

**CVG4184 / 6305: Rock Mechanics
Winter 2020**

Chapter 1: Introduction to Rock Mechanics

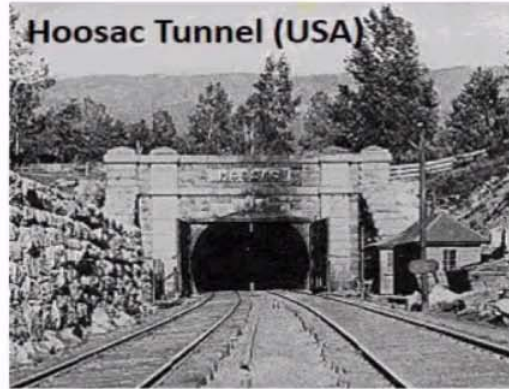
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Introduction

- Historically, different structures have been built on or in rocks, including tunnels, bridges, dams and caverns.



(forums.france2.fr)



(american-rails.com)



(shutterstock.com)



(vajont.info)

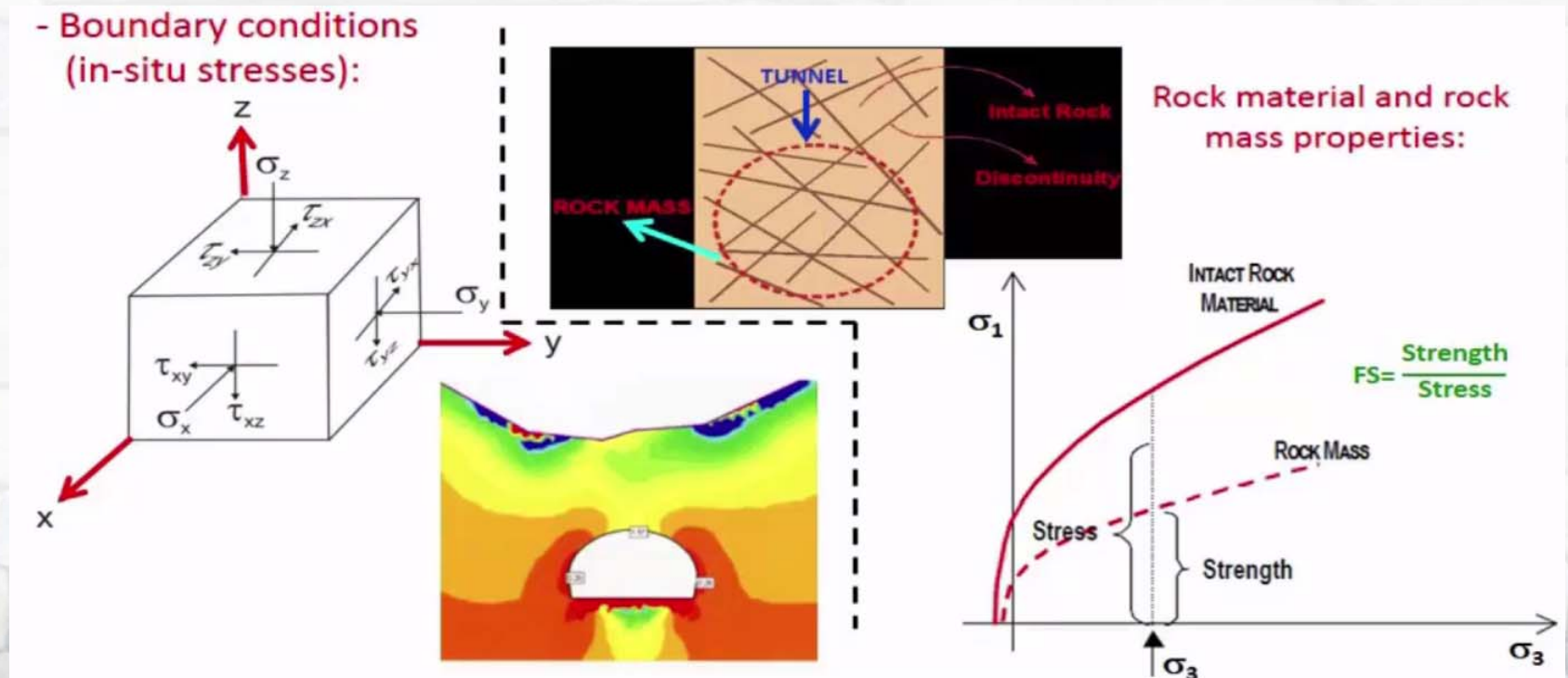
Vajont Dam (Italy)



(famouswonders.com)

Rock mechanics

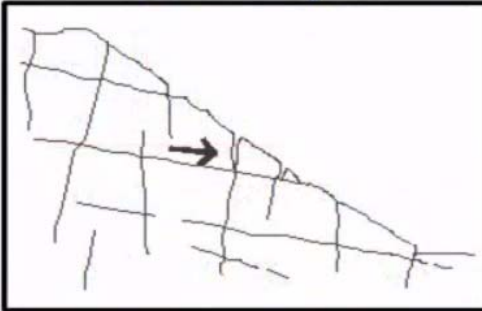
- **Rock Mechanics** includes all studies relative to the physical and mechanical behaviour of rocks and rock masses and the applications of this knowledge for the better understanding of geological processes and in the fields of Engineering (ISRM Statutes).



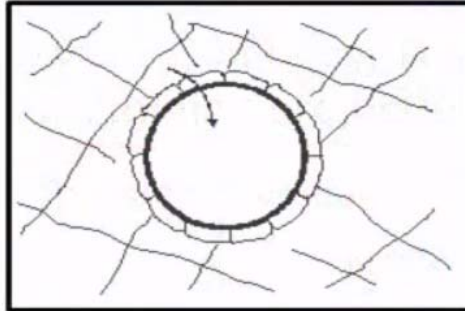
Engineering applications of Rock Mechanics

- Main areas of application of Rock Mechanics

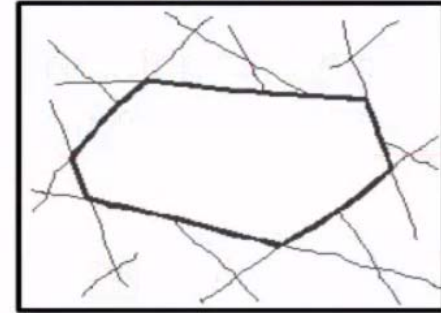
Rock Slopes



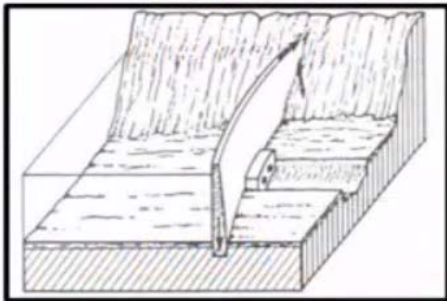
Shafts & Tunnels



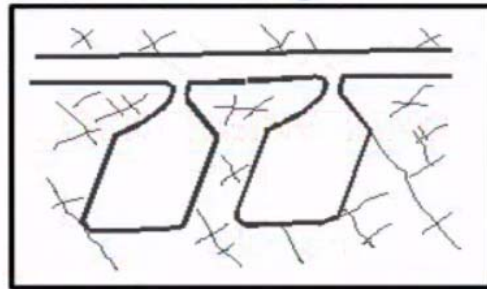
Caverns



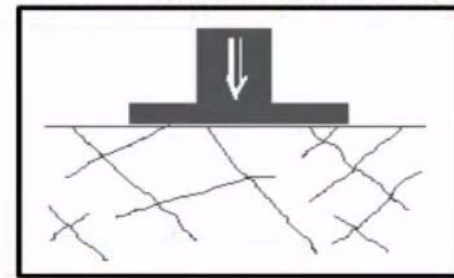
Dams



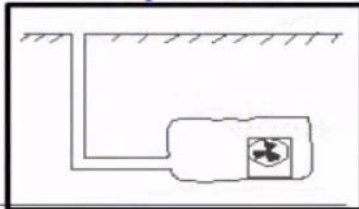
Mining



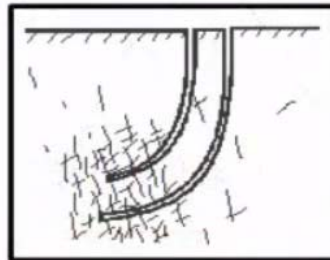
Foundations



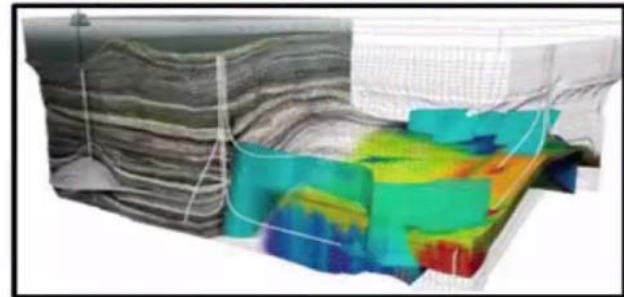
Radioactive Waste Disposals



Geothermal Energy



Petroleum Geomechanics



(Rearranged from Hudson, 1989)

Engineering applications of Rock Mechanics

- **Building construction**: deep foundations; stability of deep open excavations.
- **Surface mining**: slope stability; rock mass excavation; drilling and blasting; fragmentation.
- **Underground mining**: shaft, pillar, drift and stope design; drilling and blasting; fragmentation; cavability and rockbursts evaluation; in-situ recovery.
- **Transportation**: highway and railway slopes, tunnels and bridge foundations; canals and waterways; urban rapid transport tunnels and stations; pipelines.
- **Utilities**: dam foundations; stability of reservoir slopes; water supply and sanitation tunnels; waste treatment plants; underground storages.

Development of rock mechanics

- **Two major disasters** triggered the need for better understanding and more research into rock mechanics principles:
 - The failure of **Malpasset** concrete arch dam in France on December 3, 1959, killing 450 people;
 - The upstream landslide that displaced a large volume of water, overtopping **Vajont** Dam in Italy on October 9, 1963, claiming more than 2000 lives downstream.

Remains of the Malpasset dam as seen today.



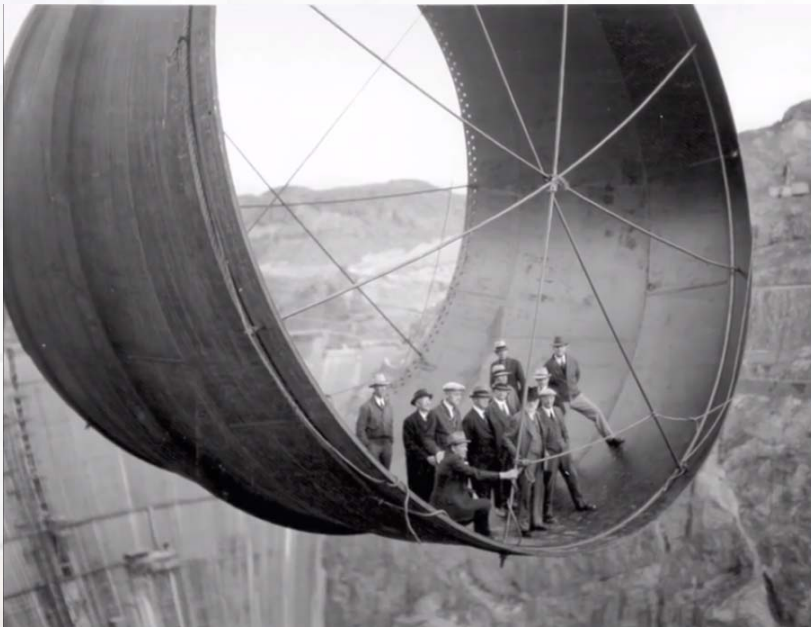
The Vajont dam failure

When: October 9, 1963

Where: 100 km north of Venice, Italy

The Dam

- Height: 265.5 m
- Width: 160 m
- Thickness: 22.11 m (base); 3.4 m (top)
- Capacity: 168 million cubic meters

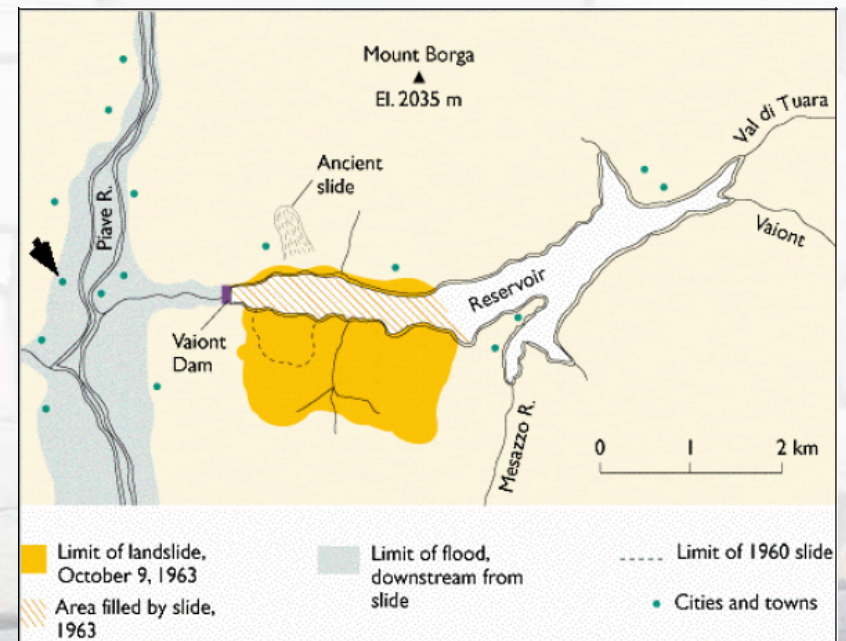
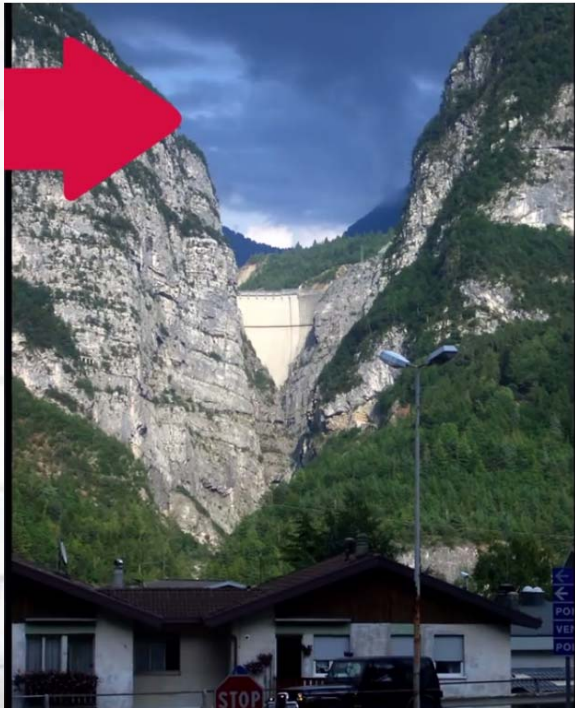


The Vajont dam

The Vajont dam failure

The landslide

- Area: 2 x 1.6 km
- Volume: 240 million cubic meters
- Duration: 15-30 seconds
- Mega tsunami: 250 m high
- Sliding velocity: 20-30 m/s



The Vajont dam failure

The aftermath

- more than 2000 dead
- the hostel on the right abutment swept away
- millions in economic damage
- the dam itself did not fail
- following the slide, **many countries revised their regulations** governing reservoir slopes.
- failure has prompted engineers to place **more emphasis on the study of geological settings** and their bearing on site constructability.

The town of Longarone, located downstream of the Vajont dam, before and after the Mount Toc failure



The Vajont dam failure - causes

- **Geologic features**

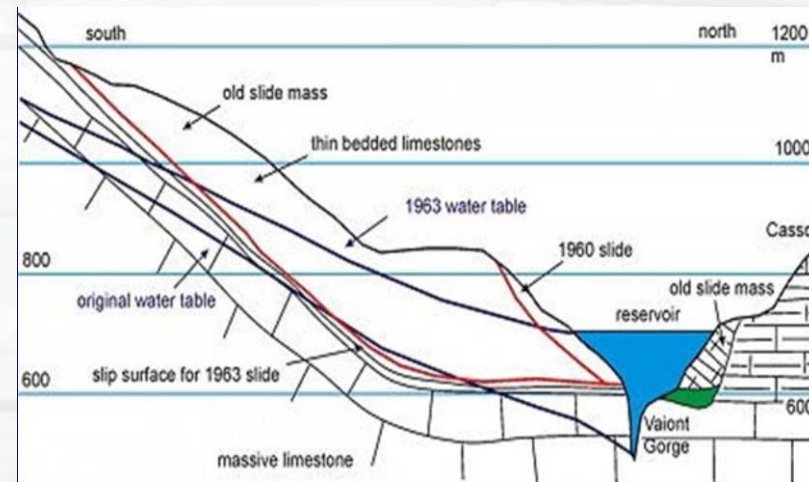
- weak sedimentary rocks with frequent clayey interbeds;
- rocks with low shearing resistance;
- cavities, tubes and sinkholes;
- relief joints parallel to slopes;
- Steep slopes (high gravity loads).

- **Man-made causes**

- Impounding reservoir submerged the toe of the slope;
- Raised ground water table increased hydrostatic uplift forces at the base.

- **Natural causes**

- Progressive weakening of rock mass accelerated by excessive rainfall;
- Rainfall increased the bulk density of rock mass.



Characteristics of the rock masses

- **Discontinuous rock masses:**
 - An important feature of rock masses is that they are **broken up by joints and faults**.
 - Josef Stini (1920-1958) first emphasized the importance of **structural discontinuities** in controlling the behavior of rock masses.
 - **Discontinuities** radically alter the behavior of rock in place from that predictable on the basis of testing intact samples.



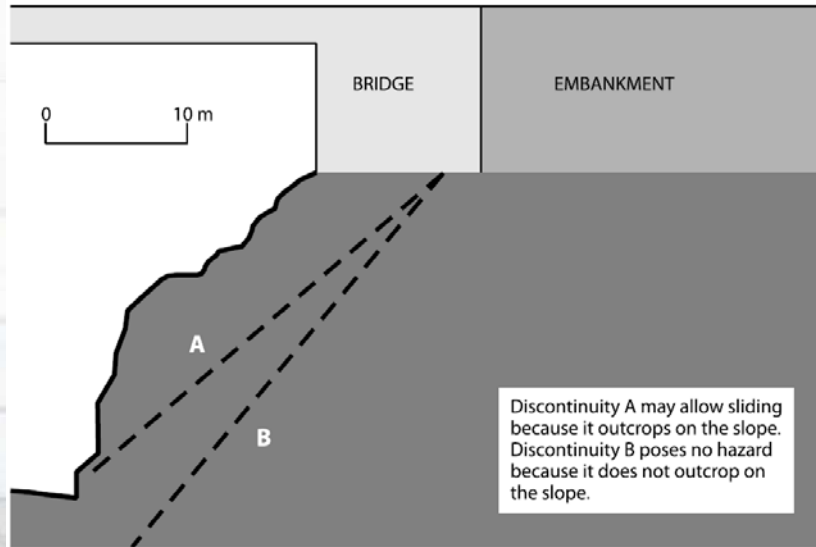
A wedge failure controlled by intersecting structural features in the rock mass

Characteristics of the rock masses

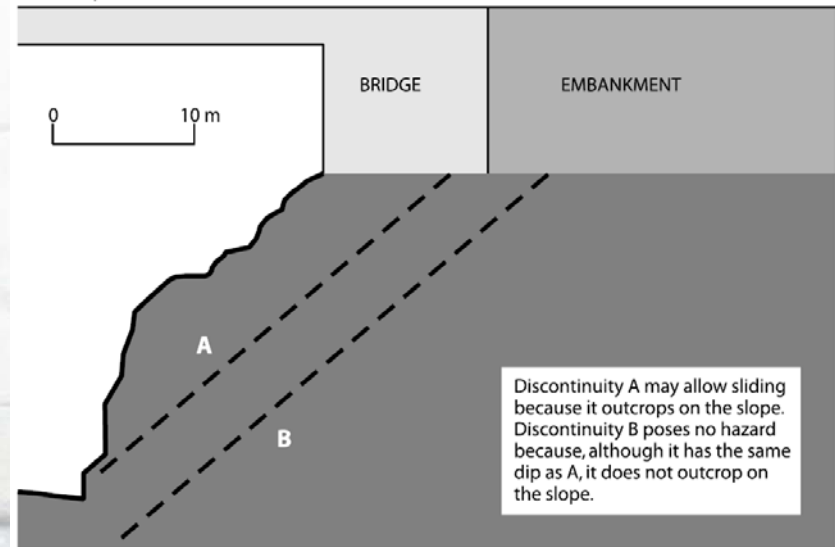
- Importance of discontinuities

- they are planes of weakness in the much stronger, intact rock so failure tends to occur preferentially along these surfaces.
- The properties of discontinuities relative to stability include **orientation**, **persistence**, **roughness** and **infilling**.

a The importance of discontinuity orientation



b The importance of location



Characteristics of the rock masses

- A clear distinction must be made between the **intact rock or rock material** and the **rock mass**.
- The **intact rock** may be considered as a continuum or polycrystalline solid between discontinuities.
- The **rock mass** is the in situ medium comprised of intact rock blocks separated by discontinuities such as joints, bedding planes, folds, sheared zones and faults.
- In **rock mechanics**, two distinct problems are always involved:
 - the study of the **properties and fabric of the rock** between the joints;
 - the study of the **orientations and properties of the joints**.

Soil versus rock mechanics

- The **continuum approach** of soil mechanics is only applicable to a limited number of special cases in rock mechanics.
- The **presence of discontinuities** in rock masses has major effect on its properties.
- Both soils and in-situ rock masses contain **water**, but the **static and dynamic behaviour** of the water is different.
- The soil mechanics approach allows **strength and deformation tests** to be carried out on relatively small samples in the laboratory, while in most cases it yields misleading results if applied to rock mechanics problems.

Analysis of rock masses

- **Stages** in rock mechanics practical analysis:
 - **Geological and geophysical investigation:** to establish the lithologies and boundaries of the rock types involved.
 - **Drilling or investigatory excavations:** to establish the detailed pattern of jointing and obtain rock samples for laboratory testing.
 - **Laboratory testing program:** to determine the mechanical and petrological properties of intact rock samples.
 - ***In situ* testing:** to measure the *in situ* rock stresses that are present in the unexcavated rock.

Rock-forming minerals

- **Mineral:** any naturally occurring inorganic solid that possesses an orderly crystalline structure and a definite chemical composition (with some variation).
- **Physical properties:** colour, streak, hardness, cleavage, fracture, luster, habit (or form), tenacity, specific gravity, magnetism, odour, taste and feel.

Table 1.1 Mohs scale of hardness

Hardness	Mineral
1	Talc
2	Gypsum
3	Calcite
4	Fluorite
5	Apatite
6	Orthoclase
7	Quartz
8	Topaz
9	Corundum
10	Diamond

Table 1.2 Specific gravity of some common minerals

Mineral	Specific gravity	Mineral	Specific gravity
Apatite	3.2	Hematite	4.72
Calcite	2.71	Magnetite	5.2
Chlorite	2.6–3.3	Pyrite	5.01
Clay minerals	2.5–2.8	Muscovite	2.8–3.0
Dolomite	2.85	Quartz	2.65
Feldspar	2.56–2.7	Rutile	4.2
Garnet	3.7–4.3	Topaz	3.6
Gypsum	2.32	Tourmaline	3.0–3.2
Hornblende	3.2	Zircon	4.7
Halite	2.16		

Rock-forming minerals

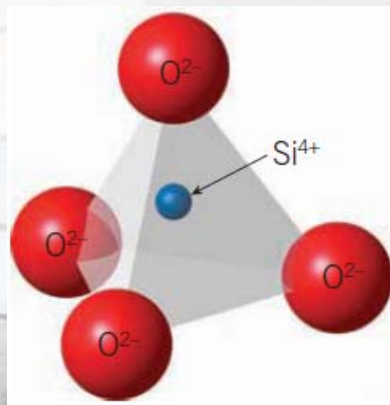
- In civil engineering practice, it is important to have knowledge of the minerals that form the rocks, i.e., the **rock-forming minerals**.
- **Silicates** and **carbonates** are the essential rock-forming minerals.

Table 1.3 Essential rock-forming minerals

<i>Silicates</i>	<i>Carbonates</i>
Silica (SiO_2)	Calcite (Ca carbonates)
Feldspars (Na, K, Ca and Al silicates)	Dolomite (Ca–Mg carbonates)
Amphiboles (Na, Ca, Mg, Fe and Al silicates)	
Pyroxenes (Mg, Fe, Ca and Al silicates)	
Micas (K, Mg, Fe and Al silicates)	
Garnets (Fe, Mg, Mn, Ca and Al silicates)	
Olivines (Mg and Fe silicates)	
Clay minerals (K, Fe, Mg and Al silicates)	

Rock-forming minerals – The Silicates

- **Silicate minerals** form the bulk (about 95%) of the Earth's crust.
- **Silica and feldspars** are the most common silicate minerals in the Earth's crust.
- Every silicate mineral contains oxygen and silicon.



Mineral/Formula	Cleavage	Silicate Structure	Example
Olivine group (Mg, Fe) $_2\text{SiO}_4$	None	Single tetrahedra 	 Olivine
Pyroxene group (Augite) (Mg, Fe) SiO_3	Two planes at 90°	Single chains 	 Augite
Amphibole group (Hornblende) $\text{Ca}_2(\text{Fe, Mg})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	Two planes at 60° and 120°	Double chains 	 Hornblende
Micas	One plane	Sheets 	 Biotite
			 Muscovite
Feldspars	Two planes at 90°	Three-dimensional networks 	 Potassium feldspar
			 Quartz
Potassium feldspar (Orthoclase) KAlSi_3O_8	Two planes at 90°		
Plagioclase (Ca, Na) AlSi_3O_8			
Quartz SiO_2	None		

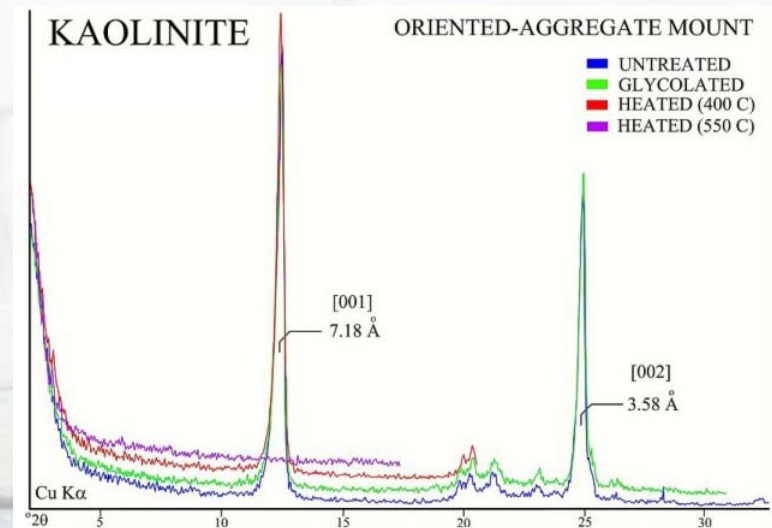
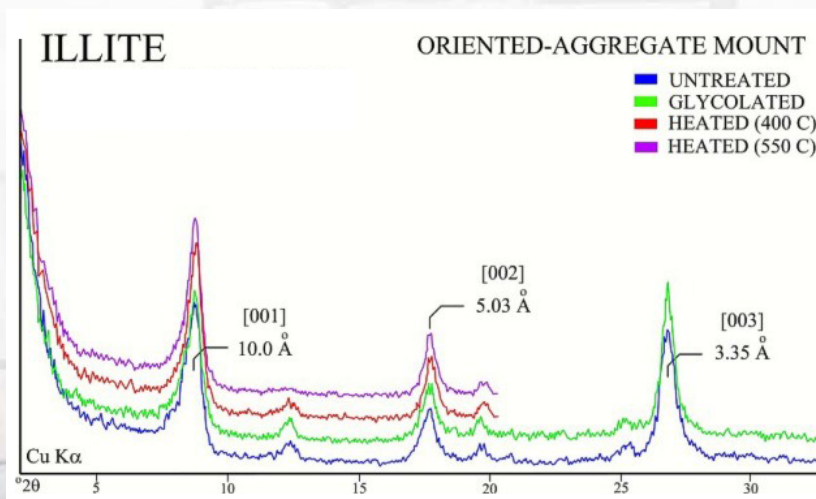
Rock-forming minerals – The Carbonates

- The two most common carbonate minerals: **calcite**, CaCO_3 (calcium carbonate) and **dolomite**, $\text{CaMg}(\text{CO}_3)_2$ (calcium/ magnesium carbonate).
- Calcite and dolomite are usually found together as the primary constituents in the sedimentary rocks, e.g., **limestone**.
- Limestone has many uses, including as road aggregate, as building stone, and as the main ingredient in Portland cement.



Mineral Identification

- Most of the common rock-forming minerals can be identified by visual examination (grain size > 1mm).
- X-ray diffraction and electron microscopic analysis are used for identification of **clay minerals** (< 2 μ m).
- **X-Ray Diffraction**: used to determine the atomic and molecular structure of a crystal, in which the crystalline atoms cause a beam of incident X-rays to diffract into many specific directions.



Rock formations and types

- Rocks are formed by the following processes:
 - **Crystallization** of molten rock (magma) by cooling;
 - **Settling, depositional** or **precipitation** processes;
 - **Heating** or **squeezing** processes.
- On the basis of their formation, rocks are classified as follows:
 - Igneous rocks
 - Sedimentary rocks
 - Metamorphic rocks

Rock formations and types

- **Igneous rocks**: 95% of the volume of the Earth's crust.
 - Rocks derived from **magma** (e.g., granite, basalt);
 - Usually **hard** and **crystalline** in character;
 - The **silicates** are the common igneous rock-forming minerals (e.g., silica, feldspars, amphiboles, pyroxenes, micas and olivine);
 - **Intrusive** and **extrusive** igneous rocks.



Granite



Basalt

Rock formations and types

- **Sedimentary rocks**: formed when the products of weathering are subjected, to transportation (by running water, wind, glaciers and gravity), deposition and subsequent compaction or consolidation.
 - Examples are sandstone, shale, conglomerate, breccias, limestone, coal;
 - Minerals forming the sedimentary rocks are kaolinite, illite, smectite, calcite, dolomite, gypsum.



Sandstone



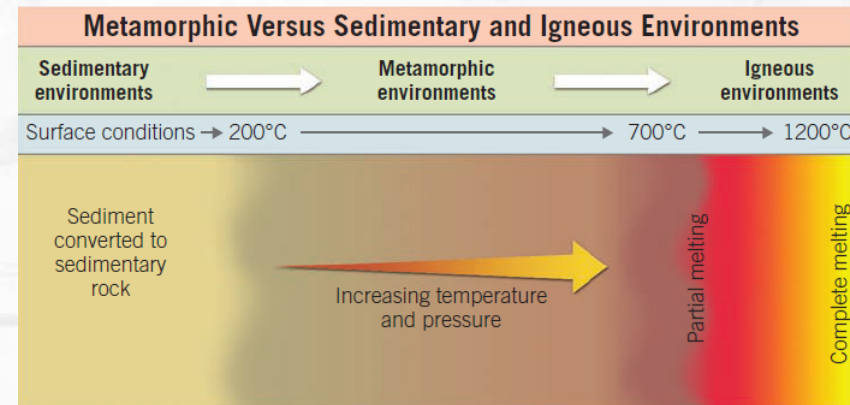
Conglomerate



Limestone

Rock formations and types

- **Metamorphic rocks**: rocks that have undergone some chemical or physical changes (quartzite, marble, mica)
- This is mainly due to four factors:
 - **temperature**;
 - **uniform pressure**;
 - **directional pressure**;
 - **chemically reactive fluids**.
- Common metamorphic rock-forming minerals are serpentine, talc, chlorite, kyanite, biotite, garnet.



Marble



Mica



Quartzite

Rock formations and types

- Summary of Rock Groups and Types

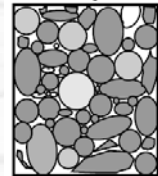
IGNEOUS		
<i>Intrusive (Coarse Grained)</i>	<i>Extrusive (Fine Grained)</i>	<i>Pyroclastic</i>
Granite Syenite Diorite Diabase Gabbro Peridotite Pegmatite	Rhyolite Trachyte Andesite Basalt	Obsidian Pumice Tuff
SEDIMENTARY		
<i>Clastic (Sediment)</i>	<i>Chemically Formed</i>	<i>Organic Remains</i>
Shale Mudstone Claystone Siltstone Sandstone Conglomerate Limestone, oolitic	Limestone Dolomite Gypsum Halite	Chalk Coquina Lignite Coal
METAMORPHIC		
<i>Foliated</i>	<i>Nonfoliated</i>	
Slate Phyllite Schist Gneiss	Quartzite Amphibolite Marble Hornfels	

Rock formations and types

- Rock Identification for Engineering Purposes

Grain size dia. (mm)	A. Bedded rocks SEDIMENTARY		B. Foliated rocks METAMORPHIC	C. Massive and crystalline IGNEOUS		Grain size dia. (mm)
	CLASTIC	CRYSTALLINE				
COARSE 1 3	CONGLOMERATE Rounded rock fragments in a finer matrix BRECCIA Angular rock fragments in a finer matrix (rudaceous)	CLASTIC LIMESTONE Calc-arenite or calcarenite	GNEISS Interlayered mica schists and crystalline, sometimes appearing granitic, coarser rock.	GRANITE 1. Porphyry	GABBRO 2.	Grains easily seen by eye
MEDIUM 2 0.6 0.02	SANDSTONE Quartzite quartz grains with quartz cement (arenaceous)	CRYSTALLINE LIMESTONE & Dolomite Calc-arenite or calcarenite	SCHIST Foliated crystalline rock often micaceous	MICRO-GRANITE 1. Porphyry	DOLERITE 2.	Grains most easily seen with lens
FINE 0.06	MUDSTONE SHALE Fissile (argillaceous)	CHALK (Calc-lutite or calcite)	SLATE Very regular closely spaced foliation gives flat parallel layered texture: splits easily along layers, strong across them	RHYOLITE 3, 4. Porphyry	BASALT 3, 4.	Grains only seen with aid of powerful lens or under microscope
0.002 <0.002 Amorphous	CLASTIC SILICEOUS Flint, chert Siliceous layers found in limestone	CRYSTALLINE CALCAREOUS Carbonaceous composed of vegetable remains	Mylonite Finely ground glassy rock in fault zones	Obsidian Volcanic glass		Amorphous
2		Colour Light ← Quartz rich → Dark Quartz poor				

CLASTIC e.g. Sandstone

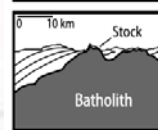


CRYSTALLINE e.g. Microgranite

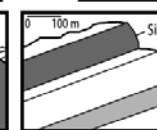


TO IDENTIFY a rock

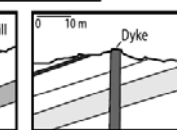
- Place into group A, B or C.
 - Describe mineralogy and texture
 - Establish grain size to give name
- Bedding reflects phases of deposition of sedimentary rocks and, on a small scale, is usually planar. Foliation is layering imposed by metamorphism, usually undulating or contorted, except for slates. Massive rocks show no bedding or foliation. Bedding and foliation spacing may be greater than the usual size of a hand specimen and is best observed in outcrop.



1. Batholith

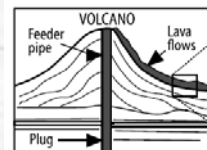


2. Sill

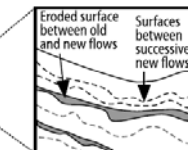


3. Dyke

Crystal grains in crystalline rock fit closely together giving non-porous rock; broken crystals reflect light. Clastic rocks have grains, often rounded, with pore spaces between. Siliceous rocks contain quartz, which cannot be scratched with a knife. Calcareous rocks contain calcite, which can be scratched with steel, and will react with dilute hydrochloric acid.



4. Plugs and lava flows



Porphyries are igneous rocks with some mineral grains very much larger than the majority of grains. All igneous rocks can be porphyritic. Igneous rocks are associated with particular forms of intrusive or extrusive bodies (1, 2, 3, 4).

Sedimentary rocks may contain fossils. Evaporites are often composed of one mineral. Carbonaceous rocks are black.

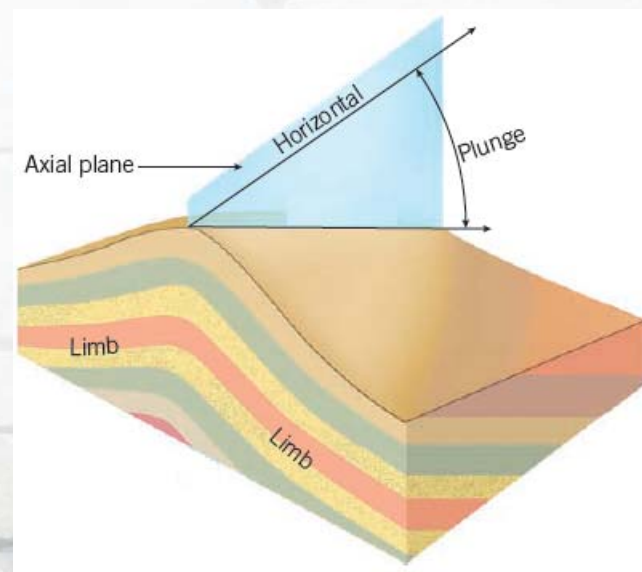
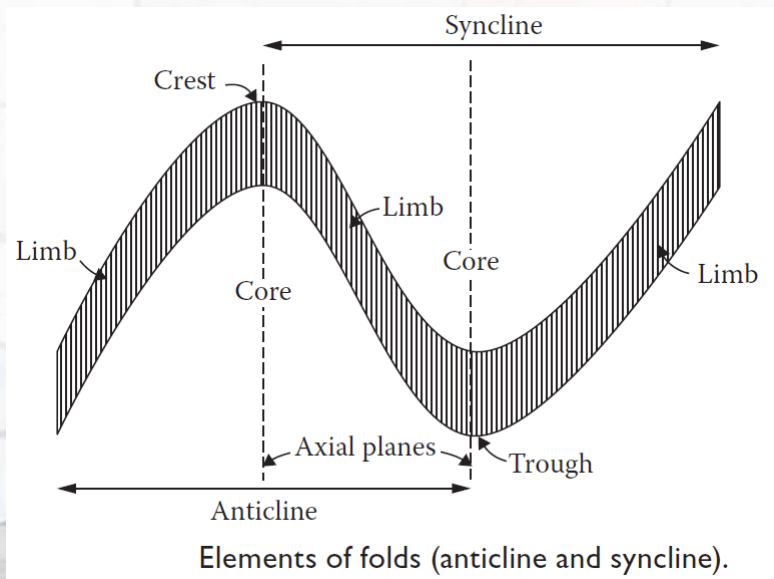
Price (2009)

Geological structures and discontinuities

- **Deformation** is a general term that refers to the changes in the shape or position of a rock body in response to differential stress.
- The basic geologic features that form as a result of deformation are called **geological structures**.
- Geological structures include:
 - **folds** (wave-like undulations);
 - **faults** (fractures along which one rock body slides past another);
 - **joints** (cracks);
 - **small-scale structural unconformities**.

Geological structures and discontinuities

- **Folds**: wavy undulations developed in the rocks of the Earth's crust due to horizontal compression resulting from gradual cooling.
 - An **anticline** is an upfold where the limbs dip away from the axis of fold on either side.
 - A **syncline** is a downfold where the limbs dip towards the axis of the fold on either side.



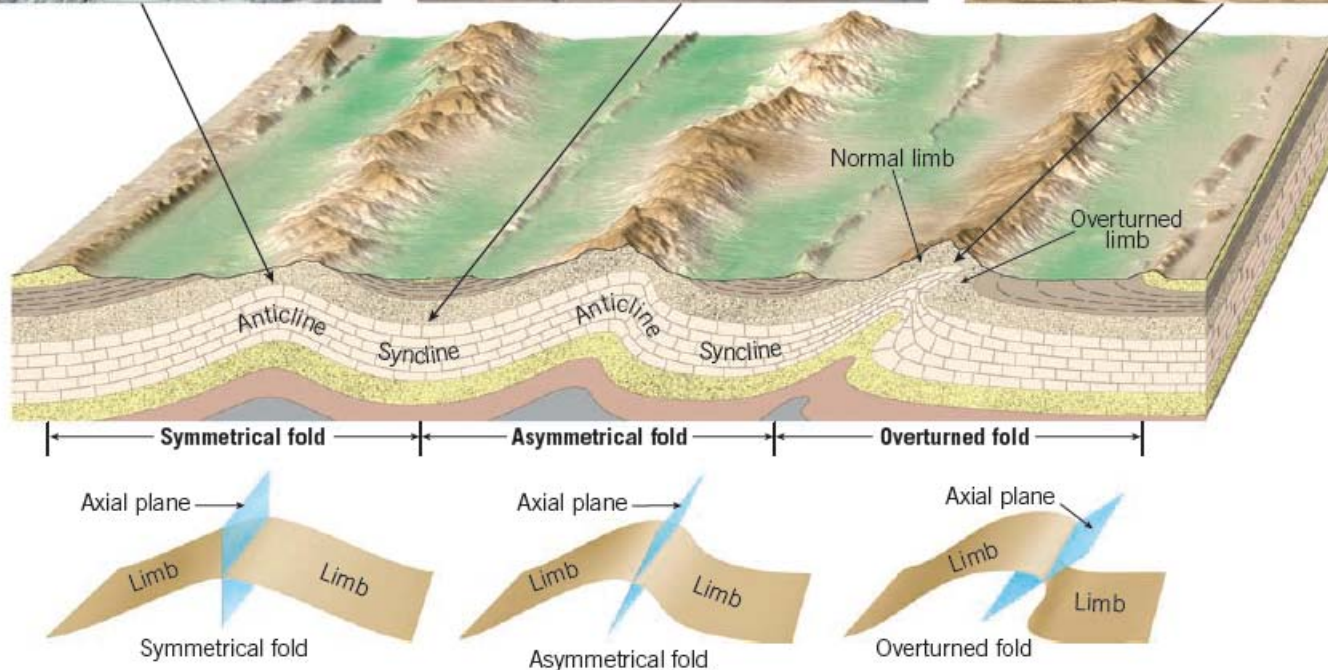
Geological structures and discontinuities

- Folds

- The highest point on the arch of an anticline is called the **crest** of the fold and the lowest point on the syncline is called the **trough**.
- The sloping sides of a fold are called **limbs**.
- A reference plane that divides a fold into two equal halves is called an **axial plane**.
- The line of intersection of the axial plane and the surface of any constituent rock bed is called the **axis of the fold**.
- The inclination of the axis of the fold with the horizontal is called the **plunge** of the fold.

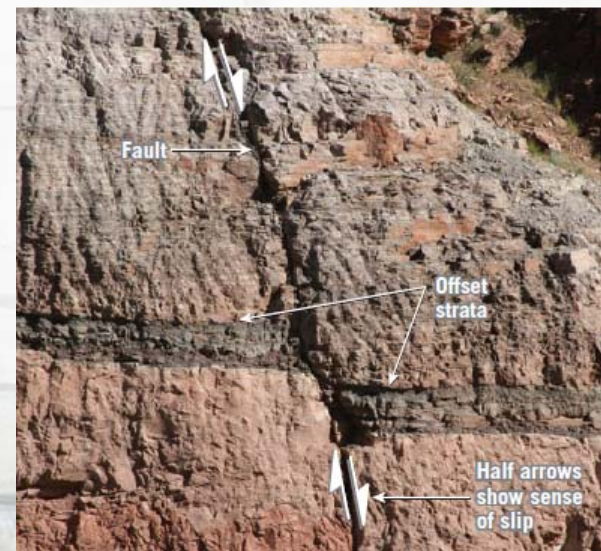
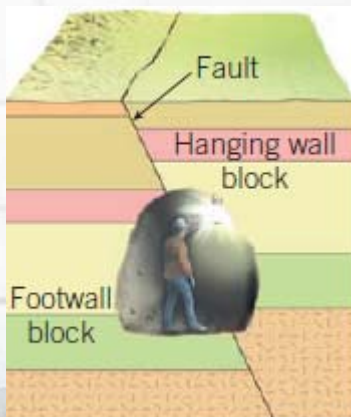
Geological structures and discontinuities

- Folds



Geological structures and discontinuities

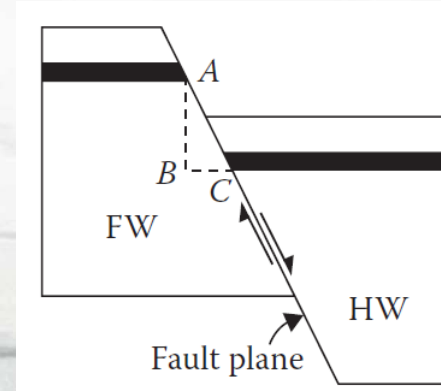
- **Faults**: fractures in crustal strata along which appreciable shear displacement of the adjacent rock blocks have occurred relative to each other, probably due to tectonic activities.
- The fracture along which the shear displacement has taken place is called a **fault plane**.
- The rock immediately above a fault surface is the **hanging wall block**, and the one below is called the **footwall block**.



Geological structures and discontinuities

- **Faults**

- The total displacement AC that occurs along the fault plane is called the **net slip**.
- The vertical component AB of the net slip AC is called the **throw** or **vertical slip**;
- The horizontal component BC of the net slip AC is called the **heave** or **horizontal slip**.
- The angle between the fault plane and any vertical plane striking in the same direction is called the **hade of the fault** ($\angle BAC$).



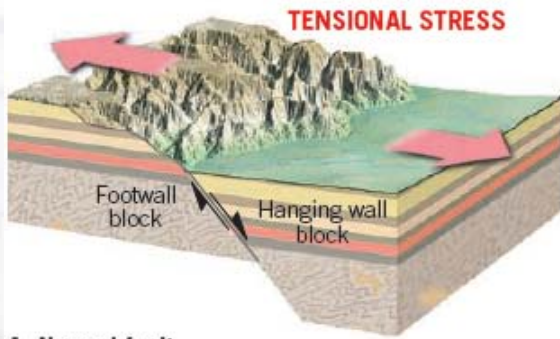
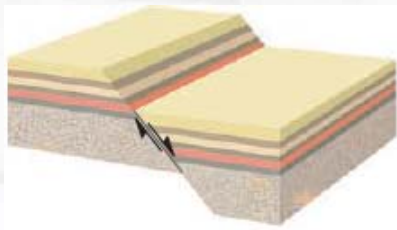
Geological structures and discontinuities

- **Fault types**

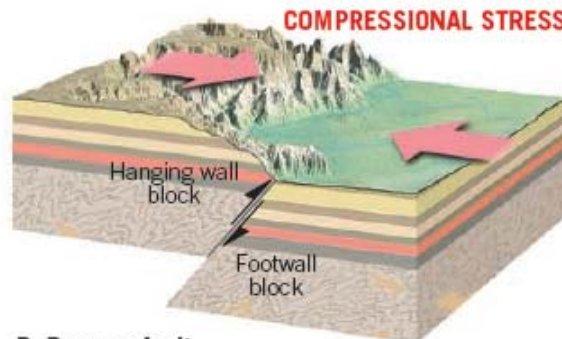
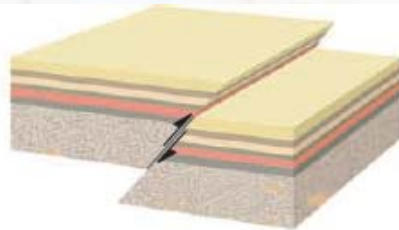
- **Normal faults:** when the hanging wall block moves down relative to the footwall block.
- **Reverse faults:** hanging wall block moves up relative to the footwall block.
- **Thrust faults:** a type of reverse faults having dips less than 45° , so the overlying block moves nearly horizontally over the underlying block.
- **Strike-Slip:** movement along the fault is horizontal, parallel to the strike of the fault plane.

Geological structures and discontinuities

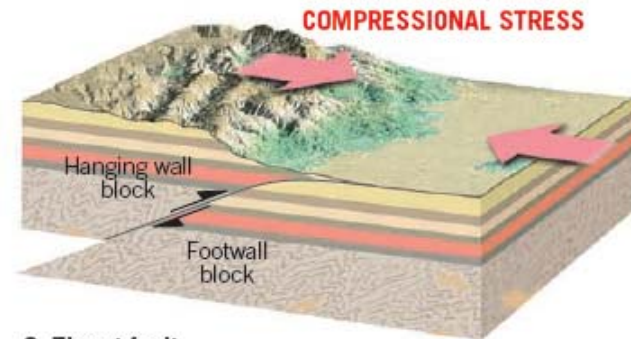
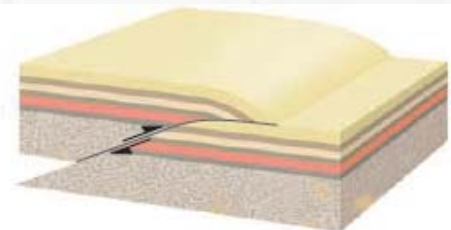
- Fault types



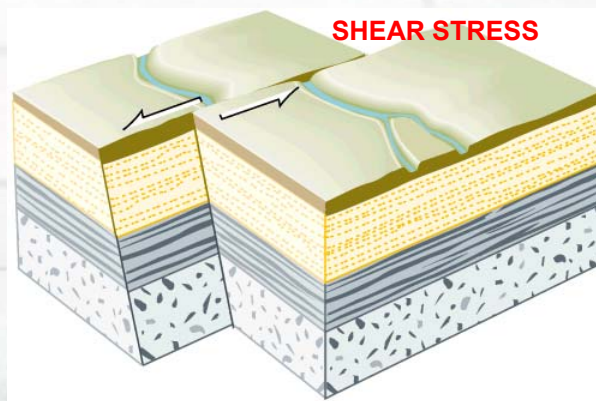
A. Normal fault



B. Reverse fault



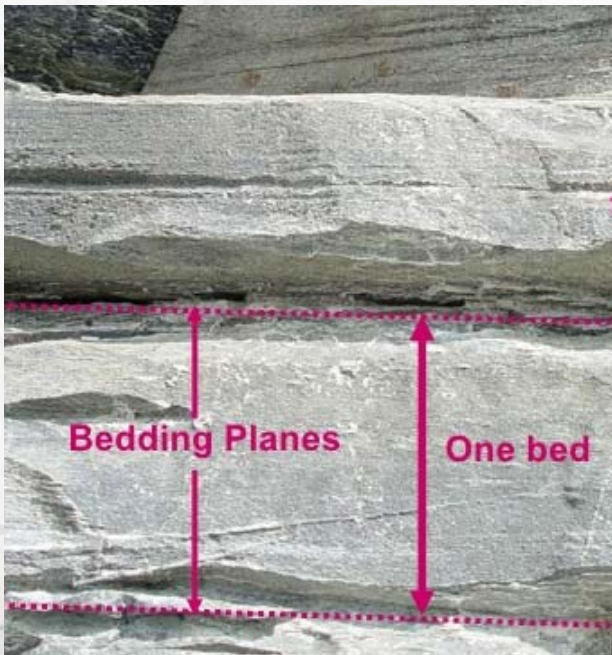
C. Thrust fault



D. Strike-slip fault

Geological structures and discontinuities

- **Discontinuity** is a term used for all structural breaks (bedding planes, fractures and joints) in solid geologic materials that usually have zero to low tensile strength.
- **Bedding planes** occur in sedimentary rocks and form a surface parallel to the surface of deposition.



Geological structures and discontinuities

- **Foliation** is the parallel orientation of platy minerals, or mineral banding in metamorphic rocks.
- **Schistosity** is the foliation in schist or other coarse grained crystalline rock due to the parallel arrangement of mineral grains of the platy or prismatic type, such as mica.



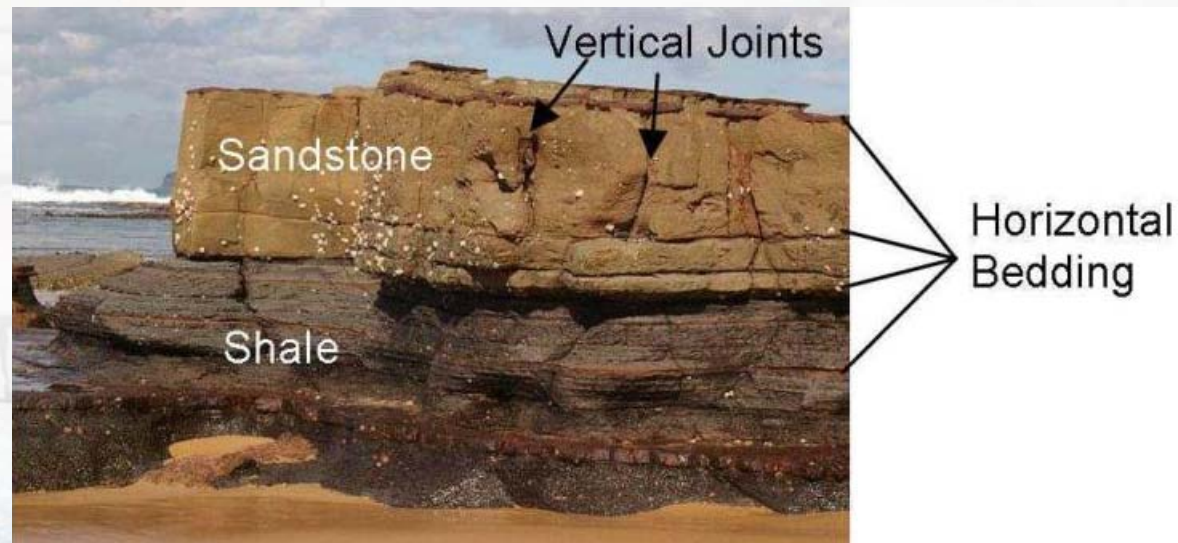
Foliation



Schistosity

Geological structures and discontinuities

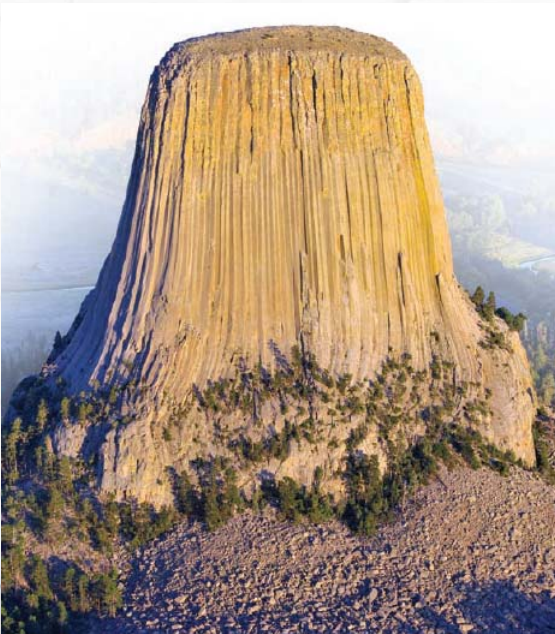
- A **fracture** is where the continuity of the rock mass breaks and **relative movement has occurred**.
- A **joint** is a fracture where **little or no movement has taken** place.
 - often occur in sets and are approximately **parallel** within a specific set.
 - two or more intersecting sets produce a joint system.



Geological structures and discontinuities

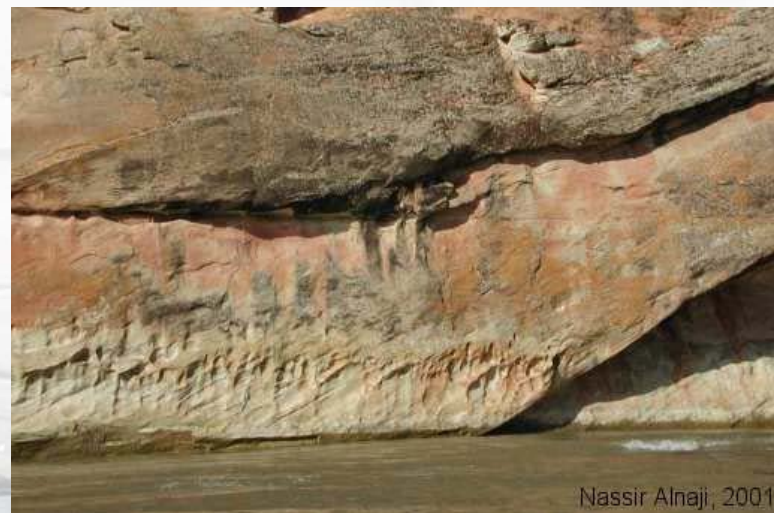
- Joints

- Produced when rocks in the outermost crust are deformed, causing the rock to fail by brittle fracture.
- Many rocks are broken by sets of intersecting joints which exert a strong influence on other geologic processes (e.g., weathering, ground water flow).



Geological structures and discontinuities

- **Unconformities:** planes of separation between two series of rock beds/geological formations that belong to two different geologic ages and are different in their geologic structure.
- The unconformity signifies a time gap between the deposition/formation of one series of beds and the other.
- It is either a surface of erosion or non-deposition.

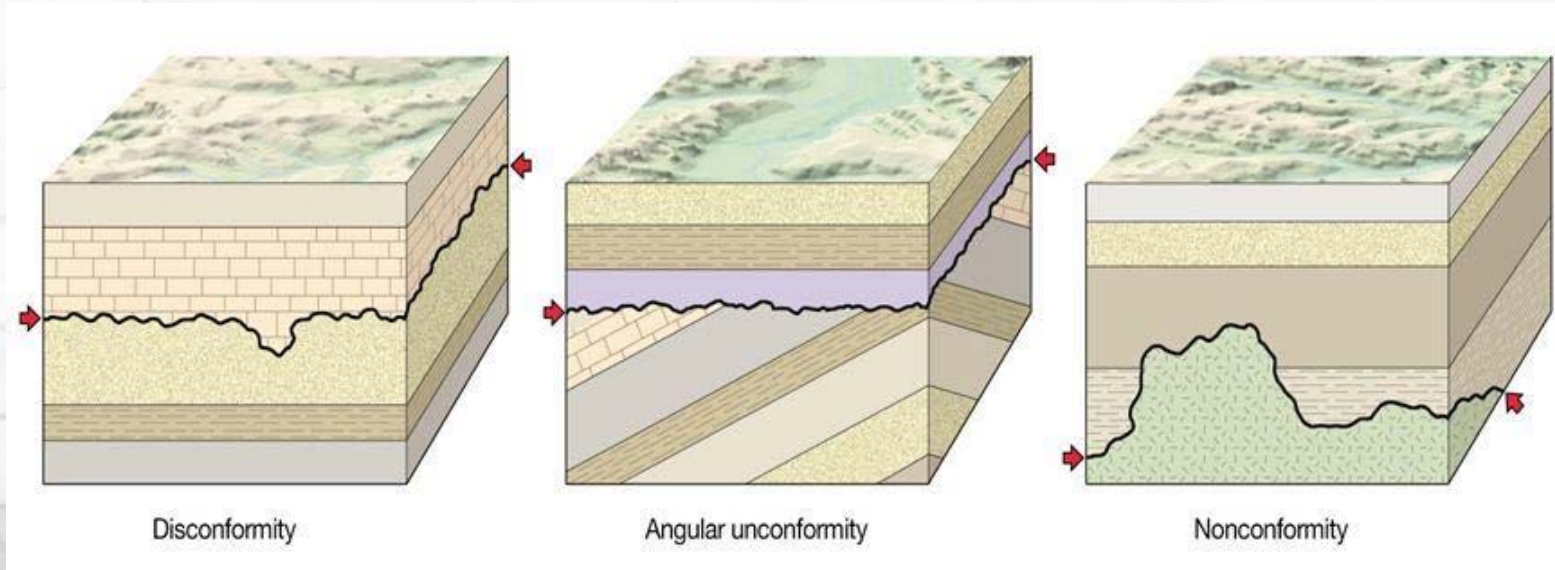


Nassir Alnaji, 2001

Geological structures and discontinuities

- **Types of Unconformities**

- **Disconformity** – An unconformity in which the upper and lower layers are horizontal.
- **Angular Unconformity** – An unconformity in which the upper and lower layers are not parallel.
- **Nonconformity** – An unconformity in which the upper layers overlie metamorphic or igneous rocks.



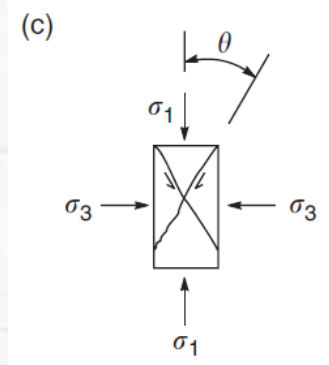
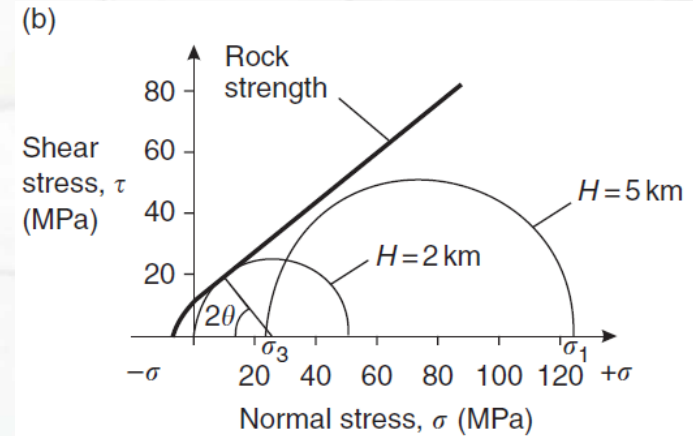
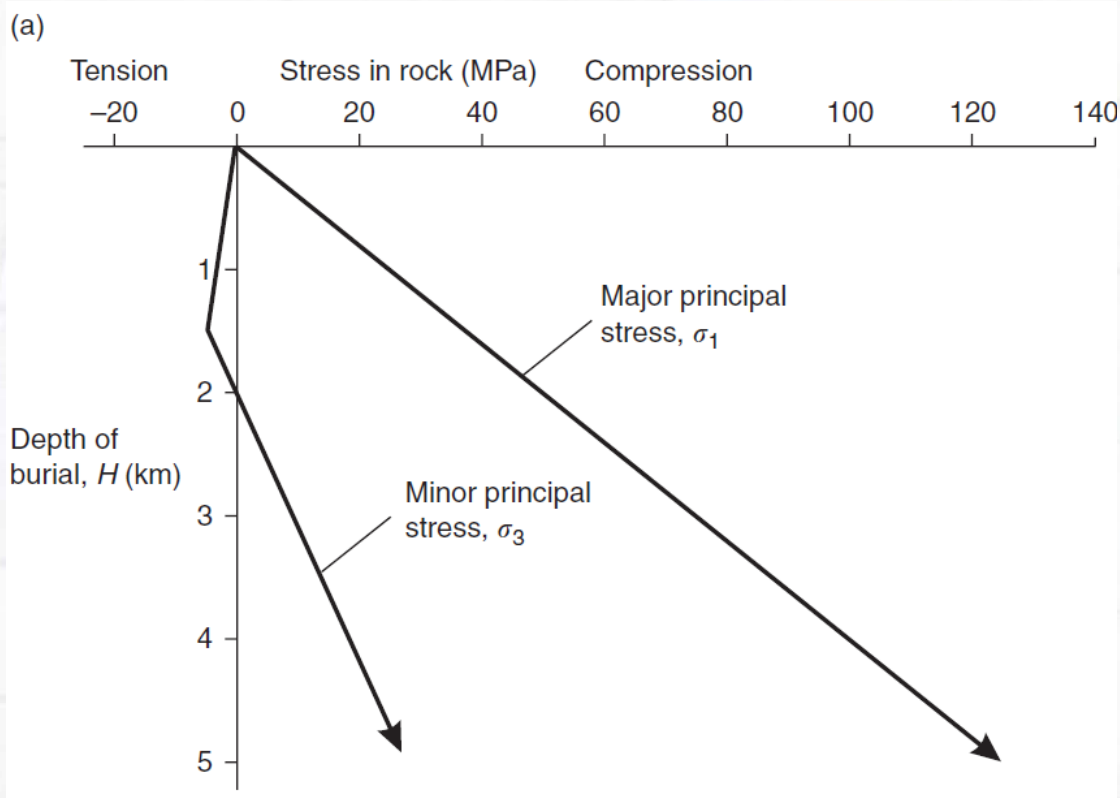
Geological structures and discontinuities

- **Rock discontinuity description**

- **Type**: joints, fractures, faults, closed, open, or filled.
- **Spacing**: the perpendicular distance between adjacent discontinuities of the same set (mm).
- **Aperture and width**: perpendicular distance separating the adjacent rock walls (mm).
- **Type and amount of infilling**: material separating the adjacent rock walls of discontinuities.
- **Roughness** (e.g., rough, smooth, planar, stepped).
- **Fracture frequency**: The number of naturally occurring fractures observed in each 0.5 m core.

Geological structures and discontinuities

- Mechanism of discontinuity formation

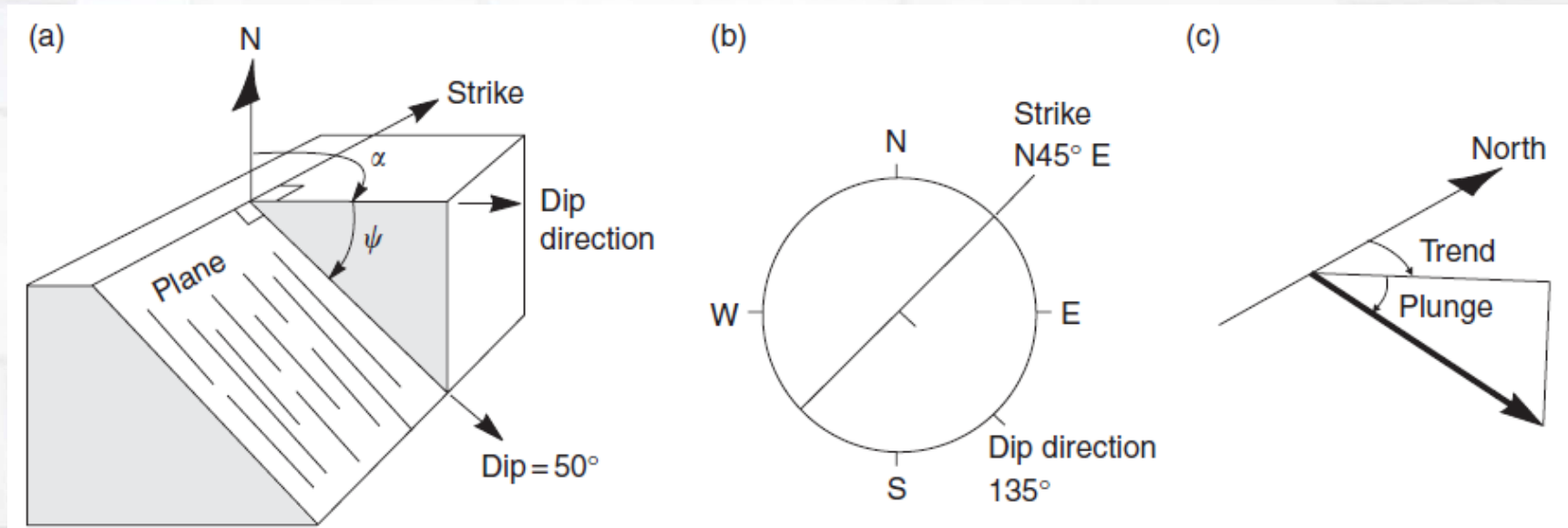


Development of jointing due to burial and uplift of rock: (a) stress changes in rock during burial; (b) Mohr diagram showing conditions for rock fracture; (c) inclination of joints with respect to stress direction (adapted from Davis and Reynolds, 1996).

Geological structures and discontinuities

- **Orientation of discontinuities:**

- The first step in the investigation of discontinuities is to analyze their orientation.
- orientation is described in terms of **strike** (S-S) and **dip** (ψ), or **dip** (ψ) and **dip direction** (α).



Discontinuity orientation: (a) isometric view of plane (dip and dip direction); (b) plan view of plane; (c) isometric view of line (plunge and trend). (Wyllie and Mah, 2004).

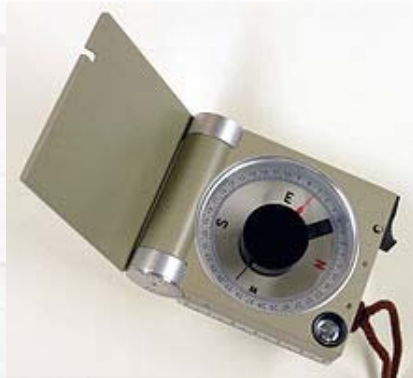
Geological structures and discontinuities

- The **strike** line of a bed, fault, or other planar feature, is a line representing the intersection of that feature with a horizontal plane (e.g., **N45° E or 45°**)
- The **dip** gives the steepest angle of descent of a tilted bed or feature relative to a horizontal plane, and is given by the number (0° - 90°) as well as a letter (N,S,E,W) with rough direction in which the bed is dipping (e.g., **50°SE**).
- The **dip direction (dip azimuth)** is the direction the dip as projected to the horizontal, which is 90° off the strike angle (0° - 360°).
- **Nomenclature**: dip is given as two digits and dip direction as three digits (e.g., 50/135).

Geological structures and discontinuities

- Orientation of discontinuities:

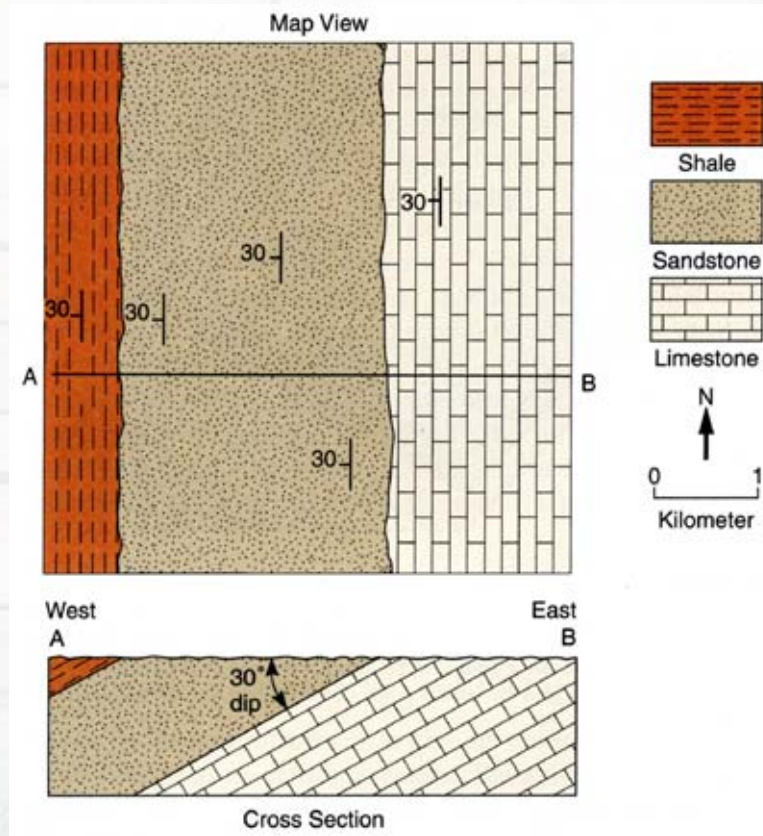
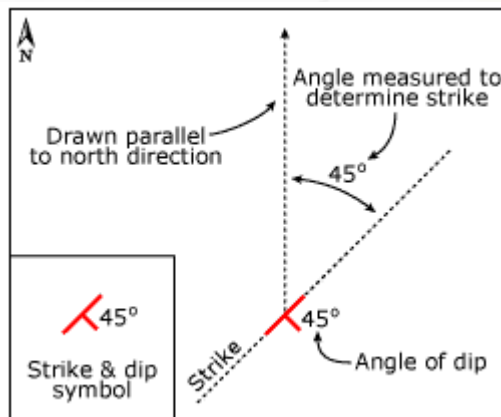
- orientation can also be described in terms of **plunge** and **trend**.
- **The plunge is the dip of the line**, with a positive plunge being below the horizontal and a negative plunge being above the horizontal.
- **The trend** is the direction of the horizontal projection of the line measured clockwise from north, and corresponds to the **dip direction** of a plane.



[Using geological compass](#)

Geological structures and discontinuities

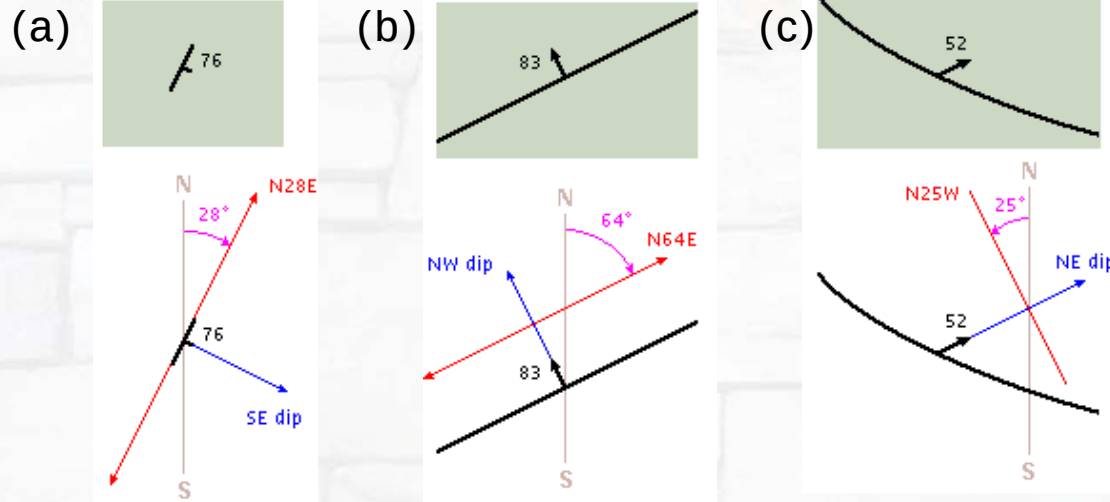
- Representing discontinuity orientation on maps:
 - the strike and dip are indicated by a line parallel to the strike with a tick and number value to indicate the dip direction and dip, respectively



Geological structures and discontinuities

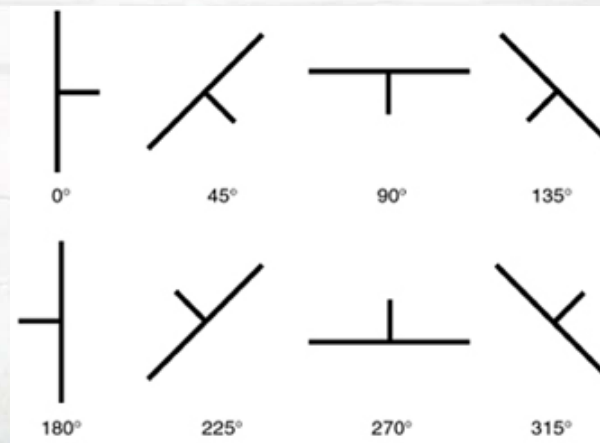
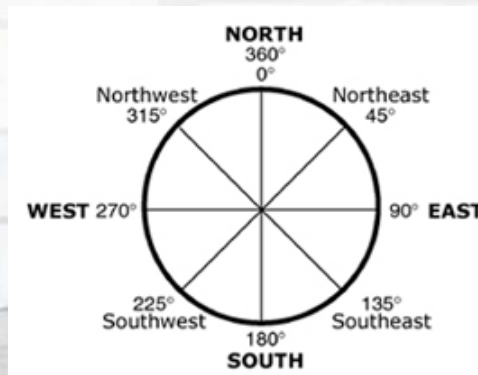
- Representing discontinuity orientation on maps:

- Strike quadrants



Discontinuity orientation:
(a) planar geologic feature;
(b) planar fault;
(c) non-planar fault.

- Strike azimuths

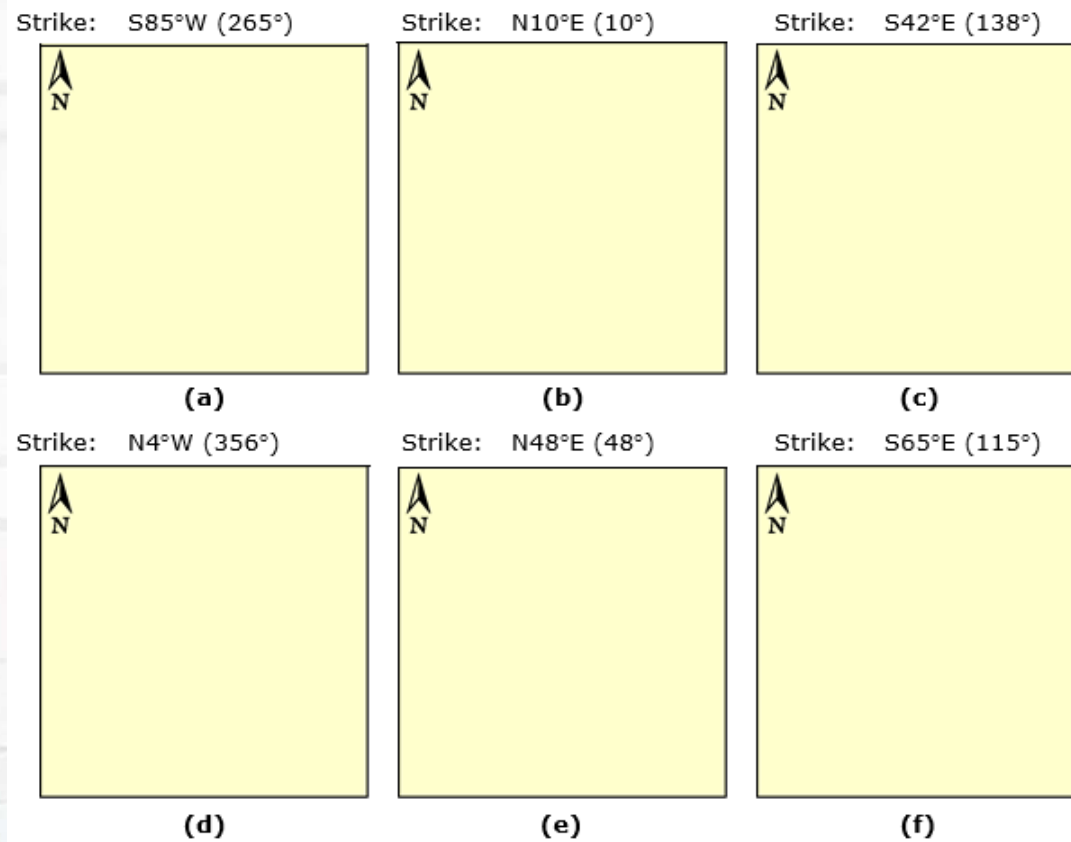


Note: the angles on this figure are **strike azimuths** which are **never** given on a map!

Geological structures and discontinuities

Example 1

The figure below shows six blank maps. Above each map is the strike of a rock unit expressed as a quadrant and as an azimuth. Use this strike to draw the unit on the map.



Weathering of rock and soil formation

- **Weathering**: the continuous decay, disintegration and decomposition of exposed rocks under the influence of physical, chemical and biological agents.
- The degree of weathering may be reflected by changes in engineering properties, such as strength, density, void ratio, clay content, deformation, permeability.
- In general, the **strength** of the rock tends to decrease as the degree of weathering increases.
- The engineering suitability of rocks greatly depends on two principal modes of weathering:
 - **physical/mechanical weathering (disintegration);**
 - **chemical weathering (decomposition).**

Weathering of rock and soil formation

Table 1.4 Engineering rock weathering classification

<i>Grade</i>	<i>Degree of weathering</i>	<i>Field recognition</i>	<i>Engineering properties</i>
VI	Soil	Surface layer contains humus and plant roots; no recognisable rock structure; unstable on slopes when vegetable cover destroyed	Unsuitable for important foundations; unsuitable on slopes when cover is destroyed
V	Completely weathered	Rock completely decomposed by weathering in place but texture still recognisable; in rock types of granite origin, feldspars completely decomposed to clay minerals; cores cannot be recovered by ordinary rotary drilling methods; can be excavated by hand	Can be excavated by hand or ripping without use of explosives; unsuitable for foundations of concrete dams or large structures; may be suitable for foundations of earth dams and for fill; unsuitable in high cuttings at steep slope angles; requires erosion protection
IV	Highly weathered	Rock so weakened by weathering that fairly large pieces can be broken and crumbled in the hands; sometimes recovered as core by careful rotary drilling; stained by limonite	Similar to grade V; unlikely to be suitable for foundations of concrete dams; erratic presence of boulders makes it an unreliable foundation stratum for large structures
III	Moderately weathered	Considerably weathered; possessing some strength in large pieces (e.g., NX drill cores); often limonite stained; difficult to excavate without use of explosives	Excavated with difficulty without use of explosives; mostly crushes under bulldozer tracks; suitable for foundations of small concrete structures and rockfill dams; may be suitable for semi-pervious fill; stability in cuttings depends on structural features, especially joint attitudes
II	Slightly weathered	Distinctly weathered with slight limonite staining; some decomposed feldspars in granites, strength approaching that of fresh rock; explosives required for excavation	Requires explosives for excavation; suitable for concrete dam foundations; high permeability through open joints; often more permeable than zones above or below; questionable as concrete aggregate
I	Fresh rock	Fresh rock may have some limonite-stained joints immediately beneath weathered rock	Staining indicates water percolation along joints; individual pieces may be loosened by blasting or stress relief and support may be required in tunnels and shafts

Source: Little, A.L., *Proceeding of the 7th International Conference on Soil Mechanics and Foundation Engineering*, Vol. I, pp. 1–10, 1969.

Movement of groundwater through rock

- The groundwater moves through intergranular pores and natural cavities, called **primary openings**, and discontinuities (joints, fractures and solution cavities), called **secondary openings** in rocks.
- **Primary openings** are generally found in sedimentary rocks, while **secondary openings** are found in most igneous and metamorphic rocks.

Table 1.7 Typical values of porosity and permeability of some common rocks, soils and rock fracture zones

Rocks, soils and rock fracture zones	Porosity (%)	Permeability (m/day)
Fractured sandstone	15	5
Cavernous limestone	5	Erratic
Shale	3	0.0001
Granite	1	0.0001
Sand	30	20
Gravel	25	300
Clay	50	0.0002
Rock fracture zones	10	50

Source: Waltham, T., *Foundations of Engineering Geology*, Spon Press, London, 2002.

Movement of groundwater through rock

- Typical **aquifers** are sand, gravel, sandstone, limestone, grit, conglomerate, etc.
- The fault-zones, shear-zones, joints and so on, in igneous and metamorphic rocks, may also act as **aquifers**.
- Clays, shales, mudstones and siltstones are some examples of **aquicludes**.
- Compact granite, syenite, gabbro, gneiss and quartzite without discontinuities are typical examples of **aquifuges**.