text{OH})_4 \ n\text{H}_2\text{O}$$

Step 1: 3 KAlSi$_3$O$_8$ + 2 H$^+$ + 12 H$_2$O --> KAl$_3$Si$_3$O$_{10}$(OH)$_2$ + 6 H$_4$SiO$_4$ + 2 K$^+$
orthoclase
illite(~muscovite)

Step 2: 2 KAl$_3$Si$_3$O$_{10}$(OH)$_2$ + 2 H$^+$ + 3 H$_2$O --> 3 Al$_2$Si$_2$O$_5$(OH)$_4$ + 2 K$^+$
illite
kaolinite
Weathering Sequence of Basalt Parent Rock

\[
\text{CaAl}_2\text{Si}_2\text{O}_8 + 2\text{H}_2\text{O} + 4\text{H}^+ \rightarrow \text{Ca}^{2+} + 2\text{Al}^{3+} + 2\text{Si(OH)}_4
\]

*Ca- plagioclase*  *Soluble silica*

**Hydrolysis Reaction**

\[
\text{Al}^{3+} + \text{Si(OH)}_4 + \frac{1}{2}\text{H}_2\text{O} \rightarrow \text{H}^+ + \frac{1}{2}\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4
\]

*Kaolinite*

**Synthesis Reaction**

\[
\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 5\text{H}_2\text{O} \rightarrow 2\text{Si(OH)}_4 + 2\text{Al(OH)}_3
\]

*Kaolinite*  *Soluble silica*  *Gibbsite*

**Desilication**
<table>
<thead>
<tr>
<th>Relative Degree of Soil Development</th>
<th>Prominent Minerals in Soil Clay Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gypsum, sulfides, and soluble salts</td>
</tr>
<tr>
<td>2</td>
<td>Calcite, dolomite, and apatite</td>
</tr>
<tr>
<td>3</td>
<td>Olivine, amphiboles, and pyroxenes</td>
</tr>
<tr>
<td>4</td>
<td>Micas and chlorite</td>
</tr>
<tr>
<td>5</td>
<td>Feldspars</td>
</tr>
<tr>
<td>6</td>
<td>Quartz</td>
</tr>
<tr>
<td>7</td>
<td>Muscovite</td>
</tr>
<tr>
<td>8</td>
<td>Vermiculite and hydrous micas</td>
</tr>
<tr>
<td>9</td>
<td>Montmorillonites</td>
</tr>
<tr>
<td>10</td>
<td>Kaolinite and halloysite</td>
</tr>
<tr>
<td>11</td>
<td>Gibbsite and allophane</td>
</tr>
<tr>
<td>12</td>
<td>Goethite, limonite, and hematite</td>
</tr>
<tr>
<td>13</td>
<td>Titanium oxides, zircon, and corundum.</td>
</tr>
</tbody>
</table>

*Adapted from M. L. Jackson and G. D. Sherman. *Advances in Agronomy.*
Climate and Soil Diversity

Precipitation

Wet = high weathering, acid & infertile
*Haiku* series

Dry = less weathering, fertile
*Keahua* series

Photos: J. Deenik
25 – 30” Precipitation
**Waimea series**
- nutrient rich
- neutral pH
- high organic matter

120 “ Precipitation
**Honokaa series**
- nutrient depleted
- acid pH
- high organic matter

Projection: NAD 1983, UTM Zone 5N
Source: Natural Resources Conservation Service
The impact of climate on the biogeochemical functioning of volcanic soils


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Abstract

Rainfall and the amount of water available to leach ions from soil are among the most important features determining mineral weathering, secondary mineral synthesis and soil chemical properties. Along an arid to humid climosequence on Kohala Mountain, Hawaii, we sampled 16 soil profiles and found that weathering and soil properties change in a nonlinear fashion with increased rainfall. The lavas are influenced by a strong rain shadow with mean annual precipitation (MAP) averaging 160 mm near the coast and rising to &gt;3000 mm near the summit. A temperature decline from 24 to 15 °C with increasing elevation is matched by lower potential evapotranspiration (ET). A water balance model (monthly precipitation minus monthly ET) defines three broad climate zones along the sampling transect: an arid zone with moisture deficit in every month, an intermediate zone with moisture deficit during low-rainfall summer months and moisture surplus during high-rainfall winter months, and a humid zone with moisture surplus during every month. The annualized water balance can be related to the integrated porosity of the top meter of soil to provide a leaching index.

The index reaches 1 (total filling of the pore space on an annual basis) at about 1400 mm MAP. Index values ≥1 imply intense leaching conditions because of pore water replacement. In these 170 ka soils, leaching losses of soluble base cations and Si are nearly complete at index values ≥1, whereas only 60% of Al has been lost. At index values &lt;1 leaching losses are progressively lower with the lowest rainfall sites having lost 10–20% of the original base cations and Si and none of the Al. At all sites, the secondary clay mineral assemblage is dominated by metastable non-crystalline weathering products; humid soil profiles contain very few crystalline minerals whereas the arid profiles contain halloysite, hematite, gibbsite and small amounts of carbonates. Soil surface exchange properties are influenced strongly by climate conditions and show a dramatic threshold in base cation saturation, pH and effective cation exchange capacity (ECEC) at leaching index of 1 (1400 mm MAP). Soils with leaching index of &lt;1 have high base cation saturation, near-neutral pH and high ECEC. At MAP &gt;1400 mm, soil buffering capacity has been totally exhausted leading to low pH and low ECEC.

The nonlinear decline in ECEC is irreversible under natural conditions; base cation depleted soils will remain so even if the climate shifts to drier conditions. In contrast, a climate shift to wetter conditions can drastically modify surface chemical
Soil Forming Processes

- ADDITIONS
  - Precipitation (including ions and solid particles);
  - organic matter

Ground surface

- Soil
- TRANSFORMATIONS
  - Organic matter → humus
  - Primary minerals
    - hydrous oxides
    - clays
    - ions, $\text{H}_4\text{SiO}_4$

- TRANSFERS
  - Humus compounds, clays, ions, $\text{H}_4\text{SiO}_4$

- TRANSFERS
  - Ions, $\text{H}_4\text{SiO}_4$

- LOSSES
  - Ions, $\text{H}_4\text{SiO}_4$
Human Activities

Terra Preta soil
enhanced soil quality

Cultivated Andisol
degraded soil quality

http://replantingtherainforests.org/site/images/stories/tp1.jpg
Weathering Intensity and Soil Fertility

Fox et al. (1991)
Lualualei soil series

*Fine, smectitic, Isohyperthermic, Typic, Gypsitorrerts*

- slightly alkaline pH
- high CEC
- rich in plant nutrients
- shrink swell clays

[Image of montmorillonite](webmineral.com/specimens/photos/Smectite.jpg)
Weathering Intensity and Soil Fertility

Fox et al. (1991)
Haiku soil series

*Fine, ferritic,*  
*Isohyperthermic,*  
*Ustic, Palehumults*

- acid pH, Al toxicity  
- low CEC  
- rich in organic matter  
- low in plant nutrients

*kaolinite*
Weathering Intensity and Soil Fertility

Fox et al. (1991)
Kapaa soil series

Very fine, sequic, iso-Hyperthermic, anionic, acrudox

- acid pH
- very low CEC
- low nutrient reserves
Weathering Intensity and Soil Fertility

Fox et al. (1991)