108.01

工程地質

Engineering Geology

第十四週

岩石與土壤的工程性質

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土壤與其工程性質+

土壤的形成與土壤剖面

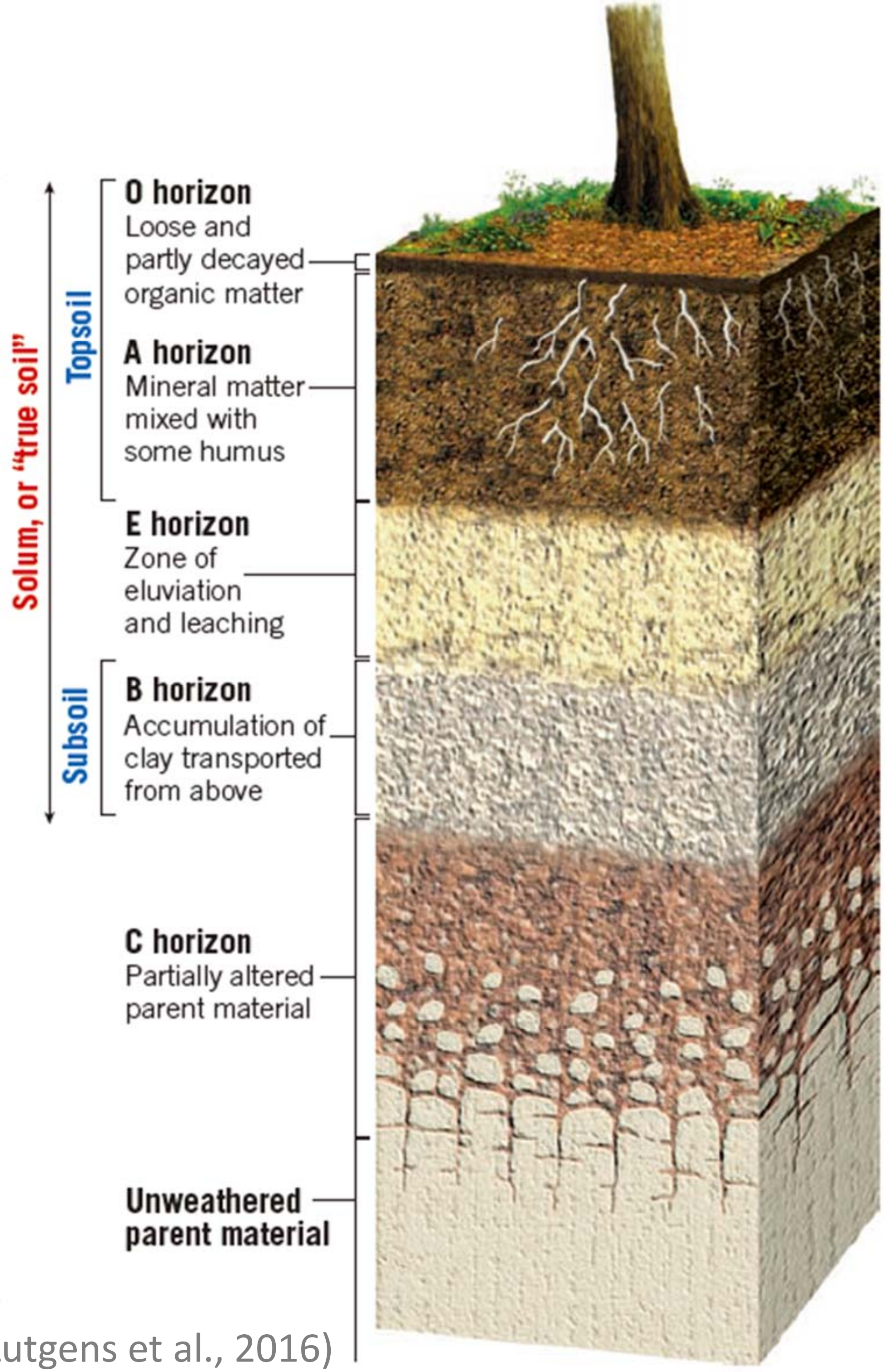
主要土壤類型

土壤的形成

- 土壤的形成歷經下列三個作用
  - **產生岩屑**：岩石經化學與物理風化作用產生岩屑或新的礦物顆粒(主要是黏土)及溶液中的離子。
  - **與水作用**：雨水滲入岩屑並將容於其中的離子及黏土向下搬運，形成「淋溶層」(zone of leaching)。淋溶作用是岩屑受下滲水體的離子萃取、吸收及搬運的過程。在淋溶層的下方，新的礦物會直接由水中沉澱結晶或由水與岩屑反應而成。另外，水中的細粒黏土會因水的搬運能力降低而澱積下來。這個有新礦物的形成與黏土堆積的層位，稱為「澱積層」(zone of accumulation)。
  - **有機物的作用**：微生物與沉積物交互作用，藉由吸取養分元素及遺骸有積物，產生酸性物質—腐植質，加速風化作用。

土壤剖面

- 土壤的組織及成分與原始岩屑差異極大，在土壤內，生物與物理因素交互作用至為明顯。
- 不同深度的土壤有不同的形成機制，通常會形成物理和化學性質明顯不同的水平土層，稱為**土壤化育層(soil horizon)**，其垂直的序列稱為土壤剖面(soil profile)。



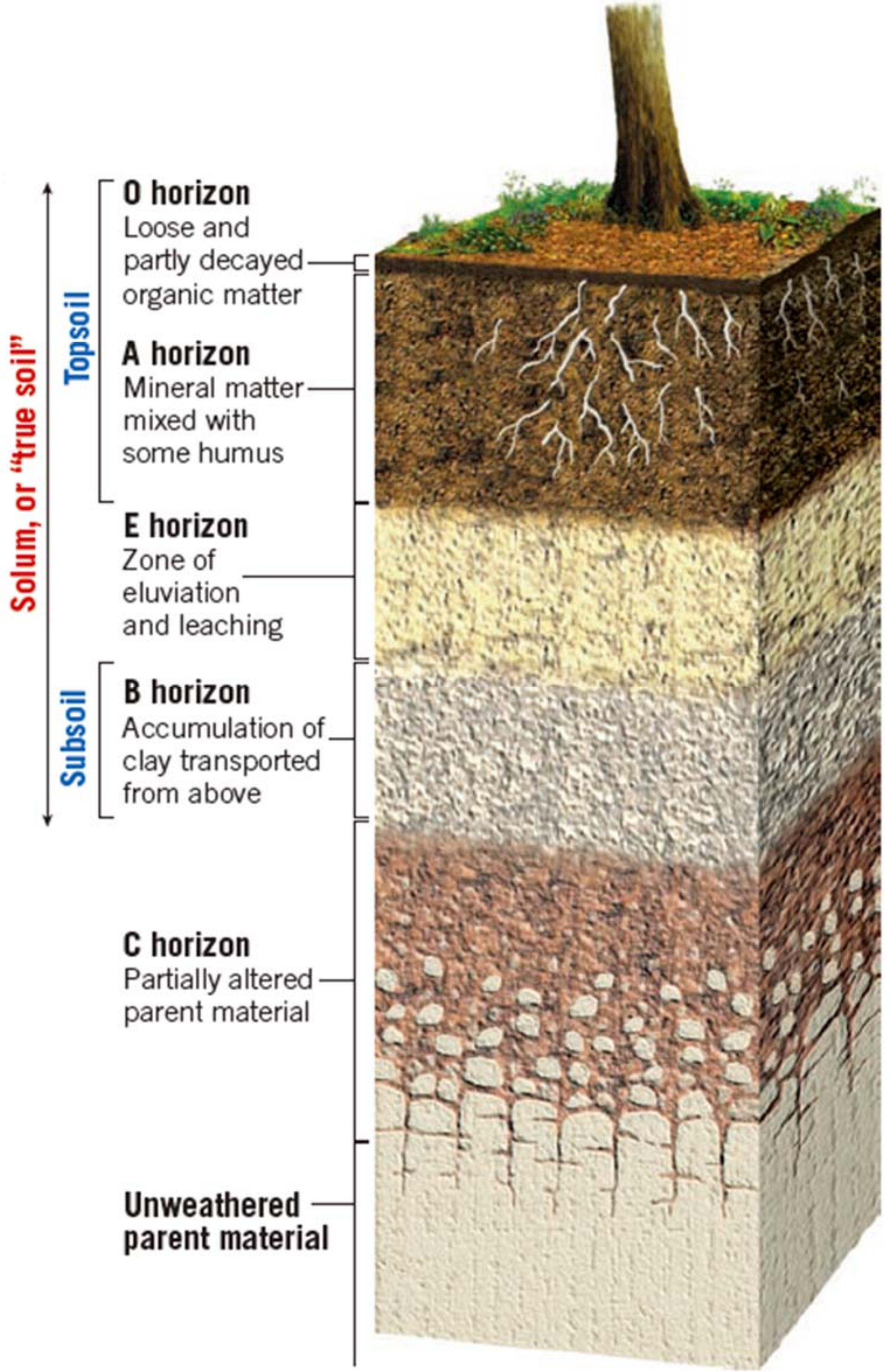
(Lutgens et al., 2016)

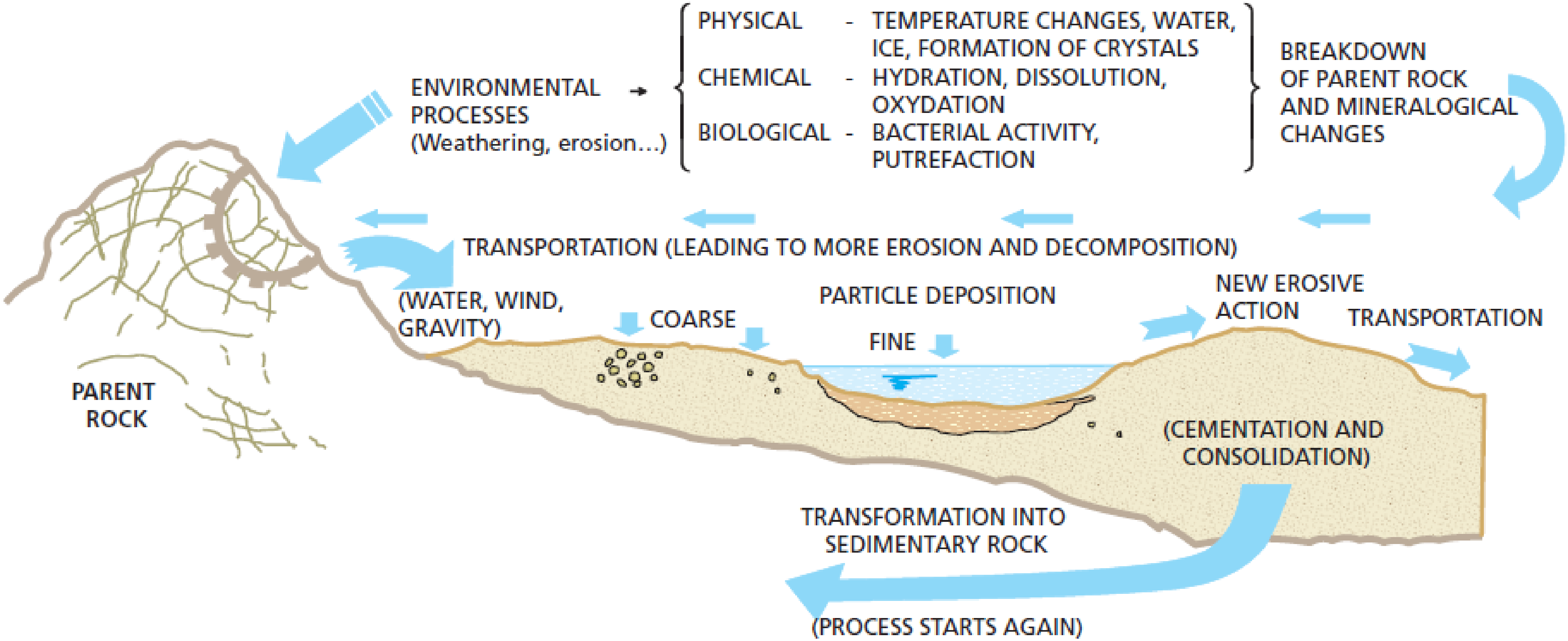
土壤剖面

淋溶層

表土

- **O層**：有機質層，由腐爛的有機物質所組成，幾乎不含任何礦物
- **A層**：腐植質更加腐爛分解，並與礦物顆粒(黏土、粉砂及砂)混合在一起。水滲透進A層導致化學風化產生，造成離子解離及產生新的黏土礦物。
- E層：灰色或白色，發生強烈淋溶作用，但尚未與有機物質混合層。常為酸性土壤，發育在常綠森林中
- **B層**：心土或澱積層，富含黏土與鐵和鋁的氫氧化物，A層及E層的淋溶物質沉澱於此。
- K層：乾燥地區因強烈的蒸發作用沉澱出過飽和的碳酸鈣。
- **C層**：由受到化學風化，但尚未經歷淋溶及澱積的岩屑所組成
- C層以下為未風化的母岩





FINAL RESULT:

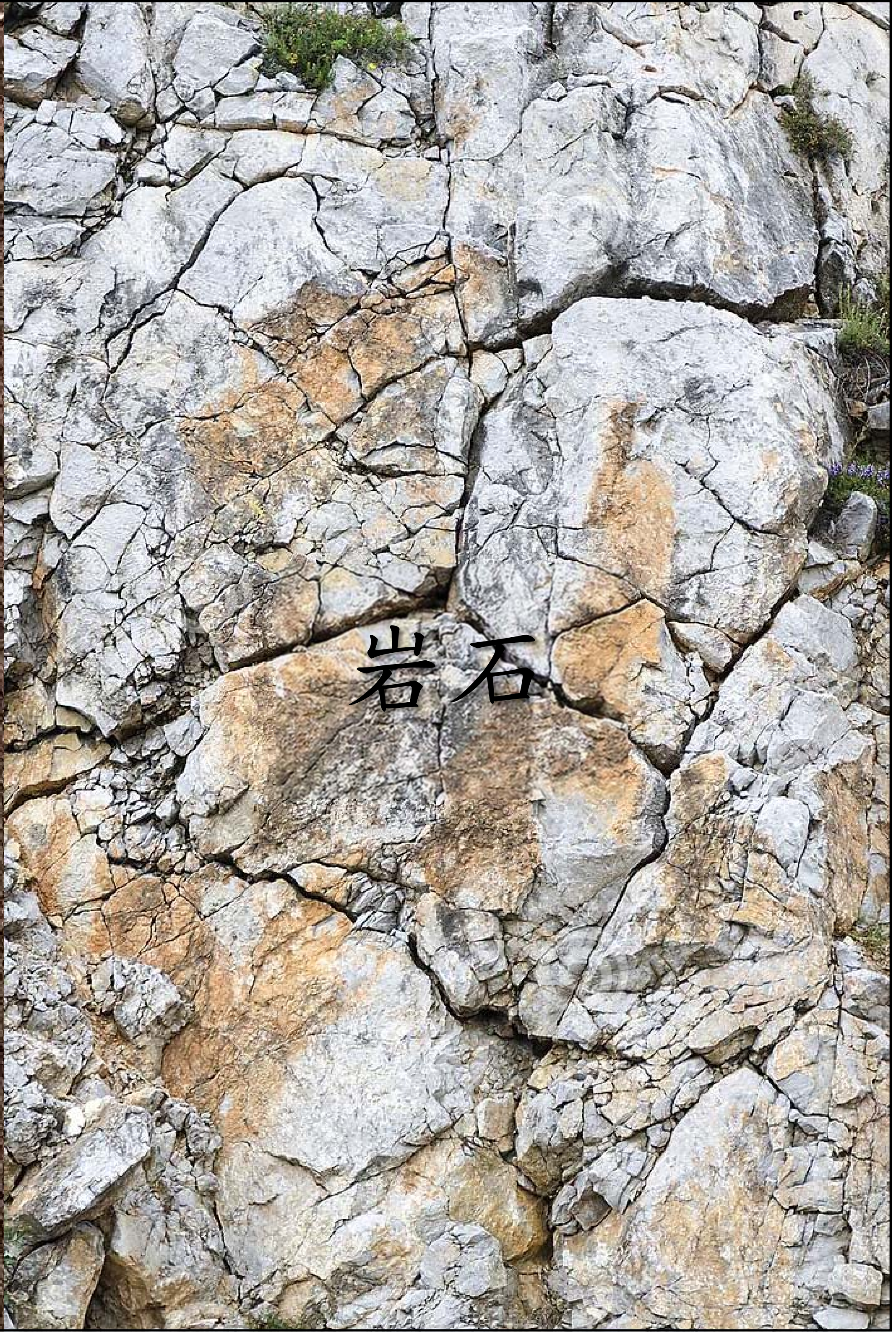
- SYSTEM OF PARTICLES OF DIVERSE ORIGIN (PARTICLE SIZES FROM COARSE (cm) TO FINE (microns)
- STRUCTURE AND FABRIC DEPENDS ON MINERAL ORIGIN, TRANSPORTATION, CEMENTING AGENTS. GEO-ENVIRONMENTAL CONDITIONS.
- PRESENCE OF VOIDS
  - WITH WATER (SATURATED SOIL)
  - WITH AIR AND WATER (SEMI-SATURATED)
  - WITH AIR
- TWO OR THREE PHASE MEDIUM
  - NON-DEFORMABLE AND DEFORMABLE PARTICLES
  - INCOMPRESSIBLE INTERSTITIAL FLUID (AND COMPRESSIBLE AIR)
  - DEFORMATION CAUSED BY ROLLING AND SLIDING OF THE PARTICLES, EXPULSION OF WATER AND AIR.

Figure 2.2 Origins of soils from rocks.

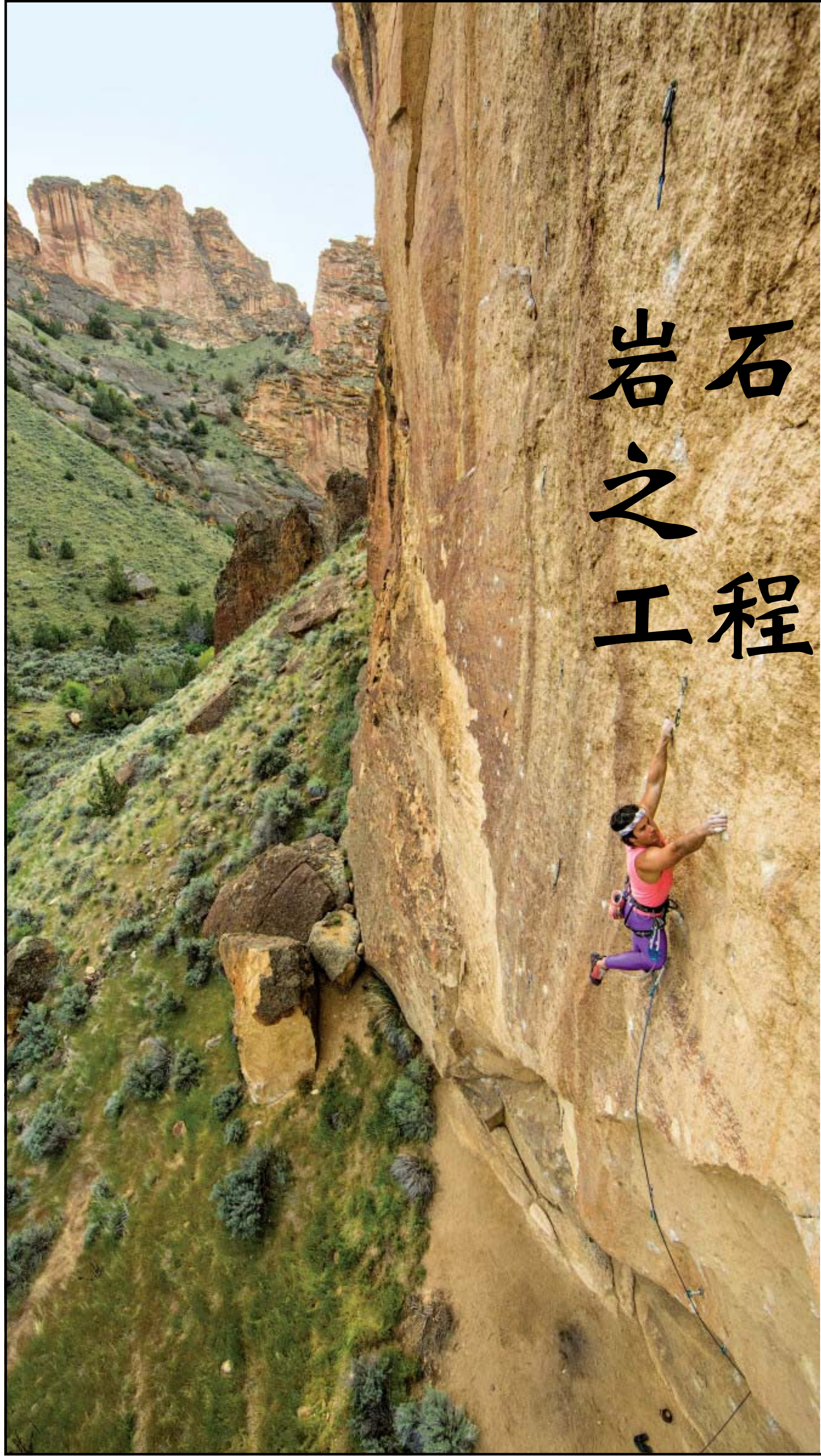
(González de Vallejo & Ferrer, 2011)

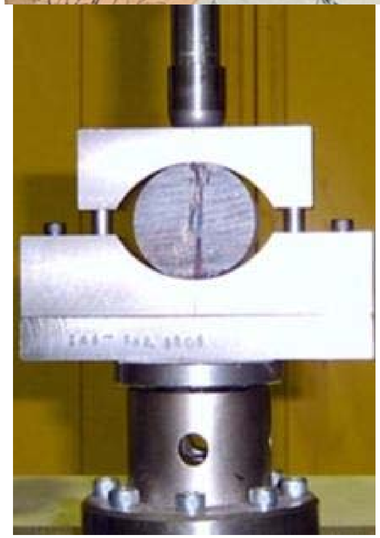
土壤分類

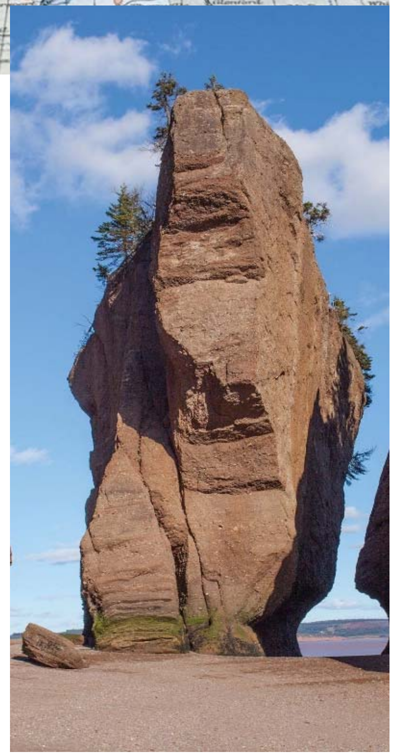
- 根據礦物組成和氣候條件分類
  - **鈣層土**(pedocal)：溫帶乾燥地區土壤，降雨量太低以至於無O層，因強烈蒸發作用，地下水攜帶溶解的碳酸鈣沉澱在B層下形成K層。
  - **鐵鋁土**(pedalfer)：溫帶潮濕地區土壤，受雨量多及常綠植物森林影響，地表有厚的O層，淋溶作用帶來大量的黏土礦物堆積在A層之下，形成酸性土壤的E層。
  - **紅土**(laterite)：熱帶多雨地區土壤，因受強烈淋溶作用影響，所有溶解的礦物均被淋溶而流失，僅留下富含鐵及鋁的氧化物和氫氧化物。


土壤

岩石

岩石之工程性質







岩體、完整岩石與不連續面

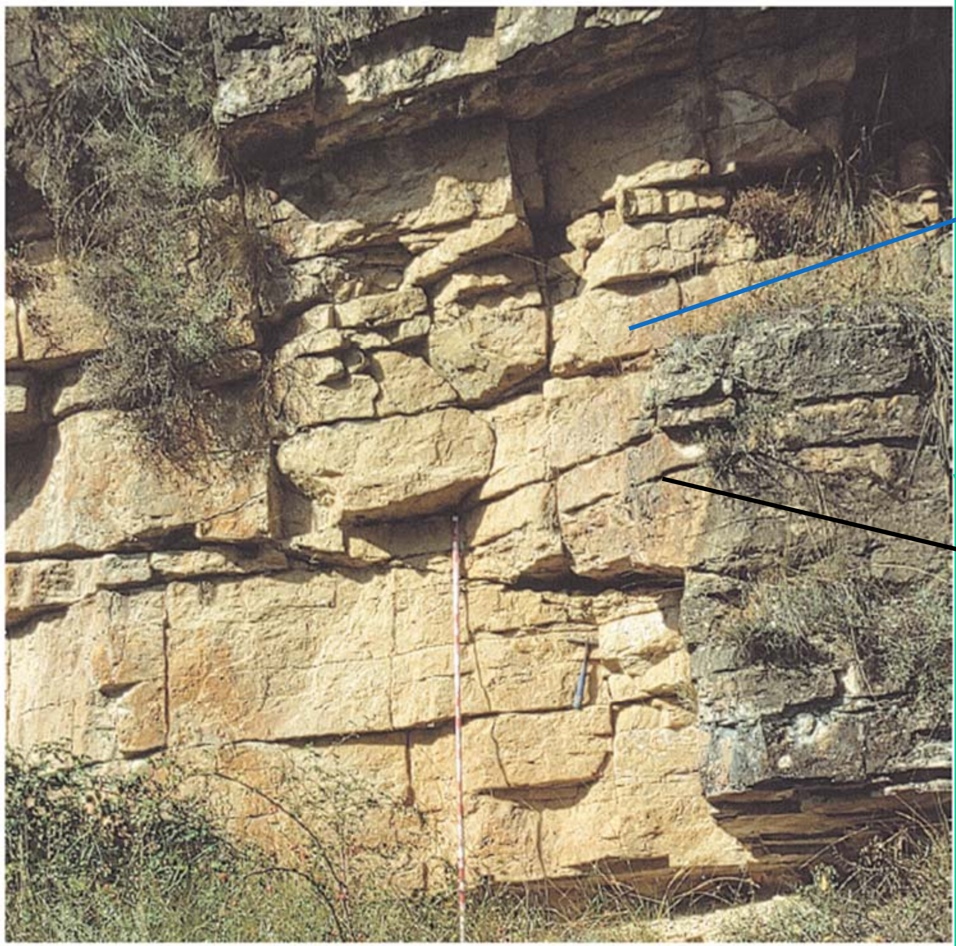


Figure 3.1 Rock mass. Blocks of Bunter sandstone separated by discontinuities.

- 岩石指的是完整的、沒有裂隙或不連續面切割的地質體，稱為**完整岩石(intact rock)**
- 如果岩石被不連續面所切割，失去完整性，就稱為**岩體(rock mass)**
- **不連續面(discontinuity)**指發育於岩體中，具有一定方向及延伸性，以及一定厚度的各種地質界面，如斷層、節理、層理、葉理、不整合面等都屬之。不連續面是岩體內的面狀構造。

小尺度：僅考慮完整岩石

- Rock properties and how they vary deals with the chemical composition (化學組成) of the heterogeneous crystal aggregates and amorphous particles forming the rocks.
- Rock fabric (petrofabric, 岩石組構) is the result of its genesis and geological history, shows its preferred anisotropy in the orientation of grains and crystals.

花崗岩：礦物結晶鑲嵌在一起

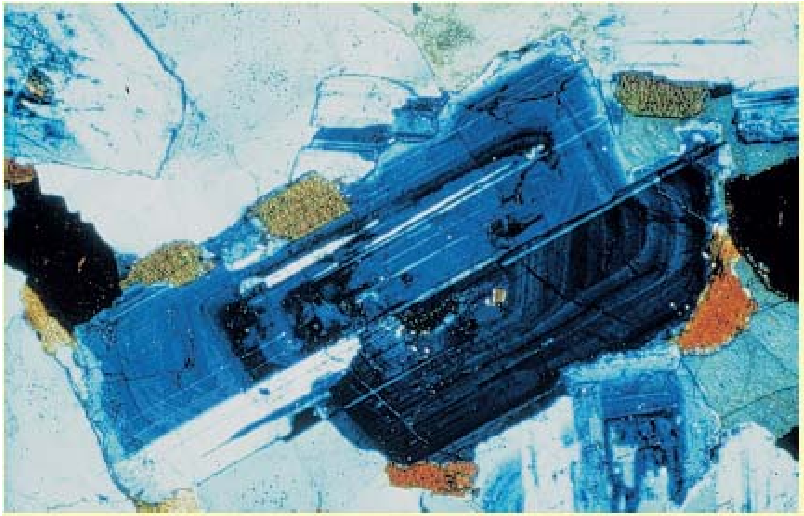


Photo A (view through petrological microscope)

泥岩：黏土礦物排列具有方向性

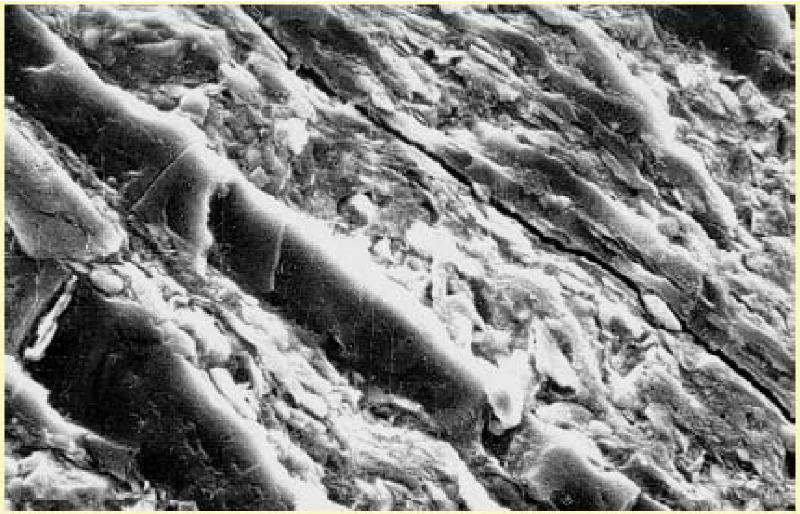
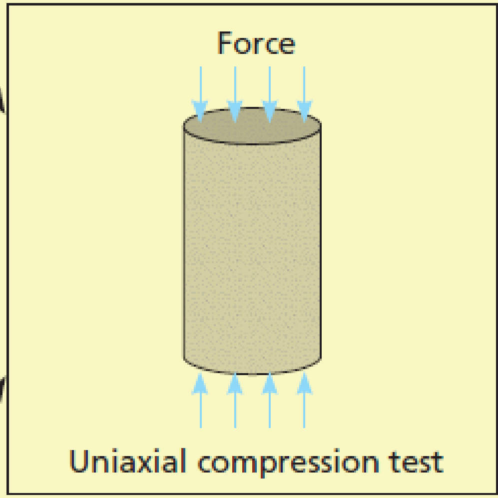


Photo B (electronic microscope image)

脆性(brittle)&延性(ductile)

Granite (Photo A)
- Intrusive acid igneous rock.
- Interconnected coarse-grained crystals with no preferred orientation.
- Composition: quartz, feldspar, micas and mafic minerals.

花崗岩：礦物結晶鑲嵌在一起



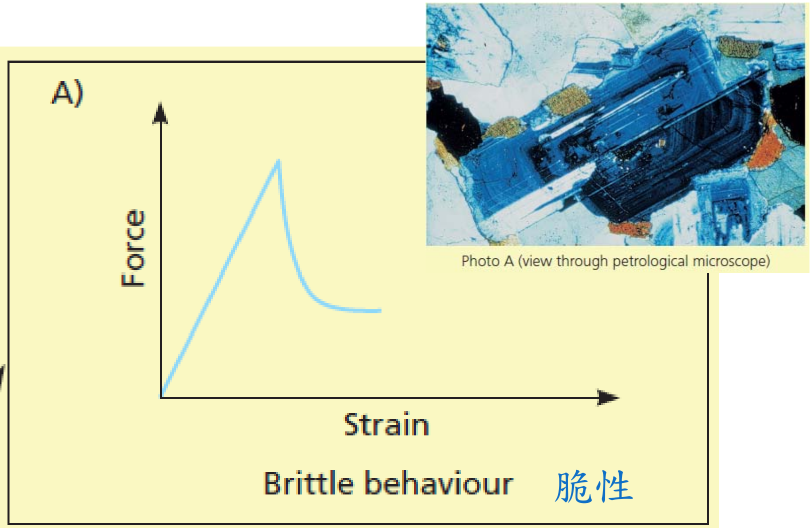


Photo A (view through petrological microscope)

Mudstone (Photo B)
- Clayey clastic sedimentary rock.
- Fine grains with banding and parallel orientation of minerals.
- Composition: clayey minerals (mainly illite and kaolinite), quartz and other minerals.

泥岩：黏土礦物排列具有方向性

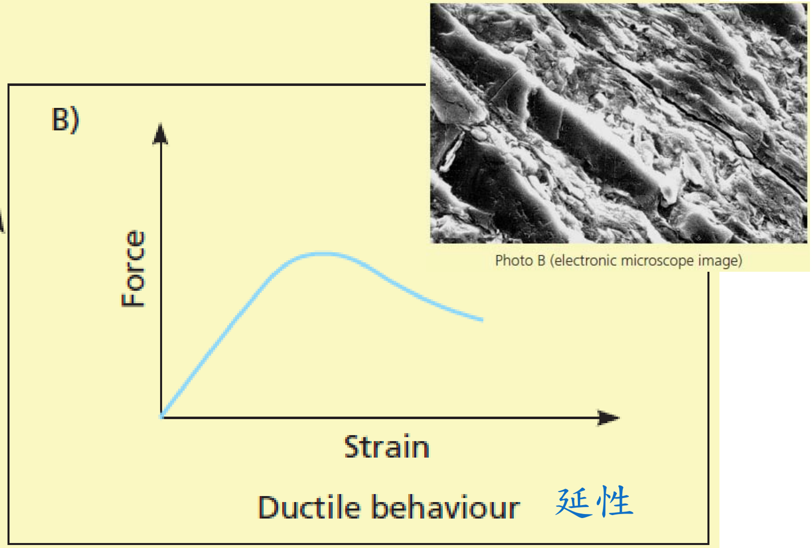
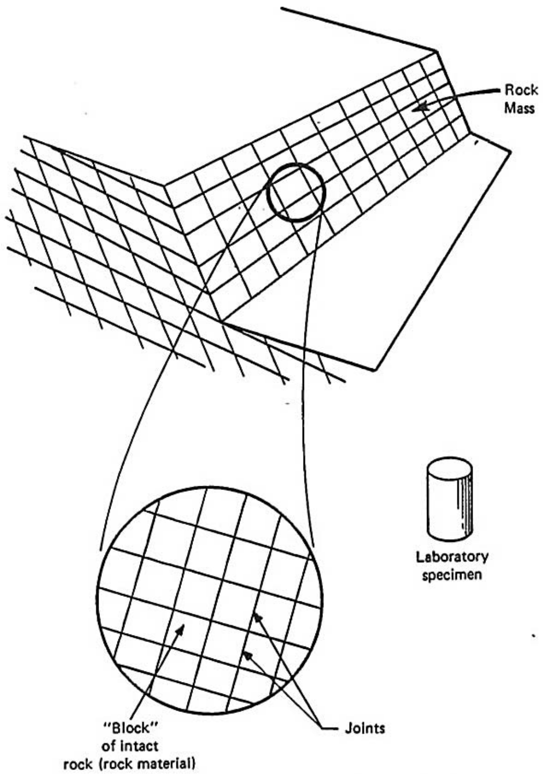


Photo B (electronic microscope image)

大尺度：完整岩石+不連續面

- In these cases, to evaluate the influence of these discontinuities, the scale or scope of the project must also be considered.



Definitions of *rock mass* and *rock material*.

岩體

岩體
(rock mass)

=

完整岩石
(intact rock)

+

不連續面
(discontinuity)

規模效應(scale effect)

- If the weak planes or zones are large enough to affect the behaviour of the rock mass on the site, a separate study of them must be carried out.

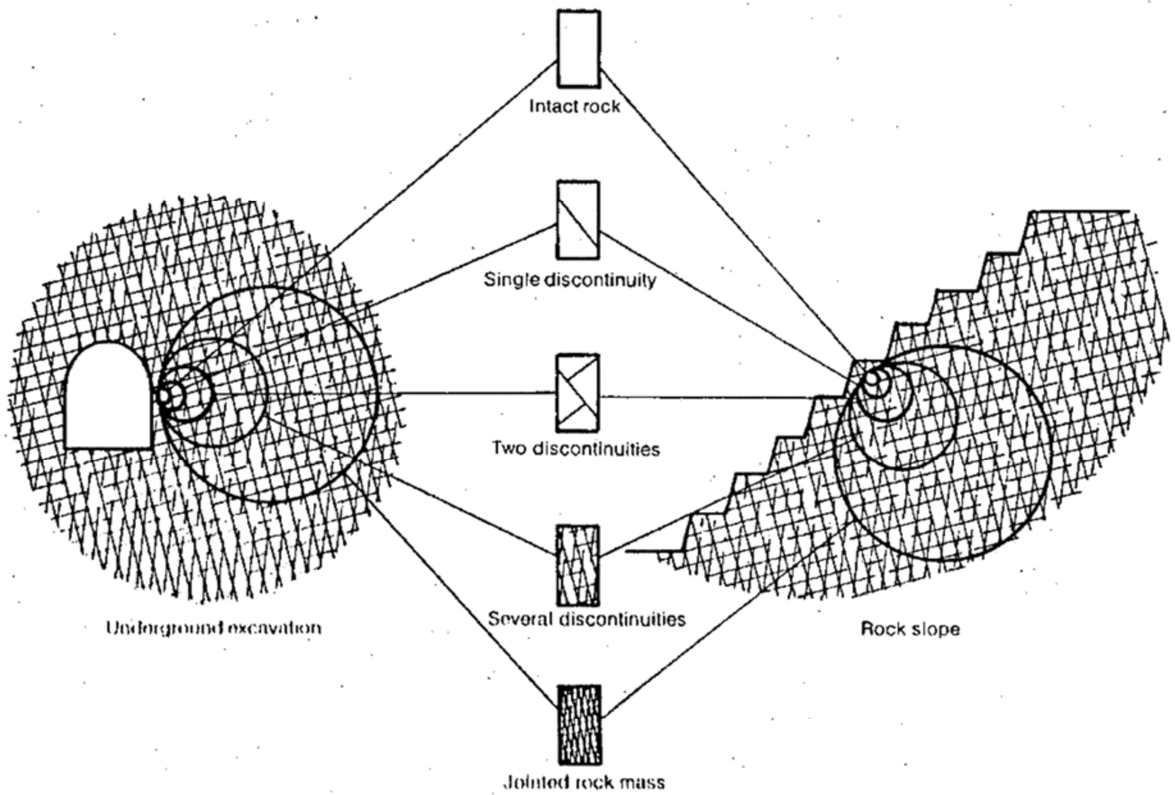


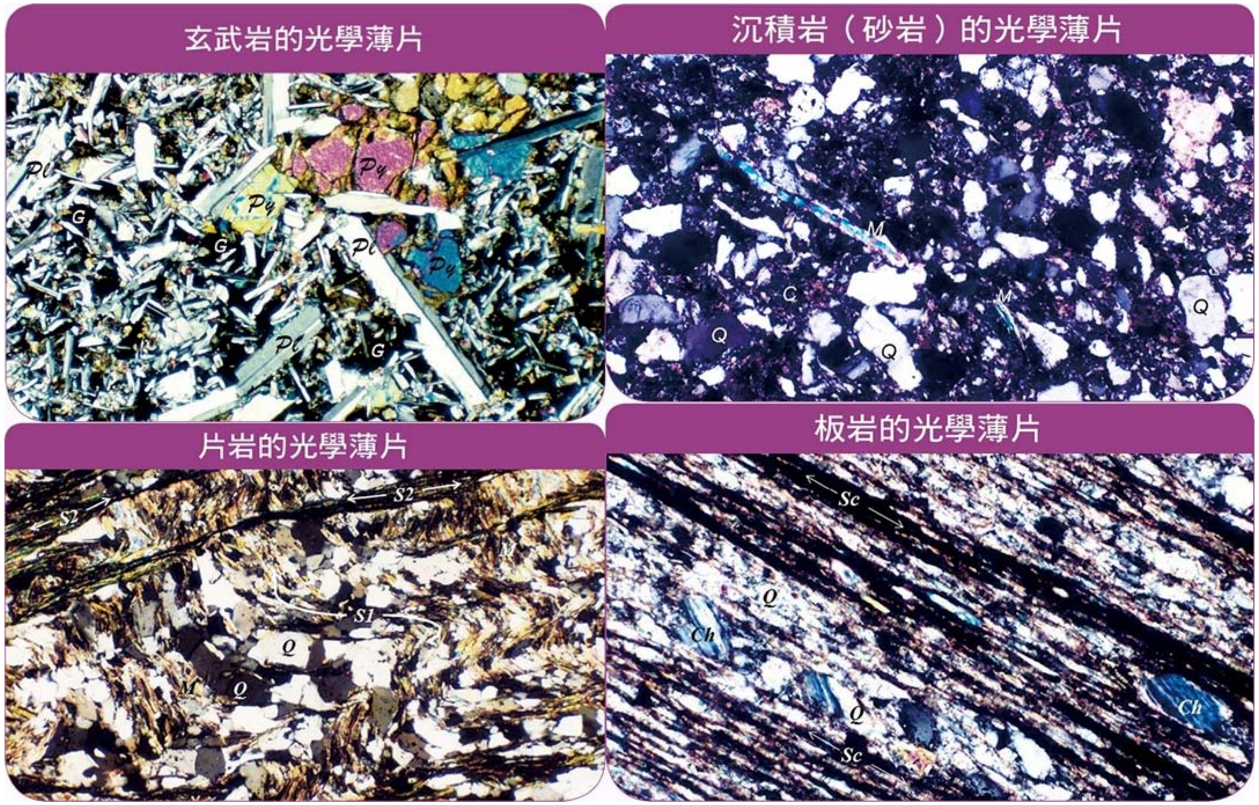
Figure 1. Effect of scale on the type of rock mass behavior model which should be used in designing underground excavations and slopes (after Hoek, 1983).

完整岩石的力學特性及測定方法

Table 3.1	PROPERTIES OF INTACT ROCK AND HOW THEY ARE DETERMINED	
	Properties	**Determination methods**
Identification and classification properties	Mineralogical composition. Fabric and texture. Grain size. Colour.	Visual description. Optical and electronic microscopy. X-ray diffraction.
	Porosity (n)	Laboratory techniques.
	Unit weight (γ)	
	Water content.	
	Permeability (permeability coefficient, k)	Permeability test.
	Durability. Alterability (alterability index)	Alterability tests.
Mechanical properties	Uniaxial compressive strength (σ_c)	Uniaxial compression test. Point load test. Schmidt hammer.
	Tensile strength (σ_t)	Direct tension test. Indirect tension test.
	Sonic wave velocity (V_p, V_s)	Laboratory measurement of elastic waves velocity.
	Strength (parameters c and ϕ)	Triaxial compression test.
	Deformability (static or dynamic elastic deformation modules: E, ν)	Uniaxial compression test. Sonic velocity test.

岩石的地質描述

- The geological description of a rock includes its name, mineralogy, texture, type of cementation and degree of alteration.
- 岩相描述(petrographic description)必須透過光學顯微鏡、電子顯微鏡拍攝微觀影像，和X光繞射技術的輔助進行判斷。



孔隙率

- **Porosity** is the ratio between the rock pore volume, Vv, and the total volume V (solid particles + pore spaces or voids):

  n(%) = Vv /V.

- Inversely proportional to strength and density, and directly proportional to deformability.
- Pores may be microcracks or cracks in the intact rock.
- In general, porosity decreases with depth and the age of the rocks.

Table 3.2 **TYPICAL VALUES FOR UNIT WEIGHT AND POROSITY OF ROCKS**

Rock	Unit weight (kN/m^3)	Porosity (%)
Andesite	22–23.5	10–15
Amphibolite	29–30	–
Basalt	27–29	0.1–2
Chalk	17–23	30
Coal	10–20	10
Diabase	29	0.1
Diorite	27–28.5	–
Dolomite	25–26	0.5–10
Gabbro	30–31	0.1–0.2
Gneiss	27–30	0.5–1-5
Granite	26–27	0.5–1.5 (0.9)
Greywacke	28	3
Gypsum	23	5
Limestone	23–26	5–20 (11)
Marble	26–28	0.3–2 (0.6)
Mudstone	22–26	2–15
Quartzite	26–27	0.1–0.5
Rhyolite	24–26	4–6
Salt	21–22	5
Sandstone	23–26	5–25 (16)
Schist	25–28	3
Shale	25–27	0.1–1
Tuff	19–23	14–40

單位重

- **Unit weight** of the rock depends on its components and is defined as the weight per unit volume.
- γ = ρ g

$$\gamma_{dry} = G\gamma_w(1-n)$$

$$\gamma_{dry} = \frac{r_{wet}}{1+\omega}$$

$$n = \frac{\omega \cdot G}{1+\omega \cdot G}$$

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Schist	25–28	3
Shale	25–27	0.1–1
Tuff	19–23	14–40

滲透性

- **Permeability** is the water-transmitting capacity of a rock
- Most rocks have low or very low permeability.
- Water infiltrates and flows through intact rock through pores and cracks, and the permeability is determined by how these are interconnected and other factors, such as the degree of weathering, anisotropy and the state of stress the material is subjected to.
- The coefficient of permeability or hydraulic conductivity, ***k***, expressed in m/s, cm/s or m/day.
- $Q = kiA$
- $q_x = k(dh/dx)A$

滲透性

Table 3.3 TYPICAL PERMEABILITY VALUES FOR INTACT ROCK

Rock	k (m/s)
Granite	10^{-9}–10^{-12}
Limestone and dolomite	10^{-6}–10^{-12}
Metamorphic rocks	10^{-9}–10^{-12}
Mudstone	10^{-9}–10^{-13}
Salt	$<10^{-11}$–10^{-13}
Sandstone	10^{-5}–10^{-10}
Schist	10^{-7}–10^{-8}
Shale	10^{-11}–10^{-13}
Volcanic rocks	10^{-7}–10^{-12}

耐久性

- **Durability** is the resistance of rock to weakening and disintegration processes.
- This property is also described as **alterability**, defined in this case as the tendency of the intact rock components or structures to failure.
- The properties of intact rock are changed by a number of processes including hydration, dissolution and oxidation.
- Durability is measured with the **Slake Durability test** (SDT), which subjects previously fragmented rock samples to standard 10 minute drying and wetting cycles in the laboratory.

消散耐久試驗

- Oven-dry the fragments of rock ~500 g (10塊)
- Weighed the fragments of rock and placed in a drum with a 2 mm external mesh.
- The drum is placed in a bath filled with water to a level below the drum axis and then rotated for ten minutes. 20 rev./min, 10 min
- The samples remaining in the drum are taken out, oven-dried and weighed.
- Repeat the process.

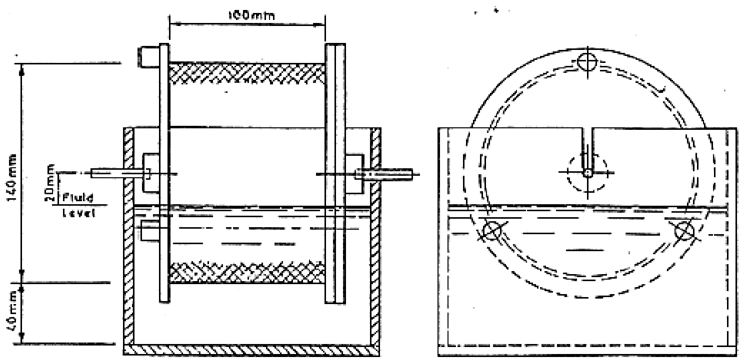


Fig. 4. Critical dimensions of slake-durability test equipment.

Figure 3.8 Slake durability test apparatus.

消散耐久試驗

- The **slake-durability index, *I_D***, represents the proportion of dry-weight rock remaining in the drum after one or two disintegration cycles (I_{D1}, I_{D2}), and may vary from 0% to 100%:

$$I_D(\%) = \frac{\text{Dry weight after 1 or 2 cycles}}{\text{Initial weight of sample}}$$

- Standard classification is based on the value of I_{D2}.

Table 3.4 **DURABILITY CLASSIFICATION BASED ON THE I_{D2} INDEX**

Durability	% weight retained after 2 cycles
Very high	>98
High	95–98
Medium-high	85–95
Medium	60–85
Low	30–60
Very low	<30

Table 3.5 DURABILITY CLASSIFICATION BASED ON THE I_{D1} INDEX

Durability	% weight retained after 1 cycle (1)	(2)
Extremely high	–	>95
Very high	>99	90–95
High	98–99	75–90
Medium-high	95–98	–
Medium	85–95	50–75
Low	60–85	25–50
Very low	<60	<25

(1) Gamble, 1971 (in: Goodman, 1989)
(2) Frankling and Chandra, 1972 (in: Johnson and De Graff, 1988)

強度

- **Uniaxial compressive strength** or uniaxial strength is the maximum stress the rock can carry under uniaxial compression, measured on an unconfined cylindrical specimen in the laboratory and is given by:

$$\sigma_C = \frac{F_C}{A} = \frac{\text{Compressive force applied}}{\text{Area of application}}$$

Table 3.6 **STRENGTH VALUES FOR FRESH INTACT ROCK**

Fresh rock	Uniaxial compressive strength (MPa)		Tensile strength (MPa)
	Average values	Range of values	
Andesite	210–320	100–500	7
Amphibolite	280	210–530	23
Anhydrite	90	80–130	6–12
Basalt	80–200	60–350	5–25
Diabase	240–350	130–365	55
Diorite	180–245	120–335	8–30
Dolerite	200–300	100–350	15–35
Dolomite	60–200	50–350	5–25
Gabbro	210–280	180–300	14–30
Gneiss	60–200	50–250	5–20
Granite	70–200	50–300	7–25
Greywacke	100–150	80–220	5.5–15
Gypsum	25	10–40	1–2.5
Limestone	60–140	50–200	4–30
Marble	120–200	60–250	6–20
Marl	30–70	20–90	–
Mudstone	20–40	10–90	1.5–10 0.5–1*
Quartzite	200–320	100–500	10–30
Salt	12	5–30	–
Sandstone	55–140	30–235	5–20
Schist	30–60	20–160	2–5.5
Shale	40–150	30–200	7–20
Siltstone	–	35–250	2.7
Tuff	–	10–46	1–4

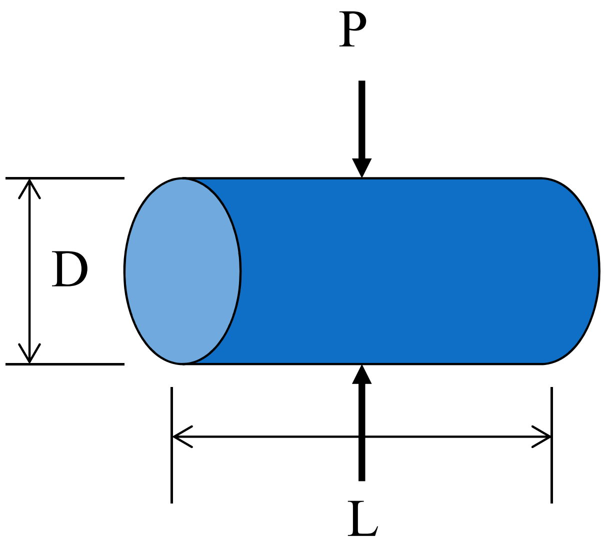
(*) Along lamination planes.
Data selected from Rahn (1986), Walthan (1999), Obert and Duvall (1967), Farmer (1968).

強度

- The approximate compressive strength can also be estimated from correlation with indexes obtained with simple field tests, such as the **Point Load test** (PLt) or the **Schmidt hammer test**.

Schmidt hammer test

點荷重試驗



$$L \geq 1.4D$$

$$I_s = \frac{P}{D^2}$$

(a) (b)

Figure 3.11 (a) Point load tester and (b) conical platen.

When D=50 mm, $q_u = 24 I_{s(50)}$

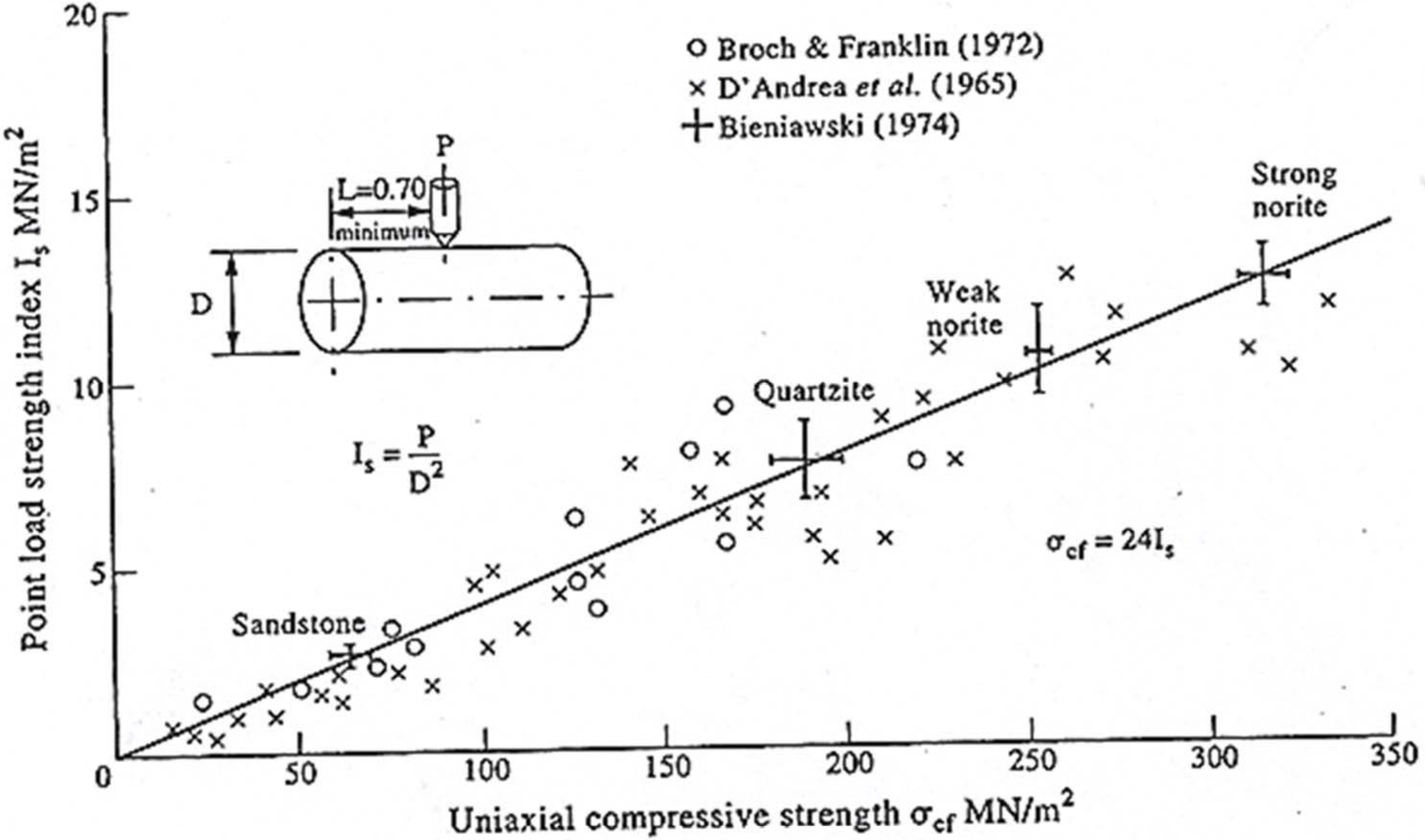


Figure 11.6 Schmidt hammer and point load test calibration curves.

Point-Load Test

(Reference: ISRM(1985), "Suggested Method for Determining Point-Load Strength," Int. J. R. M. vol.22, no.2, pp.51-60)

(1) Point-Load Index(strength)

$$I_{s(50)} = I_s \times F$$

where

$I_{s(50)}$ = size-corrected point-load strength (index)

$I_s = P/D_e^2$: uncorrected point-load strength

$F = \left(D_e/50\right)^{0.45}$ (unit:mm) : size correction factor

P : point load

$D_e^2 = D^2$ for diametral test

$4A/\pi$ for axial, block and lump tests

and

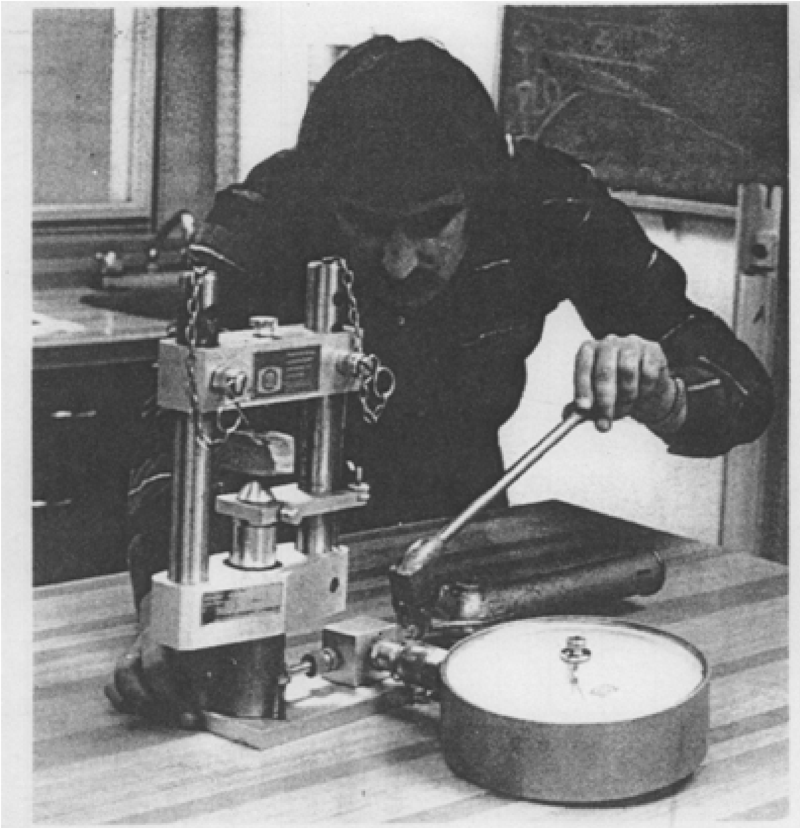
$A = WD$ = minimum cross sectional area of a plane through the platen contact points

(2) (i) uniaxial compressive strength,

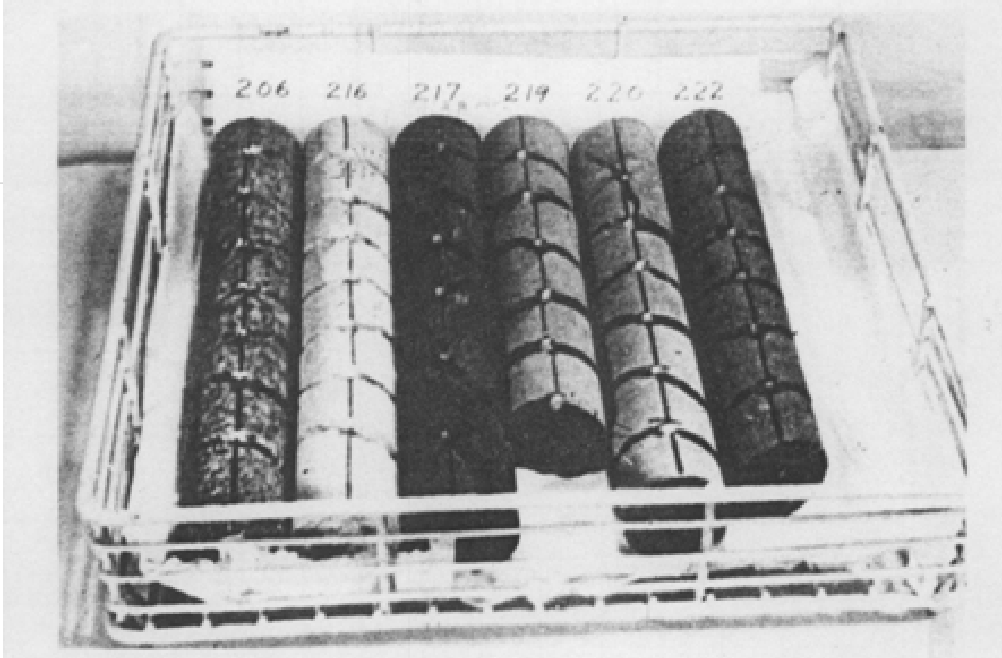
$$\sigma_c = (20 \sim 25) I_{s(50)}$$

(ii) uniaxial tensile strength,

$$\sigma_t = 1.25 I_{s(50)}$$



(a)



(b)

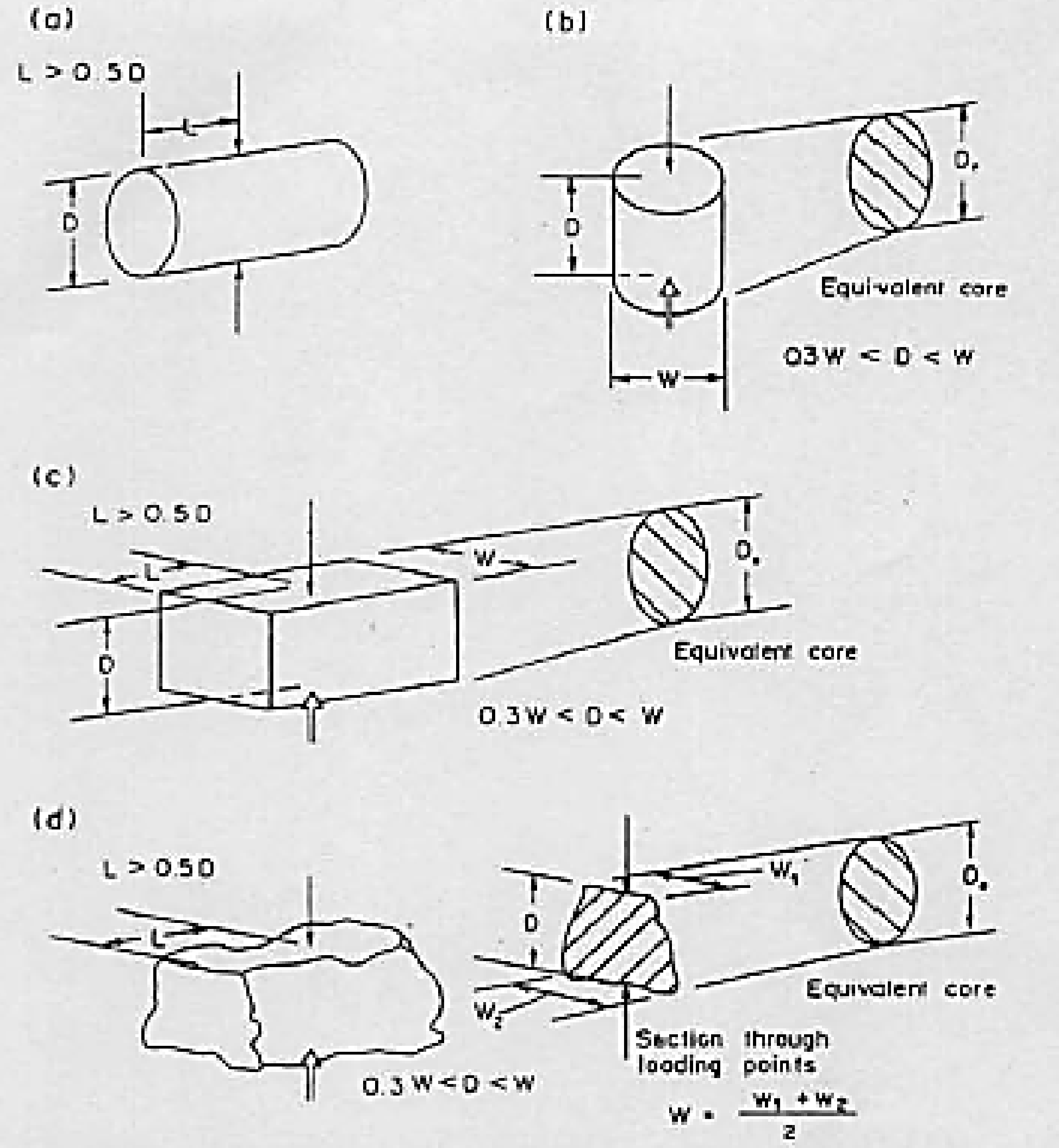


Fig. Specimen shape requirements for (a) the diametral test, (b) the axial test, (c) the block test, and (d) the irregular lump test.

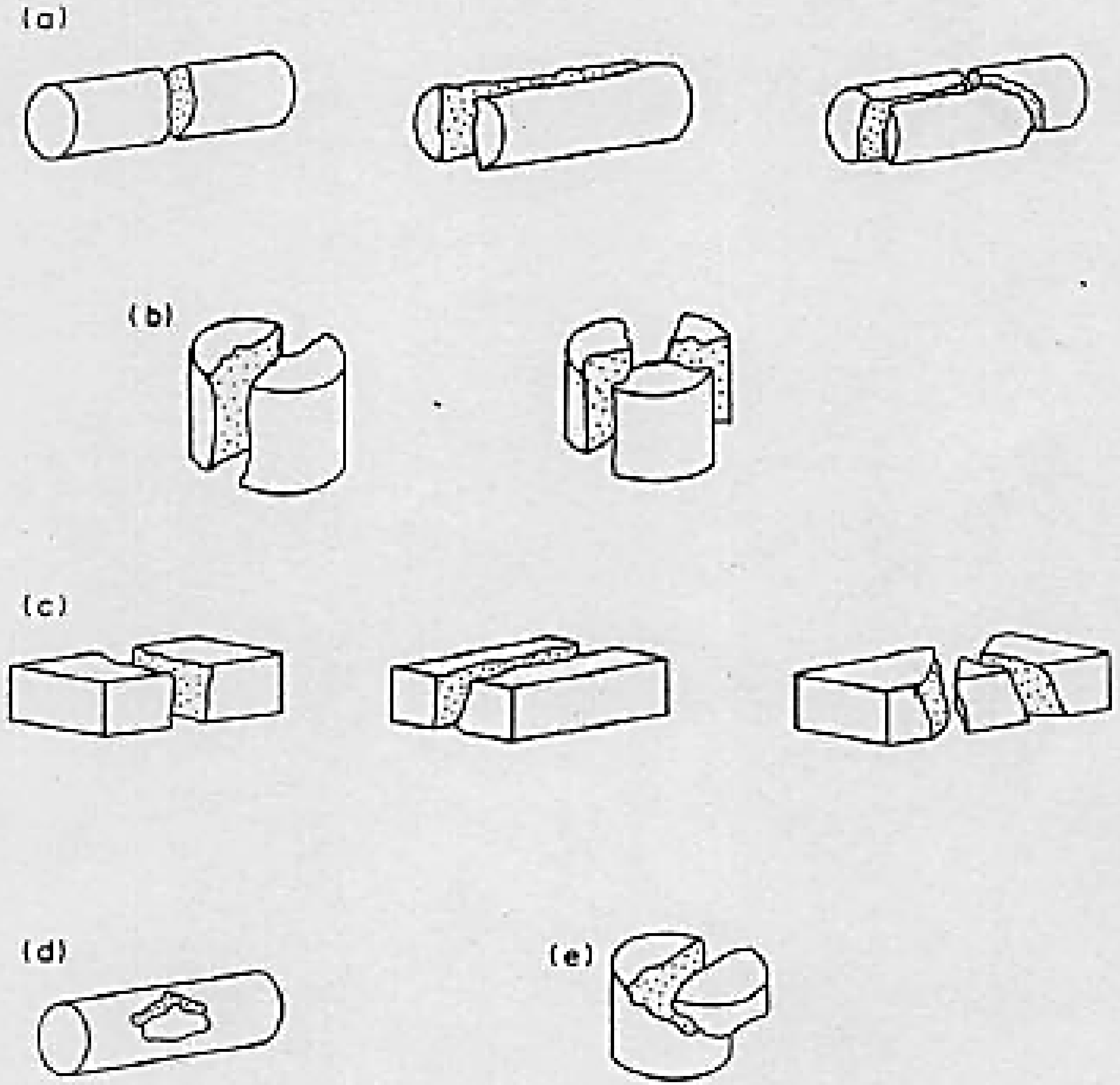
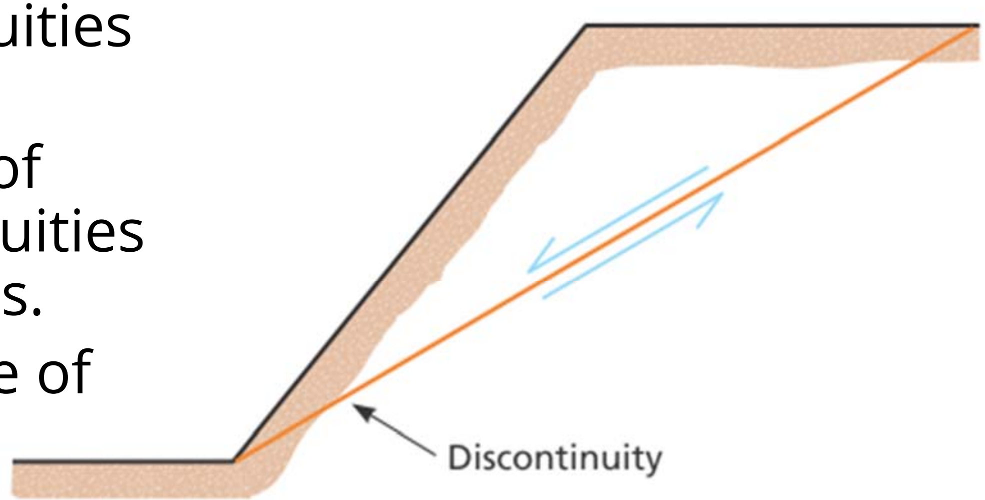


Fig. Typical modes of failure for valid and invalid tests. (a) Valid diametral tests; (b) valid axial tests; (c) valid block tests; (d) invalid core test; (e) invalid axial test.

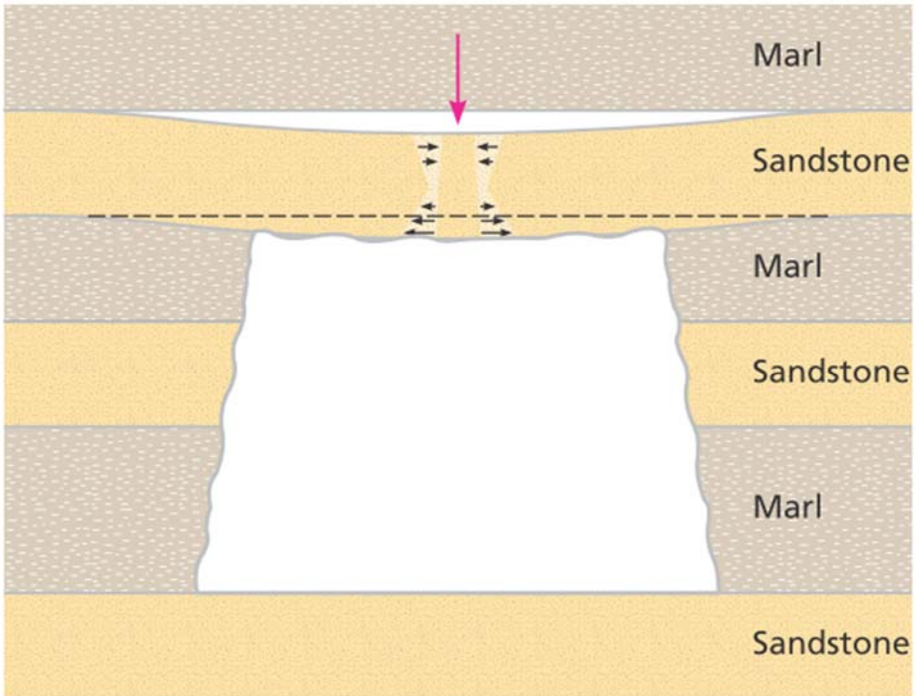
破壞機制(failure mechanism)

- Failure in rocks is a varied and complex process in which different types of phenomena and numerous factors are involved acting together.
- **Shear stress failure**. This takes place when a specific rock surface is subjected to shear stresses that are high enough to cause one face of the surface to slip relative to the other.
    - Failure along discontinuities in rock slopes.
    - Collapse of a tunnel roof along vertical discontinuities bounding stiff side walls.
    - The most common type of failure and the most important.



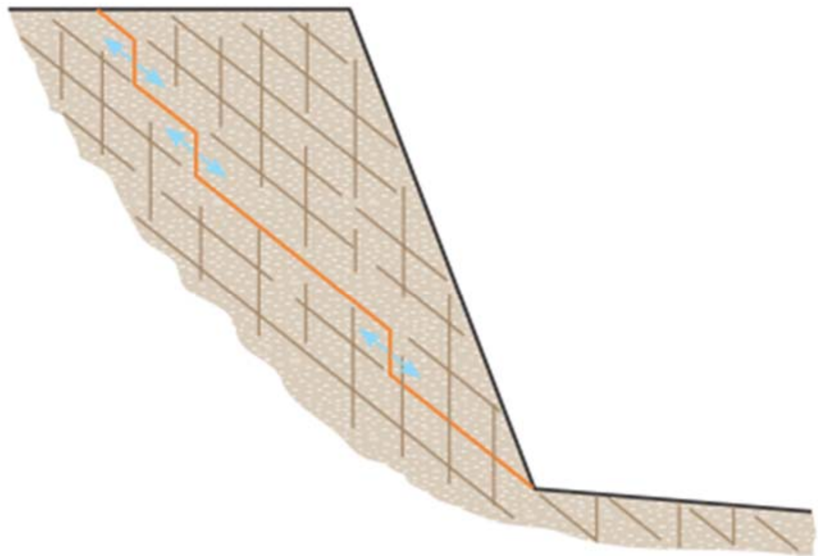
a) Shear failure in a slope

- **Flexure failure**. This occurs when a section of rock is subjected to a series of variable stresses, failing in the area where tensional stresses accumulate.
    - The capping beams of underground galleries or in the roofs of karstic cavities.



b) Failure from strata flexure in the roof of a mine.

- **Direct tension failure**. This type of failure takes place when a certain section of the rock is subjected to pure or almost pure tension due to the configuration and/or structure of the rock mass.



c) Discontinuity surfaces subjected to direct tension.

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