

國立中央大學地球科學系
GP3087 Sedimentary Geology

Instructor: 林殿順

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

Boggs, S., Jr., 2006, *Principles of Sedimentology and Stratigraphy*, fourth edition: Prentice Hall, New Jersey, 662 pp.

Course Schedule

Class: 22 September ~ 3 November 2016; Midterm exam: 10 November 2016

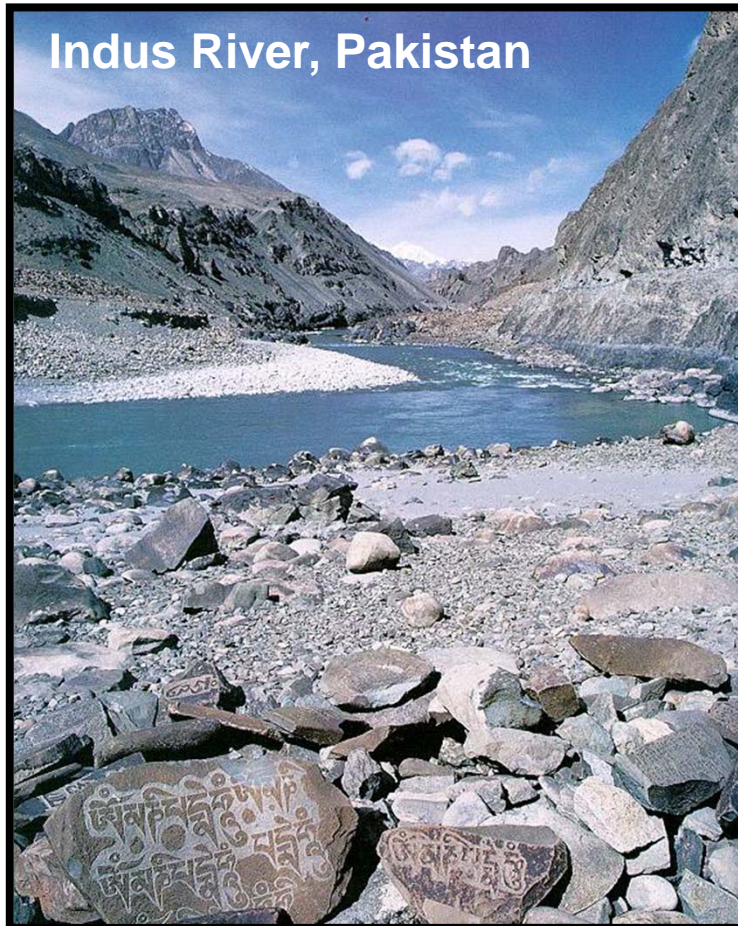
Class: 17 November 2016 ~ 5 January 2017; Final exam: 12 January 2017

Field trip: 17 ~ 18 December 2016 (Southwest Taiwan, 曾文溪、七股瀉湖)

Grading: Midterm exam 35%; Final exam 35%;

Field trip 20%; Assignments 10%

Chapter 1. Weathering and Soils



Mechanical

Chemical

How sediments are made and landscapes formed

1.1 Introduction

Weathering

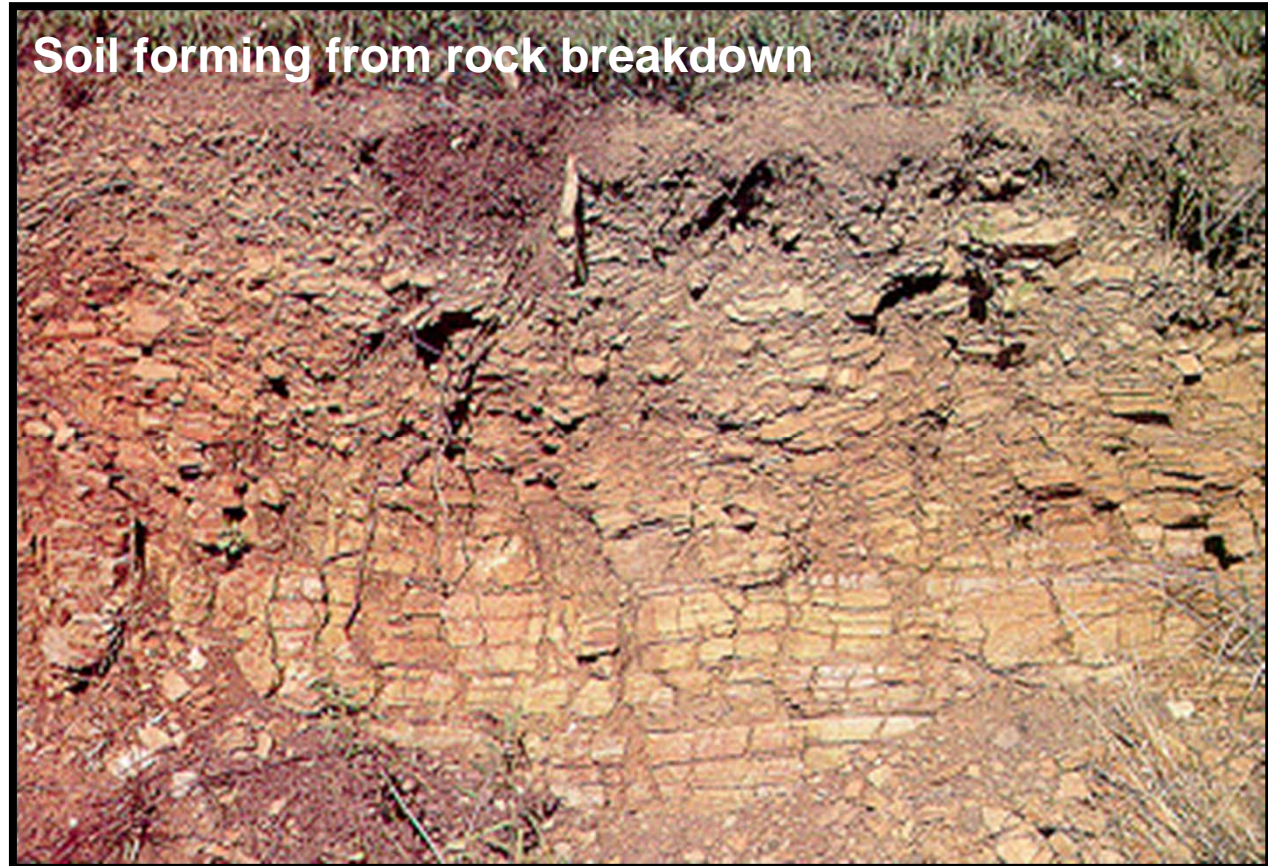
岩石因物理崩解、化學與生物作用而形成殘餘的固態物質與溶解 (dissolved) 的化學物質的過程稱為風化作用。

Regolith(表岩屑)

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

Erosion

Transport of regolith and the wearing down of bedrock



The Rock Cycle

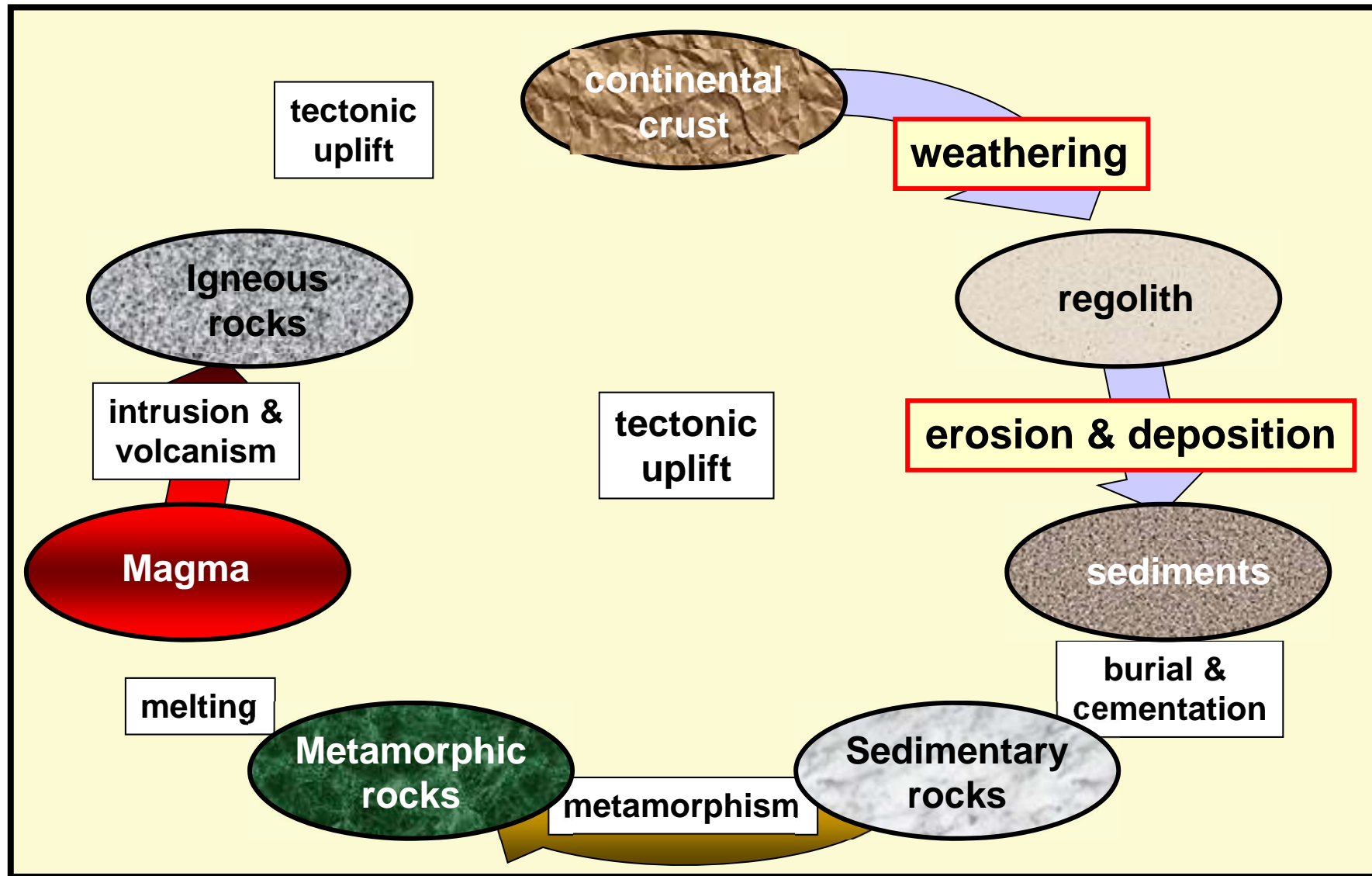


Figure from Dr. Alan Jay Kaufman at <http://www.geol.umd.edu/%7Ekaufman/kaufman.html>

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

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)

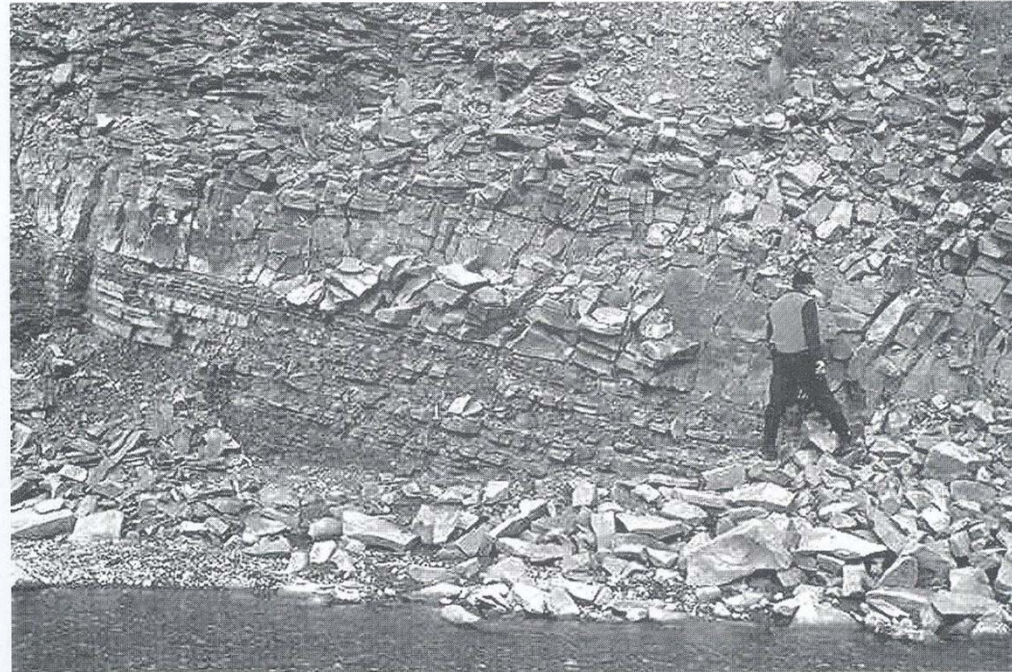


Fig. 1.1 Large, angular blocks of rock generated by **freeze-thaw weathering** of thin-bedded sandstones and mudstones of the Canning formation (Paleocene) exposed along the Canning River, Arctic National Wildlife Refuge, Alaska.

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.





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.

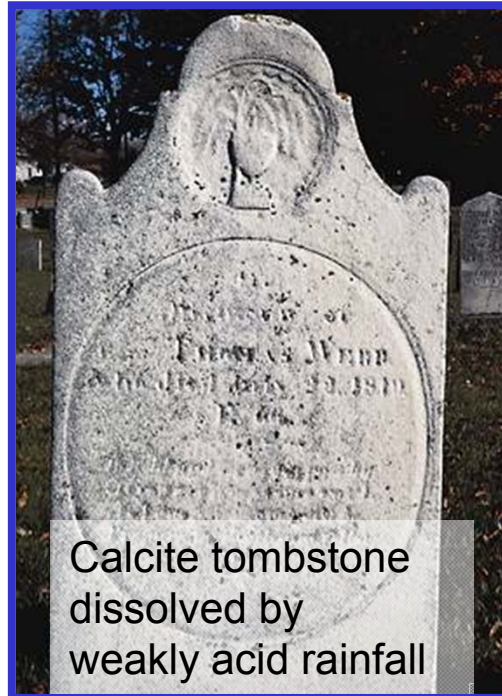
Fig. 1.2 Spheroidal weathering in granite. Note low successive, thin layers of weathered rock are spalled off to produce a spheroidal core.



**Weathering exploits joint surfaces:
Example from Penghu basalts**

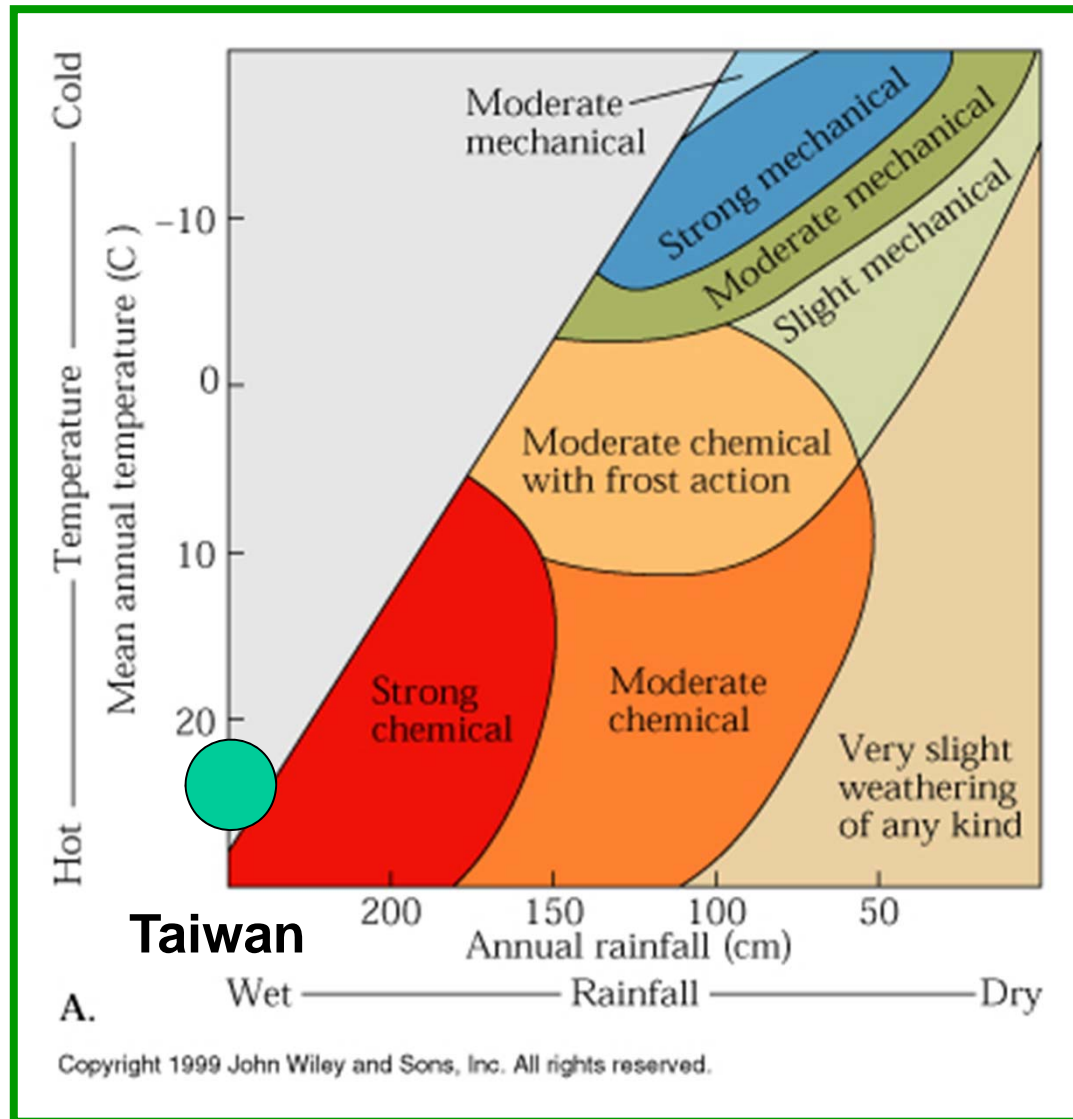
1.2.2 Chemical Weathering

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



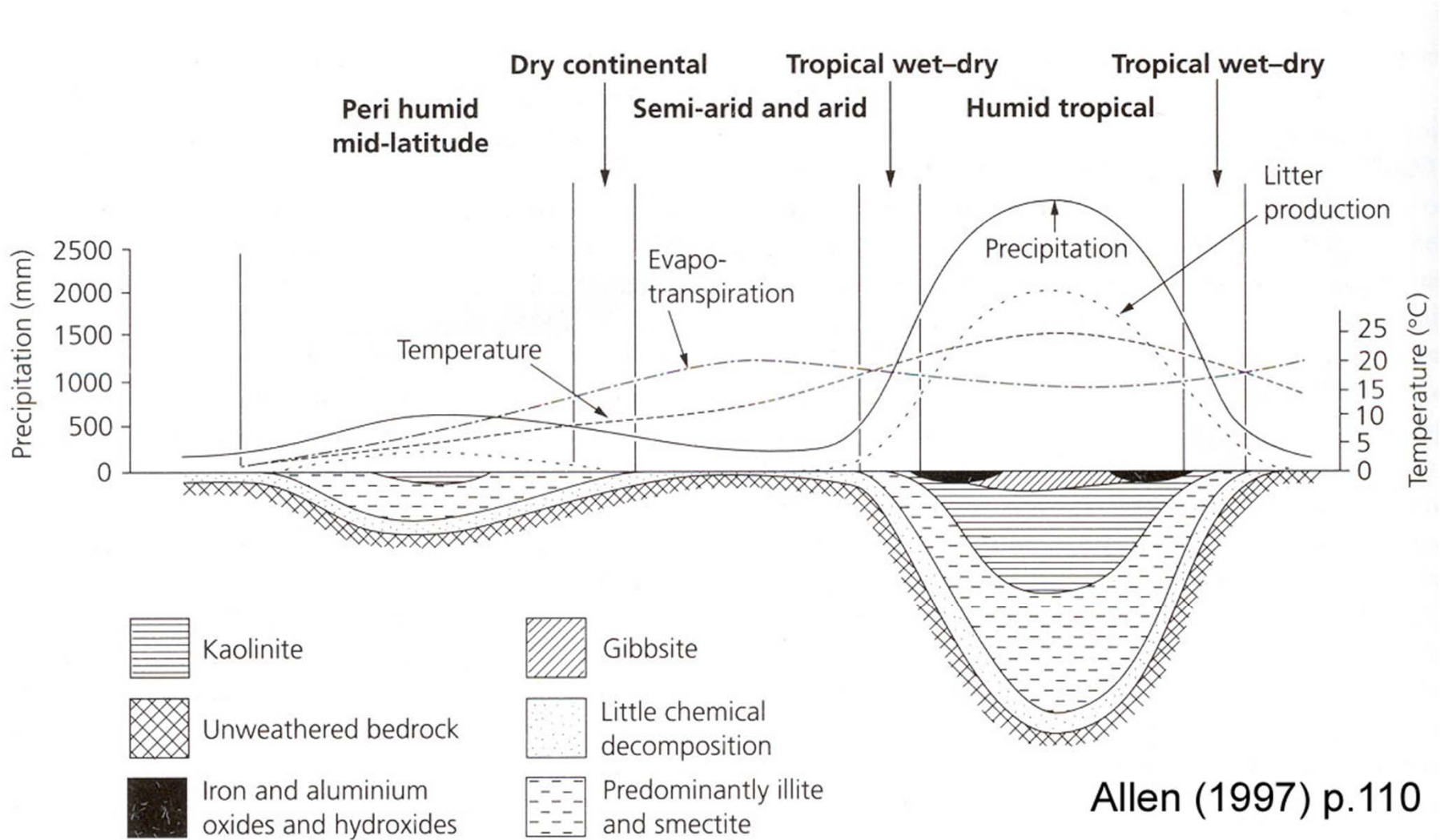
Climate affects chemical weathering strongly

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

Happens in any oxygenated environment (air, most water)

台灣平均雨量為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

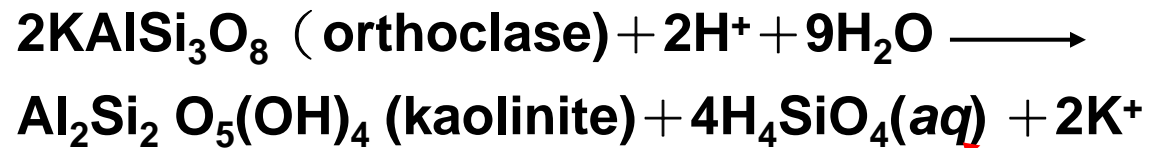
Most important processes	Examples	Principal kinds of rock materials affected
Simple (congruent) Solution —Dissolution of soluble minerals in H ₂ O (direct solution) or in H ₂ O + CO ₂ (carbonation) to yield cations and anions in solution	SiO ₂ + 2H ₂ O → H ₄ SiO ₄ (direct solution) (quartz) (silicic acid) aq	Highly soluble minerals (e.g., gypsum, halite), quartz
	CaCO ₃ + H ₂ O + CO ₂ ↔ Ca ²⁺ + 2HCO ₃ ⁻ (Carbonation) (calcite) aq aq	Carbonate rocks
Hydrolysis (incongruent dissolution) —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)	2KAlSi ₃ O ₈ + 2H ⁺ + 9H ₂ O → H ₄ Al ₂ Si ₂ O ₉ + 4H ₄ SiO ₄ + 2K ⁺ (orthoclase) aq (kaolinite) (silicic acid) aq	Silicate minerals
	2NaAlSi ₃ O ₈ + 2H ⁺ + 9H ₂ O → H ₄ Al ₂ Si ₂ O ₉ + 4H ₄ SiO ₄ + 2Na ⁺ (albite) aq (kaolinite) (silicic acid) aq	
Oxidation —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)	2FeS ₂ + 15/2O ₂ + 4H ₂ O → Fe ₂ O ₃ + 4SO ₄ ²⁻ + 8H ⁺ (pyrite) (hematite) aq aq	Iron- and manganese-bearing silicate minerals, iron sulfides
	MnSiO ₃ + 1/2O ₂ + 2H ₂ O → MnO ₂ + H ₄ SiO ₄ (rhodonite) (pyrolusite) (silicic acid)	
Other Processes		
Hydration and Dehydration —Gain (hydration) or loss (dehydration) of water molecules from a mineral, resulting in formation of a new mineral	Fe ₂ O ₃ + H ₂ O ↔ 2FeOOH (hydration) (hematite) (goethite)	Ferric oxides
	CaSO ₄ · 2H ₂ O ↔ CaSO ₄ + 2H ₂ O (dehydration) (gypsum) (anhydrite)	Evaporites
Ion Exchange —Exchange of ions, principally cations, between solutions and minerals	K-clay + Mg ²⁺ ↔ Mg-clay + K ⁺ Ca-zeolite + Na ⁺ ↔ Na-zeolite + Ca ²⁺	Clay minerals and zeolites
Chelation —Bonding of metal ions to organic molecules having ring structures	Metal ions (cations) + chelating agent (e.g., secreted by lichens) → H ⁺ ions + chelate (metal ions/organic molecules in solution)	Silicate minerals

B. Hydrolysis

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⁺, Ca²⁺, Mg²⁺)，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!

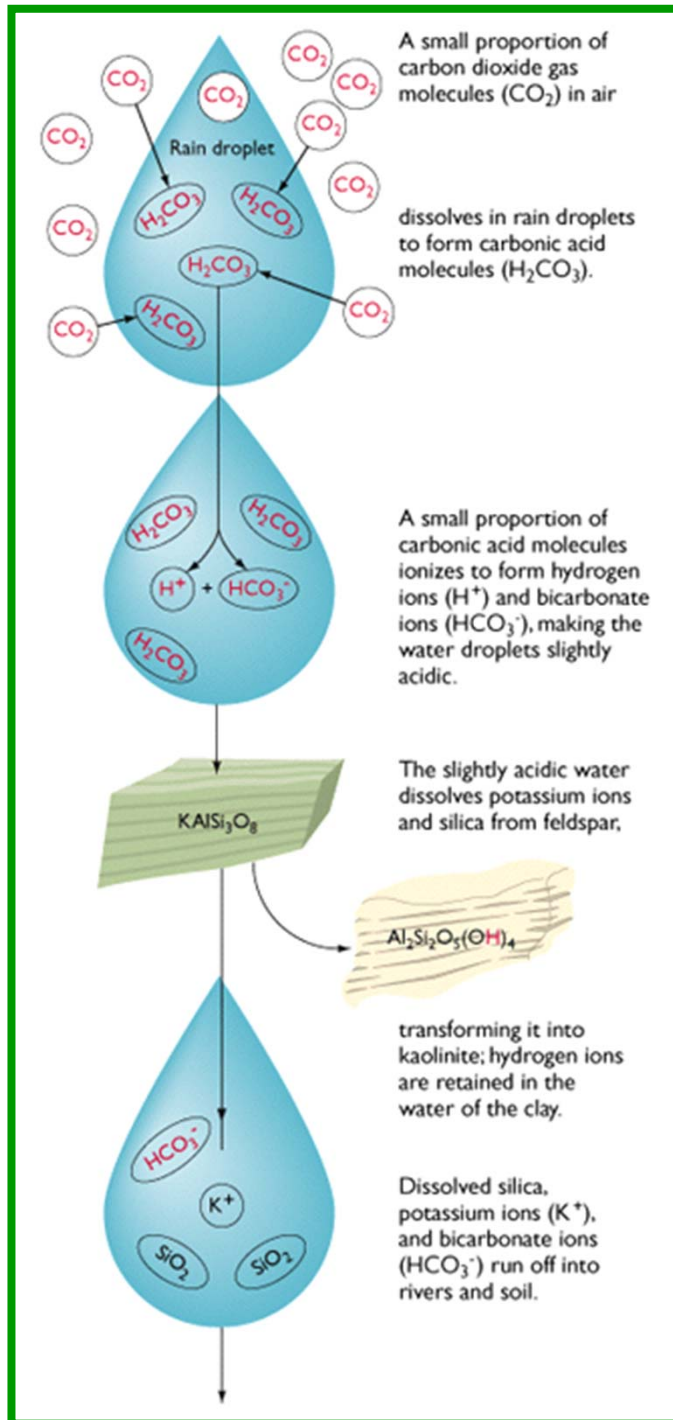
CO₂和水作用產生H⁺與HCO₃⁻形成弱酸性



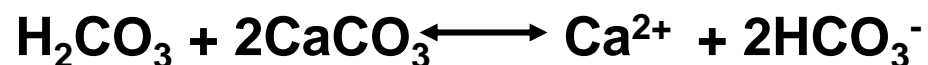
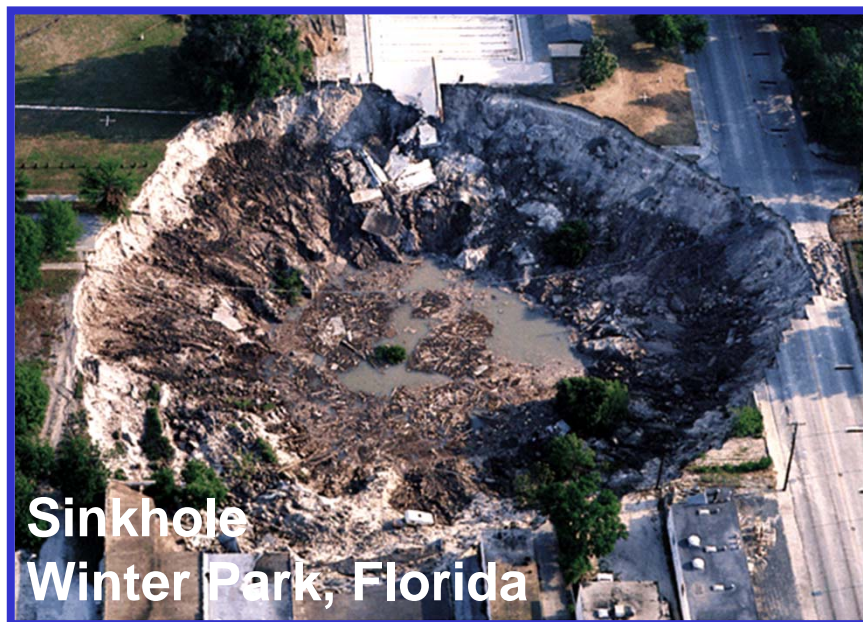
Weak acids strip cations out of minerals

This is the main process of:

- weathering silicates
- making clays



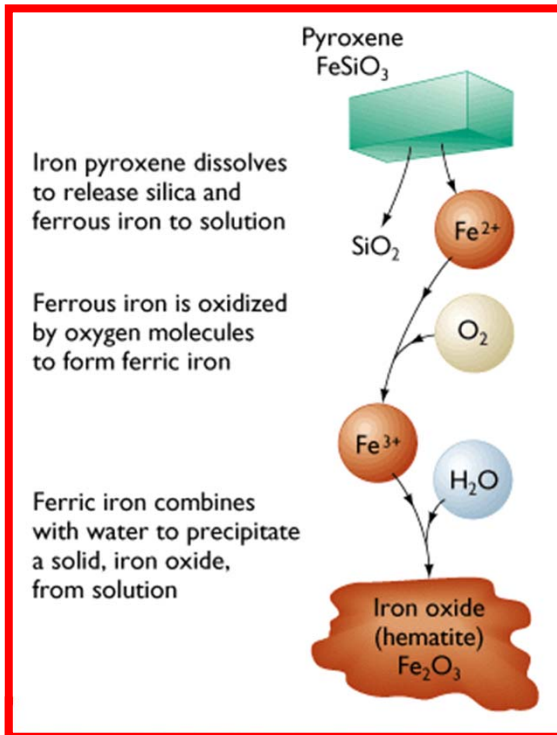
石灰岩的化學風化作用主要是碳酸化作用(Carbonation)



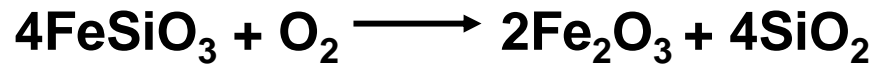
若CO₂多則反應向右，石灰岩溶解，形成卡斯特(karst)地形與鐘乳石洞或滲穴(sinkhole)；若CO₂少反應向左，碳酸鈣沉澱，形成鐘乳石。在乾燥氣候下，碳酸鈣於土壤中沉澱，形成鈣質結礫岩(calcrete)。



C. Oxidation

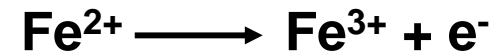


Loss of an electron from an element (commonly Fe or Mn) in a mineral, resulting in the formation of oxides or, if water is present, hydroxides.




pyroxene

hematite



Products of oxidation

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

Si的氧化物	石英、非晶質矽石(amorphous silica)、蛋白石質矽石(opaline silica)	
Al的氫氧化物	Gibbsite(三水鋁石 $\text{Al}(\text{OH})_3$), boehmite(軟水鋁石 $\gamma\text{Al}(\text{OH})_3$) 一水硬鋁石(diaspore, $\alpha\text{AlO}(\text{OH})$)	
Fe的氧化物與氫氧化物	Hematite (赤鐵礦 Fe_2O_3), Magnetite (磁鐵礦, Fe_3O_4), goethite(針鐵礦 $\alpha\text{Fe}(\text{OH})$)	
Ti的氧化物	Anatase (銳鈦礦, TiO_2)	

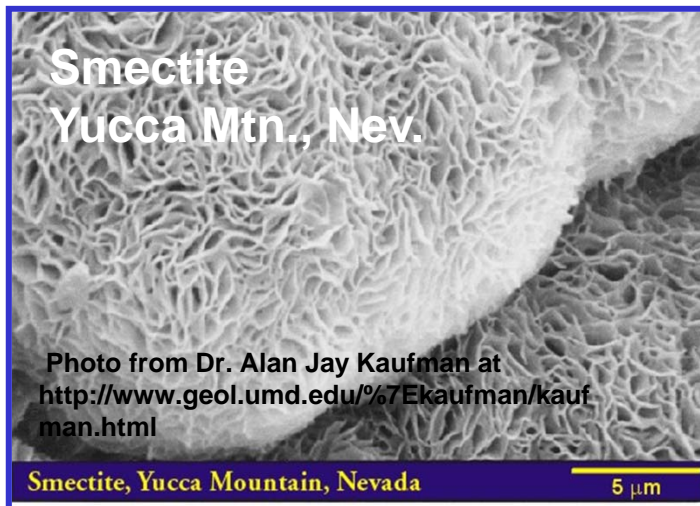
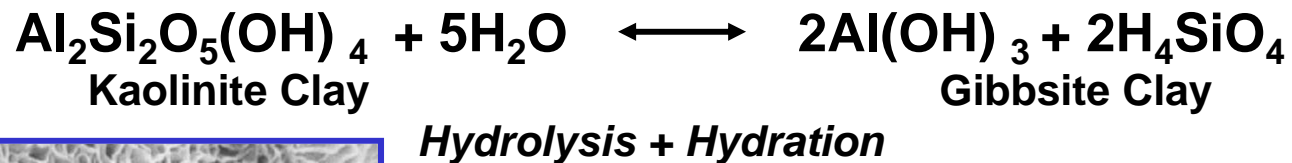
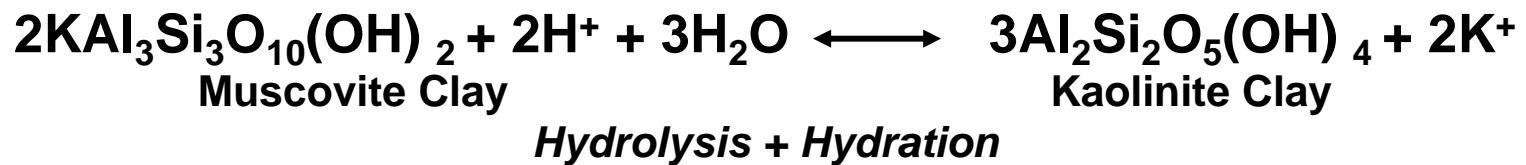
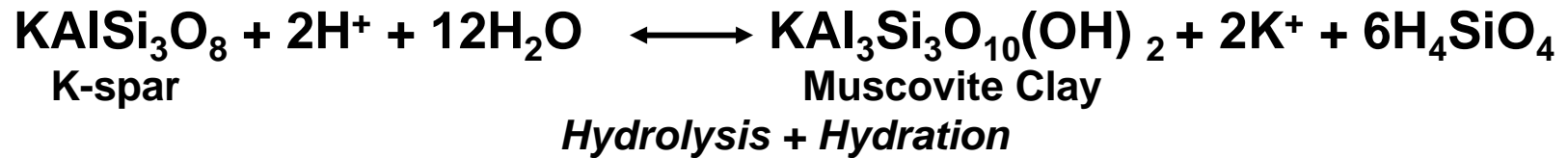
Bauxite (鋁土礦), the principal ore of aluminum, is a rock mixture consisting mostly of several hydrous aluminum oxide minerals, including boehmite, diaspore, gibbsite, and impurities such as QUARTZ, CLAY MINERALS, and iron hydroxides.

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

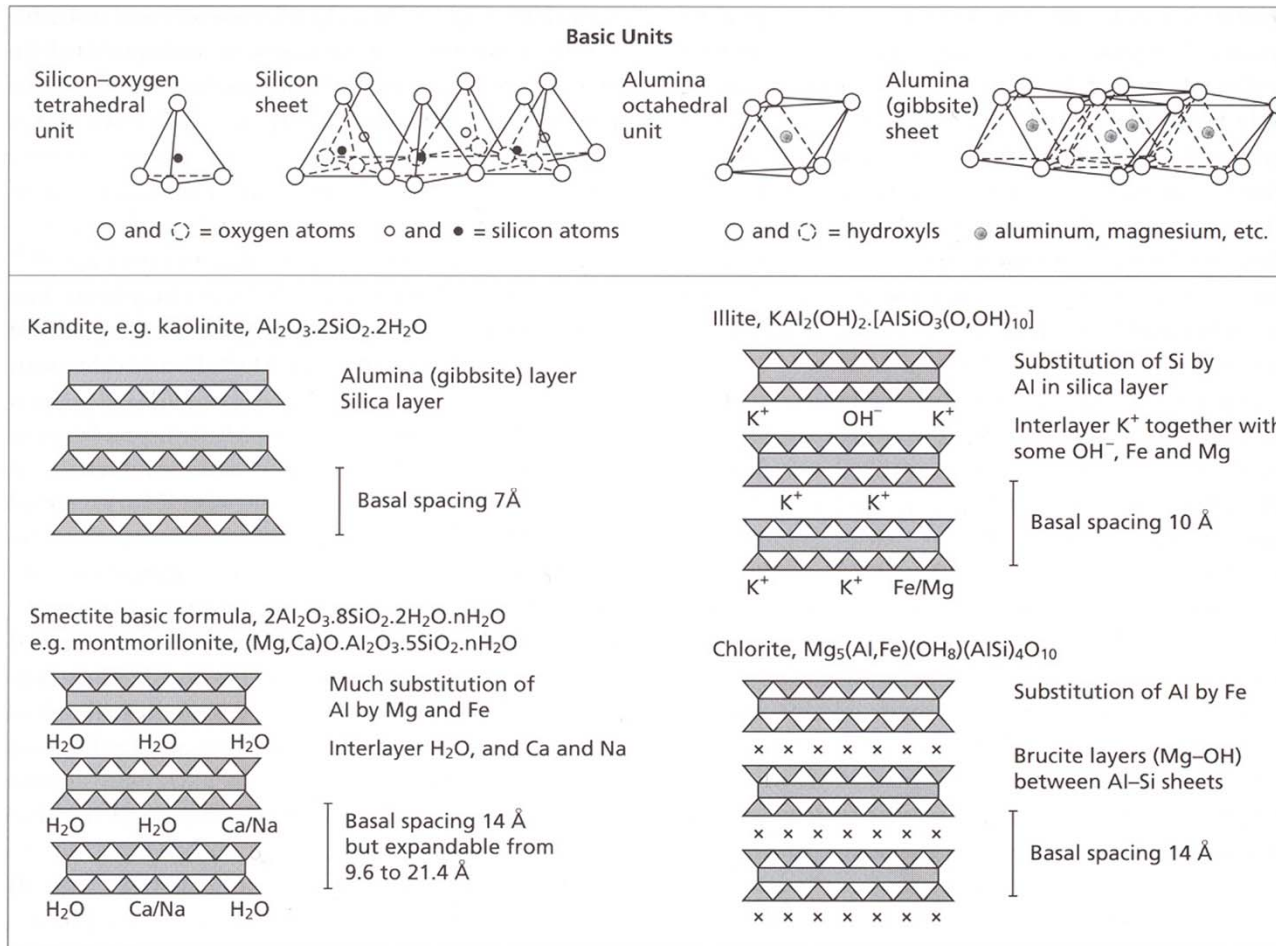


Clay Minerals

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(phyllsilicates)。

礦物群	化學成分	主要礦物	四面體 (tetrahedral) 層：八面體 (octahedral) 層	附註
Kandite group	含水、鋁矽酸鹽 hydrous aluminium silicate	Kaolinite(高嶺石 $Al_2Si_2O_5(OH)_4$), halloysite (禾樂石 $Al_2Si_2O_5(OH)_4 \cdot nH_2O$)	1:1	
Illite group	含水、鉀矽酸鹽	Illite(伊萊石 $(K, H_3O)(Al, Mg, Fe)_2(Si, Al)_4O_{10}(OH)_2 \cdot H_2O$)	2:1	illite最常見的黏土礦物
Smectite group	複合、含水、鎂鋁矽酸鹽	Montmorillonite(蒙脫石, 大約化學式 $(Al, Fe, Mg, Zn, Ca, Na)_4(Si_4O_{10})_2(OH)_4 \cdot nH_2O$); vermiculite(蛭石, $Mg_3(Si, Al)_4(OH)_2 \cdot 4.5H_2O[Mg]_{0.35}$)	2:1	Expandable clay
Chlorite group	Hydrous silicate of Al, Fe and Mg	Chlorite (綠泥石, $(Mg, Fe)_3(Si, Al)_4O_{10} \cdot (Mg, Fe)_3(OH)_6$)	2:2	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)
Mixed-layer group	混成黏土	Illite-montmorillonite mixed-layers		

Structures of clay minerals



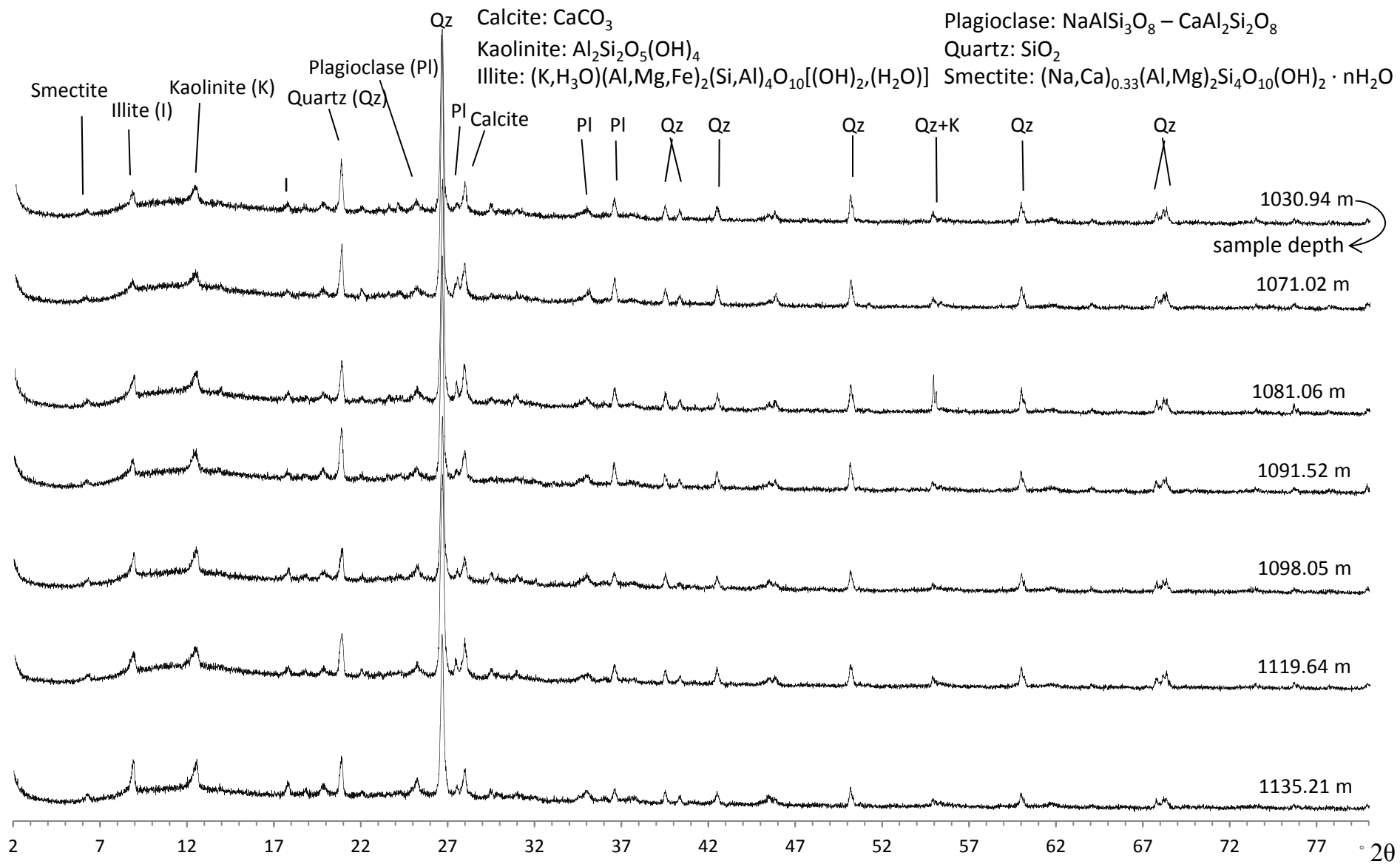
Tucker (2001) p.98

note: gibbsite layer: 由Al-O/OH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/OH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.



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>



Basin Research Group
National Central University

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臺灣四週環海，因此對於海域資源的開發與利用十分重要，而為致力於海域資源的探勘與研究，中央大學地球物理研究所於 2010 年 9 月成立沉積物分析實驗室，實驗室負責人為林殿順教授。為使岩心樣本儘可能保持原有記錄地球環境變化的訊息，實驗室配有冷藏櫃；另外，在樣本的備製與分析方面，其主要的儀器設備包含有 X 光繞射儀、雷射粒徑分析儀、岩心攝像儀、偏光顯微鏡、立體顯微鏡、冷凍乾燥機等，可分別對於樣本的顆粒粒徑、淘選度、礦物組成以及有孔蟲的種屬做分析鑑定，以下分別對各設備之原理及應用介紹之：



掃描式電子顯微鏡(SEM)
X光螢光分析儀(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

Basalt

Minerals	Solid weathering products	Soluble ions in solution	Neutral species in solution
Feldspar	→ Clay minerals	+ Na ¹⁺ and Ca ²⁺	Silica
Fe ²⁺ mineral	→ Clay minerals and goethite	+ Mg ²⁺	Silica
Magnetite	→ Goethite		
Feldspar	→ Clay minerals	+ Na ¹⁺ and K ¹⁺	Silica
Mica	→ Clay minerals	+ K ¹⁺	
Fe ²⁺ mineral	→ Clay minerals and goethite	+ Mg ²⁺	Silica
Quartz	→ Quartz		

Granite

1.2.3 Weathering Rate

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

Table 1.2 Relative stability of common sand-size minerals and various clay-size minerals under conditions of weathering

Sand- and silt-size minerals*		Clay-size minerals**
Mafic minerals	Felsic minerals	
unstable	Olivine	1. Gypsum, halite
	Pyroxene	2. Calcite, dolomite, apatite
	Amphibole	3. Olivine, amphiboles, pyroxenes
	Biotite	4. Biotite
		5. Na plagioclase, Ca plagioclase, K-feldspar, volcanic glass
	Ca plagioclase	6. Quartz
	Ca-Na plagioclase	7. Muscovite
	Na-Ca plagioclase	8. Vermiculite (clay mineral)
	Na plagioclase	9. Smectite (clay mineral)
	K-feldspar, muscovite, quartz	10. Pedogenic (soil) chlorite
		11. Allophane (clay mineral)
		12. Kaolinite, halloysite (clay minerals)
		13. Gibbsite, boehmite (clay minerals)
		14. Hematite, goethite, magnetite
		15. Anatase, titanite, rutile, ilmenite (all, titanium-bearing minerals), zircon
	(Increasing stability) ↓	

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.

Weathering process	Type of weathering product	Example	Ultimate depositional product
Physical weathering	Particulate residues	Silicate minerals such as quartz and feldspar; all types of rock fragments	Sandstones, conglomerates, mudrocks
Chemical weathering			
Hydrolysis	Soluble constituents	Silicic acid (H_4SiO_4); K^+ , Na^+ , Mg^{2+} , Ca^{2+} , etc.	Cherts, limestones, etc.
	Secondary minerals	Clay minerals	Mudrocks (shales)
Simple solution	Soluble constituents	Silicic acid; K^+ , Na^+ , Mg^{2+} , Ca^{2+} , HCO_3^- , SO_4^{2-} , etc.	Limestones, evaporites, chert, etc.
Oxidation	Secondary minerals	Ferric oxides (Fe_2OOH); manganese oxides (MnO_2)	Minor constituent in siliciclastic rocks
	Soluble constituents	Silicic acid; SO_4^{2-}	Chert, evaporites, etc.

Products of weathering:

A. siliciclastic sedimentary rocks

砂質沉積岩占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，稱為砂質顆粒(siliciclastic grains)，由這些顆粒造成的沉積岩稱為砂質沉積岩。砂質沉積岩包括礫岩、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)。

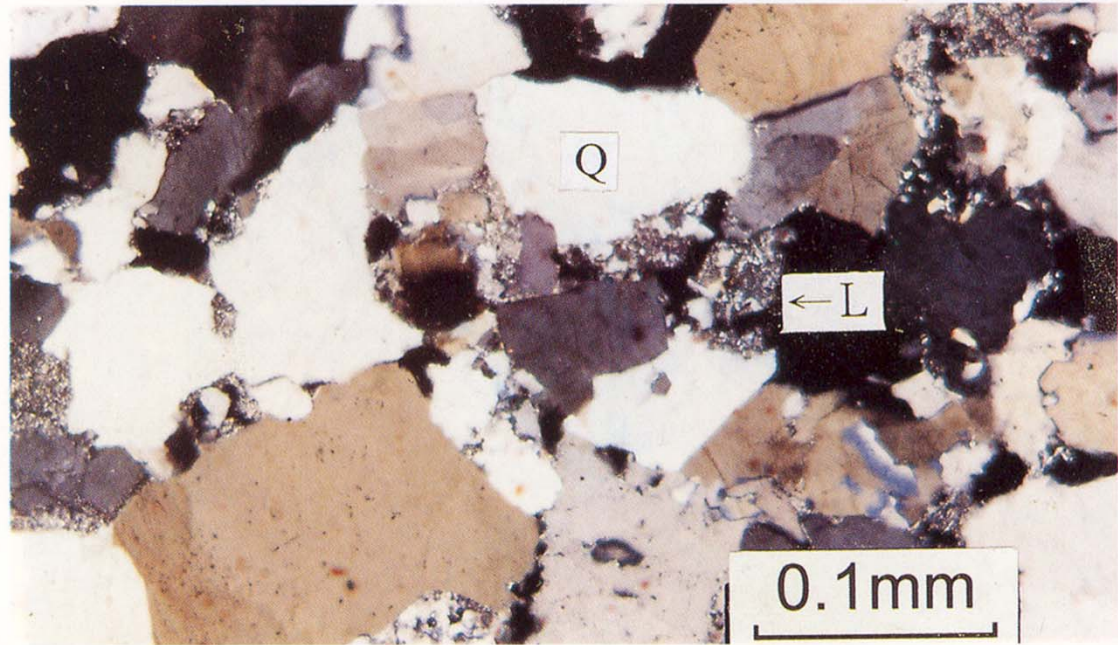


圖3-26 石英砂岩岩象

顯微鏡下的白冷層石英砂岩，由石英(Q)和少許岩屑(L)組成。顆粒多次角形，淘選度佳。由於受過深埋，所以顆粒間有些微的壓溶現象，形成齒狀穿插的邊緣(南投縣水里鄉)。

鄧屬予(1997)

海岸山脈--大港口層 (2003 中央大學野地野外實習)



Weathering products

**Clay-sized products:
Mudstone or shale**

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

恆春-- 四重溪層(2003 中央大學野地野外實習)

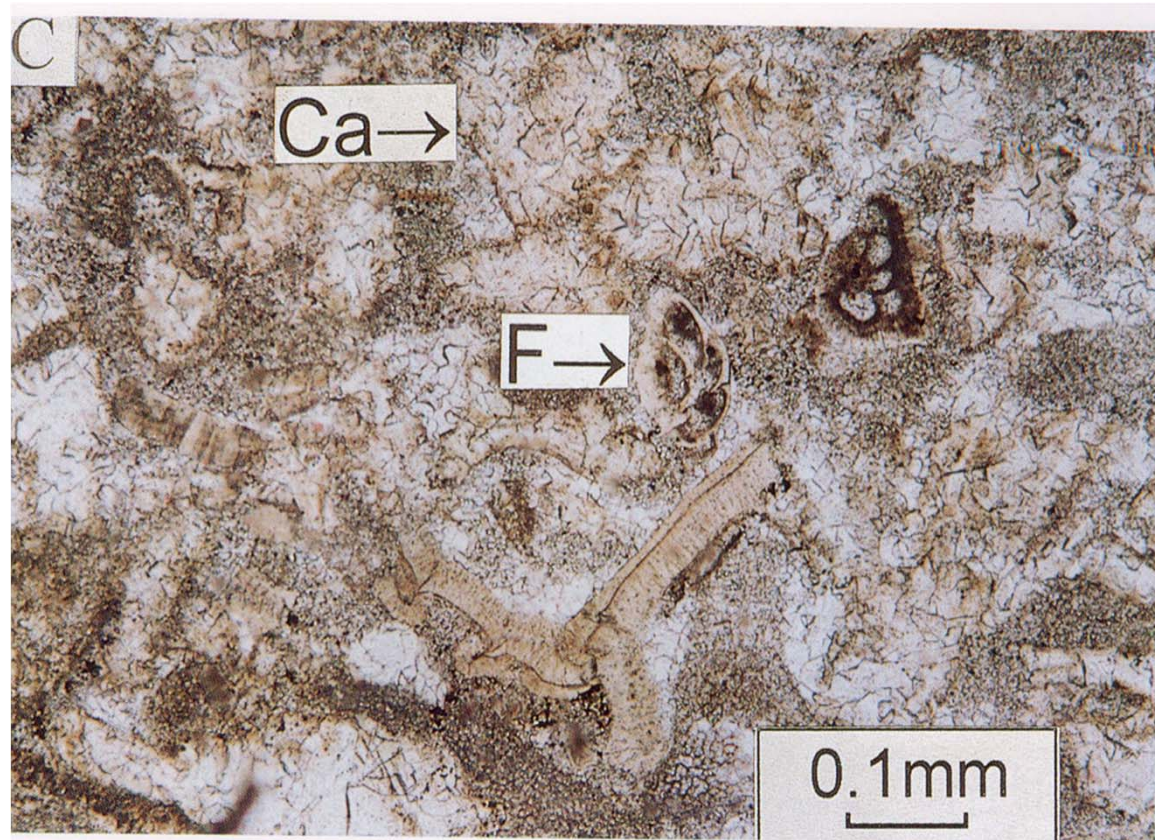


Products of weathering:

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

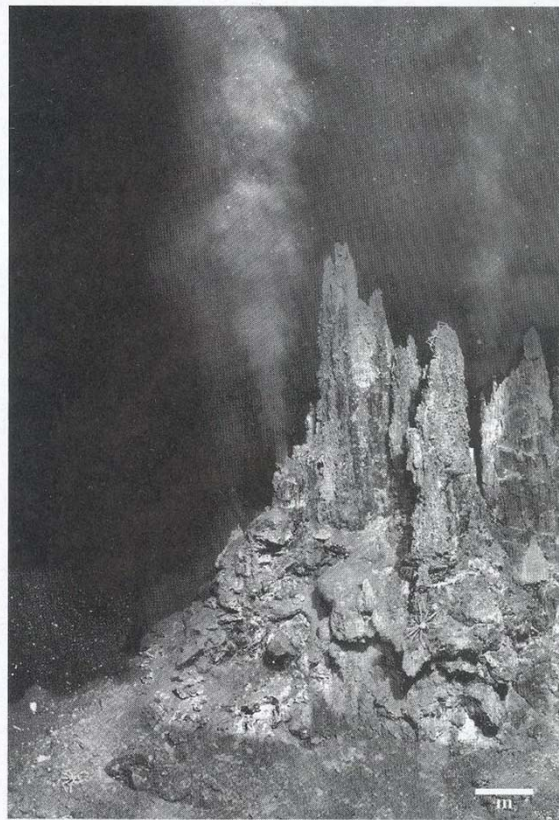


Fig. 1.3 A multiple-orifice black smoker, Faulty Towers complex, Mothra hydrothermal vent field, Endeavour Segment, Juan de Fuca ridge. The constructional chimneys in the foreground were built by precipitation of sulfides and other minerals from heated water issuing from the vents at temperatures exceeding 250°C.

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, FeS_2 , chalcopyrite, CuFeS_2), sulfate and oxides.
2. Low-temperature ($<20^\circ\text{C}$) 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

Photo from Dr. Alan Jay Kaufman at <http://www.geol.umd.edu/%7Ekaufman/kaufman.html>

Important soil-forming processes

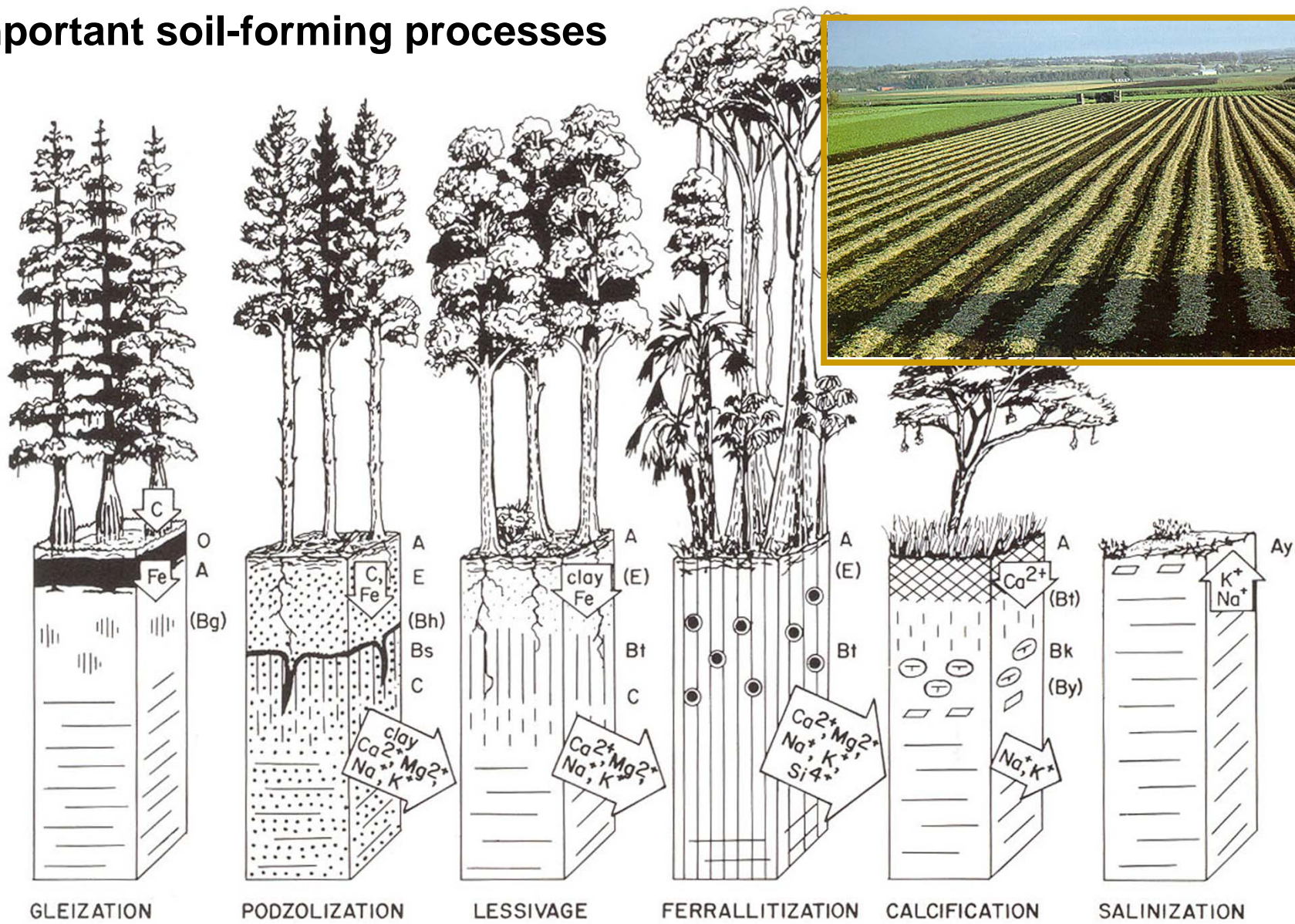
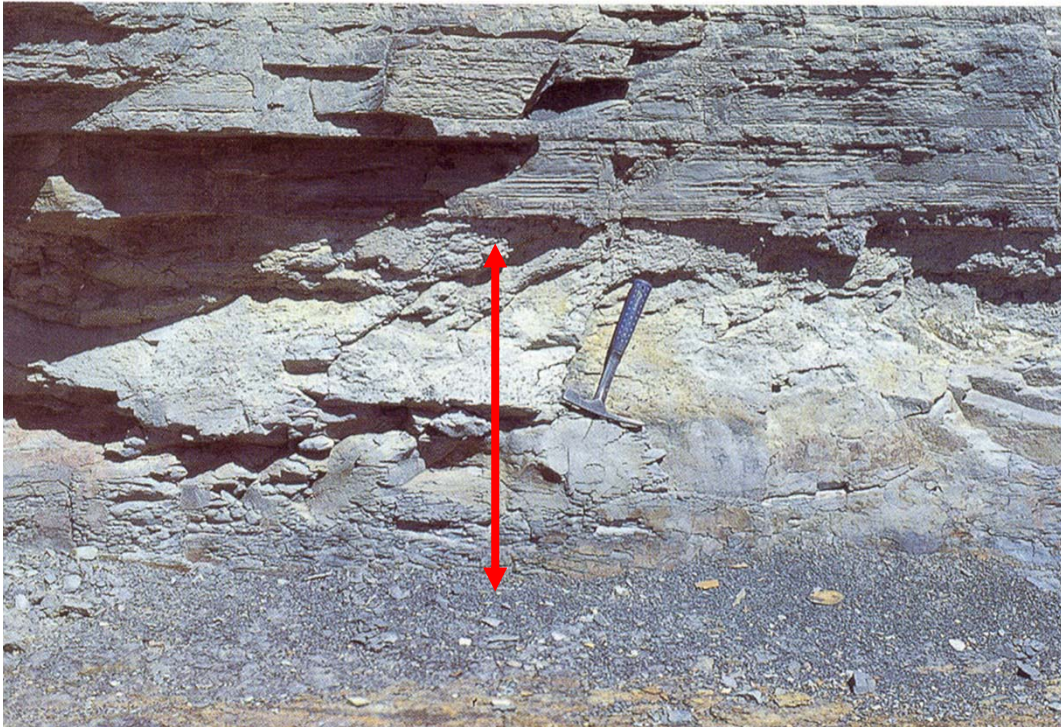


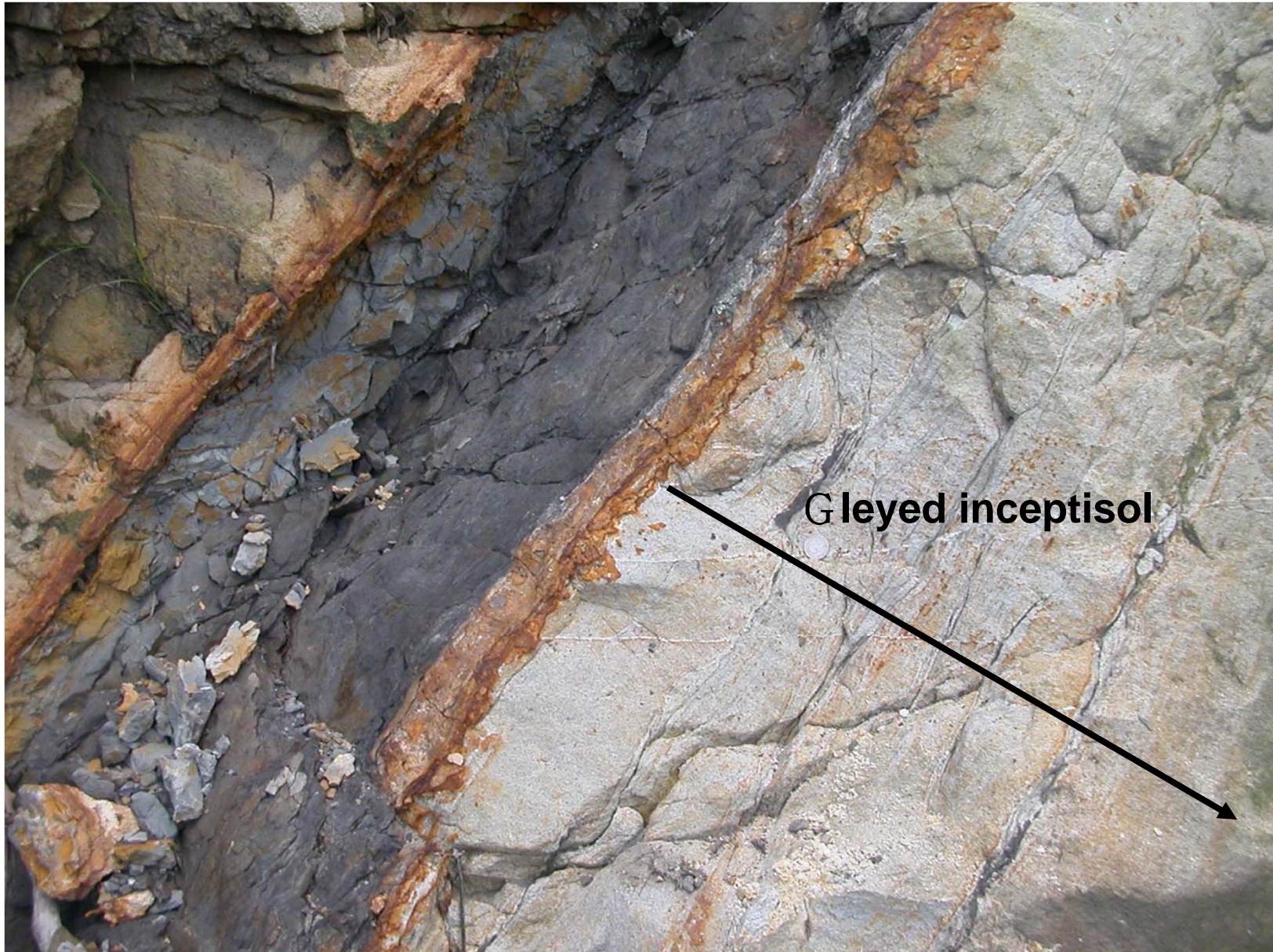
Figure 1.17. Common soil-forming regimes (from Retallack, 1990a, *Soils of the past*, fig. 4.12, with permission of Chapman & Hall)

Gleization (潛水灰化作用)

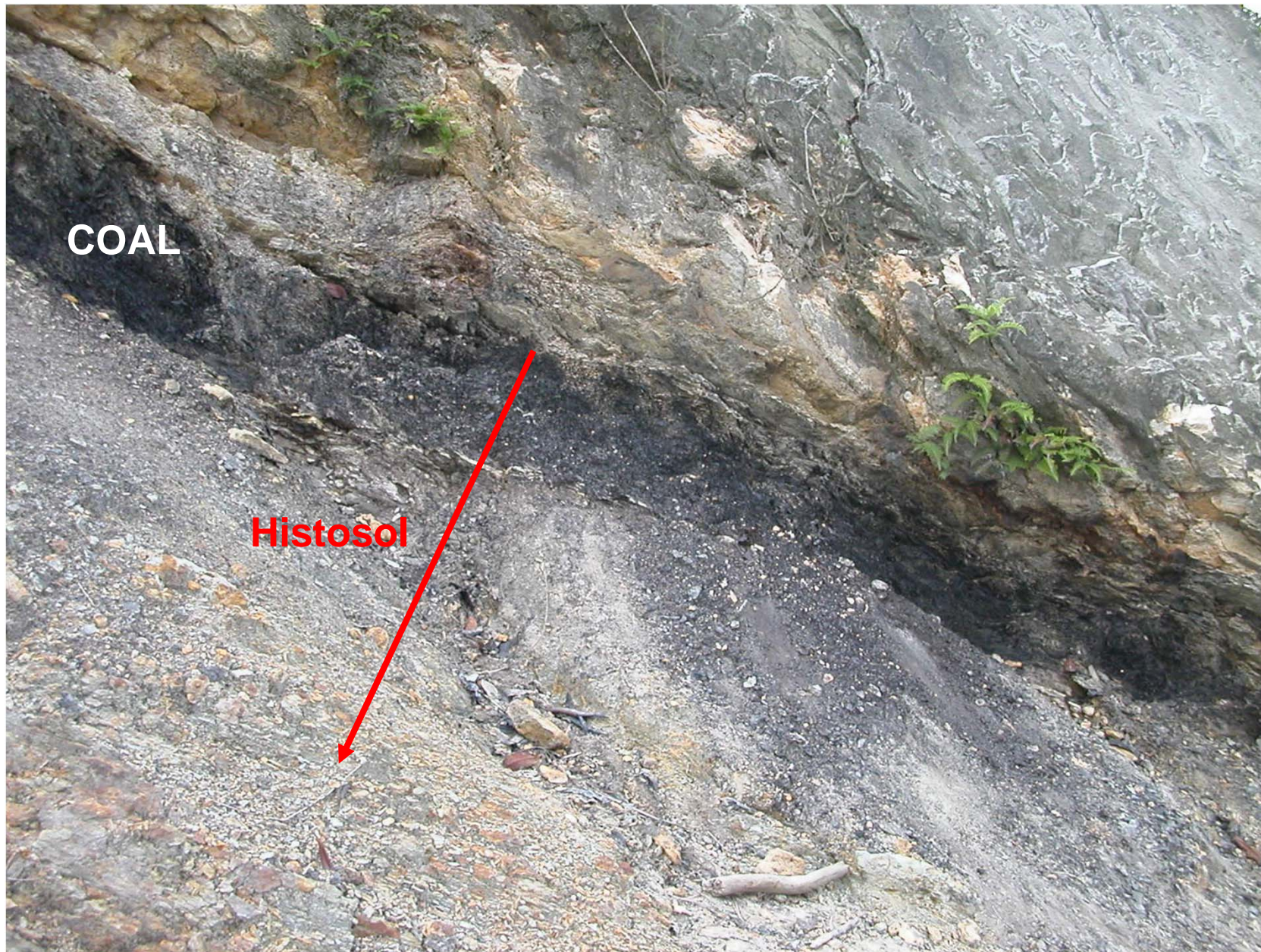
在缺(低)氧的泡水土壤中(**waterlogged soil**)，使 Fe^{3+} 還原成 Fe^{2+} ，形成藍灰色或綠灰色土壤的作用。



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 Aquept. 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.



東坑層(苗栗明德水庫)



東坑層(苗栗明德水庫)

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

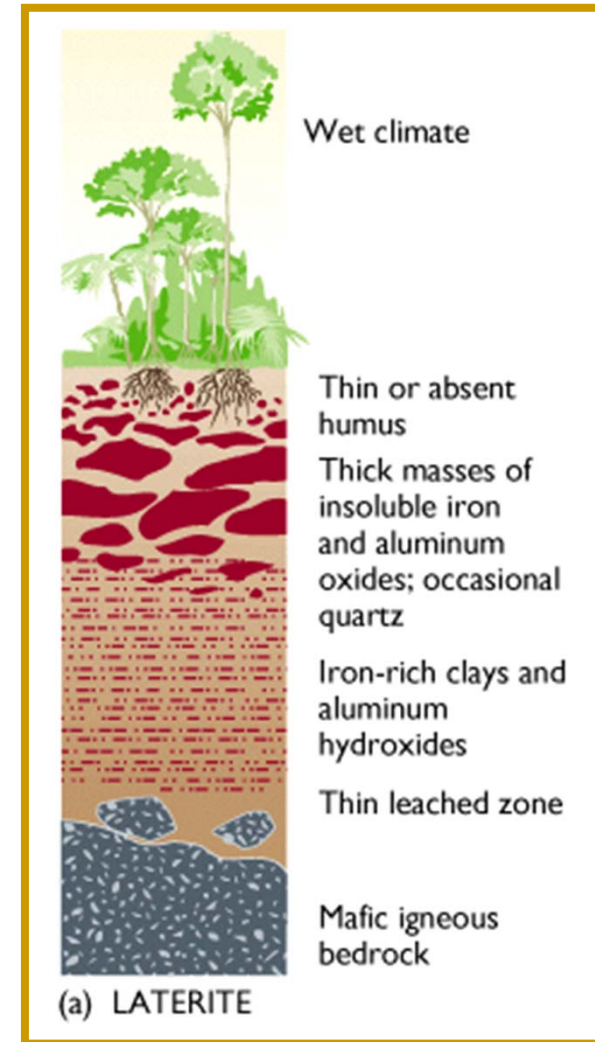
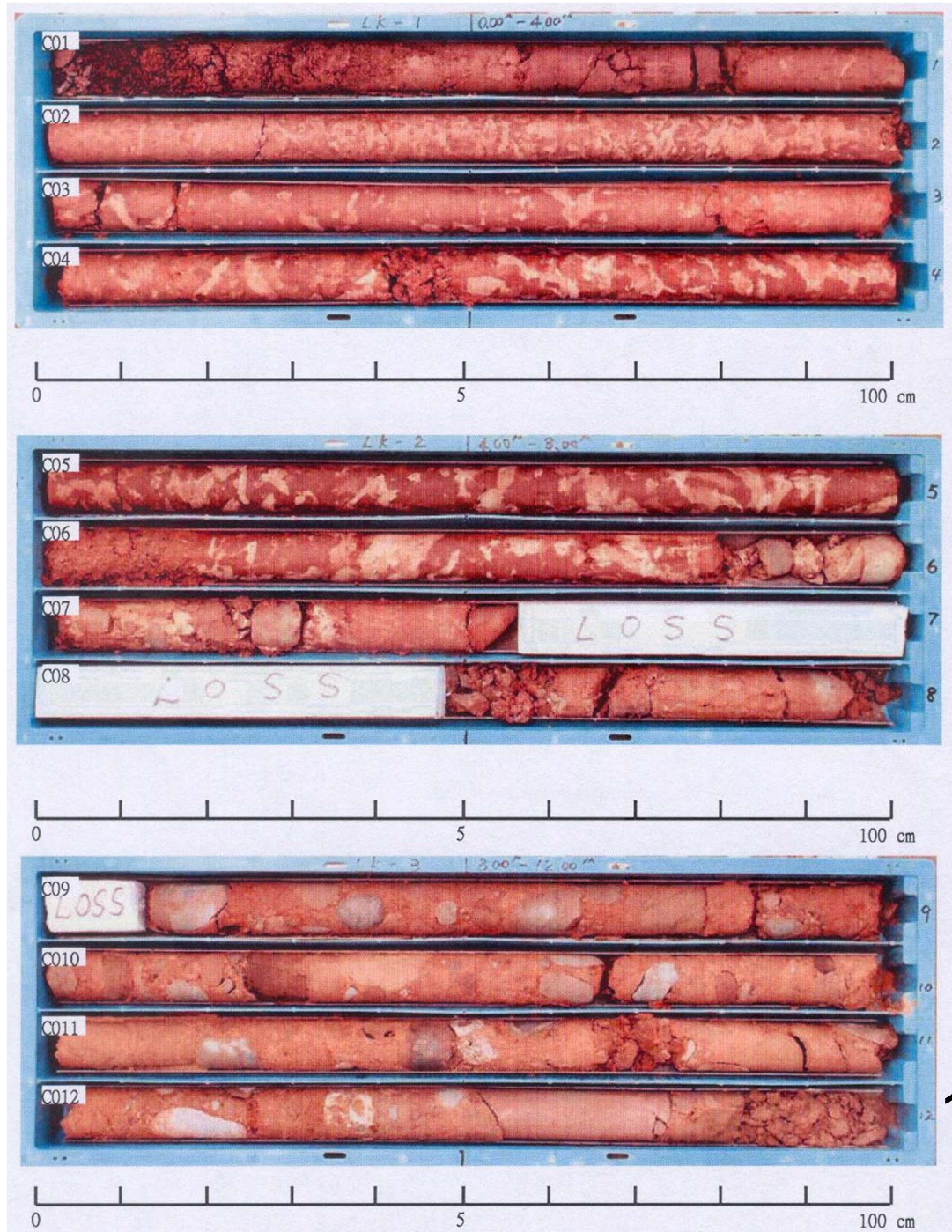


Figure from Dr. Alan Jay Kaufman at <http://www.geol.umd.edu/%7Ekaufman/kaufman.html>

1.4.2 Soil profiles and soil classification

0 m

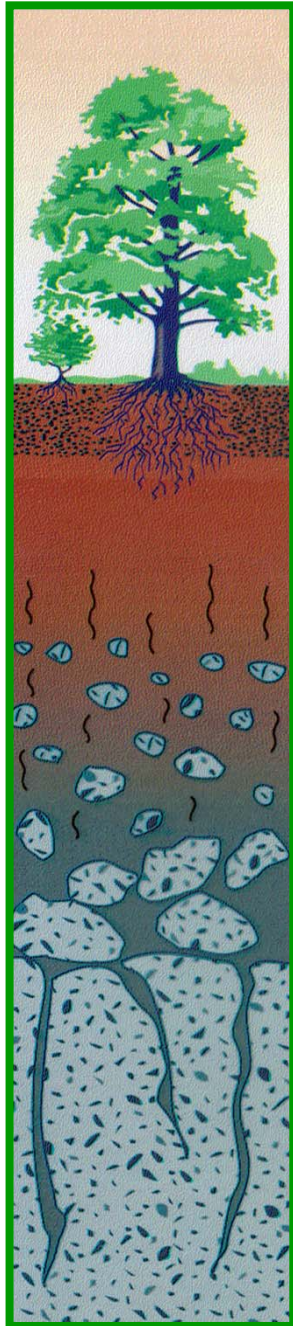
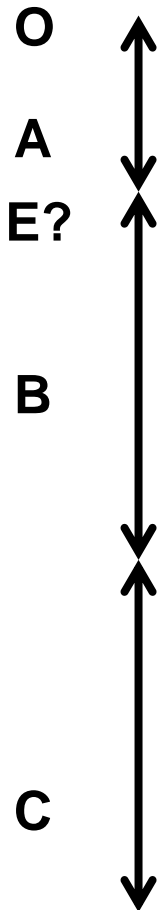


林口台地紅土剖面

12 m

Soil Profile

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 mater; dissolved minerals from A horizon precipitated

Bedrock cracked and weathered

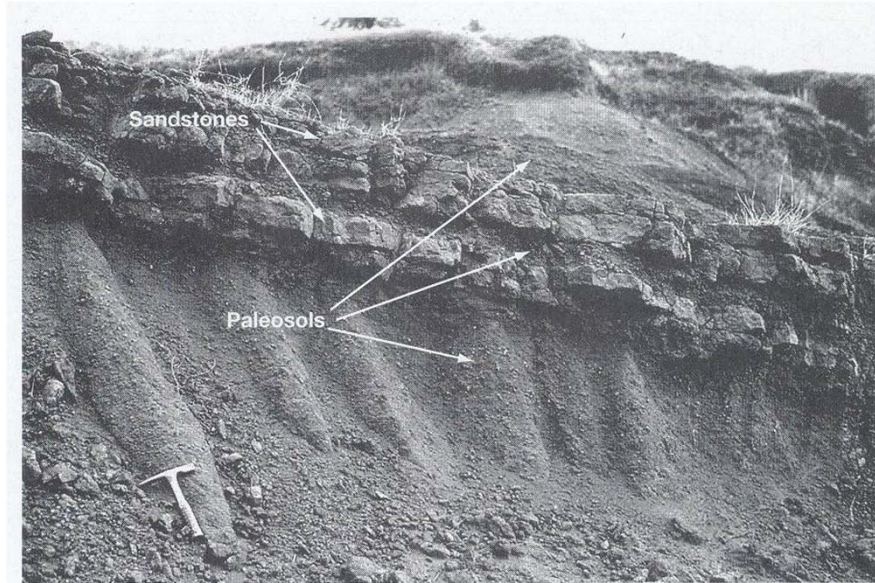
Organic processes

Hydrolisis and Oxidation

Hydrolisis
New Minerals

Mechanical weathering

1.4.3 Paleosols



Paleosols in the Miocene Penghu basalts

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


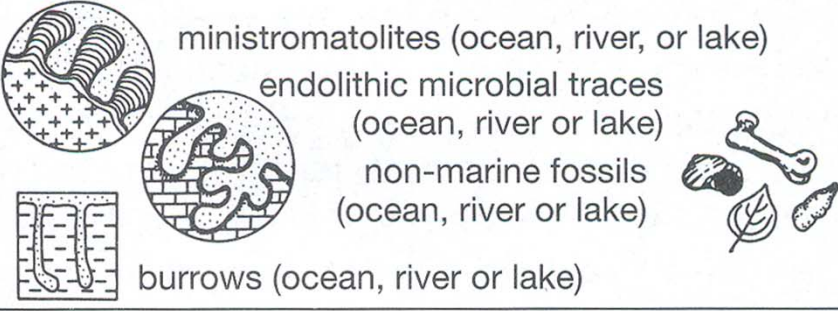
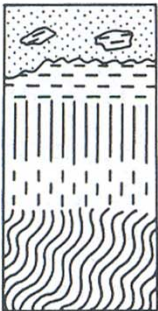

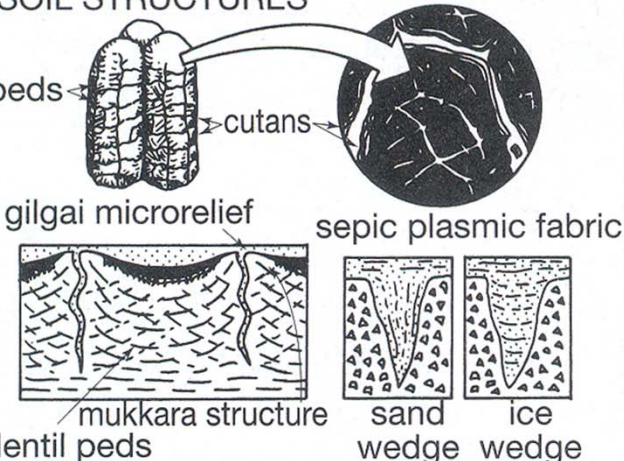

DIAGNOSTIC FEATURES OF PALEOSOLS	PROMINENT OR COMMON FEATURES OF PALEOSOLS (and where else formed)
<p>ROOT TRACES</p>  <p>truncated tops downward taper downward branching</p>	 <p>ministromatolites (ocean, river, or lake) endolithic microbial traces (ocean, river or lake) non-marine fossils (ocean, river or lake) burrows (ocean, river or lake)</p>
<p>SOIL HORIZONS</p>  <p>rip-up clasts in overlying sediment erosional, sharp top gradational changes downward little altered parent material</p>	 <p>coal and carbonaceous shale (ocean, river or lake) zones of base depletion (hydrothermal system) quartz-rich residuum (ocean, river or lake) zones of clay accumulation (ocean, river, lake, deep burial, or hydrothermal system) zones of carbonate accumulation (ocean, river, lake, shallow or deep burial, or hydrothermal system) zones of iron accumulation (ocean, river, lake, or hydrothermal system)</p>
<p>SOIL STRUCTURES</p>  <p>peds cutans gilgai microrelief mukgara structure sand wedge ice wedge sepic plasmic fabric</p>	 <p>nodules and concretions (ocean, river, lake, shallow burial, volcanic ash or hydrothermal system) "desert roses" and crystals (playa lake, sabkha) relict bedding (ocean, river, or lake) relict crystal structure (playa lake, sabkha, shallow or deep burial, metamorphic, hydrothermal or igneous) relict foliation (fault zone, or metamorphic)</p>

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.



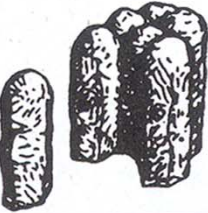
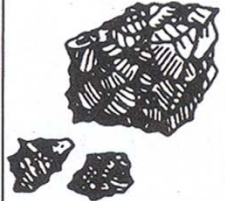

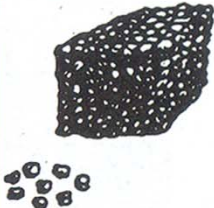
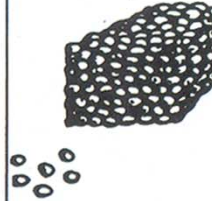
TYPE	PLATY	PRISMATIC	COLUMNAR	ANGULAR BLOCKY	SUBANGULAR BLOCKY	GRANULAR	CRUMB
SKETCH							
DESCRIPTION	tabular and horizontal to land surface	elongate with flat top and vertical to land surface	elongate with domed top and vertical to surface	equant with sharp interlocking edges	equant with dull interlocking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

Fig. 1.6 Characteristics of various kinds of soil peds.

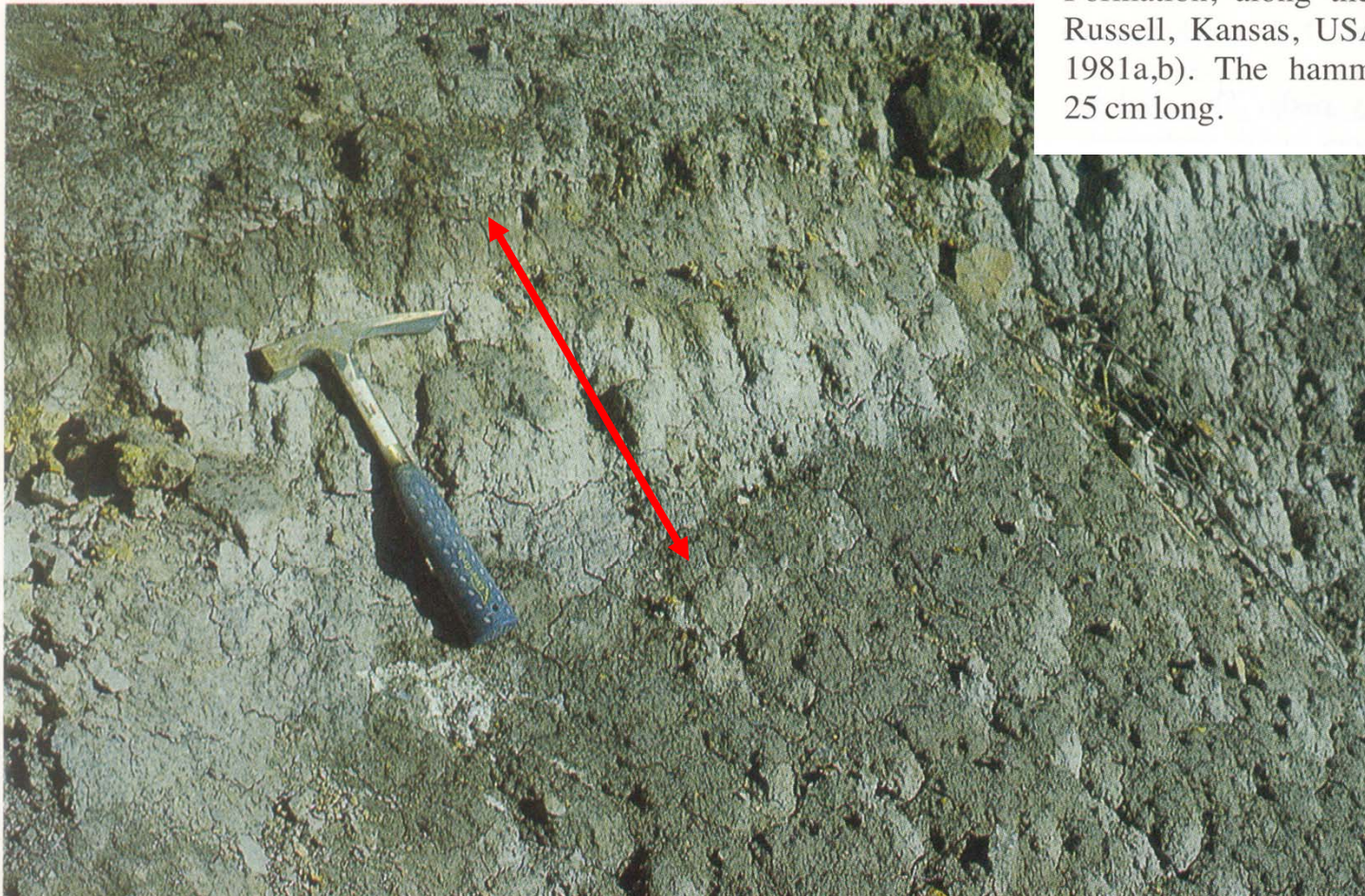
Colour photo 38. **Blocky peds.** The slickensided purplish black surfaces of this rock specimen are former cutans of iron-manganese oxides (mangans) which define a coarse angular blocky ped. The greenish grey interior of the ped is visible to the upper right, where it has broken open. This rock specimen is from the gleyed subsurface (Bg) horizon of an Aquept 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 magnafacies, in road cuts along interstate highway 188 near Unadilla, New York, USA (Gordon & Bridge, 1987). Hammer for scale has a handle 25 cm long.



南莊層(苗栗)

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"