Workshop on Geology of Singapore

Fundamentals of Geology

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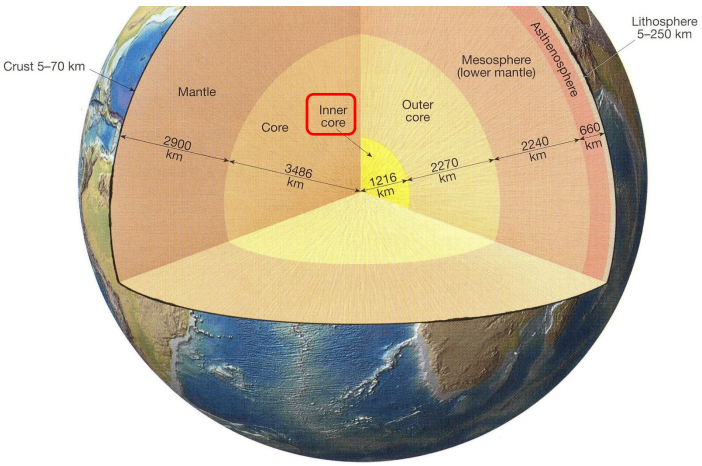
Last revised on 23/3/2010

Topics for today

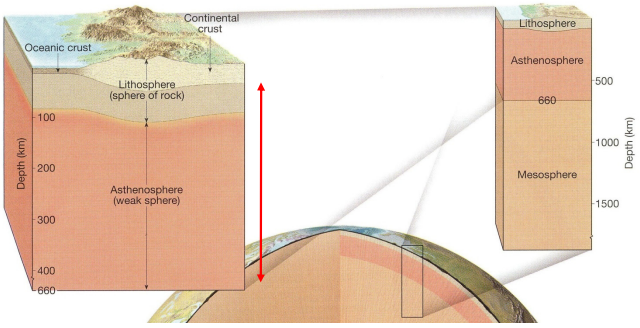
- Plate Tectonics
- Geologic Time Scale
- Minerals
- Rocks
- Rock Cycle
- Geological Structures
- Earth Processes

Plate Tectonics - Earth layered structure



The principal divisions of the solid Earth include: the **inner core**, a solid, iron-rich zone having a radius of **1216 kilometers**

Plate Tectonics - Earth layered structure



Earth's crust is further divided into **continental crust** and **oceanic crust**.

The **continental crust** is roughly **35** kilometers thick, and may exceed 60 kilometers in regions of prominent mountains.

By contrast, the **oceanic crust** is much thinner, averaging only 5 kilometers in thickness.

Plate Tectonics

- Earth's rigid outer shell (lithosphere) is broken into numerous slabs called **plates**, which are in motion and are continually changing shape and size. They move independently several cm per year, riding on discontinuities somewhere in the plastic upper portion of the **mantle**.
- **Seven major plates**: North American, South American, Pacific, African, Eurasian, Australian, and Antarctic.
- Some plates include an **entire continent** plus a large area of seafloor (e.g. South American plate). However, **none** of the plates are defined entirely by the margins of a single continent.

Plate Tectonics – World Plates

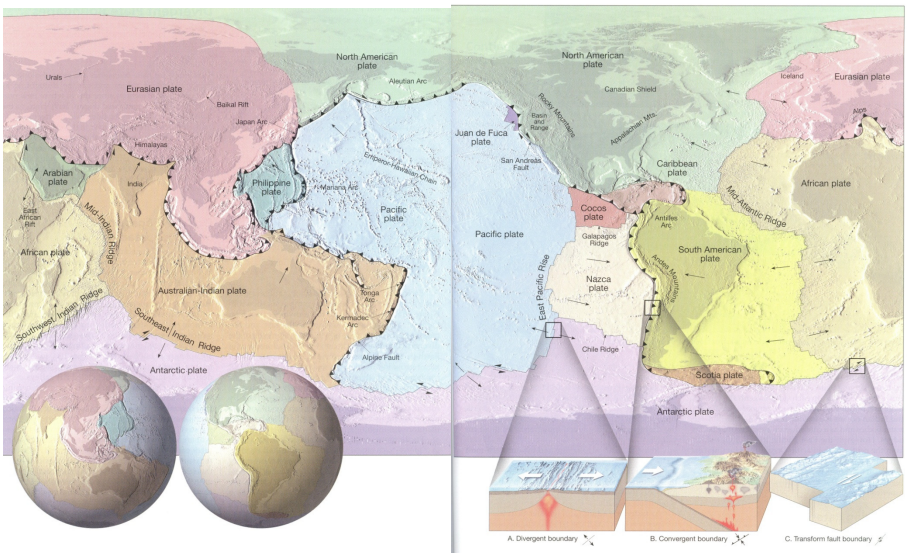


Plate Tectonics

- The **lithospheric plates** move relative to each other at a very slow but continuous rate that averages about 5 cm a year.
- Plate Tectonics Animation http://www.youtube.com/watch?v=ZLJLFYXp-0Q
- This movement is ultimately driven by the unequal distribution of **heat** within Earth. Hot material found deep in the mantle moves slowly upward and serves as one part of our planet's internal **convective system**.
- Concurrently, cooler, denser slabs of lithosphere **descend back** into the mantle, setting Earth's rigid outer shell in motion.
- Ultimately, the titantic, grinding movements of Earth's lithospheric plates generate **earthquakes**, create **volcanoes**, and deform large masses of rock into **mountains**.

Plate Tectonics

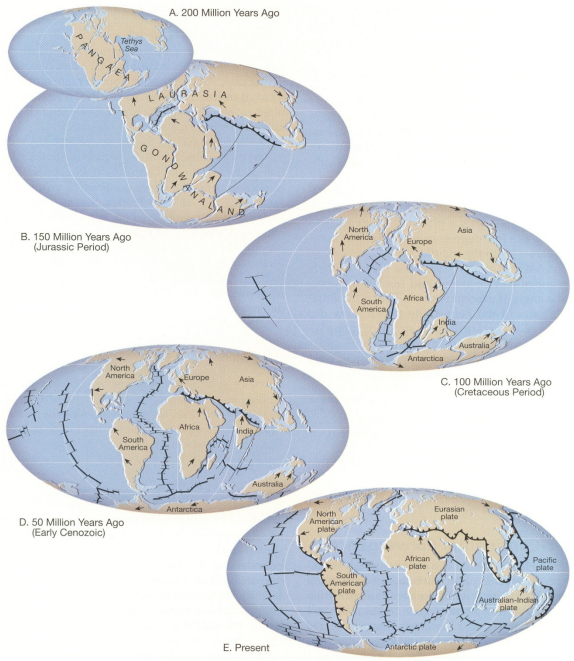
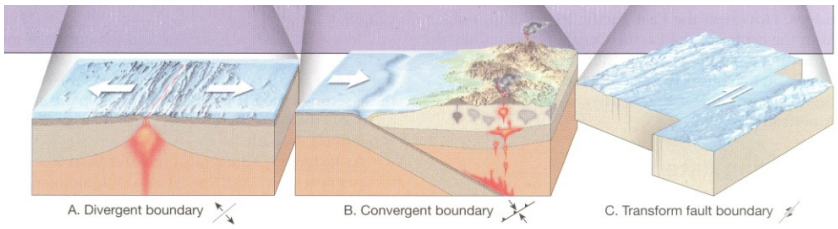


Plate Tectonics – Plate boundaries

A. Divergent boundaries – zones where plates move apart, leaving a gap between them

B. Convergent boundaries – zones where plates move together, causing one to go beneath the other

C. Transform fault boundaries – zones where plates slide past each other, scraping and deforming as they pass.



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Geologic Time Scale

The age of the earth

Archbishop James Ussher (1654) – earth was created in 4004 B.C.

James Hutton (late 18th century) - **uniformitarianism** – The physical, chemical, and biological laws that operate today have also operated in the geologic past. The present is the key to the past. e.g. volcanic eruption, water flow, sediment deposit….

By modern dating techniques, the age of the earth is estimated to be around _____ billion years.

Age Game

Guess about how long it would take just to count to 4.5 billion if you could count one number per second without stopping?

a.5 years
b.10 years
c.50 years
d.100 years
e.150 years

An appreciation for the magnitude of geologic time is important because many of Earth's processes are **so gradual** that vast spans of time are needed for significant changes to occur.

Geologic Time Scale

- The geologic time scale divides Earth's history into **units** of varying magnitude. It is commonly presented in chart form, with the **oldest** time and event at the bottom and the **youngest** at the top.

- The principal subdivisions of the geologic time scale, called **eons**, include the **Hadean**, **Archean**, **Proterozoic** (together, these three eons are commonly referred to as the **Precambrian**), and beginning about 540 million years ago, the **Phanerozoic** .

- The **Phanerozoic** (meaning "visible life") **eon,** which began about **540 million years ago,** is divided into the following **eras** according to dominant life-forms: **Paleozoic** ("ancient life"), **Mesozoic** ("middle life"), and **Cenozoic** ("recent life").

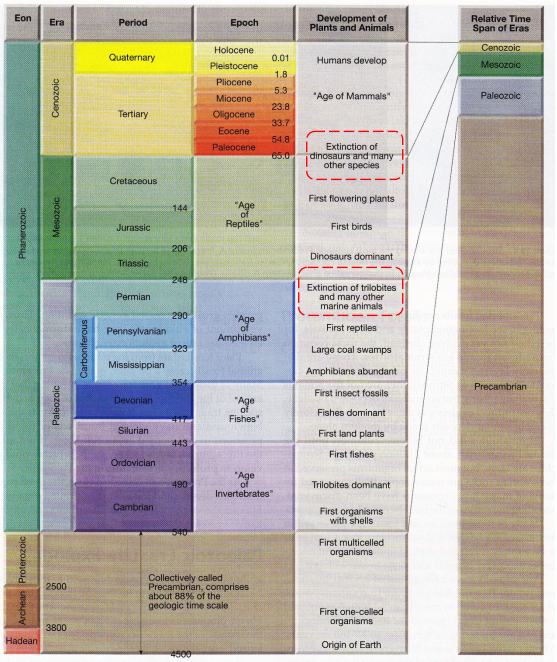

Figure 19.5 The geologic time scale. Numbers on the time scale represent time in millions of years before the present. These dates were added long after the time scale had been established using relative dating techniques. The Precambrian accounts for about 88 percent of geologic time. (Data from Geological Society of America)

tribolite

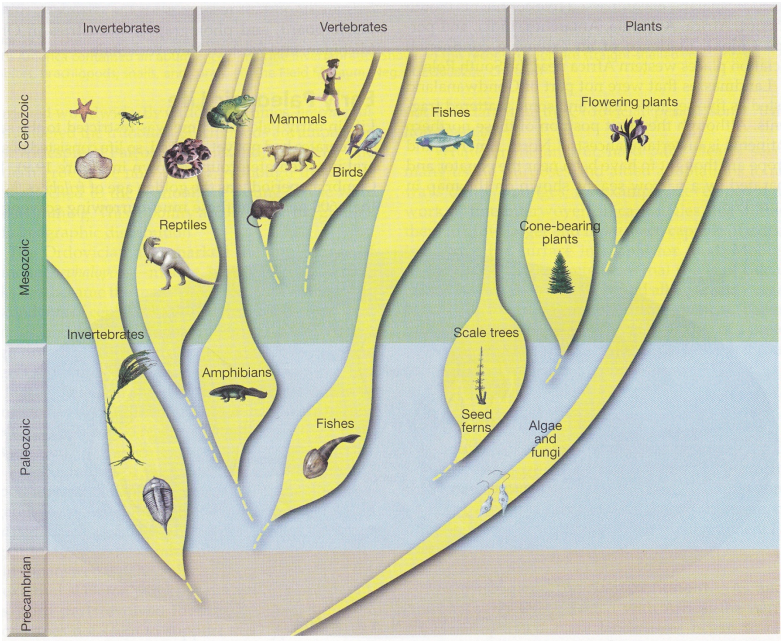

Figure 19.7 This chart indicates the times of appearance and relative abundance of major groups of organisms. The wider the band, the more dominant the group.

15

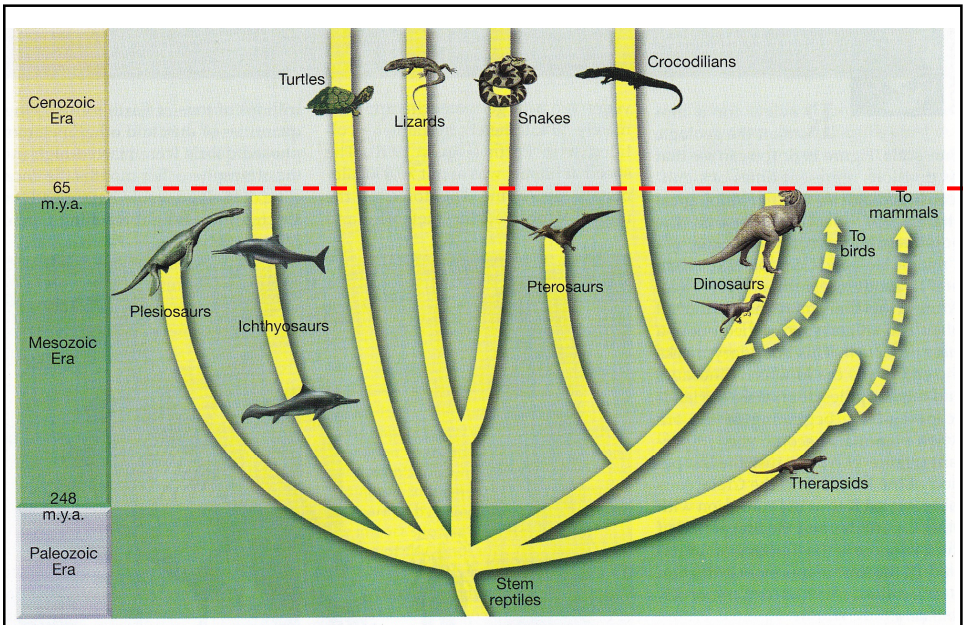

Figure 19.18 Adaptive radiation of major reptile groups during the Mesozoic era—"the golden age of reptiles." Dinosaurs, pterosaurs (flying reptiles), and large marine reptiles all became extinct by the end of the Mesozoic.

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Game Time

1. About what percent of Earth's 4.5 billion-year history is represented by Precambrian time?

A.65%

B.88%

C.95%

2. Which is the greatest expanse of time?

A.Era

B.Epoch

C.Eon

D.Period

E.None of the above

Game Time (cont)

3. Which is a subdivision of an epoch?

A.Era

B.Eon

C.Period

D.None of these

4. Mesozoic is an example of what?

A.Era

B.Epoch

C.Eon

D.Period

E.None of the above

Game Time (cont)

5. Eons are divided into these:
A.Era
B.Eon
C.Period
D.None of these

6. Which is the smallest time span on the geologic time scale?
A.Era
B.Epoch
C.Eon
D.Period
E.None of the above

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Minerals

naturally occurring inorganic solids, which possess an orderly internal structure and a definite chemical composition (>2000 types), e.g. quartz

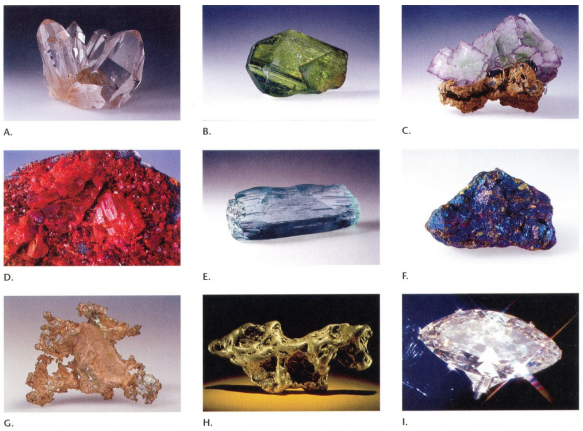


Figure 2.1 Mineral samples. **A.** Quartz; **B.** Olivine (variety Fosterite); **C.** Fluorite; **D.** Realgar; **E.** Beryl (variety aquamarine); **F.** Bornite and Chalcopyrite; **G.** Native copper; **H.** Gold nugget; **I.** Cut diamond. (Photos A–F by Dennis Tasa; G by E. J. Tarbuck; H and I by Dane Pendland, courtesy of Smithsonian Institution)

Minerals

Based on the definition of a mineral, evaluate the following statements

1) Gold is a mineral (T/F)
2) Synthetic diamonds are mineral(T/F)
3) Minerals must be solid (T/F)
4) Quartz is considered a mineral (T/F)
5) Petroleum is a mineral (T/F)
6) Animal bone is a mineral (T/F)
7) Ice is a mineral (T/F)
8) Granite is a mineral (T/F)
9) Steel is a mineral (T/F)

Minerals

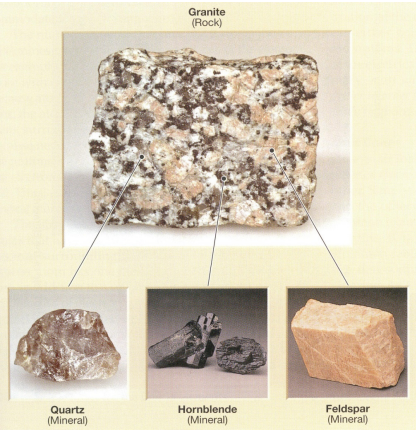
1) Gold is a mineral (**T**)
2) Synthetic diamonds are mineral (**F**: They are manufactured, not naturally occurring)
3) Minerals must be solid (**T**)
4) Quartz is considered a mineral (**T**)
5) Petroleum is a mineral (**F**: It is a liquid)
6) Animal bone is a mineral (**F**: It is organic)
7) Ice is a mineral (**T**)
8) Granite is a mineral (**F**: It is a rock composed of several minerals)
9) Steel is a mineral (**F**: It is not naturally occurring)

Answers to previous questions.

Minerals vs Rocks

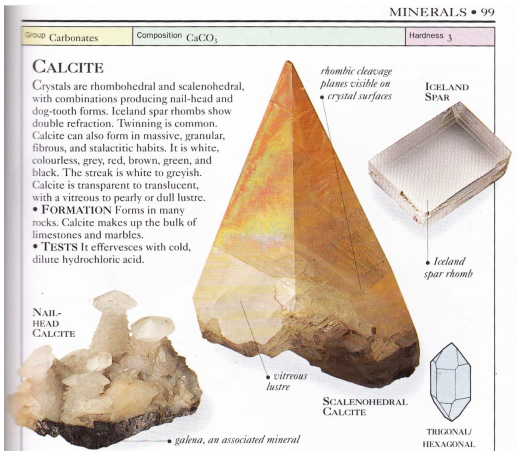
Rock – an aggregate of one or more minerals.

The term aggregate implies that the minerals are found together as a **mixture** in which the properties of the individual minerals are retained. e.g. granite (quartz, feldspar, mica)



Minerals vs Rocks

Although most rocks are composed of more than **one mineral**, certain minerals are found by themselves in large, impure quantities, e.g. limestone (calcite)



Minerals

Silicate Structures (Minerals)

-The most common group of rock-forming minerals are the silicates

-**Silicon-oxygen tetrahedron** is the fundamental building block

-4 oxygen atoms surrounding a silicon atom)

-Quartz : SiO_2

-Silicon atoms can be replaced by ions of Fe, Mg, K, Na, Al, Ca

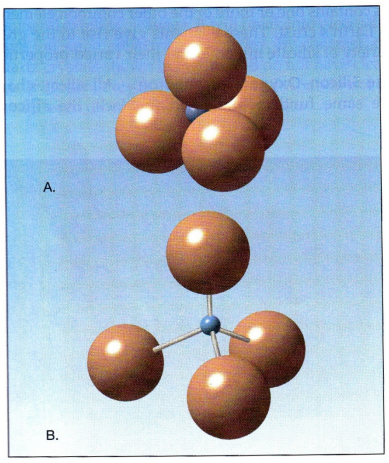


Figure 2.13 Two representations of the silicon–oxygen tetrahedron. **A.** The four large spheres represent oxygen atoms and the blue sphere represents a silicon atom. The spheres are drawn in proportion to the radii of the atoms. **B.** A model of the tetrahedron using rods to depict the bonds that connect the atoms.

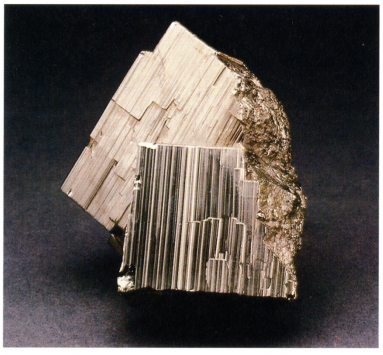
Minerals

Mineral		Idealized Formula	Cleavage	Silicate Structure
Olivine		$(Mg, Fe)_2SiO_4$	None	Single tetrahedron
Pyroxene group (Augite)		$(Mg,Fe)SiO_3$	Two planes at right angles	Single chains
Amphibole group (Hornblende)		$Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$	Two planes at 60° and 120°	Double chains
Micas	Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	One plane	Sheets
	Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$		
Feld-spars	Orthoclase (Potassium feldspar)	$KAlSi_3O_8$	Two planes at 90°	Three-dimensional networks
	Plagioclase	$(Ca,Na)AlSi_3O_8$		
Quartz		SiO_2	None	

Figure 2.16 Common silicate minerals. Note that the complexity of the silicate structure increases down the chart.

Physical Properties of Minerals

Crystal Form – external expression of a mineral that reflects the orderly internal arrangement of atoms (if without restriction). e.g. cubic, hexagonal



A.

B.

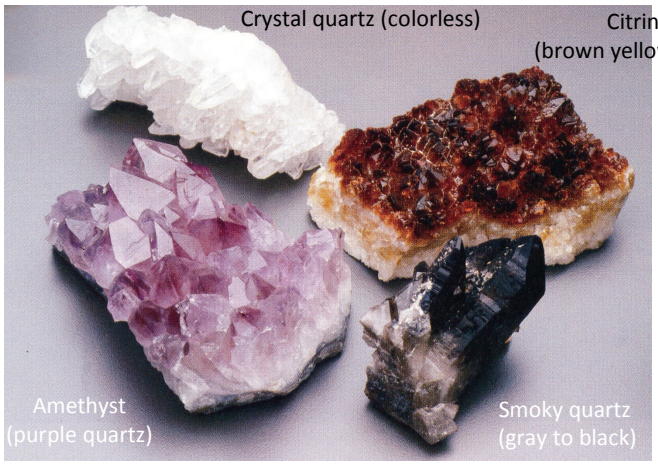
Figure 2.8 Crystal form is the external expression of a mineral's orderly internal structure. **A.** Pyrite, commonly known as "fool's gold," often forms cubic crystals that may exhibit parallel lines called striations. (Photo by E. J. Tarbuck) **B.** Quartz sample that exhibits well-developed hexagonal (six-sided) crystals with pyramidal-shaped ends. (Photo by Breck P. Kent)

Physical Properties of Minerals

Luster – appearance or quality of light reflected from the surface of a mineral (metallic, nonmetallic, glassy, pearly, silky, resinous, earthy)

Physical Properties of Minerals

Color – is not always a useful diagnostic property. E.g. slight impurities in the mineral quartz give it a variety of colors



Physical Properties of Minerals

Streak – color of a mineral in its powdered form and obtained by rubbing a mineral across a piece of unglazed porcelain (streak plate). *Not necessary equivalent to color.*

Physical Properties of Minerals

Streak

For instance **hematite** may look black, but it will always produce a **RED/BROWN streak** on a streak plate.

Pyrite looks yellow-gold in the crystal form, but gives a **GRAY** streak when the plate is used.

Care must be taken if the mineral being tested is harder than the porcelain, the result will be a powder produced by the porcelain plate being scratched and will always be white.

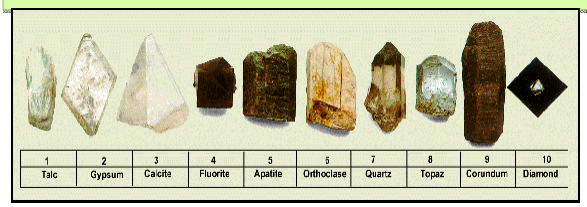
Hematite on left
Pyrite on the right

http://www.theimage.com/geology/notes3/index4.html

Physical Properties of Minerals

Hardness – resistance of a mineral to abrasion or scratching; *relative* property determined by rubbing a mineral of unknown hardness against one of the known hardness.

Mohs scale: (1) Talc (2) Gypsum (3) Calcite (4) Fluorite (5) Apatite (6) Orthoclase (7) Quartz (8) Topaz (9) Corundum (10) Diamond



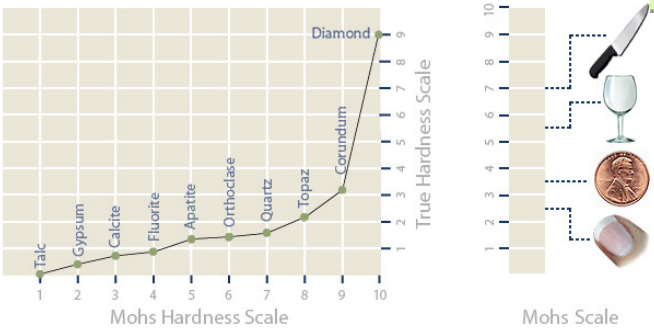
(2.5) Fingernail
(3) Copper penny
(5.5) Glass

http://invsee.asu.edu/srinivas/Carbonmod/hardness.html

Physical Properties of Minerals

Hardness

Mohs scale: (1) Talc (2) Gypsum (3) Calcite (4) Fluorite (5) Apatite (6) Orthoclase (7) Quartz (8) Topaz (9) Corundum (10) Diamond

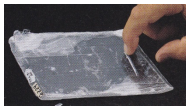


(7) Knife blade

(5.5) Glass

(3) Copper penny

(2.5) Fingernail



http://www.khulsey.com/jewelry/mohs_hardness_scale.html

Physical Properties of Minerals

Cleavage – smooth surfaces when mineral is broken due to planes of weak bonding. e.g. micas, which has weak chemical bonds in one direction, they cleave to form thin, flat sheets.
e.g. calcite is a mineral whose cleavage angle is 75 degrees.
e.g. hornblende has 2 cleavages, one at 60 degrees and one at 120 degrees

Figure 2.9 The thin sheets shown here were produced by splitting a mica (muscovite) crystal parallel to its perfect cleavage. (Photo by Breck P. Kent)

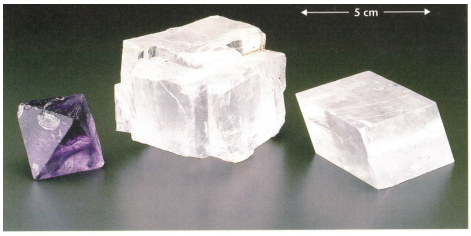


Figure 2.10 Smooth surfaces produced when a mineral with cleavage is broken. The sample on the left (fluorite) exhibits four planes of cleavage (eight sides), whereas the other two samples exhibit three planes of cleavage (six sides). Also notice that the mineral in the center (halite) has cleavage planes that meet at 90-degree angles, whereas the mineral on the right (calcite) has cleavage planes that meet at 75-degree angles. (Photo by E. J. Tarbuck)

Physical Properties of Minerals

Cleavage – e.g. hornblende has 2 cleavages, one at 60 degrees and one at 120 degrees

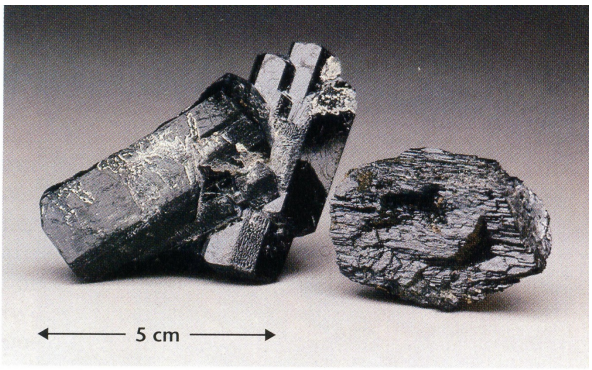


Figure 2.17 Hornblende amphibole. Hornblende is a common dark silicate mineral having two cleavage directions that intersect at roughly 60° and 120°. (Photo by E. J. Tarbuck)

Physical Properties of Minerals

•It is important not to confuse **cleavage** with **crystal form**. Remember, crystal form is the external expression of a mineral's orderly arrangement of atoms. Whereas, cleavage is the tendency of minerals to break along planes of weakness.

•All minerals have **crystal form**, but some minerals lack **cleavage**. Minerals that do not exhibit cleavage when broken are said to fracture.

Figure 2.11 Conchoidal fracture. The smooth curved surfaces result when minerals break in a glasslike manner. (Photo by E. J. Tarbuck)

Physical Properties of Minerals

Specific gravity – ratio of weight of a mineral to the weight of an equal volume of water; common range 2.5 to 3

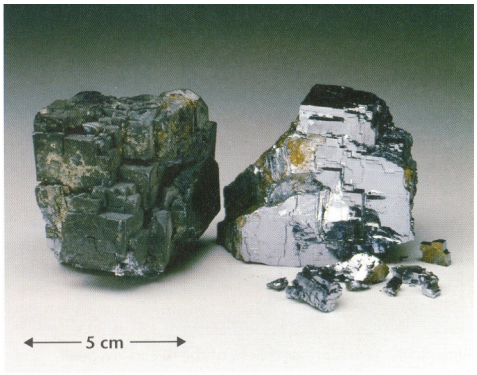


Figure 2.12 Galena is lead sulfide. Like other metallic ores, it has a relatively high specific gravity and therefore feels heavy when hefted. (Photo by E. J. Tarbuck)

Two general groups of silicate minerals on the basis of their chemical makeup

A.Ferromagnesian (dark) silicates – containing ions of iron (iron = ferro) and/or magnesium; typically *dark* in color; specific gravity = 3.2-3.6

B.Nonferromagnesian (light) silicates – not containing these iron/magnesium ions; *light* in color; specific gravity = ~2.7

Ferromagnesian silicates

Olivine
-Black to olivine green (hence name)
-Glassy luster
-Conchoidal fracture
-Granular appearance
-Individual tetrahedron

https://sharepoint.cisat.jmu.edu/isat/klevicca/Web/IDLS/olivine/oodsnup.htm

http://www.iun.edu/~geos/Zoran%20IUN/G%20101/Lecture%20Outlines/Minerals.htm

Ferromagnesian silicates (continued)

Pyroxene

- black, opaque
- 2 planes of cleavage that meet at nearly at 90 degrees

http://csmres.jmu.edu/geollab/fichter/RockMin/pyrox-70.html

Ferromagnesian silicates (continued)

Amphiboles (Group)

-Hornblende is the most common member

-Dark green to black

-Cleavages at about 60 degrees and 120 degrees

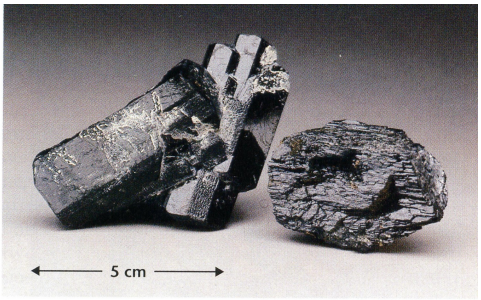


Figure 2.17 Hornblende amphibole. Hornblende is a common dark silicate mineral having two cleavage directions that intersect at roughly 60° and 120°. (Photo by E. J. Tarbuck)

Ferromagnesian silicates (continued)

Biotite
-Iron rich member of mica family
-Sheet structure, hence excellent cleavage in one direction
-Shiny black appearance

http://geology.com/minerals/biotite.shtml

Ferromagnesian silicates (continued)

Garnet
-Glassy luster
-Lacks cleavage; possesses conchoidal fracture
-Brown to deep red

http://crystal-cure.com/garnet.html

http://www.jewelrystones.org/garnet

Nonferromagnesian silicates

Muscovite

-member of mica family
-Sheet structure, hence excellent cleavage in one direction
-Light color and pearly luster

http://mulch.cropsoil.uga.edu/soilsandhydrology/Important%20Rocks%20&%20Minerals.htm

Nonferromagnesian silicates (continued)

Feldspar

-Most common mineral group
-Two planes of cleavage at or near 90 degrees, hence rectangular shape
-Luster ranges from glassy to pearly

orthoclase

http://tasaclips.com/photos.html

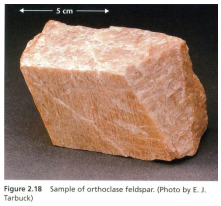


Figure 2.18 Sample of orthoclase feldspar. (Photo by E. J. Tarbuck)

orthoclase

plagioclase

http://www.learnearthscience.com/pages/Unit_Links/images/Plagioclase%20feldspar.jpg

Orthoclase	Plagioclase
K ions rich	Na and Ca ions rich
Light cream to salmon pink	White to medium gray
Striations absent	Striations on cleavage faces

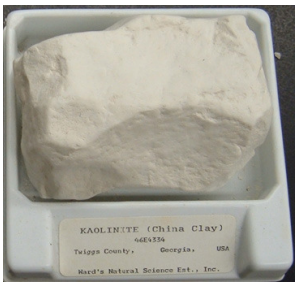
Nonferromagnesian silicates (continued)

Quartz (Silica)
-Consists entirely of silicon and oxygen
-Strong silicon-oxygen bond
-Hard, very resistant to weathering,
-does not have cleavage, exhibits conchoidal fracture

http://www.learnearthscience.com/pages/Unit_Links/mineral_images.htm

Nonferromagnesian silicates (continued)

Clay minerals
-Sheet structure (microscopic scale)
-Usually fine-grained (not equivalent to clay-sized particles, in association with silt, sand, cobble)
-Products of weathering
-e.g. kaolinite for manufacture of fine chinaware, pottery



http://www.farleygraphics.com/images/Kaolinite(ChinaClay).jpg

Nonsilicate minerals

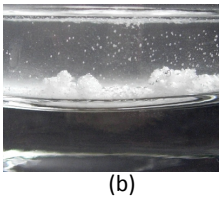
Carbonate minerals

-Calcite, $CaCO_3$ *(rock is called limestone)*
-Dolomite, $CaMg(CO_3)_2$ *(rock is called dolostone)*
-Both have vitreous (glassy) luster
-Both have hardness between 3 and 4
-Both have nearly perfect rhombic cleavage

Q: How to differentiate?
A: Apply dilute hydrochloric acid – (a) calcite reacts vigorously, (b) dolomite only reacts in powder form

(a)

http://saltthesandbox.org/rocks/acidtest.htm



(b)

http://geology.about.com/od/mineral_ident/ig/acidtest/acidtestdolo.htm

Nonsilicate minerals

Evaporite

-Minerals found in ancient seas that have long evaporated
-Halite (NaCl)
-Gypsum ($CaSO_4 \cdot 2H_2O$)

halite

http://chemistry.about.com/od/growingcrystals/ig/Crystal-Photo-Gallery/Salt-Crystal---Sodium-Chloride.htm

halite

http://www.msnucleus.org/membership/html/k-6/rc/minerals/2/rcm2_5a.html

Rock gypsum

http://www.mii.org/Minerals/photogyp.html

Topics for today

- Plate Tectonics
- Geologic Time Scale
- Minerals
- Rocks
- Rock Cycle
- Geological Structures
- Earth Processes

Rocks

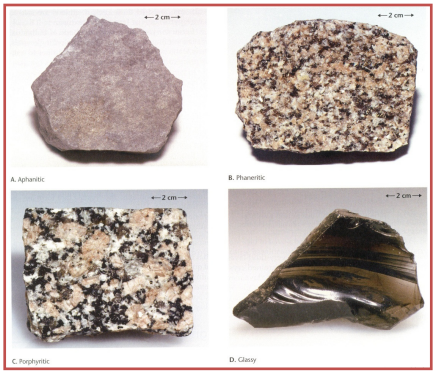
- Igneous Rocks
- Sedimentary Rocks
- Metamorphic Rocks

Igneous rocks can be classified as intrusive or extrusive types.

a) **Intrusive** (plutonic) igneous rocks form when **magma** cools and crystallizes (solidifies).

b) **Extrusive** (volcanic) igneous rocks result when **lava** cools at the surface.

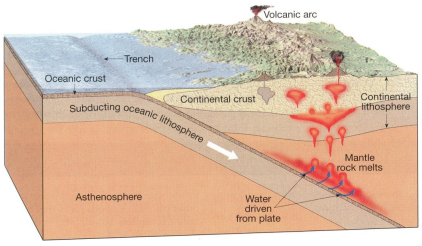
The rate of cooling greatly affects both the size, shape and arrangement of the crystals, a property called **texture**.



Molten rock (**magma**) originates in the mantle and crust as a result of partial melting of solid rock. Because the magma body is less dense than the surrounding rocks, it works its way toward the surface, occasionally producing a volcanic eruption.

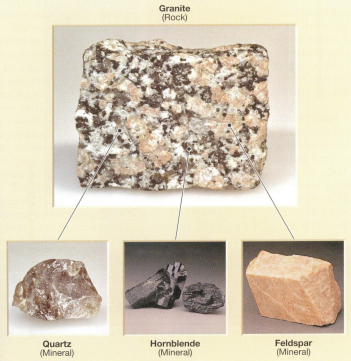
Most magma never reaches the surface. Rather it **crystallizes at depth** to produce intrusive or plutonic igneous rocks.

Although intrusive igneous rocks form at depth, uplifting and erosion often expose them at the surface.



Igneous rocks that form at the surface, or as small masses within the upper crust, possess a fine-grained texture termed **aphanitic**. The grains in **aphanitic** rocks are too small for individual minerals to be distinguished with the unaided eye.

When large masses of magma solidify **at depth**, they form igneous rocks that exhibit a coarse-grained texture described as **phaneritic**, within intergrown crystals that are roughly equal in size. Individual minerals can be identified with the unaided ey



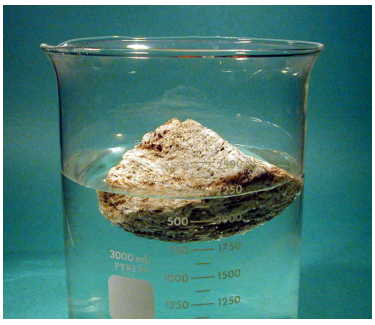
In addition to the igneous textures already considered, some igneous rocks have **large** crystals (phenocrysts) embedded in a matrix of **smaller** crystals (groundmass). These rocks are said to have a **porphyritic texture**.

http://nicholas.duke.edu/eos/geo41/rks.htm

Rapid cooling of lavas may generate a glassy texture. Glass results when the ions are **unordered**, i.e. they have not formed an orderly crystalline structure.

Rocks with a glassy texture, like **obsidian**, also form when silica-rich lava is extruded as a viscous mass that solidifies as a glass.

During some volcanic eruptions, silica-rich lava is ejected into the atmosphere where it is **chilled** quickly. These events can generate a frothy mass of fine shards of interwined glass called **pumice**.



http://www.gc.maricopa.edu/earthsci/imagearchive/floating_pumice_big.jpg

Figure 3.4 Scoria is a volcanic rock that exhibits a vesicular texture. Vesicles are small holes left by escaping gas bubbles. (Photo by E. J. Tarbuck)

Grain size variation for granitic rocks

Plate 3.3 Pegmatite lens within coarse-grained granite

Plate 3.4 Coarse-grained granite

Plate 3.5 Medium-grained granite

Plate 3.6 Fine-grained granite

Plate 3.7 Rhyolite

Diffuse vs sharp contact

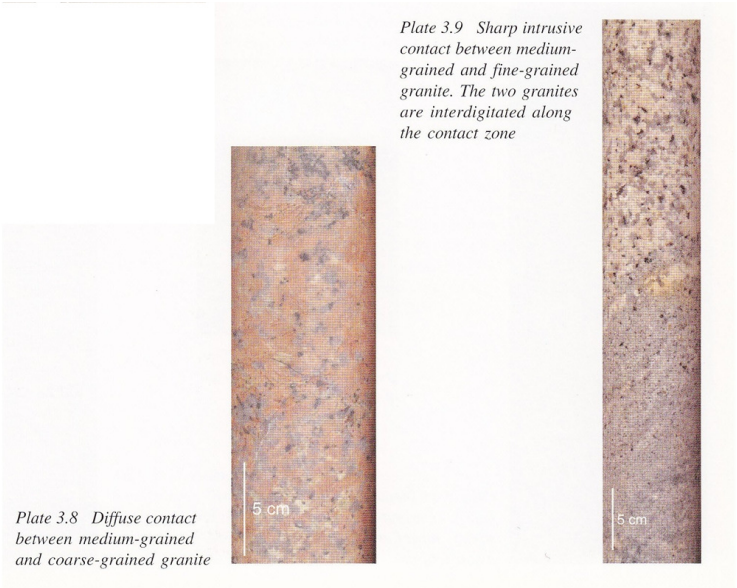


Plate 3.9 Sharp intrusive contact between medium-grained and fine-grained granite. The two granites are interdigitated along the contact zone

Plate 3.8 Diffuse contact between medium-grained and coarse-grained granite

Why does a **large variety of igneous rocks** exist, when the composition of magmas appears to be relatively homogeneous around the globe?

It can be explained by the **Bowen's Reaction Series**.

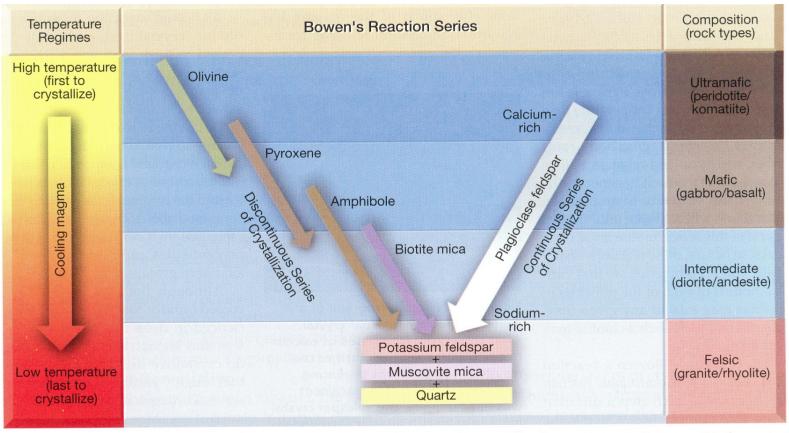


Figure 3.16 Bowen's reaction series shows the sequence in which minerals crystallize from a magma. Compare this figure to the mineral composition of the rock groups in Figure 3.7. Note that each rock group consists of minerals that crystallize in the same temperature range.

Mineralogy of common igneous rocks and magmas

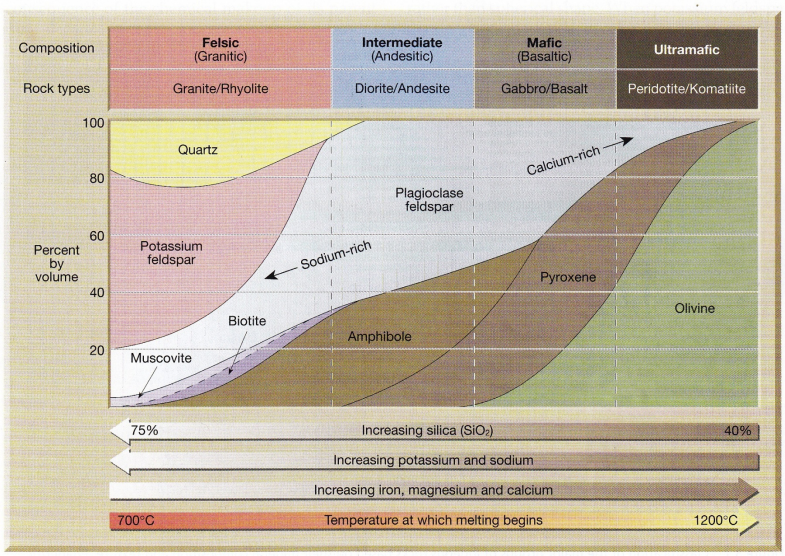


Figure 3.6 Mineralogy of common igneous rocks and the magmas from which they form. (After Dietrich, Daily, and Larsen)

Rocks

- Igneous Rocks
- Sedimentary Rocks
- Metamorphic Rocks

Sedimentary rocks form when the products of **weathering** (sediments) are transported to a new location where they are deposited and eventually **lithified** into solid rock.

Sediment has two principal sources:
1.Detrital material, which originates and is transported as solid particles from both **mechanical** and **chemical** weathering, which, when lithified, forms detrital sedimentary rocks.

Detrital sedimentary rocks

http://www.soil-net.com/album/Soils_Rocks/slides/Rock%20Conglomerate.jpg

2.From soluble material produced largely by **chemical weathering**, which, when precipitated, forms chemical sedimentary rocks.

Quartz, the other main component of granite, is very resistant to chemical weathering. Hence, with the decomposition of feldspar, quartz grains are released.

These **resistant** grains may accumulate as dunes, beaches, or other sandy deposits.

Erosional agents such as running water, wind, waves, and ice remove the products of weathering and transport them to other locations.

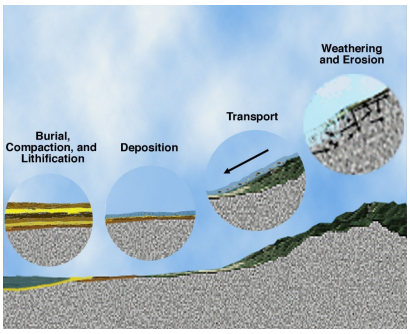
Eventually, these solid particles and dissolved substances, called sediment, are deposited.

Next, the sediments undergo **lithification**, meaning "conversion to rock". Unconsolidated sediments are transformed into solid sedimentary rock, mostly by **compaction** and/or **cementation**. **Sedimentary rocks** then form.

Compaction occurs when the weight of overlying materials compresses the deeper sediments.

Cementation occurs as percolating water coats the sediment with mineral matter, and gradually cements the particles together. The soluble cementing materials include calcite, silica, and iron oxide.

For recent deposits, the degree of compaction and cementation is still small, **sedimentary deposits** are formed. Sedimentary rocks are not yet formed.



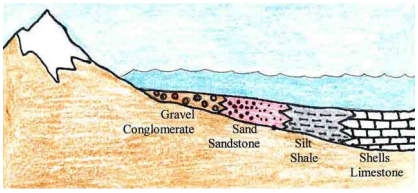
http://www.indiana.edu/~g103/G103/wk4/sedproc%20copy.jpg

Particle size is the primary basis for distinguishing among various detrital sedimentary rocks.

The **size** of the particles in a detrital rock indicates the **energy** of the medium that transported them. For example, gravels are moved by swiftly flowing rivers, whereas less energy is required to transport sand.

Table 6.1 Particle size classification for detrital rocks.

Size Range (millimeters)	Particle Name	Common Sediment Name	Detrital Rock
>256	Boulder	Gravel	Conglomerate or breccia
64–256	Cobble		
4–64	Pebble		
2–4	Granule		
1/16–2	Sand	Sand	Sandstone
1/256–1/16	Silt	Mud	Shale or mudstone
<1/256	Clay		



http://geologyonline.museum.state.il.us/tools/lessons/12.2/diagram.jpg

The particles in **conglomerate** become rounded as they are transported, most frequently by streams.

The angular pieces in **breccia** indicate the particles were not transported very far from their source prior to deposition.

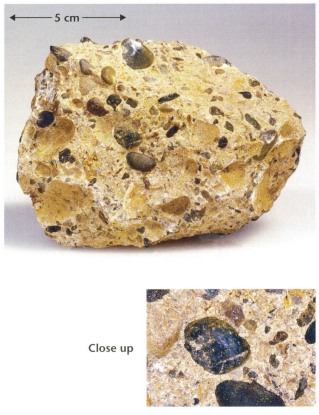


Figure 6.6 Conglomerate is composed primarily of rounded gravel-sized particles. (Photos by E. J. Tarbuck)

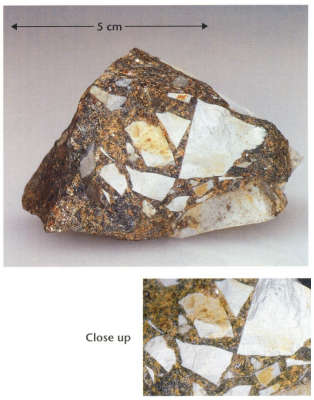
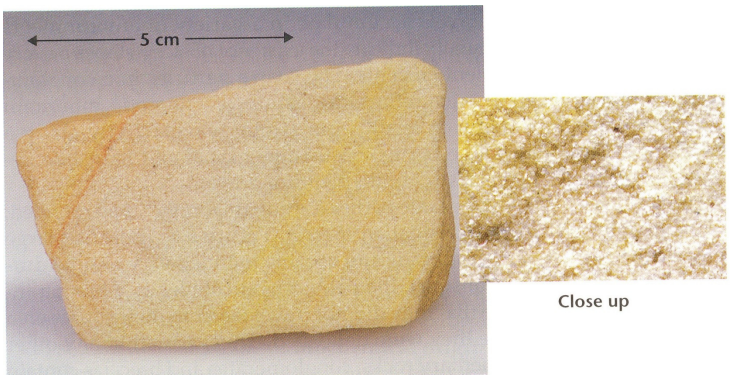


Figure 6.7 When the gravel-sized particles in a detrital rock are angular, the rock is called breccia. (Photos by E. J. Tarbuck)

Sandstone is the name given to rocks when sand-sized grains dominate. It is very durable due to the presence of quartz, the predominant mineral in most sandstones.



When substantial quantities of feldspar are present in **sandstone**, the rock is called **arkose**.

http://geology.about.com/od/rocks/ig/sedrockindex/rocpicarkose.htm

http://www.farleygraphics.com/geology.htm

The presence of **abundant feldspar** suggests that there was little chemical weathering of the sediment – something we might associate with a dry climate.

When the tiniest **silt** and **clay-sized particles** predominate, the common sediment name is **mud**, and **shale** or **mudstone** is the name given to the rock.

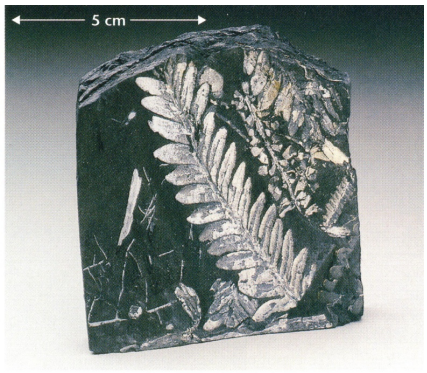


Figure 6.2 Shale is a fine-grained detrital rock that is by far the most abundant of all sedimentary rocks. Dark shales containing plant remains are relatively common. (Photo

Unlike detrital rocks which form from the solid products of weathering, the source of sediment for **chemical** sedimentary rocks is materials dissolved in water.

When material in **solution precipitates**, it forms chemical sediments, which become rocks such as limestone, chert, and rock salt.

Precipitation of chemical sediments occurs in two ways:
(1)by **inorganic processes** such as evaporation, temperature change, and chemical activity, or
(2)by **organic** processes of water-dwelling organisms that produce sediments of biochemical origin.

Limestone, the most abundant chemical sedimentary rock, is composed chiefly of the mineral calcite and forms either by inorganic means or as the result of biochemical processes.

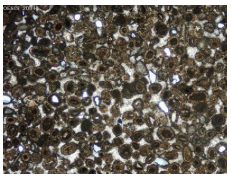
Inorganic limestones include **travertine**, which is commonly seen in caves, and **oolitic limestone (oolitie)**, consisting of small spherical grains of calcium carbonate.

travertine

http://njminerals.org/travertine.jpg

oolitic limestone (oolitie)

http://www.beachfamily.net/Martin/Oolite.html



Field of view 4.5 mm

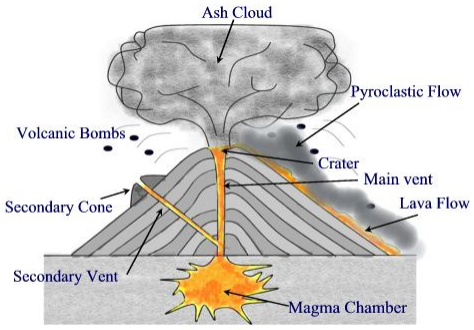
http://www.earth.ox.ac.uk/~oesis/micro/index.html

Table 6.2 Classification of sedimentary rocks.

Texture	Sediment Name and Particle Size	Comments	Rock Name
		DETRITAL ROCKS	
Clastic	Gravel (>2 mm)	Rounded rock fragments	Conglomerate
		Angular rock fragments	Breccia
	Sand (1/16–2 mm)	Quartz predominates	Quartz sandstone
		Quartz with considerable feldspar	Arkose
		Dark color; quartz with considerable feldspar, clay, and rocky fragments	Graywacke
	Mud (<1/16 mm)	Splits into thin layers Breaks into clumps or blocks	Shale Mudstone
Group	**Texture**	**CHEMICAL ROCKS Composition**	**Rock Name**
Inorganic	Clastic or nonclastic	Calcite, $CaCO_3$	Limestone
	Nonclastic	Dolomite, $CaMg(CO_3)_2$	Dolostone
	Nonclastic	Microcrystalline quartz, SiO_2	Chert
	Nonclastic	Halite, NaCl	Rock salt
	Nonclastic	Gypsum, $CaSO_4 \cdot 2H_2O$	Rock gypsum
Biochemical	Clastic or nonclastic	Calcite, $CaCO_3$	Limestone
	Nonclastic	Microcrystalline quartz, SiO_2	Chert
	Nonclastic	Altered plant remains	Coal

Volcanic eruptions may produce pyroclastic debris such as ash and cinders -> formation of pyroclastic rocks.

Along with **pyroclastic debris**, volcanic eruptions can produce extensive lava flows. (lava = on surface; magma = below surface)

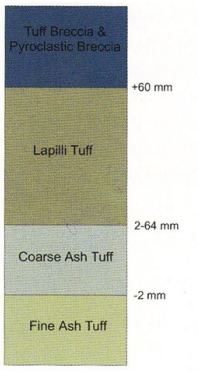


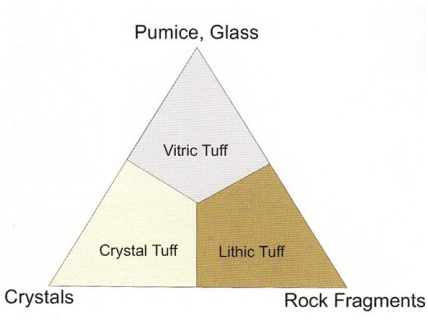
Main Features of a Volcano

http://rst.gsfc.nasa.gov/Sect2/VolcanoStructure.jpg

Pyroclastic rocks

- The rocks are named according to grain size (blocks, lapilli, ash) and main components (crystals, rock fragments, glass)





Pyroclastic rocks

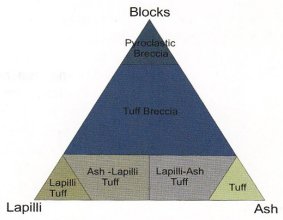


Figure 5.3 Classification of pyroclastic rocks based on clast size (after Schmid, 1981; Fisher & Schminke, 1984)

Plate 5.3 Lapilli lithic tuff

Plate 5.4 Coarse ash lithic tuff

Plate 5.5 Coarse ash crystal tuff

Plate 5.6 Fine ash vitric tuff

Rocks

- Igneous Rocks
- Sedimentary Rocks
- Metamorphic Rocks

Metamorphism involves the transformation of pre-existing rocks (parent rocks). The parent rocks can be igneous rocks, sedimentary rocks, or even from other metamorphic rocks.

Metamorphism takes place where preexisting rock is subjected to **temperatures** and **pressures** unlike those in which it formed.

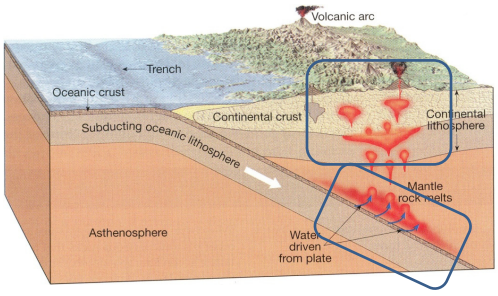
During metamorphism, the rock must remain essentially **solid**, for it complete melting occurs, we have entered the realm of igneous activity. The changes that occur in metamorphosed rocks are textural as well as mineralogical.

http://www.americansouthwest.net/arizona/photographs700/bwrocks.jpg

The agents of metamorphism are **heat, pressure (stress) and chemically active fluids**.

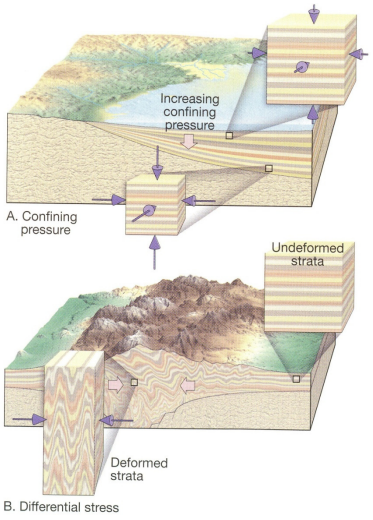
(1) Heat provides the energy to drive chemical reactions.

Rocks found near the surface of Earth may be subjected to intense heat when they are intruded by **magma**, a process called **contact metamorphism**.



Rocks may also be subjected to high temperatures if they are **carried deep** within Earth

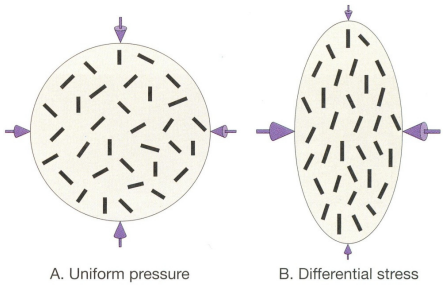
(2) Pressure, like temperature, also increases with depth. Buried rocks are subjected to **pressure**, or **stress**, exerted by the load above.



The **confining pressure** is applied equally in all directions and causes a reduction in volume, thereby generating a more compact (dense) rock.

Rocks are also subjected to forces during mountain building that are unequal in different directions, called **differential stresses**.

Subjected to differential stress, some minerals, such as micas which have a sheet structure, and hornblende which has an elongated structure, will recrystallize with a **preferred orientation**. The new orientation will be essentially perpendicular to the direction of stress.



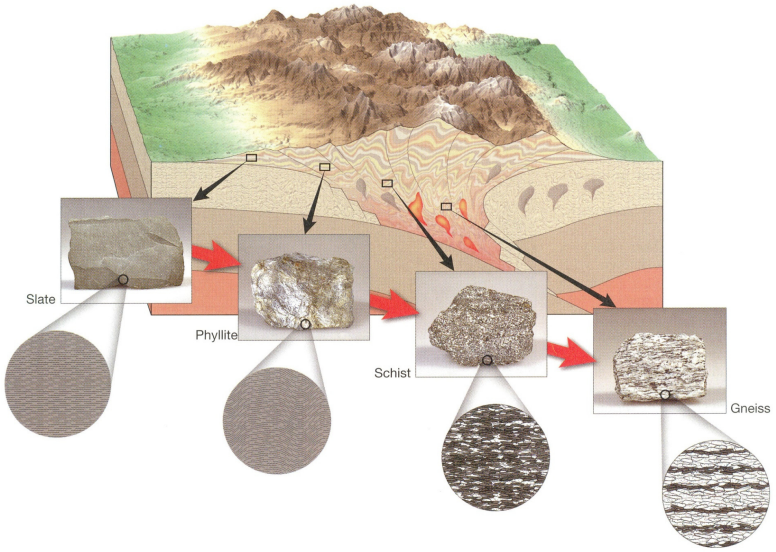
At depth, rocks are warm and ductile, which accounts for their ability to deform by flowing when subjected to differential stresses.

(3) Chemically active fluids, most commonly hot water containing ions in solution, also enhance the metamorphic process.

For example, along oceanic ridges, seawater circulates through hot **basaltic** rocks, transforming the existing iron-rich **minerals** into metamorphic minerals such as serpentine and talc

Source of chemically active fluids:
-Water in pore spaces in sedimentary rocks
-Water in fractures in igneous rocks
-Hydrated minerals such as clays, micas, and amphiboles

Common foliated metamorphic rocks include **slate**, **phyllite**, various types of **schists** (e.g. garnet-mica schist), and **gneiss**.



Foliation refers to any planar (nearly flat) arrangement of platy and elongated mineral grains or structural features within a rock.

Recall the term **texture** describes the size, shape, and arrangement of grains within a rock.

Figure 7.8 This rock displays a gneissic texture. Notice that the dark biotite flakes and light silicate minerals are segregated, giving the rock a banded or layered appearance. (Photo by E. J. Tarbuck)

Foliated Textures

Slaty cleavage – The type of foliation characteristic of slates in which there is a parallel arrangement of **fine-grained** metamorphic minerals. It consists of closely spaced planar surfaces along which rocks split into thin, tabular slabs when hit with a hammer.

Schistosity – A type of foliation characteristic of **coarser-grained** metamorphic rocks. Such rocks have a parallel arrangement of platy minerals such as micas.

Gneissic texture – The texture displayed by the metamorphic rock gneiss in which dark and light silicate minerals have separated, giving the rock a **banded appearance**.

Metamorphic rocks composed of only one mineral that forms equidimensional crystals are generally **nonfoliated**, e.g. marble (parent rock – limestone) and quartzite (parent rock – mostly quartz sandstone).

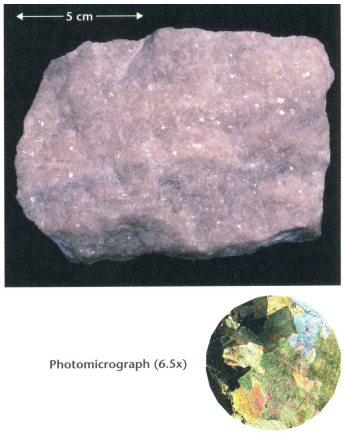


Figure 7.13 Marble, a crystalline rock formed by the metamorphism of limestone. Photomicrograph shows interlocking calcite crystals using polarized light. (Photos by E. J. Tarbuck)

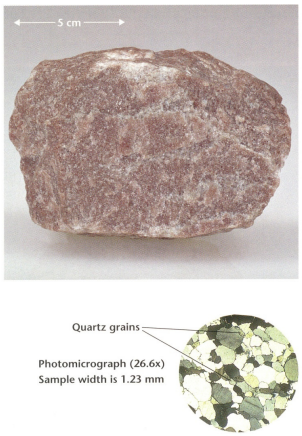


Figure 7.14 Quartzite is a nonfoliated metamorphic rock formed from quartz sandstone. The photomicrograph shows the interlocking quartz grains typical of quartzite. (Photos by E. J. Tarbuck)

Classification of metamorphic rocks

Rock Name	Texture	Grain Size	Comments	Parent Rock
Slate	Foliated (Increasing Metamorphism)	Very fine	Excellent rock cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite		Fine	Breaks along wavey surfaces, glossy sheen	Slate
Schist		Medium to Coarse	Micaceous minerals dominate, scaly foliation	Phyllite
Gneiss		Medium to Coarse	Compositional banding due to segregation of minerals	Schist, granite, or volcanic rocks
Migmatite		Medium to Coarse	Banded rock with zones of light-colored crystalline minerals	Gneiss
Mylonite	Weakly Foliated	Fine	When very fine-grained, resembles chert, often breaks into slabs	Any rock type
Metaconglomerate		Coarse-grained	Stretched pebbles with preferred orientation	Quartz-rich conglomerate
Marble	Nonfoliated	Medium to coarse	Interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite		Medium to coarse	Fused quartz grains, massive, very hard	Quartz sandstone
Hornfels		Fine	Usually, dark massive rock with dull luster	Any rock type
Anthracite		Fine	Shiny black rock that may exhibit conchoidal fracture	Bituminous coal
Fault breccia		Medium to very coarse	Broken fragments in a haphazard arrangement	Any rock type

migmatite

http://www.earth.edu.waseda.ac.jp/photogeology/200504rocky/BigornMtS/1K_DSC_0588.jpg

Fault breccia

http://www.portervillecollege.edu/richardgoode/Southern%20California%20Shoreline%20Features%20Pictures.htm

Rock Cycle

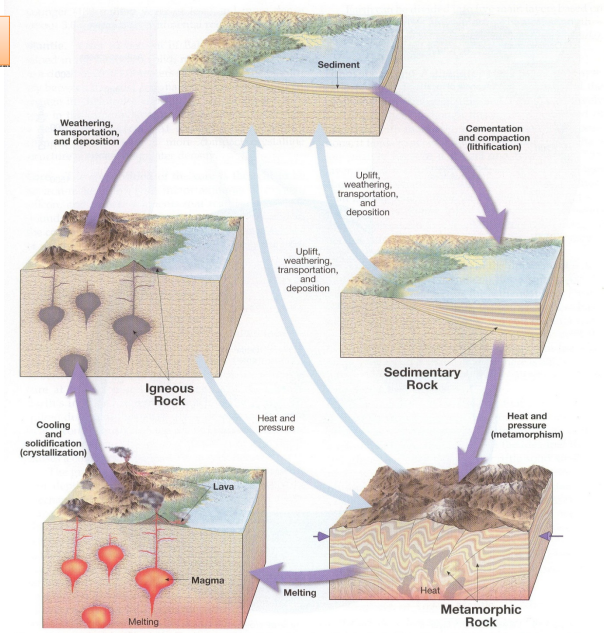


Figure 1.9 Viewed over long spans, rocks are constantly forming, changing, and reforming. The rock cycle helps us understand the origin of the three basic rock groups. Arrows represent processes that link each group to the others.

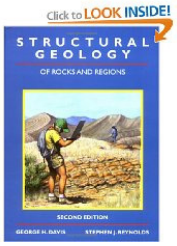
Topics for today

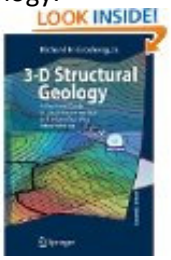
- Plate Tectonics
- Geologic Time Scale
- Minerals
- Rocks
- Rock Cycle
- Geological Structures
- Earth Processes

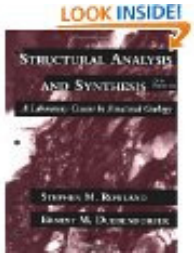
Geological Structures

- ***Structural geology*** is the study of the forms rock take in the earth's crust.

- Forces originating inside the earth cause movements on the land surface which result in the *displacement* and *rearrangement* of rock masses. The study of how earth movements affect rock masses is a fundamental part of geology.





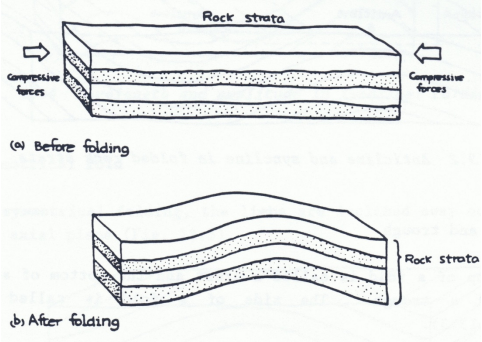


Geological Structures

- Folds
- Faults
- Joints

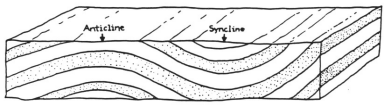
Folds

Formation – *compression* of the earth's crust through the movement of crustal plates has folded the rocks. Folds can most clearly be seen in rocks having *distinct bedding*, i.e. sedimentary rocks.



Anticline and Syncline

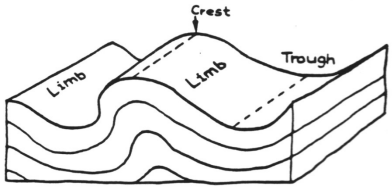
- An ***anticline*** is an upfold, in which the two sides or limbs dip *outwards* from one another.
- A ***syncline*** is a downfold, in which the two sides or limbs dip *towards* one another.

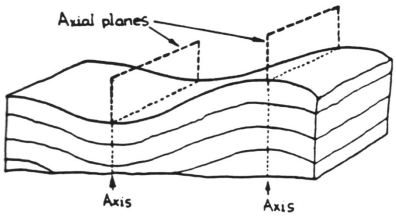


Synclinal folds in bedrock, near Saint-Godard-de-Lejeune, Canada. (Source: Natural Resources Canada).
http://www.eoearth.org/article/Folding_and_faulting_in_the_Earth's_crust

Crest, Trough, axis, axial plane

- The top of a fold is called a ***crest*** and the bottom of a fold is called a ***trough***.
- The side of a fold is called a ***limb***.
- The two limbs of a fold meet in a line which is called the ***axis of the fold***.
- A surface passing through the axis of each bed forms an ***axial plane***.





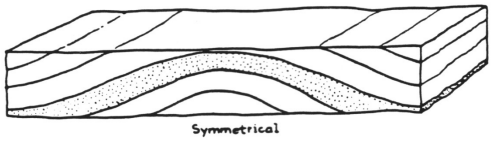
Symmetry of fold

- Symmetrical fold
- Unsymmetrical fold
- Recumbent fold

See examples on following slides

Symmetrical Fold

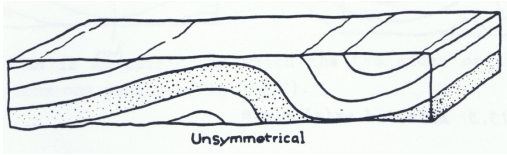
The limbs are inclined away equally from the axial plane.



http://farm3.static.flickr.com/2547/4001796006_efd1c0e9a9_m.jpg

Unsymmetrical Fold

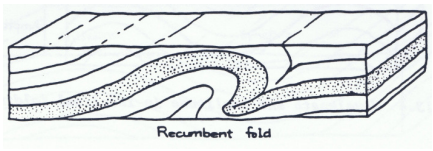
One limb of the fold is steeper than the other.

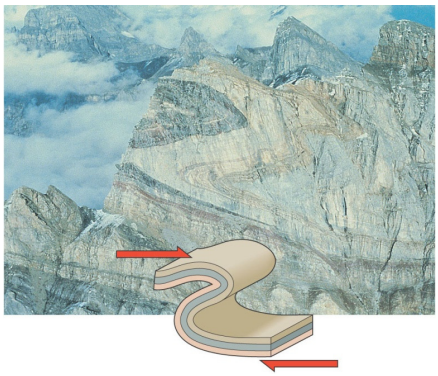


http://www.science.ulster.ac.uk/qec/Rock%20tectonics.html

Recumbent Fold

The fold many be so distorted that it is overturned. Such a fold is called a ***recumbent*** or an ***overturned*** fold. Note that in such folds, one limb of beds is inverted or upside down.

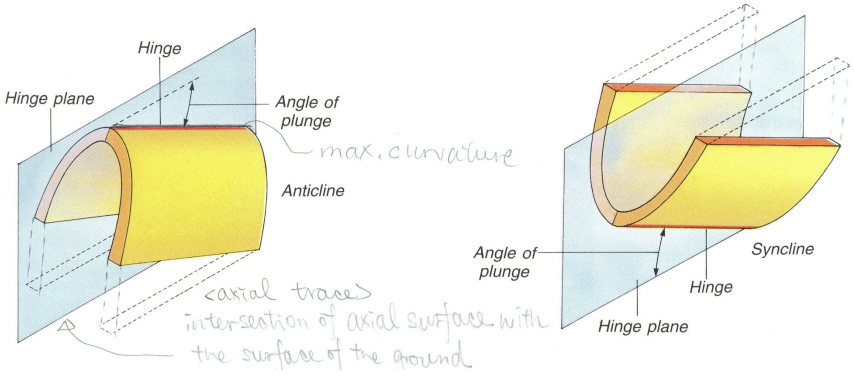




http://www.indiana.edu/~g103/G103/week9/recumb.jpg

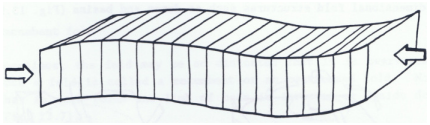
Plunge/Pitch

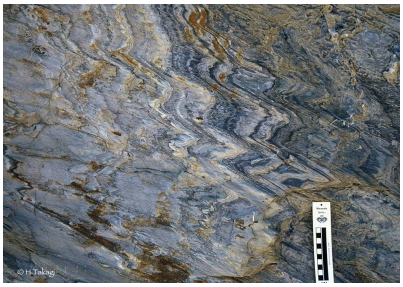
Folds are described to plunge or pitch when the fold hinge is inclined towards the horizontal.



Effects of Folds on Rocks

1. **Cleavage formation** – A cleavage often results from folding and is oriented at **90º** to the direction of maximum pressure.

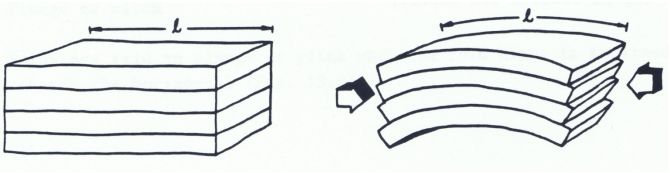




http://www.dept.edu.waseda.ac.jp/htakagi/HideoPhoto/Nepal/Syabrubensi%20MCT/Syabrubensi%20MCT.html

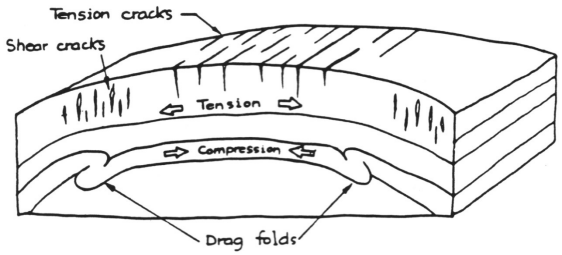
Effects of Folds on Rocks

2. **Stress inducement** – In true folding, the length of beds remains constant and slip occurs between and along bedding planes. This type of folding can be illustrated by bending a pack of cards. In the diagram, "**l**", the length of a bed, is constant.



Effects of Folds on Rocks

3. **Stress inducement** (cont) – Folding induces stresses in rocks similar to those induced when a concrete beam is bent, i.e. tension and compression. Such stresses in rocks cause tension cracks, shear cracks and drag folds.



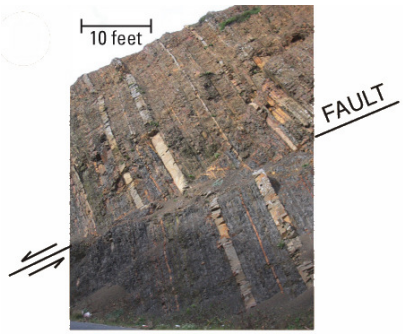
Geological Structures

- Folds
- Faults
- Joints

Faults

Brittle rocks, however, may not deform into folds but fracture along a plane surface. Such a feature is called a fault.

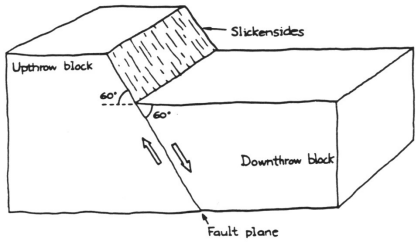
Faults are dislocations or breaks in the earth's crust along which ***displacements*** may have occurred and continue to occur. Such movement can be vertical, horizontal or inclined.



http://geomaps.wr.usgs.gov/sfgeo/quaternary/images/fault.jpg

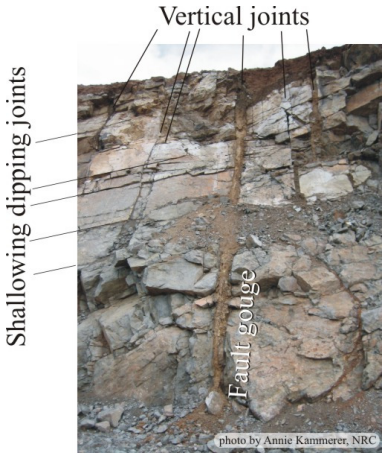
Faults - features

- The surface of the break is called a fault plane and this dislocation surface has a *dip* (dip angle) and a *strike*.
- The fault plane is, in fact, a *fault zone* containing broken rock called fault **breccia** (angular broken rock), **mylonite** or **gouge** (powdered rock or clay). In a big fault, this fault zone may be many metres wide.



The direction of movement of a fault can sometimes be found by scratches or striations on fault planes known as *slickensides*.

Fault Gauge



http://www.geolab.unc.edu/faculty/glazner/Images/Structure/Faults.html

Fault Breccia

http://www.hrg.ca/i/photos/prognoz01.jpg

Slickensides

http://www.emgs.org.uk/files/gallery/165_slickenside_ecton_240609.jpg

http://geology.about.com/od/geoprocesses/ig/slickensides/slickbasaltclose.htm

This sample displays the aligned mineral grains and polished surface that define a slickenside.

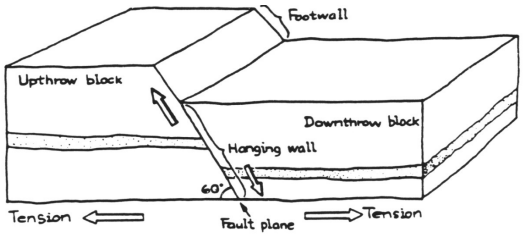
Faults - features

Similar to folds, there are ***qualitative*** and ***quantitative*** ways to describe the fault occurrence in the field.

http://www.geology.wisc.edu/courses/g112/Images/salv_faults.jpg

Fault Type – (1) Normal Faulting

- This is the most common type of faulting, with the fault plane at about 60^{o} to the horizontal.
- It is thought to be due to the tension in the earth's crust, and, during normal faulting there is an increase in the length of the earth's crust. The upper side of an inclined fault is known as a ***hanging wall*** and the lower side is known as a ***foot wall***.

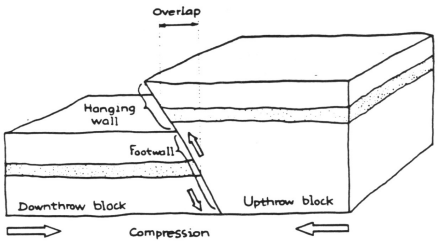


Concept of **footwall** and **hanging wall** at a small fault near Las Vegas, Nevada. Their feet are on the footwall, and the hanging wall is hanging over their heads. This is a small **normal fault**. Grooves and scratches on the fault plane run down the dip of the plane.

http://www.geolab.unc.edu/faculty/glazner/Images/Structure/Faults.html

Fault Type – (2) Reversed Faulting

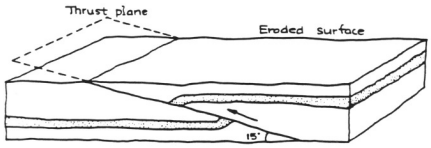
- This is less common than normal faulting.
- It is thought to be due to the compression in the earth's crust, and, during reverse faulting there is a decrease in the length of the earth's crust. The upthrow block will form an ***hanging wall*** and will overlap.

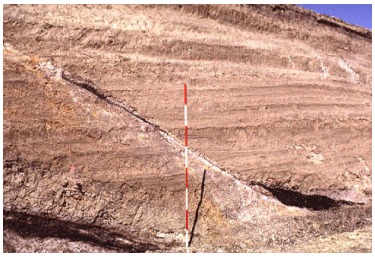


http://rst.gsfc.nasa.gov/Sect2/Sect2_7.html

Fault Type – (3) Low-angle Faulting (Thrusts)

- **Low-angle**, flat-dipping faults due to compression in the earth's crust are called thrusts, and are commonly oriented at **15º** to the horizontal.
- The displacement may be kilometres in length and , in some places, older rocks have been thrust over younger rocks.

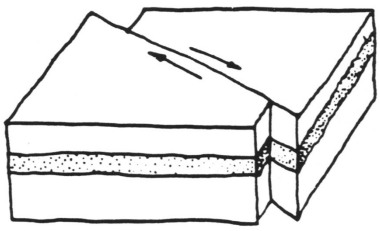




http://academic.emporia.edu/aberjame/ice/lec16/f16l2.jpg

Fault Type – (4) Transcurrent Faulting

- Movement is **horizontal**.
- Displacements can be very large – many kilometres in some cases.
- It is thought that movements of a few centimetres or metres take place at irregular intervals.
- The San Andreas fault moved 7 metres in 1906.



Geological Structures

- Folds
- Faults
- Joints

Joints - general

- **Joints** are cracks or breaks in rock along which there is ***no*** movement or displacement.

http://www.outreach.canterbury.ac.nz/resources/geology/page6.shtml

Joints – hexgonal joints

- **Shrinkage joints** are produced by the drying out of sediments or by the cooling of molten lavas (not magma!).
- **Columnar jointing** is common in lavas where shrinkage cracks develop around regularly spaced centres towards which tensional stresses coverage.
- Interferences between neighbouring centres leads to a honeycomb pattern of hexagonal joints.

http://www.answersincreation.org/curriculum/geology/usnv9106.jpeg

http://www.cedd.gov.hk/eng/about/organisation/kkh_brief.htm

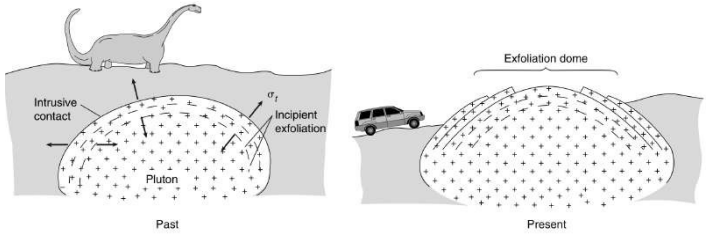
Joints – sheeting joints

- **Sheeting joints (exfoliation)**, which are related to topography, are roughly parallel to the **land surface** and may cause landslides on hillsides.

http://www.d.umn.edu/~pmorton/geol2300/geol2300pics/fieldtripphotos/sheetingjts42nd3.JPG

Joints – sheeting joints (cont)

- Earth surfaces is eroded and relieves **vertical stress** but **lateral stress** is not reduced proportionally. Therefore vertical stress becomes minimum principal stress and joints form perpendicular to land surface.
- **Shrinkage** of cooling plutons (large homogenous igneous masses masses may also produce sheeting joints or exfoliation.



http://ic.ucsc.edu/~casey/eart150/Lectures/Joints/OrigExfolJnts.jpg

Topics for today

- Plate Tectonics
- Geologic Time Scale
- Minerals
- Rocks
- Rock Cycle
- Geological Structures
- Earth Processes

Earth Processes

- **Weathering** – disintegration and decomposition of rock at or near the surface the earth through **physical** and **chemical** reactions with the atmosphere.
- **Erosion** – incorporation and transportation of material by a mobile agent, usually water, wind or ice.
- **Mass wasting** – transfer of rock material downslope under the influence of gravity.

Physical Weathering

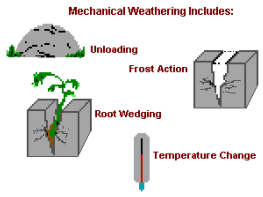
Unloading joints: stress relief fractures due to overburden removal

Thermal expansion: fracturing due to daily temperature change

Wetting and drying: movement due to loss of gain of water in clays

Root action: tree root expansion in fissures and rootlet growth in pores

Crystallization: growth of salt crystals where groundwater evaporates



http://www.berkeleycitycollege.edu/faculty/rhaberlin/images/mwmech.gif

Chemical Weathering

Dissolution (solution): mainly calcite and gypsum, in sandstone cement, veins and limestone

Leaching: selective removal of solutes or specific elements

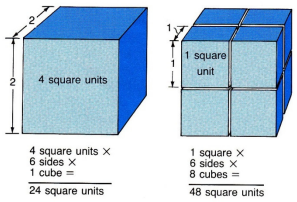
Oxidation: rusting and breakdown of iron

Hydrolysis: most silicates react with water to form clay minerals.

Weathering

- Rock disintegration is greatly ***influenced*** by patterns of joints, bedding, and other planes of structural weakness in the parent rock materials.

- The major results of weathering are
  - formation of a discontinuous blanket of disaggregated and decomposed **rock debris (regolith)**
  - rocks of various sizes modified into spherical forms.



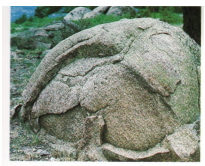


FIGURE 4.4 An example of spheroidal weathering. Successive shells are loosened as the weathering process continues to penetrate ever deeper into the rock. (Photo by Kenneth Hasson)

Weathering in Granite

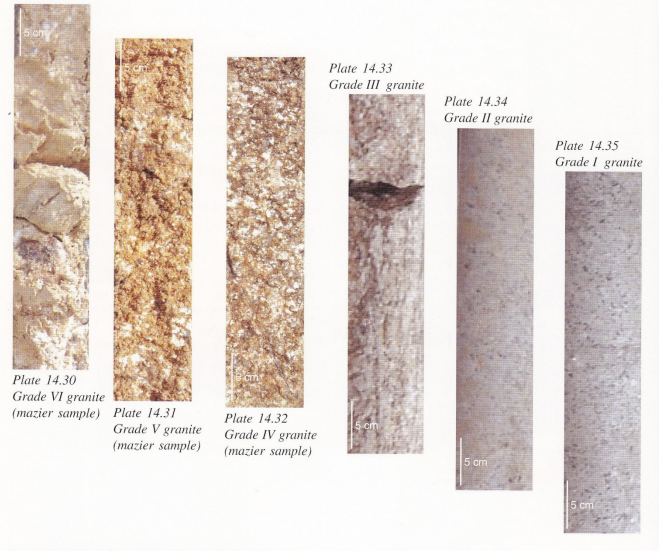


Plate 14.30
Grade VI granite
(mazier sample)

Plate 14.31
Grade V granite
(mazier sample)

Plate 14.32
Grade IV granite
(mazier sample)

Plate 14.33
Grade III granite

Plate 14.34
Grade II granite

Plate 14.35
Grade I granite