ENGINEERING GEOLOGY CE1301

Lecture #1 Introduction & Architecture of the earth surface

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WHAT IS GEOLOGY

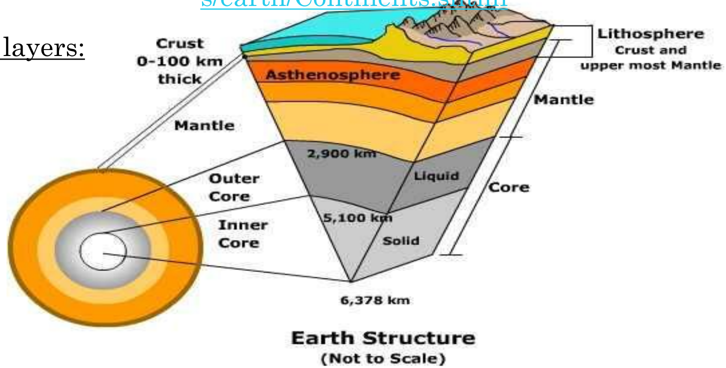
- **Geology**: The science of Geology is concerned with the Earth and the rocks of which it is composed, the processes by which they were formed during geological time, and the modelling of the Earth's surface in the past and at the present.
- **Engineering geology**: is the application of the principles of geology in engineering field for the purpose of assuring that the geological elements such as the location, planning, design, construction, operation and maintenance of engineering projects are considered.
- **Economic geology**: deals with the Earth's natural resources, in terms of location and management, such as petroleum and coal, and minerals resources.
- **Mining geology**: deals with the extraction of minerals from the ground for industrial and economical benefits. This includes mining for minerals, gemstones, metals.
- **Petroleum geology**: deals with the subsurface exploration for the purpose of locating extractable hydrocarbons, such as petroleum and natural gas.

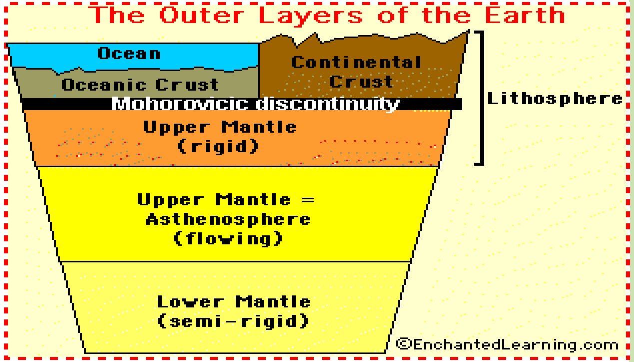
RELEVANCE OF ENGINEERING GEOLOGY TO CIVIL ENGINEERING

- Knowledge of **construction material**, its occurrence, composition, durability and other properties. Example of such construction materials is building stones, road metal, clay, limestones and laterite.
- Helps in planning and carrying out major **civil engineering works which can be affected by natural agents such as water, wind, ice and earthquakes**. For example the knowledge of erosion, transportation and deposition helps greatly in solving the expensive problems of river control, coastal and harbour work and soil conservation.
- Knowledge of **ground water** (quantity and depth of occurrence) is the water which occurs in the subsurface rocks.
- **In checking foundation stability of engineering constructions**. Stability of dams, bridges and buildings are directly related to the geology of the area where they are to be built.
- **In slopes and cuts stability**: important in tunnelling, constructing roads, canals, docks and in determining the stability of cuts and slopes, the knowledge about the nature and structure of rocks is very necessary.
- **In preparing geological maps and sections for engineering constructions**: Before staring a major engineering project at a place, a detailed geological report which is accompanied by, is prepared. Such a report helps in planning and constructing the projects.
- **In the study of soil mechanics**, it is necessary to know how the soil materials are formed in nature.
- The cost of engineering works will considerably reduced of the geological survey of the area concerned is done before hand.

Earth's Layers

Source:http://www.enchantedlearning.com/subjects/astronomy/planets/earth/Continents.shtml





<u>Earth is comprised of the following layers:</u>

–The Crust:
- Continental
- Oceanic

–The Mantle.
- Upper
- Lower

–The Core.
- Outer Core.
- Inner Core.

<u>The Crust:</u> The outermost layer of Earth with variable thickness.

–Thickest under mountain ranges (70 km).

–Thinnest under mid-ocean ridges (3 km).

- The Moho discontinuity is the lower boundary which separates the crust from the upper mantle.

<u>Earth's Mantle:</u> Solid rock layer between the crust and the core.

- 2,885 km thick, the mantle is 82% of Earth's volume.
- Below ~100-150 km, the rock is hot enough to flow.
- It convects: hot mantle rises, cold mantle sinks.
- Three subdivisions: rigid, flowing, and semi-rigid.

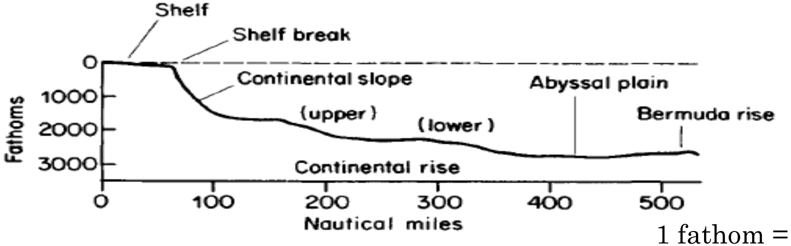
<u>The Core:</u> An iron-rich sphere with a radius of 3,471 km.

–Outer core
- Liquid iron-nickel-sulfur
- 2,255 km thick
- Density – 10-12 g/cm^3

–Inner core
- Solid iron-nickel alloy
- Radius of 1,220 km.
- Density – 13 g/cm^3

<u>Dimensions and surface relief</u>

- The radius of the Earth at the equator is 6370 km and the polar radius is shorter by about 22 km; thus the Earth is not quite a perfect sphere. The planet has a surface area of 510 x 10^{6}km^2, of which some 29 per cent is land.
- Surface topography is very varied; mountains rise to several kilometres above sea level, with a maximum of 8.9 km at Everest. The average height of land above sea level is 0.86 km and the mean depth of the ocean floor is about 3.8 km.
- The topographical features of a continental margin, such as that of the North Atlantic is as shown below.



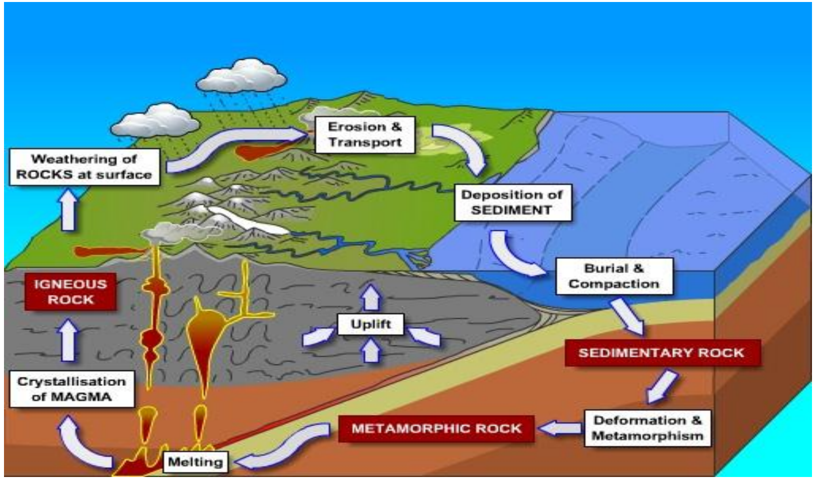
1 fathom =1.8288 meters

Source: http://www.geolsoc.org.uk/ks3/gsl/education/resources/rockcycle.html

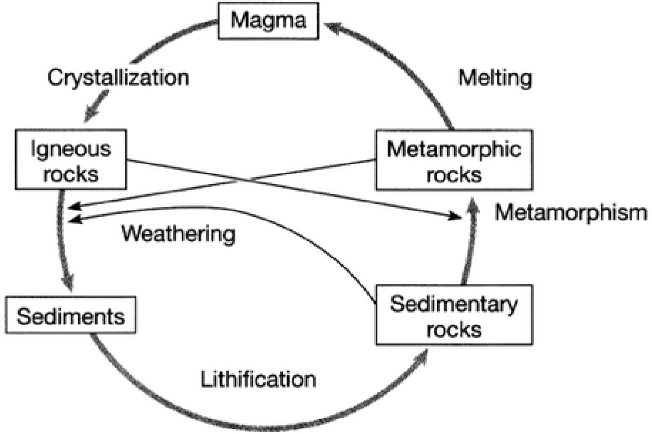
ROCK CYCLE

Rock types

- **Igneous Rocks** are formed by cooling magma or lava *(lava is a magma which cools on earth's surface).*
- **Sedimentary Rocks** are formed by the chemical precipitation of mineral grains; or by the sedimentation and cementation of fragments of plants, animals or other rocks, transported by water, wind or ice to a site of deposition.
- **Metamorphic Rocks** are formed after a rock is subjected to intense temperatures and/or pressures, resulting in the transformation of original compounds (minerals) and/or textures (grain size).



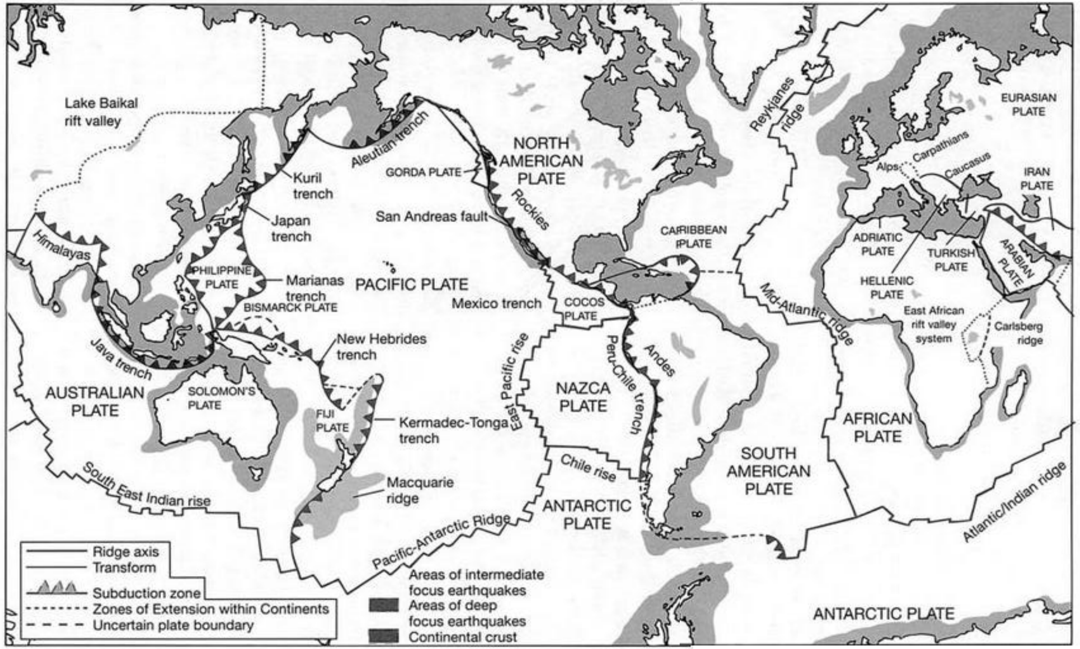
- ➢ Beginning with magma, crystallisation yields igneous rock, which can be either intrusive or extrusive.
- ➢ These rocks can weather, giving broken rock fragments. When sediments become lithified, they give sedimentary rocks.
- ➢ Metamorphism of these rocks produces metamorphic rocks, which in turn, on melting provide magma once more.
- ➢ Shortcuts across the cycle are shown: igneous rocks can be metamorphosed to metamorphic rocks. Sedimentary rocks and metamorphic rocks can be weathered to sediments.



ARCHITECTURE OF THE EARTH SURFACE

- The continents would fit together if they merely moved around. For example, south America could be slipped under Africa.
- Seafloor spreading and plate tectonics occurred during the past 200 million years contributed to this separation.
- Lithospheric plates: are rigid slabs consisting of a continental and/or oceanic crustal cap plus part of the underlying mantle. Continental plates or oceanic plates extend thousands of kilometres across but only 100 to 200 km thick).
- Plate tectonics: refer to the movement that occur at the boundaries plates, caused by the underlying weak and plastic zones known as asthenosphere.
- The earth surface is divided to 8 large plates and 12 other small plates

Plates and plate boundaries of the earth



- There are 3 basic types of plate boundaries:

1) The zones of divergence or spreading, that is the typical ocean ridges;
2) The transform margins where plates slide sideways past each other, and
3) The zones of convergences where the plates move directly toward each other.

- Most deep-seated earthquakes occur mostly along the zones of convergence.
- Plate tectonics are important for many aspect of a global significance, such as: volcanoes, earthquakes, folded mountains, continents, etc.

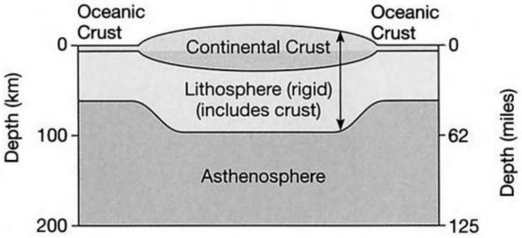


FIGURE 1.5 Cross section of the upper portion of the Earth, showing the continental crust, oceanic crust, lithosphere, and partially molten asthenosphere.

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Lecture #2 Minerals

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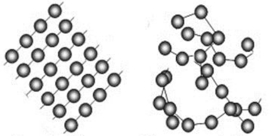
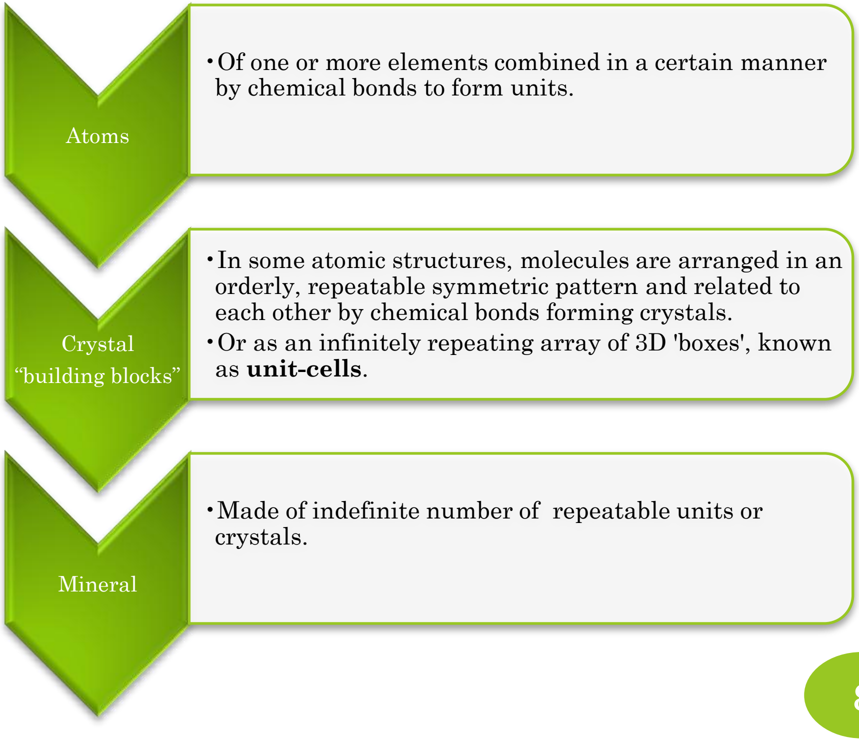
WHAT IS A MINERAL?

- A **mineral** is a natural inorganic solid substance having a particular chemical composition or range of composition, and a regular atomic structure to which its crystalline form is related.
- <u>Therefore every mineral:</u>
  - is naturally occurring;
  - is inorganic;
  - is solid;
  - has particular chemical composition;
  - has ordered atomic structure.
- A mineral is composed of atoms of one or more elements bonded by atomic bonding:
  - Covalent bond;
  - Ionic bond;
  - Van der Waals bond;
  - Hydrogen bond;
  - Metallic bond.
  - A **crystal** is a piece of a homogeneous solid substance having a naturally geometrically regular form with symmetrically arranged plane faces.
  - A **crystalline solid** is a solid material with its atoms, molecules or ions, are arranged in a highly ordered microscopic structure, forming a crystal structure that extends in all directions.
  - **Non crystalline solid (amorphous)** (like glass) has no long-range orderly arrangement of atoms.



Crystalline Noncrystalline

- **Cation**: is an ion with positive charge.
- **Anion**: is an ion with negative change.



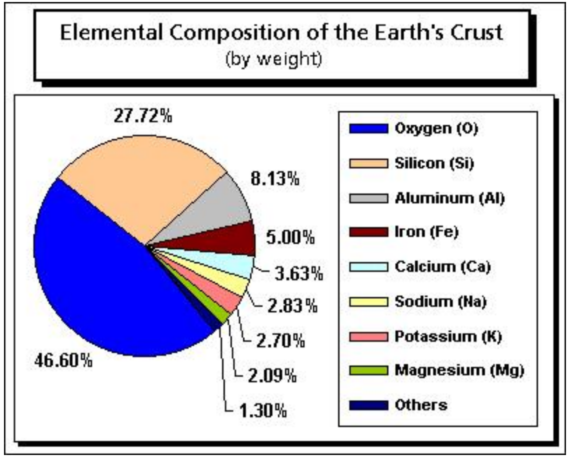
Atoms
- Of one or more elements combined in a certain manner by chemical bonds to form units.

Crystal “building blocks”
- In some atomic structures, molecules are arranged in an orderly, repeatable symmetric pattern and related to each other by chemical bonds forming crystals.
- Or as an infinitely repeating array of 3D 'boxes', known as **unit-cells**.

Mineral
- Made of indefinite number of repeatable units or crystals.

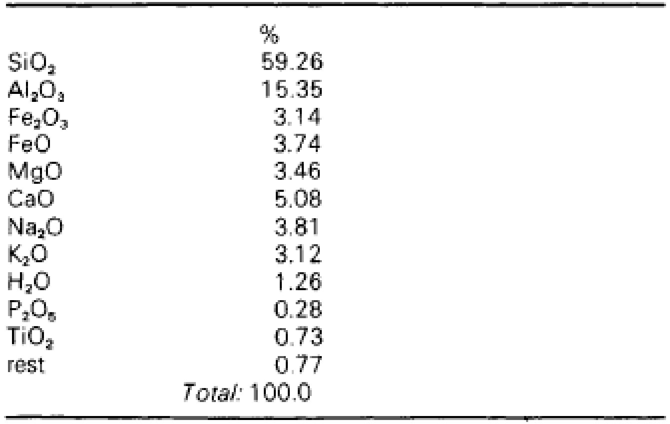
AVERAGE ELEMENTAL COMPOSITION OF THE CRUST

- Eight elements in their order of abundance in crustal rocks.
- Silicon and oxygen together make up nearly 75 per cent of crustal rocks, and the other elements over 98 per cent.
- Since silicon and oxygen preponderate in the rocks, the chief rock-forming minerals are silicates.



Source: www.geog.ucsb.edu

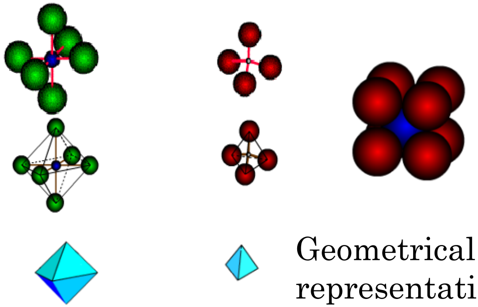
- The average composition of crustal rocks:



	%
SiO_2	59.26
Al_2O_3	15.35
Fe_2O_3	3.14
FeO	3.74
MgO	3.46
CaO	5.08
Na_2O	3.81
K_2O	3.12
H_2O	1.26
P_2O_5	0.28
TiO_2	0.73
rest	0.77
	Total: 100.0

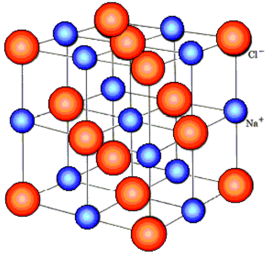
ATOMIC STRUCTURES

- Refers to the arrangement and spacing of the atoms of a given crystal which controls its regular form and properties.
- In most cases bonds in minerals are combinations of covalent and ionic bonds.
- Octahedron, tetrahedron and cube units

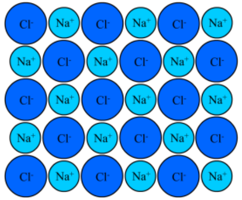


Geometrical representation

Halite: composition (NaCl)

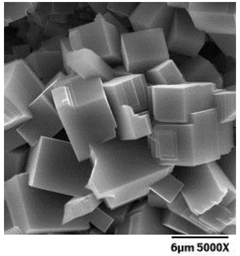


Cubical internal structure



Cl^-	Na^+	Cl^-	Na^+	Cl^-	Na^+
Na^+	Cl^-	Na^+	Cl^-	Na^+	Cl^-
Cl^-	Na^+	Cl^-	Na^+	Cl^-	Na^+
Na^+	Cl^-	Na^+	Cl^-	Na^+	Cl^-
Cl^-	Na^+	Cl^-	Na^+	Cl^-	Na^+

Ionic bonds



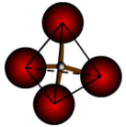
Microscopic view of

Halite crystals

- Chloride anions gain electrons to fill their outer shell.
- Sodium cations throw away their outer shell.
- Therefore, anions tend to occupy a much larger volume than cations of similar mass.
- The crystal structure is mostly determined by the packing arrangement of anions.

- Each Na+ ion is surrounded by 6 Cl^- ions.
- Each crystal has millions of Na^+ and Cl^- ions.

Quartz: composition (SiO2)



- Each SiO_4 tetrahedron is bonded to 4 other SiO_4 tetrahedrons in the 3D structure.
- Crystal structure: hexagonal continuous framework of SiO_4 tetrahedrons.

Physical Properties of Minerals

○ Colour

Some minerals have a distinctive colour, for example the green colour of **chlorite**, but most naturally occurring minerals contain traces of substances which modify their colour.

Thus **quartz**, which is colourless when pure, may be white, grey, pink or yellow, when certain chemical impurities or included particles are present.

Chlorite

quartz

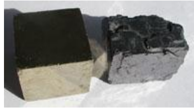
○ Streak

Is the color of the powder produced when the mineral is rubbed on a piece of unglazed porcelain (streak-plate). If no streak seems to be made, the mineral's streak is said to be white or colorless. Streak is particularly important as a diagnostic for opaque and colored materials. It is less useful for silicate minerals, most of which have a white streak or are too hard to powder easily.

○ Luster

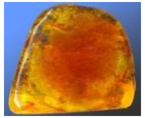
is the way light interacts with the surface of a crystal, rock, or mineral.

- *Metallic***:** having the look of a polished metal as in **pyrite** and **galena**.
- *Adamantine:* having a hard, sparkly look of a **diamond**
- *Resinous:* having a look of yellow, dark orange, or brown that is slightly reflective as in **amber.**
- *Vitreous:* having the look of glass as **quartz.**
- *Pearly:* having the look of a pearl as in **talc.**
- *Greasy:* having the look of an oil coated surface as in **chalcedony.**
- *Earthy:* having the look of soil or clay as in **sulfur.**
- *Silky:* having the look of fine, parallel fibers such as **satin spar** (fibrous gypsum).
- *Dull:* having no luster as in **kaolin**



Pyrite (left) and galena (right)

Diamond



Amber

Quartz

Talc

Chalcedony

Malachite (green), sulphur (yellow) and cinnabar (red)

Satin spar (fibrous gypsum)

Kaolin

PHYSICAL PROPERTIES OF MINERALS

Hardness

Hardness, or resistance to abrasion, is measured relative to a standard scale often minerals, known as Mohs' Scale of Hardness.

Moh's hardness	Mineral	Chemical formula	like
1	Talc	$Mg_3Si_4O_{10}(OH)_2$	
2	Gypsum	$CaSO_4 \cdot 2H_2O$	Fingernail (2.5)
3	Calcite	$CaCO_3$	
4	Fluorite	CaF_2	
5	Apatite	$Ca_5(PO_4)_3(OH^-,Cl^-,F^-)$	Glass plate (5.5)
6	Orthoclase	$KAlSi_3O_8$	Steel nail (6.5)
7	Quartz	SiO_2	
8	Topaz	$Al_2SiO_4(OH^-,F^-)_2$	Masonry drill bit (8.5)
9	Corundum	Al_2O_3	
10	Diamond	C	







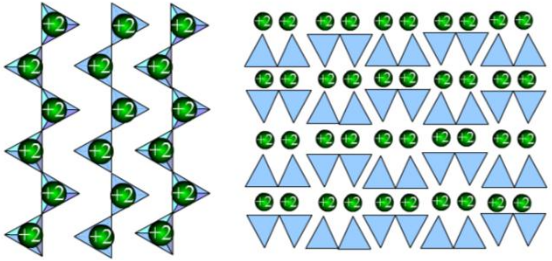



* Mineral strength is a function of hardness and lack of cleavage.

Cleavage

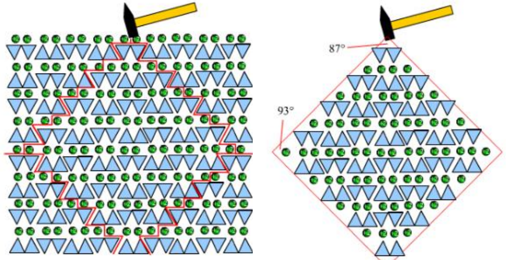
Many minerals possess a tendency to split easily in certain regular directions, and yield smooth plane surfaces called cleavage planes when broken. These directions depend on the arrangement of the atoms in a mineral, and are parallel to definite crystal faces. Perfect, good, distinct, and imperfect are terms used to describe the quality of mineral cleavage.

Cleavage in pyroxene



The structure breaks through the weak ionic bonds between the negatively and positively charged ions.

Cross sections through pyroxene structure, parallel and normal to the SiO_4 chains. The negatively charged chains are linked together by the positively charged cations. (each chain is negatively charged: $6Si^{+4}+ 18\ O^{-2}=-12$



Source: http://ansatte.uit.no/kare.kullerud/webgeology/

PHYSICAL PROPERTIES OF MINERALS

Fracturing

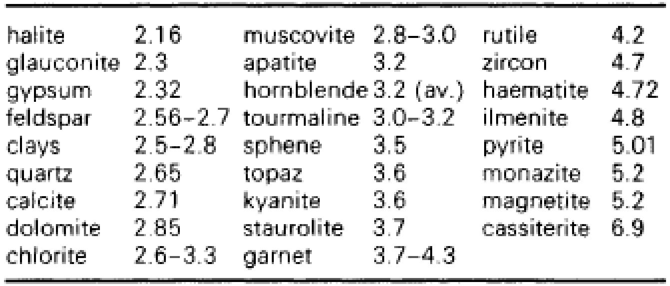
As explained above, quartz has a structure made of 3D framework of SiO_4 tetrahedrons bonded by covalent bonds.

Because that these bonds are equally strong in all directions, no cleavage exists. Instead, the mineral would fracture when stressed (just like glass).

Specific gravity

Is the ratio of the density of a substance to the density (mass of the same unit volume) of water. The specific gravity of a mineral determines how heavy it is by its relative weight to water.

Specific gravity of most minerals ranges between 2 and 7, see the table below.



halite	2.16	muscovite	2.8–3.0	rutile	4.2
glauconite	2.3	apatite	3.2	zircon	4.7
gypsum	2.32	hornblende	3.2 (av.)	haematite	4.72
feldspar	2.56–2.7	tourmaline	3.0–3.2	ilmenite	4.8
clays	2.5–2.8	sphene	3.5	pyrite	5.01
quartz	2.65	topaz	3.6	monazite	5.2
calcite	2.71	kyanite	3.6	magnetite	5.2
dolomite	2.85	staurolite	3.7	cassiterite	6.9
chlorite	2.6–3.3	garnet	3.7–4.3		

Magnetism

Most of iron bearing minerals like Magnetite are magnetic.

Crystal systems

- When a mineral substance grows freely from a liquid state (or out of solution, or by sublimation), it tends to assume its own characteristic crystal shape.

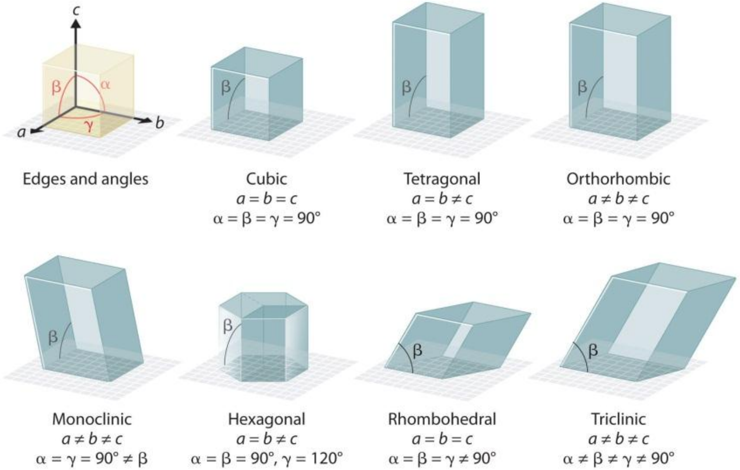
- **Crystal Faces** are conveniently defined by reference to *crystallographic axes*. Crystal faces are formed during crystallization process whereas cleavage faces formed when mineral breaks.

- The arrangements of faces in crystals possess varying degrees of symmetry, and according to their type of symmetry, crystals can be arranged in seven Systems, which are summarized below and illustrated in the figure next page.

- A **plane of symmetry** divides a crystal into exactly similar halves, each of which is the mirror image of the other; it contains one or more of the crystallographic axes.

- A **crystal structure** describes a highly ordered repeatable arrangement of atoms within a given type of crystal.
- The **unit cell** is the smallest complete unit of pattern in the atomic structure of a crystal. The unit cell is represented in terms of the lengths of the cell edges (a,b and c) and the angles between them (alpha, beta and gamma).

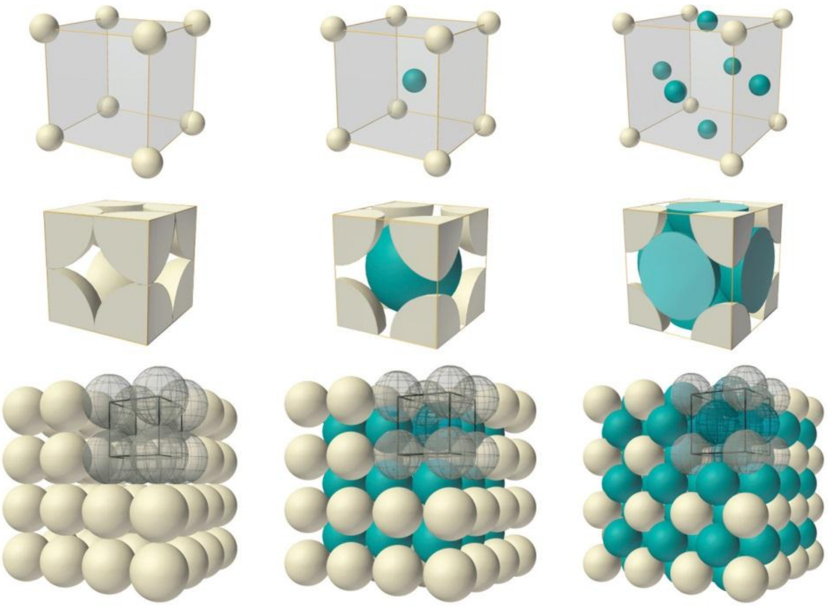
THE UNIT CELL



source: http://chemwiki.ucdavis.edu/

The General Features of the Seven Basic Unit Cells.

- If the cubic unit cell consists of eight component atoms, molecules, or ions located at the corners of the cube, then it is called simple cubic (Figure a).
- If the unit cell also contains an identical component in the center of the cube, then it is body-centered cubic (Figure b).
- If there are components in the center of each face in addition to those at the corners of the cube, then the unit cell is face-centered cubic (Figure c).



(a) Simple cubic **(b) Body-centered cubic** **(c) Face-centered cubic**

The figure above suggests that mineral density is directly affected by the atomic arrangement within the unit cell.

- **Factors controlling the minerals type:**

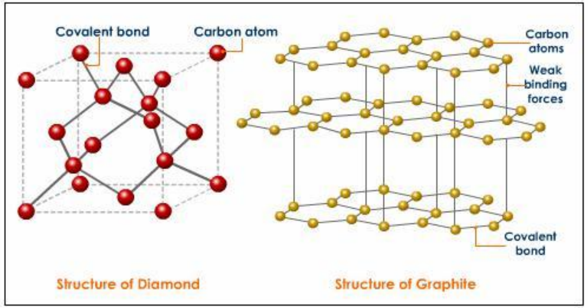
- chemical composition of the mineral;

-the crystal structure and the type of bonds.

Polymorphs:

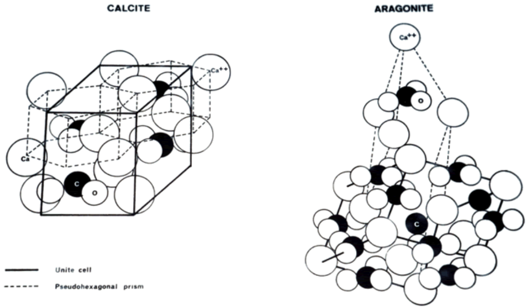
Minerals with the same chemical composition but with different crystal structure:

- Diamond/graphite:
both composed of carbon (C)



Source: openstudy.com

Calcite/aragonite ($CaCO_3$)



- Pyrite/marcasite(FeS_2)
- Quartz/cristobolite (SiO_2)

Source: http://itssedimentary.tumblr.com/post/79587108044/a-tale-of-two-caco3s-calcite-and-aragonite

- **Cation substitution**

-Ions have different sizes and charges.

- If two cations have *similar size* and *similar charge*, a cation substitution is possible. Anions are usually much larger than cations and anions usually are very tightly bonded (covalent bond) so it is not easy to break them loose and reconnected with substituted anions. Many cations are loosely bonded and allow some substitution.
- The mineral olivine, as common example, may have magnesium (Mg_2SiO_4) or iron (Fe_2SiO_4) or a combination of both ((Fe_2Mg_2)SiO_4).

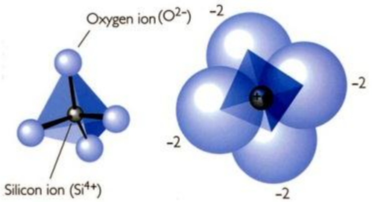
MAJOR MINERAL GROUPS

Minerals are grouped based on their chemical composition. Minerals are classified into seven groups:

- Silicates
- Oxides
- Sulfates
- Sulfides
- Carbonates
- Native Elements
- Halide

SILICATE MINERALS

Silicate structure



In most silicate minerals, a large number of silicate tetrahedrons are linked together to form chains, sheets, or three-dimensional frameworks.

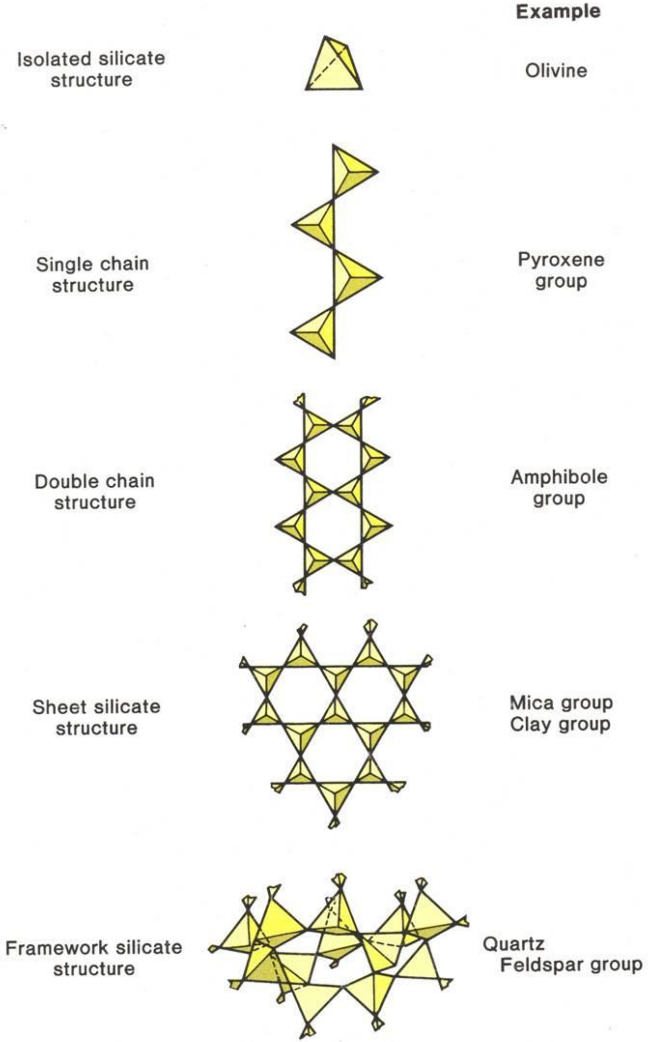
Isolated tetrahedron: no oxygen is shared between SiO_4 tetrahedrons. The mineral is held together by the attraction between SiO_4 tetrahedrons and other positive ions. Example mineral: Olivine.
Net charge: Si(+4)+O_2(-2*4)=-4

Single chain silicates: two oxygen atoms are shared between SiO_4 tetrahedrons to form a chain. Example mineral: pyroxene.

Double chain silicates: formed when two single chains share oxygen atoms. Example mineral: amphibole.

Sheet Silicates: formed when each SiO_4 tetrahedron shares three oxygen atoms with the adjacent SiO_4 tetrahedrons. Example minerals: Muscovite mica.

Framework Silicates formed when each SiO_4 tetrahedron shares the four oxygen atoms with the adjacent SiO_4 tetrahedrons. Example mineral: potassium feldspar.



Source: http://www.thisoldearth.net/

COMMON ROCK-FORMING MINERALS

Silicate minerals

The most important rock-forming minerals are quartz, feldspars, micas, amphiboles, pyroxenes, and olivine.

Source: http://www.oakton.edu/user/4/billtong/eas100lab/mintable.htm

Name	H	Color	Streak	Luster	Prominent Cleavage	Composition	Other Properties
Augite (pyroxene)	6	dark green to black	gray	vitreous	YES - 2 dir. at nearly 90°	complex silicate	Most common pyroxene; often appears as short, stubby, prismatic crystals in rock.
Hornblende (amphibole)	6	black, dark green, or brown	grayish-white	vitreous	YES - 2 directions, ith angles at 56° and 24°	complex silicate	Most common amphibole; found in many igneous rocks. Characterized by dark, elongated crystals
Olivine	6	olive green or brownish	white or gray	vitreous to adamantine	Not obvious - indistinct	$(Mg,Fe)_2SiO_4$	Often found as "sugary" granular masses of dunite (olivine rock); gem variety called peridot
Plagioclase feldspar (including Albite, Labradorite, etc.)	6	white to dark gray	colorless or white	vitreous	YES - 2 dir. at nearly 90°	$NaAlSi_3O_8$ to $CaAlSi_2O_8$	Sodium-rich varieties are white or light gray; calcium-rich varieties are medium to dark gray.
Potassium feldspar (Orthoclase, Microcline)	6	white, tan to orange, red, green, also colorless	colorless or white	vitreous or pearly	YES - 2 dir. at nearly 90°	$KAlSi_3O_8$	Most commonly found in granites and pegmatites.
Biotite Mica	2.5	Black, dark green, or brown	gray to white	vitreous or pearly	YES - 1 dir. (sheets)	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$	Flexible and elastic sheets
Muscovite Mica	2.5	Colorless, gray, or green	white	vitreous	YES - 1 dir. (sheets)	$Kal_2(AlSi_3O_{10})(OH)_2$	Flexible and elastic sheets
Quartz (crystalline varieties)	7	colorless, white, gray, purple, pink, black, yellow, green	colorless	vitreous	NO - shows conchoidal fracture	SiO_2	Varieties named by color: Rock crystal (colorless), Milky (white), Smoky (gray), Amethyst (purple), Rose (pink), Citrine (yellow); 6-sided crystals common

THE ROCK-FORMING MINERALS

- **Other common rock-forming minerals** Including calcite, magnetite pyrite and clay minerals.

Source: http://www.oakton.edu/user/4/billtong/eas100lab/mintable.htm

Name	H	Color	Streak	Luster	Prominent Cleavage	Composition	Other Properties
Calcite	3	Colorless or white; impurities may discolor it yellow or brown	white	vitreous	YES - 3 dir., not at 90°(rhombic)	$CaCO_3$	Effervesces vigorously with cold dilute hydrochloric acid. Transparent calcite shows double refraction.
Pyrite	6 - 6.5	Pale brassy yellow	greenish to brownish black	-	NO	FeS_2	Known as "Fool's Gold." Brittle, common in crystals, but also granular and massive (no obvious form).
Magnetite	5.5 - 6.5	Black	black	-	NO (but sometimes shows parting)	Fe_3O_4	Strongly magnetic; lodestone variety shows polarity; often in octahedral (8-sided) crystals
Bauxite	2 - 7	White to brown	white	earthy-dull	NO	Mixture of AlO(OH), Al(OH $_3$, and $HAlO_2$	Mixture of 3 clay minerals: Boehmite, Gibbsite, and Diaspore. Earthy odor when breathed on.
Gypsum	2	Colorless; white, gray, yellowish	white	vitreous	Only obvious in the selenite variety - 3 dir. (rhombic)	$CaSO_4.2H_2O$	3 common varieties: -selenite: clear, transparent -satin spar: fibrous, silky -alabaster: granular, sugary
Dolomite	3 - 3.5	White, gray, brown, pink	white	vitreous to pearly	YES, but not always obvious (rhombic).	$CaMg(CO_3)_2$	Effervesces slowly with dilute cold hydrochloric acid, but only when powdered

INDUSTRIAL USE OF SOME MINERALS

Source: **http://www.nma.org/index.php/minerals-publications/40-common-minerals-and-their-uses**

- **Sulfur**

Used in the manufacture of sulfuric acid, fertilizers, petroleum refining; and metal mining.

- **Phosphate rock**

Used to produce phosphoric acid for ammoniated phosphate fertilizers, feed additives for livestock, elemental phosphorus, and a variety of phosphate chemicals for industrial and home consumers.

- **Halite (sodium chloride--salt)**

Used in human and animal diet, food seasoning and food preservation; used to prepare sodium hydroxide, soda ash, caustic soda, hydrochloric acid, chlorine, metallic sodium; used in ceramic glazes; metallurgy, curing of hides; mineral waters; soap manufacturing; home water softeners; highway de-icing; photography; in scientific equipment for optical parts.

- **Gypsum**

Processed and used as prefabricated wallboard or an industrial or building plaster; used in cement manufacturing; agriculture and other uses.

- **Quartz (silica)**

As a crystal, quartz is used as a semiprecious gem stone. Crystalline varieties include amethyst, citrine, rose quartz, smoky quartz, etc. Cryptocrystalline forms include agate, jasper, onyx, etc. Because of its piezoelectric properties quartz is used for pressure gauges, oscillators, resonators and wave stabilizes; because of its ability to rotate the plane of polarization of light and its transparency in ultraviolet rays, it is used in heat-ray lamps, prism and spectrographic lenses. Also used in manufacturing glass, paints, abrasives, refractory materials and precision instruments.

- **Feldspar**

A rock-forming mineral; industrially important in glass and ceramic industries; enamelware; soaps; bond for abrasive wheels; cements; insulating compositions; fertilizer; tarred roofing materials; and as a sizing, or filler, in textiles and paper.

- **Clays**

Used in floor and wall tile as an absorbent, in sanitation, mud drilling, foundry sand bond, iron pelletizing, brick, light weight aggregate and cement. Bentonite is used for drilling mud, pet waste absorbent, iron ore pelletizing and foundry sand bond. Kaolin is used for paper coating and filling, refractory products, fiberglass, paint, rubber and catalyst manufacture. Common clay is used in brick, light aggregate and cement.

- **Iron Ore**

Used to manufacture steels of various types. Powdered iron: used in metallurgy products; magnets; high-frequency cores; auto parts; catalyst. Radioactive iron (iron 59): in medicine; tracer element in biochemical and metallurgical research. Iron blue: in paints, printing inks, plastics, cosmetics, paper dyeing. Black iron oxide: as pigment; in polishing compounds; metallurgy; medicine; magnetic inks.

- **Aluminum**

Aluminum originates as an oxide called alumina. Bauxite ore is the main source of aluminum. Used in transportation (automobiles), packaging, building/construction, electrical, machinery and other uses.

- **Pyrite**

Used in the manufacture of sulfur, sulfuric acid and sulfur dioxide; pellets of pressed pyrite dust are used to recover iron, gold, copper, cobalt, nickel; used to make inexpensive jewellery.

MINERAL RESOURCES OF IRAQ

Geoserv, Iraq Source:
http://iraqmining.com/index.php/index.php?option=com_content&view=article&id=19&Itemid=7

Native sulfur:- About 600 m.t. of proved reserves were discovered in Nineva Governorate, 60% of which is extractable by modified Frash method. Mining in MI field started in 1969 at 1 m.t./year designed production capacity. Mostly used in chemical industries and for export.

Phosphorite:- More than 10 000 m.t. of proved reserves were discovered in Akashat and surrounding areas (Anbar Governorate). Mining started in 1983 at 3.2 m.t./year designed production rate to supply the phosphate fertilizer plant at Al-Qaim.

Salt (NaCl):-About 50 m.t. of proved reserves are located at Samawa saltern (Muthana Governorate) in addition to several smaller salterns in the Jazira area. Used in chemical and petrochemical industries, as well as in food industry. Production rate about 200 000 t/year.

Glauberite:- About 22 m.t. of proved reserves are found in the Shari Saltern (Salahuldin Governorate). Used in the production of sodium sulfate. New plant is needed.

Gypsum:- More than 130 m.t. are proved in several localities of the Low-Folded Zone (Northern Zone) of Iraq. Mostly used in the production of plaster.

Limestone:- More than 8000 m.t. are proved in various parts of Iraq and are being exploited for the production of cement.

Quartz-sand:- More than 850 m.t. of proved reserves are available of almost pure quartz-sand. Presently mined from one site in Anbar Governorate and used in glass, ceramics and refractories production.

Feldspathic sand:- A small reserve (about 2 m.t.) of silica sands containing up to 20% feldspar minerals are located in Najaf Governorate. Used for ceramic industry and need a floatation plant for upgrading.

Kaolinitic claystones:- These deposits are found in several localities in Anbar Governorate with total reserves reaching up to 1200 m.t. of various grades (white and colored). Mostly used in ceramic industry, but is considered the only source in Iraq for alumina in the future.

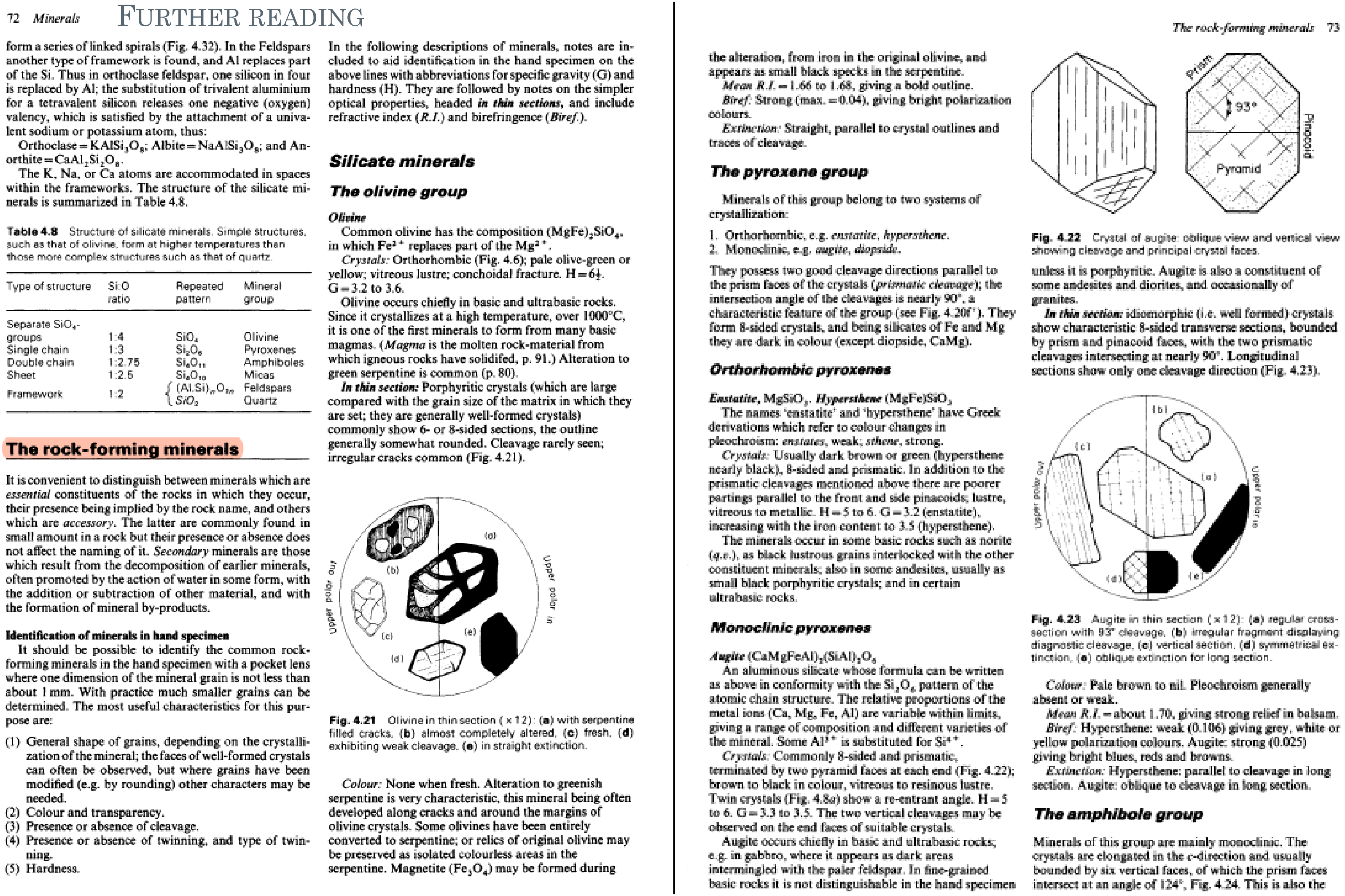
Bentonite:- About 22 m.t. of Ca-montmorillonitic clay are found in Anbar Governorate. At present it is mainly used for oil-well drilling after on-site Na-activation. A plant for Na-activation is needed with 75000 t./year production capacity.

Ironstone:- A sedimentary pisolitic medium grade ironstone deposit is located in Anbar Governorate with about 60 m.t. of reserves. The quality and grade permit using the ore in cement industry only. A new mine is needed.

Bauxite:- Very small and scattered Karst bauxite and bauxitic claystones are found in Anbar Governorate. Locally used for refractories.

Metallic Minerals:- A few deposits of Zn-Pb-pyrite deposits are located in Kurdstan Region. Non of them is exploited. Some are associated with barite. Numerous showings of Cu, Cr-Ni, Mn-Fe and Fe are found in the igneous complexes of the Zagros Suture Zone of Kurdstan Region. All of them require more exploration work to show their economic potential.

FURTHER READING



form a series of linked spirals (Fig. 4.32). In the Feldspars another type of framework is found, and Al replaces part of the Si. Thus in orthoclase feldspar, one silicon in four is replaced by Al; the substitution of trivalent aluminium for a tetravalent silicon releases one negative (oxygen) valency, which is satisfied by the attachment of a univalent sodium or potassium atom, thus:

Orthoclase = $KAlSi_3O_8$; Albite = $NaAlSi_3O_8$; and Anorthite = $CaAl_2Si_2O_8$.

The K, Na, or Ca atoms are accommodated in spaces within the frameworks. The structure of the silicate minerals is summarized in Table 4.8.

Table 4.8 Structure of silicate minerals. Simple structures, such as that of olivine, form at higher temperatures than those more complex structures such as that of quartz.

Type of structure	Si:O ratio	Repeated pattern	Mineral group
Separate SiO_4-groups	1:4	SiO_4	Olivine
Single chain	1:3	Si_2O_6	Pyroxenes
Double chain	1:2.75	Si_4O_{11}	Amphiboles
Sheet	1:2.5	Si_4O_{10}	Micas
Framework	1:2	$(Al,Si)_nO_{2n}$	Feldspars
		SiO_2	Quartz

The rock-forming minerals

It is convenient to distinguish between minerals which are *essential* constituents of the rocks in which they occur, their presence being implied by the rock name, and others which are *accessory*. The latter are commonly found in small amount in a rock but their presence or absence does not affect the naming of it. *Secondary* minerals are those which result from the decomposition of earlier minerals, often promoted by the action of water in some form, with the addition or subtraction of other material, and with the formation of mineral by-products.

Identification of minerals in hand specimen

It should be possible to identify the common rock-forming minerals in the hand specimen with a pocket lens where one dimension of the mineral grain is not less than about 1 mm. With practice much smaller grains can be determined. The most useful characteristics for this purpose are:

(1) General shape of grains, depending on the crystallization of the mineral; the faces of well-formed crystals can often be observed, but where grains have been modified (e.g. by rounding) other characters may be needed.
(2) Colour and transparency.
(3) Presence or absence of cleavage.
(4) Presence or absence of twinning, and type of twinning.
(5) Hardness.

In the following descriptions of minerals, notes are included to aid identification in the hand specimen on the above lines with abbreviations for specific gravity (G) and hardness (H). They are followed by notes on the simpler optical properties, headed ***in thin sections***, and include refractive index (*R.I.*) and birefringence (*Biref.*).

Silicate minerals

The olivine group

Olivine

Common olivine has the composition $(MgFe)_2SiO_4$, in which Fe^{2+} replaces part of the Mg^{2+}.

Crystals: Orthorhombic (Fig. 4.6); pale olive-green or yellow; vitreous lustre; conchoidal fracture. $H = 6\frac{1}{2}$. $G = 3.2$ to 3.6.

Olivine occurs chiefly in basic and ultrabasic rocks. Since it crystallizes at a high temperature, over 1000°C, it is one of the first minerals to form from many basic magmas. (*Magma* is the molten rock-material from which igneous rocks have solidifed, p. 91.) Alteration to green serpentine is common (p. 80).

In thin section: Porphyritic crystals (which are large compared with the grain size of the matrix in which they are set; they are generally well-formed crystals) commonly show 6- or 8-sided sections, the outline generally somewhat rounded. Cleavage rarely seen; irregular cracks common (Fig. 4.21).

Fig. 4.21 Olivine in thin section (×12): (**a**) with serpentine filled cracks, (**b**) almost completely altered, (**c**) fresh, (**d**) exhibiting weak cleavage, (**e**) in straight extinction.

Colour: None when fresh. Alteration to greenish serpentine is very characteristic, this mineral being often developed along cracks and around the margins of olivine crystals. Some olivines have been entirely converted to serpentine; or relics of original olivine may be preserved as isolated colourless areas in the serpentine. Magnetite (Fe_3O_4) may be formed during the alteration, from iron in the original olivine, and appears as small black specks in the serpentine.

Mean R.I. = 1.66 to 1.68, giving a bold outline.

Biref: Strong (max. = 0.04), giving bright polarization colours.

Extinction: Straight, parallel to crystal outlines and traces of cleavage.

The pyroxene group

Minerals of this group belong to two systems of crystallization:

1. Orthorhombic, e.g. *enstatite*, *hypersthene*.
2. Monoclinic, e.g. *augite*, *diopside*.

They possess two good cleavage directions parallel to the prism faces of the crystals (*prismatic cleavage*); the intersection angle of the cleavages is nearly 90°, a characteristic feature of the group (see Fig. 4.20f′). They form 8-sided crystals, and being silicates of Fe and Mg they are dark in colour (except diopside, CaMg).

Orthorhombic pyroxenes

Enstatite, $MgSiO_3$. ***Hypersthene*** $(MgFe)SiO_3$

The names 'enstatite' and 'hypersthene' have Greek derivations which refer to colour changes in pleochroism: *enstates*, weak; *sthene*, strong.

Crystals: Usually dark brown or green (hypersthene nearly black), 8-sided and prismatic. In addition to the prismatic cleavages mentioned above there are poorer partings parallel to the front and side pinacoids; lustre, vitreous to metallic. $H = 5$ to 6. $G = 3.2$ (enstatite), increasing with the iron content to 3.5 (hypersthene).

The minerals occur in some basic rocks such as norite (*q.v.*), as black lustrous grains interlocked with the other constituent minerals; also in some andesites, usually as small black porphyritic crystals; and in certain ultrabasic rocks.

Monoclinic pyroxenes

Augite $(CaMgFeAl)_2(SiAl)_2O_6$

An aluminous silicate whose formula can be written as above in conformity with the Si_2O_6 pattern of the atomic chain structure. The relative proportions of the metal ions (Ca, Mg, Fe, Al) are variable within limits, giving a range of composition and different varieties of the mineral. Some Al^{3+} is substituted for Si^{4+}.

Crystals: Commonly 8-sided and prismatic, terminated by two pyramid faces at each end (Fig. 4.22); brown to black in colour, vitreous to resinous lustre. Twin crystals (Fig. 4.8*a*) show a re-entrant angle. $H = 5$ to 6. $G = 3.3$ to 3.5. The two vertical cleavages may be observed on the end faces of suitable crystals.

Augite occurs chiefly in basic and ultrabasic rocks; e.g. in gabbro, where it appears as dark areas intermingled with the paler feldspar. In fine-grained basic rocks it is not distinguishable in the hand specimen unless it is porphyritic. Augite is also a constituent of some andesites and diorites, and occasionally of granites.

Fig. 4.22 Crystal of augite: oblique view and vertical view showing cleavage and principal crystal faces.

In thin section: idiomorphic (i.e. well formed) crystals show characteristic 8-sided transverse sections, bounded by prism and pinacoid faces, with the two prismatic cleavages intersecting at nearly 90°. Longitudinal sections show only one cleavage direction (Fig. 4.23).

Fig. 4.23 Augite in thin section (×12): (**a**) regular cross-section with 93° cleavage, (**b**) irregular fragment displaying diagnostic cleavage, (**c**) vertical section, (**d**) symmetrical extinction, (**e**) oblique extinction for long section.

Colour: Pale brown to nil. Pleochroism generally absent or weak.

Mean R.I. = about 1.70, giving strong relief in balsam.

Biref: Hypersthene: weak (0.106) giving grey, white or yellow polarization colours. Augite: strong (0.025) giving bright blues, reds and browns.

Extinction: Hypersthene: parallel to cleavage in long section. Augite: oblique to cleavage in long section.

The amphibole group

Minerals of this group are mainly monoclinic. The crystals are elongated in the *c*-direction and usually bounded by six vertical faces, of which the prism faces intersect at an angle of 124°, Fig. 4.24. This is also the

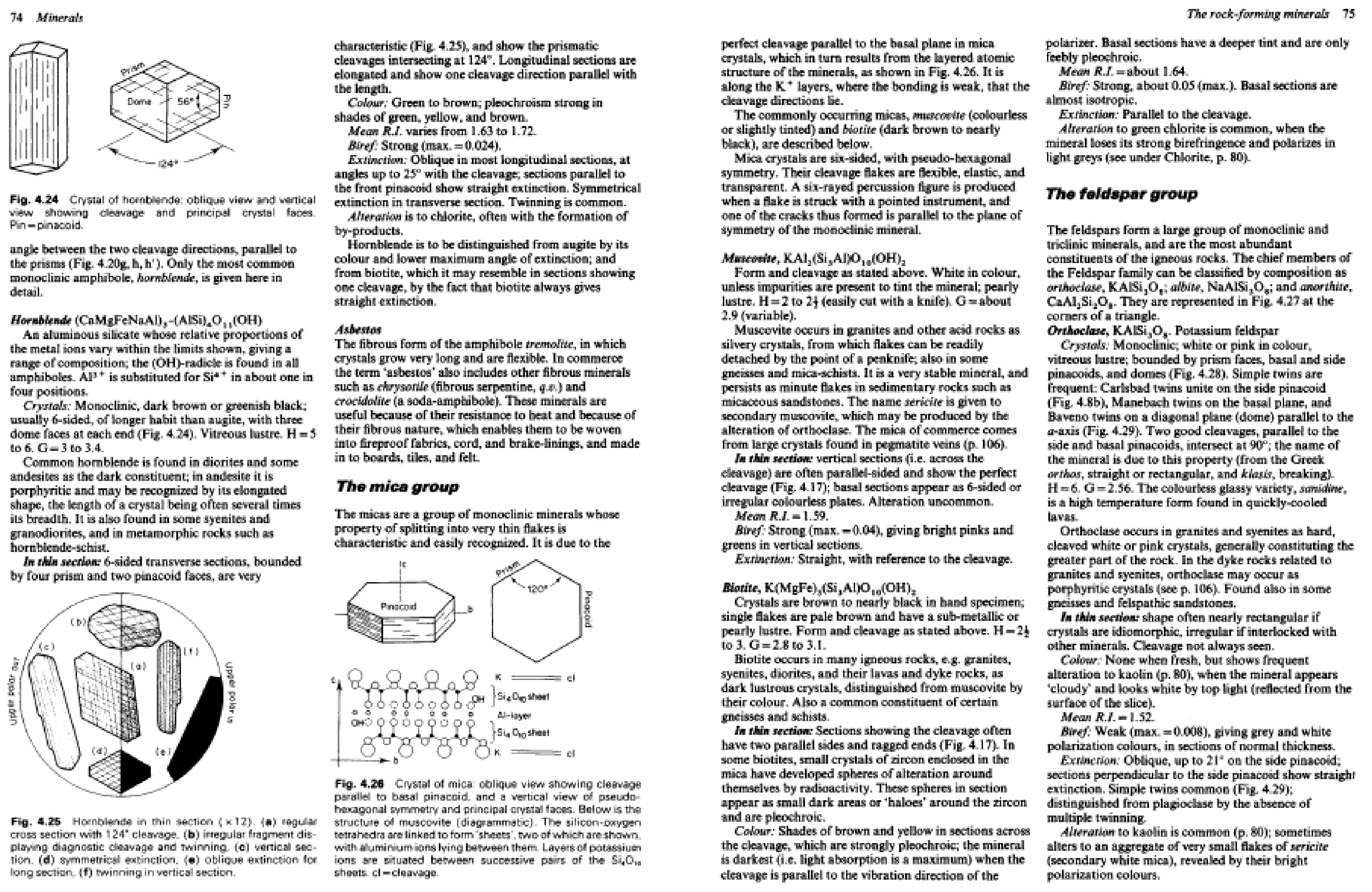


Fig. 4.24 Crystal of hornblende: oblique view and vertical view showing cleavage and principal crystal faces. Pin = pinacoid.

angle between the two cleavage directions, parallel to the prisms (Fig. 4.20g, h, h′). Only the most common monoclinic amphibole, *hornblende*, is given here in detail.

Hornblende $(CaMgFeNaAl)_3$-$(AlSi)_4O_{11}(OH)$
An aluminous silicate whose relative proportions of the metal ions vary within the limits shown, giving a range of composition; the (OH)-radicle is found in all amphiboles. Al^{3+} is substituted for Si^{4+} in about one in four positions.

Crystals: Monoclinic, dark brown or greenish black; usually 6-sided, of longer habit than augite, with three dome faces at each end (Fig. 4.24). Vitreous lustre. H = 5 to 6. G = 3 to 3.4.

Common hornblende is found in diorites and some andesites as the dark constituent; in andesite it is porphyritic and may be recognized by its elongated shape, the length of a crystal being often several times its breadth. It is also found in some syenites and granodiorites, and in metamorphic rocks such as hornblende-schist.

In thin section: 6-sided transverse sections, bounded by four prism and two pinacoid faces, are very characteristic (Fig. 4.25), and show the prismatic cleavages intersecting at 124°. Longitudinal sections are elongated and show one cleavage direction parallel with the length.

Colour: Green to brown; pleochroism strong in shades of green, yellow, and brown.

Mean R.I. varies from 1.63 to 1.72.

Biref: Strong (max. = 0.024).

Extinction: Oblique in most longitudinal sections, at angles up to 25° with the cleavage; sections parallel to the front pinacoid show straight extinction. Symmetrical extinction in transverse section. Twinning is common.

Alteration is to chlorite, often with the formation of by-products.

Hornblende is to be distinguished from augite by its colour and lower maximum angle of extinction; and from biotite, which it may resemble in sections showing one cleavage, by the fact that biotite always gives straight extinction.

Fig. 4.25 Hornblende in thin section (×12). **(a)** regular cross section with 124° cleavage. **(b)** irregular fragment displaying diagnostic cleavage and twinning. **(c)** vertical section. **(d)** symmetrical extinction. **(e)** oblique extinction for long section. **(f)** twinning in vertical section.

Asbestos
The fibrous form of the amphibole *tremolite*, in which crystals grow very long and are flexible. In commerce the term 'asbestos' also includes other fibrous minerals such as *chrysotile* (fibrous serpentine, *q.v.*) and *crocidolite* (a soda-amphibole). These minerals are useful because of their resistance to heat and because of their fibrous nature, which enables them to be woven into fireproof fabrics, cord, and brake-linings, and made in to boards, tiles, and felt.

The mica group

The micas are a group of monoclinic minerals whose property of splitting into very thin flakes is characteristic and easily recognized. It is due to the perfect cleavage parallel to the basal plane in mica crystals, which in turn results from the layered atomic structure of the minerals, as shown in Fig. 4.26. It is along the K^+ layers, where the bonding is weak, that the cleavage directions lie.

Fig. 4.26 Crystal of mica: oblique view showing cleavage parallel to basal pinacoid, and a vertical view of pseudo-hexagonal symmetry and principal crystal faces. Below is the structure of muscovite (diagrammatic). The silicon-oxygen tetrahedra are linked to form 'sheets', two of which are shown, with aluminium ions lying between them. Layers of potassium ions are situated between successive pairs of the Si_4O_{10} sheets. cl = cleavage.

The commonly occurring micas, *muscovite* (colourless or slightly tinted) and *biotite* (dark brown to nearly black), are described below.

Mica crystals are six-sided, with pseudo-hexagonal symmetry. Their cleavage flakes are flexible, elastic, and transparent. A six-rayed percussion figure is produced when a flake is struck with a pointed instrument, and one of the cracks thus formed is parallel to the plane of symmetry of the monoclinic mineral.

Muscovite, $KAl_2(Si_3Al)O_{10}(OH)_2$
Form and cleavage as stated above. White in colour, unless impurities are present to tint the mineral; pearly lustre. H = 2 to 2½ (easily cut with a knife). G = about 2.9 (variable).

Muscovite occurs in granites and other acid rocks as silvery crystals, from which flakes can be readily detached by the point of a penknife; also in some gneisses and mica-schists. It is a very stable mineral, and persists as minute flakes in sedimentary rocks such as micaceous sandstones. The name *sericite* is given to secondary muscovite, which may be produced by the alteration of orthoclase. The mica of commerce comes from large crystals found in pegmatite veins (p. 106).

In thin section: vertical sections (i.e. across the cleavage) are often parallel-sided and show the perfect cleavage (Fig. 4.17); basal sections appear as 6-sided or irregular colourless plates. Alteration uncommon.

Mean R.I. = 1.59.

Biref: Strong (max. = 0.04), giving bright pinks and greens in vertical sections.

Extinction: Straight, with reference to the cleavage.

Biotite, $K(MgFe)_3(Si_3Al)O_{10}(OH)_2$
Crystals are brown to nearly black in hand specimen; single flakes are pale brown and have a sub-metallic or pearly lustre. Form and cleavage as stated above. H = 2½ to 3. G = 2.8 to 3.1.

Biotite occurs in many igneous rocks, e.g. granites, syenites, diorites, and their lavas and dyke rocks, as dark lustrous crystals, distinguished from muscovite by their colour. Also a common constituent of certain gneisses and schists.

In thin section: Sections showing the cleavage often have two parallel sides and ragged ends (Fig. 4.17). In some biotites, small crystals of zircon enclosed in the mica have developed spheres of alteration around themselves by radioactivity. These spheres in section appear as small dark areas or 'haloes' around the zircon and are pleochroic.

Colour: Shades of brown and yellow in sections across the cleavage, which are strongly pleochroic; the mineral is darkest (i.e. light absorption is a maximum) when the cleavage is parallel to the vibration direction of the polarizer. Basal sections have a deeper tint and are only feebly pleochroic.

Mean R.I. = about 1.64.

Biref: Strong, about 0.05 (max.). Basal sections are almost isotropic.

Extinction: Parallel to the cleavage.

Alteration to green chlorite is common, when the mineral loses its strong birefringence and polarizes in light greys (see under Chlorite, p. 80).

The feldspar group

The feldspars form a large group of monoclinic and triclinic minerals, and are the most abundant constituents of the igneous rocks. The chief members of the Feldspar family can be classified by composition as *orthoclase*, $KAlSi_3O_8$; *albite*, $NaAlSi_3O_8$; and *anorthite*, $CaAl_2Si_2O_8$. They are represented in Fig. 4.27 at the corners of a triangle.

Orthoclase, $KAlSi_3O_8$. Potassium feldspar
Crystals: Monoclinic; white or pink in colour, vitreous lustre; bounded by prism faces, basal and side pinacoids, and domes (Fig. 4.28). Simple twins are frequent: Carlsbad twins unite on the side pinacoid (Fig. 4.8b), Manebach twins on the basal plane, and Baveno twins on a diagonal plane (dome) parallel to the *a*-axis (Fig. 4.29). Two good cleavages, parallel to the side and basal pinacoids, intersect at 90°; the name of the mineral is due to this property (from the Greek *orthos*, straight or rectangular, and *klasis*, breaking). H = 6. G = 2.56. The colourless glassy variety, *sanidine*, is a high temperature form found in quickly-cooled lavas.

Orthoclase occurs in granites and syenites as hard, cleaved white or pink crystals, generally constituting the greater part of the rock. In the dyke rocks related to granites and syenites, orthoclase may occur as porphyritic crystals (see p. 106). Found also in some gneisses and felspathic sandstones.

In thin section: shape often nearly rectangular if crystals are idiomorphic, irregular if interlocked with other minerals. Cleavage not always seen.

Colour: None when fresh, but shows frequent alteration to kaolin (p. 80), when the mineral appears 'cloudy' and looks white by top light (reflected from the surface of the slice).

Mean R.I. = 1.52.

Biref: Weak (max. = 0.008), giving grey and white polarization colours, in sections of normal thickness.

Extinction: Oblique, up to 21° on the side pinacoid; sections perpendicular to the side pinacoid show straight extinction. Simple twins common (Fig. 4.29); distinguished from plagioclase by the absence of multiple twinning.

Alteration to kaolin is common (p. 80); sometimes alters to an aggregate of very small flakes of *sericite* (secondary white mica), revealed by their bright polarization colours.

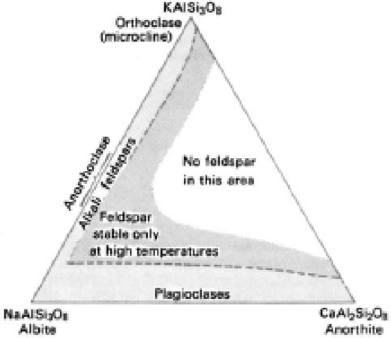


Fig. 4.27 Feldspar composition diagram. For a feldspar represented by a point within the triangle, the proportions of the three quantities Orthoclase, Albite, Anorthite are given by the lengths of the perpendiculars from the point onto the sides of the triangle. Each corner represents 100% of the component named there. With increasing Ca the plagioclases grade from Albite (0–10% $CaAl_2$) to Oligoclase, Andesine, Labradorite, Bytownite and Anorthite (90–100% $CaAl_2$).

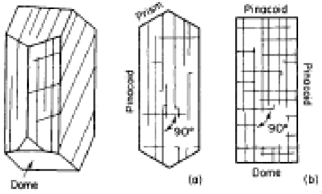


Fig. 4.28 Crystal of orthoclase (left) showing cleavage: (**a**) cross section and (**b**) vertical section showing cleavage and principal crystal faces.

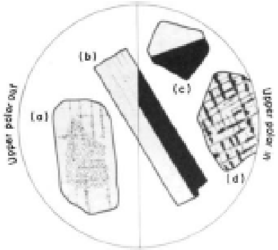


Fig. 4.29 Orthoclase in thin section (× 3). (**a**) alteration to kaolin, (**b**) vertical section exhibiting Carlsbad twin, (**c**) Baveno twin, (**d**) Microcline.

Microcline, $KAlSi_3O_8$. Triclinic; the low temperature form of potassium feldspar.

Crystal form is similar to that of orthoclase, but the two cleavages (parallel to the basal and side pinacoids) intersect at about 89° instead of 90°.

Colour: White, pink, or green.

R.I. and *Biref:* Similar to orthoclase. Multiple twinning, with two intersecting sets of gently tapering twin-lamellae; in thin sections this is seen as a characteristic 'cross-hatching' effect between crossed polars, and distinguishes microcline from other feldspars (Fig. 4.29).

Anorthoclase Triclinic. (Fig. 4.27.) The beautiful grey schillerized feldspar which occurs in *laurvikite* (a Norwegian syenite, p. 107); it is also found as rhomb-shaped crystals in *rhomb-porphyry* in the Oslo district.

Schiller is the play of colours seen by reflected light in some minerals, in which minute platy inclusions are arranged in parallel planes; the effect is produced by the interference of light from these platy inclusions.

The Plagioclases

Feldspars of this series are formed of mixtures (solid solutions) of albite, $NaAlSi_3O_8$, and anorthite, $CaAl_2Si_2O_8$, in all proportions. The range of composition is divided into six parts, which are named. A plagioclase, for example, containing 40 per cent albite and 60 per cent anorthite would be called labradorite (written $Ab_{40}An_{60}$).

Crystals: Triclinic; white or colourless (albite) to grey (anorthite), bounded by prisms, basal and side pinacoids, and domes (Fig. 4.30). Vitreous lustre. Cleavages parallel to the basal and side pinacoids meet at an angle of about 86° (hence the name; Greek *plagios*, oblique; *klasis*, breaking). Multiple twins parallel to the side pinacoid (Albite twinning, Figs 4.8c and 4.31a) are characteristic of plagioclases; the closely spaced twin-lamellae can often be seen with a lens as stripes on the basal cleavage and other surfaces. Another set of twins is sometimes developed on planes, parallel to the *b*-axis, which make a small angle with the basal pinacoid, Fig. 4.31 (Pericline twinning). H = 6 to 6½. G = 2.60 (albite), rising to 2.76 (anorthite).

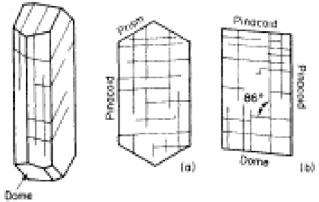


Fig. 4.30 Crystal of albite (a plagioclase): oblique view showing cleavage. (**a**) cross section and (**b**) vertical section, showing cleavage and principal crystal faces.

Plagioclase feldspars occur in most igneous rocks, and in some sedimentary and metamorphic rocks. They appear as white or grey cleaved crystals in the coarse-grained igneous rocks, where their multiple twinning may be seen with a hand lens in suitable crystals.

In thin section: idiomorphic crystals (e.g. in lavas) commonly show rectangular sections; parallel-sided 'laths', with their length several times as great as their breadth, are seen when the crystals sectioned are flat and thin parallel to the side pinacoid (see Fig. 5.19). Cleavage not often visible. The minerals are normally colourless but may be clouded with alteration products: these are mainly kaolin in Na-rich, and epidote in Ca-rich varieties.

The characteristic multiple twinning appears as light and dark grey parallel stripes between crossed polars (Fig. 4.31), and sets of alternate stripes extinguish obliquely in different positions. Average values for the optical properties of the plagioclases are: *R.I.* = 1.55, birefringence weak (0.009) which gives grey and yellow polarization colours, and oblique extinction of long sections that varies from approximately 15° for albite to 40° for anorthite.

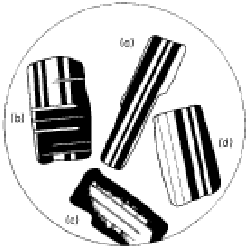


Fig. 4.31 Plagioclase in thin section (× 2) (upper polar in) – see also Fig. 4.17. (**a**) Common albite twin, (**b**) pericline twin, (**c**) zoned, (**d**) combined carlsbad-albite twin.

Zoned crystals Many crystals possess internal variations of composition which are expressed (*i*) by colour, e.g. tourmaline, Fig. 4.36; (ii) by inclusions, small particles locked up in a crystal at some stage in its growth, e.g. quartz, Fig. 4.33, or (*iii*) by zones of different composition. This last is particularly evident in some plagioclases, where it results from differences in successive layers of material acquired during a crystal's growth. For example, a plagioclase may have begun to grow as anorthite; but because of changes in the relative concentrations of constituents in the melt that was breeding the crystal, further growth may have used material containing less anorthite and more albite. A slice of such a crystal seen between crossed polars does not show sharp extinction in one position, but the zones of different composition extinguish successively at slightly different angles as the slice is rotated (Fig. 4.31c). Augite and hornblende may also show compositional zoning of this kind.

The feldspathoid group

Minerals of this group resemble the feldspars chemically, and have 3-dimensional framework structures; they differ from the feldspars in their lower content of silicon. Stated in another way, the Al:Si ratio is higher in the feldspathoids than in the corresponding feldspars. The two chief minerals of the group, which are not discussed here because their occurrence is somewhat limited in nature, are:

Leucite, $K(AlSi_2)O_6$ (cf. Orthoclase)

Nepheline, $Na(AlSi)O_4$ (cf. Albite), usually with a little K.

Feldspathoids occur in certain undersaturated lavas, which have a low silica- and high alkali-content, such as the leucite-basalts from Vesuvius.

Forms of silica

Silica is found uncombined with other elements in several crystalline forms of which *quartz*, one of the most common minerals in nature, is of special importance. As the quartz content of a rock increases so may its strength and also its abrasiveness to machinery used for drilling and excavating. When drilling quartz-rich rock fine dust may be created which should not be inhaled as it may damage lung tissue. Other forms of silica include the high temperature *tridymite* (see below); *chalcedony*, aggregates of quartz fibres; and the cryptocrystalline forms *flint* and *opal*, and *chert* (p. 126).

Quartz, SiO_2

In the structure of quartz the silicon-oxygen tetrahedra build up a three-dimensional framework in which each oxygen is shared between two silicons. There are no substitutions of other ions in the silicon positions.

Crystals: Trigonal with 6-sided prisms and rhombohedral terminations (Figs. 4.32 and 4.7); faces sometimes unequally developed; occasionally other faces belonging to trigonal forms are present. Vitreous lustre; conchoidal fracture. Colourless when pure (e.g. '*rock crystal*'), but many coloured varieties occur, the colour being due to traces of impurities, e.g. *rose quartz* (pink), *smoky quartz* (grey), *milky quartz* (white), *amethyst* (violet). Some quartz contains minute inclusions or liquid-filled cavities, which may be arranged in regular directions in a crystal. No cleavage; twins rare. H = 7, cannot be scratched with a knife. G = 2.66.

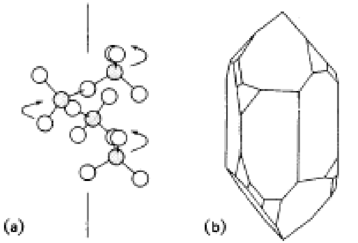


Fig. 4.32 (**a**) Spiral structure in atomic framework of quartz. (**b**) Quartz crystal with extra (trigonal) faces.

Quartz is an essential constituent of granites, and can be recognized in the rock as hard, glassy grains of irregular shape and without cleavage. It occurs in smaller amount in granodiorite and quartz-diorite, and is present as well-shaped porphyritic crystals in acid dyke-rocks and lavas. *Vein quartz* is an aggregate of interlocking crystals of glassy or milky appearance, filling fractures in rocks; the boundaries of the crystals may be coated with brown iron oxide. Well-shaped quartz crystals are found in cavities (*druses*) in both veins and granitic rocks. Most sands and sandstones have quartz as their main constituent; the grains have a high resistance to abrasion and thus persist over long periods during erosion and transport. The mineral is also found abundantly in gneisses, quartzites, and in some schists and other metamorphic rocks.

In thin section: basal sections are regular hexagons (Fig. 4.16) when the crystals are well formed; also see Fig. 4.16 for longitudinal section. When the mineral has crystallized among others, as in granite, its shape is irregular (Figs. 4.33 and 5.24).

Colourless. Never shows alteration, but crystals in lavas sometimes have corroded and embayed margins.

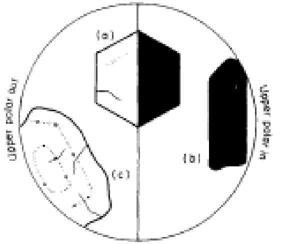


Fig. 4.33 Quartz in thin section (× 10). (**a**) Cross-section normal to *c*-axis; (**b**) vertical section parallel to *c*-axis; and (**c**) irregular (from an igneous rock such as granite), lines of minute inclusions (dots) may be present.

R.I. = 1.553 (max.), 1.544 (min.); weak outline in Canada balsam.

Biref. = 0.009 (max.) (see p. 68).

Extinction: Straight in longitudinal sections.

Quartz is distinguished from orthoclase by the absence of twinning and by its entire lack of alteration; it always appears fresh, although inclusions may be present. The mineral may show strain polarization in rocks which have been deformed and then has no sharp extinction position.

Chalcedony, SiO_2

Radiating aggregates of quartz fibres, their ends often forming a curved surface; white or brownish colour and of waxy appearance in the mass. Chiefly found in layers lining the vesicles of igneous rocks (Fig. 4.2a). In thin section, such layers show a radiating structure, of which the crystal fibres have straight extinction and give an extinction 'brush' which remains in position as the stage is rotated. *R.I.* = 1.54; polarization colours are light greys.

Flint Cryptocrystalline (i.e. made of a large number of minute crystals which are too small to be distinguished separately except under very high magnification) silica, possibly with an admixture of opal, representing a dried-up gel; occurs in nodules in the chalk (see p. 127). Often black in colour on a freshly broken surface, with conchoidal fracture. Split flints were much used in the past as a decorative facing to buildings.

Opal Hydrated silica, SiO_2nH_2O; amorphous. White, grey, or yellow in colour, with a pearly appearance (opalescence), and often displaying coloured internal reflections. Conchoidal fracture. H = about 6. G = 2.2. Occurs as a filling to cracks and cavities in igneous rocks. When it replaces woody tissues it preserves the original textures and is known as *wood opal*. The microscopic organisms known as *diatoms* (p. 30) which live in oceans and lakes, are also composed of opaline silica. Opal is an undesirable constituent in rocks used for concrete aggregates, owing to the possibility of reaction occurring between it and alkalis in the cement (*q.v.*).

In thin section, colourless and isotropic, with low *R.I.* (1.44).

Accessory minerals

Minerals that occur as small crystals and in limited quantities are described as accessory. Occasionally they may develop to form large crystals and in certain circumstances can be concentrated to become a major rock constituent.

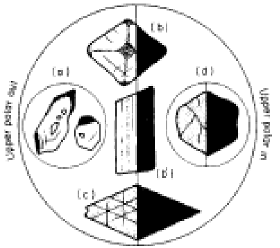


Fig. 4.34 Some accessory minerals in thin section (× 15). (**a**) Zircon (at greater magnification than other minerals shown). (**b**) Chiastolite cross-section, (b') long section. (**c**) Sphene. (**d**) Garnet, showing isotropic character under crossed polars.

Zircon, $ZrSiO_4$

Tetragonal. H = 7.5, G = 4.7. Zircon occurs in granites and syenites as an original constituent. Crystals are usually very small and in thin section are recognized chiefly by their shape: Fig. 4.34*a*.

Andalusite, Al_2OSiO_4

Orthorhombic. Colour, pink or grey. H = 7.5, G = 3.2. Andalusite occurs in contact metamorphosed shales and slates. Crystals are prismatic and have a nearly square transverse section. The variety *chiastolite* contains inclusions of carbon (Fig. 4.34*b*). Two other forms of Al_2OSiO_4 are *sillimanite* (formed at high temperature as in an aureole) and *kyanite* (a pale blue mineral formed under high stress and moderate temperature).

Sphene, $CaTiSO_4$ (O, OH, F)

Monoclinic. H = 5, G = 3.5. Sphene occurs as small wedge-shaped crystals (Gr. *sphene*, a wedge) in granite, diorites and syenites. Fig. 4.34*c*.

Garnet $(Ca, Mg, Fe^{2+}, Mn)_3\,(Al, Fe^{3+}, Cr)_2\,(SiO_4)_3$

Cubic (Fig. 4.35). Colour, pale pink. H = 6.5 to 7.5, G = 3.5 to 4.0 according to species of mineral. Garnet occurs in metamorphic rocks such as mica-schist. In thin section crystals are isotropic. Fig. 4.34d.

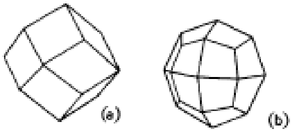


Fig. 4.35 Crystals of garnet oblique views. (**a**) rhombdodecahedron; (**b**) trapezohedron.

Tourmaline. Complex silicate of Na, Mg, Fe, Al with Si_6O_{18} rings.

Trigonal. Colour, black, red, green, blue. H = 7, G = 3.0. Tourmaline occurs in granites and vein rocks such as pegmatites. The variety *schorl* commonly grows in radiating clusters (Fig. 4.1e) e.g. in pneumatolysed granites. Yellow in thin section with extinction parallel to length. Fig. 4.36*a*–*c*.

Cordierite, $Mg_2Al_3(AlSi_5)O_{18}$

Orthorhombic but commonly appears nearly hexagonal in shape when crystals grow together as twins (Fig. 4.36*d*). Occurs in metamorphic rocks such as hornfels (p. 136).

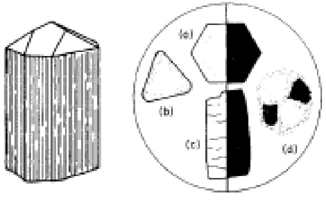


Fig. 4.36 Crystal of tourmaline. Tourmaline seen in thin section (× 5). (**a**) and (**b**) cross-sections; (**c**) vertical section. Also shown is cordierite (**d**).

Secondary minerals

Described under this head are the minerals *chlorite*, *serpentine*, *talc*, *kaolin*, *epidote* and *zeolite*, all of which result from the alteration of pre-existent minerals. These minerals have little mechanical strength and small angles of friction. Their presence on fractures can significantly reduce the strength of a rock mass.

Chlorite $(MgFe)_5Al(Si_3Al)O_{10}(OH)_8$, variable

The chlorites (Greek *chloros*, green) form a family of green flaky minerals which are hydrous silicates of

Next Page

magnesium and aluminium. Some Fe replaces Mg and gives colour to the chlorite. Like the micas, they have a perfect cleavage, due to the atomic sheet structure (Fig. 4.26). Different kinds of chlorite are given distinctive names (e.g. penninite, clinochlore); these are not distinguished in the following general description.

Crystals: Monoclinic, frequently 6-sided in shape, with a perfect cleavage parallel to the basal plane; the mineral splits into hexagonal flakes which are flexible but not elastic (cf. mica). H = 2 to 2½ (often soft enough to be scratched by the finger-nail). G = 2.65 to 3.0.

Chlorite is found in igneous rocks, as described below, and in metamorphic rocks such as chlorite-schist, and in some clays.

In thin section: Chlorite occurs as an alteration product of biotite, augite, or hornblende; it may replace these minerals completely, forming a *pseudomorph* (= 'false form') in which the aggregate of chlorite flakes and fibres retains the shape of the original mineral. Together with other minerals such as calcite, chlorite also forms an infilling to cavities in basalts (*q.v.*).

Colour: Shades of bluish-green and yellowish-green, sometimes very pale; noticeably pleochroic; cleavage often seen.

Mean R.I. = about 1.58.

Biref: Weak grey.

Serpentine, $Mg_6Si_4O_{10}(OH)_8$, some Fe replaces Mg, in part

Serpentine is an alteration product of olivine, of orthorhombic pyroxene, or of hornblende. This reaction takes place in an igneous rock while it is still moderately hot (*hydrothermal action*), the source of the hot water being magmatic; it is thought that the change from olivine to serpentine may also be brought about by the action of water and silica.

Serpentine grows as a mass of green fibres or plates, which replace the original mineral as a pseudomorph. A fibrous variety is called *chrysotile*, and is worked in veins for commercial asbestos. In the mass, serpentine is rather soapy to the touch, and may be coloured red if iron oxide is present. H = 3 to 4. G = 2.6. Serpentine is found in basic and ultrabasic rocks (p. 101), and in serpentine-marble.

In this section: as a pseudomorph after olivine, serpentine appears as a matte of pale green fibres, weakly birefringent, and having a low *R.I.* (1.57). Specks of black magnetite, the oxidized by-product from iron in the original olivine, are often present. The change to serpentine involves an increase in volume, and this expansion may fracture the surrounding minerals in the rock, fine threads of serpentine being developed in the cracks so formed.

Talc, $Mg_3Si_4O_{10}(OH)_2$

A soft, flaky mineral, white or greenish in colour, which occurs as a secondary product in basic and ultrabasic rocks, and in talc-schist (p. 140). It is often associated with serpentine. Flakes are flexible but not elastic, and are easily scratched by the finger-nail. H = 1.

Kaolin (china clay)

This substance is largely made up of the mineral *kaolinite*, $Al_4Si_4O_{10}(OH)_8$, one of the group of Clay Minerals which, like the micas, are built up of silicon-oxygen sheets (Fig. 4.26).

Kaolin is derived from the breakdown of feldspar by the action of water and carbon dioxide; the chemical equation for the change is given and the kaolinization of granite masses is described on p. 138. It is white or grey, soft, and floury to the touch, with a clayey smell when damp. G = 2.6. In thin section it is seen as a decomposition product of feldspar (Fig. 4.29), which when altered appears clouded and looks white by top light (i.e. by light reflected from the surface of the slice and not transmitted through it).

Epidote, $Ca_2(AlFe)_3(SiO_4)_3(OH)$

The monoclinic crystals of this mineral are typically of a yellowish-green colour. Often in radiating clusters; vitreous lustre. H = 6 to 7. G = 3.4.

Epidote occurs as an alteration product of calcic plagioclases or of augite; also as infillings to vesicles in basalts, and as pale green veins traversing igneous and metamorphoc rocks.

Zeolites

These form a group of hydrous aluminous silicates of calcium, sodium, or potassium; they contain molecular water which is readily driven off on heating, a property to which the name refers (Greek *zein*, to boil). They occur as white or glassy crystals clusters, filling or lining the cavities left by escaping gases (amygdales, p. 100) in basic lavas, or filling open joints, and are derived from feldspars or feldspathoids by hydration.

Two commonly occurring natural zeolites are:

Analcite, $NaAlSi_2O_6H_2O$

Cubic; crystallized as trapezohedra (as in Fig. 4.35b), white in colour. G = 2.25. Occurs in the amygdales of basalts.

Natrolite, $Na_2Al_2Si_3O_{10}2H_2O$

Forms white, acicular orthorhombic crystals, generally in radiating clusters. G = 2.2.

Clay minerals

Clays can form as either primary or secondary minerals. Here they are grouped under one heading because of their economic importance, their presence in most profiles of weathering and their influence upon the mechanical character of rocks and less well consolidated sediments. Being minute they can be seen using only an electron microscope (Fig. 4.37), but their presence may be revealed by placing a few particles of material that is

ENGINEERING GEOLOGY CE1301

Lecture #3 Igneous Rocks

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WHAT ARE IGNEOUS ROCKS?

- A **rock:** is a naturally occuring solid aggregate of one or more minerals or amorphous solids.
- **Magma:** is generated by local heating and melting of rocks within the Earth's crust, mostly at depths between 10 and around 100 km.

Most compositions of rock melt at temperatures of 800–1200°C.

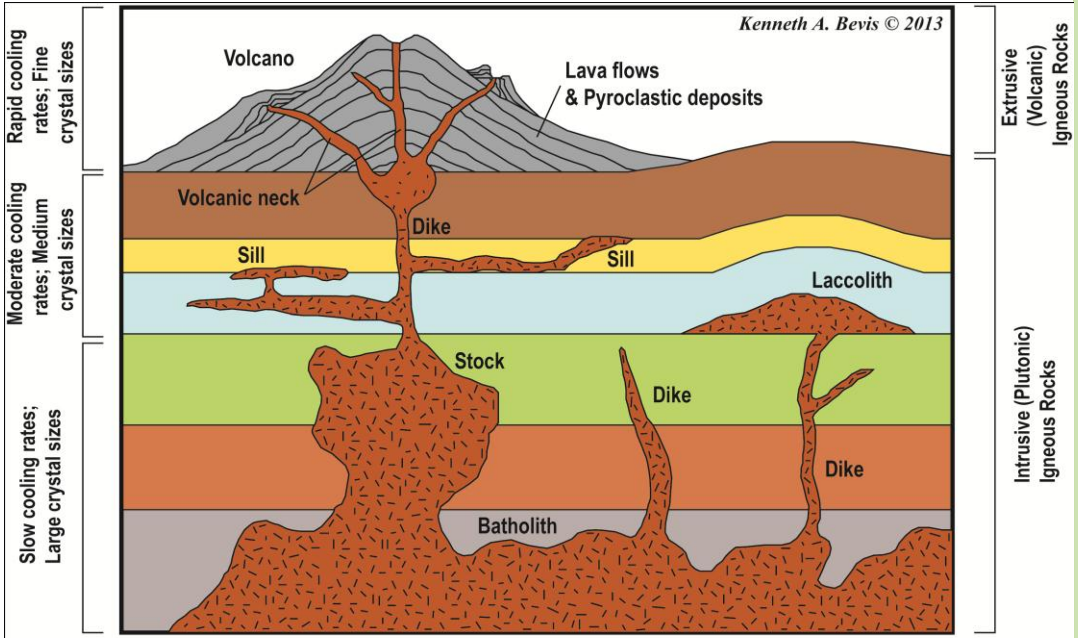
- **Lava:** is the name for both molten rock on the surface, and also the solid rock formed when it cools.
- **Igneous Rocks:** are formed by cooling magma or lava *(lava is a magma which cools on earth's surface).*
- **1- Intrusive** or **plutonic rocks:** formed from magma forced into older rocks at depths within the Earth's crust, which then slowly solidifies below the Earth's surface, though it may later be exposed by erosion. Igneous intrusions form a variety of rock types.

Large visible crystals are formed due to the relatively slow rate of cooling of magma.

- 2- **Extrusive or volcanic rock:** formed from lava that was poured out or ejected at the Earth's surface.

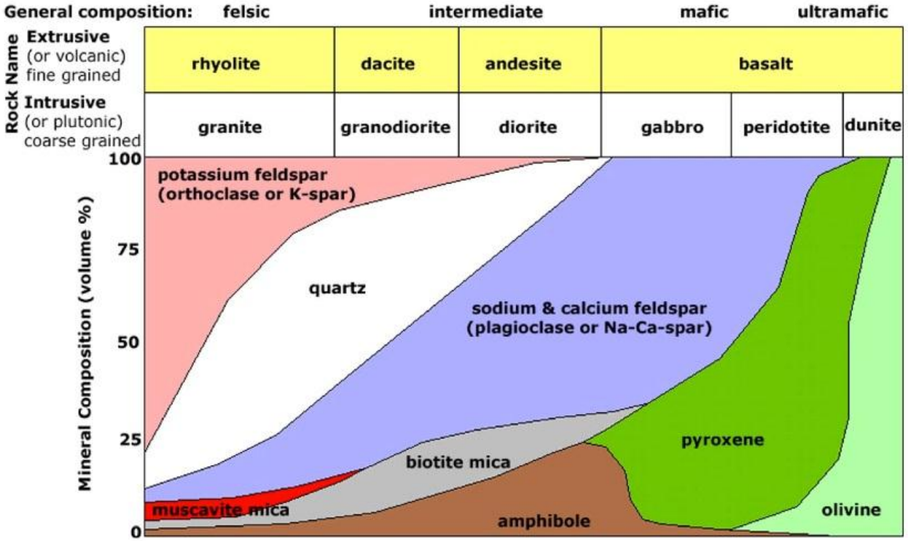
No visible crystals are formed because lava crystallizes very quickly.

Source: http://intheplaygroundofgiants.com

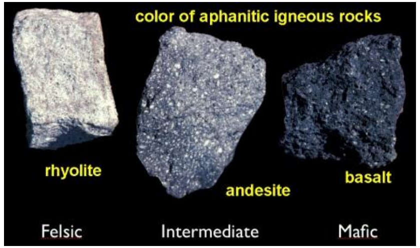


- **Batholiths:** are large blob-shaped intrusions, roughly equi-dimensional and commonly 5–50 km in diameter. Most are of granite.
- **Dykes** are smaller sheet intrusions formed where magma has flowed into a fissure, Mostly 1–50 m wide; may extend for many Kilometres.
- **Sills:** are sheet intrusions parallel to the bedding of the country rocks into which the magma was intruded.
- **Pyroclastic rocks** (meaning fire fragmental) are formed of material, collectively known as tephra, thrown into the air from an explosive volcano. Most tephra is cooled in flight, and lands to form various types of ash, tuff and agglomerate, all with the properties of sedimentary rocks.
- **Laccolith** – dome-shaped magma formed by intruding layered sedimentary rocks.

CLASSIFICATION OF IGNEOUS ROCKS



Source: http://geologycafe.com/



- Igneous rocks classification is based on combinations of their: 1) mineral composition, 2) grain size, 3) color, and 4) texture.
- General composition is of little significance in the context of most engineering applications.

Texture and composition

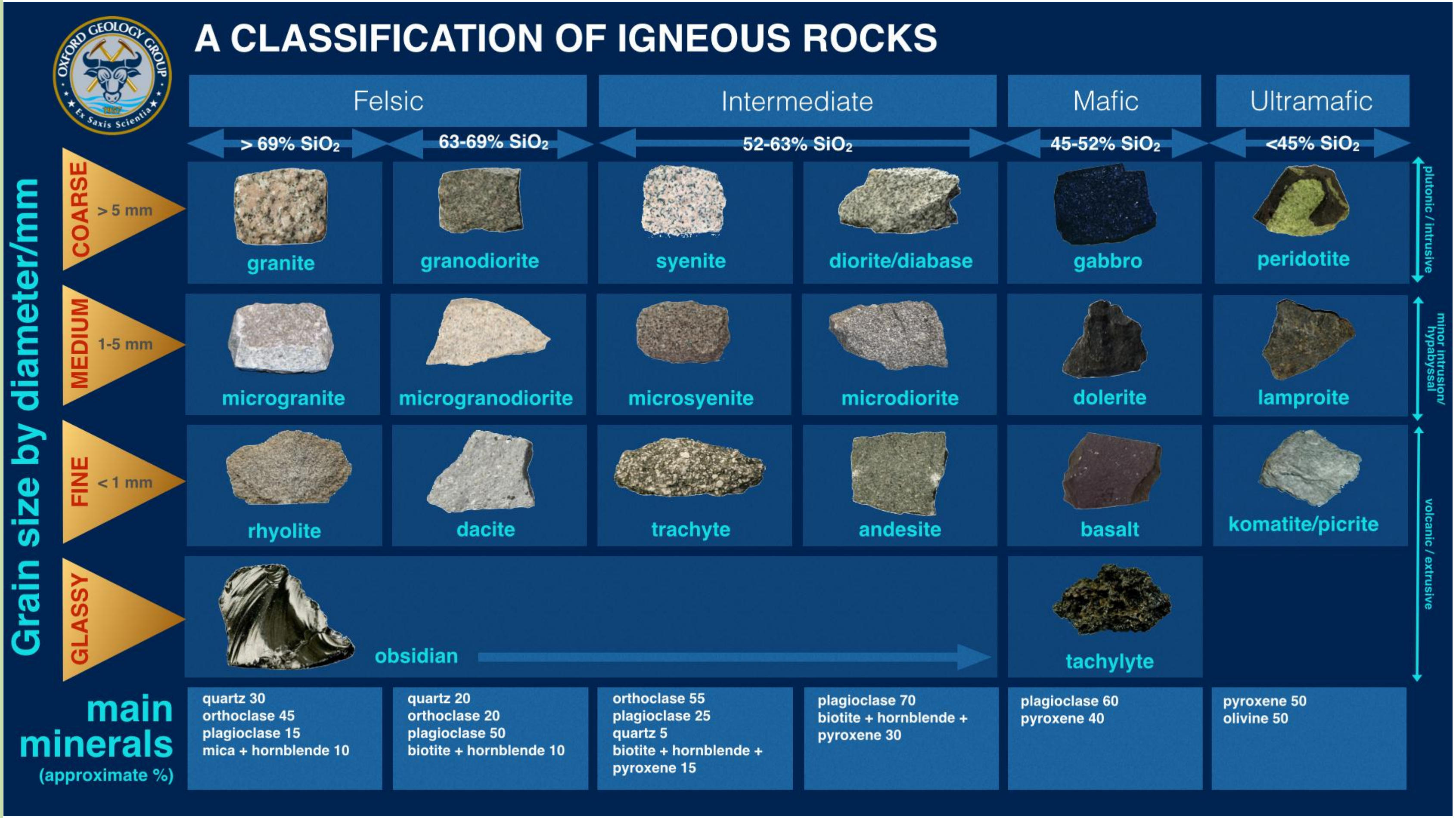
1. *Degree of crystallinity* (commonly reflects speed of cooling)
Holocrystalline = entirely composed of crystals (cooled slowly)
Hypocrystalline = composed of crystals and glass
Hyalocrystalline = no crystals, i.e. glassy (cooled quickly)

2. *Visible crystallinity* (commonly reflects speed of cooling)
Phaneritic = individual crystals can be distinguished (cooled slowly)
Aphanitic = granularity from the presence of crystals can be seen, but individual crystals cannot be distinguished
Glassy = entirely glass-like, or some crystals set in glass (cooled quickly)

3. *Crystal size* (commonly reflects speed of cooling)
Coarse= > 2 mm
Medium = 2-0.06 mm
Fine= <0.06mm
(Microcrystalline = must be observed using a microscope)

4. *Relative crystal size* (commonly reflects abundance of ions and uniformity of cooling history)
Equigranular = all crystals are approximately of equal size
Inequigranular = some crystals are clearly larger than others
Porphyritic = large crystals surrounded by much smaller crystals

5. *Crystal shape* (commonly reflects sequence of crystallization)
Euhedral = well defined regular shape (crystallized early from melt) (= idiomorphic)
Anhedral = poorly defined and irregular outlines (crystallized late from melt)



A CLASSIFICATION OF IGNEOUS ROCKS

Grain size by diameter/mm

	Felsic		Intermediate		Mafic	Ultramafic	
	> 69% SiO_2	63-69% SiO_2	52-63% SiO_2		45-52% SiO_2	<45% SiO_2	
COARSE > 5 mm	granite	granodiorite	syenite	diorite/diabase	gabbro	peridotite	plutonic / intrusive
MEDIUM 1-5 mm	microgranite	microgranodiorite	microsyenite	microdiorite	dolerite	lamproite	minor intrusion/ hypabyssal
FINE < 1 mm	rhyolite	dacite	trachyte	andesite	basalt	komatite/picrite	volcanic / extrusive
GLASSY	obsidian				tachylyte		
main minerals (approximate %)	quartz 30 orthoclase 45 plagioclase 15 mica + hornblende 10	quartz 20 orthoclase 20 plagioclase 50 biotite + hornblende 10	orthoclase 55 plagioclase 25 quartz 5 biotite + hornblende + pyroxene 15	plagioclase 70 biotite + hornblende + pyroxene 30	plagioclase 60 pyroxene 40	pyroxene 50 olivine 50	

Source: http://alexandriadarcy.com/tag/igneous-rocks/

SOME ENGINEERING CONSIDERATIONS

- The use of igneous rocks in Portland cement as aggregates can cause problems related to volume expansion due to the alkali-silica reaction.
- Coarse grained igneous rocks are undesirable for use as aggregates for construction due the reduction of abrasion resistance with increasing aggregate size. The rock is less suitable for use as base coarse (in roads) or riprap (for slope protection along rivers and seacoasts).
- Weathered igneous rocks are to be avoided in dams, bridge piers.
- Igneous rocks are commonly used as dimension stone due to their resistance to weathering.

IGNEOUS ROCKS – FURTHER READING

give the rocks a dark appearance. Specific gravity ranges from about 2.9 to 3.2. Because basic lavas are relatively fluid, basalt is frequently (though finely) crystalline; it may grade into dolerite with increase of crystal size, and similarly dolerite may grade into gabbro as the texture grows coarser.

Gabbro

Minerals

Essential minerals are a plagioclase (generally labradorite) and a monoclinic pyroxene (augite or diallage). The plagioclase composition reflects the high CaO and low Na_2O content in gabbro (see analysis, p. 100). Other minerals which may be present in different gabbros are hypersthene, olivine, hornblende, biotite, and sometimes nepheline. Ilmenite, magnetite, and apatite are common accessories. Quartz in very small amount may be present in some gabbros (see below). Mafic minerals make up over 50% of the rock, Fig. 5.18a.

Fig. 5.18 Polished surface of gabbro of ring-dyke, Ardnamurchan, Scotland (×1). Plagioclase, light; ferro-magnesian minerals, dark.

Texture

Coarsely crystalline, rarely porphyritic, sometimes with finer modifications. Hand specimens appear mottled dark grey to greenish-black in colour because of the large mafic content. Under the microscope the texture appears as interlocking crystals (Fig. 5.19). Olivine if present is often in well-formed crystals because of its early separation from the magma, and commonly encloses black grains of iron oxide. Serpentine after olivine, and chlorite after pyroxene are common alteration products.

Varieties

If a mafic mineral in addition to augite is present, its name is added to the rock name, thus: hypersthene-gabbro, olivine-gabbro, hornblende-gabbro; nepheline-gabbro, = *essexite*.

Norite is a variety containing essentially hypersthene instead of augite, i.e. a hypersthene–labradorite rock, and is of common occurrence.

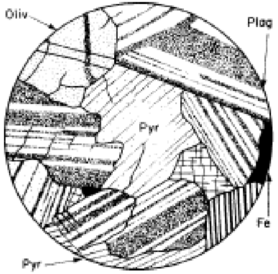


Fig. 5.19 Gabbro seen in thin section; crossed polars (×12). Oliv = olivine; Pyr = pyroxene; Fe = iron-ore; Plag = plagioclase.

Troctolite has olivine and plagioclase (no augite).

Quartz-gabbro contains a little interstitial quartz, derived from the last liquid to crystallize from a magma with slightly higher silica content than normal; e.g. the Carrock Fell rock, Cumberland.

In Britain gabbros are found in Skye (the Cuillins), Ardnamurchan (ring dykes), Northern Ireland (Slieve Gullion), the Lake District, and the Lizard. The large basic sheets of Aberdeenshire as at Insch, Haddo House, and Huntly contain much norite and hypersthene-gabbro. In other countries much larger gabbro intrusions include those of Skaergard, Sudbury, and the Bushveld, which are now briefly described.

The *Skaergaard intrusion* is shaped like an inverted cone or funnel, with an area of 50 km² at the surface, and is exposed on the east coast of Greenland to a vertical depth of some 2500 m; the funnel-shaped mass may continue below this for a similar distance. The lowest part of the exposed gabbro possesses a nearly horizontal layering, consisting of dark bands rich in olivine (formed by the gravity-settling of olivine crystals in the magma) separated by broader bands of olivine-gabbro and hypersthene gabbro. A small scale layering which is repeated many times is called *rhythmic banding*. The layered rocks pass upwards into gabbros without olivine, succeeded by iron-rich gabbros and finally by quartz-gabbros. The plagioclase in the gabbros ranges from labradorite in the lower rocks to andesine in the upper. At the margins of the mass fine-grained gabbros are present.

The *Bushveld complex* of the Transvaal, S. Africa, is a vast lopolith, one of the largest known igneous bodies, with a width at the surface of about 390 km (Fig. 5.15). The lowest rocks which outcrop along its margins are norites, with bands of ultrabasic rock, some containing important *chromite* deposits. Above them lie hypersthene–gabbros which reach a thickness of some 5 km, and which show layering by mineral composition. They in turn are overlain by a zone of red rocks, alkaline diorites and syenites. Valuable concentrations of *platinum* and *magnetite* are found at certain levels in the gabbros.

The large nickel-bearing intrusion of Sudbury, Ontario, is also of lopolith form (Fig. 5.15) with an overall length and width of some 57 and 24 km respectively. A thick norite sheet occupies the lowest part of the elongated basin, and nickel sulphide ores are concentrated near its base and in mineralized dykes. Above the norite lie granophyric rocks (p. 106) which may be a separate intrusion; they are covered by sedimentary rocks in the centre of the lopolith. The combined thickness of the norite and granophyre is about 2.4 km. It has been suggested that the depression now occupied by the Sudbury norite is a crater formed by the impact of a large meteorite.

Dolerite

The chemistry of this intrusive rock corresponds to gabbro but its texture is finer. Dolerite forms dykes, sills, and other intrusions. The rock is dark grey in colour, except where its content of feldspar is greater than average. Dolerite is important as a road-stone for surfacing because of its toughness, and its capacity for holding a coating of bitumen and giving a good 'bind'. In its unweathered state dolerite is one of the strongest of the building stones and used for vaults and strong-rooms, as in the Bank of England.

Minerals

As for gabbro, but the plagioclase is usually lath-shaped.

Texture

Medium to fine-grained; some dolerites have a coarser texture, when the lath-like shape of the feldspar is less emphatic and the rock tends towards a gabbro. When the plagioclase 'laths' are partly or completely enclosed in augite the texture is called *ophitic* (Fig. 5.20); this interlocking of the chief components gives a very strong, tough rock.

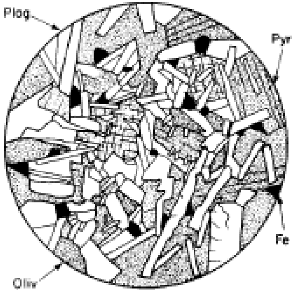


Fig. 5.20 Ophitic dolerite seen in thin section with upper polar out (×12). Plag = plagioclase; Pyr = pyroxene; Oliv = olivine; Fe = iron ore.

Varieties

Normal dolerite = labradorite + augite + iron oxides; if olivine is present the term *olivine–dolerite* is used. Much altered dolerites, in which both the feldspars and mafic minerals show alteration products are called *diabase*, though in America the term is often used synonymously with the British usage of dolerite.

Basalt

Basalt is a dark, dense-looking rock, often with small porphyritic crystals, and weathering to a brown colour on exposed surfaces. It is the commonest of all lavas, the basalt flows of the world being estimated to have five times the volume of all other extrusive rocks together. Basalt also forms small intrusions.

Minerals

Essentially plagioclase (labradorite) and augite; but some basalts have a more calcic plagioclase. Olivine occurs in many basalts and may show alteration to serpentine. Magnetite and ilmenite are common accessories; if vesicles are present they may be filled with calcite, chlorite, chalcedony, and other secondary minerals. Nepheline, leucite, and analcite are found in basalts with a low content of silica.

Texture

Fine-grained or partly glassy; hand specimens appear even-textured on broken surfaces, unless the rock is porphyritic or vesicular (Fig. 5.16); small porphyritic crystals of olivine or augite may need some magnification for identification. Under the microscope the texture is microcrystalline to cryptocrystalline or partly glassy. At the chilled margins of small intrusions a selvedge of black basalt glass, or *tachylite*, is formed by the rapid cooling.

Varieties

Basalt and olivine–basalt are abundant (Fig. 5.21*a*); varieties containing feldspathoids include nepheline–basalt and leucite–basalt (e.g. the lavas from Vesuvius). Soda-rich basalts in which the plagioclase is mainly albite are called *spilites*, and often show 'pillow-structure' in the mass, resembling a pile of sacks; they are erupted on the sea floor, Fig. 5.21b. Their rapid cooling in the sea prevents the minerals crystallized from achieving chemical equilibrium; they are *reactive* and alter readily. Between the pillows are baked marine sediments, often containing chert and jasper (SiO_2). These features of pillow lavas make them a most unsuitable form of basalt for concrete aggregate.

Some of the great flows of basalt in different parts of the world have been referred to earlier; their virtually

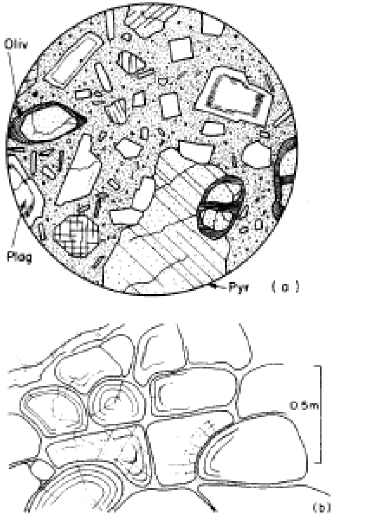


Fig. 5.21 (**a**) Olivine-basalt seen in thin section with upper polar out (×12). Oliv = olivine; Pyr = pyroxene; Plag = plagioclase. (**b**) Pillow lavas exposed in excavation. Note their concentric internal structure and how they sag into the space between underlying pillows.

constant composition suggests a common source, the basaltic layer of the Earth's crust.

Intermediate rocks

Diorite and andesite

The intermediate rocks shown in Fig. 5.17 typically contain little or no quartz. Diorite is related to granite, and by increase of silica content and the incoming of orthoclase grades into the acid rocks, thus: *diorite → quartz-diorite → granodiorite → granite*. The average specific gravity of diorite is 2.87.

Diorite

Minerals

Plagioclase (andesine) and hornblende; a small amount of biotite or pyroxene, and a little quartz may be present, and occasional orthoclase. Accessories include Fe-oxides, apatite and sphene. The dark minerals make up from 15% to 40% of the rock, and hand specimens are less dark than gabbro.

Texture

Coarse to medium-grained, rarely porphyritic. In hand specimens minerals can usually be distinguished with the aid of a lens. Under the microscope minerals show interlocking outlines, the mafic minerals tending to be *idiomorphic* (= exhibit a regular shape).

Varieties

Quartz-diorite (the amount of quartz is much less than in granite) is perhaps more common than diorite as defined above. Fine-grained varieties are called *microdiorite*.

Diorites are found in relatively small masses and frequently form local modifications to granodiorite and granite intrusions; e.g. at the margins of the Newer Granites of Scotland. Small diorite masses occur at Comrie and Garabal Hill, Perthshire.

Andesite

Andesites are fine-grained volcanic rocks, are common as lava flows in orogenic regions and occasionally form small intrusions. They are compact, sometimes vesicular, often brown in colour, and in total extent are second only to basalts. Most andesite flows are found on continental areas, e.g. in the Andes of South America (whence the name is taken), where many volcanoes have emitted ash and lava of andesitic composition; also in parts of the Cordilleras of North America. Certain ores are associated with andesites (p. 110).

Minerals and texture

Essentially plagioclase (mainly adesine) and a mafic mineral (hornblende, biotite, augite, enstatite); the small porphyritic crystals are set in a groundmass that may be glassy, cryptocrystalline, or microlithic (Fig. 5.22). The *microlithic* texture contains many small elongated feldspars, or *microliths*, often having a sub-parallel arrangement, *cf.* the trachytic textures, p. 108). Opaque iron oxides (e.g. magnetite) are common accessories. Hornblende may show dark borders due to reaction with magma.

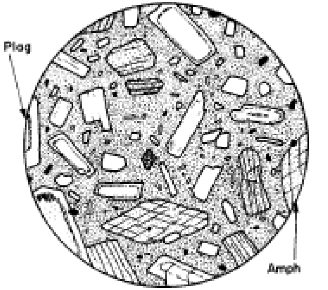


Fig. 5.22 Hornblende-andesite seen in thin section with upper polar out (×12). Plag = plagioclase; Amph = amphibole.

Varieties Hornblende-andesite, augite-andesite, enstatite-andesite, biotite-andesite, and quartz-andesite (= *dacite*). The pyroxene-bearing varieties are abundant and may grade into basalts. Andesites that have been altered by hot mineralizing waters of volcanic origin (see Fig. 5.28a), with the production of secondary minerals, are called *propylites*.

In Britain, andesite lavas of Old Red Sandstone age are found in the Pentland Hills, Edinburgh; Glencoe and Ben Nevis; the Lorne volcanic plateau, Argyll; the Cheviot Hills; and as small intrusions in the Shelve area, Shropshire.

Acid rocks

Granite and granodiorite

The acid plutonic rocks, granite and granodiorite, make the greater part of the large batholiths, found in the cores of mountain fold-belts (p. 17); they also form smaller masses in the upper levels of the Earth's crust, and they are the most abundant of all plutonic rocks. Granite is an important structural stone because of its good appearance, hardness and resistance to weathering (except when crystals of mica are large and weather leaving voids which pit the finished surface), and its strength in compression; the crushing strength of sound granite ranges from about 135×10^6 to 240×10^6 Nm^{-2}. The strength of the rock and its rough fracture are also valuable properties when it is used as concrete aggregate. The average specific gravities are: granite, 2.67, granodiorite, 2.72.

It should be noted that in commerce the term 'granite' is used for some rocks that are not granite in the geological sense.

Granite

Minerals

Quartz, alkali feldspar, a smaller amount of plagioclase, and mica are essential constituents; in some rocks microcline is present. The feldspar may form up to 50% of the rock; the mica is biotite or muscovite, or both. Other minerals found in some granites include hornblende and tourmaline; alkaline types of granite may have Na-rich minerals such as aegirite and riebeckite. Accessory minerals are apatite, magnetite, sphene, zircon, and occasionally garnet (Fig. 5.23).

The average composition of granite is shown in Table 5.3.

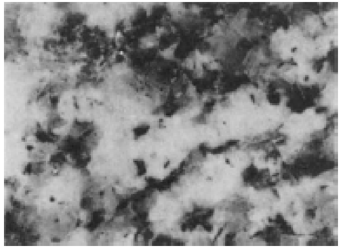


Fig. 5.23 Polished surface of biotite-granite. Merriv Dartmoor (×1). Feldspar, white; quartz, grey; biotite, bl

Texture

Coarse-grained; individual minerals – cleaved feldspar, glassy quartz, and flaky mica – can be distinguished without a lens. Porphyritic granites contain some much larger feldspar crystals than those in the groundmass; fragments of country-rock that have been enclosed in the granite during intrusion may be present as xenoliths (Fig. 5.14).

Under the microscope the crystals show interlocking outlines (Fig. 5.24). Less coarse varieties include *microgranite*, a fine-grained rock frequently found as chilled margins to a larger mass or as a vein rock.

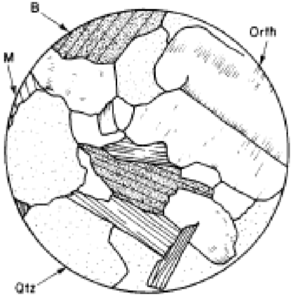


Fig. 5.24 Muscovite-biotite granite seen in thin section, upper polar out (×12). M = muscovite; B = biotite; Orth = orthoclase; Qtz = quartz.

Graphic granite contains intergrowths of quartz and feldspar due to simultaneous crystallization of the two minerals, with angular pockets of quartz in orthoclase or microcline, resembling cuneiform writing. In thin section with crossed polars groups of the quartz areas show simultaneous extinction, indicating that they belong to a single quartz structure interpenetrating the feldspar. When fine-grained the texture is called *micrographic*, and is seen in the rock *granophyre*. The proportion of alkali feldspar to quartz in graphic granite is practically constant, about 70:30, and results from the crystallization of a eutectic mixture of the two minerals. Similar textures on a small scale, however, may sometimes result from the *replacement* of parts of the feldspar by quartz.

Varieties

Varieties of granite are named according to the chief mineral present other than quartz and feldspar, thus: biotite-granite, muscovite-granite, muscovite-biotite-granite, hornblende-granite, or tourmaline-granite.

The worldwide extent of granitic rocks has been mentioned earlier; the larger granite masses of the British Isles are shown in Fig. 2.18.

ENGINEERING GEOLOGY CE1301

Lecture #4 **Surface Processes and Sedimentary Rocks**

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SURFACE PROCESSES

Weathering is the gradual breakdown of rock under atmospheric conditions. It takes place in surface rocks (directly exposed to atmosphere) as well as in the fractured subsurface rocks.

1- Mechanical weathering: the processes that cause physical decomposition of the rock without changing its chemical composition.

2- Chemical weathering: the processes that cause chemical decomposition of the rock.

- **Dissolution**: is the process of dissolving soluble components of matter into solution.
- **Leaching**: is the dissolving and washing out soluble material.
- **Erosion:** is the process by which rock particles are grinded and moved to another place by action of gravity, wind, water (main agent) or ice.

- Land areas are continually being reduced and their shape modified by weathering and erosion, and the general term for this is ***denudation***.
- Weathering leads to a decrease in density and strength, and to increasing deformability. An increase in the mass permeability frequently occurs during the initial stages of weathering due to the development of fractures, but if clay material is produced as minerals breakdown, then the permeability may be reduced. Widening of discontinuities in carbonate rock masses by dissolution leads to a progressive increase in permeability.
- By these processes a covering layer of weathered rock is formed on a land surface. Normally the upper layers of this cover are continually removed, exposing the fresher material beneath it to the influence of the weathering agents; in this way the work of denudation continues. In some circumstances the weathered material may remain in position as a ***residual deposit*** or soil that retains many characters of its parent rock and differs significantly in its mechanical properties from soils formed by the deposition of sediment.

CHEMICAL WEATHERING

Chemical weathering leads to mineral alteration and the solution of rocks. The processes most commonly involved in chemical weathering are listed in the table. Their rate of operation depends upon the presence of water and is greater in wet climates than in dry climates.

Process	**Description**
Dissolution	Dissociation of minerals into ions, greatly aided by the presence of CO_2 in the soil profile, which forms carbonic acid (H_2CO_3) with percolating rainwater.
Oxidation	The combination of oxygen with a mineral to form oxides and hydroxides or any other reaction in which the oxidation number of the oxidized elements is increased. Free oxygen is an important agent in the decay of all rocks that contain oxidizable substances, iron and sulphur being especially suspect.
Hydration	Absorption of water molecules into the mineral structure. Note: this normally results in expansion, some clays expand as much as 60%, and by admitting water accelerate the processes of solution, oxidation, and hydrolysis.
Hydrolysis	Hydrogen ions in percolating water replace mineral cations: no oxidation occurs.
Leaching	The migration of ions produced by the above processes. Note: the mobility of ions depends upon their ionic potential: Ca, Mg, Na, K are easily leached by moving water, Fe is more resistant, Si is difficult to leach and Al is almost immobile.
Cation Exchange	Absorption onto the surface of negatively charged clay of positively charged cations in solution, especially Ca, H, K, Mg.

CHEMICAL WEATHERING

- Chemical weathering is seen most readily in its solvent action on some rocks, notably limestones and those rocks containing the minerals Halite (NaCl), Anhydrite ($CaSO_4$) and Gypsum ($CaSO_4.2H_2O$).
- Common hydration reaction: $CaSO_4 + 2H_2O \rightarrow CaSO_4.2H_2O$
- This reaction produces an increase in volume of approximately 6% and, accordingly, causes the enclosing rocks to be wedged further apart.
- Common dissolution reaction: the calcium carbonate of the limestone is slowly dissolved by rainwater containing carbon dioxide, and is held in solution as calcium bicarbonate, thus:

  $CaCO_3 + H_2O + CO_2 \leftrightarrow Ca(HCO_3)_2$ (Calcium bicarbonate)
- The ground surface of a limestone area commonly shows solution hollows, depressions that may continue downwards as tapering or irregular channels. These may be filled with sediment such as sand or clay.
- Vertical joints in the rock are widened by solution as rain passes down over their walls, and are then known as ***grikes***.
- Continued solution may lead to the formation of ***swallow holes*** (also known as sinkholes) at the intersection of vertical joints.
- **Karst topography** is an area formed by the dissolution (chemical weathering) of soluble rocks such as limestone, dolomite, and gypsum. It is characterized by underground drainage systems with sinkholes and caverns.
- As water charged with calcium bicarbonate drips from the roofs of caves, part of it evaporates and calcium carbonate is slowly re-deposited as loss of carbon dioxide occurs (i.e. the equation above is reversible).

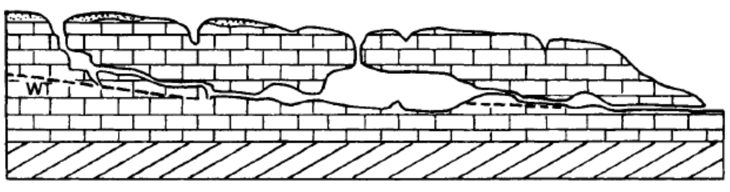


Fig. 3.2 Section through a limestone plateau to show solution features. WT = water table.

Source: brennanjordan.org

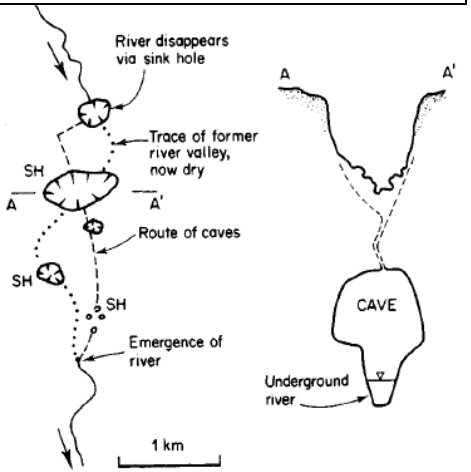


Fig. 3.3 Map showing a river that disappears from the surface to continue its course below ground (SH = sink hole), and a vertical section illustrating the nature of an underground river in Karstic regions.

Source: www.curriculumvisions.com

- The most easily weathered rocks are limestones; of greater resistance are sandstones and shales. Igneous rocks (excluding certain volcanic rocks that weather rapidly) and quartzites are the most resistant.

CHEMICAL WEATHERING

Formation of clay minerals

- Feldspars decompose when subjected to chemical weathering to form clay minerals, which are the most abundant residual products.
- The process is led by the hydrolysing action of carbonated water (in which carbon dioxide gas, CO_2, under pressure has been dissolved) that leaches the bases out of the feldspars and produces clays in suspended form.
- The alkalies are removed in solution as **carbonates** from orthoclase ($K_2\mathbf{CO_3}$) and albite ($Na_2\mathbf{CO_3}$), and as **bicarbonate** from anorthite [$Ca(\mathbf{HCO_3})_2$].
- Although the exact mechanism of the process is not fully understood, the following equation is an approximation towards the truth:

$$2KAlSi_3O_6 + 6H_2O + CO_2 \rightarrow Al_2Si_2O_5(OH)_4 + 4H_2SiO_4 + K_2CO_3$$

(orthoclase) (kaolinite)

- The suspended clay eventually crystallizes as an aggregate of small clay minerals. Deposits of kaolin are formed when percolating acidified waters decompose the feldspars contained in granitic rocks.
- Clays are hydrated aluminium silicates, and when they are subjected to severe chemical weathering in tropical regimes, notably with wet and dry seasons, they break down to form laterite (**Laterites** are soil types rich in iron and aluminium, formed in hot and wet tropical areas) or bauxite (main source of aluminium).
- The process involves the removal of siliceous material by the action of carbonated waters. Intensive leaching of soluble mineral matter from surface rocks takes place during the wet season.
- During the subsequent dry season, groundwater is drawn to the surface by capillary action, and minerals are precipitated there as the water evaporates.

BIOLOGICAL WEATHERING

- Weathering effects which are small in themselves but noticeable in the aggregate can be attributed to plants and animals *(biotic weathering)*. Plants retain moisture and any rock surface on which they grow is kept damp, thus promoting the solvent action of the water. The chemical decay of rock is also aided by the formation of organic products derived from plants, and this is helped by the action of bacteria.
- The mechanical break-up of rocks is hastened when the roots of plants penetrate into cracks and wedge apart the walls of the crack.

MECHANICAL WEATHERING

The processes most commonly involved in mechanical weathering are listed in the table.

Process	Description
Mechanical Unloading	Vertical expansion due to the reduction of vertical load by erosion. This will open existing fractures and may permit the creation of new fractures.
Mechanical Loading	Causes impact on rock, and abrasion, by sand and silt size particles in deserts. Impact on soil and weak rocks by rain drops during intense rainfall.
Thermal Loading	Expansion by the freezing of water in pores and fractures in cold regions, or by the heating of rocks in hot regions. Contraction by the cooling of rocks and soils in cold regions.
Wetting and Drying	Expansion and contraction associated with the repeated absorption and loss of water molecules from mineral surfaces and structures: (see hydration in the previous table).
Crystallization	Expansion of pores and fissures by crystallization of minerals that were originally in solution. Note: expansion is only severe when crystallization occurs within a confined space.

- Mechanical weathering is particularly effective in climatic regions that experience significant diurnal changes of temperature.
- In hot climates, when a rock surface is exposed to a considerable daily range of temperature, as in arid and semi-arid regions, the expansion that occurs during the day and the contraction at night, constantly repeated, weaken the structure of the rock. The outer heated layers tend to pull away from the cooler rock underneath and flakes and slabs split off (**exfoliation**). The effects of exfoliation are concentrated at the corners and edges of rocks so that their shape gradually become rounded.
- A large range of temperature occurs daily in deserts, commonly 30^0C and sometimes as high as 50^0C; the daily range for rock surfaces is often higher than for air. Strain is set up in a rock by the unequal expansion and contraction of its different mineral constituents and its texture is thereby loosened.
- A more homogeneous rock, made up largely of minerals having similar thermal expansion, would not be affected so much as a rock containing several kinds of minerals having different rates of expansion.
- Under natural conditions, insolation of rock faces may result in the opening of many small cracks - some of hair-like fineness - into which water and dissolved salts enter; and thus both the decomposition of the rock and its disintegration are promoted.
- The crystallization of salts from solution in confined spaces, such as cracks and pore spaces may speed the process of weathering in deserts and coastal areas in arid regions, e.g. as along the Arabian coasts.

- In previously hot, semi-arid regions, where evaporation from the ground had been rapid and nearly equal to the rainfall, chemical decomposition of the rocks will have proceeded to great depths and a hard, superficial crust formed by the deposition of mineral matter just below the soil. The water from the occasional rains carries dissolved salts only a short distance below the surface, where they are retained by capillarity, with the result that as evaporation proceeds a mineral deposit is built up. If solutions are saturated with calcium carbonate the deposit will be a calcareous one, like that which covers large areas in Iraq.

- There are three ways by which salts within a rock can cause its mechanical breakdown: by pressure of crystallization, by hydration pressure, and by differential thermal expansion.

The grade of weathering

- The grade of weathering of a given rock is assessed in terms of its macroscopic and microscopic petrography.
- The macroscopic factors included an evaluation of the amount of discoloration, decomposition and disintegration shown by the rock.
- The microscopic analysis involved assessment of mineral composition and degree of alteration by modal analysis and micro-fracture analysis.
- Changes in chemical and physical properties in rock also have been used to assess the grade of weathering such as bulk density and index tests like the absorption.
- Example of the use of physical tests for the recognition of weathering grades: Coefficient of weathering, *K*, for granitic rock, based upon the ultrasonic velocities of the rock material according to the expression:

$K = (Vu - Vw)/Vu$

where *V*u and *V*w are the ultrasonic velocities of the fresh and weathered rocks, respectively, see the tale below.

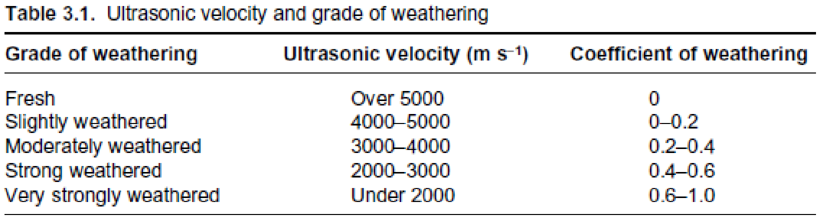


Table 3.1. Ultrasonic velocity and grade of weathering

Grade of weathering	Ultrasonic velocity (m s^{-1})	Coefficient of weathering
Fresh	Over 5000	0
Slightly weathered	4000–5000	0–0.2
Moderately weathered	3000–4000	0.2–0.4
Strong weathered	2000–3000	0.4–0.6
Very strongly weathered	Under 2000	0.6–1.0

- **Sediments** are inorganic or organic material derived from the weathering and erosion of rocks on the Earth's surface.
- **Deposition**: is the process of laying down of sediments transported by wind, water, or ice.
- **The land** represents the erosional environment; it is the source of sediment.
- **The sea** represents the main depositional environment; sediment is buried beneath subsequent layers, and eventually forms most of the sedimentary rocks.

Clastic rocks are composed of fragments, or clasts (particles of rocks), of pre-existing minerals and rock broken off other rocks by mechanical weathering.

- 95% of the outer 16 km of the earth curst is composed of igneous and metamorphic rocks. However 75% of all rocks at the surface are sedimentary rocks.
- Of the sedimentary rocks on the surface, 46% are shales, 32% are sandstones and 22% are limestones.

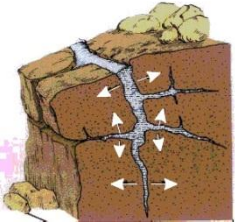
Sedimentary rocks	Mineral grains/ substance
Sandstone 	- mostly quartz, also muscovite - Rock fragments and volcanic debris 
Clays	clay minerals
Limestone 	- **Organic debris:** dominated by calcite from marine shell debris - **Solutes:** dominantly calcite precipitated from sea water largely due to biological activity
Minor rocks	Organic debris: plant material to form peat and coal
Minor rocks	Solutes: including gypsum and salt, and other less abundant soluble compounds

SEDIMENT TRANSPORT

- The most abundant sediment is clastic or detrital material consisting of particles of clay, sand and rock debris.
- Water is far the most important agent of sediment transport. Rivers move the majority of sediment on land. Coarser debris is rolled along the river beds; finer particles are carried in suspension. Water's ability to transport sediment depends on its velocity—larger particles can only be moved by faster flows. Sediment is therefore sorted (to one size) during water transport.
- Sediment is also moved in the sea, mainly in coastal waters where wave action reaches the shallow sea bed.

Other transport processes have only limited scope:

- • Gravity alone works mainly on the steeper slopes, producing landslides and colluvium.
- • Wind moves only fine dry particles.
- • Ice transport is powerful, but restricted by climate.
- • Volcanoes may blast debris over limited distances.
- Some minerals are transported by solution in water. Organic sediment is rarely carried far from its source.



Deposition Environment

Water on land:

- Sorted and stratified, mostly sand and clay.
- Alluvium in river valleys is mostly temporary, later eroded away, except in subsiding deltas.
- Lake sediment includes salts precipitated due to desert evaporation.

The sea:

- Final destination of most clastic sediment.
- Sorted and stratified in beds, mostly in shallow shelf seas.
- Turbidity currents carry sediment into deeper basins.
- Shell debris in shallow seas, with no land detritus, forms the main limestones.

Slopes:

- Localized poorly sorted of broken rock fragments and slide debris.

- Desert regions:

- Trasported by wind.
- Very well sorted sand and silt, mostly in or near dry areas.

Glaciers:

- Unsorted debris dumped in the melt zones of glaciers. Localized today but extensive in past Ice Ages.

Volcano slopes (pyroclastic sediment)

- Fine: sorted airfall ash, wind-blown over large areas;
- Coarse: unsorted flow and surge deposits.

Source: http://geology.com/rocks/limestone.shtml
"**A Limestone-Forming Environment:** Here the entire seafloor is covered by a wide variety of corals which produce calcium carbonate skeletons. A United States Geological Survey image by Curt Storlazzi."

LITHIFICATION

- **Lithification**: The processes by which a weak loose sediment is turned into a stronger sedimentary rock.

\- Induced by burial pressure and slightly increased temperature beneath a kilometre or more of overlying sediment.

<u>Three main processes of lithification:</u>

- **Compaction:** Restructuring and change of grain packing, with decrease in volume, due to burial pressure, with consequent reduction of porosity as air and water is squeezed out.

\- Increase in strength is due to more grain to grain contact. The dominant process in clays.

- **Cementation:** The filling of the pore spaces between individual particles by cementing material brought in by circulating groundwater. These cementing materials then precipitate in the pores and crystallize to give the binding effect.

\- Rock strength is largely dependant on the type of cement, which may be silica (strongest), iron oxides, calcite or clay (weakest). The dominant process in sandstones.

- **Recrystallization:** Minerals within solution crystallize and crystals of existing minerals increase in size.

Result may be similar to cementation, but may produce stronger mosaic texture. Can also include change of state and growth of new more stable minerals. The dominant process in limestones.

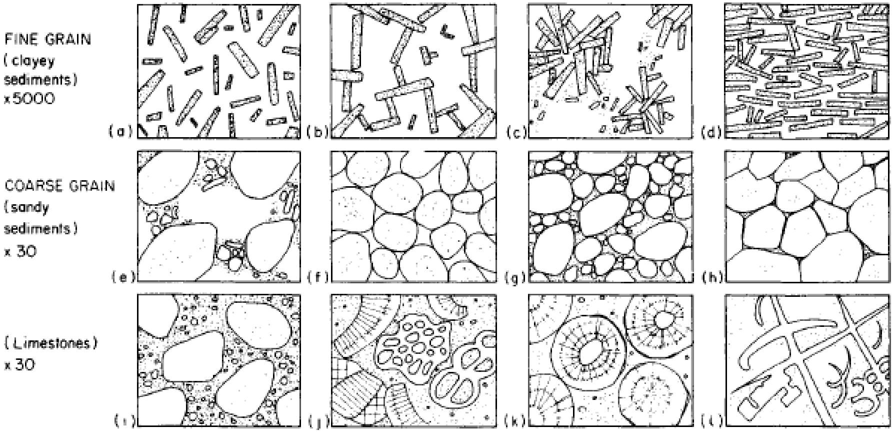


Fig. 6.3 Microscopic texture of some common sediments. Clays, (**a**) dispersed as a colloidal suspension prior to sedimentation; (**b**) aggregated edge to face as often deposited in fresh water; (**c**) flocculated, the form of many newly deposited marine clays; (**d**) compacted with parallel packing, the eventual form of many clays after burial. Sands, (**e**) grains separated by finer matrix; (**f**) grains in contact; (**g**) dense and closely packed grains; (**h**) grain boundaries in contact (*sutured*), as when severely compressed by deep burial. Limestones, (**i**) grains separated by matrix of lime mud; (**j**) shelly limestone; (**k**) oolitic limestone; (**l**) shelly limestone broken by fractures with both shells and fractures enlarged by dissolution to create voids.

- **CONSOLIDATION:** generally refers to the decrease in volume and increase in strength in clays, due to their restructuring, improved packing, loss of water and reduced porosity caused by compaction under load.

\- *Normally consolidated clays* have never been under a higher load than their existing overburden; these include most clay soils.

\- *Over-consolidated clays* have been under a higher load in the past, imposed by cover rocks since removed by erosion; these include nearly all clays within rock sequences. They have lower porosity and higher strength due to their history of burial and exposure.

SEDIMENTARY ROCKS CLASSIFICATION

Based on texture

- **Clastic;**
- **Coarsely crystalline;**
- **Fine grained or cryptocrystalline;**
- **Whole fossils or their products**.

1- Clastic sedimentary rocks:

Composed of pre-existing mineral grains or rock pieces that settled out of water and were subsequently cemented or compressed together.

The classification below is based on Wentworth scale used by geologists. The rock name is decided by the size of the most prevalent grains

Sediment	Size (mm)	Sedimentary rock
Gravel	>2	Conglomerate (if particles rounded), Breccia (if angular)
Sand	2 - 1/16	Sandstone
silt	1/16 - 1/256	Siltstone (commonly called shale)
Clay	<1/256	Claystone (commonly called shale)
Silt and clay		Shale

Conglomerate

Erosion process in which rock pieces are round during transport by stream flow some distance before reaching the sedimentation basin.

Breccia

Angular pieces denote a short transport distance with quick burial

Sandstone

- Many quartz and feldspar-rich sandstones are only partially cemented and have high degree of interconnected pores.
- Many sandstones are good reservoir rocks for water, petroleum and natural gas, due to their high porosity.
- On the other hand, a great amount of water can outflow during tunnelling leading to delay the work and reduce the safety of workers.
  - When the grains of the rock are all composed of quartz, the rock is called quartz sandstone.
  - When the grains of the rock are all composed of feldspar, the rock is called arkosic sandstone

SEDIMENTARY ROCKS CLASSIFICATION

- Dark rock particles from basalt comprise sandstones are called **graywackes**. They are more strongly cemented (due to the existence of clay minerals) than quartz sandstones.
- The sandstone that is mostly quartz with some calcite perhaps as a cement is commonly called **calcareous sandstone.**

Shales

- Shale are composed of silt and clay. They show fissility (closely spaced bedding planes along which the rock will break.

Shales

2- Coarsely crystalline sedimentary rocks

- These rocks composed mostly of carbonate, sulfate and chloride minerals.
- Formed by precipitation from water or by recrystallization of a finer material during and after lithification.
- Precipitation occurs when solutions becomes saturated or oversaturated with certain compound (either by temperature decrease—pH will change, or by reduction in liquid volume by evaporation).
- The interlocking texture can be distinguished with their rounded grains held together by a cementation agent.

Carbonates

- The two most common carbonate rocks are limestone (composed of mostly of calcite ($CaCO_3$) and dolomite which is composed primarily of the mineral dolomite [$CaMg(CO_3)_2$] plus varying amount of ($CaCO_3$).
- A considerable amount of $CaCO_3$ is known to precipitate directly from solution in the open and warm oceans.
- Dolomites are formed commonly by the substitution of Mg^{++} for some of the Ca^{++} in the limestone long after the lithification.

Limestone

Dolomite

SEDIMENTARY ROCKS CLASSIFICATION

Evaporates

- Evaporates are sedimentary rocks derived when sea water is evaporated in an isolated portion of the ocean.
- Minerals precipitate sequentially with decreasing water volume and the order of crystallization is dictated by the relative solubilities of the mineral constituents.
- Seawater contains about 3.5% dissolved solids. 78% of the solids are Na^+ and Cl^-.
- If seawater volume is reduced to about 1/2 , calcium and some iron oxide are precipitated.
- With additional reduction in water volume to about 1/5, gypsum $CaSO_4.2H_2O$ is precipitated from seawater in an evaporate deposit.
- Gypsum is altered to anhydrite (CaSO4) at depth under the heat and pressure of a growing rock column in a sedimentary basin.
- Gypsum is formed again when erosion brings the evaporate deposit close enough to the surface that ground water comes in contact with it.
- Salt solution rise by capillary could also lead to deposit gypsum and anhydrite at the surface when water evaporates
-


Gypsum


Anhydrite

- With 10% remaining seawater volume, NaCl begins to crystallize (rock salt) and Magnesium salts (MgSO4 and MgCl2) are formed on further evaporation.

3- Fine grained or cryptocrystalline sedimentary rocks;

- Are those rocks with textures that are too fine to distinguish with naked eye.

Chert

- In its unweathered condition, it has many properties of quartz such as hradness (7) and high resistence to chemical weathering.
- Formed through primary deposition of silica in the ocean or a secondary replacement in carbonate rocks after deposition.

4- Whole fossils or their products.

- Are those rocks with textures fromed from calcite fossils or materials with a high organic content, including coal.

Fossiliferous limestones

- Consist of calcite fossils of sand size or bigger, cemented together by minor amount of calcite.
- Rocks of this type are too weak to be used for aggregates in concrete or bituminous mixes or for base course.

Rocks rich with organic matter

- Organic matter is present in nearly all sedimentary rocks, especially in fine-grained rocks. (0.5% to 10%) by weight.
- Important group: coal (peat, brown coal, bituminous coal).
- Organic debris comprises the petroleum-rich rocks.

FEATURES OF SEDIMENTARY ROCKS

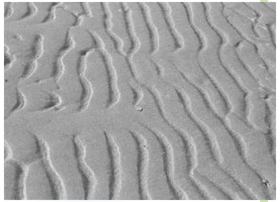
Bedding

a bed is the smallest division of a geologic formation or stratigraphic rock series marked by well-defined divisional planes (bedding planes) separating it from layers above and below. Each layer is characterized by its color, mineral content or texture.

- Bedding provides important information on directional properties of sedimentary rocks such as permeability, compressibility and strength.
- The bedding planes in most cases are horizontal because most sedimentary rocks have a shallow marine origin on the continental shelf where the bottom is almost horizontal.
- For sedimentary rock used as dimension stones or bearing stones, bedding planes should be placed in horizontal position to reduce the chance of water breaking through the stones.

Image source: http://geologycafe.com/images/cross_bedding.jpg

ripple marks: a series of small folds in sand formed by water tides or by wind.



Cross bedding: inclined formations meet at acute angle in some sedimentary rocks related to ripples and dunes caused by fluid movements (water or wind).

Graded bedding— refers to the systematic change in gradation properties (i.e. particle size) with depth. The coarse particles precipitate (faster) at the bottom while the fine grains precipitate (slower) at the top.

Desiccation cracks (mudcracks): crakes developed in the fine grained cohesive material (silt and clay) caused by shrinkage under water loss conditions.

All of the above features are preserved in the cross section of a sedimentary rock!

ENGINEERING CONSIDERATIONS OF SEDIMENTARY ROCKS

- 1- Limestone and dolomite provide the best sedimentary aggregates for construction materials. Siltstone, shale, quartz are generally not accepted, while graywacke is marginal.
- 2- Stream and terrace gravels commonly contain weak pieces that yield nondurable aggregates in concrete.
- 3- Weathered siltstone, clay carbonate, hale and chert can cause pop-outs at the concrete surface after a number of freeze-thaw cycle.
- 4- Coarse-grained limestones abrade (particles reduce in size) too severely to be used for aggregates for construction.
- 5 - Sedimentary rocks used as dimension stone for the facing should be resistant to weathering effects, such as clastic limestones. Quartz sandstones are used for flagstone wall.
- 6- Shales and siltstones can provide a suitable foundation for buildings, dams and bridges. However, there are few concerns related to the effect of weathering and slabbing loose of rock due to stress release after excavation.
- 7- Limestones, dolomite and evaporates deposits can show an irregular soil-rock interface in their weathering profiles. Therefore care must be taken to place heavy structures on solid rocks.
- 8- Sinkholes and underground conduits in limestone and dolomite must be recognised and properly dealt with before construction.
- 9- For dams constructed on rocks involving limestone, presence of solution channels in dams reservoir will lead to leakage unless the channels are grouted.
- 10- Some shales used as rock fills in highway embankments suffer from softening when exposed to water, thus causing certain problems such as subsidence and slope instability. These shales must be broken then compacted into solid mass.
- 11- Special treatment should be considered when conglomerates are encountered in dam works. These sedimentary rocks are poorly cemented and can be highly permeable to water.
- 12- Sedimentary rocks containing anhydrite are troublesome to engineering structures such as dams, highways because of alteration of anhydrite to gypsum upon wetting which is accompanied by volume increase.
- 13- Sedimentary rocks containing gypsum are also troublesome to engineering structures due to salt dissolution in water leading to sever collapsing in the superstructures.

dimension stone

www.ags.gov.ab.ca

solution channel

Fagstone wall

Sinkhole

GYPSEOUS SOILS IN IRAQ

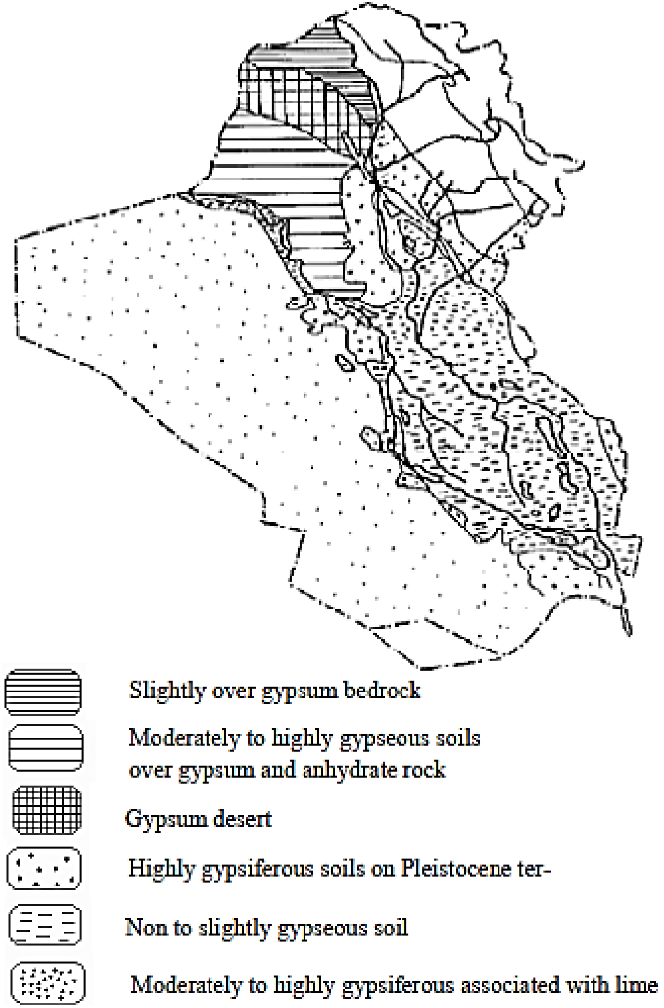
Collapsibility

Collapse potential of soil is calculated from the results of a lab test called double oedometer test on two identical samples; one on them is compressed in its natural water content while the other one is soaked with water. The collapse potential C.P. is identified as

C.P. = $\Delta e / 1 + e_0$

where Δe is the difference in void ratio of the two samples at a given stress and e_0 is the natural void ratio. The collapse severity in relation to the collapse potential is as shown in table below.

Severity	No problem	Moderate	Trouble	Severe	Very Severe
C.P. %	0-1	1-5	5-10	10-20	> 20



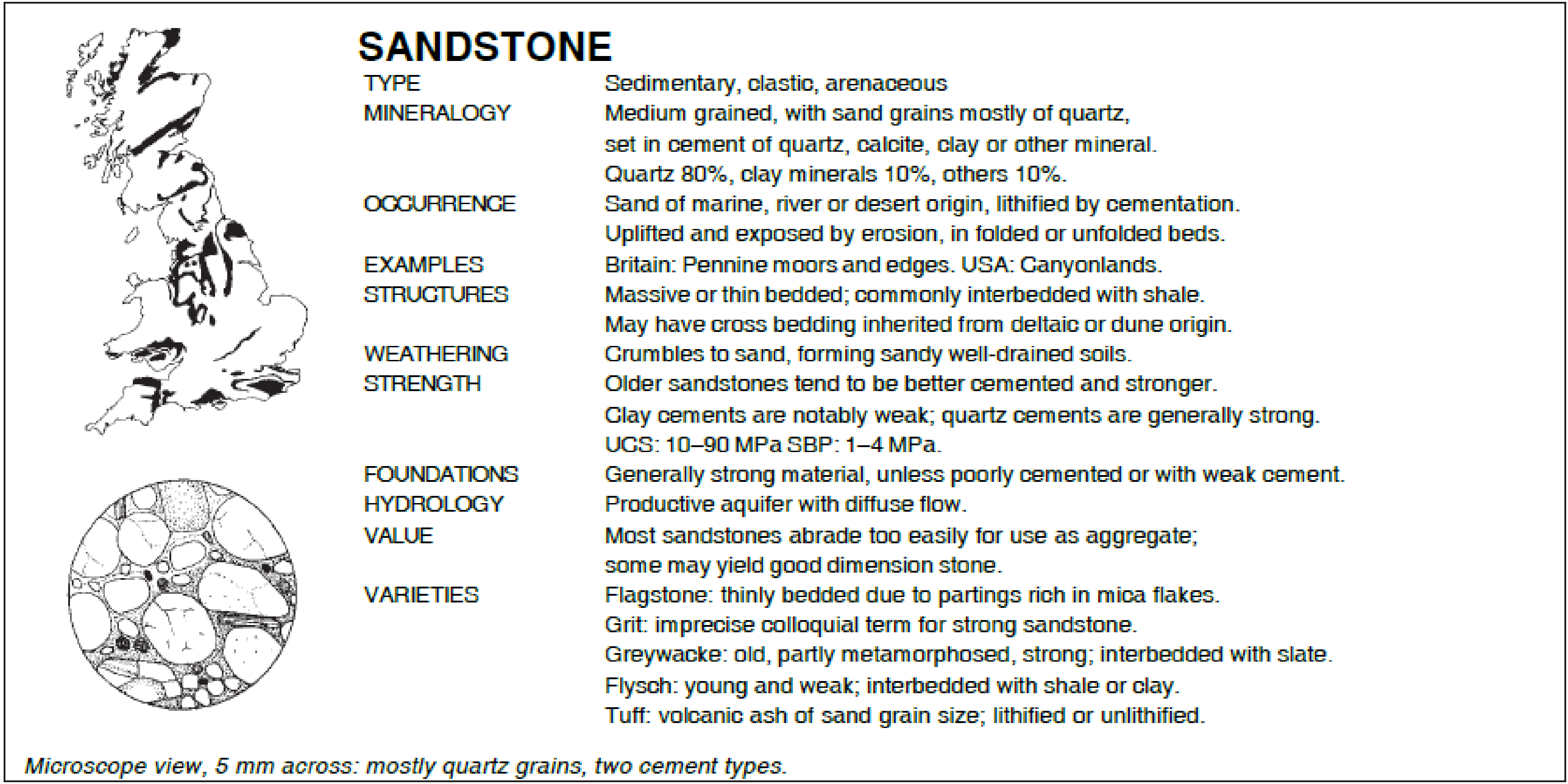
Reference: Al-Barazanji A. F. (1973). Gypsiferous soils in Iraq. PhD. Dissertation. *Ghent University. Belgium*.

Uses of Gypsum

<u>Gypsum has variety of industrial uses, including:</u>

- Manufacturing of wallboard and ceiling boards,
- Plaster of Paris, cement,
- Soil conditioner,
- A hardening retarder in Portland cement.

Source: Foundations of Engineering Geology



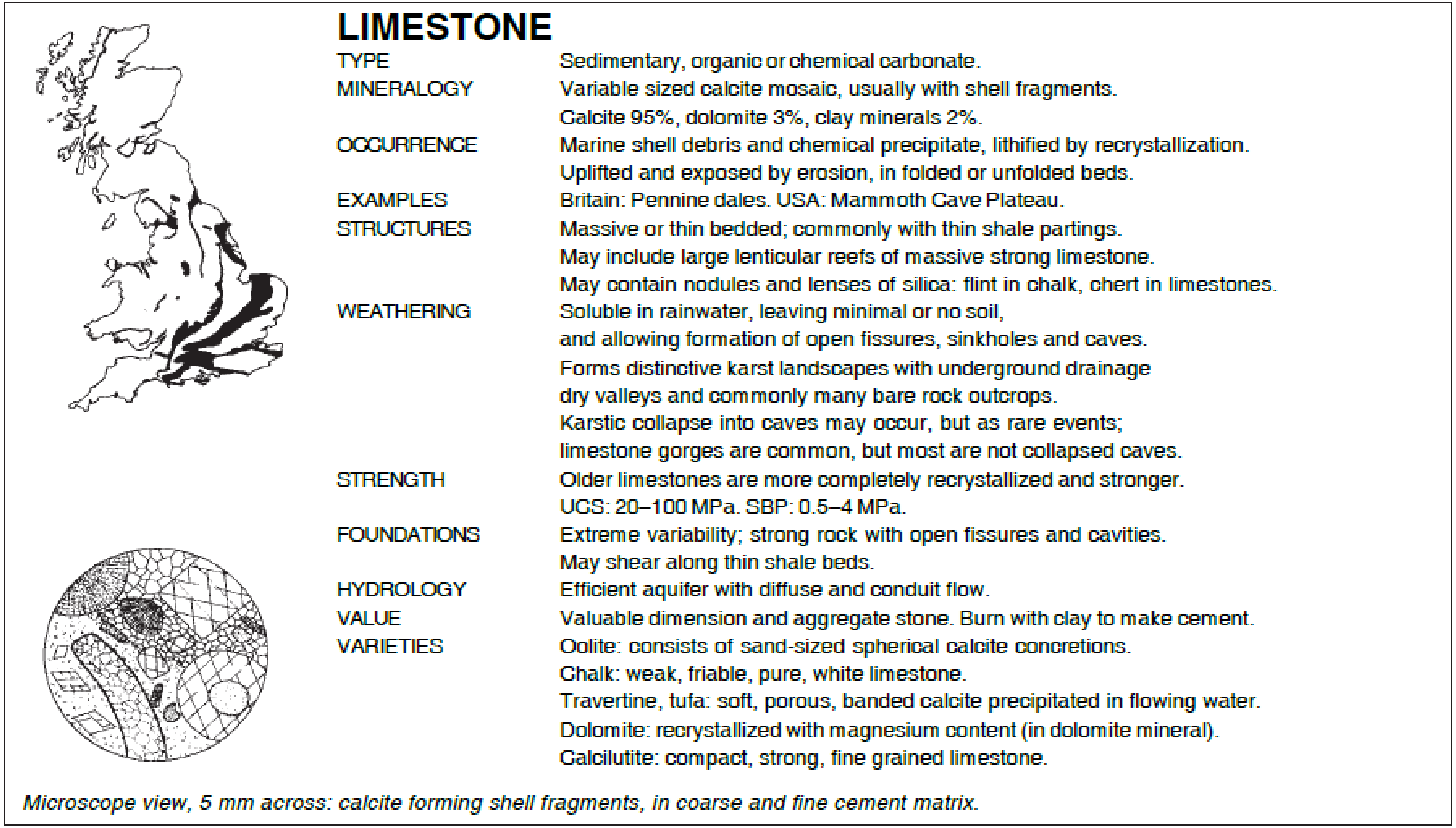
SANDSTONE

TYPE	Sedimentary, clastic, arenaceous
MINERALOGY	Medium grained, with sand grains mostly of quartz, set in cement of quartz, calcite, clay or other mineral. Quartz 80%, clay minerals 10%, others 10%.
OCCURRENCE	Sand of marine, river or desert origin, lithified by cementation. Uplifted and exposed by erosion, in folded or unfolded beds.
EXAMPLES	Britain: Pennine moors and edges. USA: Canyonlands.
STRUCTURES	Massive or thin bedded; commonly interbedded with shale. May have cross bedding inherited from deltaic or dune origin.
WEATHERING	Crumbles to sand, forming sandy well-drained soils.
STRENGTH	Older sandstones tend to be better cemented and stronger. Clay cements are notably weak; quartz cements are generally strong. UCS: 10–90 MPa SBP: 1–4 MPa.
FOUNDATIONS	Generally strong material, unless poorly cemented or with weak cement.
HYDROLOGY	Productive aquifer with diffuse flow.
VALUE	Most sandstones abrade too easily for use as aggregate; some may yield good dimension stone.
VARIETIES	Flagstone: thinly bedded due to partings rich in mica flakes. Grit: imprecise colloquial term for strong sandstone. Greywacke: old, partly metamorphosed, strong; interbedded with slate. Flysch: young and weak; interbedded with shale or clay. Tuff: volcanic ash of sand grain size; lithified or unlithified.

Microscope view, 5 mm across: mostly quartz grains, two cement types.

UCS: Unconfined compression strength; SBP: safe bearing pressure

Source: Foundations of Engineering Geology

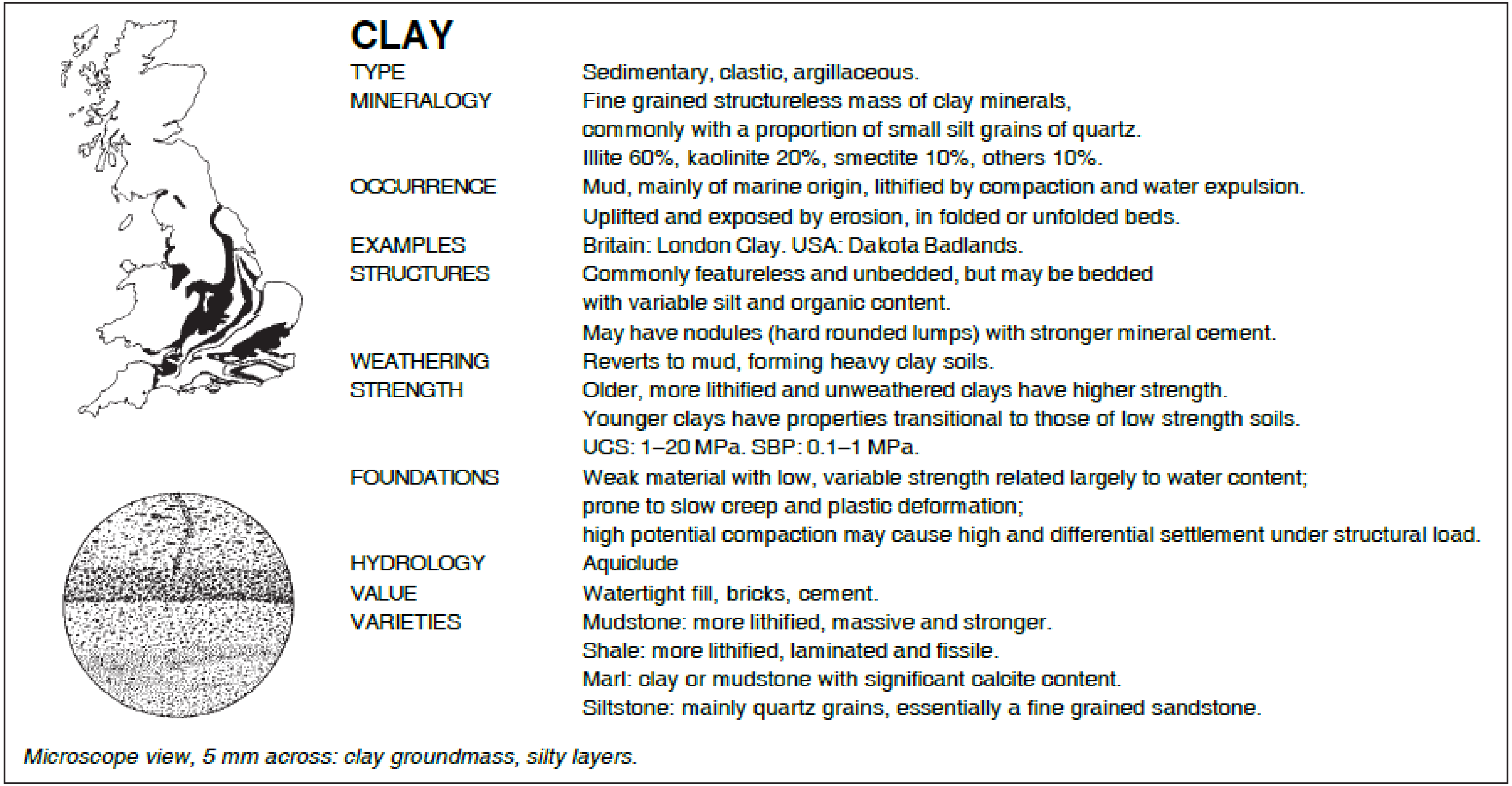


LIMESTONE

TYPE	Sedimentary, organic or chemical carbonate.
MINERALOGY	Variable sized calcite mosaic, usually with shell fragments. Calcite 95%, dolomite 3%, clay minerals 2%.
OCCURRENCE	Marine shell debris and chemical precipitate, lithified by recrystallization. Uplifted and exposed by erosion, in folded or unfolded beds.
EXAMPLES	Britain: Pennine dales. USA: Mammoth Cave Plateau.
STRUCTURES	Massive or thin bedded; commonly with thin shale partings. May include large lenticular reefs of massive strong limestone. May contain nodules and lenses of silica: flint in chalk, chert in limestones.
WEATHERING	Soluble in rainwater, leaving minimal or no soil, and allowing formation of open fissures, sinkholes and caves. Forms distinctive karst landscapes with underground drainage dry valleys and commonly many bare rock outcrops. Karstic collapse into caves may occur, but as rare events; limestone gorges are common, but most are not collapsed caves.
STRENGTH	Older limestones are more completely recrystallized and stronger. UCS: 20–100 MPa. SBP: 0.5–4 MPa.
FOUNDATIONS	Extreme variability; strong rock with open fissures and cavities. May shear along thin shale beds.
HYDROLOGY	Efficient aquifer with diffuse and conduit flow.
VALUE	Valuable dimension and aggregate stone. Burn with clay to make cement.
VARIETIES	Oolite: consists of sand-sized spherical calcite concretions. Chalk: weak, friable, pure, white limestone. Travertine, tufa: soft, porous, banded calcite precipitated in flowing water. Dolomite: recrystallized with magnesium content (in dolomite mineral). Calcilutite: compact, strong, fine grained limestone.

Microscope view, 5 mm across: calcite forming shell fragments, in coarse and fine cement matrix.

Source: Foundations of Engineering Geology



CLAY

TYPE	Sedimentary, clastic, argillaceous.
MINERALOGY	Fine grained structureless mass of clay minerals, commonly with a proportion of small silt grains of quartz. Illite 60%, kaolinite 20%, smectite 10%, others 10%.
OCCURRENCE	Mud, mainly of marine origin, lithified by compaction and water expulsion. Uplifted and exposed by erosion, in folded or unfolded beds.
EXAMPLES	Britain: London Clay. USA: Dakota Badlands.
STRUCTURES	Commonly featureless and unbedded, but may be bedded with variable silt and organic content. May have nodules (hard rounded lumps) with stronger mineral cement.
WEATHERING	Reverts to mud, forming heavy clay soils.
STRENGTH	Older, more lithified and unweathered clays have higher strength. Younger clays have properties transitional to those of low strength soils. UCS: 1–20 MPa. SBP: 0.1–1 MPa.
FOUNDATIONS	Weak material with low, variable strength related largely to water content; prone to slow creep and plastic deformation; high potential compaction may cause high and differential settlement under structural load.
HYDROLOGY	Aquiclude
VALUE	Watertight fill, bricks, cement.
VARIETIES	Mudstone: more lithified, massive and stronger. Shale: more lithified, laminated and fissile. Marl: clay or mudstone with significant calcite content. Siltstone: mainly quartz grains, essentially a fine grained sandstone.

Microscope view, 5 mm across: clay groundmass, silty layers.

ENGINEERING GEOLOGY CE1301

Lecture #5 **Metamorphic rocks**

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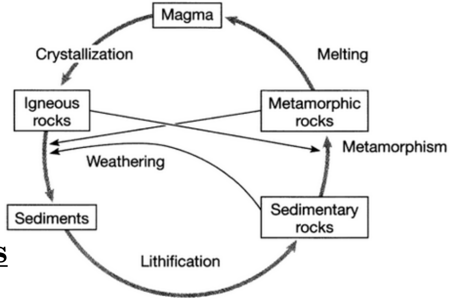
WHAT ARE METAMORPHIC ROCKS?

Metamorphic rocks: Formed within the earth's crust from pre-existing rocks through the action of heat and pressure.

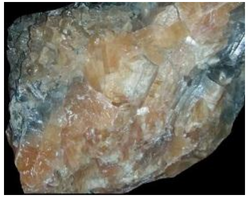
- The metamorphism *"change in form"* process involves the growth of existing minerals with rearrangement or changing of the overall chemical composition keeping that the solid state of the rock is retained.
- If complete melting occurs, the process is igneous rather than metamorphic.



Metamorphic processes

1- Contact metamorphism:

- when the metamorphism reaction occurs locally at the zone of contact (few centimeters to 2 kilometers).
- Examples of this type are skarns and hornfels.

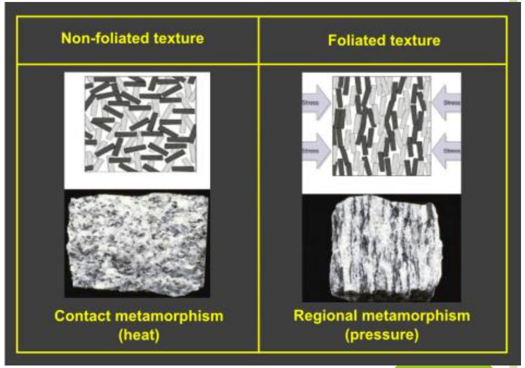


2- Regional metamorphism:

- Occurs on extremely large areas (thousands of square kilometers) and thicknesses of 1 kilometer or more.
- The increased heat weakens chemical bonds and accelerates the rate of chemical reaction, thus encouraging new minerals to form.
- The pressure encourages crystals to align themselves in a manner that will minimize pressure effects.
- The final outcome is the formation of new minerals, of increased size, oriented in a preferred direction.
- For sedimentary rocks, metamorphism occurs in sedimentary basins at depths 9-12 km. to bring these rocks to the surface, extensive uplift and erosion must have occurred.

Texture of metamorphic rocks

Foliation: refers to the pattern of mineral alignment during metamorphism (mostly with regional metamorphism) where minerals tend to align in parallel flat layers or elongated grains in segregated bands of colors. Foliated rocks tend to break along planes of weakness associated with the foliation.



Source: https://leakuhta.wordpress.com/2013/11/18/under-pressure-metamorphic-rocks/

Types of Foliation

1- Slaty cleavage: consists of fractures along smooth planes in a rock that are separated by distances measuring less than a millimeter.

2- Phyllitic cleavage: consists of parallel fractures that are closely spaced but generally farther apart than slaty cleavage.

3- Schistose cleavage: consists of flakes or plates that are visible to the naked eye. The plates are formed by mica sheets or by needle- shaped minerals such as hornblende.

4- Gneissic structure: consists of alternating bands of coarsely crystalline minerals a few millimeters or centimeters thick.

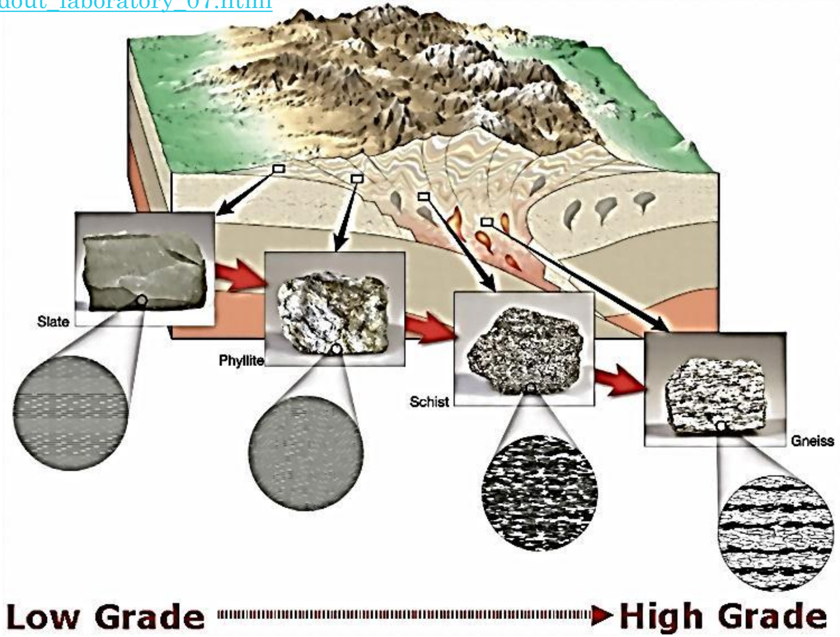
Types of metamorphic rocks

Slate: is a rock formed from shale through low-grade metamorphism. The slaty cleavage is a result of microscopic flakes of muscovite.

Phyllite: has the same composition as slate but with larger pieces and greater quantity of muscovite. It has higher gade of metamorphism than slate.

Schist: the most abundant rock formed by regional metamorphism. The visible flakes of minerals can be for example muscovite, biotite, talc. The needle-shaped minerals can be for example hornblende.

Source:http://www.ocean.odu.edu/~spars001/physical_geology/laboratory/laboratory_07/handout_laboratory_07.html



Gneiss: is a coarse grained metamorphic rock with a banded appearance caused by alternating layers of silicate minerals such as quartz and feldspar. It is formed during high grade regional metamorphism.

Other rocks such as:

marble: composed almost entirely of calcite or dolomite and formed by either contact or regional metamorphism.

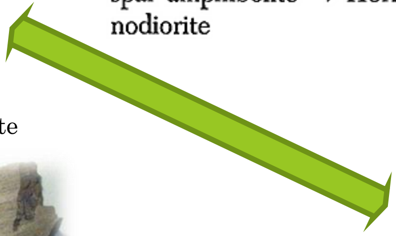
Quartzite: non-foliated formed by the metamorphism of quartz sandstone.

Metamorphic grade

- As the intensity of heat and pressure increase, the grade increases. A sequence of changes can be noted with increasing grade of metamorphism.

Shale → Argillite → Slate → Phyllite → Mica schist → Feldspar schist → Migmatite → Granite

Basalt → Greenstone → Hornblende schist → Feldspar amphibolite → Hornblende migmatite → Granodiorite



Shale

Argillite

Slate

Phyllite

Mica schist

Migmatite

Granite

Basalt

Greenstone

Horhblende schist

Feldspar amphibolite

Hornblende Migmatite

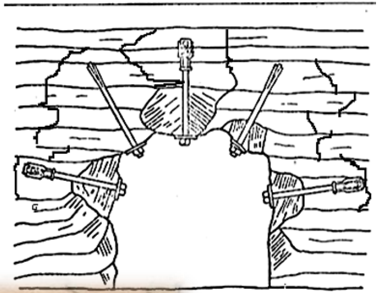
Granodiorite

Engineering considerations of metamorphic rocks

- 1- Foiled metamorphic rocks when crushed commonly gives flat and elongated shapes. If used in concrete, they cause directional properties in hardened concrete.
- 2- Gneiss containing abundant mica can show problems if used as a concrete aggregate because of the failure on cleavage plane caused by freezing-thawing, drying-wetting effects.
- 3- Schists typically are not used as aggregates because of the abundant mica present.
- 4- Foliated rocks possess prominent directional properties. Shear strength, permeability, thermal conductivity and seismic velocity are affected by the direction of foliation. Therefore care should be taken that loads (from dams, bridges and building foundations) are not transferred to foliated rocks in direction parallel to the foliation.
- 5- Coarse grained gneisses, like granites, lose gradation by abrasion when used as aggregates for construction.
- 6- Slate, schist and phyllite are subject to rock overbreak during blasting of rock cuts or tunnels because of their pronounced rock cleavage. High stress concentrations in tunnels may occur for the same reason.
- 7- The stability of rock slopes is greatly affected by the pattern of foliation with respect to the rock slope direction. When foliated dips steeply into an opening, rock slides commonly occur. Rocks bolts or tendons may be needed to prevent such failure.
- 8- Phyllite and argillite can yield alkali-silica reactive aggregates.
- 9- Marble is subject to the same problems as limestone. Solution cavities and channels may develop, resulting in leakage of reservoirs and collapse of newly formed sinkholes.
- 10- Quartzite is a massive, hard rock and has a major abrasive effect on crushing and sizing equipment. It is more expensive than most rocks because of this property.

Source: www.chicken-wire.org

Source: www.techcorr.com



Source: www.fnal.gov

ENGINEERING GEOLOGY CE1301

Lecture #6 Engineering Properties of Rocks

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ROCKS PROPERTIES

From engineering point of view, rocks are significant for two major reasons:

- Many engineering structures are founded on rock;
- They are an important building material with numerous applications.

The **physical properties** of rocks determine their mechanical behaviour. Physical properties are commonly determined by:

Testing small laboratory samples to determine "rock properties"

Testing intact rocks in the field to obtain "rock mass properties'. These properties are controlled by weakness planes in the rock rather than by the properties of the intact material .

Rock	**Stone**
Refers to geological formation in its natural location as a part of the bedrock mass.	Refers to blocks or fragments excavated from quarry ledges that have been prepared for construction use.

1- Specific gravity, Mass density, Absorption

Specific gravity, Gs:

$$G_s = \frac{\text{Mass of solid in Air}}{\text{Mass of solid in Air} - \text{Mass of solid in Water}}$$

if A= mass of solid in air, dried for 24 hrs in an oven;
B=mass of solid in air, saturated surface dried;
C=mass of solid in water, saturated, then:

Bulk Gs=A/(B-C);

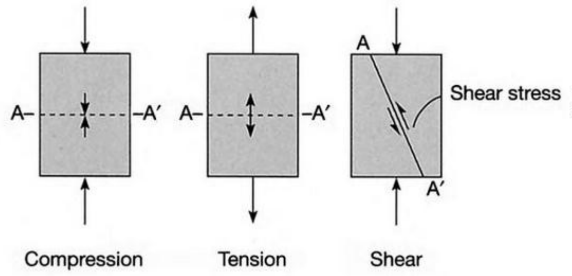
Bulk Gs, saturated surface dried=B/(B-C);

Apparent Gs=A/(A-C)

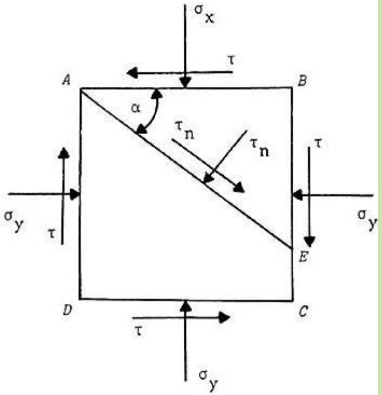
The density can be calculated as=Gs* the density of water.

%absorption=(B-A)/A *100

2- Rock strength



Only normal stresses



Normal and shear stresses

- The compressive strength: is the compressive stress required to break the specimen, calculated for the unconfined case as:

$$\sigma = \frac{F}{A}$$

where F is the maximum applied axial load and A is the cross section area of the specimen.

- The tensile strength of rock is considerably less than their compressive strength (10% or even less). Tensile strength governs behaviour when a rock is under bending stresses.

ROCKS PROPERTIES

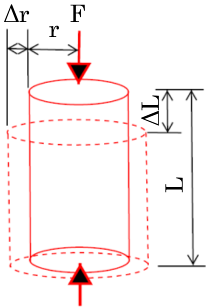
3- Elasticity of rocks

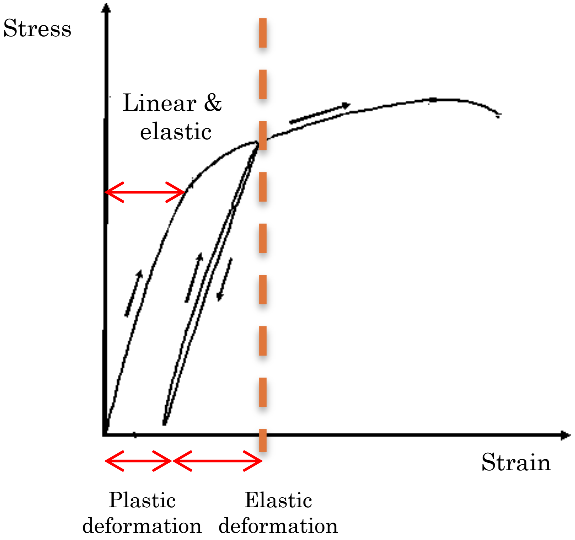
Material deform under loading. When the load is removed, some of the deformation is recovered (elastic deformation). The unrecoverable amount is termed (plastic deformation).

- Commonly, the elastic deformation of rock is directly proportional to the applied stress:

$$E = \frac{\text{stress}}{\text{strain}} = \frac{F/A}{\Delta L/L}$$

where L is the original length, ΔL is axial deformation and E is the elastic modulus (Young's modulus).

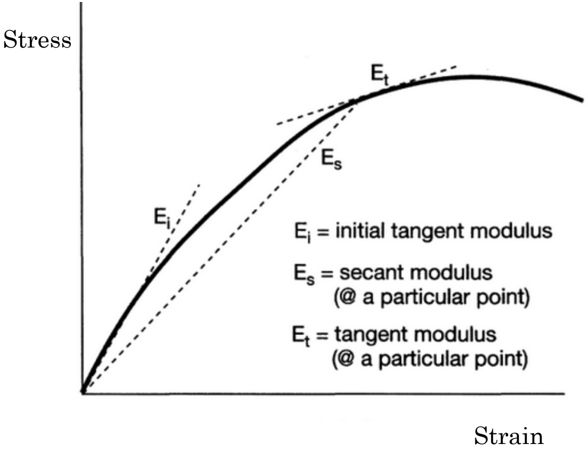




- Rocks as a natural material shows different properties for different directions (anisotropic). This is specially true for those rocks with bedding or foliation.
- The E value is lower when a rock is loaded perpendicular to the bedding or foliation than that when the rock is loaded parallel to those directional features.
- During axial compression, some lateral deformation happens that expressed as a ratio of the axial deformation:

$$\nu = \frac{\text{Lateral strain}}{\text{Axial strain}} = \frac{\Delta B/B}{\Delta L/L} \text{ or } \nu = \frac{\Delta r/r}{\Delta L/L}$$

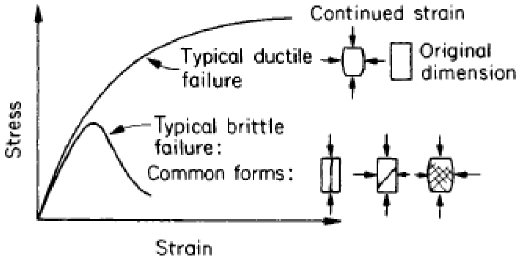
where B is the lateral dimension, r is the radius and ν is the Poisson's ratio ranging for most rocks between 0.10 and 0.50.



General material behaviour

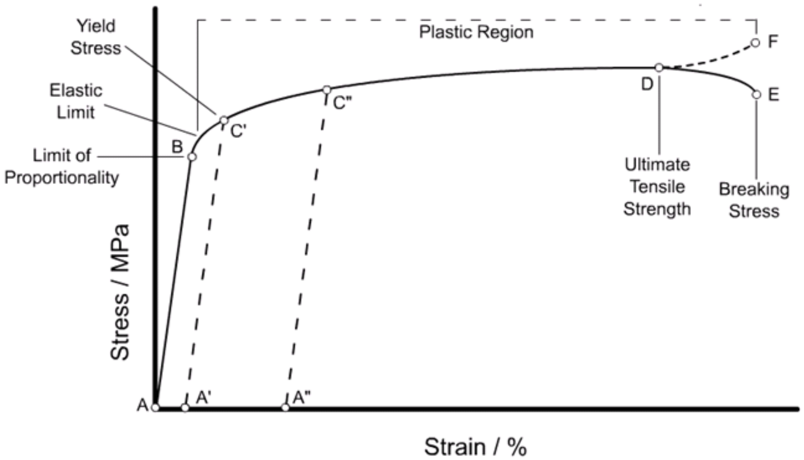
Brittle materials

Such as rocks, cast iron, and glass. Rupture occurs in these materials without any clear previous change in the rate of elongation.



Ductile materials

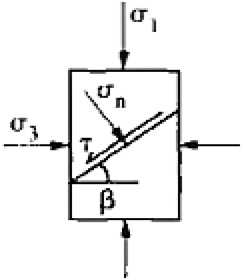
Such as reinforcing steel and many alloys of other metals. They have the ability to yield at normal temperatures.



Source: www.spaceflight.esa.int

Failure criteria in rocks

- ***The Mohr-Coulomb Criterion:*** Rock fails at a critical combination of normal and shear stresses:



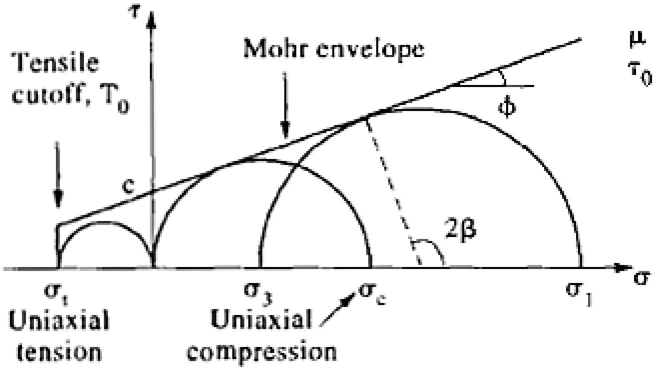
$$|\tau| = \tau_0 + \mu\sigma_n$$

τ_0 = cohesion μ = coeff. of friction

$$|\tau| = \tfrac{1}{2}(\sigma_1 - \sigma_3)\sin 2\beta$$

$$\sigma_n = \tfrac{1}{2}(\sigma_1 + \sigma_3) + \tfrac{1}{2}(\sigma_1 - \sigma_3)\cos 2\beta$$

The equation for $|\tau|$ and σ_n are the equations of a circle in (σ, τ) space:



$\mu = \tan\phi$
$\tau_0 = c$

At failure,
$2\beta = 90 + \phi$
$\Rightarrow \beta = 45 + \frac{\phi}{2}$

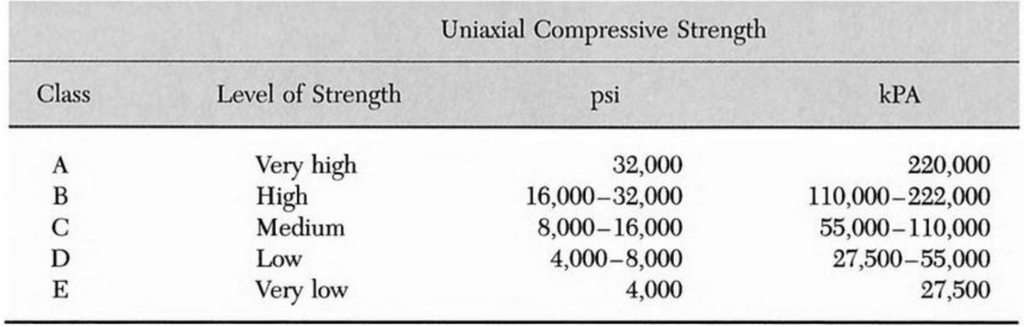
See engineering rock mechanics book, Section 6.5

Engineering classification of intact rocks

1- Based on compressive strength

- The following classification is proposed by Deere and Miller (1966) based on the uniaxial compressive strength and the modulus of elasticity;
- Intact rock is that which can be tested in the laboratory and is free of large scale weakness planes such as joining, bedding and shear planes;
- The modulus of elasticity is the tangent modulus at one-half the ultimate strength (one-half of the ultimate strength is commonly assumed as the allowable strength);
- Rock is subdivided in to five categories as shown the following table

Table 6.2 Ref# , Engineering classification of intact rock based on ultimate strength (Deere and Miller, 1966)



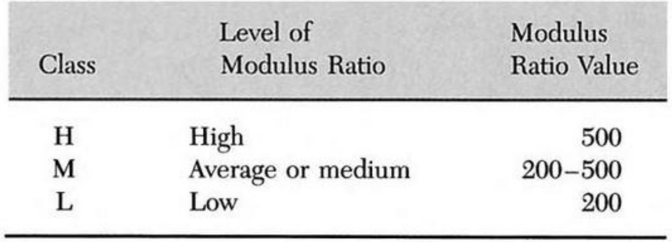
		Uniaxial Compressive Strength	
Class	Level of Strength	psi	kPA
A	Very high	32,000	220,000
B	High	16,000–32,000	110,000–222,000
C	Medium	8,000–16,000	55,000–110,000
D	Low	4,000–8,000	27,500–55,000
E	Very low	4,000	27,500

Class	**Typical Rocks**
A	Quartzite, diabase, and dense basalt
B	Most igneous rocks, some metamorphic rocks, most limestones, and dolomite, well-cemented, sandstones and shales
C	Most shales, porous sandstones, and limestones
D	Friable sandstones, porous tuff
E	Clay-shale, rock salt

Engineering classification of intact rocks

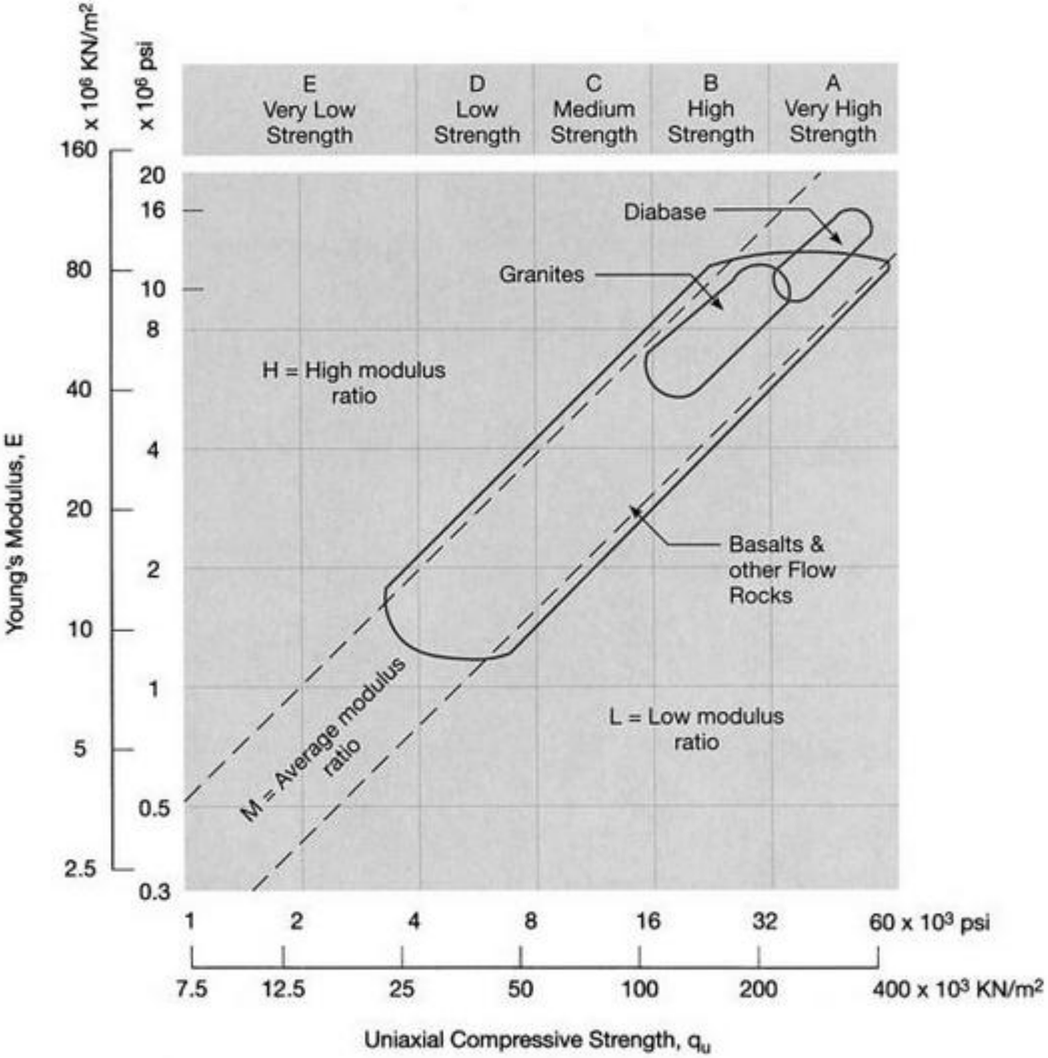
2- Based on modulus ratio of (E/unconfined compressive strength)

Table 6.3 Ref# , (Deere and Miller, 1966)

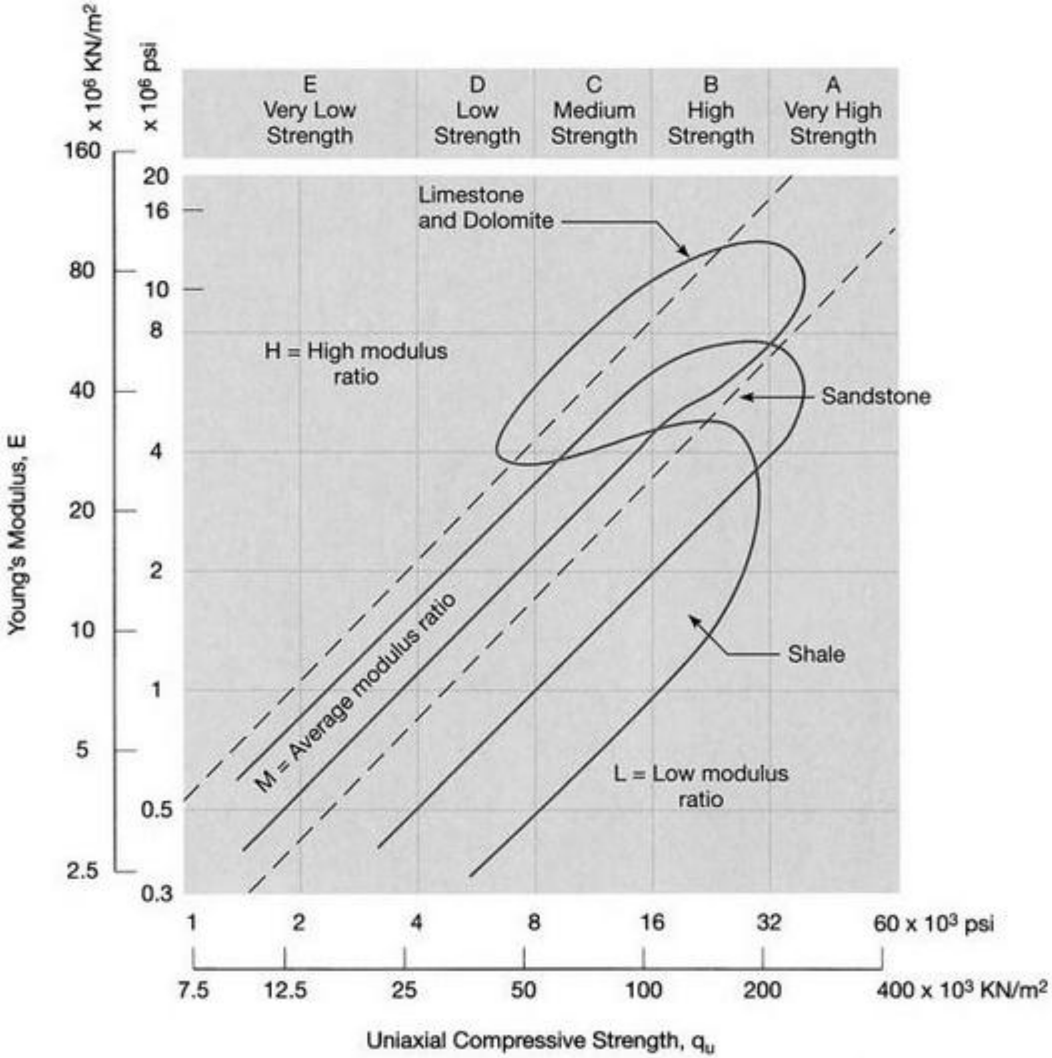


Class	Level of Modulus Ratio	Modulus Ratio Value
H	High	500
M	Average or medium	200–500
L	Low	200

Summary plot: Engineering classification of intact rocks- Igneous rocks, see Geology Applied to Engineering book.



Summary plot: Engineering classification of intact rocks-Sedimentary rocks, see Geology Applied to Engineering book.



Summary plot: Engineering classification of intact rocks-Metamorphic rocks, see Geology Applied to Engineering book.

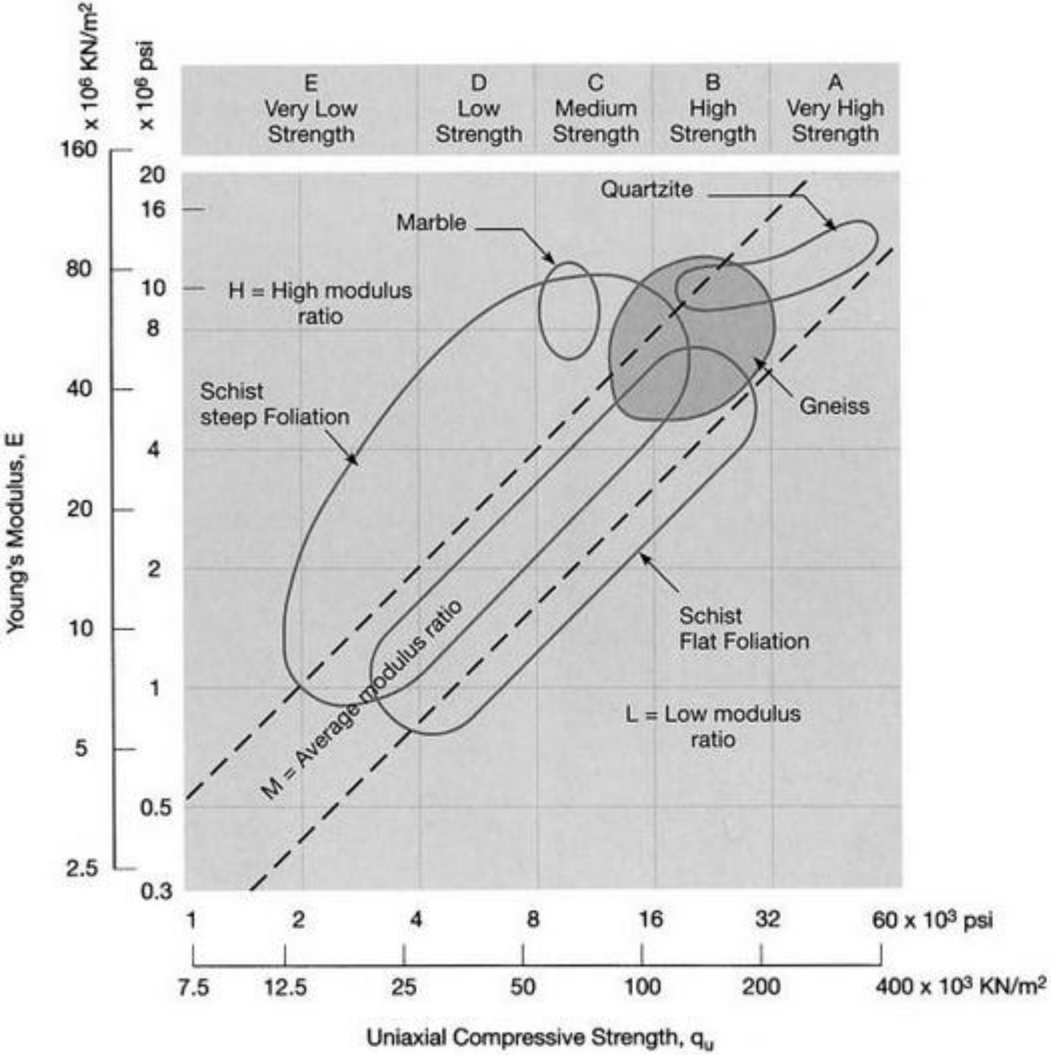
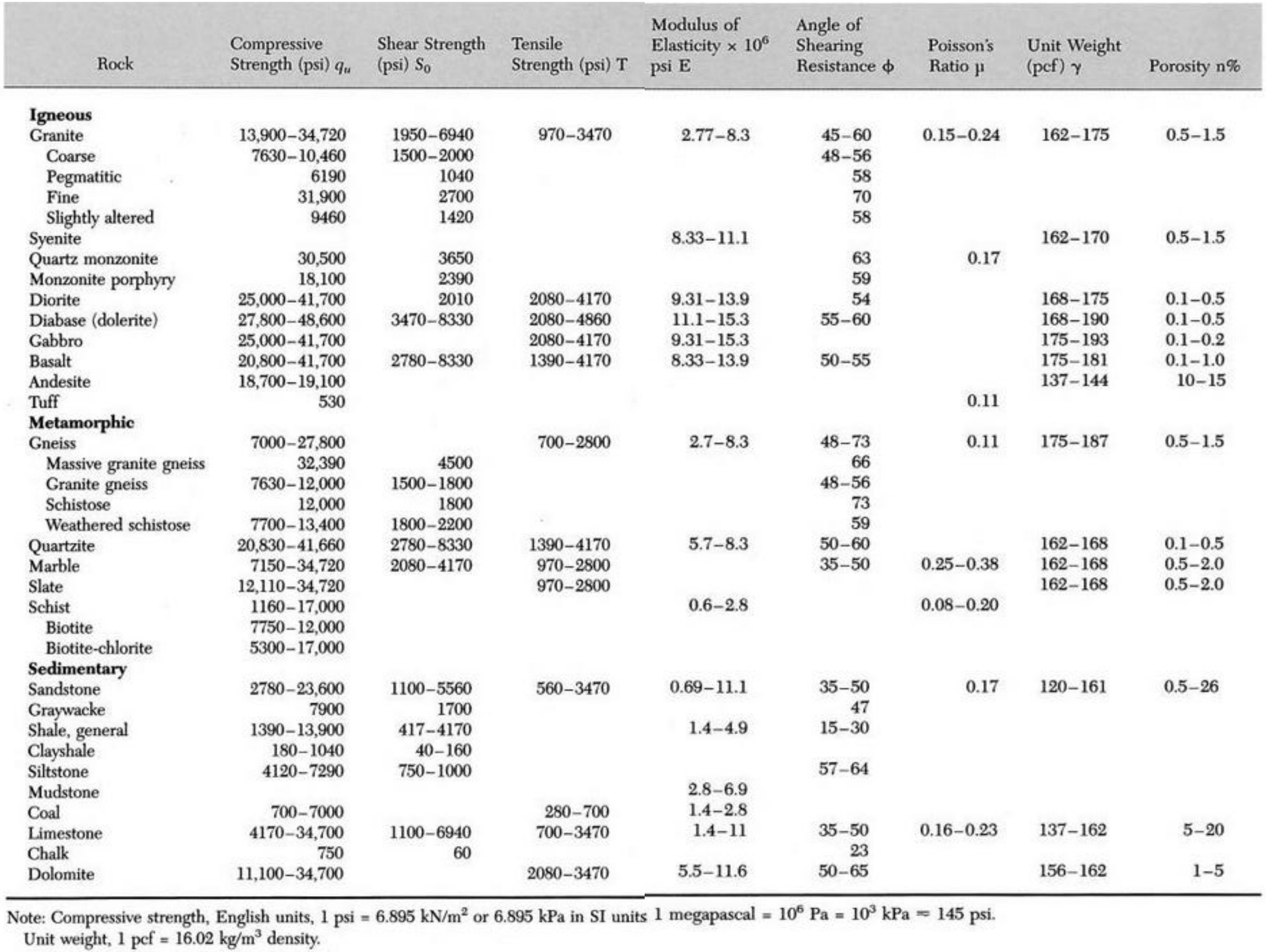


Table 6.1 in Geology Applied to Engineering book. Physical properties of rocks



Rock	Compressive Strength (psi) q_u	Shear Strength (psi) S_0	Tensile Strength (psi) T	Modulus of Elasticity $\times 10^6$ psi E	Angle of Shearing Resistance ϕ	Poisson's Ratio μ	Unit Weight (pcf) γ	Porosity n%
Igneous								
Granite	13,900–34,720	1950–6940	970–3470	2.77–8.3	45–60	0.15–0.24	162–175	0.5–1.5
Coarse	7630–10,460	1500–2000			48–56			
Pegmatitic	6190	1040			58			
Fine	31,900	2700			70			
Slightly altered	9460	1420			58			
Syenite				8.33–11.1			162–170	0.5–1.5
Quartz monzonite	30,500	3650			63	0.17		
Monzonite porphyry	18,100	2390			59			
Diorite	25,000–41,700	2010	2080–4170	9.31–13.9	54		168–175	0.1–0.5
Diabase (dolerite)	27,800–48,600	3470–8330	2080–4860	11.1–15.3	55–60		168–190	0.1–0.5
Gabbro	25,000–41,700		2080–4170	9.31–15.3			175–193	0.1–0.2
Basalt	20,800–41,700	2780–8330	1390–4170	8.33–13.9	50–55		175–181	0.1–1.0
Andesite	18,700–19,100						137–144	10–15
Tuff	530					0.11		
Metamorphic								
Gneiss	7000–27,800		700–2800	2.7–8.3	48–73	0.11	175–187	0.5–1.5
Massive granite gneiss	32,390	4500			66			
Granite gneiss	7630–12,000	1500–1800			48–56			
Schistose	12,000	1800			73			
Weathered schistose	7700–13,400	1800–2200			59			
Quartzite	20,830–41,660	2780–8330	1390–4170	5.7–8.3	50–60		162–168	0.1–0.5
Marble	7150–34,720	2080–4170	970–2800		35–50	0.25–0.38	162–168	0.5–2.0
Slate	12,110–34,720		970–2800				162–168	0.5–2.0
Schist	1160–17,000			0.6–2.8		0.08–0.20		
Biotite	7750–12,000							
Biotite-chlorite	5300–17,000							
Sedimentary								
Sandstone	2780–23,600	1100–5560	560–3470	0.69–11.1	35–50	0.17	120–161	0.5–26
Graywacke	7900	1700			47			
Shale, general	1390–13,900	417–4170		1.4–4.9	15–30			
Clayshale	180–1040	40–160						
Siltstone	4120–7290	750–1000			57–64			
Mudstone				2.8–6.9				
Coal	700–7000		280–700	1.4–2.8				
Limestone	4170–34,700	1100–6940	700–3470	1.4–11	35–50	0.16–0.23	137–162	5–20
Chalk	750	60			23			
Dolomite	11,100–34,700		2080–3470	5.5–11.6	50–65		156–162	1–5

Note: Compressive strength, English units, 1 psi = 6.895 kN/m^2 or 6.895 kPa in SI units 1 megapascal = 10^6 Pa = 10^3 kPa = 145 psi.
Unit weight, 1 pcf = 16.02 kg/m^3 density.

Los Angeles Abrasion test

The test designed to measure aggregate resistance to crushing, degradation and disintegration.

Testing material for engineering use

- **Strength** and **durability** are the most important aspects to be investigated to decide the suitability of a given rock as a construction material.
- Durability: generally, refers to the ability to resist wear, pressure, or damage.
- Strength of construction material is normally evaluated by conducting abrasion test rather than conducting compression test.
- Durability test is performed by using the sulfate soundness test and freezing and thawing test.

The concept

A coarse aggregate sample retained on the No. 12 (1.70 mm) sieve is placed in a rotating drum with steel balls. As the drum rotates the aggregate degrades by abrasion due to the rotation and the contact with the other aggregates and the steel balls. The drum is rotated for certain number of cycles. Then, the aggregate is removed from the drum and sieved again on the No. 12 (1.70 mm) sieve. Percentage of the finer aggregate indicates the abrasion level.

Lower loss values means more resistant to abrasion and higher toughness aggregate.

$$loss = \frac{(Mass_{original} - Mass_{final})}{Mass_{original}} \times 100$$

Source: www.globalgilson.com

Aggregate mineralogy	Typical Los Angeles Abrasion loss values %
Basalt	10-20
Dolomite	15-30
Gneiss	30-60
Granite	25-50
Limestone	20-30
Quartzite	20-35

Source: http://www.pavementinteractive.org/article/los-angeles-abrasion/

Sulfate soundness by use of sodium sulfate or magnesium sulfate :

Used to describe the ability of an aggregate (both coarse and fine) to withstand the effects of freezing and thawing.

Test concept:

- The sulfate is used to subject an aggregate sample to the effects of salt crystallisation inside the pores, which simulate ice crystal formation during freezing.
- The test is performed by exposing an aggregate sample to repeated immersions in the sulfate solution and later oven drying it to simulate the thawing process.
- One immersion and drying is considered a soundness cycle.
- Typically, five cycles are specified by agencies.
- Sample is then washed to remove the salt and then dried and sieved on specific set of sieves.
- The loss in weight for each specific sieve size is calculated and a weighted average percent loss for the whole sample is obtained.
- Low values of soundness loss are necessary to ensure that an aggregate is not likely to weathering by freezing and thawing.

Source: www.pavementinteractive.org

ENGINEERING GEOLOGY CE1301

Lecture #7 **Structural Geology**

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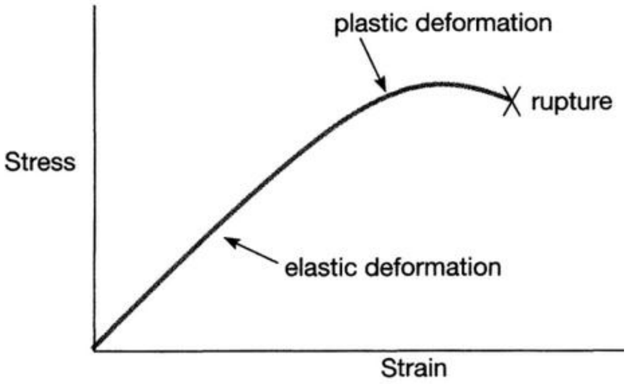
STRUCTURAL GEOLOGY

- Involves the study of rocks that have been deformed by earth stresses and includes a description of their position in space, or attitude, which occurs as a consequence of the deformation.
- Sedimentary rocks that show titling or folding indicate deformation by compression or extension and uplift of the strata.
- Geological structures range in size from the microscopic features of a fine-grained specimen to large geometric forms in a rock mass that may be measured in a rock mass.
- Foliation in metamorphic rock, flow banding in extrusive igneous rocks and bedding in sedimentary rocks are examples of structures that can be observed with the unaided eye.
- Structural geology on a regional scale is called tectonic or geotectonics.



Rock Deformation

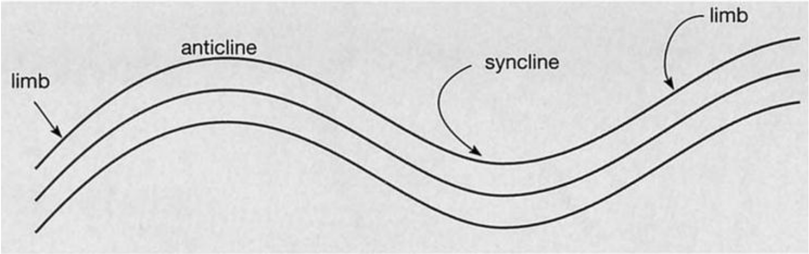
- Rock deformation occurs slowly under high confining pressures and elevated temperature.
- This causes the rocks to be less brittle so that plastic deformation can occur.
- During elastic deformation, such as that caused by small earthquake, the rock returns to its original shape when the load is removed.
- folding in rocks occurs in the plastic range of the curve. Compressive forces slowly deform the rock but after removal of this load by uplift and erosion, the rock still retains the folded shape.
- Faulting occurs when the rocks rupture (plastic deformation).

Folding in rocks

Folds in rock

- Commonly, folds are caused by compressional forces which buckle rock units.
- Syncline: is the trough or downwarped portion of the fold.
- Anticline: is the crest portion.
- Monocline: only one direction of dip prevails in the fold system.
- Limb: is the sloping portion of a fold that connects the crests and troughs.
- The axial plane: is an imaginary plane used to divide the fold into two nearly equal portions. It is used to describe the degree of symmetry of the fold system.
- The axis: represents the intersection of the axial plane with the bedding surface.

  - If the axial plane is vertical, the fold is **symmetrical**, otherwise it is not symmetrical.
  - If the axial plane is tilted with the limbs dipping at not the same angle, the fold is **asymmetrical**.
  - If the axial plane is tilted with the limbs dipping at the same angle, the fold is **overturned**.
  - If the axial plane essentially horizontal , the fold is **recumbent**.



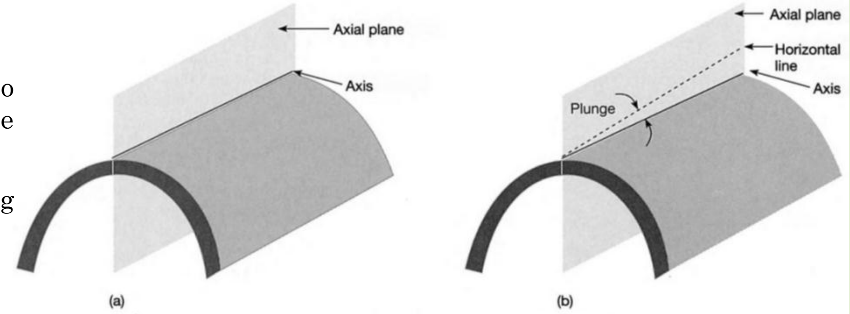


FIGURE 10.3 Anticline, with axial plane and axis. (a) Nonplunging. (b) Fold plunging to the rear.

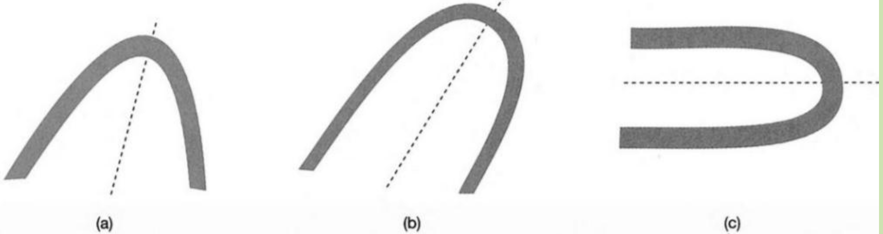


FIGURE 10.4 Attitudes of asymmetrical anticlines: (a) asymmetrical, (b) overturned, and (c) recumbent.

1) Strike and Dip

- Dip: is the angle measured at the maximum inclination between inclined bed and a horizontal plane.
- Strike: is the compass direction (measured from true north) of the line of intersection between the horizontal plane and the inclined plane.
- Strike and dip directions are mutually perpendicular. For example, a bed dipping to the east will have a north-south strike.
- The strike and dip symbol looks similar to a T, with the stem indicating the dip direction and the cross bar indicating the strike. The lower numbered bed is always the oldest in these diagrams.
- Trend: is the compass direction of the line formed by the intersection of the planar geologic structure with the ground surface. It is similar to strike when the ground surface is parallel to the horizontal plane.

First rule of anticlines

- The rule states that for the map view of an anticline, the oldest beds are in the center and the beds become progressively younger in each direction.
- Note that bed 2 is bounded on both sides by bed 3, which is bounded in turn by bed 4.
- Conversely, for synclines the youngest bed is in the center and the beds get progressively older in each direction.
- This rule makes it possible to distinguish between anticlines and synclines in map view even when strike and dip symbols are lacking.
- Viewing the top portion of the fold system alone, the inclination of the axial planes indicates the extend of symmetry of either the anticline or syncline.
- Also the age of the beds indicates whether an anticline or syncline is present.

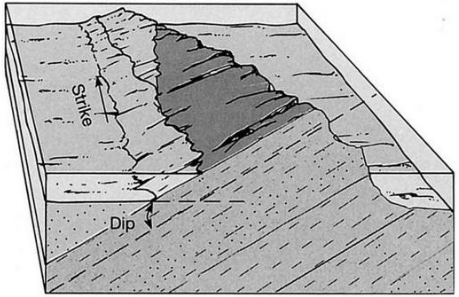


FIGURE 10.5 Dip and strike of inclined bed.

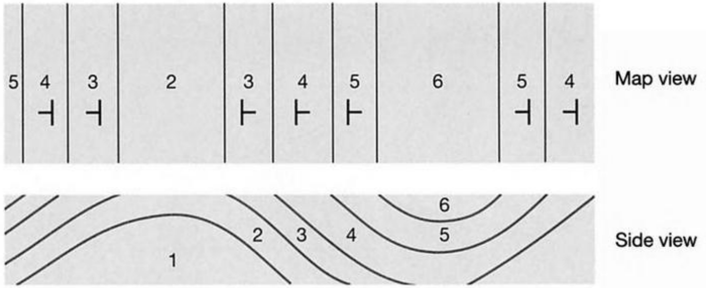


FIGURE 10.6 Anticlines and synclines, with strike and dip symbols.

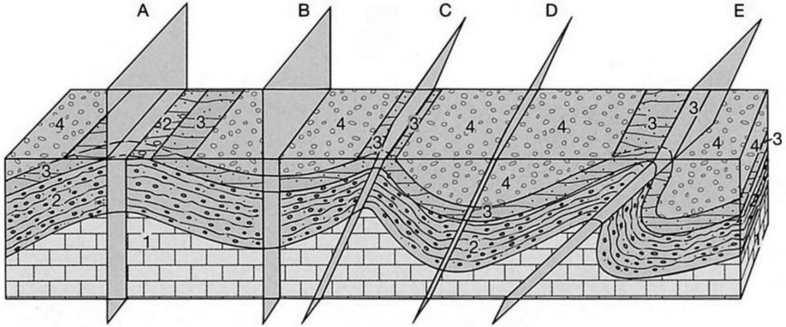


FIGURE 10.7 Diagram of anticlines and synclines.

Bed outcrop width relative to dip

- The width of bed 3, for example, is not the same on the opposite side of the axial plane.
- On the left side, where the bed is less steep, the outcropped bed width is greater than that on the right side.
- W=t/sinθ where W is the bed width of the outcrop, t is the thickness of the bed and θ is the angle of dip.
- For vertical beds W=t, its minimum width and for horizontal beds, W becomes infinite. Symmetrical folds will have equal bed width on opposite sides of the axial plane because the opposing dip angles are the same.

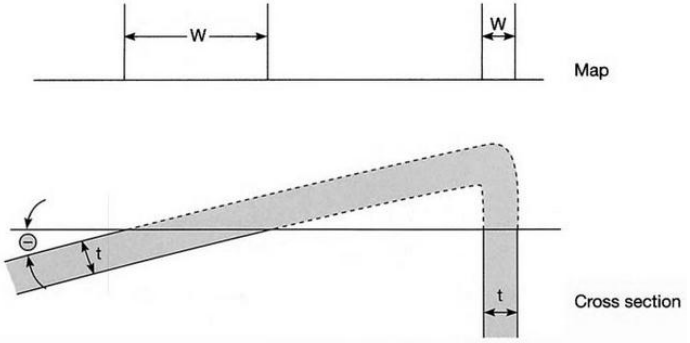


FIGURE 10.8 Outcrop bed width as related to dip.

Plunge folds

- The figure shows the intersection of a plunging syncline and in turn of a plunging anticline with a horizontal plane.
- The shape and direction of the intersection is of importance.
- In Figure (a): the syncline is plunging (lose elevation) to the right. The nose shape, formed by the intersection with the horizontal plane, points to the left; that is, it points in the direction opposite to the plunge.
- In figure (b): conversely, the nose for anticline points in the same direction as the direction of plunge.

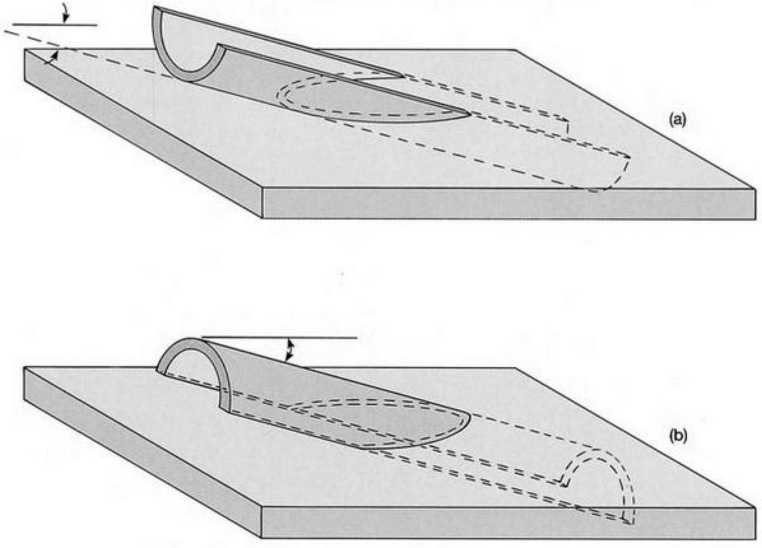
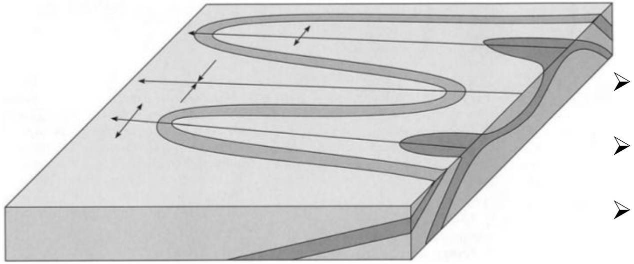


FIGURE 10.9 (a) Plunging synclines and (b) anticlines.

Second rule of anticline

- For a plunging anticline, the nose formed by the intersection of the fold system with a horizontal plane points in the same direction as the plunge.
- Conversely, for a plunging syncline, the nose points in the direction opposite to that of the plunge.
- The 3D view of the fold system is shown in the figure.



Standard structural symbols used on geological maps

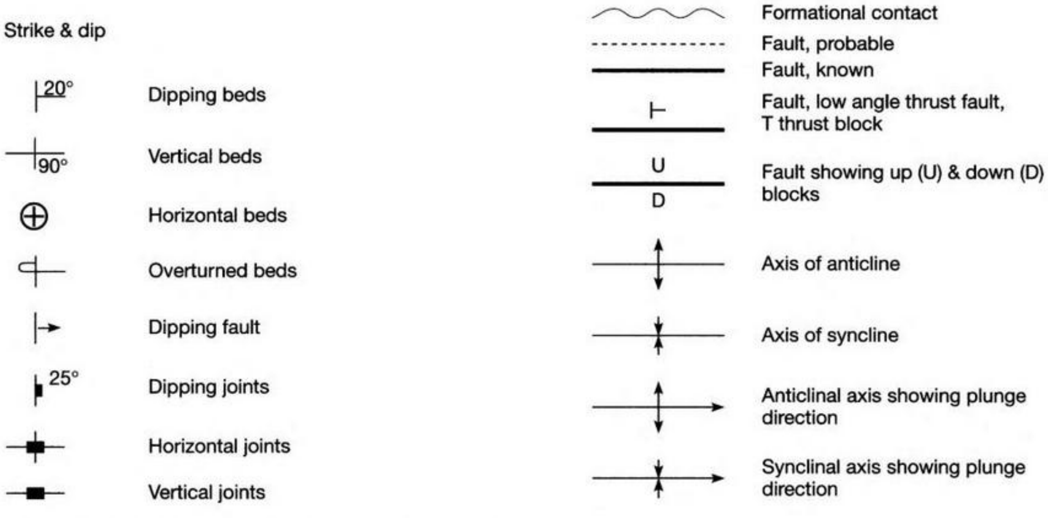
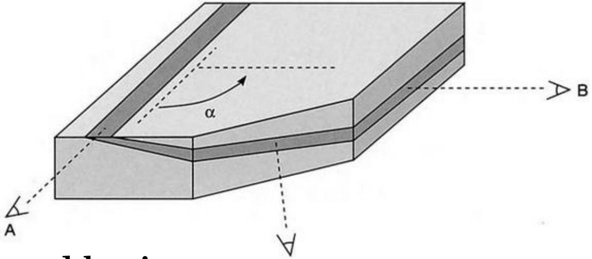


FIGURE 10.11 Standard structural symbols used on geologic maps.

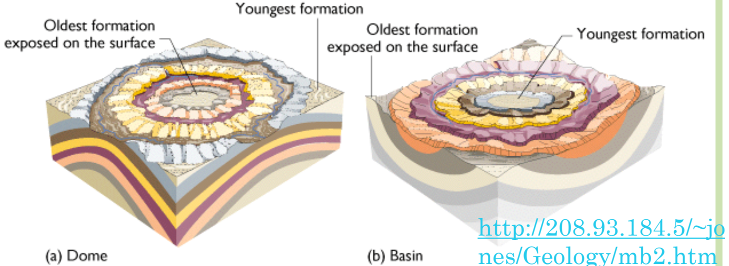
Apparent and true dip

- For line of sight A, a true dip (θ_{true}) of the bed is observed.
- For line of sight B, the apparent dip of the bed is zero.
- As the line of sight moves from A towards B, the apparent dip decreases and can be obtained from: $\theta_{apparent} = \theta_{true} \cos\alpha$



Domes and basins

- 3D fold features also occur in nature.
- A structural dome (represents 3D anticline) is a fold in which the beds slope away from the center in all directions.
- A structural basin (represents 3D syncline) has bed that slopes inward in all directions.



(a) Dome

(b) Basin

http://208.93.184.5/~jones/Geology/mb2.htm

2) Rock Fractures

Fractures in rock are narrow openings along which the rock mass has lost grain-to-grain contact.

Types of fractures

There are three types of fractures based on the relative movement of the rock blocks on opposite sides of the fracture:

A) Joints

- Are rock fractures along which no movement has occurred parallel to the joint surface.
- Some displacement perpendicular to the joint may develop because of frost wedging or gravity effects.
- The strike and dip terms are also used to describe joints planes.
- There is a tendency for joints to occur in sets of parallel fractures rather than as a single isolated plane.
- Release of confining pressure forms joints in some rocks, for example, along steep exposures of rock.
- Even horizontal sedimentary rock exhibit joint sets, usually parallel to the slight regional dip or perpendicular to it.

B) Shear zones

- Are fractures in rock along which some movement has occurred but not a great amount.
- Most movements is due to slippage of the rock to compensate for distortions caused by folding.
- Rocks with shear zones are typically weak and have low strength. Ground water flows through these zones. Therefore they are not desirable areas for tunnelling, slope excavation and foundations for engineering works.

C)Faults

- Are fractures along which significantly movement has occurred (minimum of 1 m but it can be up to kilometers).

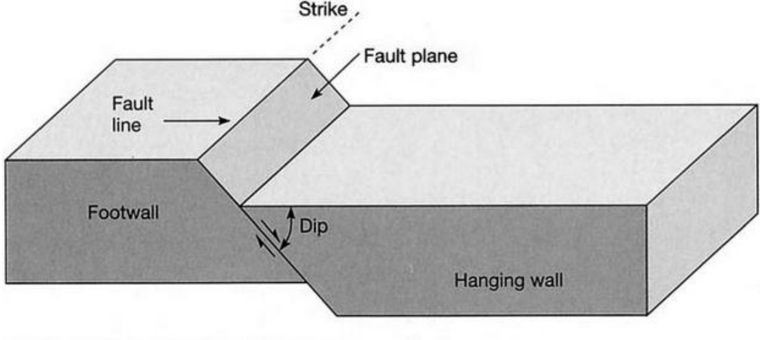


FIGURE 10.13 Fault terminology.

Source: geomaps.wr.usgs.gov640 × 420Search by image
Photograph of faulted sedimentary rock layers exposed in a road cut in Guatemala

- The block above the fault plane is called the hanging wall while the block below is called the foot wall.
- The fault line is the intersection of the fault plane with the surface of the earth.

Types of movement along the fault plane:-

1- Dip-slip faults:

a) Normal fault: the hanging wall moves down relative the foot wall and caused by vertical compressive force or by a horizontal tensile force.

b) Reverse fault: the hanging wall moves up relative to the foot wall and caused by horizontal compressive force or by a vertical tensile force. With low dip angle this fault is called a thrust fault.

2- Strike-slip faults:

- Occurs when the relative movement is horizontal so that the blocks are displaced along the strike direction.
- Two types: right lateral and left lateral strike-slip fault.

Source: www.livescience.com

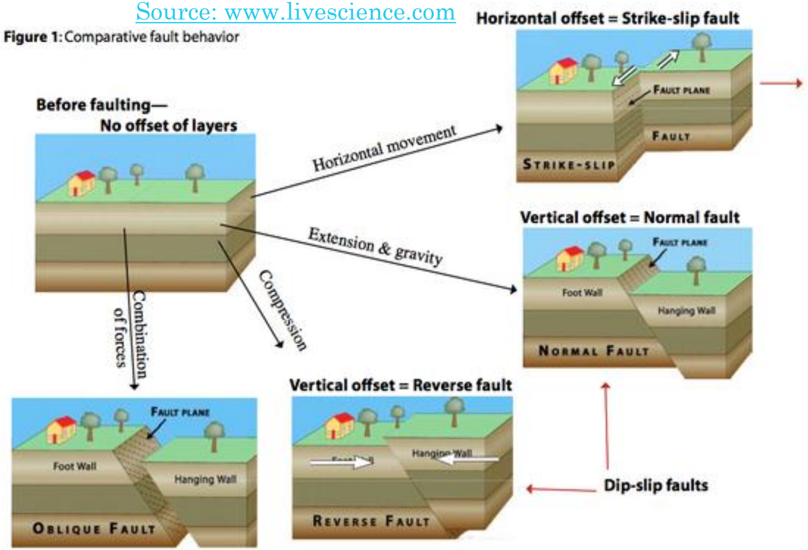


Figure 1: Comparative fault behavior

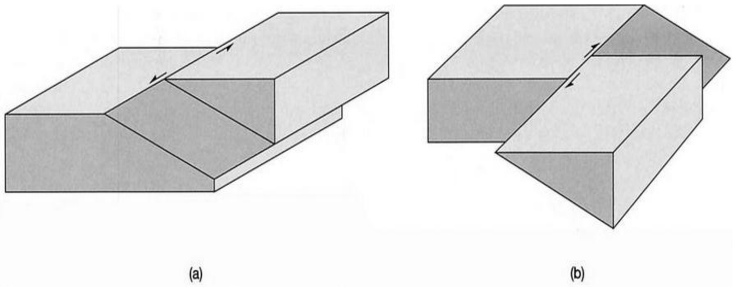


FIGURE 10.15 Strike-slip faults: (a) left lateral and (b) right lateral.

3- Translation fault:

- Occurs when the fault movement has both a strike-slipe and dip-slip component. The net movement is the net slip.

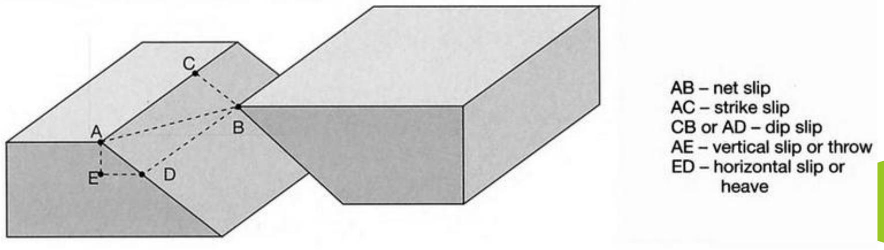


FIGURE 10.16 Translation fault.

Other considerations

- For strike-slip faults it is rather easy to determine the relative movement involved if a marker bed is present in the fault block.
- In dip-slip faults it is more difficult to decipher the relative movements as a result of differential erosion subsequent to the faulting. Typically the uppermost block is eroded much faster than the lower block, yielding a horizontal surface across them.
- Block faulting sometimes occur and involves the movement of 3D blocks of rock upward and downward along steeply dipping fault plane

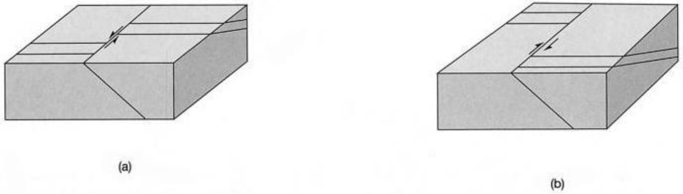


FIGURE 10.17 Strike-slip movement and marker beds: (a) left lateral and (b) right lateral.

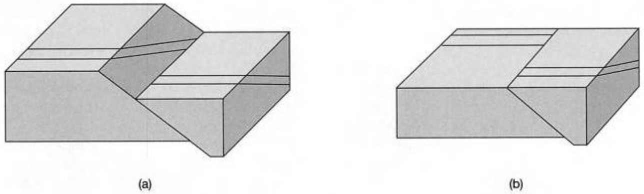


FIGURE 10.18 Dip-slip fault related to erosion: (a) before erosion and (b) after erosion.

Field recognition of faulting

- The existence of fault should be considered early in the site selection investigation.
- Some details helping in the detection of faults:
- * **landform features associated with the fault line**, such as the offset of geological structures and marked change in elevation
- * **abnormal stratigraphic sequences** caused by faulting which usually involves the repetition or the omission of the normal beds within that sequence. For instance, the figure shows a series of rocks with a normal sequence of folded sedimentary rocks, which has been disrupted at two locations by faulting (note the F designations). A repetition of beds is shown on the left side of the diagram and an omission of beds on the right side.
- * **features of the fault plane**, seen in plan view or in cross section, can be used to establish the existence of the fault.

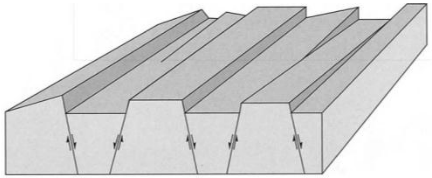


FIGURE 10.19 Block faulting.

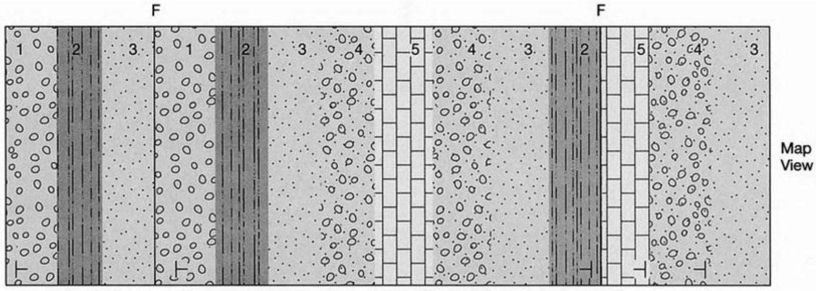


FIGURE 10.21 Faulting indicated by repetition and omission of beds.

3) Folds and faults combined

- **The first figure** is an example of a non-plunging syncline and it completes the details for combinations of folds and dip-slip faults.
- Not that the beds of the syncline converge with depth. Therefore, because the beds are closer together in the front block, that block had to have originated at a lower depth
- Consequently, the front block has moved upward relative to the rear block, yielding a rev fault.
- **In The subsequent figures**, for the anticline, observe that as you proceed lower in the cross section, the outcrop of the dipping bed will move further apart (diverges).
- Therefore, the bed had to have originated at a higher elevation, and consequently the back block has moved downward.

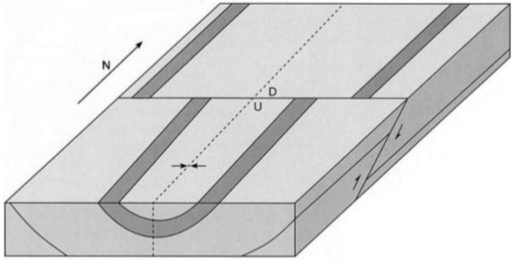


FIGURE 10.25 Symmetrical syncline cut by an east–west striking reverse fa southward.

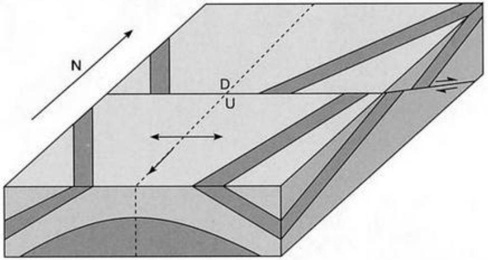


FIGURE 10.23 South plunging symmetrical anticline cut by an east–west striking normal fault dipping northward.

FIGURE 10.24 Front view of anticline from Figure 10.23.

4) Direction of stress and fault orientation

- When rocks are anisotropic, the orientation of the weakness planes (known as ***s* planes**) can influence the direction of breakage or faulting.
- Shear planes examples are noticeable bedding in sedimentary rocks, foliation in metamorphic rock or flow banding in extrusive igneous rocks.

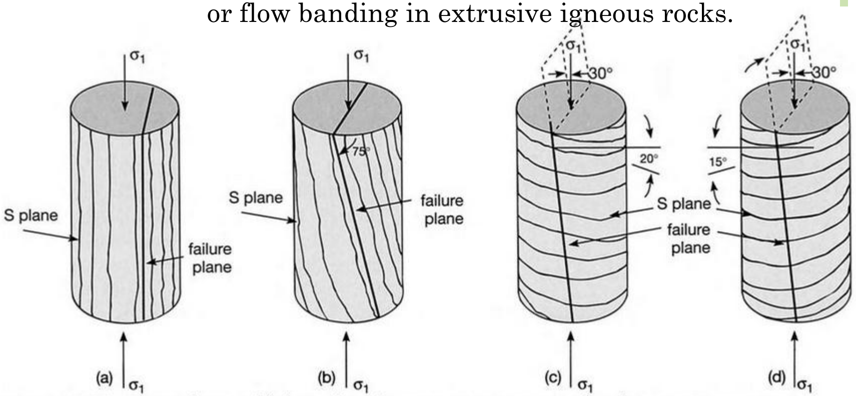
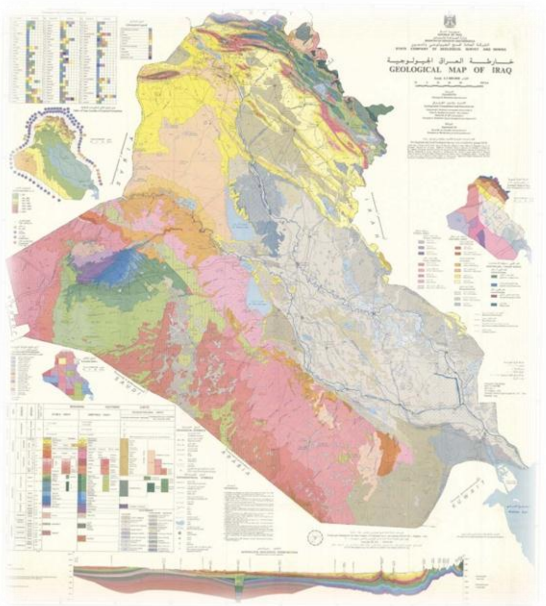


FIGURE 10.27 Dependence of failure plane location on orientation of *s* planes in test specimens.

- The figure above shows that if σ_1 is oriented within 60° of the *s plane*, failure will occur along or be controlled to some extent by the weakness plane. Otherwise, *s plane* will have little influence on the direction of failure.
- Major forces from engineering constructions should not be transferred to layered rocks in a direction parallel to the bedding planes to avoid risk of failure by slippage along these planes.

ENGINEERING GEOLOGY CE1301

Lecture #8 **Topographic and Geologic maps**



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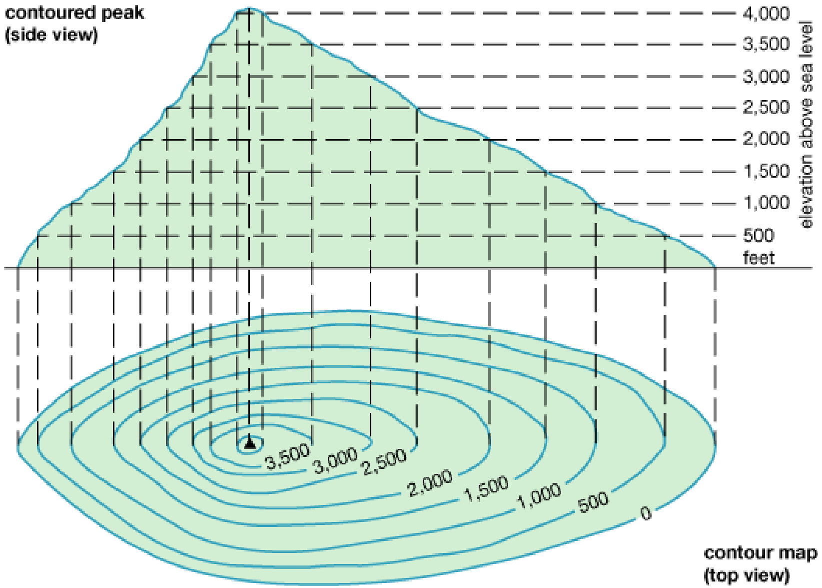
TOPOGRAPHIC MAPS

- **Topography:** general configuration and shape of the land surface, graphically delineated on topographic maps with elevation contours (*topographic contours).*
- **Contour lines:** lines that connect points of equal elevation on a curved surface above or below a reference datum such as sea level, projected orthographically on a reference plane, usually a map.
- **Index contour lines:** contour lines plotted in bold to distinguish it from intermediate contours, and they are labelled with elevations.
- **Contour interval:** is the difference between two successive contour lines.
- **Benchmark** (B.M.) is a point of known elevation serves as a reference for other points.
- **Topographic contours:** represents the shape of the ground surface.
- **Structure contours:** represents the shape of the geological surface including bedding planes, fold shapes, fault planes, etc.



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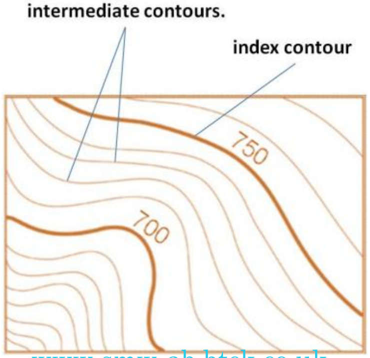
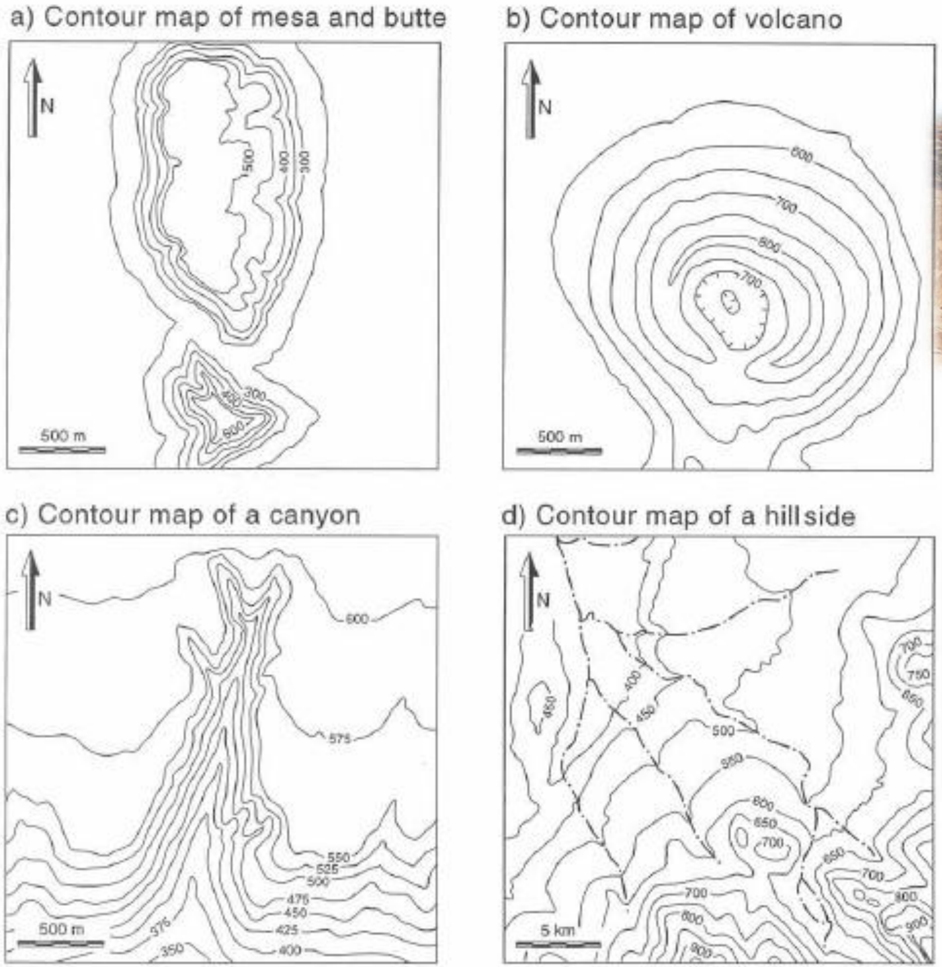
Contours have general characteristics such as:
topographic contour lines reflect the shape of the land's surface. *Structure contour line* record the height of geological surfaces.

- Contour lines do not cross. Crossing contour lines denote overhanging cliff.
- The spacing of the contour lines reflects the gradient of the slope. The closer the contours, the steeper the ground. Very near contours indicate steep slope or cliff. Widely spaced contours imply gently inclined slopes. Regularly spaced contour lines indicate uniform slope.
- The difference in elevation between adjacent contour lines is constant on any given map.



www.smw-ab.btck.co.uk

Example contour maps



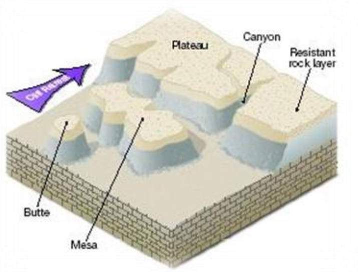
a) Contour map of mesa and butte

b) Contour map of volcano

c) Contour map of a canyon

d) Contour map of a hillside

www.canyontours.com



Constructing Contour lines from 3 elevation points

❖ For the three elevation points, a simple contour map can be plotted as following:

- Connect the three points with a temporary dashed lines;
- Select a sensible contour interval, let’s say 5 m;
- Find the relative positions of the subdivisions on each dashed lines and mark them with small lines or circles, etc. This can be done by using the following relationship:

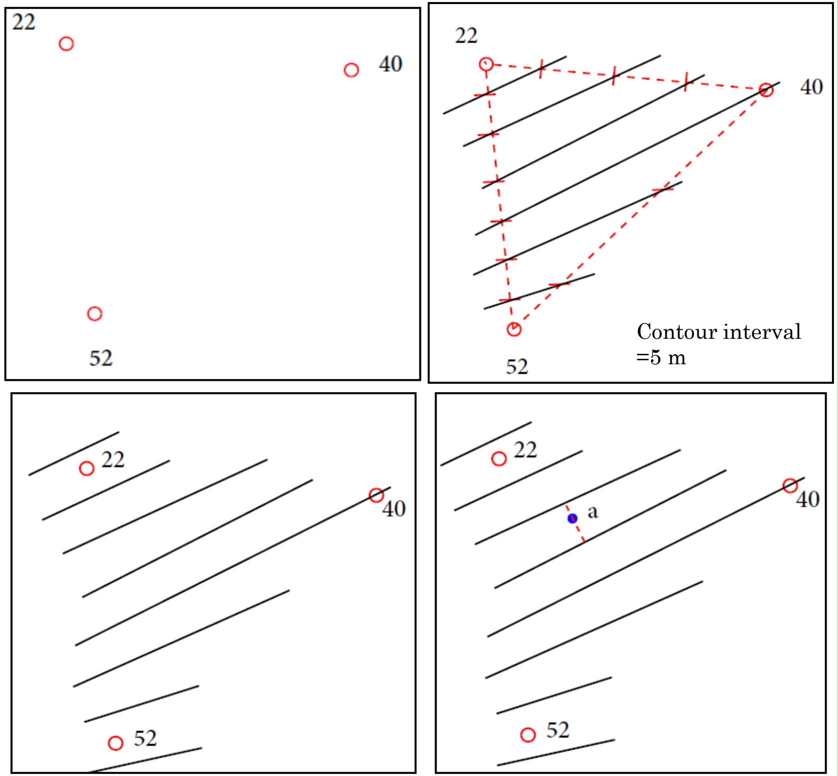
D=d*e1/e2

where
D=Distance, on the map, from the smallest elevation;
d=distance between the two elevation points,
e1= difference in elevation between the required elevation and points
e2= difference in elevation between the two points.

For example, to find the relative position on contour line at elev. 45m, passing between the elevations 40m and 52m, and if contour interval is 5 m and *d= 10 cm, then*

D=10(45-40)/(52-40)=4.2 cm from elev.40.*

- Connect points of the elevations with straight contour lines.
- Note that the resulting contour map represents a planner surface just because the elevation points do not offer enough flexibility to represent the actual topography.
- The final contour map is obtained by eliminating the dashed lines.

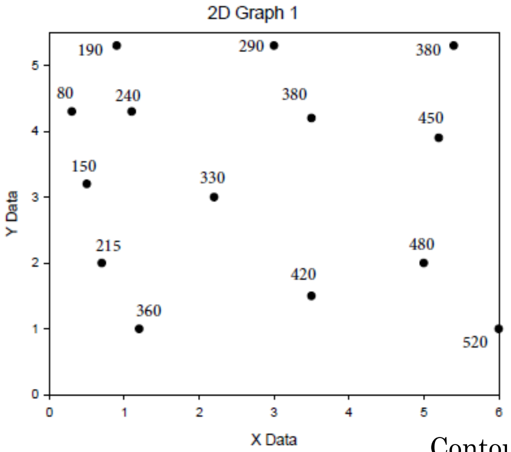


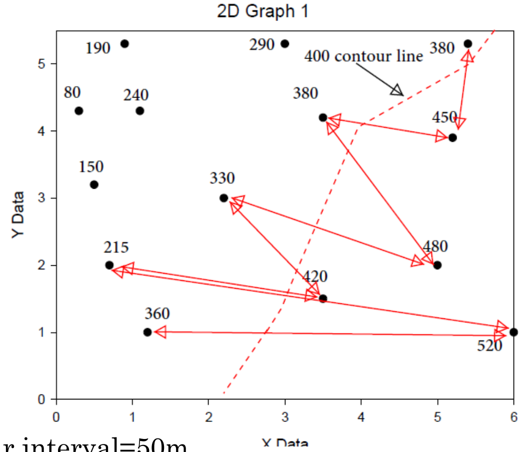
- Elevation of point *a*?

This elevation can be obtained by knowing the relative normal distance of the point between the two successive contour lines 30 and 35 as following:
Let’s assume that the length of the dashed line is 1 cm and the distance to point *a* from the contour line 30 is 0.3 cm, then
elevation of point *a*=30 + (0.3/1)*5= 31.5 m.

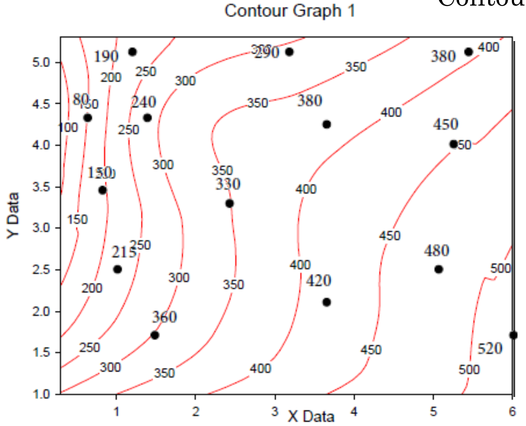
Constructing Contour lines from more than 3 elevation points

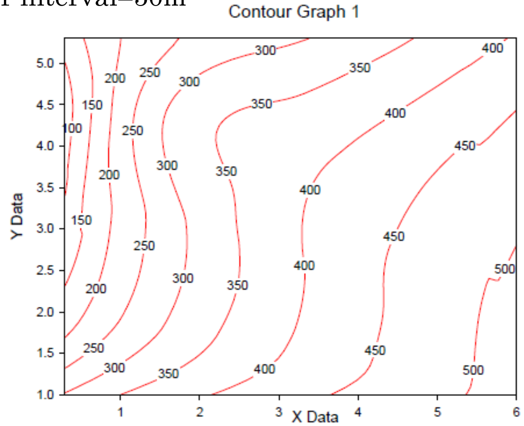
- Contour lines are plotted following the same steps described in the previous case.
- A typical fitting exercise is shown for the contour line 400.
- The resulting contour map is shown is no longer planer.





Contour interval=50m





The above map was plotted by using SigmaPlot software. Many other software can also be used such as Matlab, Surfer, etc.

Vertical cross-sections through topographical and geological surfaces

See ref. Geological structures and maps

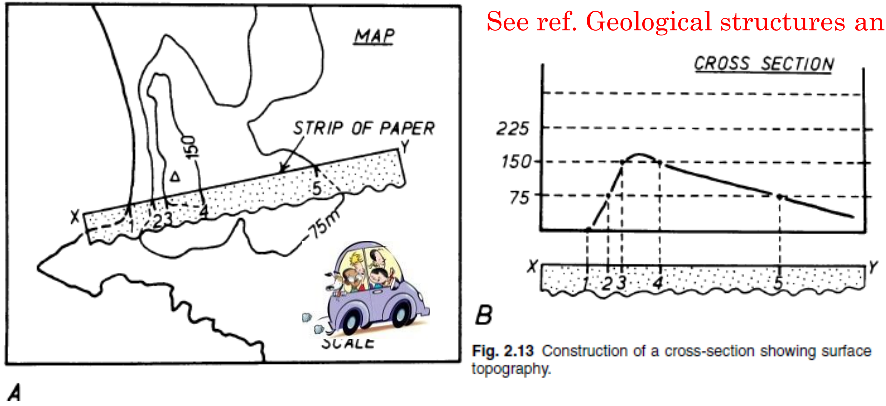


Fig. 2.13 Construction of a cross-section showing surface topography.

Example Figure 2.14A shows a set of structure contours for the surface defined by the base of a sandstone bed**. Find the direction of strike**, **the direction of dip and the angle of dip of the base of the sandstone bed**. **What is the apparent dip in the direction XZ** (Fig. 2.14B)? Vertical sections.

- **Strike direction:** the strike of the surface at any point is given by the trend of the contours for that surface. On Fig. 2.14A the trend of the contours (measured with a protractor) is 120°N.

- **Dip direction and dip angle:** 90° different from the strike direction; giving 030° and 210° as the two possible directions of dip. The heights of the structure contours decrease towards the southwest, which tells us that the surface slopes down in that direction. The direction 210° rather than 030° must therefore be the correct dip direction.

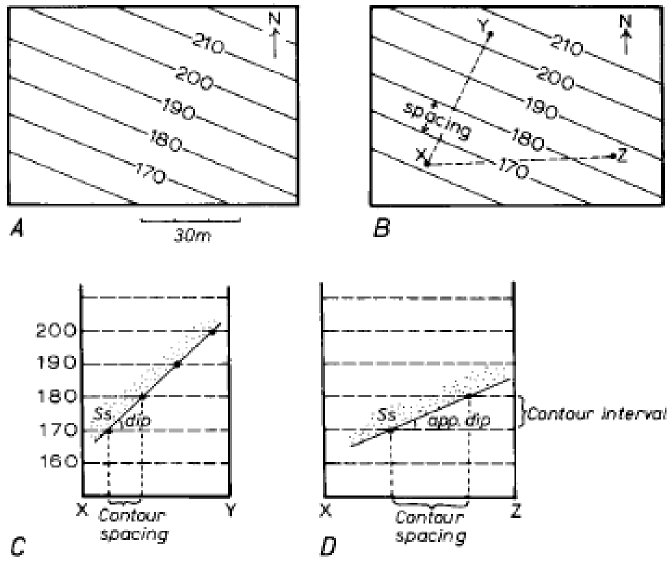


Fig. 2.14 Drawing sections.

Angle of dip of the base of the sandstone: we must calculate the inclination of a line on the surface at right angles to the strike. A constructed vertical cross-section along a line XY on Fig. 2.14B will tell us the true dip.

From the cross section in (Fig. 2.14C) :

Tangent (angle of dip) =contour interval/ spacing on map between contours

=10m/10m= 1

Angle of dip = $\tan^{-1}(1) = 45°$.

Apparent dip in direction XZ: is the observed inclination of the sandstone bed in true scale (vertical scale = horizontal scale) vertical section along the line XZ. The same formula can be used as for the angle of dip above except 'spacing between contours' is now the apparent spacing observed along the line XZ.

GEOLOGICAL MAP

Geological map: a map on which is recorded geologic information, such as the elevation, distribution, nature and age relationships of rock units, structural symbols and features (folds and faults), etc.

The use of geological map

The most obvious use of a geological map is to indicate the nature of the near-surface bedrock.

- To study the geological history of an area and to gather information about forms of common geological structures such as faults and folds;
- For civil engineers to advise on the excavation of road cuttings or on the siting of dams and bridges;
- To study the use of land and minerals exploiting.

Outcrop patterns of geological surfaces exposed on the ground

- A geological surface crops out at points where it has the same height as the ground surface.
- The line of outcrop of a geological surface crosses a structure contour for the surface only at points where the ground height matches that of the structure contour.

Ref: Structural geology book

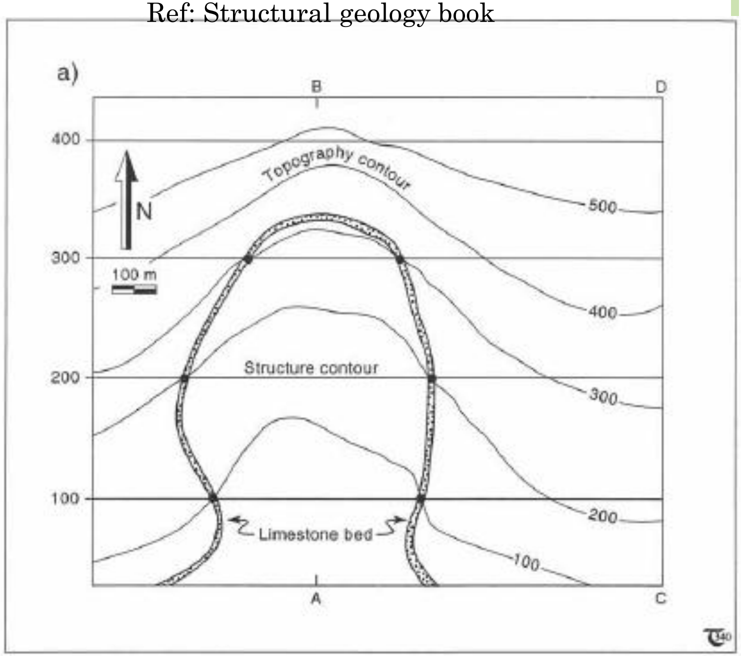


Figure 5-7a: Geological map, including three types of contours: elevation contours, structure contours, and contours outlining the outcrop pattern of a limestone bed. Contours are in meters.

GEOLOGICAL MAP

Outcrop patterns of geological surfaces exposed on the ground

Prediction of the map outcrop pattern of the coal seam from the map in Figure 2.16a.

- The thin coal seam in the previous example only occurs at the ground surface along a single line. The surface at other points on the map (a point not on the line of outcrop) is either buried (beneath ground level) or eroded (above ground level).
- The line of outcrop in Fig. 2.16B divides the map into two kinds of areas:
  - (a) areas where height (coal) > height (topography), so that the surface can be thought to have existed above the present topography but has since been **eroded** away, and
  - (b) areas where height (coal) < height (topography) so that the coal must exist below the topography, i.e. it is **buried**.

The boundary line between these two types of areas is given by the line of outcrop, i.e. where height (coal) = height (topography).

- The red shaded area is the part of the area underlain by coal, see Figure 2.16C.
- A geological surface is buried below the topographic surface when height (topography) > height (geological surface). The difference (height of topography minus height of geological surface) equals the depth of burial at any point on the map. **Depths** of burial determined at a number of points on a map provide data that can be contoured to yield lines of equal depth of burial called ***isobaths***, as shown in see Figure 2.16D.

Ref: geological Structures and maps book

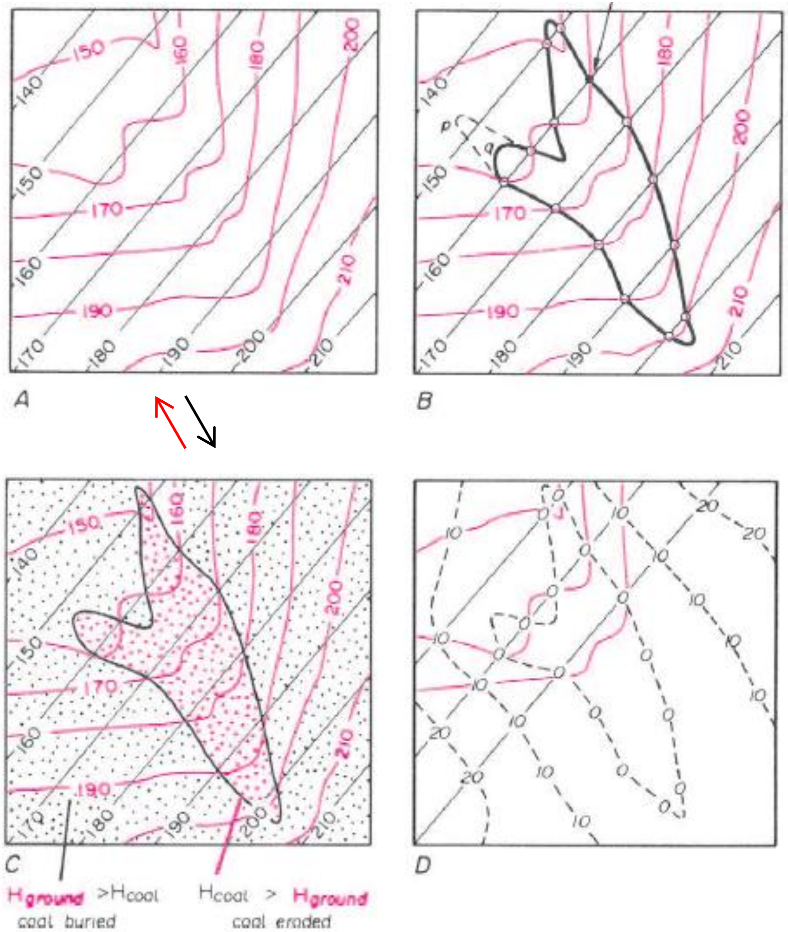


Fig. 2.16 Predicting outcrop and isobaths from structure contour information. Topographic contours are shown in red; structure contours for the coal seam are black.

Ref: geological Structures and maps book

GEOLOGICAL MAP

Structure contours from outcrop patterns

A map showing outcrops of a surface together with topographic contours can be used to construct structure contours for that surface. The underlying principles are:
(a) where a surface crops out, the height of the surface equals the height of the topography,
(b) if the height of a planar surface is known at a minimum of three places, the structure contours for that surface can be constructed.

Example

Draw strike lines for the limestone bed in Fig. 2.20A. What assumptions are involved?

- Join points on the outcrop which share the same height. These join lines are structure contours for that particular height (Fig. 2.20B).
- Draw as many structure contours as possible to test the assumption of constant dip (planarity of surface).

The structure contours in Fig. 2.20B are parallel and evenly spaced. This confirms that the limestone bed has a uniform dip.

Stratigraphic thickness

- ➢ The *true* or *stratigraphic thickness* of a unit is the distance between its bounding surfaces measured in a direction perpendicular to these surfaces (TT in Fig. 2.21).
- ➢ The *vertical thickness* (*VT*) is more readily calculated from structure contour maps. The vertical thickness is the height difference between the top and base of the unit at any point. It is the vertical 'drilled' thickness, and is obtained by subtracting the height of the base from the height of the top.
- ➢ Depending on the angle of dip, the vertical thickness (*VT*) differs from the true thickness (*TT*), because from Fig. 2.20B:

$$\cos(\text{dip}) = TT/VT$$

and

$$TT = VT \cos(\text{dip}).$$

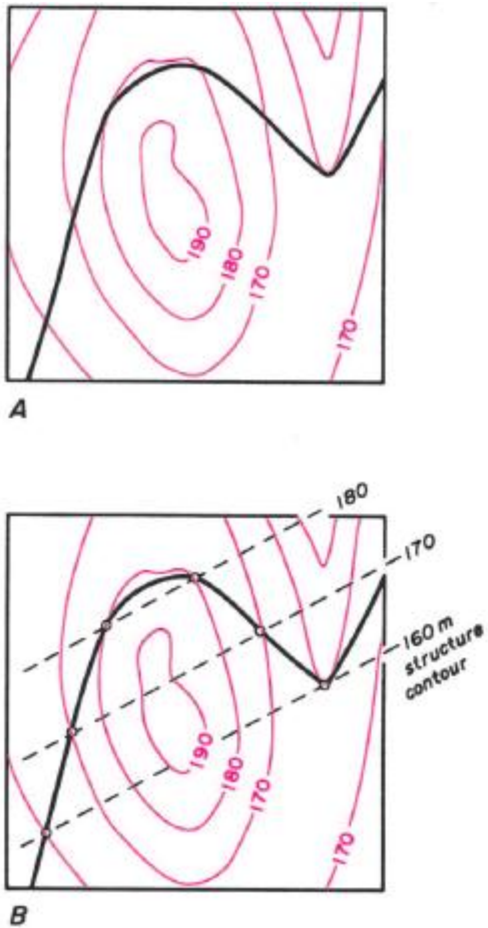


Fig. 2.20 Drawing structure contours.

GEOLOGICAL MAP

- The previous equation can be used to calculate the true thickness if the vertical thickness is known.
- The *horizontal thickness* (*HT*) is a distance measured at right angles to the strike between a point on the base of the unit and a point of the same height on the top of the unit. It can be found by taking the separation on the map between a contour line for the base of the bed and one for the top of the bed of the same altitude.

- From Fig. 2.21B is can be also seen that

sin (dip) = TT/HT

therefore,

TT = sin (dip) HT.

If VT and HT are both known, the dip can be calculated from

tan (dip) =VT/HT.

- It is important to note that the *width of outcrop* of a bed on a map (W on Fig. 2.21) is not equal to the horizontal thickness unless the ground surface is horizontal. In cross-sections care must be taken when interpreting thicknesses.
- Vertical thickness will be correct in any vertical section but the true thickness will only be visible in cross-sections parallel to the dip direction of the beds.

Example

Find the vertical thickness, horizontal thickness, true thickness and angle of dip of the sandstone formation from the structure contours in Fig. 2.22.

Ref: geological Structures and maps book

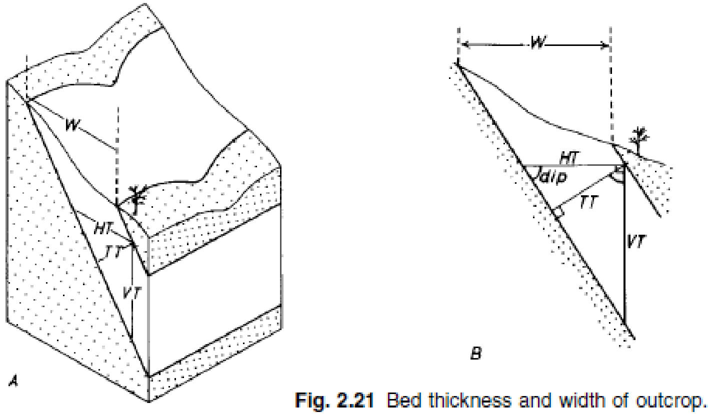


Fig. 2.21 Bed thickness and width of outcrop.

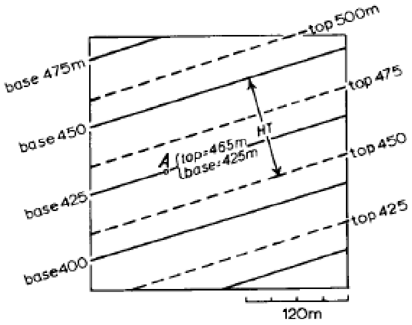


Fig. 2.22 Calculation of thickness from structure contours.

The vertical thickness is obtained by taking any point on the map, say A, and using the equation:

Vertical thickness = height of top – height of base

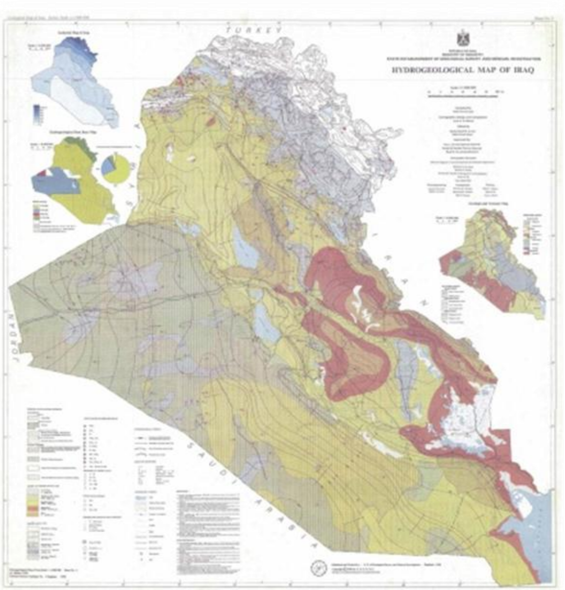
= 465 m – 425m

= 40m.

The horizontal thickness is given by the horizontal separation of any pair of structure contours of the same altitude (one for base, one for top). The horizontal thickness in this example is 120 m.

ENGINEERING GEOLOGY CE1301

Lecture #9 **Ground-water Geology**



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GROUNDWATER

- **Groundwater** is the water located beneath Earth's surface in soil pore spaces and in the fractures of rock formations.

Ground water represents a primary source of water for human use. It represents a major storage reservoir for freshwater (only 5% of the total freshwater supplies are contained in the earth's atmosphere or on its surface. It is Used for the major categories: rural, both domestic and farms; public water supply; industry; and irrigation.

Significance of ground water from engineering perspective

Civil engineering encounters, in many instances, problems related to ground water such as:

- Water supply from wells is a major area of interest for civil engineers. Water treatment of ground water typically involves only chlorination to kill bacteria.
- Engineering works with considerations of ground water involve for example: land drainage, irrigation, seepage, control of water drainage during soil and rock excavation, settlement of foundations and slope stability.

Advantages of the use of groundwater rather than surface water for water supply purposes

1- It is commonly free of some harmful organisms and hence required no purification for domestic or industrial use.

2- The temperature is nearly constant, which is important for heat exchange purposes.

3- Color and turbidity effects are usually minimal.

4- Chemical composition for a single source is essentially constant.

5- Ground water reservoirs are generally larger than those for surface water and therefore are not effected by drought of short duration.

6- Biological and radiological contamination of ground water is more difficult and less likely to occur.

7- Can be found in areas that do not have significant surface supplies.

Disadvantages of the use of groundwater rather than surface water for water supply purposes

1- It may not be available in sufficient quantities to match anticipated needs and rocks have too low permeability to transmit much water to a well.

2- In most cases ground water has more dissolved solids present than does the surface water in the same region.

3- The cost of developing wells, particularly in humid areas, may likely be greater than that of impounding reservoirs on small streams for surface supplies.

4- Ground water contamination by industrial chemicals has become prevalent in some urban areas.

Aquifers and aquicludes

- An **aquifer**: consists of a formation or a strata from which ground water can be obtained for beneficial use. Typical aquifers are gravel, sand, sandstone, limestone and fractured igneous and metamorphic rocks.
- An **aquiclude**: an impermeable body of rock or stratum of sediment that acts as a barrier to the flow of groundwater. Typical aquicludes are clay, mudstone, shale, evaporite and unfractured igneous and metamorphic rock.

- Soluble strata such as limestone and evaporite may have voids created or enlarged by dissolution to form caves and tunnels and in volcanic rocks lava tunnels may exist.
- The majority of soils transmit water through their pores whereas transmission through most rocks is by pores and fractures.
- Fractures normally transmit more water than pores as illustrated by the following values for the Chalk of S.E. England, a major aquifer:

	Fractures	*Pores*
Void space as	< 2%	25-45%
Permeability	>100 m/day	$\approx 1 \times 10^{-4}$ m/day

- The size of pathways provided by pores and fractures will reduce if applied loads cause them to close.
- Shrinkage due to desiccation can open cracks in clays and dissolution can widen voids in soluble materials.

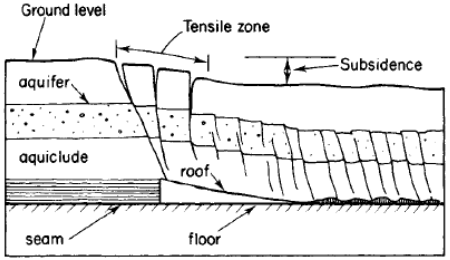
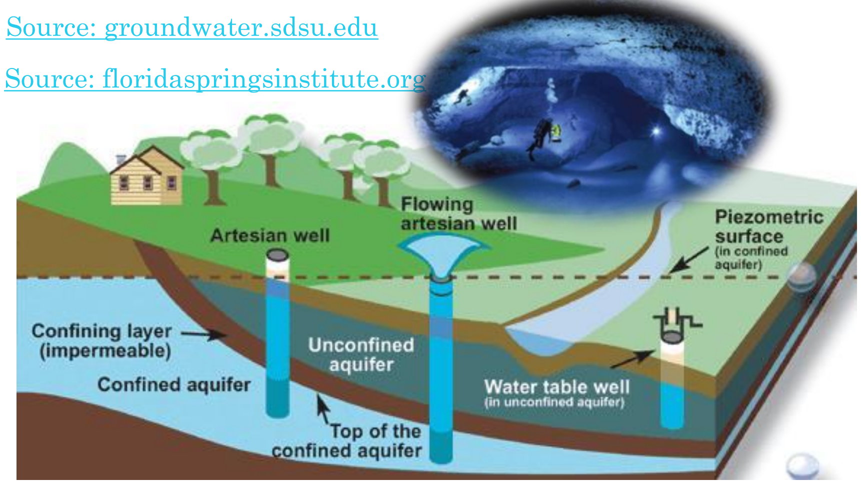


Fig. 13.13 Geological boundary moving above a mined area. Note that the increased fracturing greatly increases permeability.

Source: groundwater.sdsu.edu

Source: floridaspringsinstitute.org



Anisotropy

Igneous, sedimentary and metamorphic rocks, and most soils, are rarely so uniform that their thickness, degree of fracturing, porosity and permeability are the same throughout. Usually these properties vary from place to place, and with direction. An important source of variation in sediments is bedding, where the hydraulic properties in the direction parallel to bedding differ from those orthogonal to it. In these respects most aquifers and many aquicludes are anisotropic and calculations to predict ground-water flow must use values of permeability that are appropriate for the direction of flow in the ground.

Groundwater flow

The movement of ground-water and its dissolved constituents may be considered the result of two mechanisms:

(1) the physical movement of molecules together with their associated solutes, called *advective flow,* and

(2) the chemical movement of solutes, called *diffusive flow*.

- When rates of advective flow are extremely slow, diffusion becomes the dominant form of mass transfer in response to chemical gradients in the ground. Ground-water that moves sufficiently fast to be of concern to most engineering work is predominantly advective.

- The potential of water to flow is defined by Bernoulli in terms of *elevation* (He) and *pressure* head (Hp), both of which are illustrated in Fig. 13.16, and *velocity* head (Hv): the latter is usually so small a component that it can be ignored in most assessments of groundwater flow. Elevation plus pressure head equal *total* head and flow is always from high to low total head (or water level).

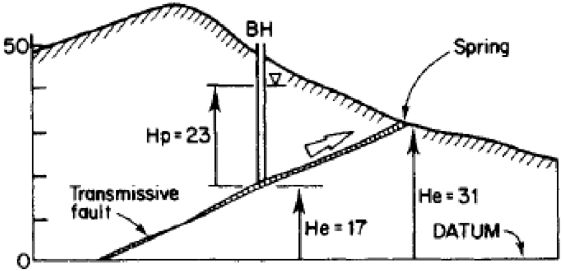
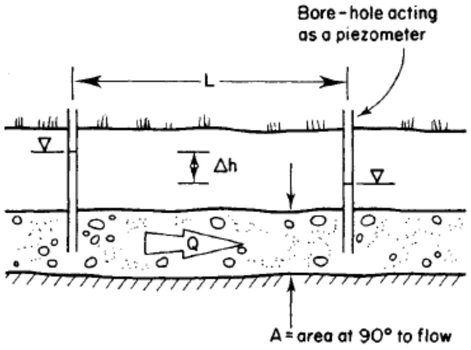


Fig. 13.16 Total head at bore-hole (BH) = 17 + 23 = 40. Total head at spring = 31 + 0 = 31. Flow of ground-water is from high to low total head (or water level). He = elevation head, Hp = pressure head: all measurements are in metres.

The discharge



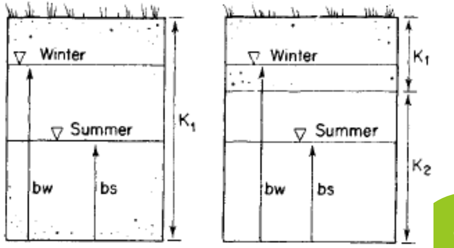
The discharge of ground-water Q (dimensions L^3/T) through the aquifer illustrated in below, of area A (dimensions L^2) at 90° to the direction of flow, is given by the relationship:

$$Q = k\frac{\Delta h}{L}A$$

where $\Delta h[L$ is the loss in total head per unit length of flow (i.e. the hydraulic gradient: dimensionless L/L) and k, called the *coefficient of permeability*. Permeability has the dimensions of velocity (i.e. L/T).

- Permeability is rarely the same in all directions and the appropriate value to use is that in the direction of ground-water flow.
- The greatest value of permeability in sediments and sedimentary rocks is usually in the direction of bedding.
- If ground contains horizons of different permeability an overall value is required and obtained from permeability tests conducted in-situ.

Transmissivity



Transmissivity: is the rate of horizontal groundwater flow through an aquifer.

Water-supply engineers commonly combine the overall value of *in-situ* permeability of strata (k) with its saturated thickness (b) to produce transmissivity (saturated) = $k * b$ (dimensions L^2/T).

Origin of subsurface water

- Most of the water in the subsurface has been supplied via the atmosphere by the way of **hydrologic cycle**.
- Most moisture is evaporated directly from the oceans (≈328000 km^3/year), from the land surface including lakes, streams and the soil (≈61400 km^3/year), and as a result of transpiration by plants.
- The continental land masses receive ≈98300 km^3/year of freshwater. ≈614000 km^3/year of water is returned to the atmosphere by evaporation with the remainder shared by runoff and infiltration. In that way the cycle continues from year to year.

1- Ocean water

Oceans were formed in the early ages of the earth from clouds of water vapor given off by the cooling earth.

2- Connate water

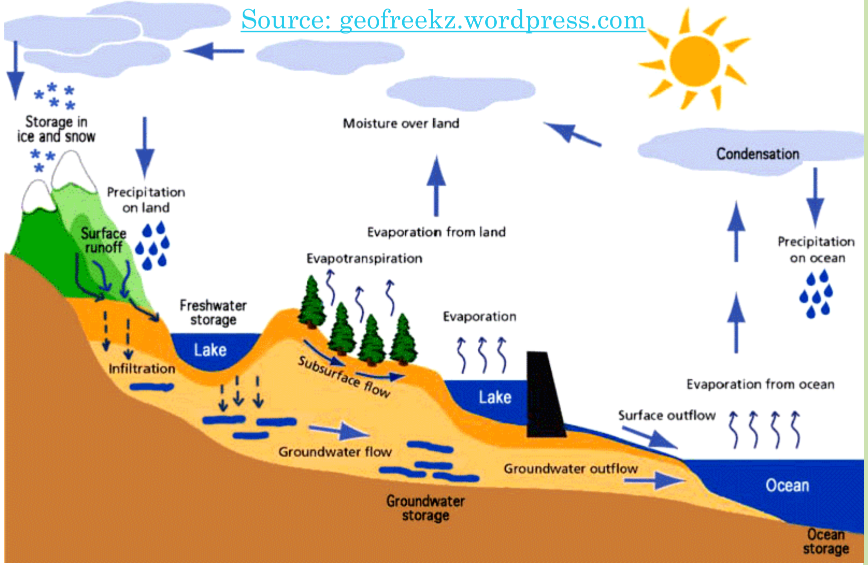
- Connate water are liquids that were trapped in the pores of sedimentary rocks as they were deposited.
- For marine sediments, the most common, connate water originates as seawater.
- If the pore fluid is salt-rich , it will be unsuitable for most uses as water supply.
- Formations containing salty connate water are not considered an aquifer as the water is not suitable for human consumption. Such formations may be potential sites for waste disposal.

3- Magmatic water

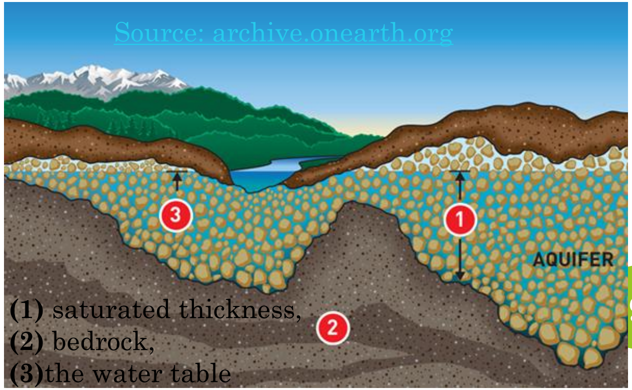
- Magmatic water: is that water absorbed by magma then released by in a form of steam when extrusive rocks flow onto the surface.

4- Juvenile water

- Original water: formed as a result of magmatic processes. Juvenile water has never been in the atmosphere


Source: geofreekz.wordpress.com

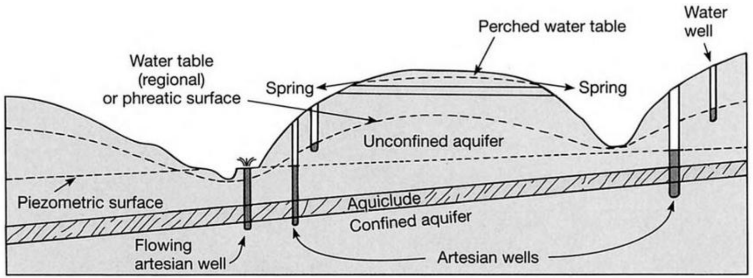
Rainfall=Evaporation + Transpiration + Infiltration + Runoff


Source: archive.onearth.org

(1) saturated thickness,
(2) bedrock,
(3)the water table

Water table (WT)

- The water table is the surface in an unconfined aquifer along which the hydrostatic pressure of the water is equal to the atmospheric pressure (i.e. gauge pressure = 0).
- Can be obtained by drilling wells that penetrate the saturated zone.
- The shape of groundwater is controlled partly by the topography of the land where WT tends to follow, generally, the outline of the land surface.
- Perched aquifer: is an aquifer that occurs above the regional water table, in the vadose zone. The aquifer occurs between the surface and an impermeable layer of rock or sedimentary soil (known as aquiclude).



Vodase zone

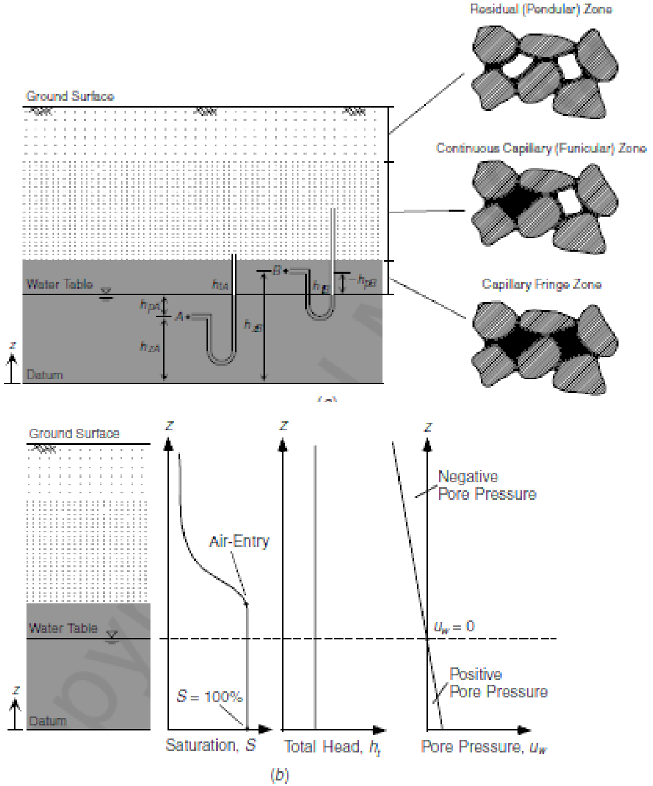
- The vadose zone, (unsaturated zone), is the part of Earth between the land surface and the water table.

Vodase zone can be subdivided into three zones:

(1) capillary fringe zone : in which the soil remains saturated under negative pore water pressure;

(2) Continuous capillary zone: in which soil is unsaturated but with a continuous water phase. Water pressure is negative;

(3) a residual zone: in which water phase is isolated and discontinuous. The pores is largely filled with air.



Artesian conditions

- Artesian aquifer is a confined aquifer with a positive pore water pressure which causes the water level in a well to rise to a point where the hydrostatic equilibrium has been achieved.
- The well drilled into such aquifer is called artesian well.

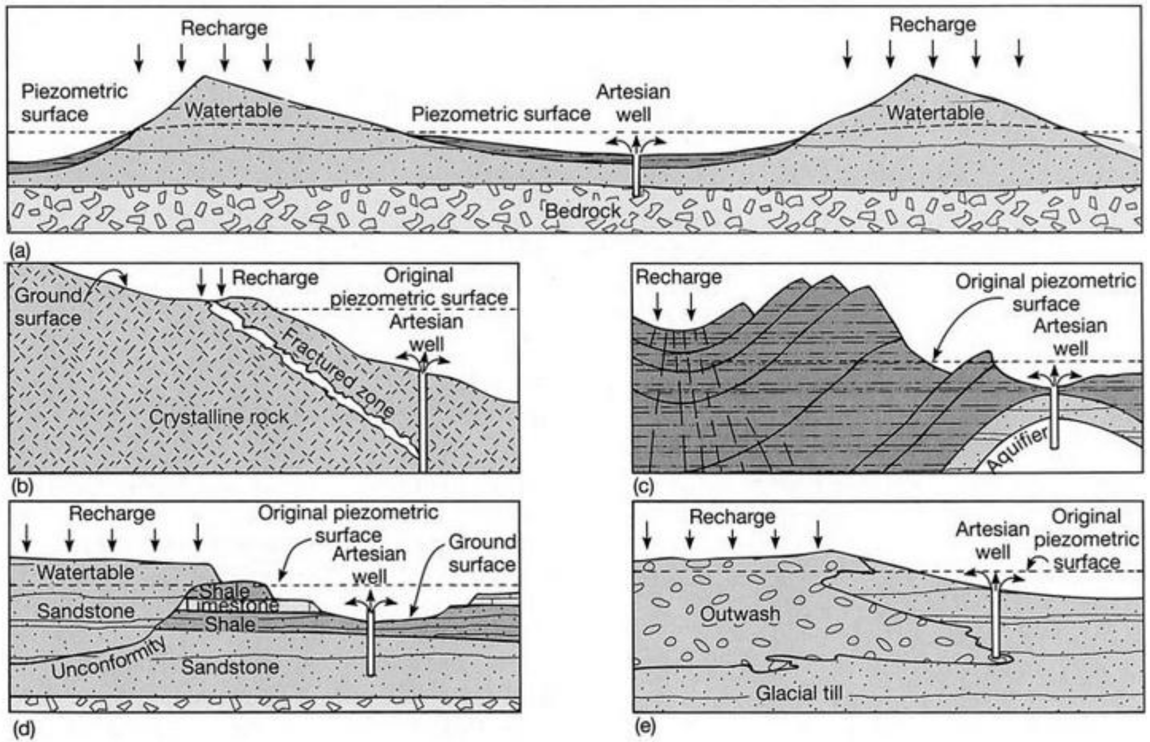


FIGURE 15.4 Geologic settings yielding artesian conditions. (a) Stabilized sand dunes, (b) crystalline rock, (c) complexly folded and fractured sedimentary rocks, (d) horizontal sedimentary rocks, and (e) glacial deposits.

Hydrogeological investigations

❖ The hydrogeological investigations that enable predictions to be made either of **the influence of ground-water upon engineering works**, or its potential as a **source for water supply**, should be designed to assess the following:

(1) the location and thickness of aquifer horizons and zones, their confinement and their hydrogeological boundaries;

(2) the levels of water in the ground, their variation over an area and their fluctuation with time;

(3) the storage and transmissive characters of the ground; and

(4) the quality of the ground-water.

1- Surface investigations

Normally there are three objectives for surveys that are conducted at ground level:

(1) To make a hydrogeological map of the area so as to show the distribution of aquifers, of geological boundaries, especially those created by stratigraphy and faulting, and of hydrological boundaries such as rivers, lakes and spring lines.

* Ground of exceptional permeability may be located at the intersection of faults.

* The mapping of large areas, as needed for large water supply, or hydro-power or irrigation schemes, can be helped greatly by the use of various forms of remote sensing that reveal the presence of water and water-bearing strata.

(2) To draw one or more vertical sections across the area to illustrate geological structure, the thickness and confinement of aquifers, and the dip of hydrogeological boundaries.

(3) To reconstruct the geological history of the area.

See: A geology for engineers book

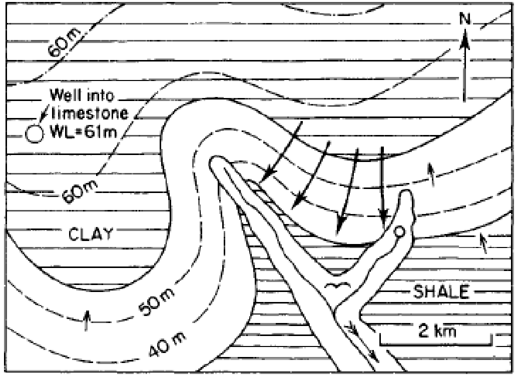


Fig. 13.23 Hydrogeological map. A limestone aquifer lies between two aquicludes: shale below and clay above. The strata dip N. Rivers issue from springs (see UNESCO, 1970). The direction of ground-water flow may be deduced from flow lines drawn orthogonal to the water level contours -- =water level in limestone. 60 m = height above datum to which water in limestone will rise in a bore. =alluvium. ○ =spring. → =flow line for ground-water.

2- Sub-surface investigations

These are required to confirm:

(1) the level of water in the ground;

(2) the depth, thickness and lateral extent of aquifers and aquicludes;

(3) the permeability of these zones and the storage of aquifers;

(4) the chemistry of the aquifers and their contained water, and their temperature, if required.

Groundwater pollution

- See the book geology applied to engineering