This course introduces the principles of sedimentology and stratigraphy. Topics will be covered are: origin and transport of sedimentary materials, physical properties of sedimentary rocks, composition, classification, and diagenesis of sedimentary rocks, depositional environments, and principles of stratigraphy and basin analysis. This course includes a two-day field training in SW Taiwan.

Course Outline

Part I: Origin and Transport of Sedimentary Materials
1. Weathering and soils
2. Transport and deposition of siliciclastic sediments

Part II: Physical Properties of Sedimentary Rocks
3. Sedimentary textures
4. Sedimentary structures

Part III: Composition, Classification, and Diagenesis of Sedimentary Rocks
5. Siliciclastic sedimentary rocks
6. Carbonate sedimentary rocks
7. Other chemical/biochemical and carbonaceous sedimentary rocks
Part IV: Depositional Environments
8. Continental (terrestrial) environments
9. Marginal-marine environments
10. Siliciclastic marine environments
11. Carbonate and evaporite environments

Part V: Stratigraphy and Basin Analysis
12. Lithostratigraphy
13. Sequence and magnetic stratigraphy
14. Biostratigraphy
15. Chronostratigraphy and geologic time
16. Basin Analysis, Tectonics, and Sedimentation

Textbook

Course Schedule
Class: 19 September ~ 7 November 2013; Midterm exam: 14 November 2013
Class: 21 November 2013 ~ 9 January 2014; Final exam: 16 January 2014
Field trip: 14 ~15 December 2013 (Southwest Taiwan, 曾文溪、七股潟湖)
Grading: Midterm exam 35%; Final exam 35%; Field trip 20%; Assignments 10%
Chapter 1. Weathering and Soils

Indus River, Pakistan

Bryce Canyon, Utah

Mechanical Chemical
How sediments are made and landscapes formed

Photos from Dr. Alan Jay Kaufman at http://www.geol.umd.edu/~kaufman/kaufman.html
1.1 Introduction

Weathering

Rocks are broken down by physical, chemical and biological processes. The remaining solid material and dissolved chemicals are called weathering.

Regolith

The loose layer of broken rock and mineral fragments on the surface.

Erosion

Transport of regolith and the wearing down of bedrock.

Photo from Dr. Alan Jay Kaufman at http://www.geol.umd.edu/~kaufman/kaufman.html
The Rock Cycle

- **Magma**
  - Intrusion & Volcanism
  - Melting

- **Igneous Rocks**
  - Tectonic Uplift

- **Metamorphic Rocks**
  - Metamorphism

- **Sedimentary Rocks**
  - Weathering
  - Erosion & Deposition
  - Sediments
  - Burial & Cementation

- **Continental Crust**

Figure from Dr. Alan Jay Kaufman at http://www.geol.umd.edu/~ekaufman/kaufman.html
1.2 Subaerial weathering processes

1.2.1 Physical Weathering

The physical breaking of rocks into small particles

- Freeze-thaw (frost) weathering (ice wedging)
- Isolation (thermal) weathering
- Salt weathering
- Wetting and drying
- Stress-release weathering

Most mechanical weathering exploits JOINTS, pre-existing fractures in the rock

Photos from Dr. Alan Jay Kaufman at http://www.geol.umd.edu/%7Ekaufman/kaufman.html
Freeze-thaw cycles: Ice wedging
The physical breaking of rocks into small particles

Water creeps into cracks during warm weather; it then expands as it freezes (about 9%)

This puts great pressure on the rocks

Ice wedging is important:
• Arctic climates
• Temperate climates
• High altitudes (mountains)

Fig. 1.1 Large, angular blocks of rock generated by freeze-thaw weathering of thin-bedded sandstones and mudstones of the Canning formation (Paleocene) exposed along the Canning River, Arctic National Wildlife Refuge, Alaska.
Release of overburden pressure

Large, thin sheets of rock that fall off bedrock

Upward rebound of the rocks creates tensile stresses, causing fractures to develop that are oriented nearly parallel to the topographic surface.

Photos from Dr. Alan Jay Kaufman at http://www.geol.umd.edu/%7Ekaufman/kaufman.html
Spheroidal weathering is smaller-scale weathering of roughly massive rock masses, cut by intersecting joints, causing layers or “skins” to spall off to produce spheroidal cores.

Fig. 1.2 Spheroidal weathering in granite. Note low successive, thin layers of weathered rock are spalled off to produce a spheroidal core.

Weathering exploits joint surfaces: Example from Penghu basalts
1.2.2 Chemical Weathering

Chemical weathering alters both the chemical and mineralogical composition of rocks.

A. Simple solution (congruent dissolution)
B. Hydrolysis (水解)
C. Oxidation (氧化)
D. Others: Hydration (水合), Ion exchange (離子交換), Chelation
Chemical Weathering: Climate

Climate affects chemical weathering strongly

- More water
- More vegetation
- More soils
- Hotter Temperatures

Happens in any oxygenated environment (air, most water)

Taiwan 平均降雨量為 250 cm/yr
Chemical weathering products vs. climate

Allen (1997) p.110

Fig. 3.9 Latitudinal zonation of regolith thickness and type. Modified from Strakhov (1967) [10].
### Table. 1.1 Principal processes of chemical weathering

<table>
<thead>
<tr>
<th>Most important processes</th>
<th>Examples</th>
<th>Principal kinds of rock materials affected</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Simple (congruent) Solution</strong>—Dissolution of soluble minerals in H₂O (direct solution) or in H₂O + CO₂ (carbonation) to yield cations and anions in solution</td>
<td>SiO₂ + 2H₂O → H₂SiO₄ (direct solution) (quartz) (silicic acid) aq</td>
<td>Highly soluble minerals (e.g., gypsum, halite), quartz</td>
</tr>
<tr>
<td></td>
<td>CaCO₃ + H₂O + CO₂ ↔ Ca²⁺ + 2HCO₃⁻ (Carbonation) (calcite) aq</td>
<td>Carbonate rocks</td>
</tr>
<tr>
<td><strong>Hydrolysis (incongruent dissolution)</strong>—Reaction between H⁺ and OH⁻ ions of water and the ions of silicate minerals, yielding soluble cations, silicic acid, and clay minerals (if Al present)</td>
<td>2KAlSi₃O₈ + 2H⁺ + 9H₂O → H₂Al₂Si₂O₉ + 4H₂SiO₄ + 2K⁺ (orthoclase) aq (kaolinite) (silicic acid) aq</td>
<td>Silicate minerals</td>
</tr>
<tr>
<td></td>
<td>2NaAlSi₃O₈ + 2H⁺ + 9H₂O → H₄Al₂Si₂O₉ + 4H₂SiO₄ + 2Na⁺ (albite) aq (kaolinite) (silicic acid) aq</td>
<td></td>
</tr>
<tr>
<td><strong>Oxidation</strong>—Loss of an electron from an element (commonly Fe or Mn) in a mineral, resulting in the formation of oxides or hydroxides (if water present)</td>
<td>2FeS₂ + 15/2O₂ + 4H₂O → Fe₂O₃ + 4SO₄²⁻ + 8H⁺ (pyrite) (hematite) aq aq</td>
<td>Iron- and manganese-bearing silicate minerals, iron sulfides</td>
</tr>
<tr>
<td></td>
<td>MnSiO₃ + 1/2O₂ + 2H₂O → MnO₂ + H₄SiO₄ (rhodonite) (pyrolusite) (silicic acid)</td>
<td></td>
</tr>
<tr>
<td><strong>Other Processes</strong></td>
<td><strong>Hydration and Dehydration</strong>—Gain (hydration) or loss (dehydration) of water molecules from a mineral, resulting in formation of a new mineral</td>
<td>Fe₂O₃ + H₂O ↔ 2FeOOH (hydration) (hematite) (goethite)</td>
</tr>
<tr>
<td></td>
<td>CaSO₄ · 2H₂O ↔ CaSO₄ + 2H₂O (dehydration) (gypsum) (anhydrite)</td>
<td>Evaporites</td>
</tr>
<tr>
<td></td>
<td><strong>Ion Exchange</strong>—Exchange of ions, principally cations, between solutions and minerals</td>
<td>K-clay + Mg²⁺ ↔ Mg-clay + K⁺</td>
</tr>
<tr>
<td></td>
<td>Ca-zeolite + Na⁺ ↔ Na-zeolite + Ca²⁺</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Chelation</strong>—Bonding of metal ions to organic molecules having ring structures</td>
<td>Metal ions (cations) + chelating agent (e.g., secreted by lichens) → H⁺ ions + chelate (metal ions/organic molecules in solution)</td>
</tr>
</tbody>
</table>
B. Hydrolisis

水解作用指由氫(H+)或氫氧根(OH-)離子取代原來礦物的其他元素(如K+, Na+, Ca^{2+}, Mg^{2+})，而形成新的礦物。水解作用有CO₂加入，則稱為碳酸化作用(Carbonation)。

NEEDS WATER TO OCCUR!

CO₂和水作用產生H⁺與HCO₃⁻形成弱酸性

\[ 2\text{KAlSi}_3\text{O}_8 \text{(orthoclase)} + 2\text{H}^+ + 9\text{H}_2\text{O} \rightarrow \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \text{(kaolinite)} + 4\text{H}_4\text{SiO}_4(\text{aq}) + 2\text{K}^+ \]

Weak acids strip cations out of minerals

This is the main process of:
  • weathering silicates
  • making clays

Figure from Dr. Alan Jay Kaufman at http://www.geol.umd.edu/~kaufman/kaufman.html
石灰岩的化学风化作用主要是碳酸化作用 (Carbonation)

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

若 CO₂ 多则反应向右，石灰岩溶解，形成卡斯特 (karst) 地形与钟乳石洞或渗穴 (sinkhole)；若 CO₂ 少反应向左，碳酸钙沉澱，形成钟乳石。在乾燥气候下，碳酸鈣於土壤中沉澱，形成鈣質結礫岩 (calcrete)。
C. Oxidation

Loss of an electron from an element (commonly Fe or Mn) in a mineral, resulting in the formation of oxides or, if water is present, hydroxides.

\[
4\text{FeSiO}_3 + O_2 \rightarrow 2\text{Fe}_2\text{O}_3 + 4\text{SiO}_2
\]

pyroxene \hspace{1cm} hematite

\[
\text{Fe}^{2+} \rightarrow \text{Fe}^{3+} + e^-
\]

Photos from Dr. Alan Jay Kaufman at http://www.geol.umd.edu/~kaufman/kaufman.html
D. Other chemical weathering processes: Hydration

某些礦物可將水分子(H₂O)納入其結晶格內，如此結晶內的孔隙加大，使此水化合物更容易受風化。另外，礦物體積膨脹之後，岩石的內部壓力加大，可以導致岩石破碎。

2Fe₂O₃ + 3H₂O → 2Fe₂O₃·3H₂O

Hematite  Limonite

赤鐵礦  褐鐵礦

Photo from Dr. Alan Jay Kaufman at http://www.geol.umd.edu/~kaufman/kaufman.html
Products of oxidation

氧化物(Oxides)與氫氧化物(hydroxides)合稱為三氧化鋁鐵(sesquioxides)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Si的氧化物</td>
<td>石英、非晶質矽石(amorphous silica)、蛋白石質矽石(opaline silica)</td>
</tr>
<tr>
<td>Al的氫氧化物</td>
<td>Gibbsite(三水鋁石Al(OH)3, boehmite(軟水鋁石γAl(OH)3)</td>
</tr>
<tr>
<td></td>
<td>一水硬鋁石(diaspore, αAlO(OH))</td>
</tr>
<tr>
<td>Fe的氧化物與氫氧化物</td>
<td>Hematite (赤鐵礦Fe₂O₃), Magnetite (磁鐵礦,Fe₃O₄), goethite(針鐵礦αFe(OH))</td>
</tr>
<tr>
<td>Ti的氧化物</td>
<td>Anatase (銳鈦礦,TiO₂)</td>
</tr>
</tbody>
</table>

**Bauxite** (鋁土礦), the principal ore of aluminum, is a rock mixture consisting mostly of several hydrous aluminum oxide minerals, including boehmite, diaspore, gibbsite, and impurities such as QUARTZ, CLAY MINERALS, and iron hydroxides.

**Example** five Al-minerals that weather to form bauxite: kaolinite, muscovite, biotite, hornblende, feldspar.
Chemical Weathering: Clay Minerals

Generated strictly as a weather product by many types of chemical weathering

\[ \text{KAlSi}_3\text{O}_8 + 2\text{H}^+ + 12\text{H}_2\text{O} \rightleftharpoons \text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2 + 2\text{K}^+ + 6\text{H}_4\text{SiO}_4 \]

\text{K-spar} \quad \text{Muscovite Clay} \\
\text{Hydrolysis + Hydration}

\[ 2\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2 + 2\text{H}^+ + 3\text{H}_2\text{O} \rightleftharpoons 3\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 2\text{K}^+ \]

\text{Muscovite Clay} \quad \text{Kaolinite Clay} \\
\text{Hydrolysis + Hydration}

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

\text{Kaolinite Clay} \quad \text{Gibbsite Clay} \\
\text{Hydrolysis + Hydration}
黏土礦物基本上是含氫氧根(OH-)或水(H₂O)之鋁矽酸鹽，其中有些礦物會有Mg, Fe取代Al的現象。屬葉狀矽酸鹽(phyllosilicates)。

<table>
<thead>
<tr>
<th>礦物群</th>
<th>化學成分</th>
<th>主要礦物</th>
<th>四面體 (tetrahedral)層：八面體 (octahedral)層</th>
<th>附註</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kandite group</td>
<td>含水、鋁硼酸鹽 hydrous aluminium silicate</td>
<td>Kaolinite(高嶺石 Al₂Si₂O₅(OH)₄), halloysite (禾樂石 Al₂Si₂O₅(OH)₄.nH₂O)</td>
<td>1:1</td>
<td></td>
</tr>
<tr>
<td>Illite group</td>
<td>含水、鉀硼酸鹽</td>
<td>Illite(伊萊石 (K,H₂O)(Al, Mg,Fe)₂(Si,Al)₄O₁₀(OH)₂.H₂O)</td>
<td>2:1</td>
<td>illite最常見的黏土礦物</td>
</tr>
<tr>
<td>Smectite group</td>
<td>複合、含水、鎂鋁硼酸鹽</td>
<td>Montmorillonite(蒙脫石,大約化學式 (Al, Fe, Mg, Zn, Ca, Na)₄(Si₄O₁₀)₂(OH)₄.nH₂O); vermiculite(蛭石, Mg₃(Si, Al)₄(OH)₂.4.5H₂O[Mg]₀.₃₅)</td>
<td>2:1</td>
<td>Expandable clay</td>
</tr>
<tr>
<td>Chlorite group</td>
<td>Hydrous silicate of Al, Fe and Mg</td>
<td>Chlorite (綠泥石, (Mg,Fe)₃(Si,Al)₄O₁₀.₃(Mg,Fe)₃(OH)₆)</td>
<td>2:2</td>
<td>主要是非風化產物，常見於變質岩(如綠色片岩)與火成岩(Mg-Fe矽酸鹽的換質產物)</td>
</tr>
<tr>
<td>Mixed-layer group</td>
<td>混成黏土</td>
<td>Illite-montmorillonite mixed-layers</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
note: gibbsite layer: 由Al-O/H組成的八面體層片稱之，因gibbsite(水鋁石)的化學是為Al(OH)₃
Brucite layer: 由Mg-O/H組成的八面體層片稱之，因brucite(水鎂石)化學式為Mg(OH)₂
上圖Chlorite部分，x成一行表示brucite layer故為2:2
上圖層間的陽離子，很容易於風化或成岩過程中被leached out of the clay mineral by percolating waters.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kandite</td>
<td>Al₂O₃·2SiO₂·2H₂O</td>
<td>Silicate sheet</td>
</tr>
<tr>
<td>Alumina (gibbsite)</td>
<td>KAl₃(OH)s·[Al₂Si₃O₁₀(OH)]</td>
<td>Substitution of Si by Al in silica layer</td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>2Al₂O₃·8SiO₂·2H₂O.nH₂O</td>
<td>Basal spacing 7Å</td>
</tr>
<tr>
<td>Illite</td>
<td>Mg₃Al₂(Si₃Al)O₁₀(OH)₂</td>
<td>Basal spacing 10 Å</td>
</tr>
<tr>
<td>Smectite</td>
<td>2Mg₃(AlFe)(OH)₉(OH)₂</td>
<td>Much substitution of Al by Mg and Fe</td>
</tr>
<tr>
<td>Chlorite</td>
<td>Mg₃(AlFe)(OH)₉(OH)₂</td>
<td>Basal spacing 14Å but expandable from 9.6 to 21.4Å</td>
</tr>
</tbody>
</table>

Tucker (2001) p.98
XRD diffractograms of shale samples (bulk rock Chinshui Shale) from TCDP-A borehole, Taichung
國立中央大學地球科學系盆地研究室設備

http://basin.earth.ncu.edu.tw/XRD/sediment%20analysis%20lab.htm

掃描式電子顯微鏡(SEM)
X光瑩光分析儀(WD-XRF)
X光繞射儀(XRD)
雷射粒徑分析儀(Grain size analyzer)
偏光顯微鏡(Microscope)
薄片備製相關設備(Thin section preparation)
岩心攝像儀
其他相關設備(Miscellaneous)
### Effects of Chemical Weathering on Basalt and Granite

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Solid weathering products</th>
<th>Soluble ions in solution</th>
<th>Neutral species in solution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basalt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feldspar</td>
<td>Clay minerals</td>
<td>Na&lt;sup&gt;+&lt;/sup&gt; and Ca&lt;sup&gt;2+&lt;/sup&gt;</td>
<td>Silica</td>
</tr>
<tr>
<td>Fe&lt;sup&gt;2+&lt;/sup&gt; mineral</td>
<td>Clay minerals and goethite</td>
<td>Mg&lt;sup&gt;2+&lt;/sup&gt;</td>
<td>Silica</td>
</tr>
<tr>
<td>Magnetite</td>
<td>Goethite</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Granite</strong></td>
<td></td>
<td>Na&lt;sup&gt;+&lt;/sup&gt; and K&lt;sup&gt;+&lt;/sup&gt;</td>
<td>Silica</td>
</tr>
<tr>
<td>Feldspar</td>
<td>Clay minerals</td>
<td>K&lt;sup&gt;+&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Mica</td>
<td>Clay minerals</td>
<td>Mg&lt;sup&gt;2+&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Fe&lt;sup&gt;2+&lt;/sup&gt; mineral</td>
<td>Clay minerals and goethite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>Quartz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1.2.3 Weathering Rate

Goldich’s weathering series vs. Bowen’s reduction series:

<table>
<thead>
<tr>
<th>Sand- and silt-size minerals*</th>
<th>Clay-size minerals**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mafic minerals</td>
<td></td>
</tr>
<tr>
<td>Olivine</td>
<td>Ca plagioclase</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>Ca-Na plagioclase</td>
</tr>
<tr>
<td>Amphibole</td>
<td>Na-Ca plagioclase</td>
</tr>
<tr>
<td>Biotite</td>
<td>Na plagioclase</td>
</tr>
<tr>
<td>(Increasing stability)</td>
<td>K-feldspar, muscovite, quartz</td>
</tr>
<tr>
<td>Stable</td>
<td></td>
</tr>
<tr>
<td>Unstable</td>
<td></td>
</tr>
</tbody>
</table>

Source: *Goldich (1938), **Jackson (1968).
### 1.2.4 Products of subaerial weathering

*Table. 1.3* Principal kinds of products formed by subaerial weathering processes and the types of sedimentary rocks ultimately formed from these products.

<table>
<thead>
<tr>
<th>Weathering process</th>
<th>Type of weathering product</th>
<th>Example</th>
<th>Ultimate depositional product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical weathering</td>
<td>Particulate residues</td>
<td>Silicate minerals such as quartz and feldspar; all types of rock fragments</td>
<td>Sandstones, conglomerates, mudrocks</td>
</tr>
<tr>
<td>Chemical weathering</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrolysis</td>
<td>Soluble constituents</td>
<td>Silicic acid ($\text{H}_4\text{SiO}_4$); K$^+$, Na$^+$, Mg$^{2+}$, Ca$^{2+}$, etc.</td>
<td>Cherts, limestones, etc.</td>
</tr>
<tr>
<td></td>
<td>Secondary minerals</td>
<td>Clay minerals</td>
<td>Mudrocks (shales)</td>
</tr>
<tr>
<td>Simple solution</td>
<td>Soluble constituents</td>
<td>Silicic acid; K$^+$, Na$^+$, Mg$^{2+}$, Ca$^{2+}$, HCO$_3^-$, SO$_4^{2-}$, etc.</td>
<td>Limestones, evaporites, chert, etc.</td>
</tr>
<tr>
<td>Oxidation</td>
<td>Secondary minerals</td>
<td>Ferric oxides (Fe$_2$OOH); manganese oxides (MnO$_2$)</td>
<td>Minor constituent in siliciclastic rocks</td>
</tr>
<tr>
<td></td>
<td>Soluble constituents</td>
<td>Silicic acid; SO$_4^{2-}$</td>
<td>Chert, evaporites, etc.</td>
</tr>
</tbody>
</table>
Products of weathering:
A. siliciclastic sedimentary rocks

矽質沉積岩占75%的地球表面沉積物。

風化作用造成的固態物質，經常以石英為主，稱為矽質顆粒(siliciclastic grains)，由這些顆粒造成的沉積岩稱為矽質沉積岩。矽質沉積岩包括礫岩、砂岩、頁岩等。

Note: 這些風化而來的固態物質也經常來自陸地，所以他們也稱為陸源顆粒(terrigenous grains)。
Weathering products

Gravel- or sand-sized products: e.g., conglomerates and sandstones

Clay-sized products: Mudstone or shale
**Products of weathering:**

**B. Chemical/biochemical sedimentary rocks**

化學/生物化學沉積岩占25%的地球表面沉積物。

風化作用造成的溶解物（如Ca, Mg, Si）到達湖或海時，因化學或生物化學作用，將這些溶解物轉化成固態，形成沉積物。如石灰岩(limestone)、燧石(chert)、蒸發岩(evaporite)等。

Limestone (半屏山石灰岩)  

鄧屬予(1997)
1.3 Submarine weathering processes and products

1. Interaction of seawater with hot oceanic rocks along mid-ocean ridge; Magnesium, sulfate, and sodium ions are removed from seawater, whereas elements such as iron, manganese, silicon, potassium, lithium, and strontium are enriched in the seawater. Products at oceanic hot springs: sulfide (pyrite, FeS2, chalcopyrite, CuFeS2), sulfate and oxides.

2. Low-temperature (<20°C) alteration of volcanic rocks and sediments on the ocean floor. Products: smectite clay mineral, zeolite, chlorite.

Submarine weathering process is important for changes in composition of seawater owing to ion exchange during the reaction of seawater with basalts.
1.4 Soils

1.4.1 Soil-forming processes

1. **Additions to the ground surface** - precipitation of dissolved ions in rainwater; influx of solid particles such as windblown dust; addition of organic matter from surface vegetation.

2. **Transformations**
   a. Decomposition of organic matter within soils to produce organic compounds.
   b. Weathering of primary minerals; formation of secondary minerals, including iron oxides.

3. **Transfers**
   a. Movement of solids or suspended material downward from one soil horizon to a lower horizon by groundwater percolation (eluviation).
   b. Accumulation of soluble or suspended material in a lower horizon (illuviation).
   c. Transfer of ions upward by capillary movement of water and precipitation of ions in the soil profile.

4. **Removals**: removal of substances still in solution to become part of the dissolved constituents in groundwater or surface water.

5. **Bioturbation of soil** - soil disruption by animals and plants.
Soils

Important soil-forming processes

Figure 1.17. Common soil-forming regimes (from Retallack, 1990a, Soils of the past, fig. 4.12, with permission of Chapman & Hall)
Gleization (潛水灰化作用)
在缺(低)氧的泡水土壤中(waterlogged soil)，使Fe$^{3+}$還原成Fe$^{2+}$，形成藍灰色或綠灰色土壤的作用。

Colour photo 100. Gleyed Inceptisol. The massive claystone below the bedded siltstones is a paleosol with abundant siderite and the blue-grey to purple-grey colour that is characteristic of waterlogged soils. Such colours and minerals of reducing chemical conditions are called gley features. Stagnant water in the profile has allowed preservation of much organic matter, including recognizable root traces and faecal pellets. However, it was not always waterlogged, as can be seen from deeply penetrating root traces, burrows like those of earthworms (see Colour photo 19), and profile differentiation into a light-coloured surface over a purple and clayey subsurface horizon. This horizon differentiation has not completely obscured relict bedding, so the paleosol was an Inceptisol, and in view of its gleyed nature, an Aquert. This is the Turimetta clay eroded phase paleosol in the Early Triassic, Garie Formation, south of Bilgola Beach, New South Wales, Australia (Retallack, 1976, 1977). Hammer handle for scale is 25 cm long.

Retallack (1997)
Gleyed inceptisol
圖為東坑層(苗栗明德水庫)的煤炭層(Coal)及Histosol地層的圖片。
Podzolization (灰化作用)

酸性淋溶作用(leaching)，使表層的Al、Fe、有機質往下傳輸。本作用造成表層殘留石英，底層則聚集三氧化鋁鐵(sesquioxides)或有機質。

Lessivage (澱積作用)

將黏土由表層(A層)往下搬運至B層的裂隙澱積。本作用造成B層含較多的黏土，且顏色較表層為淺。

Calcification (鈣化作用)

在半乾燥到亞潮濕(subhumic)的氣候區內，碳酸鈣形成結核、聚集成帶，造成calcrete。
Ferrallitization (or laterization 紅鋁鐵礦化)

強烈與深部風化，造成厚層、成分均勻的土壤剖面。土壤富含黏土與三氧化鋁鐵。

Near the front entrance of National Central University

Figure from Dr. Alan Jay Kaufman at http://www.geol.umd.edu/~kaufman/kaufman.html
1.4.2 Soil profiles and soil classification

林口台地紅土剖面
Soil Profile

0 horizon: 有機質層 (e.g. coal)
A horizon: 表土層 (屬洗出層)
B horizon: 底土層 (屬洗入層)
C horizon: 被岩層

Soil horizons

O horizon: 有機質層 (e.g. coal)
A horizon: 表土層 (屬洗出層)
B horizon: 底土層 (屬洗入層)
C horizon: 被岩層

Topsoil

Soil leached of soluble minerals; rich in clay and insoluble minerals and organic matter

Little organic matter; dissolved minerals from A horizon precipitated

Bedrock cracked and weathered

Organic processes

Hydrolisis and Oxidation

Hydrolisis
New Minerals

Mechanical weathering

Figure from Dr. Alan Jay Kaufman at http://www.geol.umd.edu/~kaufman/kaufman.html
1.4.3 Paleosols

**Fig. 1.7** Red paleosols exposed below bedded sandstones in the Middle Miocene, Chinji Formation, Siwalik Group, in a creek bed 3 km south of Khaur, Potwar Plateau, Pakistan. The hammer is 25cm long.
### 1.4.4 Recognition of paleosols

<table>
<thead>
<tr>
<th>Diagnostic Features of Paleosols</th>
<th>Prominent or Common Features of Paleosols (and where else formed)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Root Traces</strong></td>
<td>Ministromatolites (ocean, river, or lake)</td>
</tr>
<tr>
<td>truncated tops</td>
<td>Endolithic microbial traces (ocean, river or lake)</td>
</tr>
<tr>
<td>downward taper</td>
<td>Non-marine fossils (ocean, river or lake)</td>
</tr>
<tr>
<td>downward branching</td>
<td>Burrows (ocean, river or lake)</td>
</tr>
<tr>
<td><strong>Soil Horizons</strong></td>
<td>Coal and carbonaceous shale (ocean, river or lake)</td>
</tr>
<tr>
<td>rip-up clasts in overlying</td>
<td>Zones of base depletion (hydrothermal system)</td>
</tr>
<tr>
<td>sediment</td>
<td>Quartz-rich residuum (ocean, river or lake)</td>
</tr>
<tr>
<td>erosional, sharp top</td>
<td>Zones of clay accumulation (ocean, river, lake, deep burial, or hydrothermal system)</td>
</tr>
<tr>
<td>gradational changes downward</td>
<td>Zones of carbonate accumulation (ocean, river, lake, shallow or deep burial, or hydrothermal system)</td>
</tr>
<tr>
<td>little altered parent material</td>
<td>Zones of iron accumulation (ocean, river, lake, or hydrothermal system)</td>
</tr>
<tr>
<td><strong>Soil Structures</strong></td>
<td>Nodules and concretions (ocean, river, lake, shallow burial, volcanic ash or hydrothermal system)</td>
</tr>
<tr>
<td>peds</td>
<td>&quot;Desert roses&quot; and crystals (playa lake, sabkha)</td>
</tr>
<tr>
<td>gilgai microrelief</td>
<td>Relict bedding (ocean, river, or lake)</td>
</tr>
<tr>
<td>sepic plasmic fabric</td>
<td>Relict crystal structure (playa lake, sabkha, shallow or deep burial, metamorphic, hydrothermal or igneous)</td>
</tr>
<tr>
<td>mukkara structure</td>
<td>Relict foliation (fault zone, or metamorphic)</td>
</tr>
<tr>
<td>sand wedge</td>
<td></td>
</tr>
<tr>
<td>ice wedge</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 1.4**

Characteristic and common features useful in recognition of paleosols.
Root traces – one of the indicators for paleosol

Fig. 1.5 An example of root traces in a paleosol. The original organic matter has been partially replaced by iron oxides. Early Miocene, Molalla Formation, western Oregon.
**Fig. 1.6** Characteristics of various kinds of soil peds.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>PLATY</th>
<th>PRISMATIC</th>
<th>COLUMNAR</th>
<th>ANGULAR BLOCKY</th>
<th>SUBANGULAR BLOCKY</th>
<th>GRANULAR</th>
<th>CRUMB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SKETCH</strong></td>
<td></td>
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</tr>
<tr>
<td><strong>DESCRIPTION</strong></td>
<td>tabular and horizontal to land surface</td>
<td>elongate with flat top and vertical to land surface</td>
<td>elongate with domed top and vertical to surface</td>
<td>equant with sharp interlocking edges</td>
<td>equant with dull interlocking edges</td>
<td>spheroidal with slightly interlocking edges</td>
<td>rounded and spheroidal but not interlocking</td>
</tr>
<tr>
<td><strong>USUAL HORIZON</strong></td>
<td>E, Bs, K, C</td>
<td>Bt</td>
<td>Bn</td>
<td>Bt</td>
<td>Bt</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td><strong>MAIN LIKELY CAUSES</strong></td>
<td>initial disruption of relict bedding; accretion of cementing material</td>
<td>swelling and shrinking on wetting and drying</td>
<td>as for prismatic, but with greater erosion by percolating water, and greater swelling of clay</td>
<td>cracking around roots and burrows, swelling and shrinking on wetting and drying</td>
<td>as for angular blocky, but with more erosion and deposition of material in cracks</td>
<td>active bioturbation and coating of soil with films of clay, sesquioxides, and organic matter</td>
<td>as for granular; including fecal pellets and relict soil clasts</td>
</tr>
<tr>
<td><strong>SIZE CLASS</strong></td>
<td>very thin &lt; 1 mm</td>
<td>very fine &lt; 1 cm</td>
<td>very fine &lt; 1 cm</td>
<td>very fine &lt; 0.5 cm</td>
<td>very fine &lt; 0.5 cm</td>
<td>very fine &lt; 1 mm</td>
<td>very fine &lt; 1 mm</td>
</tr>
<tr>
<td></td>
<td>thin 1 to 2 mm</td>
<td>fine 1 to 2 cm</td>
<td>fine 1 to 2 cm</td>
<td>fine 0.5 to 1 cm</td>
<td>fine 0.5 to 1 cm</td>
<td>fine 1 to 2 mm</td>
<td>fine 1 to 2 mm</td>
</tr>
<tr>
<td></td>
<td>medium 2 to 5 mm</td>
<td>medium 2 to 5 cm</td>
<td>medium 2 to 5 cm</td>
<td>medium 1 to 2 cm</td>
<td>medium 1 to 2 cm</td>
<td>medium 2 to 5 mm</td>
<td>medium 2 to 5 mm</td>
</tr>
<tr>
<td></td>
<td>thick 5 to 10 mm</td>
<td>coarse 5 to 10 cm</td>
<td>coarse 5 to 10 cm</td>
<td>coarse 2 to 5 cm</td>
<td>coarse 2 to 5 cm</td>
<td>coarse 5 to 10 mm</td>
<td>not found</td>
</tr>
<tr>
<td></td>
<td>very thick &gt; 10 mm</td>
<td>very coarse &gt; 10 cm</td>
<td>very coarse &gt; 10 cm</td>
<td>very coarse &gt; 5 cm</td>
<td>very coarse &gt; 5 cm</td>
<td>very coarse &gt; 5 cm</td>
<td>not found</td>
</tr>
</tbody>
</table>

Sedimentary Geology
Prepared by Dr. Andrew T. Lin
Colour photo 38. **Blocky peds.** The slickened purplish black surfaces of this rock specimen are former cutans of iron-manganese oxides (mangans) which define a coarse angular blocky ped. The greenish grey interior of the ped is visible to the upper right, where it has broken open. This rock specimen is from the gleyed subsurface (Bg) horizon of an Aquert paleosol in the late Eocene (Duchesnean North American Land Mammal “Age”), upper Clarno Formation in the red hill west of Hancock Field Station, near Clarno, Oregon, USA (Retallack, 1991c,d). Scale is in centimetres and millimetres.

Colour photo 39. **Slickensided clay skins.** The randomly arranged striated surfaces of this rock specimen are compacted clay skins which define very coarse angular blocky peds. The grey/pink mottling is probably due to burial gleization and hydroxide dehydration during burial of a formerly yellow-brown soil. This rock specimen is from the upper Bt horizon of the Interior clay paleosol, a Paleudalf from the late Eocene (Chadronian North American Land Mammal “Age”), Chadron Formation, in the Pinnacles area of Badlands National Park, South Dakota, USA (Retallack, 1983a). Scale is in millimetres.
Colour photo 40. **Prismatic peds.** The light coloured layer around the hammer is vertically jointed from abundant prismatic peds. This paleosol and others like it supported mangal vegetation within a large tide-dominated delta. Brackish water molluscs have been found in them (Colour photo 21). The prismatic peds are in a Bw horizon beneath a dark carbonaceous A horizon in a Sulfaquent paleosol from the mid-Cretaceous (Cenomanian), upper Dakota Formation, along the Saline River north of Russell, Kansas, USA (Retallack & Dilcher, 1981a,b). The hammer handle for scale is 25 cm long.
Retallack (1997)

Colour photo 5. Drab-haloed root traces. Drab-haloes of light green silt surround deeply penetrating root traces and are conspicuous in the red oxidized matrix of the paleosol. They probably formed early during burial of the soil as the root decomposed anaerobically. The paleosol is an Eutrochrept in the Late Devonian (Frasnian), Oneonta Formation, Catskill magnesium, in road cuts along interstate highway 188 near Unadilla, New York, USA (Gordon & Bridge, 1987). Hammer for scale has a handle 25 cm long.
Pedogenic carbonates (calcrete) from the Upper Carnian Raibl Formation, Dolomites, Southern Alps (Italy) showing columnar internal structures in a green to reddish mudstone matrix reflecting a change in paleogroundwater table.

Photo by: Lorenz Keim, Front cover of “Sedimentology 2004, v.51/1”